Radiation and the Universe

An overview of the class notes and handouts for a freshman seminar,
covering the emergence of Modern Physics and Astrophysics,
taught at Yale during fall semesters, 2004 – 2012.

Prof. Peter Parker
Yale University

Compiled in 2017.

Special thanks are acknowledged to Ann Dallavalle, my wife and my help-mate, for all her invaluable work, editing and properly referencing and formatting the materials in this compilation.

This material is intended for teachers (and others) with a background in physics and astronomy at the level of an "introductory" (non-calculus) college course. This material could be used as the basis for an upper-level AP high school course or for an introductory "freshman seminar" in any collegiate setting.

Caveat Emptor

Anyone wanting to use these notes is WARNED that a number of the sections are particularly subject to the danger of being out-of-date, even on an annual basis. These include especially Section E (Modern Nuclear Medical Applications), as well as Sections K – O (various techniques for energy production) whose pros and cons will undoubtedly face technical and scientific as well as political ups and downs in the future. Sections V, W, X are new and still developing fields that will continue to change and evolve.

TABLE OF CONTENTS

(A) In the Beginning

In a study of "Radiation and the Universe", **Day #1** is November 8, 1895. This is the afternoon during which Wilhelm Roentgen (University of Würzberg), while doing experiments with a cathode-ray tube (CRT or Crookes tube) in his lab in the cellar of his residence, discovered what he would label as *x-rays*. With the CRT device enclosed in black cardboard, in the completely darkened room, he observed that a piece of paper coated with a barium compound became fluorescent. It is important to note that, rather than simply putting this paper into a drawer in order to further darken the room, he proceeded to investigate the source and nature of the cause of this fluorescence.

During the next several days Roentgen worked long hours in secret in his laboratory, repeating and expanding his observations of the properties of these x-rays in order to convince himself of their reality. Finally, on December 28, he was confident enough to submit to the outside world the first paper describing his discovery. On January 1, l896, he distributed preprints of this pamphlet which included x-ray photographs (e.g., the x-ray image, Dec. 22, of his wife's hand with her wedding ring) to colleagues. Almost immediately (January 5) this sensational news began appearing in the local newspapers, and on January 13, he gave a demonstration of the properties of the x-rays to Emperor Wilhelm II in Berlin. The medicinal applications followed almost as rapidly, with the use of x-rays in the study of broken bones, kidney stones, and more being reported by mid-February. By the end of 1896 several private x-ray facilities had been established in hospitals and doctors' offices. Not surprisingly, not far behind was the application of such facilities to war injuries as early as 1897 in the British Sudan expedition, the Greco-Turkish war, the Boer war, the Spanish-American war, all before the turn of the century. Although already apparent in examples of skin inflammation and dermatitis from excessive x-ray exposures as early as the end of 1896, the careful study of the ill-effects of exposures to radiation does not begin until the early years of the 20th century and will be discussed in a later section. First, let us return to January 1896 and the "physics" consequences of Roentgen's discovery.

On January 20, 1896, Henri Becquerel (Museum of Natural History in Paris) was present at the weekly meeting of the French Académie des Sciences which included a discussion of Roentgen's work (one of many similar seminar discussions happening all over the world by that time). The connection between the x-rays and fluorescence/phosphorescence intrigued Becquerel who (along with his father and grandfather) had been studying luminescence for some time. Becquerel set about to systematically look for a connection between phosphorescent materials and x-rays, since the source of Roentgen's x-rays had been identified as the phosphorescent spot where the CRT beam struck the wall of the tube. The search was carried out by exposing to bright sunlight samples of phosphorescent materials positioned on top of photographic plates which had been protectively wrapped in 2 sheets of very thick black paper.

Becquerel found no effect until he used a sample of uranic salts, and he reported the exciting result in a paper to the Académie des Sciences on February 24, 1896. He carried out further tests to study this result, but on February 26 and 27 there was no sunshine in Paris, and so the plate and the uranic salt sample were put in a dark cabinet. After several additional cloudy days, on March 1 Becquerel decided to develop the photographic plate, in spite of the lack of phosphorescence from exposure to bright sunlight, and he discovered that the image of the material was even stronger than if it had been exposed to the full sunlight.

Apparently the penetrating rays which had formed this image had nothing to do with phosphorescence.

Back to the Académie des Sciences on March 2, with a <u>revised</u> and even more dramatic result.

[**The discovery of "Uranic Rays" → "Becquerel Rays" → *Radioactivity*.]**

At this same time, there were two young graduate students - *Marie Curie* (née Sklodowska) from Poland, who was studying physics at the Sorbonne in Paris and working in the area of magnetism in tempered steels, and *Ernst Rutherford* from New Zealand, who was studying physics at the Cavendish Lab in Cambridge where he was working on ionization and recombination and the detection of radio waves at longer and longer distances. As soon as they learned of the newly discovered Becquerel rays, they each immediately switched their life-long research into this field in which they rapidly became leaders, each going on to become Nobel prize winners. We shall hear much more about their work in the sections below.

[An amusing urban legend has it that Rutherford was out digging potatoes on their farm in New Zealand, when his mother came out with the letter from Cambridge accepting him into their program, whereupon he threw down his spade and announced "That's the last potato *I'll dig!" (Richard Rhodes, p. 37.)]*

"Hand mit Ringen", Roentgen's first x-ray shadowgraph of his wife's hand. Through no design of Roentgen's and much to his surprise, this dramatic photo (taken on 22 December 1895) was circulated rapidly throughout the world and in the press, turning him into an instant celebrity.

*(Photo is from Otto Glaser, **Wilhelm Conrad Rontgen und die Geschichte der Rontgenstrahlen**, Springer-Verlag, Berlin, 1931.)*

Fig. A-1

Fig. A-2

"Hands were especially popular that first year. Everyone with access to a newspaper had seen Frau Roentgen's famous ringed finger, so it was reasonable in February for the prominent New York surgeon William Tillinghast Bull to want an x-ray of the hand of one of his patients. A wealthy New Yorker, Prescott Hall Butler had accidentally shot more than one hundred pieces of buckshot into his own hand. Bull brought him to the Columbia University laboratory of the physicist Michael Pupin who, as a friend of Edison, had received a sample fluoroscope. Doubled over in pain, Butler managed to unclench his hand just long enough for the surgeon to see it on the fluoroscope."

"At this time, and for some years to come, most radiographs, such as x-ray pictures are called, took up to an hours' exposure. But as Butler clearly could not endure such a sitting, Pupin was inspired to make an instant improvement. He combined the luminescent screen of the fluoroscope with a photographic plate by placing the screen on the plate with the patient's hand atop the screen. The rays acted upon the screen first, and the screen's fluorescent light acted on the glass

plate. As Pupin recorded, "A beautiful photograph was obtained with the exposure of a few seconds. The photographic plate showed the numerous shot as if they had been drawn with pen and ink." Pupin's intensifying screen, as it was later named, was eventually adapted by many people, and Dr. Bull became the first surgeon known to have used an x-ray as an operating guide."

Naked To The Bone: Medical Imaging In The Twentieth Century
By Bettyann Kevles p. 35-36
Published by Perseus Books Group (1997)
020132833X (ISBN13: 9780201328332)

Four Remarkable Months

November 08, 1895	Roentgen discovers x-rays coming from the phosphorescent spot at the end of a cathode ray tube.
December 22, 1895	The x-ray image of Frau Roentgen's hand.
December 28, 1895	Roentgen submits first paper on x-rays.
January 01, 1896	Roentgen mails preprint pamphlet to colleagues.
January 05, 1896	News of x-rays and their images published in local newspapers.
January 13, 1896	Roentgen demonstrates x-rays to Emperor Wilhelm II.
January 20, 1896	Becquerel attends a seminar about x-rays at the French Académie des Sciences.
February 24, 1896	Becquerel reports back to the Académie about an observed connection between phosphorescent uranic salts and x-rays.
March 02, 1896	Becquerel reports back to the Académie that the observed effect has nothing to do with phosphorescence but is due to the uranium - uranic rays.

References:

G.E.M. Jauncey, "The Birth and Early Infancy of X-rays", American Journal of Physics, 13(1945), 1.

Abraham Pais, Inward Bound, Oxford University Press (1986), Chapters 1, 2, 3.

Richard Rhodes, The Making of the Atomic Bomb, Simon & Schuster (1986), Chapter 2.

H.H. Seliger, "Roentgen and the Glimmer of Light". Physics Today (Nov. 1995), p. 95.

A.B. Wolbarst, Looking Within, Univ.of California Press (1999), Chapter 1.

(B) Radioactivity Rays?

The next question has to be: What is the nature of the penetrating "uranic rays" associated with this new discovery? There were found to be three different components to these rays:

(1) One identical to J.J.Thompson's newly discovered (1897) "electron" particle in the CRT beam which could be bent in a magnetic field as a particle with mass and a negative charge.

(2) A much more massive particle with a positive charge of twice that of the electron and capable of much less penetration.

(3) An uncharged particle which was much more penetrating than the other two and came to be recognized as an electromagnetic photon. This photon was about 1000x more energetic than Roentgen's x-rays which themselves were about 1000x more energetic than visible light photons.

The radioactivity rays were arbitrarily labeled as α β γ for the positively charged, negatively charged, and neutral particles, respectively. See the comparative diagram below, from Marie Curie's Ph.D. thesis. (Fig. B-1)

[Looking forward to Section (C), because of their very different penetrabilities αs, βs , and γs have very different bio-medical effects. For example, beta particles and gamma rays can penetrate well into a human's body, while external alpha particles are effectively stopped by the layer of dead cells on the surface of our skin. Alpha-activity, however, can be very dangerous if it is ingested into the blood stream or the lungs where there is <u>no</u> protective layer of dead skin.]

The nature of α-particles was established by a very elegant experiment by Rutherford and Royds in 1908, in which α-particles from a radioactive source (radon) were collected through a very thin glass window into a vacuum chamber in which, via an electric discharge, they were observed to emit the characteristic atomic lines of <u>helium</u> . See (Fig. B-3) the diagram of their glass apparatus.

Helium is an element first discovered in the optical spectrum of the sun in 1868 by the astronomer Norman Lockyer and correspondingly named after the Greek sun god, Helios. In the early 1890s the Harvard astronomer Antonia Maury found a series of unknown lines in stellar spectra in the constellation Orion, which she labeled as "Orion lines". And in 1895, the English chemist, William Ramsey, reported that spectral analysis of the gas given off when the uranium compound, cleveite, was dissolved in sulfuric acid could be matched to Maury's Orion lines and to Lockyer's helium line.

This association of helium with uranium could have undoubtedly suggested their experimental test to Rutherford and Royds.

1868	Solar Eclipse "Helium"
1895	Gas in Terrestrial Uranium Ore
1908	α Particles = Helium

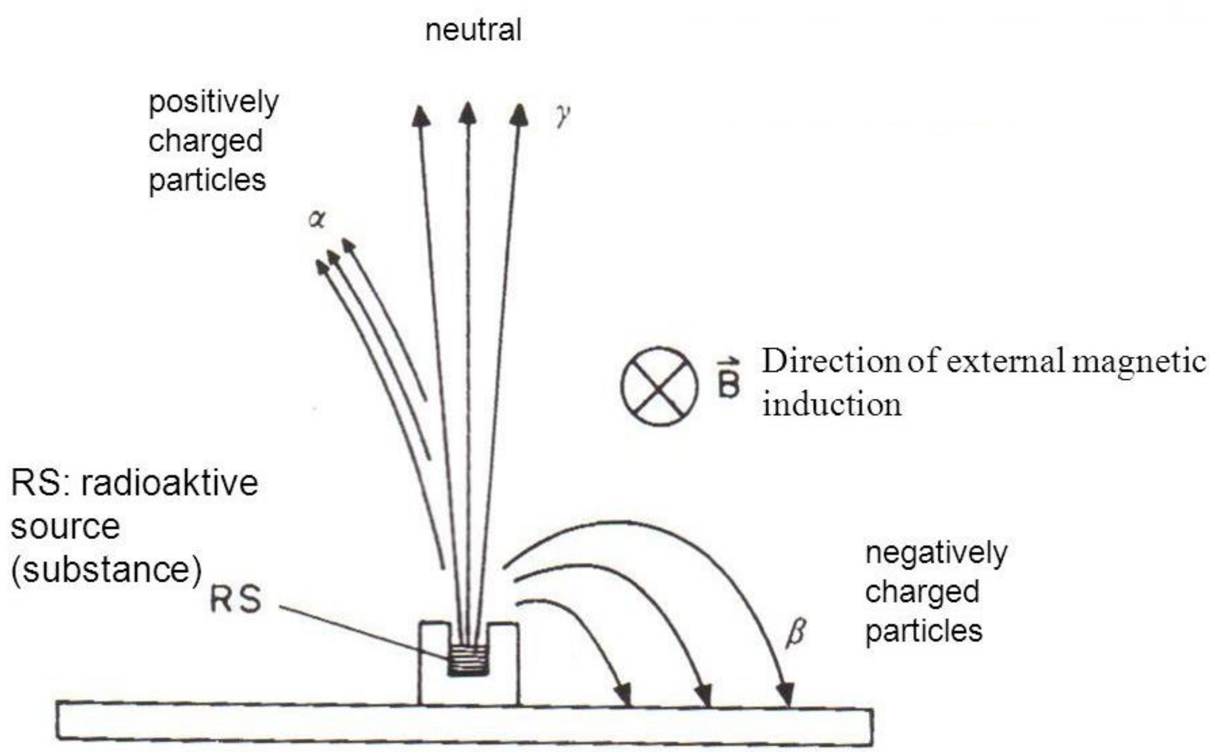
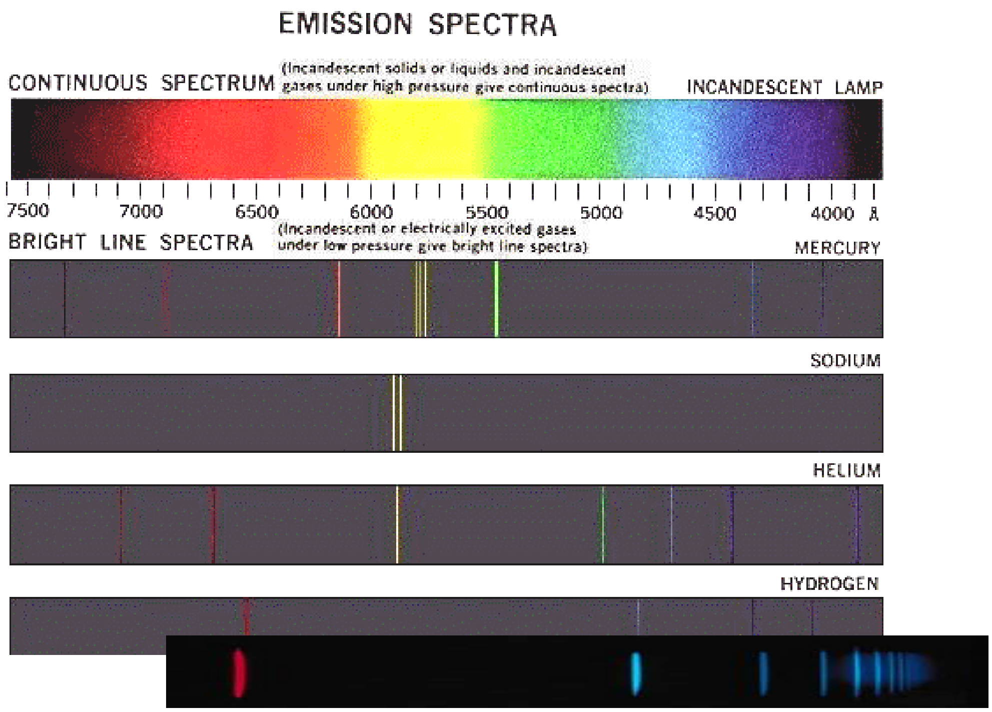


Fig. B-1

Original figure from Marie Curie's thesis (1904) illustrating the way that alpha particles are bent very little by a magnetic field whereas beta particles are bent much more, and gamma rays are not bent at all.

Fig. B-2



The Hydrogen spectrum (Balmer lines, Schalow,1988) show the UV lines as well as the visible lines.

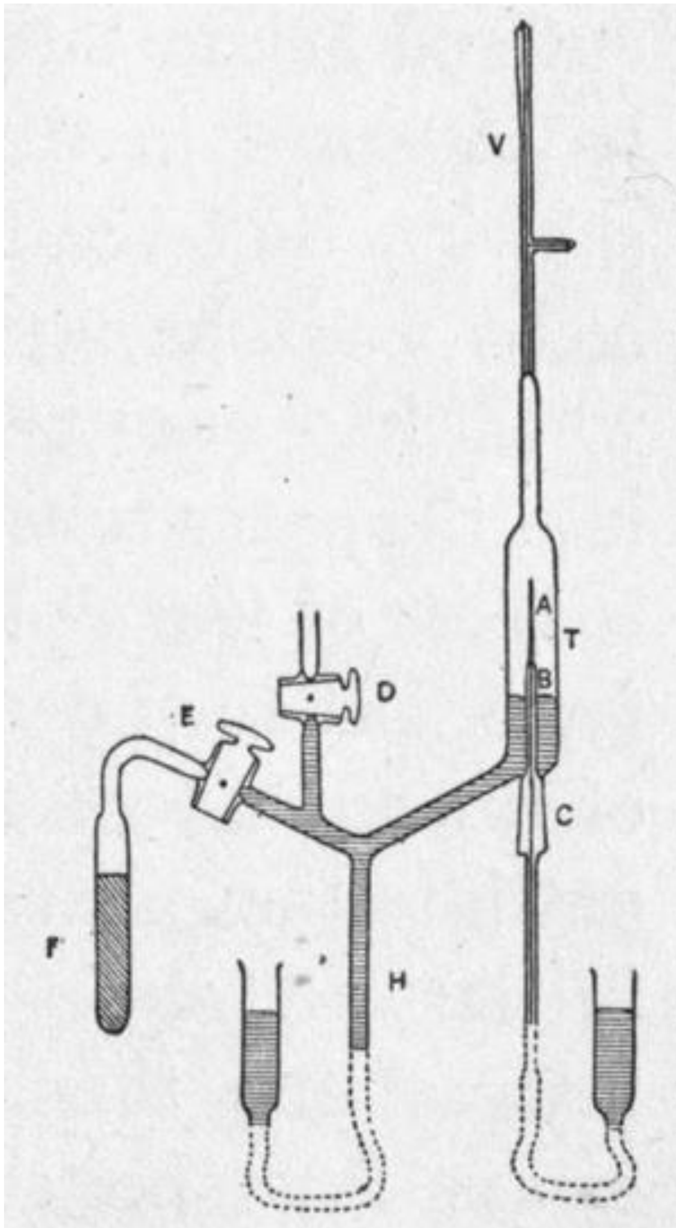


Fig. B-3

Radon contained in the thin-walled capillary tube AB expels alpha particles through the walls. Helium accumulates in the evacuated space T and when compressed in the capillary V shows, in an electric discharge, the characteristic spectrum of helium. [E. Rutherford and T. Royds, 1908.]
{Ref.: Mackintosh, et al.}

∴ All helium atoms in your party balloons are alpha particles emitted in the radioactive decay of uranium and thorium in the earth's rocks and ores.

References:

R. Mackintosh, J. A. Khalili, B. Jonson, T. Peńa, Nucleus, Johns Hopkins Univ. Press (2001), Chapter 5.

Abraham Pais, Inward Bound, Oxford University Press (1986), Chapters 1, 2, 3.

A.L. Schawlow, AIP Conference Proceedings #169, A.I.P. (1988). p. 26 (Fig.2).

Dava Sobel, The Glass Universe, Viking Press (2016), Chapter 4.

* *

With its Midterm paper and its Final term paper, over the years this seminar evolved into a “writing intensive” course for which the students could claim a Writing credit as well as a Science credit.

To emphasize this, during the first session of the course the students were given the assignment to buy a helium balloon and take it for a ride in a car (someone else driving!) and write a one page description of how the balloon behaves.
Being “Yalies”, one year one group reported taking the train to NYC and hiring a cab to drive them around a block 2 or 3 times(!). ☺ Most students contented themselves by taking advantage of a Yale van or a friend’s car to drive around New Haven.

(C) First Signs of Danger

In the midst of all the excitement over Roentgen's x-rays, the danger of x-ray exposure was noticed as early as 1896, especially in the application of this radiation to biomedical purposes. Although even small doses could be effective, it was found that larger doses might lead to rashes and dermatitis (radiation burns), and as early as 1897 lesions from excessive x-ray exposures were observed that would not heal and could even result in death.

The bio-medical effects due to Becquerel's radioactivity also became apparent but not as quickly or as damagingly as for x-rays, probably because radioactive materials were not nearly as quickly utilized in medical applications. In looking to verify a 1900 report of an infection due to exposure to radioactive material, Friedrich Giesel taped a radium source to his arm for 2 hours and after two weeks observed a similar infection followed by loss of skin, which he reported in Ber. der Deutsch. Chem. Ges.(1900). In a parallel episode, Pierre Curie sent a radium source to Becquerel for use in a lecture demonstration. After finishing his demonstration, Becquerel stuck the source in a waistcoat pocket where he forgot about it for six hours. Ten days later he found that a red spot developed on his skin, followed by the skin peeling off. He wrote to Pierre Curie about this, and Curie's reaction was similar to Giesel's – to tape a radium source to his own arm for 10 hours - and did indeed confirm Becquerel's result. (This is the same decade as Walter Reed's self-exposure to a yellow fever mosquito to demonstrate the carrier of this disease.) Becquerel and Curie subsequently submitted a joint review of their experiences to the journal of the French Académie des Sciences, Comptes Rendu, **132,** 1289 (1901).

Another interesting piece of documented radiation burns and damage to the early workers in the field involves a social visit of the Rutherfords to the Curies in Paris to celebrate Marie's doctorate in 1903. Rutherford noted that after the evening's celebration, Pierre Curie brought out a tube "containing a large amount of radium in solution" and coated with zinc sulphide . "The luminosity was brilliant in the darkness, and it was a splendid finale to an unforgettable day." But Rutherford also noted that the light was bright enough to show Pierre's hands "in a very inflamed and painful state due to exposure to radium rays." (Richard Rhodes, <u>The Making of the Atomic Bomb</u> Chapter 2.)

One further noteworthy early incidence of harmful interaction of radioactivity with humans is the case of the "radium girls". In the 1920s, workers (typically young women) were employed to hand paint luminescent numbers on airplane cockpit dials, watch faces, etc., using paint containing radium. As a result of working in an unprotected environment, with significant quantities radium and radon, and particularly due to the not unusual habit of shaping the end of the paint brush with their tongues in order to get the finest, sharpest lines, these dial-painters began to develop (and some even to die horribly from) strange degenerative diseases relating to their teeth, jaws, fingers, bone marrow, etc. - essentially radium poisoning, with calcium in their bones being replaced by ingested radium. The struggle to recognize this problem and to work to protect such workers is a whole, separate study for social and economic history, and has been cited as an origin for the Occupational Safety & Health Administration - OSHA .

This was not and is not a **solved** problem from the 1920s and ′30s; it continues to be a problem for workers in a variety of hazardous occupations. A particularly relevant example for a course on radiation is the case of uranium miners exposed to environments of radon, as part of the nuclear weapons and nuclear power industries. See, for example, the biographical piece on Leo Larson, a laid-off uranium miner in Wyoming, coughing and spitting blood in the snow in The Backbone of the World (pp. 146-170).

While on the subject of radon, an additionally noteworthy issue is the presence of radon in the cellars of buildings (including houses) in areas where the radon resulting from uranium and thorium decays can percolate through the ground and through cracks to collect in basements. See Section D for more details.

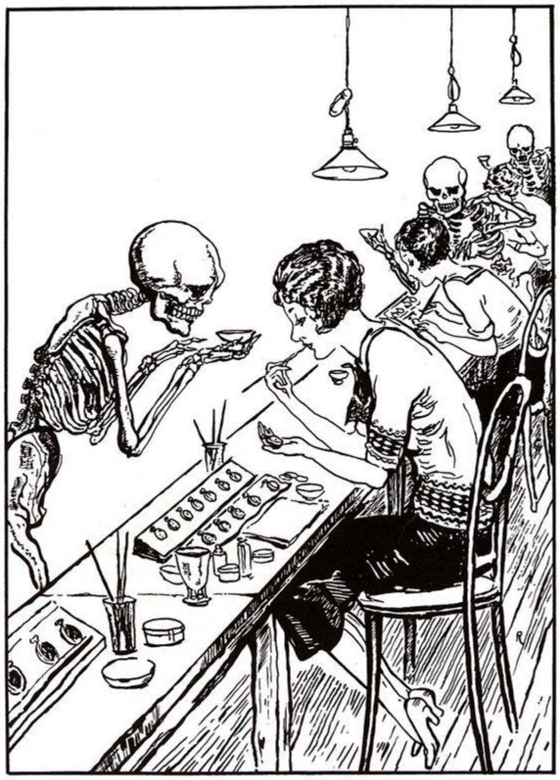


Fig. C-1

"Poisoned! – as They Chatted Merrily at Their Work
Painting the luminous Numbers on Watches, the Radium Accumulated in Their Bodies and Without Warning Began to Bombard and Destroy Teeth, Jaws and Finger Bones. Marking Fifty Young Factory Girls for Painful, Lingering, But Inevitable Death"

Through its newspaper empire, the Hearst Corporation distributed this drawing and headline to notify Americans about the plight of New Jersey's "Radium Girls". [From **American Weekly**, February 28, 1926.]

Obituary for Leo Larson, mentioned in Clifford's Backbone of the World

Leo Dean Larson

JEFFREY CITY - Jeffrey City resident Leo Dean Larson, 62, died Jan. 22, 2004, at Wyoming Medical Center in Casper, with his loving family beside him.

He was born June 30, 1941, in Albert Lea, Minn; and was a good friend.

Source: **http://trib.com/news/state-and-regional/obituaries/leo-dean-larson/article_27f2c0aa-86ff-5573-aa59-ed56173a84ab.html** (Casper Star Tribune)

References:

Claudia Clark, Radium Girls, Univ. North Carolina Press (1997).

Frank Clifford, The Backbone of the World, Broadway Books (2002).

Abraham Pais, Inward Bound, Oxford University Press (1986), Chapter 5.

Richard Rhodes, The Making of the Atomic Bomb, Simon & Schuster (1986), Chapter 2.

(D) Natural Radioactivity

The planet earth, including all life forms that inhabit it, is continually exposed to naturally occurring radioactivity (a) from the earth itself and (b) from cosmic rays bombarding the earth and its atmosphere. Terrestrial radioactivity originates in the rocks/ores of the earth – primarily in the long-lived isotopes of potassium, uranium, and thorium (and their subsequent decay products) that were part of the solar nebula that accumulated to form the earth about 5×10^9 years ago.

Cosmic rays were discovered when Victor Hess, Vienna, (Fig. D-1) ascended in balloons (beginning in 1911) to measure the expected decrease of natural radioactivity due to the absorption of this radiation by the increasing thickness of air as he rose above the surface of the earth. Instead, after an initial decrease, he found that by a height of 1000 meters the intensity of radioactivity was about the same as at sea level, and that by an altitude of 5000 meters (~16,500 ft.) the intensity had increased to approximately 9 times the intensity observed at the surface of the earth. This was clearly evidence for an extraterrestrial source, one which can therefore become a consideration for people living and/or flying at high altitudes. As compared to living at sea level, living at an altitude of 2000 m. (~6,500 ft.) nearly doubles a person's exposure to cosmic radiation, but this is only about an 8% increase over the average total radiation exposure for non-smoking U.S. residents. For high-altitude flights from the U.S. to Europe, the corresponding increase is about a 3% increase per round trip per year which, especially for airline crews, can add up significantly and has even led to the discussion of whether or not they should be categorized as radiation workers.

Among the terrestrially occurring radioactivities to which average U.S. residents are exposed, more than half (56%) comes from radon. [See the attached pages from Nuclear Choices (Richard Wolfson.)] The particular risk from radon comes from the fact that it is a noble gas which does not get tied up chemically in filters but is easily ingested into our lungs where radon's alpha decays can be very damaging since there is not a protective skin layer to shield the active lung cells. Not only is this a problem for uranium miners (as in the case noted at the end of Section C), but in many states this is a large enough problem that the selling of a house now requires a radon test of the basement, and if the level is found to be above a set standard, sufficient ventilation must be added by the seller to bring the level down to the allowed standard. Attention to this problem first surfaced in Pennsylvania in December1984; see the CDC notes dated Nov. 1, 1985 at the end of this Section. As noted in the 1985 Editorial Note at the bottom of that page, "Since similar geologic deposits are found throughout the country, the elevated radon levels in Pennsylvania may indicate a much broader national problem." In fact, in 2016 there now exist online county-by-county EPA maps for all states. See, for example, the EPA maps indicating counties (in red) where one may expect to find in-house radon levels of more than 4 picoCuries/liter for the states of New York, New Jersey, and Maryland, surrounding Pennsylvania. In cases where radon levels are found to be > 4 pCi/l , the EPA recommends mitigation by means such as enhanced ventilation.

The second largest contribution to our annual radiation exposure comes from "medical" procedures which include x-rays and other diagnostic and therapeutic nuclear procedures. Currently, more than half of all hospital admissions involve such procedures. [See Sections E and F.]

Fig. D-1

Victor Franz Hess accompanied an electroscope into the sky in a balloon and discovered a fourfold increase in ionizing radiation as the atmosphere thinned out.

[Wolfson: Nuclear Choices, Chapter 3.]

Nuclear News: Radon

Among the decay products of uranium-238 is the radioactive gas radon -222. Radon is chemically inert, meaning its atoms do not combine with others. Its gaseous nature and its chemical inactivity allow radon to move readily through soil to the atmosphere, where it is normally diluted to harmless levels. But when radon in the soil encounters the basement of a house, it can enter through cracks, drains, or openings for pipes and wiring, or by diffusing through porous foundation walls. Radon decays, with a half-life of just under 4 days, to a sequence of radioisotopes that are chemically active and are readily absorbed by the linings of human lungs.

How serious is radon contamination in our homes? It was not until the mid-1980s that scientists recognized the extent of indoor radon exposure. In fact, indoor radon is now known to be the dominant source of radiation for most Americans, greatly exceeding what we get from other natural sources, from medical procedures, or from nuclear power plants and the testing of nuclear weapons. For the average American home, where radon activity measures about 50 decays per second per cubic yard, the radon increases one's chance of fatal lung cancer by about 0.5 percent. This risk is far less than the nearly 30 percent increase in the chance of death due to cigarette smoking, and is only one-fourth as great as the one-in-fifty chance the average American has of dying in a car accident. But it is equal to the risk of dying in a fall or a fire at home, and it greatly exceeds the risks associated with other environmental pollutants, many of which are regulated to prevent cancer risks from exceeding one in a million. Put another way, the radiation doses the average American receives from indoor radon *each year* exceeds the average *lifetime* dose to Europeans resulting from the Chernobyl accident. Should we be alarmed? Should we do something? Should we stop worrying about nuclear accidents or other radiation sources that are less significant than indoor radon? These are nuclear choices, and they are not easy choices.

In some American homes – a small percentage, but still numbering perhaps 100,000 – the radon level is more than 10 times the average. In these homes, the risk from indoor radon is comparable to the risks from car accidents. Factors that increase a home's radon concentration include location (since uranium content of soils varies with geological factors), type of soil (since clay soil inhibits the flow of radon whereas sand and gravel offer little resistance), the material and condition of the foundation (since cinder blocks or cracks in concrete offer easy passage to radon), and the rate at which air infiltrates the house through poorly fitting windows or other loose construction. Ironically, radon problems may be exacerbated in tight homes designed for energy conservation. Fortunately, high radon levels are relatively easy to cure. By venting the soil below the foundation, radon is readily diverted to the outside atmosphere. The cost of doing this to an existing house is typically $1,000-$2,000. And by installing a simple under-foundation vent pipe at the time of construction, radon contamination in new homes can be effectively prevented at a cost of only about $200.

News sources: "Report Doubles the Estimate of U.S. Radiation Exposure," New York Times, November 20, 1987; "Major Radon Peril is Declared by U.S. in Call for Tests," New York Times, September 13, 1988.

[Wolfson: Nuclear Choices, Chapter 3.]

Nuclear News: Flying and Radiation

Cosmic radiation, originating in the Sun and other astronomical objects, provides a relatively small part of the average human being's normal radiation exposure. But airline crews and even passengers who spend a lot of time at high altitudes may experience much higher levels of cosmic radiation. In 1990, the U.S. Department of Transportation released a study showing that radiation doses to some flight crews could exceed those experienced by workers in nuclear power plants. On rare occasions, associated with bursts of radiation from solar flares, radiation levels in commercial aircraft exceed levels that would require high-radiation warnings in a nuclear power plant. The study showed that 100,000 airline workers flying for 20 years could develop 1,000 excess cancers as a result of exposure to cosmic radiation. An author of the Transportation Department's report urged that passengers in the crucial eighth to fifteenth weeks of pregnancy avoid flying over high-radiation routes.

The Federal Aviation Administration now finds itself wrestling with nuclear choices: Should airline crews be classified as radiation workers because of their exposure to cosmic radiation? Are the expected cancer deaths enough to warrant remedial action? How does this newfound risk weigh against the benefits of modern air transportation?

News source: "Radiation Exposure Is Termed a Big Risk for Airplane Crews," New York Times, February 14, 1990; "New Estimates Increase Radiation Risk in Flight," New York Times, February 19, 1990.

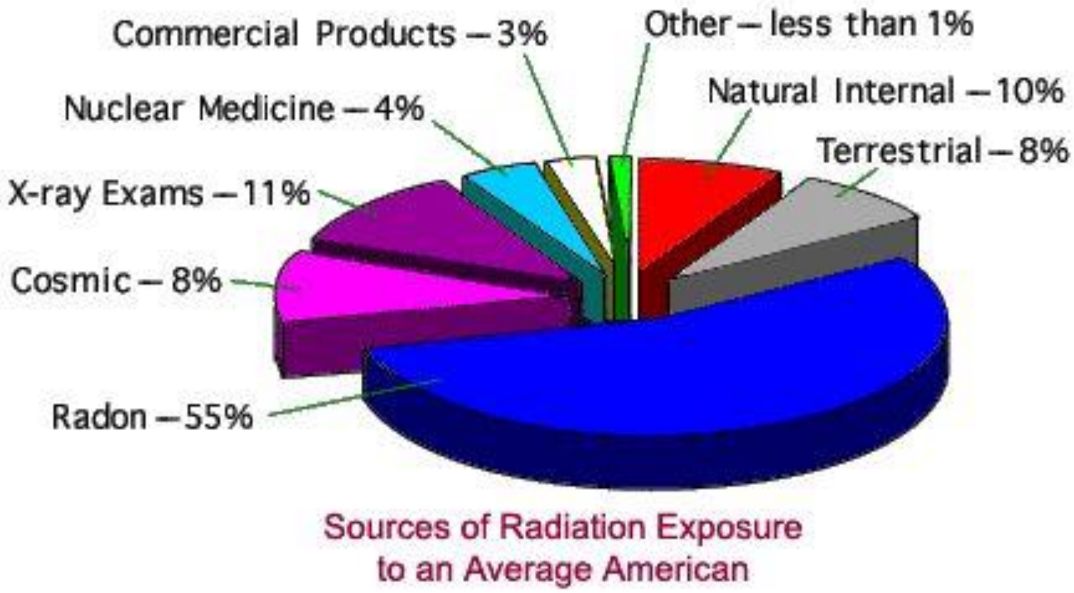


Fig. D-2

Data Source:
National Council on Radiation Protection
http://ncrponline.org/

CDC Home | Search | Health Topics A-Z

MMWR

Weekly

November 01, 1985 / 34(43);657-8

Health Hazards Associated with Elevated Levels of Indoor Radon -- Pennsylvania

As a part of the safety program at the Limerick Nuclear Power Plant in Pennsylvania, personnel entering the plant must pass through a radiation monitoring area. In December 1984, the monitoring device detected an abnormally high level of radiation in one construction worker. When an investigation was made to determine how and where this worker was being exposed to excessive radiation, investigators found that the air in the man's home contained extremely high levels of "radon daughters," the short-lived decay products of radon-222. Radon is an inert, radioactive gas formed in the decay chain of uranium-238. For each year the worker and his family lived in this house, they were exposed to over 50 times the annual occupational limit of exposure for uranium miners. The family relocated until remedial actions to lower the indoor radon levels could be completed.

As a result of this incident, in January 1985 state officials in Pennsylvania began a sampling program in which over 2,000 homes around the construction worker's house were examined. The homes are in an area of natural uranium deposits. Approximately 40% of the homes had radon levels exceeding the U.S. Environmental Protection Agency (EPA) guideline for indoor radon of 0.02 "working levels." A working level is a measure of radon daughter concentrations and is defined as any combination of radon daughters in 1 liter of air that results in 1.3 x 10((5)) million electron volts of potential alpha energy. About 7% of the homes tested had radon levels at or above the 0.1 working level. If residents in these homes spend 75% of their time indoors exposed to 0.1 working level, their yearly exposure would equal 4 working level months, the annual occupational limit of exposure. A working level month is a measure of exposure and is a function of the time of exposure and the level of radon daughters, given in working levels. Reported by J Logue, DrPH, J Fox, MD, Pennsylvania Dept of Health; Cancer Br, Div of Chronic Disease Control, Center for Environmental Health, CDC.

Editorial Note

Editorial Note: The elevated radon levels near the eastern border of Pennsylvania are associated with natural uranium deposits that extend into northern New Jersey and southern New York. Since similar geologic deposits are found throughout the country, the elevated radon levels in Pennsylvania may indicate a much broader national problem. Radon enters a building through cracks, such as those in a basement floor, and through openings around pipes and wiring. Once inside, the radon builds up in the air, particularly in poorly ventilated houses.

As radon daughters are formed, they attach to airborne particulates. When inhaled, these particulates can deliver a substantial dose of radiation to the bronchial epithelium.

No exposure limit has been established for indoor levels of radon from natural sources; however, EPA is now developing guidelines that will define action levels concerning houses with high concentrations of radon and is developing and evaluating mitigation strategies.

Exposure to radon daughters increases a person's lifetime risk of lung cancer. The risk rises in direct relationship with the length of exposure and with radon daughter levels.

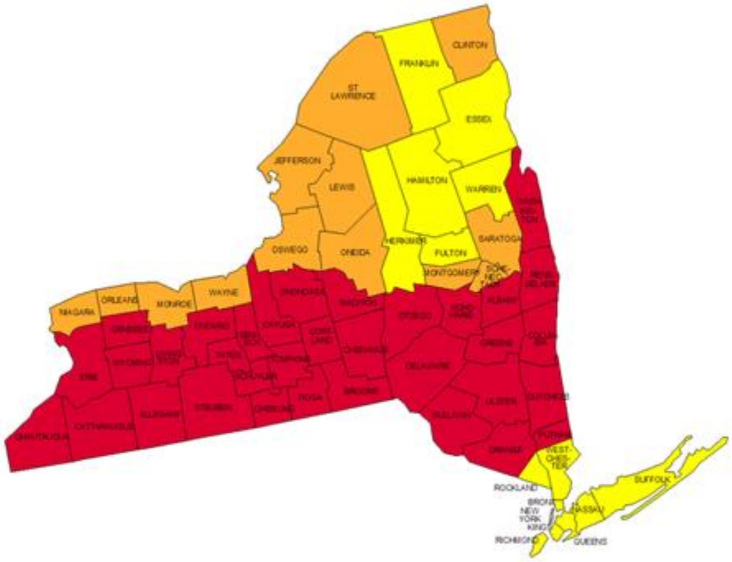
The two risk estimates in Table 1 are derived from studies of uranium miners and have been extrapolated from relatively high occupational exposures to environmental levels. The highest lifetime risk calculated from studies of uranium miners is 7.3 x 10))-4)) deaths per working level month, and the lowest generally accepted risk is 3.0 x 10))-4)) deaths per working level month (1,2). These estimates are for the general population, including smokers. The risks for nonsmokers are approximately six times less than those given in the upper portion of the table (1).

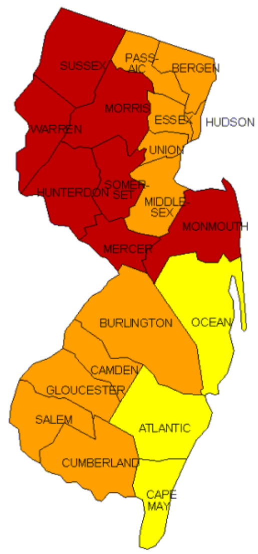
Each year, approximately 5,000-30,000 deaths may be attributed to background levels of indoor radon. The health threat from radon can be addressed by identifying geographic areas that could produce elevated levels of indoor radon, developing strategies to reduce exposure, conducting research on effective remedial measures to be taken in buildings, and providing educational programs for health officials and the public. Changes in usage patterns of high-radon areas in a home, such as the basement, and the control of future construction in geographic areas high in uranium deposits can reduce exposure. Effective remedial measures for individual dwellings can also be used to lower radon exposure. Research in these areas should be coordinated with other agencies active in this field. The educational programs can be used to inform health officials and the public about the health threat from radon and about associated risk factors, such as smoking.

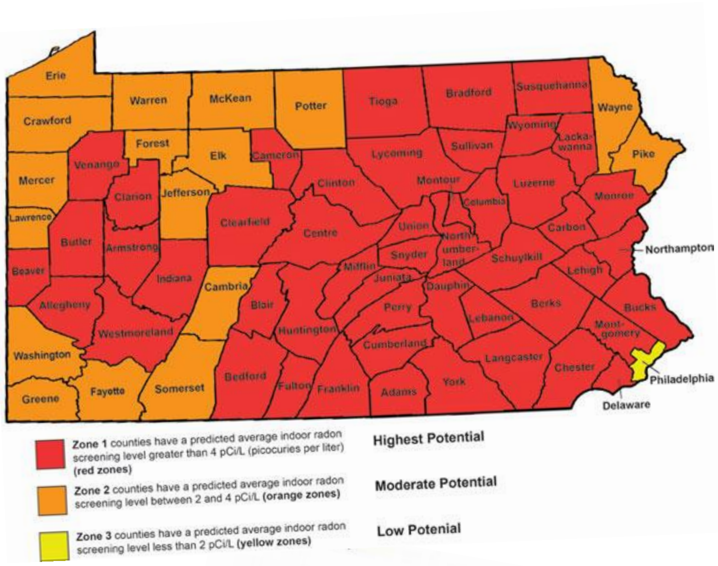
References

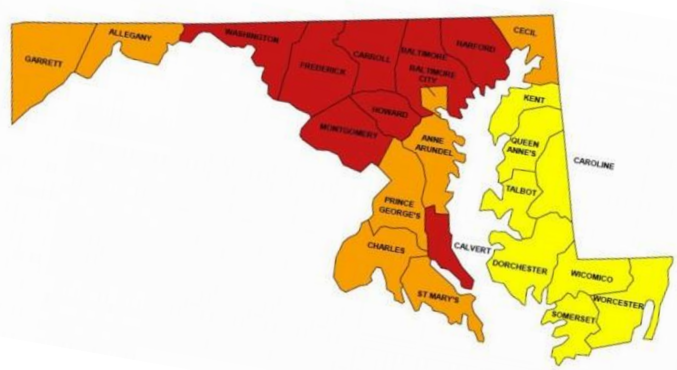
1. National Research Council. The effects on populations of exposure to low levels of ionizing radiation. Washington, D.C.: National Academy Press, 1980.
2. International Commission on Radiological Protection. Limits for intakes of radionuclides by workers. ICRP report no. 32, part 3, 1981.

Fig. D-3




SUSSEX
PASSAIC
BERGEN
MORRIS
WARREN
ESSEX
HUDSON
UNION
HUNTERDON
SOMERSET
MIDDLESEX
MONMOUTH
MERCER
BURLINGTON
OCEAN
CAMDEN
GLOUCESTER
SALEM
ATLANTIC
CUMBERLAND
CAPE MAY


Erie
Warren
McKean
Potter
Tioga
Bradford
Susquehanna
Wayne
Crawford
Forest
Elk
Cameron
Lycoming
Sullivan
Wyoming
Lackawanna
Pike
Mercer
Venango
Clarion
Jefferson
Clinton
Montour
Columbia
Luzerne
Monroe
Lawrence
Clearfield
Centre
Union
Northumberland
Carbon
Butler
Armstrong
Snyder
Schuylkill
Northampton
Beaver
Indiana
Cambria
Mifflin
Juniata
Lehigh
Allegheny
Blair
Perry
Dauphin
Berks
Bucks
Westmoreland
Huntingdon
Lebanon
Montgomery
Washington
Cumberland
Lancaster
Chester
Philadelphia
Greene
Fayette
Somerset
Bedford
Fulton
Franklin
Adams
York
Delaware
Zone 1 counties have a predicted average indoor radon screening level greater than 4 pCi/L (picocuries per liter) (red zones)
Highest Potential
Zone 2 counties have a predicted average indoor radon screening level between 2 and 4 pCi/L (orange zones)
Moderate Potential
Zone 3 counties have a predicted average indoor radon screening level less than 2 pCi/L (yellow zones)
Low Potenial



<u>Sidebar on "Half-Life"</u>

One of the considerations in the handling and use of radioactive materials is the half-life of the isotope - how quickly or slowly it decays away.

Half-life: Time during which the activity decreases by a factor of 2.
As nuclei decay there are simply fewer left to decay.

The "change-in-N" is proportional to "N".

This corresponds to what is called "*Exponential Decay*"
(a very common form of decay/discharge)

$$\frac{dN}{dt} = -\lambda N$$

$$\therefore \rightarrow \quad N(t) = \mathbf{N_0} \times e^{-\lambda t}$$

$$\text{or} \quad N(t) = \mathbf{N_0} \times (2)^{-t/t_{1/2}}$$

References:

Abraham Pais, Inward Bound, Oxford University Press (1986), Chapter 17.

Richard Wolfson, Nuclear Choices, MIT Press (2000), Chapter 3.

(E) Modern Nuclear Medical Applications

At this point in the class meetings it is useful and important to insert a section on the current status of the bio-medical effects of radiation and its uses in diagnostic and therapeutic medicine. While I was teaching this seminar, I would usually invite a faculty member from the Dept. of Therapeutic Radiology at the Yale Medical School (e.g., Professor Sara Rockwell) to lead the seminar for that session. Because this should be a presentation of the **current** status of diagnostic and therapeutic radiology, I have not included the materials from such a session, much of which would now be out of date.

(F) Diagnostic Radiology

Diagnostic radiology had its beginning almost as soon as Roentgen discovered x-rays which were almost immediately used to study fractured bones and to search for shrapnel in wounds. Diagnostic procedures using radioactivity to examine internal organs without the necessity of surgery could be done with much more specificity by being able to choose a radioactive isotope of a particular chemical which was preferentially absorbed by that organ. An obvious example is the use of radioactive iodine ^{123}I ($t_{1/2}$ = 13 hrs) to study thyroid disease.

Two further examples are seen in the case below [Anthony Wolbarst, <u>Looking Within</u>, Univ. of California Press (1999) p. 113-115] involving a long-haul trucker with severe chest pains. First, radioactive xenon gas was used to look for ventilation problems (blockages) in the patient's lungs and then, separately, radioactive technetium (attached to protein albumin) was injected into the patient's bloodstream to check for blockages in the flow of blood to the patient's lungs. In the attached figure, (a) the xenon test shows no indication for ventilation blockage whereas (b) shows evidence for a blockage in the perfusing of blood into one of the lungs – from a potentially life-threatening clot lodged in an artery leading from the heart to the lung.

> "Over time, the clot dissolved, and the renewed perfusion helped some of the lung tissue that was still marginally alive to recover. [The patient] was released after a week, but he was maintained on a blood thinning drug. He still drives a truck, but now wears support stockings and exercises his legs while on the road, and elevates them at the end of the day. All to reduce the likelihood of clot formation. His company has arranged for him to make local deliveries, so that he can avoid long hours of sitting, and he has not had a problem since."
>
> [Wolbarst, <u>Looking Within</u>, Univ. of California Press (1999) p. 115.]

Fig. F-1

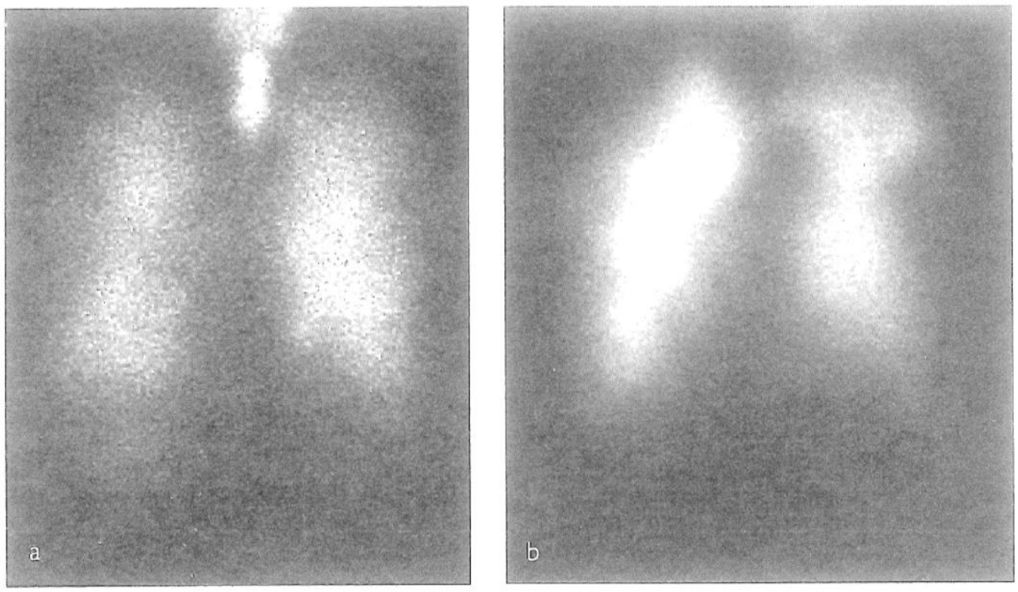


Figure 67. A ventilation/perfusion study. (a) This ventilation scan shows normal distribution of gamma-emitting xenon gas throughout the lung. (b) Dark regions in the lung perfusion study with Tc-MAA, however, reveal that blood (containing the radiopharmaceutical) is not getting to some tissues. Courtesy of Picker International, Inc.

[Wolbarst, Looking Within, Univ. of California Press (1999) p. 115.]

(G) The Discovery of Fission

- The discovery of the *neutron* **:**
  - February 1932, by Chadwick at Rutherford's Cavendish Laboratory.
  - By the reaction $^{9}Be + {}^{4}He \Rightarrow {}^{12}C + \mathbf{n}$**.**
  - With no electric charge (unlike an α-particle and a proton), the neutron was almost immediately recognized as a very useful nuclear probe since it had **<u>no</u>** Coulomb repulsion.

- By the mid-1930s, Fermi and his colleagues in Rome (as well as Hahn, Meitner, Frisch, Strassman in Germany, and Irene Curie and Fredric Joliot-Curie in France, along with many others) were all busily searching for "Transuranic" nuclei by bombarding ^{238}U and looking for subsequent "daughters" in their decays.

etc.

$\nwarrow$

$^{239}Pu_{145}$

$\nwarrow$

$^{239}Np_{146}$

$\nwarrow$

$$^{238}U_{146} + n \quad \Rightarrow \quad {}^{239}U_{147}$$

These searches were carried out by looking for and studying these decays via the "*chemistry*" of the daughters, finding <u>lots</u> of new radioactivities and half-lives.

An interesting sidelight to Fermi's initiation of experiments bombarding uranium, is the role it plays in Isaac Asimov's (1955) science fiction book, The End of Eternity, comparing the futures of time-travel and space-travel. At the end of the last chapter "The Beginning of Infinity", two time travelers are standing on the surface of the earth, and Noys explains to Harlan that all she needs to do is send

> " a letter to a peninsula called Italy here in the 20^{th}. It is now the 19.32^{nd}. In a few Centicenturies, provided I send the letter, a man of Italy will begin experimenting with the neutronic bombardment of uranium. . . . In the new reality, the final Reality, the first nuclear explosion will take place not in the 30^{th} Century but in the 19.45^{th}… and mankind will remain to reach the stars."

But in these chemistry discoveries, there wsere also **lots** of puzzles**, for example:**

- No one could understand how they are apparently making "radium" (Z=88). Knocking out **2** α–particles ?
- But then, better chemistry expoeriments seem to show that their "radium" must really be "barium" **!** (It separates with the barium carrier, whereas radium does not.) How can that be **?**

An interesting and quite extensive reference on the discovery of fission (including the personalities and intrigues as well as the political environment in Europe) and its development into the "gadgets" (two types of atomic bombs) that helped bring an end to World War II is presented in the biography of Enrico Fermi, The Pope of Physics (especially Chapters 10-32) and in Rhodes' The Making of the Atomic Bomb, particularly Chapter 9.

1938:

- In July 1938, Lise Meitner has to flee from Germany to Denmark and Sweden in order to escape Nazi persecution.
- As late as November 1938, Hahn & Strassmann publish a paper discussing the chemical properties of transuranic elements.
- Earlier in 1938, Irene Curie published several papers investigating these properties and their relationship to the properties of the rare-earth elements.
- In these papers, there was even some discussion about using a cloud chamber to look at the tracks and energetics of their α-decays. But this experimental search was apparently never carried out in 1938.

Then, by the middle of December 1938, Hahn and Strassmann were forced to the conclusion that they were producing barium, since it separates chemically with the barium carrier, whereas radium does not. But they do not understand "***how***" and find it hard to believe.

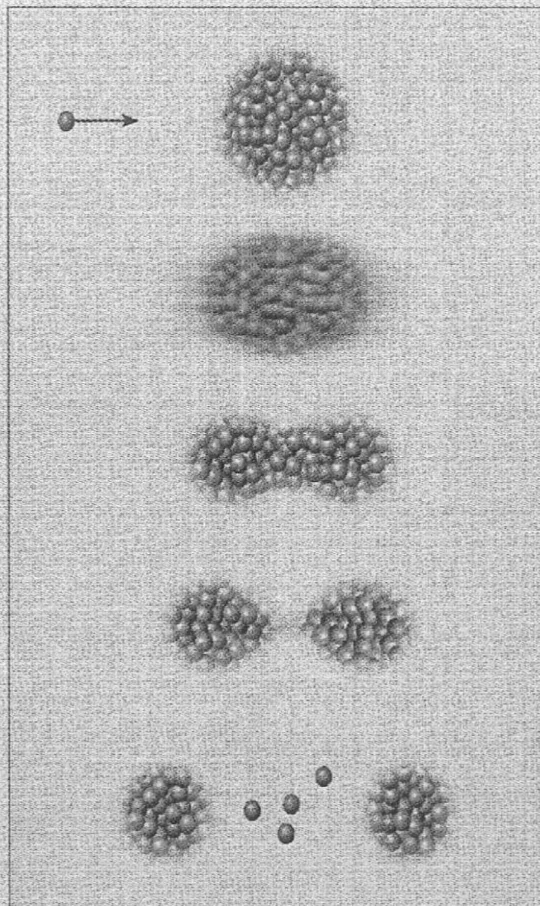
Hahn and Strassmann were still in close touch with their former colleague Lise Meitner, and it was Meitner and Frisch (her nephew) who, in the following week (between Christmas and New Year's Day) finally understood what was going on.

In a model in which a nucleus is seen as a "Liquid-Drop", held together by a nuclear force which is *strongly attractive* (overcoming the internal Coulomb repulsion), the nuclear force must be *short ranged* compared to the electrostatic Coulomb force - otherwise a nucleus would continue to easily accumulate protons and neutrons to form bigger and bigger nuclei - which are not observed.
Nuclei therefore must get to a size where the nuclear force can no longer overcome the Coulomb repulsion and the "liquid-drop" simply comes apart into two or more parts.

In this "fission", lots of energy is given off; the fission fragments are each more tightly bound than the original U+n. - by $\approx$1 MeV per nucleon **!**

$\therefore$ Expect a total energy release of $\approx$ 250 MeV **! (**compared to the few MeV seen in α and β decays), which then would be clearly seen in a cloud chamber.

Fig. G-1



Meitner and her nephew Otto Robert Frisch, 1904–1979, were the first to recognize a certain phenomenon discovered by Hahn and Strassmann as a signature of nuclear fission, the process shown above. Their fission model was based on Niels Bohr's 'liquid drop' model of nuclei, and predicted that fission releases much energy. At that time, in 1939, Meitner was taking refuge in Sweden. She spent her winter holidays with Frisch in the house on the right.

Mackintosh, et all, Nucleus, p. 77.

1939:

January 3rd, Frisch went to Bohr - whose immediate reaction was to strike his forehead - "*What idiots we have all been*."

January 13th, Frisch did experiments to find the very energetic fission fragments. ⇒ Found them immediately!

This confirmed everything; the fission model is very obvious and clear!

Meanwhile, Bohr left by boat to travel to the US to talk at an American Physical Society conference. He presented the Frisch/Meitner results at a Princeton seminar and then at the APS conference at George Washington University on Jan 26th.

Immediately everybody was measuring them and talking about them.

X-ray measurements confirmed the "chemistry" identification. The effect of paraffin (thermalizing the neutrons, e.g., Figs- H-1 and H-2) was observed, and by Feb.7th, Bohr wrote a short note already laying out the probable role of thermal-neutrons in ^{235}U+n fission (in contrast to ^{238}U+n).

Then, on March 18th, Joliot-Curie published a short piece in the journal Nature, noting the extra neutrons produced in this fission and outlining the consequent "chain reaction" possibilities.

⇒ Recognizing the potential for weaponizing fission, the literature almost immediately went silent!

[Rhodes, The Making of the Atomic Bomb, pp. 234-236.]**:**

Meanwhile Irene Curie had begun looking into uranium with a visiting Yugoslav, Pavel Savitch. They described a 3.5-hour activity the Germans had not reported and suggested it might be thorium, element 90, with which Curie had years of experience. If true, the Curie-Savitch suggestion would mean that a slow neutron somehow acquired the energy to knock an energetic alpha particle out of the uranium nucleus. The KWI trio scoffed, looked for the 3.5-hour activity, failed to find it and wrote the Radium Institute suggesting a public retraction. The French team identified the activity again and discovered they could separate it from their uranium by carrier chemistry using lanthanum (element 57, a rare earth). They proposed therefore that it must be either actinium, element 89, chemically similar to lanthanum but even harder than thorium to explain, or else a new and mysterious element.

Either way, their findings called the KWI work into doubt. Hahn met Joliot in May at a chemistry congress in Rome and told the Frenchman cordially but frankly that he was skeptical of Curie's discovery and intended to repeat her experiment and expose her error. By then, as Joliot undoubtedly knew, his wife had already raised the stakes, had tried to separate the "actinium" from its lanthanum carrier and had found it would not separate. No one imagined the substance could actually be lanthanum: how could a slow neutron transmute uranium into a much lighter rare earth thirty-four places down the periodic table? "It seems," Curie and Savitch reported that May in the Comptes Rendus*, "that this substance cannot be anything except a transuranic element, possessing very different properties from those of other known transuranics, a hypothesis which raises great difficulties for its interpretation"*

In the course of this exotic debate Meitner's status changed. Adolf Hitler bullied the young chancellor of Austria to a meeting at the German dictator's Berchtesgaden retreat in Bavaria in mid-February. "Who knows," Hitler threatened him, "perhaps I shall be suddenly overnight in Vienna: like a spring storm" On March 14 he was, triumphantly parading; the day before, with the raw new German Wehrmacht occupying its capital, Austria had proclaimed itself a province of the Third Reich and its most notorious native son had wept for joy. The Anschluss—the annexation—made Meitner a German citizen to whom all the ugly anti-Semitic laws applied that the Nazi state had been accumulating since 1933. "The years of the Hitler regime . . . were naturally very depressing," she wrote near the end of her life. "But work was a good friend, and I have often thought and said how wonderful it is that by work one may be granted a long respite of forgetfulness from oppressive political conditions." After the spring storm of the Anschluss her grant was abruptly withdrawn.

Max von Laue sought her out then. He had heard that Heinrich Himmler, head of the Nazi SS and chief of German police, had issued an order forbidding the emigration of any more academics. Meitner feared she might be expelled from the KWI and left unemployed and exposed. She made contact with Dutch colleagues including Dirk Coster, the physicist who had worked in Copenhagen with George de Hevesy in 1922 to discover hafnium. The Dutchmen persuaded their government to admit Meitner to Holland without a visa on a passport that was nothing more now than a sad souvenir.

Coster traveled to Berlin on Friday, July 16, arriving in the evening, and went straight to Dahlem to the KWI. The editor of Naturwissenschaften, Paul Rosbaud, an old friend, showed up as well, and together with Hahn the men spent the night helping Meitner pack. "I gave her a *beautiful diamond ring," Hahn remembers, "that I had inherited from my mother and which I had never worn myself but always treasured; I wanted her to be provided for in an emergency."*

Meitner left with Coster by train on Saturday morning. Nine years later she remembered the grim passage as if she had traveled alone:

"I took a train for Holland on the pretext that I wanted to spend a week's vacation. At the Dutch border, I got the scare of my life when a Nazi military patrol of five men going through the coaches picked up my Austrian passport, which had expired long ago. I got so frightened, my heart almost stopped beating. I knew that the Nazis had just declared open season on Jews, that the hunt was on. For ten minutes I sat there and waited, ten minutes that seemed like so many hours. Then one of the Nazi officials returned and handed me back the passport without a word. Two minutes later I descended on Dutch territory, where I was met by some of my Holland colleagues."

She was safe then. She moved on to Copenhagen for the emotional renewal of rest at the Carlsberg House of Honor with the Bohrs. Bohr had found a place for her in Sweden at the Physical Institute of the Academy of Sciences on the outskirts of Stockholm, a thriving laboratory directed by Karl Manne Georg Siegbahn, the 1924 Physics Nobel laureate for work in X-ray spectroscopy. The Nobel Foundation provided a grant. She traveled to that far northern exile, to a country where she had neither the language nor many friends, as if to prison.

Further details of the German fission research program during the war can be found in the book about the Alsos mission by Sam Goudsmit (on left in picture). He recounts rounding up the leading German nuclear scientists at the end of the war so that they would not fall into Russian or French hands. The book about Farm Hall by David Cassidy explores the conversations between these captive German scientists who were kept there in isolation and monitored during the months July '45 to January '46, while two fission bombs were dropped on Japan.

An interesting sidelight on limiting the German program is the sabotage of the Norsk Hydro heavy-water production facility in Nazi-occupied Norway in February 1943. The Norsk Hydro website, "1943: The Heroes of Telemark" discusses this commando raid in detail. (The 1965 film "Heroes of Telemark" provides a movie theater dramatization this raid.)

Note:
Z = 96 Curium
Z = 104 Rutherfordium
Z = 109 Meitnerium

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Fig. G-2

Fission Energetics:

1 atomic mass unit (amu) = 1/12 the mass of a ^{12}C atom.
(1 amu) × c^2 = 931.5 MwV.

e.g., $^{235}U + {}^{1}n \rightarrow {}^{94}Zr + {}^{140}Ce + 2\,{}^{1}n$

235.043924 amu	93.906315 amu
1.008665 amu	139.905433 amu
236.052589 amu	1.008665 amu
	1.008665 amu
	235.829078 amu

$\Delta m = 0.223511$ amu

x 931.5 $\rightarrow$ 208 MeV

0.223511 / 236.052589 $\rightarrow$ ~ 0.1 %

For 50 grams of ^{235}U , $\Delta m \Rightarrow$ 0.05 grams = 5×10^{-5} kg

$\Delta E = \Delta m \times c^2$ 45×10^{11} Joules

which then corresponds to ~ 1000 tons of TNT " 1 kiloton "

1 k ton = 2,000,000 lbs

Or the combined mass of ~ 13,000 150-lb students.

References:

1943: The Heroes of Telemark. https://www.hydro.com/en/about-hydro/Our-history/1929---1945/1943-The-Heroes-of-Telemark/

David Cassidy, Farm Hall and the German Atomic Project, Springer (2017).

E. Crawford, R.L. Sime, and M. Walker, "A Nobel Tale of Postwar Injustice", Physics Today (Sept. 1997), p. 26.

Samuel A. Goudsmit, Alsos, (1947); republished by A.I.P. Press (1996).

Mackintosh, et al., Nucleus, Johns Hopkins Univ. Press (2001), Chapter 6, p. 77.

Richard Rhodes, The Making of the Atomic Bomb, Simon & Schuster (1986), Chapter 9, pp. 234-236.

Gino Segre and Bettina Hoerlin, The Pope of Physics, Henry Holt & Company (2016), Chapters 10-32.

Journal papers:

Meitner & Frisch, Nature **143**, 239, (11 Feb.1939)
Frisch, Nature **143**, 276, (18 Feb.1939)

Phys.Rev. (letters to the editor section) **55,** (15 Feb.1939)

Roberts, Meyer, Hafsted (p.416)	(D.T.M., Carnegie Institution)
Green, Alvarez (p.417)	(Berkeley)
Fowler, Dodson (p.417)	(Johns Hopkins)
Abelson (p.418)	(Berkeley)
Bohr (p.418)	(I.A.S., Princeton)

[Several of which cite local newspapers as the source of the initial trigger for their measurements.]

(H) Fission and Chain Reactions

$^{235}\text{U} + \text{n}_{\text{thermal}} \;\Rightarrow\;$ fission + $\underbrace{\text{2 neutrons}}$

2 more fissions + $\underbrace{\text{4 neutrons}}$

4 more fissions + $\underbrace{\text{8 neutrons}}$

8 more fissions

+$\underbrace{\text{16 neutrons}}$

etc.

At this point, it is useful to remember the fable of a prince who wishes to thank one of his subjects and allows him to suggest his own reward. The subject points to a chess board and asks for one grain of rice on the first square, two on the second, and so on, doubling each day until the 64th square. The prince is pleased by this modest request and agrees – only to discover later that by the 64th square he will have to reward this subject with 10^{19} grains, about 30 billion tons, more than his land has produced in its entire existence. Such is the power of “doubling”.

For a chain reaction we will need:

(a) Efficient use of neutrons.

Don't let them escape.
Don't let them get used up in other reactions.

(b) To thermalize the emitted neutrons. ("Moderator")

(c) "Control" **[**Reactors (*yes*) **vs.** Bombs (*no*)**]**

By far the largest contribution to the fission probability (fission cross section) for neutrons on "uranium" comes from slow "thermal" neutrons interacting with ^{235}U. (Also for the case of a ^{239}Pu target.)   Therefore to make chain reactions easier to achieve we need to slow down the neutrons to "thermal" energies (small fraction of an eV). $\sigma \sim (1/v)$ (See Figs. H-1and H-2.)

What to use as a moderator   -   hydrogen, deuterium, carbon, etc.   ?

Protons ("light" hydrogen) are most efficient at slowing down the neutrons. They have essentially the same mass therefore share the energy very easily in elastic scattering.
[Note: Relative abundances of light (99.985%) and heavy (0.015%) hydrogen.]

Neutron thermalization:

Light Water (H_20) (protons)	~ 26 collisions to thermalize
Heavy Water (D_2O) (deuterium)	~ 31 collisions to thermalize.
Carbon (Graphite)	~ 120 collisions to thermalize
Uranium	~ 2200 collisions to thermalize

BUT protons also have a <u>much larger</u> cross section for capture of the neutrons

0.33 barns   vs.   0.00051 barns (for deuterium)

[See "How the barn was born", below.]

<u>Other considerations</u>: Design the **Geometry** to improve efficiency -
to reduce likelihood of neutrons escaping at edges/surfaces.

Use **Control Rods to** absorb neutrons.

The first nuclear reactor (to test the possibility of criticality) was constructed in the squash courts under the football stadium at the University of Chicago in the fall of 1942. When it was assembled, the reactor ("pile") would contain: 771,000 pounds of graphite (the neutron moderator), 80,590 pounds of uranium oxide, and 12,400 pounds of uranium metal. In the attached "sketch" (Fig. H-3), note the "suicide squad" of 3 young physicists in the back corner with jugs of cadmium sulfate to dump onto/into the reactor if something got out of control.

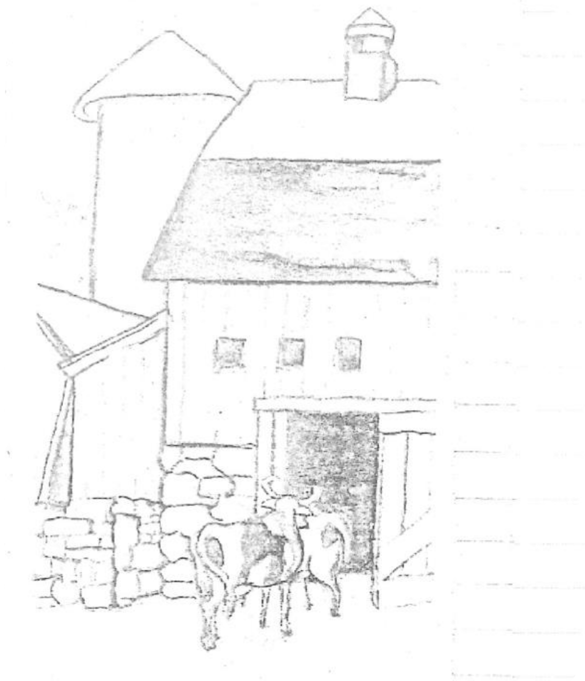
The reactor went critical at about 3:49 p.m. on the afternoon of December 02, 1942. See the strip-chart recording of the neutron detector output (Fig. H-4). Shortly thereafter the following coded message was phoned to Washington:

> "You'll be interested to know that the Italian navigator has just landed in the new world. The earth was not as large as he had estimated, and he arrived at the new world sooner than he had expected."
> "Is that so? Were the natives friendly?"
> "Everyone landed safe and happy."

However, not all of the physicists were ecstatic. Rhodes notes at the end of Chapter 13 that Slizard reported that he had commented to Fermi, "I thought that the day would go down as a black day in the history of mankind."

How the Barn was Born by M.G. Holloway and C.P. Baker

Note: The report below is the full text of Los Alamos report “Note on the Origin of the Term ‘barn’,” LAMS 523, submitted by the authors 13 September, 1944, issued 5 March, 1947 and declassified 4 August, 1948. Copied from *Physics Today* **25**, 7, 9 (1972).



Sometime in December of 1942, the authors, being hungry and deprived temporarily of domestic cooking, were eating dinner in the cafeteria of the Union Building of Purdue University. With cigarettes and coffee the conversation turned to the topic uppermost in their minds, namely cross sections. In the course of the conversation, it was lamented that there was no name for the unit of cross section of 10^{-24} cm^2. It was natural to try to remedy this situation.

The tradition of naming a unit after some great man closely associated with the field ran into difficulties since no such person could be brought to mind. Failing in this, the names Oppenheimer and Bethe were tried, since these men had suggested and made possible the work on the problem with which the Purdue project was concerned. The 'Oppenheimer' was discarded because of its length, although in retrospect an 'Oppy' or 'Oppie' would seem to be short enough. The 'Bethe' was thought to lend itself to confusion because of the widespread use of the Greek letter. Since John Manley was directing the work at Purdue, his name was tried, but the 'Manley' was thought to be too long. The 'John' was considered, but was discarded because of the use of the term for purposes other than as the name of a person. The rural background of one of the authors then led to the bridging of the gap between the 'John' and the 'barn.' This immediately seemed good, and further it was pointed out that a cross section of 10^{-24} cm^2 for nuclear processes was really as big as a barn. Such was the birth of the 'barn.'

To the best knowledge of the authors, the first public (if it may be called that) use of the barn was in Report LAMS-2 (28 June, 1943) in which the barn was defined as a cross section of 1×10^{-24} cm^2.

The authors would like to insist that the 'barn' is spelled just that way, that no capital 'b' is needed, and that the plural is 'barns' with no letter 'e' involved, and that the symbol be a small 'b.' The meanings of 'millibarn' and 'kilobarn' are obvious."

Garwin & Charpack, Megawatta and Megatons, p.38.

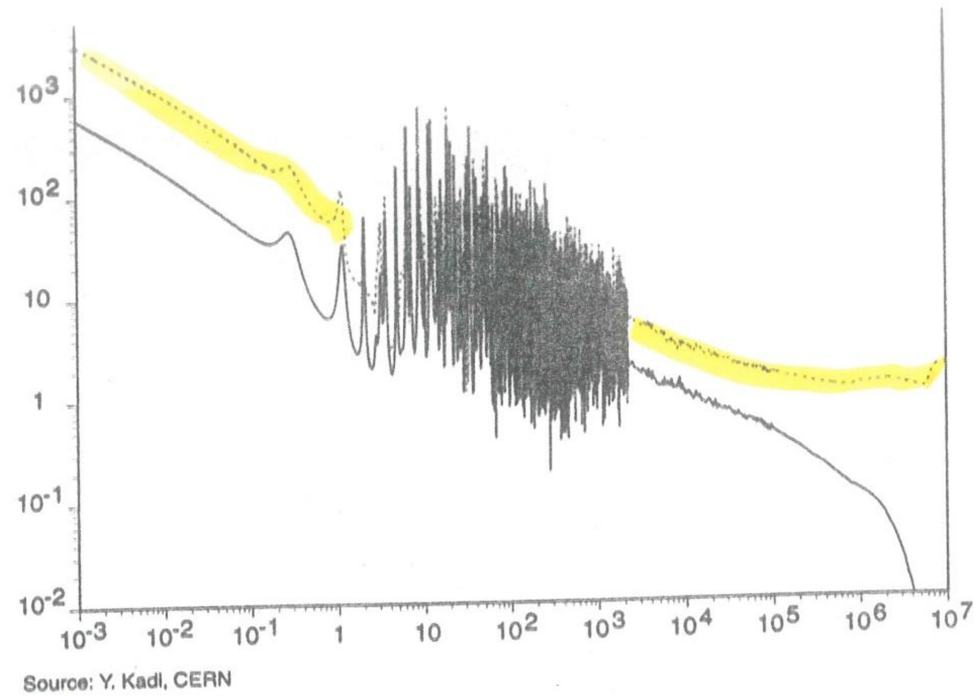


Fig. H-1 *Plot of the capture (solid line) and fission (dotted line) cross sections of U-235. Cross sections are in barn and neutron energies in eV.*

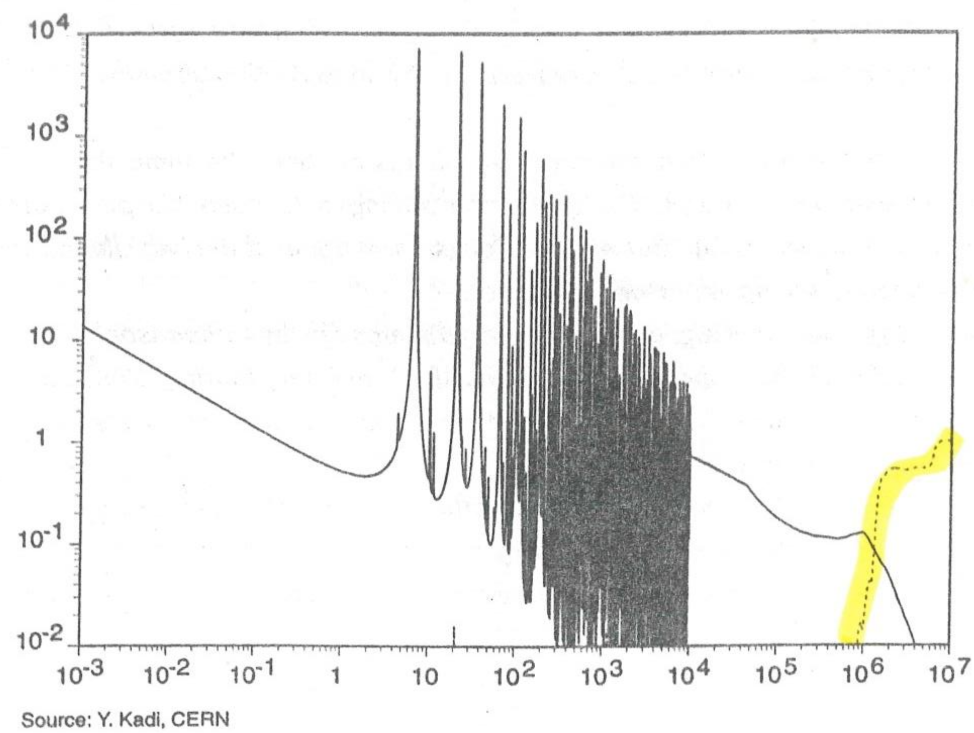
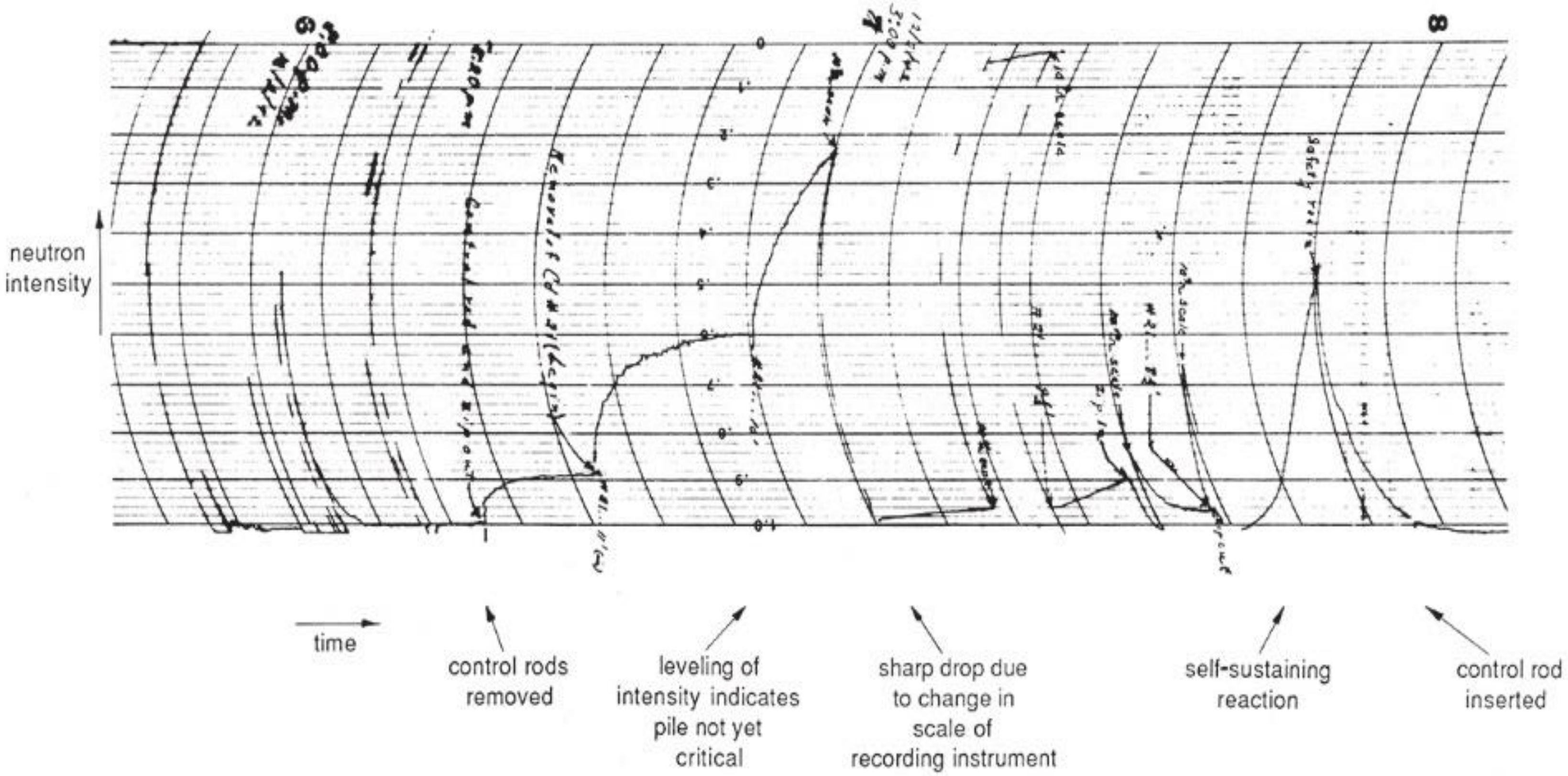


Fig. H-2 *Plot of the capture (solid line) and fission (dotted line) cross sections of U-238. Cross sections are in barn and neutron energies in eV.*

Fig. H-3 A sketch of Chicago Pile 1, the first reactor to achieve a self-sustaining chain reaction. The reactor consists of a pile of graphite blocks embedded with uranium. The man standing on the floor in front of the pile is manually removing a control rod to start the chain reaction. Because of wartime secrecy, no photographs were taken of the completed reactor. Wolfson, *Nuclear Choices*, p. 173.

Fig. H-4



Neutron intensity in the pile as recorded by the chart recorder

Rhodes, <u>The Making of the Atomic Bomb</u>, p. 441.

References:

Richard Garwin & Georges Charpack, Megawatts and Megatons, Alfred A. Knopf (2001), Chapter 2.

Richard Rhodes, The Making of the Atomic Bomb, Simon & Schuster (1986), Chapter 13.

Gino Segre and Bettina Hoerlin, The Pope of Physics, Henry Holt & Company (2016), Chapters 10-32.

Richard Wolfson, Nuclear Choices, M.I.T. Press (2000), Chapter 8.

(I) Criticality

$$K \equiv {}^{\#\,fissions\ (t)}\!\Big/_{\#\,fissions\ (one\ generation\ earlier)}$$

For K = 1, the system is said to be "critical" and the number of fissions per sec is constant. **Stable**

For K < 1, the number of fissions/sec decays away. **SubCritical**

For K > 1, the number of fissions/sec grows exponentially. **SuperCritical**.

Criticality depends on geometry - neutrons should not be able to escape from the core of the bomb or the reactor.

Weapons: Want "K" as large as possible.

K is dependent on geometry, mass and moderator.

* Concept of "critical mass" * = [The amount of fissionable material required for the reaction to go critical for a particular geometry and moderator.] (See Section H.)

Reactors: Want "K" equal to 1.000000000000

$(1.01)^n \Rightarrow 2.0$ for $n = 70$

At Stagg Field (U.Chicago) (02 Dec. 1942) (Section H)

$(1.0006)^n \Rightarrow 2.0$ for $n = 1200$

Doubling every 2 minutes!

"Control" - via "delayed" neutrons:

0.65% of neutrons following ^{235}U+n fission

("*Prompt*" neutron multiplication factor is kept below 1.0 in a reactor, but close enough to 1.0 so that the additional "*delayed*" neutrons can keep it just critical.)

Time scale of 10+ seconds = plenty of time for feedback control.

e.g., $^{235}U + n \Rightarrow \underbrace{^{95}Y_{(z=39)}} + \underbrace{^{139}I_{(z=53)}} + 2\,n$

$3\ \beta^-$ decays

$4\ \beta^-$ decays

$^{95}Mo_{(z=42)}$

$^{139}La_{(z=57)}$

[In addition to geometric model calculations of the required critical-mass (criticality), scientists at Los Alamos also carried out dangerous experiments ("tickling the tail of the dragon") to verify their criticality calculations for various geometries. See, for example, the fatal accidents during the course of just such measurements involving Haroutune Daghlian (8/21/45) (Segre & Hoerlin, p.233) and Louis Slotin (5/21/46) (Jungk, p. 195-6.)]

References:

Richard Garwin & Georges Charpak, Megawatts and Megatons, Alfred A. Knopf (2001), Chapters 2.

.

Robert Jungk, Brighter than a Thousand Suns, Harcourt (1956), pp. 193-196.

Gino Segre and Bettina Hoerlin, The Pope of Physics, Henry Holt & Company (2016), p. 233.

(J) Uncontrolled Fission

Weapons:

Fission Weapons ^{235}U or ^{239}Pu

SubCritical $\Rightarrow$ SuperCritical in *less* than 1 μsec.

Via "Gun" *vs.* "Spherical Implosion" designs.
(See Figures J-3 and J-4, respectively.)

80 doublings $2^{80} \approx 10^{24}$ (Avagadro's # = $6x10^{23}$/mole)
$\approx$ 2 moles $\approx$ 500 grams of ^{235}U

* *

Thermonuclear Bombs = "Hydrogen Bombs"
Fusion weapons.

(left-hand side of the "Binding Energy per Nucleon" plot) (Fig. J-1)

$4\,(^1H) \Rightarrow {}^4He + 2e^+ + 2\nu_e$ + 26 MeV

$(\approx 6\tfrac{1}{2}$ MeV/mass unit$)_{fusion}$ *vs.* $(\approx 1$ MeV/mass unit$)_{fission}$

e.g., $^2D+^3T \Rightarrow {}^4He+n$ + 17.6 MeV

Triggered by fission bomb to achieve the necessary density and temperature.
Main "advantage" is the increased power available

$\Rightarrow$ 100 MegaTons !

* *

"dirty bombs" or "radiological weapons" are simply "contamination" devices.

- Quantities of radioactive material which are dispersed using a conventional explosion.
- More of a *psychological* weapon!

(See NYTimes stories 26 Sept.'04; 08 Dec. '04; 08 Nov. '05)

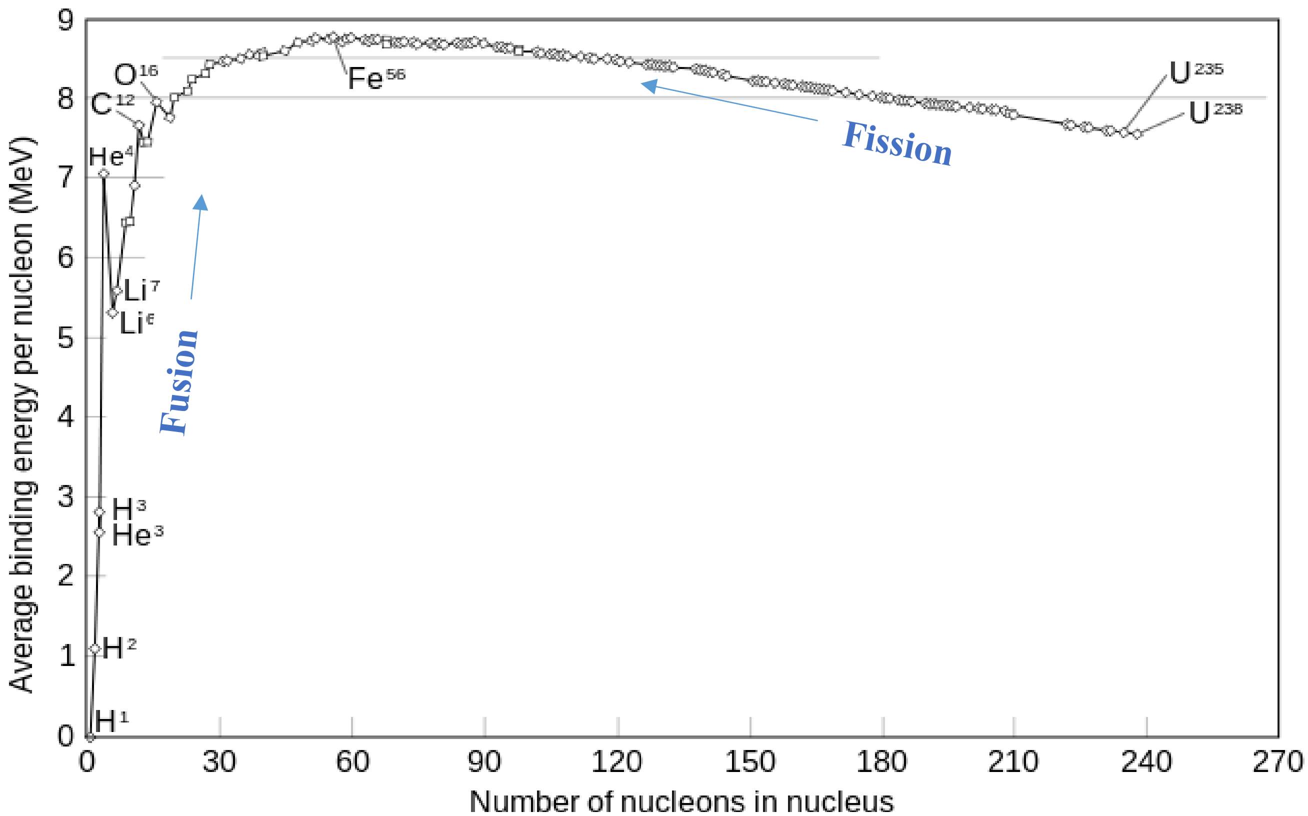


Fig. J-1

Binding Energy per nucleon plotted as a function of neutron number in a nucleus.
Binding energy gain due to fusion is shown on the left-hand side of the plot.
Binding energy gain due to fission is shown on the right-hand side of the plot.

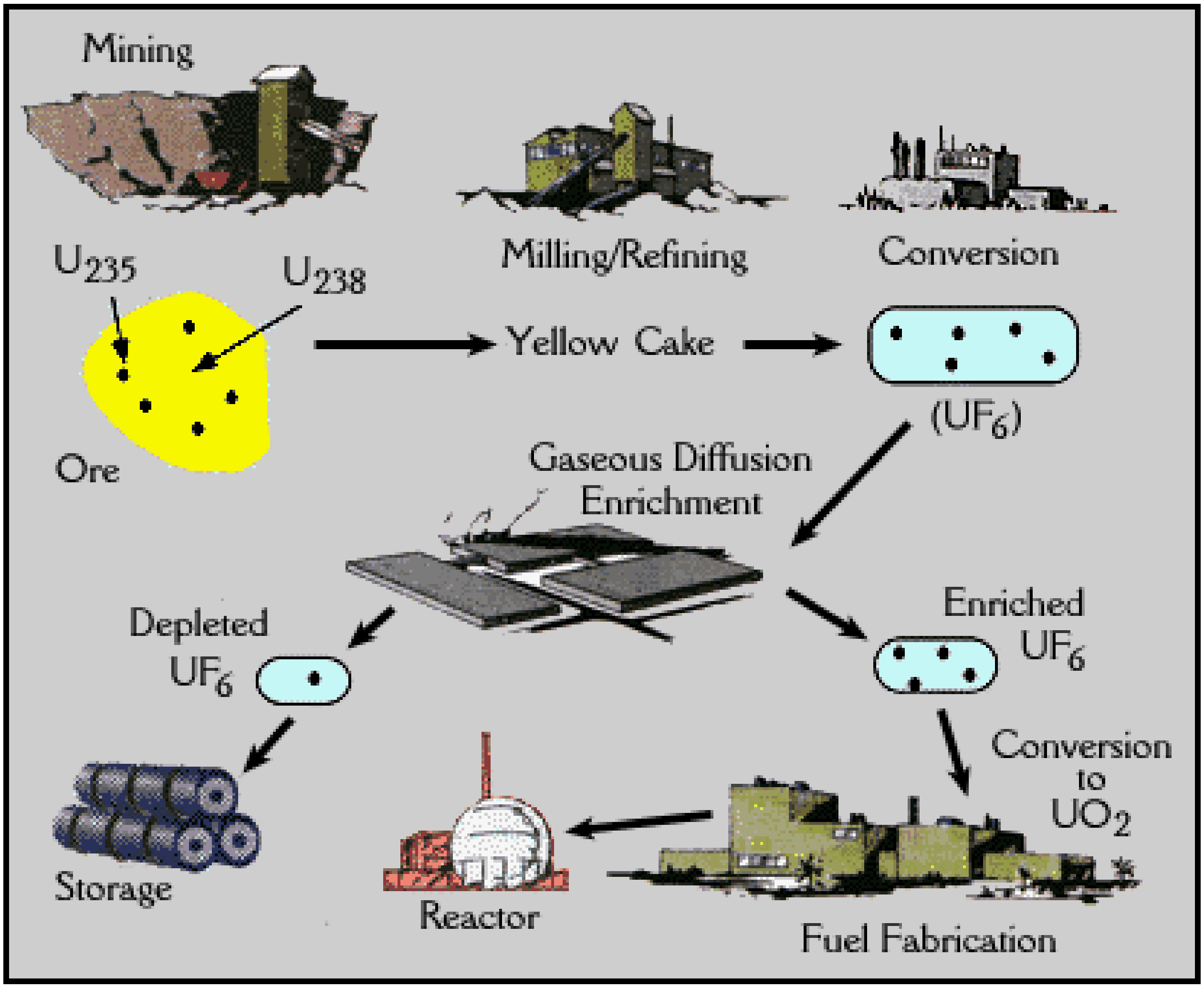


Fig. J-2

Uranium: From mining to reactor fuel rods
Source: http://web.ead.anl.gov/uranium/guide/uf6/

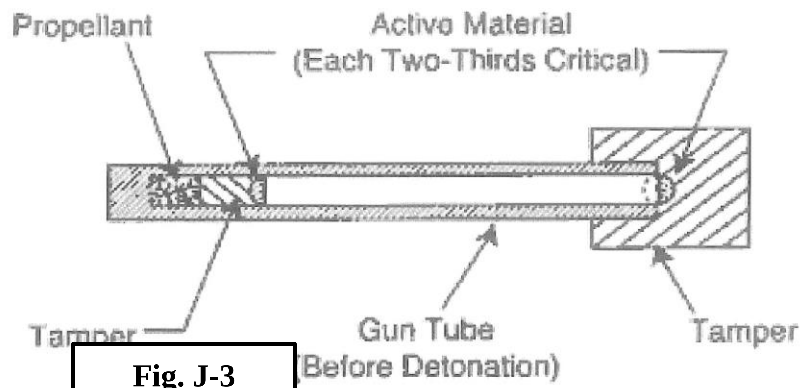


Fig. J-3

Figure 2-VII. Gun Assembly Principle

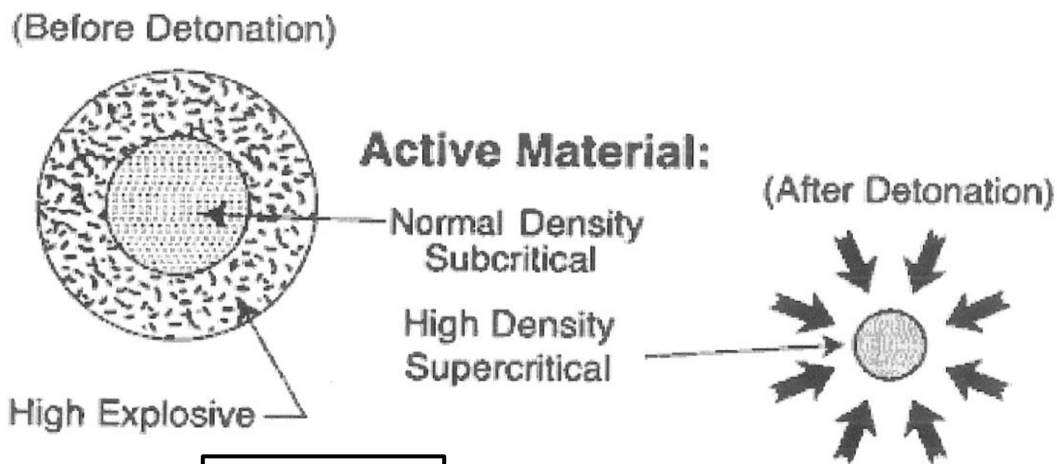
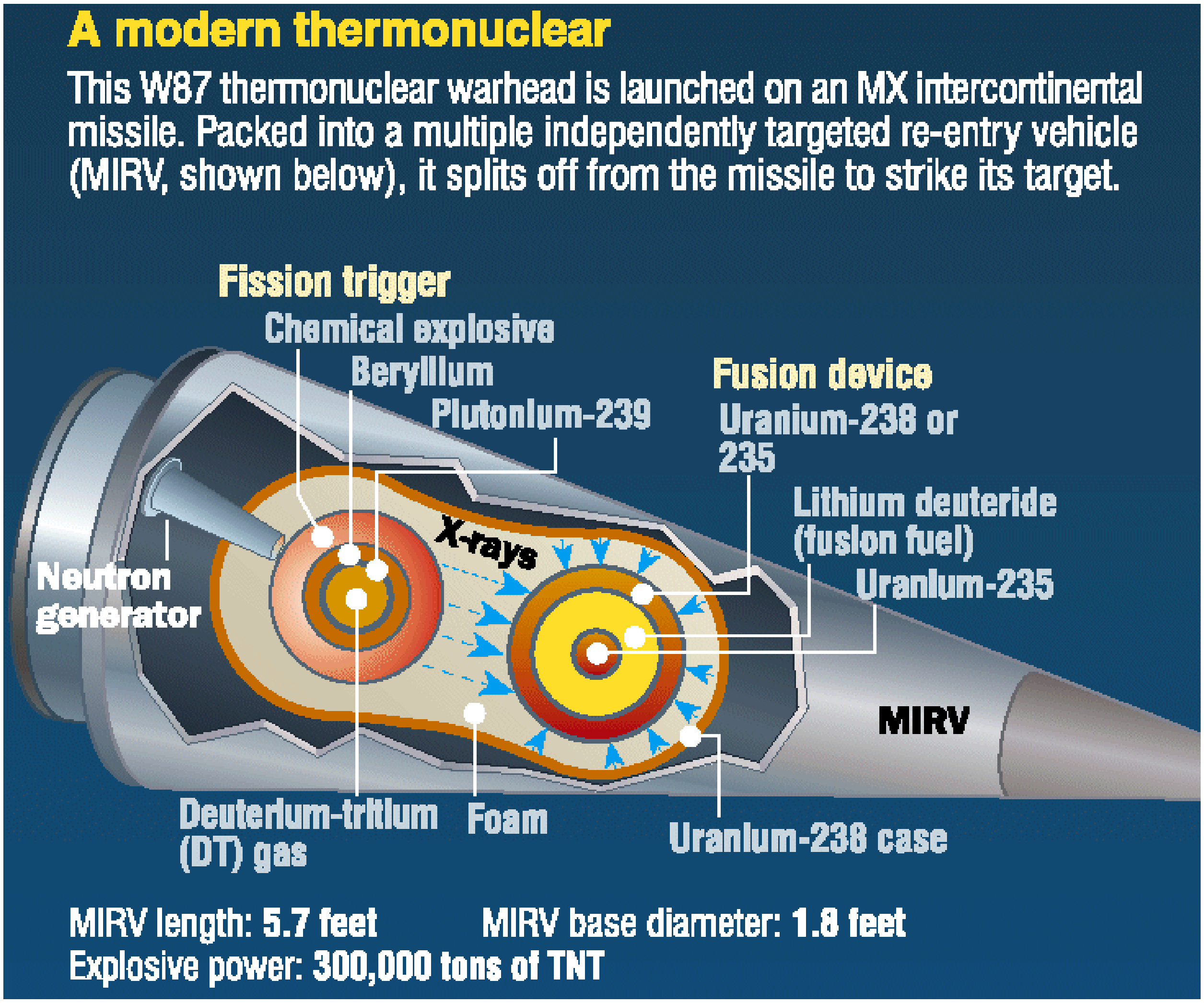


Fig. J-4

Figure 2-VIII. Implosion Assembly Principle

Source: NATO Handbook, FM 8-9 (1996), Part I – Nuclear, Chapter 2.

Fig. J-5



W87 Warhead Illustration Source:
http://nuclearweaponarchive.org/Usa/Weapons/W87.html

"But a simple neutron source would not do the job, because in this design of weapon, neutrons that are injected too early result in an explosion yield reduced by a factor of 10 to 20 from the design yield of 20 kt. Accordingly, the polonium and beryllium are separated by a thin layer of material (just a bit thicker than the range of the alpha particles from polonium), which is disrupted by the shock from the conventional explosives that travels through the plutonium core to the initiator at its center. The shock mixes the polonium and the beryllium so that the alpha particles can suddenly begin to produce neutrons. To be sure of having a neutron available in a fraction of a microsecond, many curies of polonium are required, and the polonium (usually produced by neutron irradiation of large amounts of bismuth in a nuclear reactor) has a half-life of four months and must be replaced every six months or so."
Garwin & Charpack, Megawatts and Megatons, (2001), p. 61.

Wolfson, Nuclear Choices, p.290.

Fig. J-6 A 12.5-kiloton bomb, small by today's standards, damaged or destroyed over 90 percent of Hiroshima's buildings. 100,000 people died immediately; by the end of 1945 the toll had reached 140,000, and by 1950 200,000 had died from the bombing. (Department of Defense)

References:

Richard Boyd, An Introduction to Nuclear Astrophysics, University of Chicago Press (2008), Chapter 3.

Richard Garwin & Georges Charpack, Megawatts and Megatons, Alfred A.Knopf (2001), Chapter 3.

NATO Handbook FM 8-9 (1996), Part I – Nuclear, Chapter 2.

Richard Rhodes, The Making of the Atomic Bomb, Simon & Schuster (1986).

Gino Segre and Bettina Hoerlin, The Pope of Physics, Henry Holt & Company (2016), Chapters 10-32.

This Month in Physics (May 21, 1946), APS News, May (2014), p. 2.

Richard Wolfram, Nuclear Choices, M.I.T. Press (2000), Chapter 12.

(K) Controlled Fission (K = 1.0000000000000)

Reactor References:

Nuclear Choices (Wolfson) - Chapters 8, 9, 10
Megawatts & Megatons (Garwin & Charpak) - Chapters 5, 7, 9
Before It's Too Late (Bernard Cohen) - Chapter 4

At the turn of the century (2000) the role of fission reactors in producing energy - electrical power:

France - 80 %
U.S. - 17 %
Worldwide - 18 %

One key aspect favoring nuclear power vs. carbon-based power, is simply the contrast in the amount of fuel required for these two sources. See, for example the pictures in Wolfson (Nuclear Choices, pp.16 &17) comparing the 4 truckloads of uranium fuel rods required to refuel a nuclear power plant every 18 months vs. the 110 x 14 x 75 = 115,000 railroad cars to refuel a coal-power plant over the same 18 months. But - - -

A key issue that needs to be discussed in this area is the evaluation of "***risk***" in the operation of these reactors and in their waste disposal.
⇒ This involves an examination of the hows and whys of society's willingness to accept some risks - but not others.

[If someone wants to pursue this issue as a term paper topic, in addition to Cohen's Chapter 4, they might want to look further at the following Stephen Breyer reference:
Breaking the Vicious Circle: Toward Effective Risk Regulation
Harvard University Press (1993)]

Also, the very touchy (Not In My Back Yard, **NIMBY**) question of how and where to deal with the storage/disposal of long-lived radioactive waste products.

Nuclear Fission Reactions

^{Nat}U is <u>99.3%</u> ^{238}U ($t_{1/2}$= 4.5x10^9 yrs) and <u>0.7%</u> ^{235}U ($t_{1/2}$= 7.2x10^8 yrs).

$\therefore$ 1.4x10^9 years ago, ^{235}U would have been 3% of ^{Nat}U.

A light-water reactor will not burn what is *currently* natural Uranium, but will burn 3% ^{235}U.

Therefore, it would seem that there *could* have been nuclear reactors running "<u>naturally</u>" on the earth, 1.4x10^9years ago.

$$^{235}U + n \longrightarrow \underbrace{^{236}U \longrightarrow \text{fission products} + \text{200 MeV}}_{\text{Radioactive - see Section (I)}} + \text{2 - 3 neutrons.}$$

Two "take-aways":

a) We need to worry about the safe disposal of radioactive "fission products", <u>while also considering</u> the disposal of toxic coal waste and the carbon footprint of fossil fuel power plants. What/where is the balance?

b) Can we learn anything by finding "Natural Reactors" and looking at the dispersal of their radioactive waste products?

Nuclear Waste Disposal Criteria

Considerations:

- Demographics
- Security
  - Many small sites <u>vs.</u> one centralized one ?
  - Transportation, Shipment - Wolfson, p.232
- Geology:
  - Stability
  - Ground Water

In 1972 a "Natural Reactor" is discovered in Oklo, Gabon

The **Oklo** "natural reactor" was discovered in 1972 when a lab tech was doing a routine assay of the uranium being delivered from this ore-site and found that the ^{235}U fraction was only <u>0.7171 %</u> compared to the <u>0.7202 %</u> measured everywhere else in terrestrial deposits.

> ***Was someone diverting some of the weaponizable ^{235}U to some illicit use?? No, it was the result of the operation of a natural reactor at this site ~2 billion years ago!***

Implications of Oklo to nuclear waste disposal:

- In this case, nuclear waste resulting from fission had no (!) containers, and there was an underground stream (the moderator) running through the site, available to wash the waste out.
- Nevertheless, in the ~2 billion years since then, most of the fission by-products remained where they were produced, or migrated only a few meters.
- These have to be encouraging observations for proponents for burial/containment projects, such as Yucca Mountain.

Wolfson, Nuclear Choices, p. 165-166:

Nuclear News: A Natural Reactor

In 1972 a worker at a French nuclear-fuel plant discovered a curious thing: Samples of uranium arriving from a mine at Oklo in the West African Gabon Republic contained even less fissile uranium-235 than the normally low 0.7 percent. This result was particularly baffling because the ratio of U-235 to U-238 is believed to be the same throughout the solar system, as confirmed by measurements on meteorites and moon rocks.

What could be the cause of the U-235 depletion? The clue emerged in further analysis of the Oklo samples: Not only were they depleted in U-235, but the samples also contained an unusual blend of isotopes that would normally be expected among the stable "offspring" formed in the decay of nuclear fission products. The conclusion was inescapable: A natural fission chain reaction had occurred at Oklo some 2 billion years ago. Humans did not invent the fission reactor.

We have just seen the difficult technological steps required to sustain a chain reaction, including the enrichment of uranium or the procurement of heavy water and the construction of carefully engineered reactor systems, including a moderator to slow the neutrons. How could random natural events put a reactor together? Several circumstances conspired to make the Oklo chain reaction possible. First, the ore at Oklo is rich in uranium; that is why it was developed for a mine. Second, the ore body at the time of the reaction was saturated with groundwater that could serve as a moderator, and the rich uranium vein was thick enough that fission neutrons were unlikely to escape. But how could ordinary light water moderate a chain reaction in natural uranium? We have seen how the neutron-absorbing properties of light water make that impossible in today's reactors. But 2 billion years ago, things were different. The half-life of uranium-235 is 700 million years; that of U-238 is 4.5 years. U-235 has decayed more rapidly than U-238, and that means there was a greater proportion of U-235 in the past. 2 billion years ago, in fact, the proportion of U-235 in natural uranium was about 3 percent – its value in today's enriched light-water reactor fuels.

Eventually six separate natural reactor zones were identified at Oklo. The reactors probably ran for several hundred thousand years, with a total power output between 10 and 100 kW. The chain reactions were probably kept under control by their need for moderating water: If the reaction ran too fast, water boiled away and the reaction slowed. The very low power level in the reactor zones precluded meltdown.

The fossil reactors at Oklo are more than scientific curiosities. They have served as natural laboratories for studying the long-term behavior of nuclear fission products. Analysis shows very modest migration of fission products from uranium-bearing regions into adjacent clay; plutonium decay products, on the other hand, show no migration – an indication that plutonium remained fixed at the sites where it formed for at least its 24,000-year half-life. These results are encouraging to those who advocate underground storage of nuclear wastes.

News source: "A Natural Fission Reactor," Scientific American, July 1976, p. 36.
See also: Garwin and Charpak, Chapter 2, pp. 52-54.

Yucca Mountain and W.I.P.P. (Waste Isolation Pilot Project)

Fig. K-1

Why Yucca Mountain? (pictured above)
Deserted, dry (7.5 inches/year, less likely disintegration), very deep water table (less potential for water contamination)

Proposed repository zone – 1150 acres (4.7 km^2)
Proposed withdrawal area – 230 square miles (150,000 acres)

Geological facts/concerns
Extinct volcano, made of tuff (type of rock), some fissures extend all the way to water table, seismic activity.

History
1982 Congress establishes Nuclear Waste Policy
1983 U.S. Department of Energy selects 9 possible locations, 3 sites approved by President
1987 DOE only studying Yucca Mountain
2002 Senate and Bush ok legislation approving development of repository at Yucca.
Now Yucca Mountain Project is working to get license to construct.

Situational Overview

- Yucca Mountain is a ridgeline in the Nevada desert on federal lands, within the boundaries of the Nevada Test Site (est. 1951)
- Product of extinct super-volcano
- Nuclear Waste Policy Act (NWPA) of 1982 started selection process
- Government research says it is suitable to receive 72,000 metric tons of spent fuel and nuclear waste, but there are concerns over geologic stability.
- Feds say “yes!”; Nevada says “no!”

In 2017, as part of his energy program, President Donald Trump has directed a reopening of the process of licensing of the Yucca Mountain facility.

Physics Today **70**, 10, 32 (2017); https://doi.org/10.1063/PT.3.3724

Nevada and Trump administration face off over Yucca Mountain

Thirty years ago in December, over Nevada's objections, the US Congress chose a scrubby ridge on federal land about 130 kilometers from the Las Vegas strip as the nation's underground repository for highly radioactive nuclear waste. After the expenditure of more than $10 billion to study the Yucca Mountain site's suitability, develop its design, and prepare for its licensing, the project has been moribund for eight years. The spent nuclear fuel that was destined for deposit there continues to pile up at the nation's nuclear power reactors.

The Department of Energy, which by law was to begin accepting the waste in 1998, has now paid out more than $6 billion in court-ordered judgments to nuclear plant operators for defaulting on its obligation. Those fines, meant to reimburse utilities for the cost of storing the spent fuel, continue to accrue, and DOE has estimated that the bill to taxpayers will climb to $29 billion by 2022.

Now President Trump has proposed undoing President Barack Obama's 2009 cancellation of Yucca Mountain. The White House has requested $150 million in fiscal year 2018 for DOE and the Nuclear Regulatory Commission (NRC) to restart the licensing process. Included in the $120 million DOE portion of the budget request is $10 million to begin planning for one or more interim storage sites, where spent fuel would be consolidated until a permanent repository is completed. The NRC would receive $30 million to continue the licensing procedure.

Aerial view of Yucca Mountain, Nevada, *which the Trump administration has proposed to reinstate as the nation's permanent repository for highly radioactive nuclear waste. The waste would be housed beneath the ridge that runs vertically in the center right of the photo.*

The Nevada government and congressional delegation have relentlessly opposed the repository since it was forced on the state. Senator Harry Reid (D), the majority leader in 2009, convinced Obama to halt the program. Governor Brian Sandoval (R) of Nevada has vowed to use every legal and regulatory tool available to block resumption. Four of the state's five congressional delegation members are unconditionally opposed to the repository; the other calls for the state to negotiate for better terms.

The NRC suspended its review of DOE's construction license application in 2011, after appropriations were halted. But a federal appeals court in 2013 ordered the commission to resume consideration. In 2015, using leftover appropriations, NRC staff completed their safety evaluation report. A year later, they issued a supplemental environmental impact statement on groundwater impacts; DOE had declined to prepare that statement. The NRC staff had two remaining issues before it could recommend granting a license: The state still needed to issue permits for the use of groundwater during construction and operations, and the US Air Force and the Bureau of Land Management had to resolve ambiguous land ownership issues with DOE.

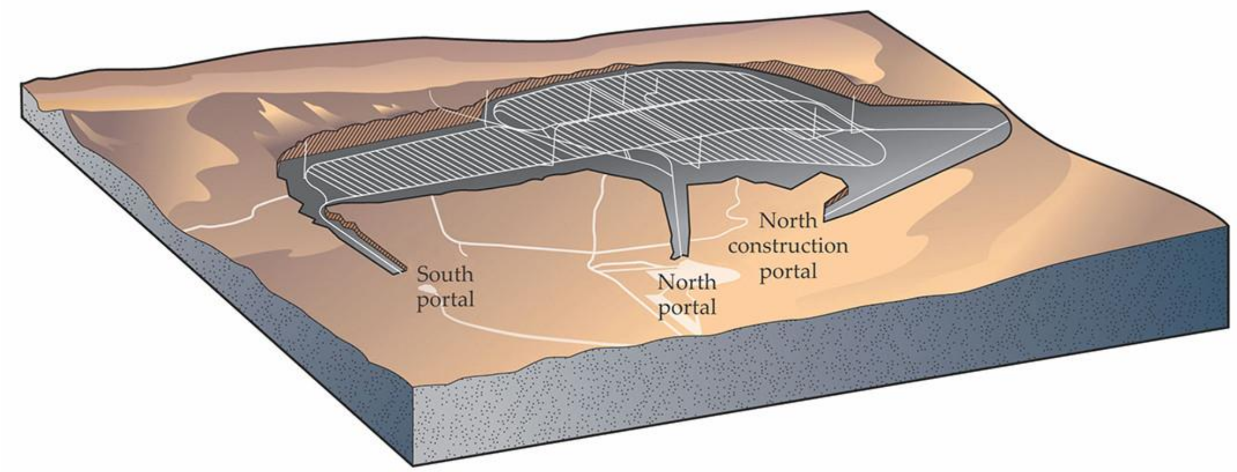
No path forward

Following Yucca Mountain's cancellation, DOE formed an advisory committee at Obama's request to help chart a new path for disposing of nuclear waste. In its 2012 report, the panel, known as the Blue Ribbon Commission on America's Nuclear Future, called for starting from scratch with a new siting process that would require the consent of states and other affected parties such as American Indian tribes. The commission also urged establishment of one or more interim storage facilities to house spent fuel until a repository is built. Two companies have applied for NRC licenses to operate such facilities, one site in west Texas and the other in southern New Mexico.

But little has come of the panel's recommendations concerning a new repository. The federal government has sole jurisdiction over high-level nuclear waste. Geoffrey Fettus, an attorney at the Natural Resources Defense Council, which opposes the Yucca Mountain project, says the commission failed to suggest how to obtain states' consent. The key, he says, is giving states a role in regulating the waste, just as they have had with other hazardous wastes. "You won't get consent if you keep federal preemption over the waste," he says.

If there's anything certain about Yucca Mountain, it's that construction is still many years away, even if the repository is ultimately approved. Nevada has filed 218 specific objections to the NRC's findings. It joins other parties, including the nuclear industry and environmental groups, who have filed their own objections. Each must be adjudicated before the Atomic Safety and Licensing Board Panel, made up of independent administrative law judges. In a trial-like process, NRC and DOE staff will be deposed and then called as witnesses. That process is expected to take two to three years. Only then would the DOE license application go before the NRC commissioners, who are political appointees, for an up or down vote. Should the license be issued, the state will challenge it in court.

Other practical considerations will delay the licensing process. An April report from the Government Accountability Office notes that DOE and NRC both will need to reconstitute the expertise they lost when the project was halted. Bringing staff members up to speed once they are hired or transferred from other duties is likely to take a year, the report says. The 180 employees who had been working on Yucca Mountain at DOE were laid off in 2010, and contracts in support of the project with the national laboratories and other entities also were terminated. According to the GAO, years had been required for DOE to recruit and train the proper mix of scientists and engineers with the required backgrounds in hydrology, geology, mathematics, and other fields.



***The proposed Yucca Mountain repository** would be located about 300 meters beneath the surface of a long ridge and about 300 meters above the water table. Consisting of 64 kilometers of tunnels (white lines), the facility would accommodate highly radioactive wastes from commercial reactors and from federal defense-related activities.*

Robert Halstead, executive director of the Nevada governor's agency for nuclear projects, says the state has kept its entire team of experts and lawyers on throughout the licensing hiatus, and he expresses confidence that the state will defeat the project on technical grounds. "If Congress forces DOE to go forward with the Yucca Mountain repository concept on which the current license application is based, I expect Nevada to defeat it. And DOE would be well advised to think about withdrawing their application for the purpose of radically changing it to address things Nevada has raised in its contentions," he says.

Groundwater is main issue

State officials object to the repository proposal on multiple grounds, including DOE's plans for transporting waste by rail and truck to the site, seismicity concerns, and even the possibility of fighter jets from the air force's adjacent Nevada Test and Training Range crashing onto surface operations. But Halstead says the issue on which the project ultimately will turn is whether potential radiological contamination of groundwater can be kept within regulatory limits for the next one million years.

Congress in 1992 instructed the Environmental Protection Agency to draft a groundwater radiation protection standard specific to Yucca Mountain. The EPA promulgated a two-part regulation that limits the dose received by a hypothetical person consuming two liters of groundwater daily at either of two locations downstream of the repository to no more than 15 *millirems per year for the first 10 000 years, and to no more than 100 millirems per year for the subsequent 990 000 years. For comparison, the dose from a mammogram is about 13 millirems, and the average US annual background exposure is around 300 millirems.*

Nevada has a court challenge, pending since 2009, objecting to the dual EPA standard. That suit, says Halstead, hinges on one question: If 15 millirems is the appropriate safety limit for the first 10 000 years, how can you increase it sixfold for the rest of the million years?

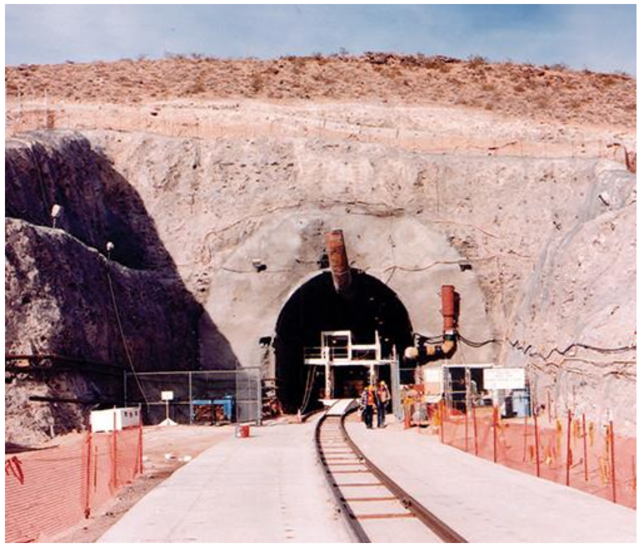
DOE did not respond to repeated requests for comment for this article. But the Nuclear Energy Institute (NEI), the industry's trade association, strongly supports the revival of Yucca Mountain. Rod McCullum, NEI's senior director for used fuel and decommissioning, maintains that Nevada's opposition is entirely political. The case for safety made by DOE and NRC staff, he says, "has a lot of science behind it; the Nevada contentions do not." Acknowledging that the repository "probably will be the most heavily litigated licensing process of all time," McCullum says he suspects nonetheless that Nevada will eventually stop the fight and negotiate with DOE to obtain greater economic benefits and a larger state role in ensuring safety during construction.
Representative Mark Amodei (R), who represents the northern portion of Nevada, advocates negotiation. He declined an interview request, but his website states his position that it's "likely the repository will eventually come to fruition through a sound scientific process over time." It also argues that Congress should work with DOE to make the location "a bastion of nuclear research and reprocessing" that would include a nuclear safety best-practices center, a training center, and R&D to address spent fuel.

Congress has sent mixed signals on Yucca Mountain so far this year. The House Appropriations Committee approved the full DOE request for FY 2018, but the Senate committee, largely at Dean Heller's (R-NV) behest, included no funding for the repository in its version of the bill. McCullum says he is optimistic that a compromise in conference committee later this year will include "something more than zero."

A 49–4 vote by the House Energy and Commerce Committee on 28 June to authorize resumption of the licensing process (H.R. 3053) signaled strong bipartisan support for the repository. A committee staffer says the lopsided vote indicated the waste issue "isn't a red state versus blue state thing" but reflects the level of constituents' concern with the growing spent fuel inventories at reactor sites nationwide. In addition to the 99 operating reactors at 61 plants, spent fuel is located at 20 shut-down reactors at 17 sites. Seven of the closed plants have been fully dismantled, and waste casks are all that remain onsite. Altogether, spent fuel is stored at 83 locations in 34 states.

More capacity needed
The Yucca Mountain license application covers 70 000 tons, including the equivalent of 7000 tons of DOE high-level wastes left over from nuclear weapons and other operations. Inventories at commercial reactor sites now total about 78 000 tons, according to the NEI. The House bill would amend the law to raise Yucca Mountain's storage cap to 110 000 tons. Room for several hundred thousand tons will be required since most of the current fleet of reactors have already been, or are expected to be, relicensed to operate for several decades to come. However, current economic conditions, mainly the low cost of natural gas, have led to the early closure of several

nuclear plants. There's room for as much as 400 000 tons inside just one ridge, and additional capacity can be developed in a second ridge that has very similar geology, McCullum says.



***One of two entrance portals** to the tunnel drilled into Yucca Mountain to investigate the site's suitability as a nuclear waste repository. More than $10 billion has been spent on the project since 1987.*

Some $40 billion has been collected in a federally controlled nuclear waste fund to pay for construction and operation of the repository. About $36 billion of that money—paid by utilities that operate nuclear plants through a surcharge on their customers' electricity rates— remains unspent.

Although contributions to the fund were suspended in 2014, they could resume once a federal court is persuaded that progress toward construction is occurring. The NEI says that assuming resumption of payments, and interest, the fund should cover the $96.2 billion estimated cost to build the repository, transport the waste, and operate the site for the 150 years it will accept material. That estimate, prepared by DOE in 2008, is the most recent available.

Other nations, including Finland, France, and Sweden, are developing repository sites, but Yucca Mountain is unique: It is the only one located above the water table. The region's sparse rainfall—which could grow with a changing climate—could seep into the 64 kilometers of tunnels where the waste is to be housed, and potentially leach radioactive materials into groundwater over time. McCullum, however, cites one advantage: Emplacements above the water table will ease the retrieval of waste should the repository be found unsuitable in the future.
Halstead argues that constructing the repository in a shale formation, such as at France's designated facility, would cost $20 billion less than Yucca Mountain, even after accounting for the billions of dollars that have already been sunk into studying the site.

Engineering questions

The less-than-ideal geology of the Nevada site—an oxidizing environment in fractured rock with a complex geologic and tectonic history—necessitated the addition of some engineered features to the repository design. For one, DOE's design calls for creating thermal zones in the pillars between the tunnels to channel away some of the heat generated by the waste while keeping the surrounding rock near 100 °C to stave off water intrusion.

Fettus, the NRDC lawyer, says the Yucca Mountain project "went off the rails" within a few years after the site's 1987 selection, when geological analyses turned up problems. After that, "it became an exercise of adjusting standards to make it work."

McCullum says the design recognizes that the engineered barriers will degrade over time. "You have this footrace between geologic processes and the radiological decay process, where the winner is the slowest. The geologic processes are slower than the decay, so by the time the [materials] break down over hundreds of thousands to a million years, no harmful radiation is released."

The most expensive, and arguably the most controversial, components of the repository are the titanium drip guards that would be installed to keep the waste casks dry. DOE estimates their cost at $7.8 billion. McCullum contends they are an unnecessary expense; Halstead questions whether a minimum of 11 500 shields weighing nearly 5 tons apiece could be installed remotely in the high-temperature, high-radiation environment in the tunnels. "Will NRC make DOE install them a century from now?" he says. "Can DOE actually fabricate and install the drip shields as proposed? Will they actually work?"

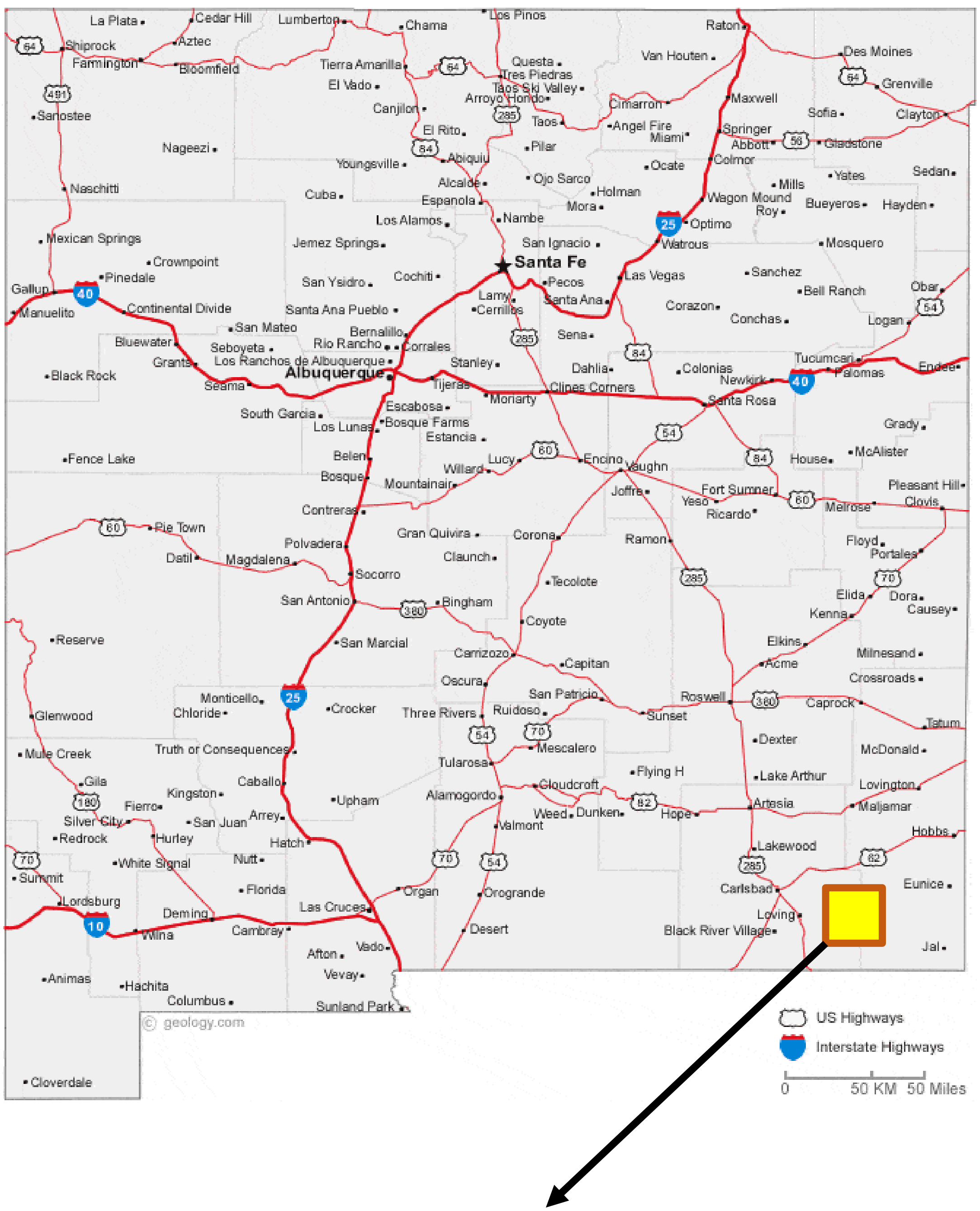
Absent the shields, groundwater contamination could exceed the 10 000-year standard in fewer than 900 years, and the million-year limit would be breached in fewer than 2000 years, Halstead maintains. The state also contends that DOE has underestimated the shields' cost by a factor of two.

Halstead notes that many Nevadans have a deep distrust of DOE, dating to the years of atmospheric nuclear tests that were carried out in the state by DOE's predecessor, the Atomic Energy Commission. At an April House hearing, Nevada Representative Dina Titus (D) recalled mushroom clouds visible from Las Vegas, less than 161 kilometers away. Since atmospheric testing ended in 1963, she said, billions of dollars have been paid out in settlements to residents of Arizona, Nevada, Utah, and other nearby states who contracted illnesses from exposure to radioactive fallout. "I give this history lesson not only to highlight the contributions that Nevada made to atomic development but also to remind you that they told us we were safe then, and they're telling us we're safe now," she testified.

W.I.P.P. (Waste Isolation Pilot Project)
Located in SE New Mexico, 2,150’ below the surface: 16 square miles of a 2,000’ thick Salt Bed from 225 million years ago. Stable for at least that many years.

Specifically set aside for “Defense Related Trans-Uranic Waste”, typically from weapons laboratories, generally consisting of protective clothing, tools, glassware and other equipment contaminated with radioactive materials. **And specifically <u>excludes</u> high-level waste and spent nuclear fuel.**

Fig. K-2



WIPP

What if the Yucca Mountain site is not opened/licensed?

Some reactor fuel rod alternatives (?): (Wolfson: Chapters 5, 8, 10)

a) Simple and already in place: Local storage in dry casks at power-reactor sites. These facilities already exist at 24 sites (with plans for 21 more); see the attached map. These sites are currently used for the "temporary" storage of spent fuel rods. The casks are estimated to be safe for least 100 years.

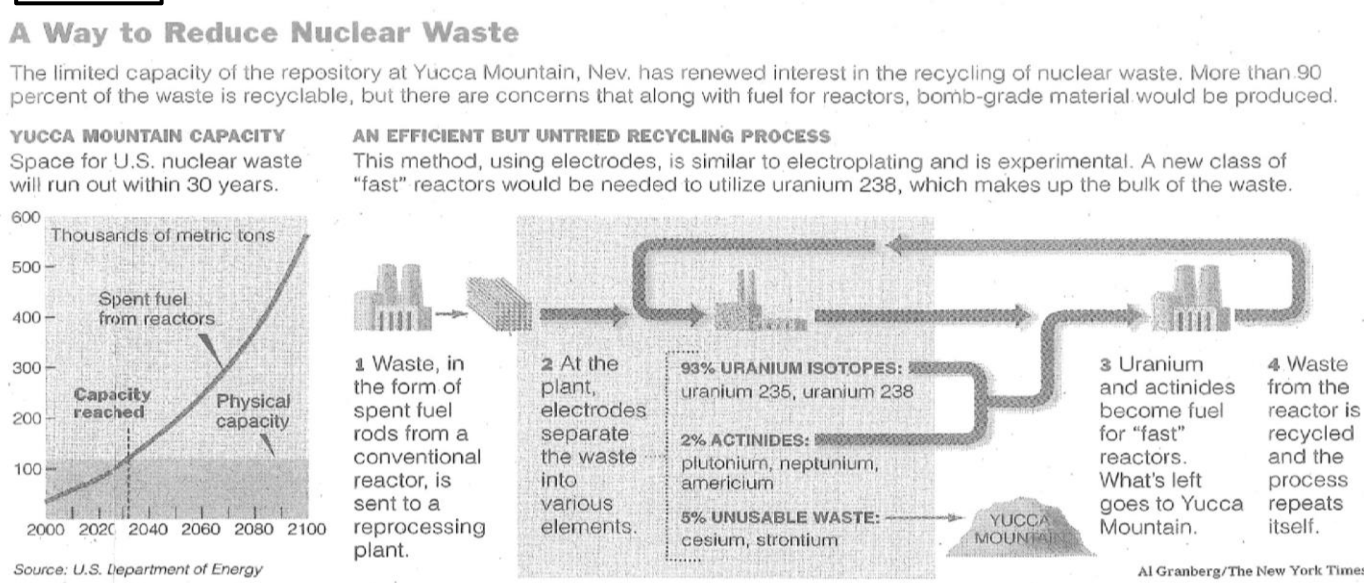
b) Reprocessing of reactor fuel rods - often referred to as *Breeder Reactors*: converting ^{238}U into fissile material.

$$^{238}U + n \;\longrightarrow\; ^{239}U \;\longrightarrow\; ^{239}Np \;\longrightarrow\; ^{238}Pu\ (!) \quad \text{(for power } \textbf{or} \text{ weapons)}$$

Converts more non-fissile material to fissile material than the amount of fissile material that was consumed. Instead of using just the ^{235}U nuclei, via this conversion, this has the potential of using all the uranium nuclei, and therefore the fission energy sources (ores) can last $\approx 100\times$ longer(!)

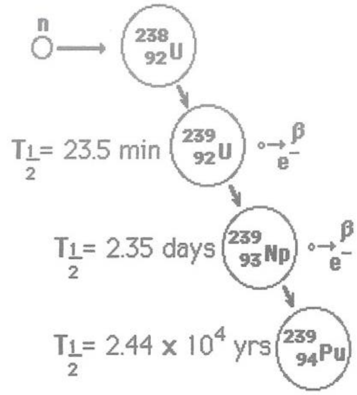
BUT $\longrightarrow$ A major danger in the development of an energy-system based on such breeder reactors is the fact that the resulting Pu could be more readily available for weapons.

Fig. K-3



"Scientists Try to Resolve Nuclear Problem With an Old Technology Made New Again"
By Matthew L. Wald , December 27, 2005, New York Times

Sample student oral report for class introduction



Breeder Reactors

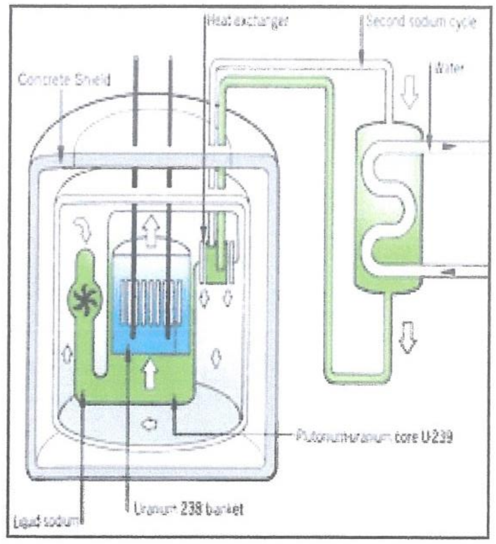
Brought to you by Heather Smith

What:

- Type of fission reactor that produces – or "breeds" – more fuel than it burns
- Fuel used is a composite of U-238 with 10% Plutonium
- Fuel core surrounded by uranium blanket

How:

- Neutrons bombard U-238, creating U-239, which beta-decays to Pu-239
- Non-fissionable uranium-238 is 140 times more abundant than the fissionable U-235 and can be efficiently converted into Pu-239 by the neutrons from a fission chain reaction.
- Sodium used as heat exchange fluid – liquid at 98°C and doesn't boil until 892°C, so very versatile medium.



Breeding ratio: the amount of fissile plutonium-239 produced compared to the amount of fissionable fuel (like U-235) used to produced it. Target ratio about 1.4

Liquid Metal Fast Breeder Reactor (LMFBR): This has been the most popular design for breeder reactors. Unlike standard light-water reactors, no moderator is used. The moderator is usually used to absorb stray neutrons/slow down fission. With no moderator, fast neutrons are allowed to bombard the uranium blanket and trigger faster generation of Pu-239 – hence "fast" breeder reactors.

The Good:

- More efficient than "burn-up" light-water fission reactors
- Energy from initial fission is captured, and additional fuel is created
- No need to pressurize core (unlike water-steam coolant system)

The Bad:

- Na is extremely reactive – combusts on contact with air or water
- No moderator, so requires three energy-transfer loops to ensure containment
- Technical problems have plagued experimental models such as SuperPhenix

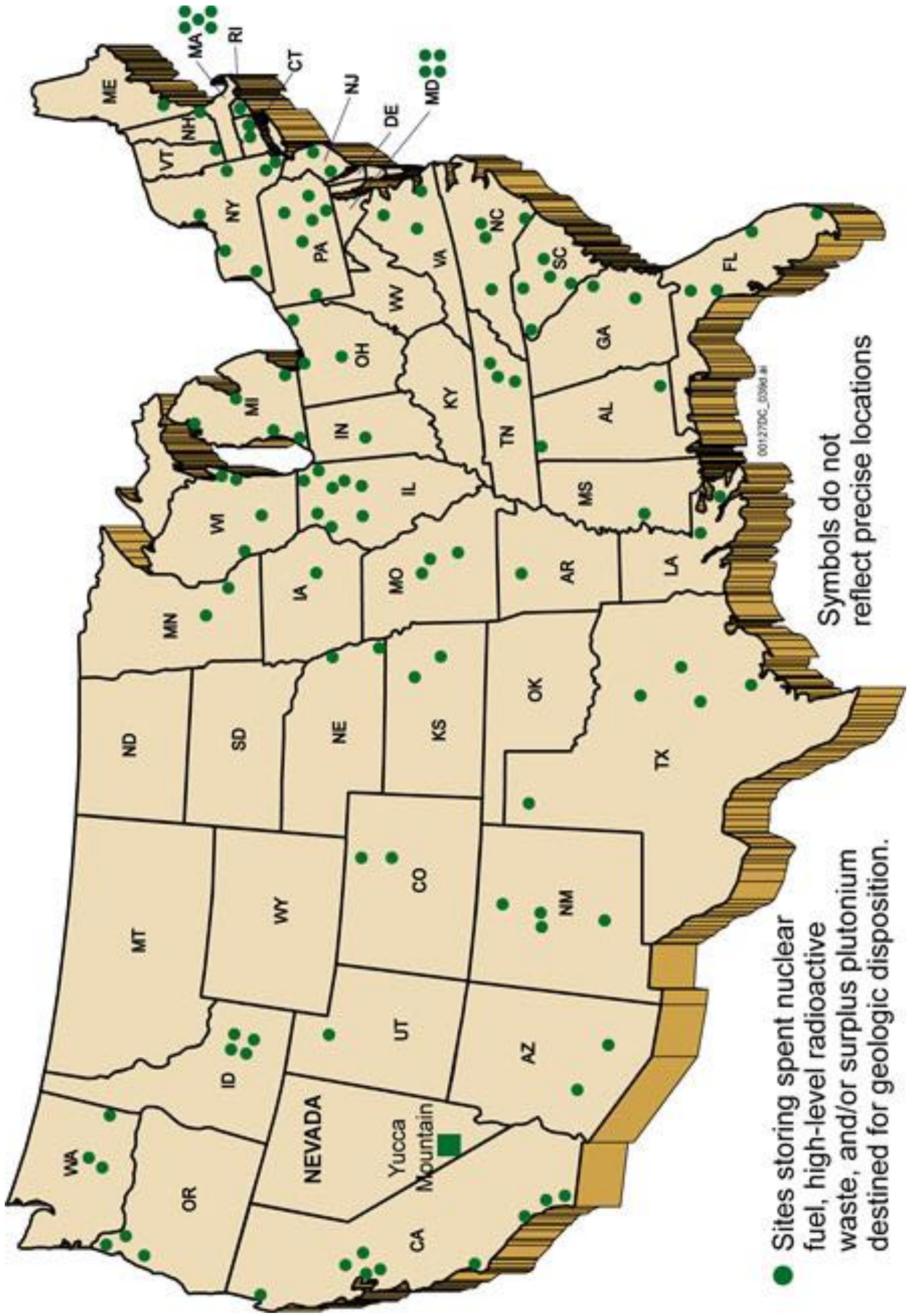
Superphénix: Fast neutron reactor in France, opened in 1985 and shut down in 1997. It was almost constantly malfunctioning, suffering from structural vibrations and other technical difficulties. At least it worked well when it worked. Despite its contribution to the research of fast breeder reactors, it has been an economic nightmare for the French government.

A few other types of breeders are...

Thermal Breeder Reactor: Similar to FBRs, but converts Th-232 into fissionable U-233. Lower-energy "thermal" neutrons bombard the blanket material.

Gas-Cooled Reactor: uses helium coolant directly to a gas turbine generator to produce electricity and would be a breeder reactor. The design might be used as a process heat source for the production of hydrogen.

Fig. K-4



Map of repository sites across the United States; courtesy of the Department of Energy

On Nuclear Waste, Finland Shows U.S. How It Can Be Done
By Henry Fountain, June 13, 2017, ***New York Times***

OLKILUOTO ISLAND, Finland — Beneath a forested patch of land on the Gulf of Bothnia, at the bottom of a steep tunnel that winds for three miles through granite bedrock, Finland is getting ready to entomb its nuclear waste. If all goes well, sometime early in the next decade the first of what will be nearly 3,000 sealed copper canisters, each up to 17 feet long and containing about two tons of spent reactor fuel from Finland's nuclear power industry, will be lowered into a vertical borehole in a side tunnel about 1,400 feet underground. As more canisters are buried, the holes and tunnels — up to 20 miles of them — will be packed with clay and eventually abandoned.
The fuel, which contains plutonium and other products of nuclear fission, will remain radioactive for tens of thousands of years — time enough for a new ice age and other epochal events. But between the two-inch-thick copper, the clay and the surrounding ancient granite, officials say, there should be no risk of contamination to future generations. "We are pretty confident we have done our business right," said Timo Aikas, a former executive with Posiva, the company that runs the project. "It seems the Olkiluoto bedrock is good for safe disposal."

The repository, called Onkalo and estimated to cost about 3.5 billion euros (currently about $3.9 billion) over the century or so that it will take to fill it, will be the world's first permanent disposal site for commercial reactor fuel. With the support of the local municipality and the national government, the project has progressed relatively smoothly for years.

That is a marked contrast to similar efforts in other countries, most notably those in the United States to create a deep repository in Nevada. The Yucca Mountain project, which would handle spent fuel that is currently stored at 75 reactor sites around the country, faced political opposition from Nevada lawmakers for years and was defunded by the Obama administration in 2012. Now, with the backing of the nuclear power industry — and with the retirement of Yucca Mountain's chief nemesis, Senator Harry Reid of Nevada — the Trump administration wants to take the project out of mothballs. But its fate remains uncertain.

Experts in nuclear waste management say the success of the Finnish project is due in part to how it was presented to the people who would be most affected by it. Each community under consideration as a repository location was consulted and promised veto power should it be selected.
In the United States, Congress in 1987 pre-emptively directed that only Yucca Mountain be studied as a potential site, effectively overruling opponents in Nevada who were worried that the project might affect water supplies or otherwise contaminate the region. "When you look at the Finnish repository, it's natural to admire the technical accomplishment," said Rodney C. Ewing, *a professor at Stanford and former chairman of the Nuclear Waste Technical Review Board, an independent federal agency that reviews Energy Department programs, including Yucca Mountain. "But of equal importance has been the social accomplishment."*

Long-Term Parking for Radioactive Waste

Granite bedrock in Western Finland will be the final resting place for the country's spent nuclear reactor fuel. A spiraling vehicle tunnel as well as access and ventilation shafts lead 1,400 feet underground, where the fuel will be stored in about 20 miles of tunnels for thousands of years.

Mr. Aikas, who was involved in the Finnish site selection process beginning in the 1980s, said he and his colleagues learned early lessons about the need to consult with local residents. "We ran into difficulties because we tried to behave as industry did back then — we'd decide and announce," he said. Invariably, he said, by presenting decisions as unreviewable, they ran into local opposition. "Very soon we learned that we had to be very open," Mr. Aikas added. "This openness and transparency creates trust." When five sites were selected for further study in 1987, offices were opened in each community to provide information. The approach proved so successful that when it came time for the national government to make a final decision on a repository in 2000, officials in Eurajoki, the municipality that includes Olkiluoto Island, agreed to host it on one condition: that Posiva not present the government an option to choose any other site. Eurajoki officials had concerns early in the process, Mr. Aikas said, but eventually came to see that the repository would provide property tax revenue and jobs.

The municipality also had experience with nuclear power: Two of the country's four operating nuclear power reactors are on Olkiluoto, less than two miles from the repository, and a third plant is under construction nearby.
"You have a community that is familiar with nuclear issues," said Dr. Ewing at Stanford. Nevada, by contrast, has no nuclear power plants. What it does have is both in the air and underground, for four decades until the 1990s. "You have to expect that a community with that experience will be a little skeptical," Dr. Ewing said. Finland's success also has its roots in an early decision by the national government. In 1983, it established the principle that the companies creating the waste — TVO, which owns the reactors at Olkiluoto, and Fortum Power and Heat, which owns the other two — are responsible for disposing of it. The government had only approval and regulatory roles.
"It has always been important to resolve this spent-fuel issue and keep it in the hands of the power company," Mr. Aikas said. Posiva, the company developing the repository, is a joint venture of the two utilities.

STORING THE FUEL
Because of radiation hazards, copper fuel canisters will be handled remotely and placed in vertical boreholes every 30 feet. Holes are located away from rock fractures that could expose canisters to water and lead to corrosion. If water did intrude, absorbent clay packed in the holes and tunnels should keep it away. In the United States, spent fuel became the responsibility of the federal government, specifically the Energy Department, subjecting the issue to more political pressures. At the Onkalo site, workers drill into the bedrock down near the 1,400-foot level, taking cores to study the characteristics of the granite. Above ground, near the curving entrance to the tunnel, construction has begun on a building where the spent fuel, currently cooling in pools at the Olkiluoto reactors, will be readied for burial, handled by remote-controlled

machinery since radiation levels will be high. Spent fuel will also eventually be shipped here from Fortum's reactors, on the country's southeastern coast.

Kimmo Kemppainen, research manager for the project, said that in characterizing and mapping the rock, it was important to locate, and avoid, fractures where water could flow, since the disposal site was below the water table. But even if water gets near a canister, he said, the clay should form a barrier and keep corrosion of the copper — which could result in a radiation leak — to a minimum, even over tens of thousands of years. Mr. Kemppainen has worked on the project for 14 years. "My personal opinion is that for this generation that has used nuclear power, at least we should do something about the waste," he said. "It's not safe to store it on the surface."
In the United States, more than 80,000 tons of spent fuel are currently stored on the surface, in pools or dry steel-and-concrete casks, at operating nuclear reactors and at other sites near now-closed plants. The original deadline to have a repository operating by 1998 is long past.

The project at Yucca Mountain, in the Mojave Desert about 100 miles northwest of Las Vegas, has been studied for years at a cost of more than $13 billion. In 2008, the Energy Department began the process of obtaining a construction license from the Nuclear Regulatory Commission. But the Obama administration moved to withdraw the license application two years later. With the election of President Trump, advocates for Yucca Mountain saw a chance to revive it. "This is a very important national project," said Rod McCullum, a senior director at the Nuclear Energy Institute, an industry group. "If we can do this safely, we would be ashamed of ourselves if we didn't do it." The Trump administration is seeking $120 million to reopen the licensing process. And in a symbolic gesture, in his first official trip as energy secretary, Rick Perry toured the site, where little exists beyond a five-mile-long exploratory tunnel. Congress rejected the licensing funds in its deliberations on the 2017 budget, and the 2018 budget process is just starting. Even if the $120 million is allocated, it could take a half-decade or longer, and much more money, to complete the licensing, which would involve a lengthy hearing before administrative judges on hundreds of environmental and safety issues raised by opponents.

Even without Mr. Reid, most members of Nevada's congressional delegation are still vowing to fight the project, arguing that there are concerns about the long-term safety of drinking water supplies — unlike the Finnish repository, the Nevada site sits above the water table — and that above all, Nevadans do not want it.

The decision to put the repository there "was based on bad politics, not good science," said Representative Dina Titus, a Democrat who represents a Las Vegas district. "The main issue is consent," she said. She and other members of the delegation have introduced a bill that would require the host state's approval before the repository could be built. In a 2012 report, an expert panel established by the Obama administration to develop a new strategy for managing spent fuel recommended a similar consent-based process. It had another Finland-like recommendation as well: that responsibility for nuclear waste be taken from the Energy Department and put in the hands of an organization created solely for that purpose.

Those recommendations have not been acted upon. But it is also unclear whether Yucca Mountain, if revived by the Trump administration, would succeed under the current approach. "It could be that the federal government could prevail and after some decades we would have a repository," Dr. Ewing said. "It could be that after several decades the federal government could fail and we would be where we are at today." There's a lot to be said for how Finland handled its situation, Dr. Ewing added. "If you treat people fairly and present them the information, if the repository is safe, you should be able to get some communities to respond positively," he said.

References:

Bernard Cohen, Before It's Too Late, Plenum Press (1983), Chapter 4.

George Cowan, A Natural Fission Reactor, Scientific American, (July 1976), p.36.

H. Fountain, New York Times, June 13, 2017, pages D1, D6; online:
On Nuclear Waste, Finland Shows U.S. How It Can Be Done.
https://www.nytimes.com/2017/06/09/science/nuclear-reactor-waste-finland.html .

Richard Garwin & Georges Charpak, Megawatts and Megatons, Alfred A. Knopf (2001), Chapters 2, 5, 7, 9.

I.A.E.A., The OKLO Phenomenon, I.A.E.A. (1975).

If Not Yucca Mountain, Then What?
http://www.yuccamountain.org/pdf/alternatives03.pdf

David Kramer, Physics Today **70**, 10, 32 (2017); ttps://doi.org/10.1063/PT.3.3724

Richard Wolfson, Nuclear Choices, M.I.T. Press (2000), Chapters 2, 5, 8, 9, 10.

(L) Marking Disposal Sites

Given the *long* 24,000 year half-life of ^{239}Pu in fission-reactor waste, Sandia National Laboratories created a panel to design and look into the efficiency for a wide variety of various types of markers. The following pages are excerpts from the report of that panel. Then full report can be found at:

> Expert Judgement on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant, Sandia National Laboratories report SAND92-1382/UC721, p. F-49.

Note well a most sensible judgement as presented in Paragraph 5.3 (Personal Thoughts of Woodruff Sullivan) towards to the end of this report.

Amusingly, the following page cannot help but call to mind the futility of such markers - as emblazoned by Percy Bysshe Shelley's poem, Ozymandias.

Ozymandias
by Percy Bysshe Shelley

I met a traveller from an antique land,
Who said—"Two vast and trunkless legs of stone
Stand in the desert. . . . Near them, on the sand,
Half sunk a shattered visage lies, whose frown,
And wrinkled lip, and sneer of cold command,
Tell that its sculptor well those passions read
Which yet survive, stamped on these lifeless things,
The hand that mocked them, and the heart that fed;
And on the pedestal, these words appear:
My name is Ozymandias, King of Kings;
Look on my Works, ye Mighty, and despair!
Nothing beside remains. Round the decay
Of that colossal Wreck, boundless and bare
The lone and level sands stretch far away."

This place is not a place of honor.

No highly esteemed deed is commemorated here.

Nothing valued is here.

This place is a message and part of a system of messages.

Pay attention to it!

Sending this message was important to us.

We considered ourselves to be a powerful culture.

Excerpts from ***Expert Judgment on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant,*** Sandia National Laboratories report SAND92-1382 / UC-721, p. F-49

Team A:

Dieter G. Ast (Cornell University), Michael Brill (Buffalo Organization for Social and Technological Innovation, Inc.), Ward Goodenough (University of Pennsylvania) , Maureen Kaplan (Eastern Research Group, Inc.), Frederick Newmeyer (University of Washington), Woodruff Sullivan (University of Washington)

Team B:

Victor R. Baker (University of Arizona), Frank R. Drake (University of California at Santa Cruz), Ben R. Finney (University of Hawaii at Manoa), David B. Givens (American Anthropological Association), Jon Lomberg (independent artist, designer, and writer), Louis Narens (University of California at Irvine), Wendell Williams (Case Western Reserve University)

http://www.wipp.energy.gov/picsprog/articles/wipp%20exhibit%20message%20to%2012,000%20a_d.htm

---

EXECUTIVE SUMMARY

Sandia National Laboratories charged a panel of outside experts with the task to design a 10,000-year marking system for the WIPP (Waste Isolation Pilot Plant) site, and estimate the efficacy of the system against various types of intrusion. The goal of the marking system is to deter inadvertent human interference with the site. The panel of experts was divided into two teams. This is the report of the A Team; a multidisciplinary group with an anthropologist (who is at home with different, but contemporary, cultures), an astronomer (who searches for extra-terrestrial intelligence), an archaeologist (who is at home with cultures that differ in both time and space from our own), an environmental designer (who studies how people perceive and react to a landscape and the buildings within them), a linguist (who studies how languages change with time), and a materials scientist (who knows the options available to us for implementing our marking system concepts). The report is a team effort. There is much consensus on the design criteria and necessary components of the marking system. Understandably, there is some diversity of opinion on some matters, and this is evident in the text.

We developed the following criteria for the marking system:

The site must be marked. Aside from the legal requirement, the site will be indelibly imprinted by the human activity associated with waste disposal. We must complete the process by explaining what has been done and why.

The site must be marked in such a manner that its purpose cannot be mistaken.

Other nuclear waste disposal sites must be marked in a similar manner within the U.S. and preferably world-wide.

A marking system must be utilized. By this we mean that components of the marking system relate to one another is such a way that the whole is more than the sum of its parts.

Redundancy must play a preeminent role in the marking system design. The designs considered here have redundancy in terms of message levels, marking system components, materials, and modes of communication.

Each component of the marking system should be made of material(s) with little intrinsic value. The destructive (or recycling) nature of people will pose a serious threat to the marking system.

The components of the marking system should be tested during the next few decades while the WIPP is in operation, not only for the longevity of the materials but for the pan-cultural nature of the message. In other words, as with the repository design itself, the team was comfortable with the thought of designing a marking system that would last 10,000 years if left undisturbed. Our efforts focused on making it understandable while providing minimal incentive to disturb it. We also consider a public information effort a necessary part of the marking system design. A system that is not understood today has no chance of being understood in the far future.

Figures 4.3-1 through 4.3-18 provide a basic description of our most developed design and other design options

The central area of interest is surrounded by earthen berms. For the WIPP site, the area of interest is where we do not want drilling or excavation to occur. In the design the central area is the area of the underground panels plus either (1) a one-fourth-mile buffer zone, or (2) the distance to which the radionuclides may migrate during the 10,000-year period, whichever is larger. The forms of the earthworks are jagged and rough, suggestive of energy radiating from the central area.

The berms serve several purposes. First, they define the area of interest. Their size is set so that sand dunes are unlikely to cover all of them entirely at the same time. Instead, the wind will leave dunes streaming behind the berms and create an even larger marker. Second, their shape sets the tone for the entire landscape -- non-natural, ominous, and repulsive. Third, the corner berms are higher than the others and provide vantage points for viewing the entire site. Fourth, the corner berms also include buried rooms with all the message levels recommended for inclusion in this marker system. As the berms erode, these rooms will become uncovered at various times.

The investigator will be guided toward the center of the site by the berms. Prior to entering the central area, however, he or she will encounter a "message kiosk" (Figure 4.3-18). Each message kiosk is composed of a message wall and a protecting wall. In terms if site layout, the message kiosks form the only "nurturing" part of the marking system design. The protecting wall is of concrete and is meant to protect the message wall from erosion. The message wall is of granite or other hard rock and is a vertical, curved form. There are two reasons for a curved *form: (1) it makes it very difficult to reuse the piece for another purpose, and (2) it is not an honorific form such as an obelisk. The vertical aspect minimizes tensile stress on the components.*

The message wall will bear what we call Level II and Level III messages (cautionary and basic information, respectively). The preliminary texts read:

Level II:

Level III:

These standing stones mark an area used to bury radioactive wastes. The area is ... by ... kilometers (or ... miles or about ... times the height of an average full-grown male person) and the buried waste is ... kilometers down. This place was chosen to put this dangerous material far away from people. The rock and water in this area may not look, feel, or smell unusual but may be poisoned by radioactive wastes. When radioactive matter decays, it gives off invisible energy that can destroy or damage people, animals, and plants.

Do not drill here. Do not dig here. Do not do anything that will change the rocks or water in the area.

Do not destroy this marker. This marking system has been designed to last 10,000 years. If the marker is difficult to read, add new markers in longer-lasting materials in languages that you speak. For more information go to the building further inside. The site was known as the WIPP (Waste Isolation Pilot Plant) site when it was closed in ...

2. The Problem of Message

2.1 Message definition

Modern understanding of the communications enterprise shows that there can be little separation of the content of a message from its form, and from its transportation vehicle. They affect each other, and all of it is message. McLuhan and Fiore [Ref. 2-1] take that even further, arguing that "the medium is the message." Given this, rather than our attempting to first articulate messages, then to select their form, and then to design their vehicle, we choose to do as much of this simultaneously as is reasonable, attempting to accomplish

a Gestalt, in which more is received than sent, *a Systems Approach, where the various elements of the communications system are linked to each other, act as indexes to each other, are co-presented and reciprocally reinforcing, and*

Redundancy, where some elements of the system can be degraded or lost without substantial damage to the system's capacity to communicate.

Everything on the site is conceived of as part of the message communication...from the very size of the whole site-marking down to the design of protected inscribed reading walls and the shapes of materials and their joints. In this report, the various levels of message content are described, as is the content of each level, the various modes of message delivery, and the most appropriate physical form of each.

We obviously recommend that a very large investment be made in the overall framework of this system, in the marking of the entire site, and in a communication mode that is non-linguistic, not rooted in any particular culture, and thus not affected by the expected certain transformation of cultures. This mode uses species-wide archetypes...of meanings bound to form, such that the physical form of the site and its constructions are both message content and mode of communication. Thus, the most emphatically delivered message is the meaning-bonded-to-form in the site itself. (See Section 4 for the message the site is asked to deliver.)

As part of a system of message communications, we recommend substantial use of verbal texts and graphics, but with little emphasis on constructed, non-natural, non-iconic symbols. These texts and graphics act as indexes to each other, and act as indexes across message levels. We also suggest the site be marked so it is anomalous to its surroundings in its physical properties such as electrical conductivity and magnetism.

2.2 Message levels and criteria

2.2.1 Message Levels

Givens [Ref. 2-2] describes four information levels for the messages:

Level I: Rudimentary Information: "Something man-made is here"

Level II: Cautionary Information: "Something man-made is here and it is dangerous"

Level III: Basic Information: Tells what, why, when, where, who, and how (in terms of information relay, not how the site was constructed)

Level IV: Complex Information: Highly detailed written records, tables, figures, graphs, maps and diagrams

Our discussions led to two expansions of Givens' work. First, we decided that it was possible to convey a sense of danger, foreboding, and dread without the use of language or pictures. This would be done within the context of site design. Under these circumstances, what would generally be considered as Level I components (e.g. earthworks) would be able to convey both Level I and Level II messages. Second, we decided to have a fifth level that lays between Givens' Level III and Level IV. The new Level IV would have more detail than Level III but still not be a *complete rulemaking record. The latter is now called Level V. Specific examples of the different level message are given in Section 4.6.2.*

The general approach taken by the team is that the emphasis is on clarity and, where possible, brevity. Overly long and complex messages will be too difficult and time-consuming to translate to be effective. The message must be straightforward. and neither understate nor overstate the hazards of the site. The difficult in formulating the message is that many normal human activities, e.g., house building and farming, can occur on the surface without jeopardizing the performance of the repository. Problems begin only when deeper drilling and excavation occur.

We decided against a large radiation symbol prominently displayed on a marker lest the potential intruders take a quick reading, find nothing more than background radiation, and ignore the rest of the message. We did decide that the incorporation of a radiation symbol was appropriate within the larger context of the message. As a symbol, it could provide a link between textual and pictorial information.

We decided against simple "Keep Out" messages with scary faces. Museums and private collections abound with such guardian figures removed from burial sites. These earlier warning messages did not work because the intruder knew that the burial goods were valuable. We did decide to include faces portraying horror and sickness (see Sections 3.3 and 4.5.1). Such faces would relate to the potential intruder wishing to protect himself or herself, rather than to protect a valued resource from thievery.

We decided against overstatement of the danger. The "Touch one stone and you will die" approach is unacceptable because it is not credible. Inevitably, someone will investigate the site in a non-intrusive manner. Nothing will happen to the person, and the rest of the message will therefore be ignored. There was consensus, however, on the need to mark the site and on the need to convey the dangers to the potential intruder.

We consider the key to a successful system to be a credible conveyance of the dangers of disturbing the repository. We must inform potential intruders what lies below and the consequences of disturbing the waste. If they decide that the value of the metal component of the waste far outweighs the risks of recovering the metal, the decision is their responsibility, not ours.

The warning information is divided up into

4. Criteria for a Marking System with Examples

4.1 Site design guidelines for a design of the entire site, so it is a major component of a system of messages

The Design Guidelines herein will be largely performance-based, that is, they describe how the design must perform, rather than what it must look like or be made of. These guidelines can, in turn, be used as criteria to evaluate designs. Because performance-based design guidelines do not describe the design, but rather what the design must do, several alternative designs can be developed in response to the guidelines. We have developed designs using the design guidelines, both as a test of the utility of the guidelines and as an expression of the team's preferred *solutions. Because all the designs cover the entire interment, and then some, we refer to them as "site designs." These designs are presented in Section 4.2.*

In this discussion and then later in the descriptions of the designs that test these design guidelines we will use the expression "the Keep" to define an area whose size and shape is the "footprint" or the vertical projection on the site's surface of the final interment area. Our team's analysis suggests that the final footprint may be larger than currently shown because of both migration of radionuclides in the salt and future expansion.

The various site designs may be listed as follows:

- *The site must be marked.*
- *All levels of message complexity should be located on-site. Thus, communication vehicles for information at Levels I, II, III, and IV should be on the WIPP site and available to humans. As well, this team has developed specific message content for each level, presented later in Section 4.6.*
- *The design of the whole site itself is to be a major source of meaning, acting as a framework for other levels of communication, reinforcing and being reinforced by those other levels in a system of communication. The message that we believe can be communication non-linguistically (through the design of the whole site), using physical form as a "natural language," encompasses Level I and portions (faces showing horror and sickness) of Level II. Put into words, it would communicate something like the following:*

This place is a message...and part of a system of messages...pay attention to it!

Sending this message was important to us. We considered ourselves to be a powerful culture.

This place is not a place of honor...no highly esteemed deed is commemorated here...nothing valued is here.

What is here is dangerous and repulsive to us. This message is a warning about danger.

The danger is in a particular location...it increases toward a center...the center of danger is here...of a particular size and shape, and below us.

The danger is still present, in your time, as it was in ours.

The danger is to the body, and it can kill.

The form of the danger is an emanation of energy.

The danger is unleashed only if you substantially disturb this place physically. This place is best shunned and left uninhabited.

- *All physical site interventions and markings must be understood as communicating a message. It is not enough to know that this is a place of importance and danger...you* *must know that the place itself is a message, that it contains messages, and is part of a system of messages, and is a system with redundancy.*

- *Redundancy of message communication is important to message survivability. Redundancy should be achieved through: (a) a high frequency of message locations, permitting some to be lost; (b) making direct and physical links among message levels, that is "co-presentation" of messages; and (c) multiple and mutually reinforcing modes of communication.*

  It is expected that the number of presentations of messages will decrease as the message complexity (or Level) increases. Thus, there will be many more presentations of Level II linguistic messages than of Level IV.

  While the system of marking should strongly embody the principles of redundancy, at the same time the methods of achieving redundancy should be carefully designed to maintain message clarity. Redundancy should not be achieved at the expense of clarity.

- *The method of site-marking must be very powerful to distinguish this place from all other types of places, so that the future must pay attention to this site. The place's physical structure should strongly suggest enhanced attention to itself and to its sub-elements. To achieve this, the volume of human effort used to make and mark this place must be understood as massive, emphasizing its importance to us. The site's constructions must be seen as an effort at the scale of a grand and committed culture, far beyond what a group or sect or organization could do.*

  About scale: "Scale" refers to the perceived size relationship between a human and something (like a house or a chair or a site). When the size of a thing gets far larger than a person, changes in scale are not easily perceived or are experienced as irrelevant. Thus, there is little difference to a person at ground level whether an earthwork is 1 mile or 2 miles long. These distances are experienced as much the same. What we propose as a marking for this site is already at a scale where it could be somewhat smaller or larger with no loss of meaning. And further, if the design were to be replicated elsewhere, it could be (somewhat) scaled up or down with no loss of meaning.

- *Vertical masonry markers alone are simply not enough to accomplish our purposes. They are not large enough, nor frequent enough, nor sufficiently distinguishing from other sites already so marked; and their use elsewhere may well make their use here somewhat trivial and certainly ambiguous. If only markers are used here, they will be seen as much like markers on other sites, which are generally sites of far less import, and also tend to be marked because they are honorific or commemorative, the opposite of the message we seek to send.*

- *Use a system of markings that utilizes the whole site as an enormous mark, and that includes: smaller markers; high points to climb from which to view the entire site; walls and places to be in that co-locate viewers with messages...an organized environment. Consider the possible retention of a currently existing structure for symbolic purposes only, as a decaying massiveness.*

As for use of existing structures, if we assume no active institutional control, the only current above-ground site structure that might endure for a substantial portion of the 10,000 years would be the thick-walled concrete "hot" cell. The other buildings will decay, or more probably be stripped of their valuable building materials for re-use.

The "hot" cell may be put to symbolic use by incorporating it into the site's design, as a mute artifact suggesting something "strong" that needed to be contained, although from its large door size, a thing that had to be easily accessible and thus was (probably) not treasure. And because the "hot" cell's openings are randomly placed, rather than symmetrical, it would tend not to be mistaken for an honorific or privileged structure. If the "hot" cell is kept, it should not be located in the geometric center of any open space, which would symbolically elevate its importance.

- *While this system of markings should represent an enormous effort and investment of resources on our part, the construction itself should be of materials of little value, and the workmanship should not bestow any value through the elegance of craft or artistry. Doing substantial work on materials of little value suggests that the place is not commemorative of phenomena highly valued by the culture that made it, but as marking something important yet quite unvalued ...not a treasure, but its opposite...a location of highly devalued material ("dangerous garbage" or an "un-treasure").*
- *The place should not suggest shelter, protection or nurture...it should suggest that it is not a place for dwelling, nor for farming or husbandry. This would be most strongly communicated if the place obviously tries to deny inhabitation and utilization. It might best be designed as a place difficult to be in, and to work in...both actually and symbolically. Given this, the center of the place should reject rather than embrace. Any attractive focus on/near that center would suggest welcome, and by extension, occupancy and utilization.*
- *We believe there is no physical barrier we can devise that (some) future technology cannot breach, and any attempt to bar entry physically to the Keep can and will be breached (by cutting through it, going under it, or coming down from above). Thus, any "barrier" placed around the Keep can only be purely symbolic, and should be used to enclose it only in a spatial sense rather than to attempt a fortification or a security barrier.*
- *As to the meaning of "center": physically to mark the WIPP site in any way makes it a different place from the surrounding desert, and creates a "figure" against a "ground." It makes a center in the desert.*
- *For human beginnings, making a center ("here we are") is the first act of marking order (Cosmos) out of undifferentiation (Chaos). All further meanings of "center" derive from this original positive valence. The meanings of "center" have always been as a highly valued place or a gathering place...the holy of holies; the statue centered within the temple, itself centered within the settlement; the dancing ground; the sacred place as the physical and spiritual center of a people, etc. In this project, we want to invert this symbolic meaning, to suggest that the center is not a place of privilege, or honor, or value, but its opposite. In symbolic terms, we suggest that the largest portion of the Keep, its center, be left open, and few (if any) structures placed there, so that symbolically it is: uninhabited, shunned, a void, a hole, a non-place.*
- *As for the geometric center, placement of anything at dead-center of the Keep would suggest that it is of the utmost importance, occupying the place of greatest privilege. We*

do not believe there is any one thing that can or should play that role on this site. (For example, someone might suggest that the highest Level IV of information might be placed at the center. But because a Level IV message may be gibberish to some intruders, while a Level II message would be well understood, no level of message is more important than any other, and no particular message or level is important enough to occupy the most privileged location.)

- *Design of the entire site and its sub-elements should avoid those forms that humans regularly tend to use to represent the "ideal," "perfection," or "aspiration." Aspiring forms are sky-reaching verticals, the obelisk, for example. Ideal and perfect ones are the perfect forms of symmetrical geometry (spheres, pyramids, hexagons) and of regular crystalline structures or polyhedrons. If such forms are used, we suggest their perfection be undermined through substantial and obviously meant "irregularity," as if its builders knew about the ideal and perfection, but asserted that this place is not about them. More appropriate types of forms to use are amorphic or jagged and horizontal, a deliberate shunning of the values of "perfection" pr "aspiration."*
- *A major site-delivered message is that this place is ominous, not to be disturbed. This Level II message can be delivered both through site design and through "reading walls," discussed later. Message levels will probably be delivered in a sequence, but no level of message is more valuable than another. The design should incorporate this parity of levels. While Level IV information is certainly the most complete and detailed of all our communications at the site, there are certainly plausible future scenarios under which it will be of less value than a Level II message, or even of no value at all, even if seen. Thus, Level IV is more complex, but not a more valuable message to us (or future people), and its location should symbolically bestow no more value or privilege on it than on other message levels.*
- *The design should provide a general sense of the magnitude, shape, and location of the original danger. Because there is no apparent danger at the site's surface, the design makes it clear that the danger is below and threatens to escape. The site design should also articulate that the dangerous material is bounded, has a substantial footprint that is of a certain shape. Going out from this on-surface imprint might be concentric bands designed to signify diminishing danger. It is not necessary to mark the Land Withdrawal boundary; it is a legal boundary that will be meaningless in a few centuries.*
- *The enormity of the site's undertaking and its shape should be visible and comprehendible in its entirety, as a panorama. A panorama, the "seeing-all" from an altitude, is an ancient human metaphor for knowing, and seeking it is natural. Thus, provide elevated points for site viewing (mound, ziggurat, tower...all of which can be climbed for viewing).*

- *The site-marking system should also function as a locator for multiple concepts of location and should:*

locate the site in relation to local centers of population of our time (which may contain archives as part of the information system);

locate this site in relationship to other disposal sites in the world;

locate the viewer ("you are here") on all three spatial axes in relationship to the entire site and its sub-elements, and to the hazard;

locate the construction of this site in time; locate all on-site position of Level III and IV messages.

4.2 Design options

Presented [here] are several alternative designs for the entire site, followed by designs for some particular spaces on it. These designs are based on the Design Guidelines just presented and thus act as tests of the efficacy of the guidelines. Of the many designs developed and reviewed, these are also the design solutions most preferred by the team. The designs utilize archetypical images whose physical forms embody and communicate meaning. We have given them names, both for identification and as verbal images for each. They are:

Landscape of Thorns

Spike Field

Spikes Bursting Through Grid

Leaning Stone Spikes

Menacing Earthworks

Forbidding Blocks

Some designs use images of dangerous emanations and wounding of the body. Some are images of shunned land...land that is poisoned, destroyed, parched, uninhabitable, unusable. Some combine these images. All designs entirely cover or define at least the interment area, called here the Keep.

Shunned land...poisoned, destroyed, unusable:

"Black Hole": *A masonry slab, either of black Basalt rock, or black-dyed concrete, is an image of an enormous black hole; an immense nothing; a void; land removed from use with nothing left behind; a useless place. It both looks uninhabitable and unfarmable, and it is, for it is exceedingly hot part of the year. Its blackness absorbs the desert's high sun-heat load and radiates it back. It is a massive effort to make a place that is fearful, ugly, and uncomfortable.*

The heat of this black slab will generate substantial thermal movement. It should have thick expansion joints in a pattern that is irregular, like a crazy-quilt, like the cracks in parched land. And the surface of the slab should undulate so as to shed sand in patterns in the direction of the wind.

"Rubble Landscape": *A square outer rim of the caliche layer of stone is dynamited and bulldozed into a crude square pile over the entire Keep. This makes a rubble-stone landscape at a level above the surrounding desert, an anomaly both topographic and in roughness of material. The outer rim from which rubble was pushed inward fills with sand, becoming a soft moat, probably with an anomalous pattern of vegetation. This all makes for an enormous* *landscape of large-stone rubble, one that is very inhospitable, being hard to walk on and difficult to bring machinery onto. It is a place that feels destroyed, rather than one that has been made.*

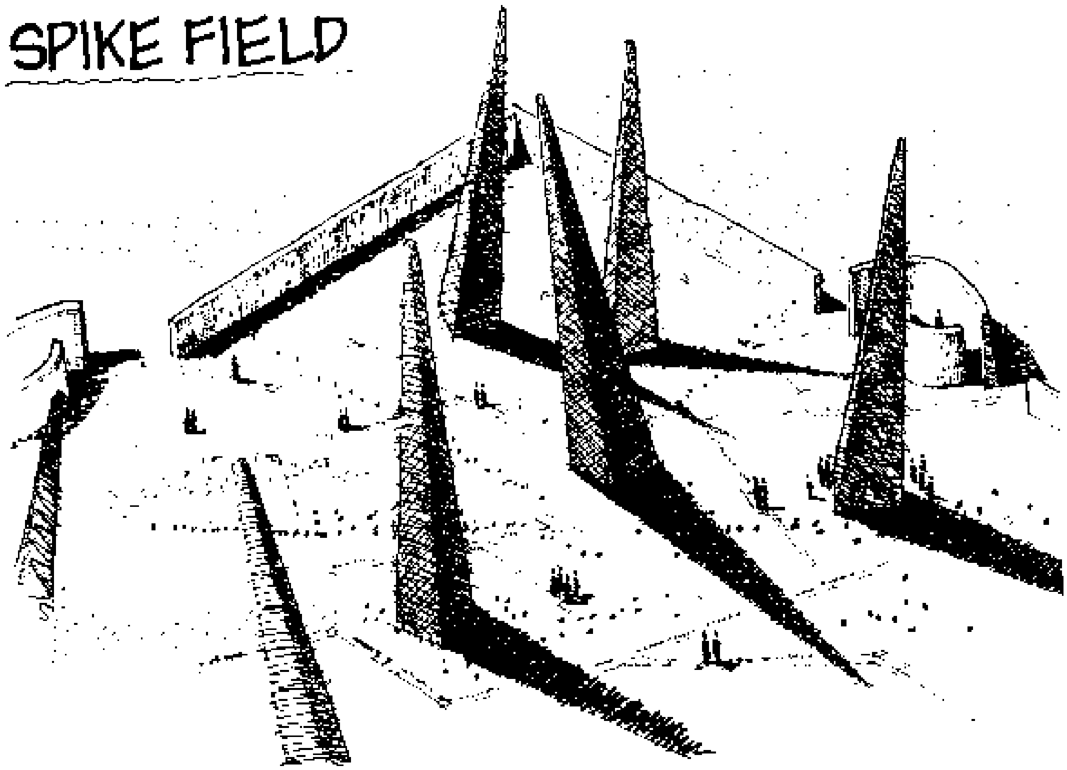


Figure 4.3-3. Spike Field, view 1 (concept and art by Michael Brill).

Shapes that hurt the body and shapes that communicate danger: *Danger seems to emanate from below, and out of the Keep in the form of stone spikes (in Spike Field, Spikes Bursting Through Grid, and Leaning Stone Spikes), concrete thorns (in Landscape of Thorns), and zig-zag earthworks emanating from the Keep (in Menacing Earthworks). The shapes suggest danger to the body...wounding forms, like thorns and spikes, even lightning. They seem active, in motion out and up, moving in various directions. They are irregular or non-repetitive in their shape, location and direction. They seem not controlled, somewhat chaotic. In the three designs that use "fields" of spikes or thorns, these spikes or thorns come out of, and define the Keep, so the whole area that is dangerous to drill down into is so marked.*

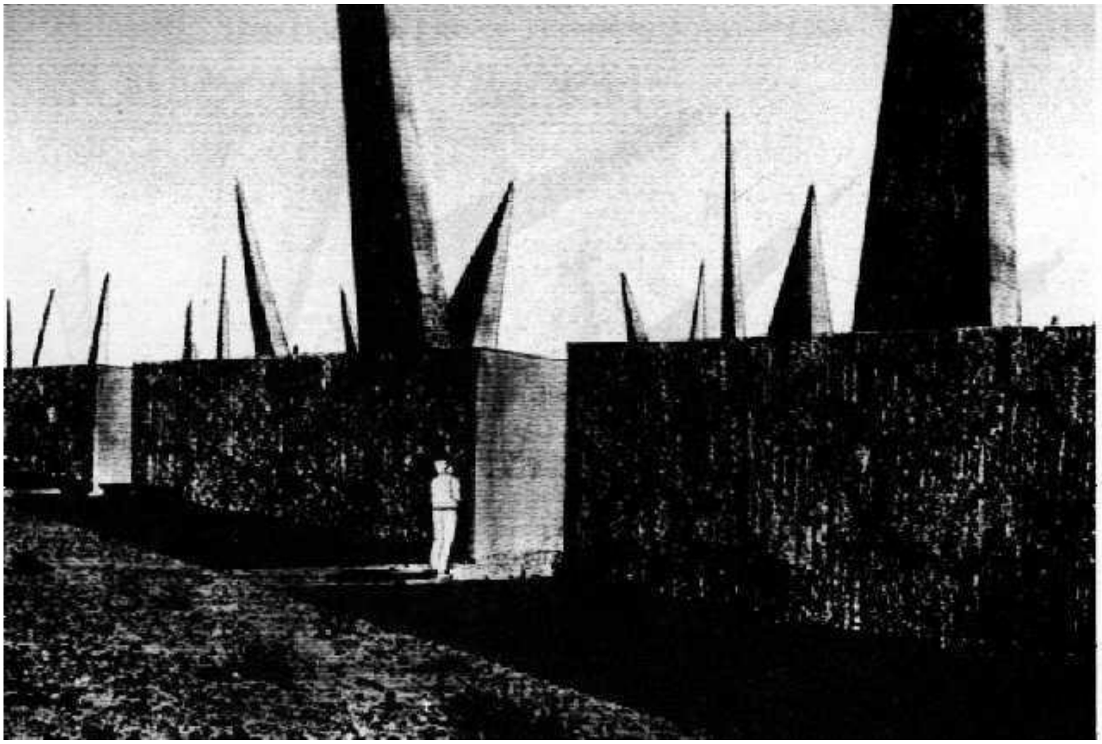


Figure 4.3-4. Spike Field, view 2 (concept by Michael Brill and art by Safdar Abidi).

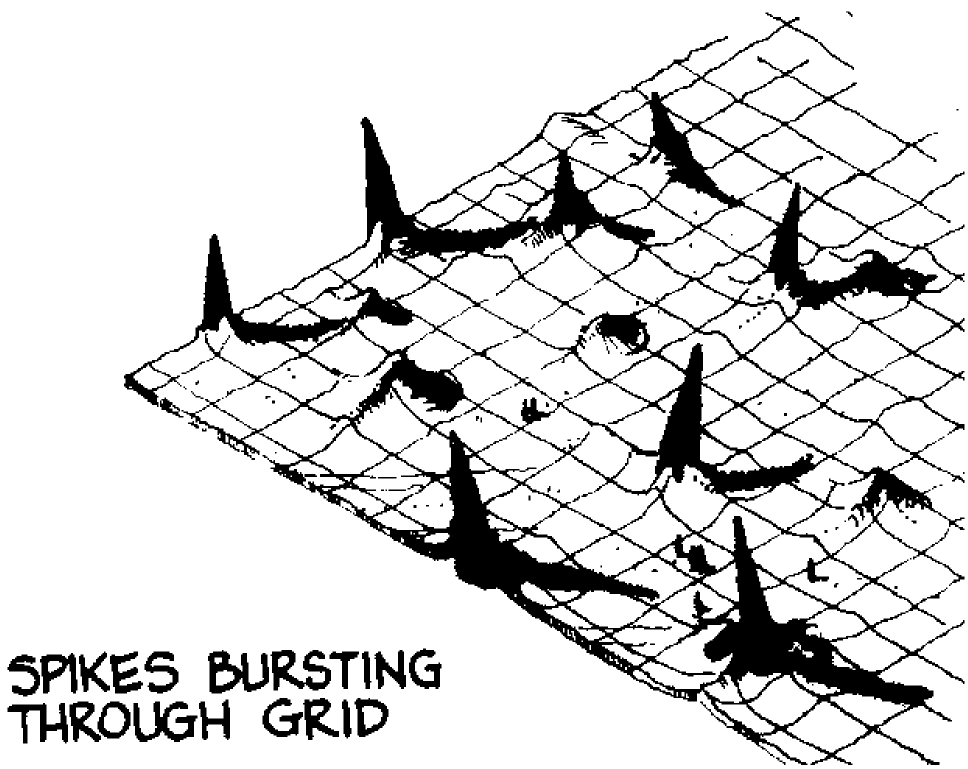


Figure 4.3-5. Spikes Bursting Through Grid, view 1 (concept and art by Michael Brill).

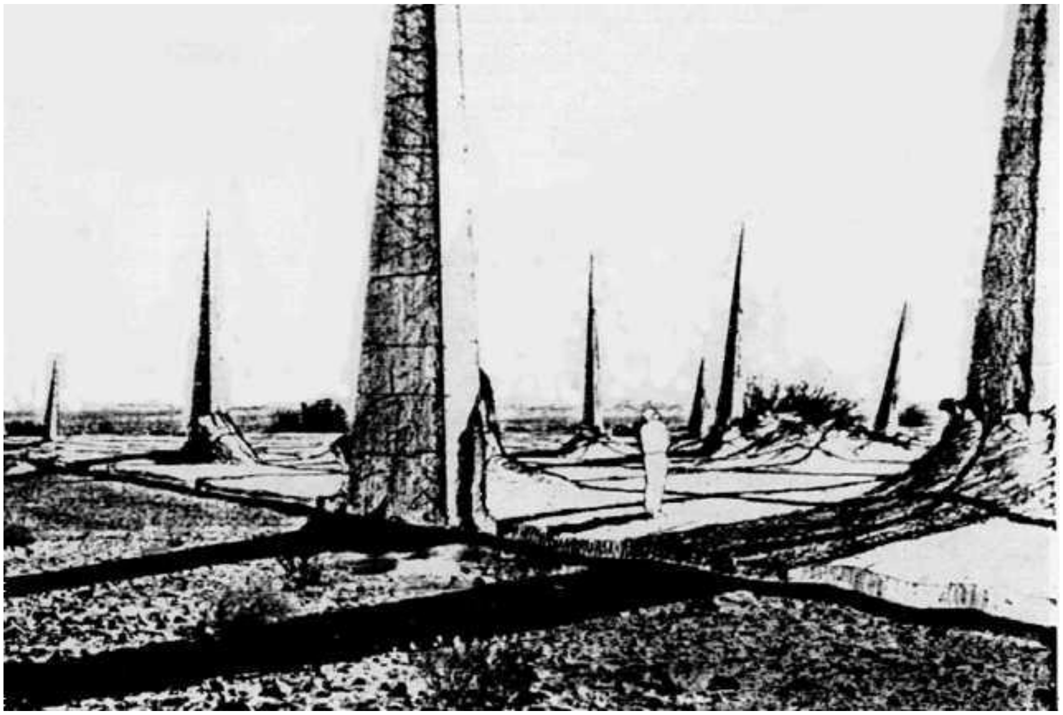


Figure 4.3-6. Spikes Bursting Through Grid, view 2 (concept by Michael Brill and art by Safdar Abidi).

Figure 4.3-1. Landscape of Thorns (concept by Michael Brill and art by Safdar Abidi).

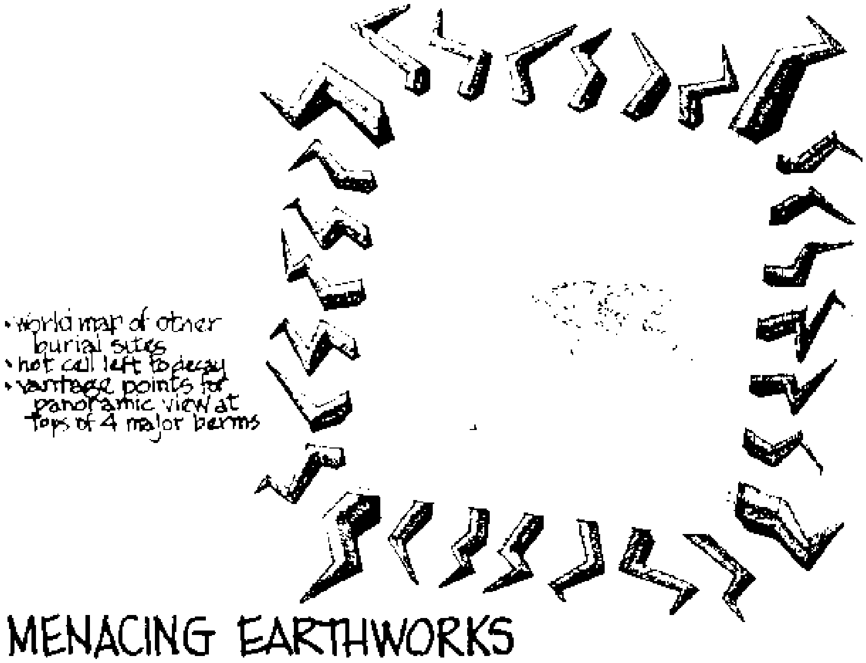


Figure 4.3-8. Menacing Earthworks, view 1 (concept and art by Michael Brill). [option recommended by Team A]

***"Menacing Earthworks":** Immense lightning-shaped earthworks radiating out of an open-centered Keep. It is very powerful when seen both from the air and from the vantage points on the tops of the four highest earthworks, the ones just off the corners of the square Keep. Walking through it, at ground level, the massive earthworks crowd in on you, dwarfing you, cutting off your sight to the horizon, a loss of connection to any sense of place.*

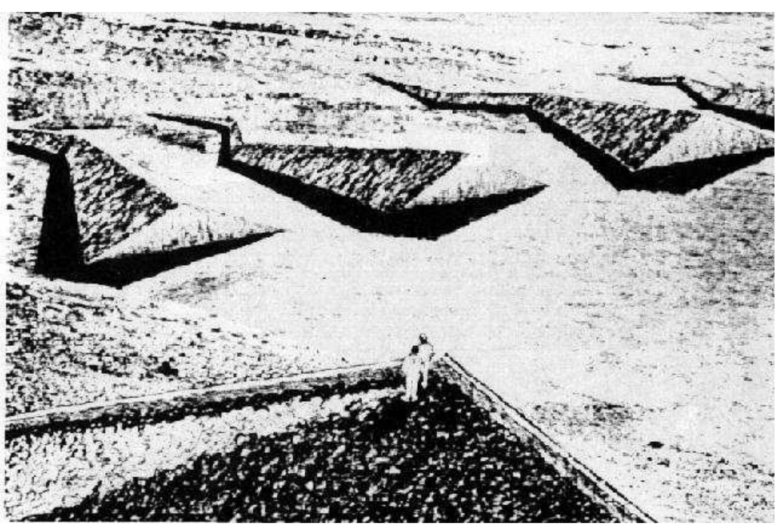


Figure 4.3-9. Menacing Earthworks, view 2 (concept by Michael Brill and art by Safdar Abidi). [option recommended by Team A]

The large expanse of center is left open, with only two elements in it: the WIPP's existing thick-walled concrete hot cell, left to ruin; a walk-on world map showing locations of all the repositories of radioactive waste on earth and a 50-foot wide map of New Mexico with the WIPP site in the geometric center of the Keep. The entire map is domed in order to shed sand blown by the wind. Underneath the slightly domed map a Level 4 room is buried. Four other rooms are located under the four tallest earthworks. Reading walls are strewn between the earthworks, encountered before the Keep is entered.

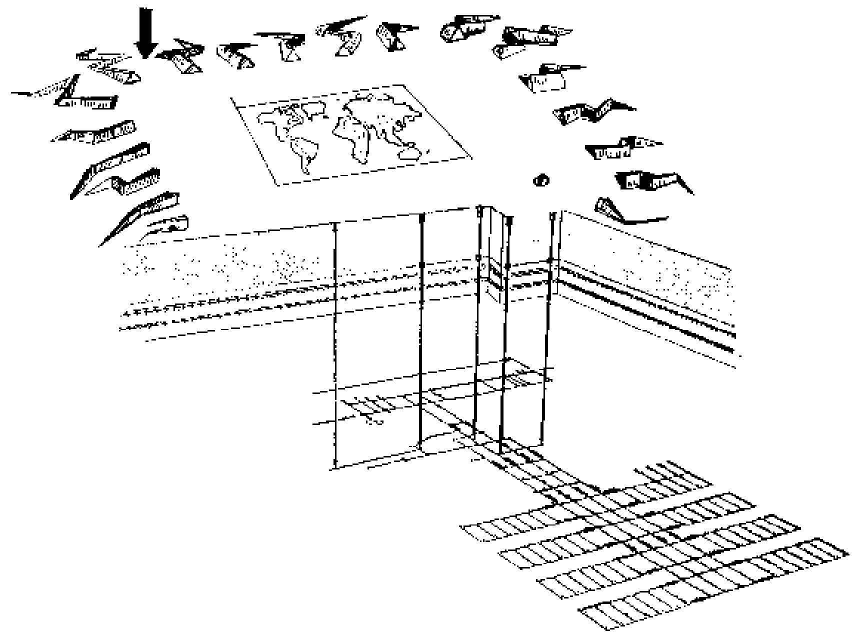


Figure 4.5-7. A perspective view of the repository for Level III messages showing waste panels, shafts, marker features, and the reader's present location on the surface (arrow).

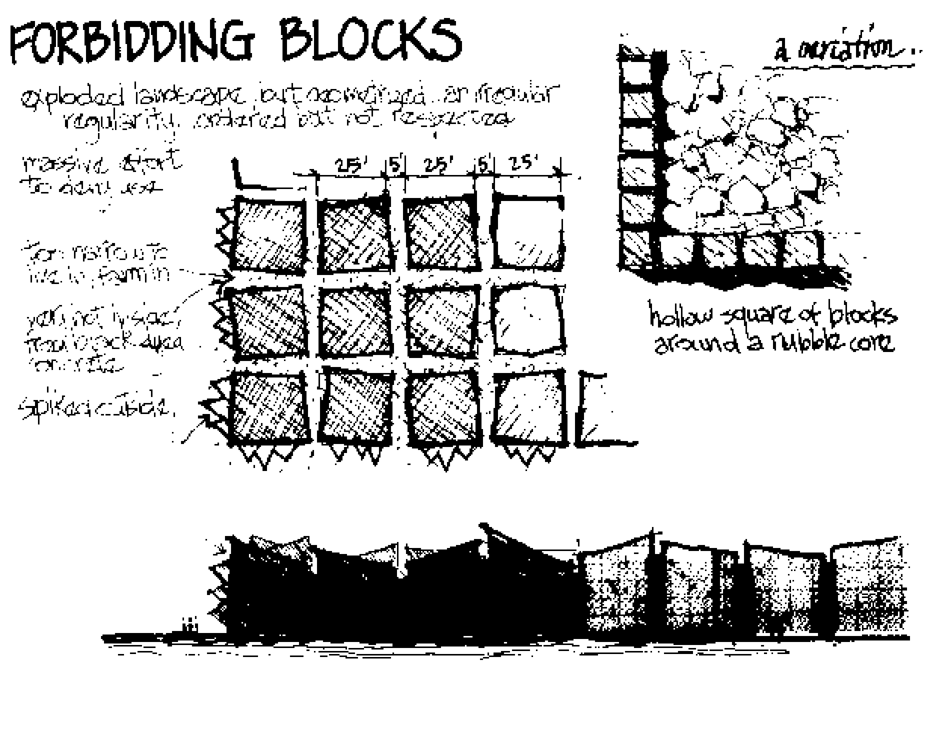


Figure 4.3-14. Forbidding Blocks, view 1 (concept and art by Michael Brill).

"Forbidding Blocks": *Stone from the outer rim of an enormous square is dynamited and then cast into large concrete/stone blocks, dyed black. Each is about 25 feet on a side. They are deliberately irregular and distorted cubes. The cubic blocks are set in a grid, defining a square, with 5-foot wide "streets" running both ways. You can even get "in" it, but the streets lead nowhere, and they are too narrow to live in, farm in, or even meet in. It is a massive effort to deny use. At certain seasons it is very, very hot inside because of the black masonry's absorption of the desert's high sun-heat load. It is an ordered place, but crude in form, forbidding, and uncomfortable.*

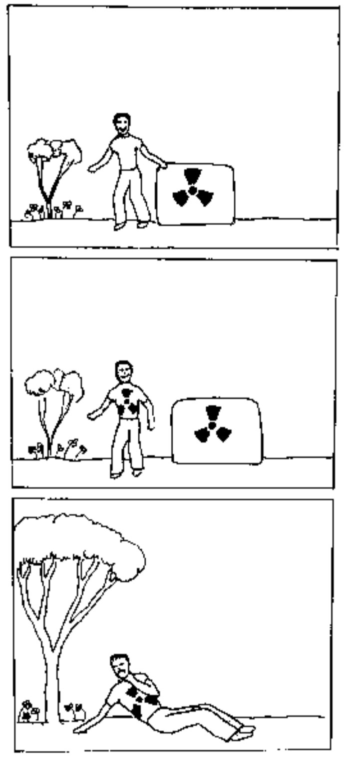
Some blocks can be of granite, or faced with it, and carry inscriptions. Their closeness to other blocks reduces their exposure and increases their durability.

Note our use of irregular geometries and denial of craftsmanship. None of our designs uses any of the regular or "ideal" geometric forms, and only crude craftsmanship is sought, except for the precision of engraved messages. Why? the geometry of ideal forms, like squares and cubes, circles and spheres, triangles and pyramids is a fundamental human invention, a seeking of perfection in an imperfect world. Historically, people have used these ideal forms in places that embody their aspirations and ideals. In our designs, there is much irregularity both of forms and in their locations and directions, yet done by people with obvious knowledge of pure geometry. This shows as understanding of the ideal, but at the same time a deliberate shunning of it...suggesting we do not value this place, that it is not one that embodies our ideals.

The same is true of craft and workmanship. Historically, people use good workmanship to bestow value on things they value. In most of our schemes, the structures that cover or define the Keep's "cover" are made crudely, or of materials that prohibit workmanship (such as rubble, or earthworks, or a large slab). At the same time, we make an enormous investment of labor in these rude materials. It speaks of a massive investment, but one not tinged with pride or honored with value-through-workmanship.

About durability: All the designs, except one, have a high probability of lasting 10,000 years. This is because of their conformity with the guidelines for materials durability in Section 4.4.

The concrete structures of the Landscape of Thorns have projecting, cantilevered elements that will have tension in their upper surfaces, causing minute cracks. These cracks will accelerate local decay. Until new materials are available, or new methods for tensioning concrete members [are found], we cannot "guarantee" the durability of this design. However, we present it here because of its strong emotive character.



5.2 The enormity of marking the WIPP site (FN)

If the WIPP is ever operational, the site may pose a greater hazard than is officially acknowledged. Yet the problems involved in marking the site to deter inadvertent intrusion for the next 10,000 years are enormous. Even if knowledge exists that would allow translation of the message on the markers, there might be little motivation to solicit such knowledge. Pictorial messages, however, are unreliable and may even convey the opposite of what is intended.

This panel member therefore recommends that the markers and the structures associated with them be conceived along truly gargantuan lines. To put their size into perspective, a simple berm, say 35-m wide and 15-m high, surrounding the proposed land-withdrawal boundary, would involve excavation, transport, and placement of around 12 million cubic meters of earth. What is proposed, of course, is on a much greater scale than that. By contrast, in the construction of the Panama Canal, 72.6 million cubic meters were excavated, and the Great Pyramid occupies 2.4 million cubic meters. In short, to ensure the probability of success, the WIPP marker undertaking will have to be one of the greatest public works ventures in history.

5.3 Personal thoughts (WS) (Woodruff Sullivan, Physics and Astronomy, Astrobiology, UW)

Working on this panel, always fascinating and usually enlightening too, has led to the following personal thoughts:

(a) We have all become very marker-prone, but shouldn't we nevertheless admit that, in the end, despite all we try to do, the most effective "marker" for any intruders will be a relatively limited amount of sickness and death caused by the radioactive waste? In other words, it is largely a self-correcting process if anyone intrudes without appropriate precautions, and it seems unlikely

that intrusion on such buried waste would lead to large-scale disasters. An analysis of the likely number of deaths over 10,000 years due to inadvertent intrusion should be conducted. This cost should be weighted against that of the marker system.

(b) The design and testing of markers and messages must involve a broad spectrum of societies and people within those societies. So-called "experts" can of course make important contributions, but they must listen carefully to all other people who represent those who might encounter the markers. In the course of working on this project, I received excellent ideas from a wide range of undergraduates, colleagues, friends, and relatives.

(c) The very exercise of designing, building, and viewing the markers creates a powerful testimony addressed to today's society about the full environmental, social, and economic costs of using nuclear materials. We can never know if we indeed have successfully communicated with our descendants 400 generations removed, but we can, in any case, perhaps convey an important message to ourselves.

5.6 "Beauty is conserved, ugliness discarded" (DGA)

To design a marker system that, left alone, will survive for 10,000 years is not a difficult engineering task.

It is quite another matter to design a marker system that will for the next 400 generations resist attempts by individuals, organized groups, and societies to destroy or remove the markers. While this report discusses some strategies to discourage vandalism and recycling of materials, we cannot anticipate what people, groups, societies may do with the markers many millennia from now.

A marker system should be chosen that instills awe, pride, and admiration, as it is these feelings that motivate people to maintain ancient markers, monuments, and buildings.

(M) Mid-Term Paper: Alternative Energy Sources

At this point in the course, I would frequently have assigned a mid-term project, including (in groups of 2) a 15-minute presentation to the rest of the class, followed by an individual mid-term paper typically on the topic of alternate energy sources or sometimes on some aspect of medical radiology.

The alternate energy sources ranged from the usual suspects to as far afield as students might be interested in wandering - including aspects of nuclear fission that we had not focused on.

Usual suspects -

- Clean Coal
- Solar Energy (thermal, electric; Several technologies)
- Bio-Mass
- Wind
- GeoThermal
- Hydro (dams, tidal, waves)
- Oceans
- and others.

Sample Guidelines for Physics 095 Mid-Term Paper

- Pick a topic from the list of alternative energy sources. (Not Fission or Fusion.)

  Coal; Solar; Wind; Hydro (rivers and/or tidal); Ocean (waves and/or thermal); GeoThermal; BioMass (e.g., ethanol, etc.); Hydrogen; Conservation; etc.

- Research the pluses and minuses associated with "*your*" energy source.

- Prepare to write a 7 - 9 page paper on your energy source.

  [Organize an outline of your key points and arguments, including your reference list and maybe tables and charts.]

- Organize as groups on each alternative. On Tues. Oct. 16th, Thurs. Oct. 18th, and Tues. Oct. 23rd we will have a round-table discussion of all the various alternatives, with each group making a 20-minute presentation (based on your research) - with questions and interruptions from everyone else.

- Over the Fall Break, with all the discussion in mind, *each* of you should then write up your topic into *your* 7 - 9 page paper which will be due on Tuesday, Oct. 30th.

The following sections (a) – (d) provide some general comments and background materials on various alternative energy sources, relevant to your comparisons of various sources in your mid-term papers:

(a) Richard Wolfson, Nuclear Choices, MIT Press (2000), Chapter 11. p. 243

Is nuclear power safe? There is no simple answer to that question, except for the certainty that no technology can be 100 percent safe. The question then becomes "Is nuclear power *acceptably* safe?" The answer, ultimately, is a personal judgment. Technical know-how can help you with that judgment, but vigorous disagreement even among nuclear experts indicates that technical considerations alone cannot decide the issue.

But one factor that *can* help you in your personal decision about nuclear power is how it stacks up against its alternatives. You may not like nuclear power, and you may not think it particularly safe. But if you want electricity and if you find the alternatives *less* safe, then you may have to judge nuclear power acceptable. Or you may conclude that existing alternatives are preferable, or that new energy sources should be developed. Finally, contemplation of nuclear power and its alternatives might lead you to a basic reconsideration of your appetite for energy.

In this chapter we will consider alternatives to nuclear power, weighing such factors as safety, economics, environmental effects, and availability to meet our short-term and long-term energy needs.

(a) Current Energy Consumption

(Megawatts and Megatons. Chapter 8, Table 8.1) (2001)

World ≈ 375 Q/year
US ≈ 100 Q/year (27%)
1996

Fossil and Nuclear Reserves (ibid, Chapter 8, Figure 8.1

Fig. M-1

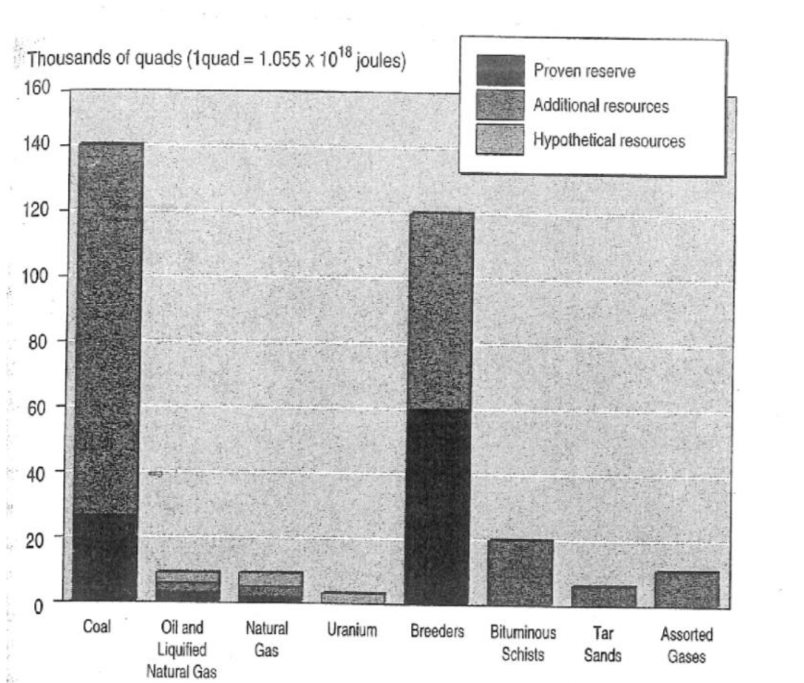


Fig. 8.1. Fuel reserves for energy production [Source: Robert Dautray, "Cinquante ans de nucléaire dans le monde," La Vie des sciences, *No. 4 (1993), pp. 359–411].*

UNITS:

"1 Quad" (Q) ≡ 10^{15} BTU → 10^{18} Joules

[Billion (10^9), Trillion (10^{12}), Quadrillion (10^{15})]

"Mtoe" → "Millions of tonnes of oil equivalent"

(c) Megawatts and Megatons. Chapter 8, Table 8.3
Fossil and Nuclear Reserves (ibid, Chapter 8, Figure 8.1)

Nonnuclear, nonfossil (that is, renewable) forms of energy that had been ignored earlier merit an intense research effort, because they are more promising, with respect to cost and pollution, than they appeared to be when the breeder was the only essentially unlimited energy resource within our technical grasp. And cleaner approaches to the use of fossil fuels may help over the next century to satisfy energy needs at acceptable cost and environmental impact, before a greatly expanded nuclear sector can be afforded or built.

The supplies of primary energy in 1995 for the United States and the world are as shown in Table 8.3.[7]

TABLE 8.3. WORLD AND U.S. ENERGY SUPPLY, 1995; PERCENT FROM EACH SOURCE SHOWN

REGION	OIL	COAL	NATURAL GAS	BIOMASS FUEL*	HYDROPOWER	NUCLEAR	OTHER†
U.S.	38	22	24	3	4	8	0.4
World	33	22	20	13	6	6	<0.5

*"Biomass" fuels are wood, charcoal, crop wastes, and manure.
†"Other" in this table are wind, solar, and geothermal.

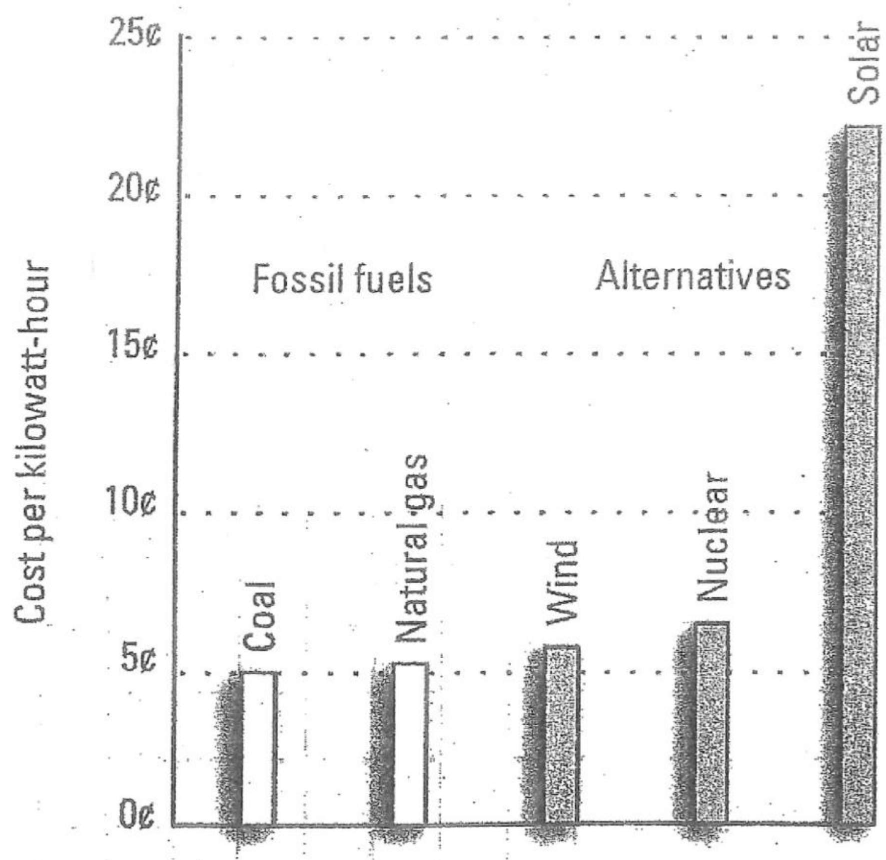
216

(d)

THE COST OF A KILOWATT-HOUR

Solar power will remain expensive for some time, as shown in a comparison of energy prices calculated for new plants coming online in 2013. But the cost of solar should fall as technology improves.

Fig. M-2

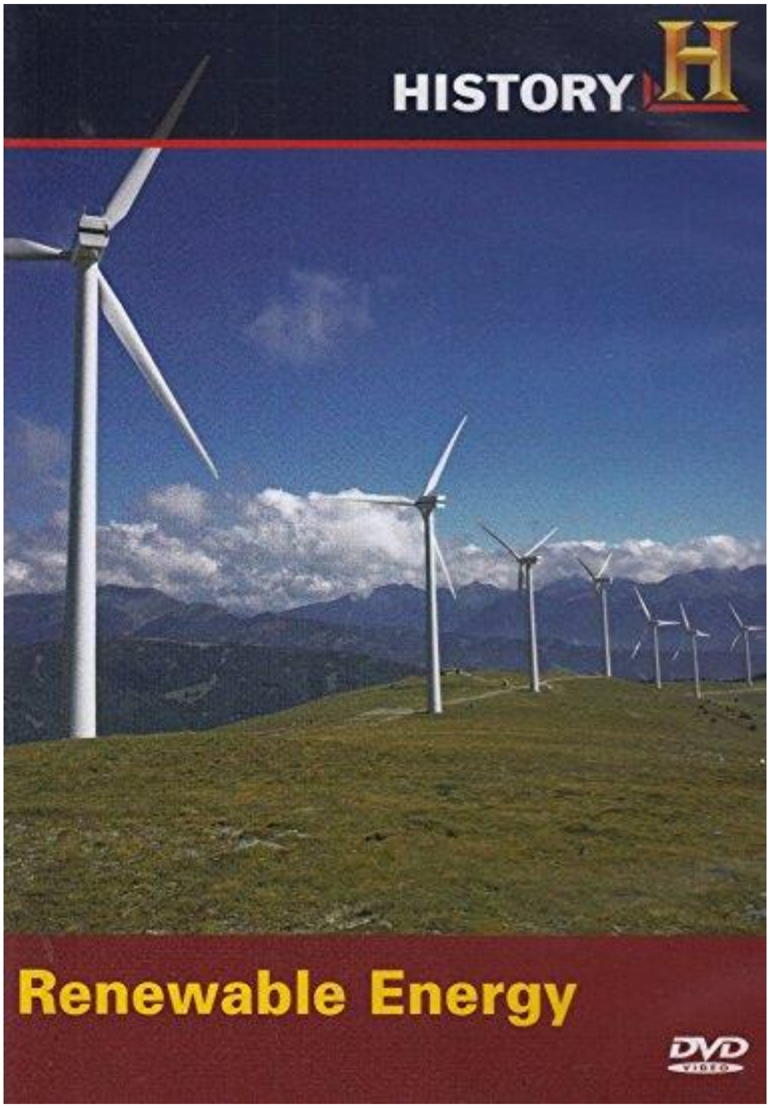


NATIONAL GEOGRAPHIC • AUGUST 2005

Renewable Energy (History Channel DVD) **ISBN:** 1-4229-1581-6

Chapter List:

1. Technology Revolution
2. Solar
3. Wind
4. Geothermal
5. Biofuels
6. Tidal (and waves, etc.)



Daniel Yergin. The Quest

CONTENTS

CHAPTER 9

Comparing Hazards of Nuclear Power and Other Energy

RISKS OF ELECTRICITY FROM COAL

MOST OF THE WORLD'S electrical energy, consumed in the motors, lights, and heaters of industry, commerce, and our homes, and in transportation and other activities, comes from fossil fuels—that is to say, from coal, oil, or gas. It is possible that there also exist important reserves of primordial gas or oil. Professor Thomas Gold of Cornell University holds this view, but it has not yet been demonstrated unambiguously. There are surely vast additional amounts of carbon-containing fuel in oil shales and in forms of methane below the seabed. The cycle of fossil fuel use begins with the extraction of raw material from mines and wells and includes transport and refining, followed by combustion that produces heat and carbon dioxide and other waste products. The carbon dioxide escapes into the atmosphere, and the ashes resulting from burning coal must be disposed of. Combustion also liberates oxides of sulfur and nitrogen into the air, and the burning of coal releases natural radioactive materials as well. The mechanisms of combustion of fossil fuels are complex, but, in contrast to the potentially catastrophic effects of error in nuclear reactor operation, their understanding and control have been obtained somewhat less rigorously and most of the time without immediate serious consequences if things go wrong. Nevertheless, mining coal used to be one of the most hazardous occupations; there have also been cases where our ignorance has led to local catastrophes, such as devastating fires fed by stored liquefied natural gas.

In recent decades, constraints have been imposed on where and how coal is burned, making the deadly fogs of London a picturesque if murderous memory. But it is well to recall that in December 1952, a four-day temperature inversion there retained the combustion products from the high-sulfur coal used for home heating, and day turned into night. Buses crawled forward only with a person leading the way. The killer fog was responsible for 4,000 to 7,000 premature deaths.

Considerable sums have been spent to limit pollutants other than carbon dioxide (which is not directly hazardous to health and cannot readily be limited—it is part of the burning process), such as sulfur oxides, nitrogen oxides and particulate emissions (fly ash). There is also now an international effort to reduce carbon dioxide emissions in order to minimize the extent of global warming.

It is well within society's technical ability to collect carbon dioxide from fossil-fueled power plants and, as mentioned in Chapter 8, to dispose of it by injection into exhausted natural gas fields or even into the deep ocean waters. The costs would be substantial—as much as 30% of the cost of electrical energy—but this disposal is technically feasible. One promising approach is to convert coal (and water) to hydrogen and carbon dioxide, inject the CO_2 into unminable coal beds nearby to flush methane gas (CH_4) to collection wells, convert that methane to hydrogen and CO_2 as well, and export hydrogen and electrical power.[1] In this approach, only about one-third as much CO_2 is rejected to the atmosphere as in the normal use of coal for producing electrical energy, and the hydrogen can be used remotely for powering vehicles or for local electrical generation.

Although the dangers in modern coal mines have substantially diminished and the era has passed in which miners suffered black-lung disease and frequent fatal accidents, large quantities of coal must be mined to fuel a power plant. A coal-fired plant, producing as much energy as a typical one-million-kilowatt (1000 MWe or 1 GWe) electric nuclear plant, burns a ton of coal every 12 seconds, which corresponds to 2.2 million tons per year. A nuclear facility of the same power uses less than a ton of uranium-235 per year, which corresponds to about 200 tons of natural uranium contained in 100,000 tons of mined uranium ore.

Exposure to Nuclear Radiation from Coal Combustion

Consideration of the adverse effects on health from the production of energy must take into account, in the pollution resulting from the use of coal and oil, the chemical substances that can cause cancer and other diseases. Hospitals fill up quickly during heavy smog in some cities. The vast fires in Indonesia in 1997, which affected that entire region as far as Malaysia, are an unfortunate case in point. Whole cities were rendered all but uninhabitable for months.

The harmful effects of coal deserve special attention because of its importance in industrialized countries and in developing nations with large populations like India or China. In the United States, 52% of the electricity is produced by coal. The quantity of radioactive material liberated by the burning of coal is considerable, since on average it contains a few parts per million of uranium and thorium. Modern coal-fired electric plants are designed and operated to reduce the emission of particulates from the stack, and also to decrease the emission of sulfur oxide and nitrogen oxide. Older plants, such as the majority of those in China, are far from meeting these standards for fly ash and gaseous emissions. When coal is burned, all the uranium daughters accumulated by disintegration—radium, radon, polonium—are also released. The United Nations Scientific Committee on the Effects of Atomic Radiation evaluates the radiation exposure to the population from this source.[2] Per gigawatt-year (GWe-yr) of electrical energy produced by coal, using the current mix of technology throughout the world, the population exposure is estimated to be about 0.8 lethal cancers per plant-year distributed over the affected population. Table 7.2 summarizes these data. With 400 GWe of coal-fired power plants in the world, this amounts to some 320 deaths per year; in the world at large, some plants have better filters and cause less harm, while others have little stack-gas cleanup and cause far more.

In addition, there is a major exposure to the radioactivity of coal that arises from the use of ash to make concrete. With about 5% of power-plant ash being incorporated into housing, the population dose for the 400 GWe of coal plant leads to an estimated 2000 cancer deaths per year. But if most of the ash went into concrete for dwellings, the annual death toll from radiation from this source would rise to about 40,000.

Some see in accidents a reason to abandon nuclear power in favor of alternate ways—so-called soft-energy paths—that they propose to help arrive at a harmonious development of industrial societies. There is much merit in both the more efficient use of energy and in its supply from renewable sources. The world used 375 quads of energy in 1996; the United States used 75. We have noted in Table 8.4 that solar electric power conceivably could amount to about 50 quads per year worldwide; fuel from biomass, 20 quads; and 9 quads from exploiting the temperature difference between the warm surface water of the oceans and the colder water at depth. Biomass, in particular, may develop beyond the 3% of U.S. energy needs that it now meets, as the revolution in biotechnology enables the production of alcohol from cellulose rather than from sugars. It is highly desirable to have small-scale energy sources if they can be achieved at affordable cost and with acceptable environmental impact. It will be necessary, however, to carefully compare these alternatives—including their harmful side effects—to the more traditional ways of producing energy—e.g., fossil-fueled plants burning coal, gas, or oil; hydropower; and nuclear power stations.

 p. 127 – 128

A MATURE PROGRAM: THE CASE OF FRANCE

As we have seen in Chapter 2, before the Second World War, France was a leader in research in radioactivity and fission. At the end of the war in Europe, France, which had been defeated and occupied by the Nazis, had the task of rebuilding its society, its economy, and its spirit. After the Atomic Energy Commission of France (Commissariat à l'Energie Atomique—CEA) was formed in 1945, France's support for nuclear energy was driven not only by its desire to produce plutonium for nuclear weapons and by the technological challenge, but also by its lack of indigenous energy resources and a recognition of the uncertainty of alliances and even of territorial possessions that might provide fuel.

The first French nuclear reactor, or "pile," began its operation on December 15, 1948. Its name, Zoé, derives from its characteristics, *zéro/oxyde/eau*, meaning zero (power), (natural uranium) oxide, and (heavy) water. We have seen that there is the choice between heavy water and purified graphite for such an experimental pile using natural uranium, and the French had experience with heavy water before the war. Zoé was the first of a line of heavy water (*eau lourde*) reactors and thus was given a second name, EL1. A second heavy-water moderated, natural-uranium reactor, EL2, began operation on October 21, 1952; this reactor was maintained at room temperature by the circulation of high-pressure carbon dioxide gas. On July 4, 1957, a third reactor, EL3, began to operate.

At the same time, the CEA began to build reactors named G1, G2, and G3 ("G" for *gaz* or gas-cooled) for the express purpose of producing plutonium for nuclear weapons. G1 began to operate on January 7, 1956, G2 in June 1958, and G3 in June 1959, producing both plutonium and electrical power.

The French Pressurized Water Reactor (PWR) program started with a company formed in 1960 owned equally by the public utility for electricity in France, Electricité de France (EDF), and a consortium of Belgian electric utilities. A 305-MWe power plant was built in France, based on the Yankee Rowe (Massachusetts) plant; this plant had been constructed by Westinghouse and had begun its operation in 1961. This first PWR in France was put into service in 1967. Additional PWRs were built in France, under license from Westinghouse, by Framatome (Société Franco-Américaine de Construction Atomique). By 1981, Framatome and Westinghouse replaced the license arrangement with an agreement for cooperation that allows Framatome to build reactors independently. In 1982, EDF launched the construction on a new (N4) series of PWRs, of 1450-MWe capacity; the first, at Chooz on the border between France and Belgium, began operation in August 1996.

With its commitment to nuclear power arising from the oil shocks of the 1970s, France has created a highly centralized industry for the supply of nuclear fuel. Electricité de France owns and operates the reactors; COGEMA (General Company for Nuclear Materials—COmpagnie GÉnérale des MAtières nucléaires) is responsible for all aspects of the nuclear fuel cycle; and ANDRA (National Agency for the Management of Radioactive Waste—Agence Nationale pour la gestion des Déchets RAdioactifs) has managed radioactive wastes since 1991. EDF, COGEMA, and CEA generate 95% of the radioactive waste. CEA oversees the development and manufacture of nuclear weapons, as well as much research and design of commercial nuclear reactors; Framatome collaborates with other technical companies of the European community; and France builds power reactors in other countries. France employs a highly standardized design in all 58 reactors currently operating there and producing electricity for EDF.

We shall describe now another type of reactor—the "breeder" reactor, which produces more nuclear fuel than it burns. The fuel for this reactor is a composite of uranium-238 with about 10% plutonium. There is no moderator such as graphite or water in the core, so that fast neutrons that do not cause fission in plutonium are largely captured in U-238 to yield more plutonium-239. The French breeder program was designed at the time of the oil shocks in the 1970s, when a shortage of uranium fuel at low prices was envisaged. The United States had built experimental fast-neutron reactors, and a single such commercial power reactor (Fermi I) that operated in Michigan for a few years beginning in 1969.

Fig. M-3

Garwin and Charpak: Megawatts and Megatons

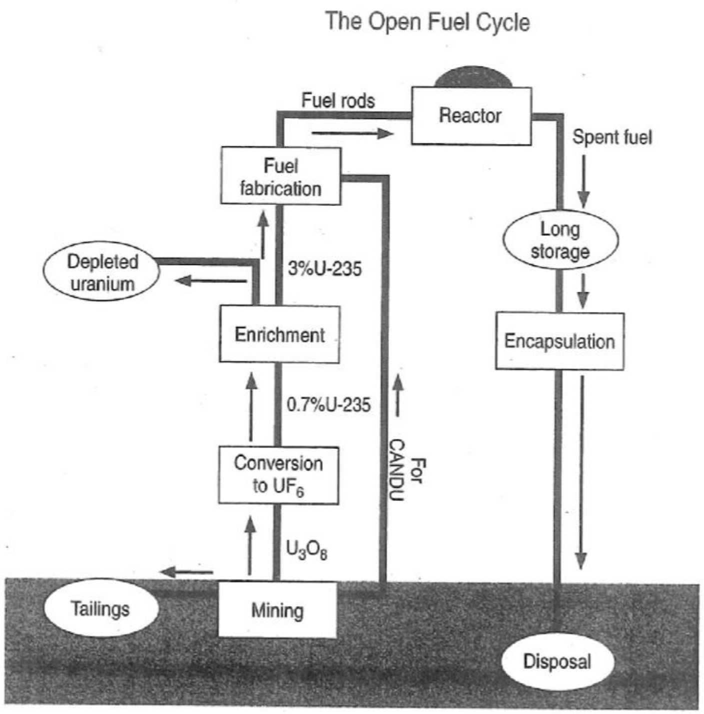


Fig. 5.4. The "open" nuclear fuel cycle (with direct disposal of spent fuel).

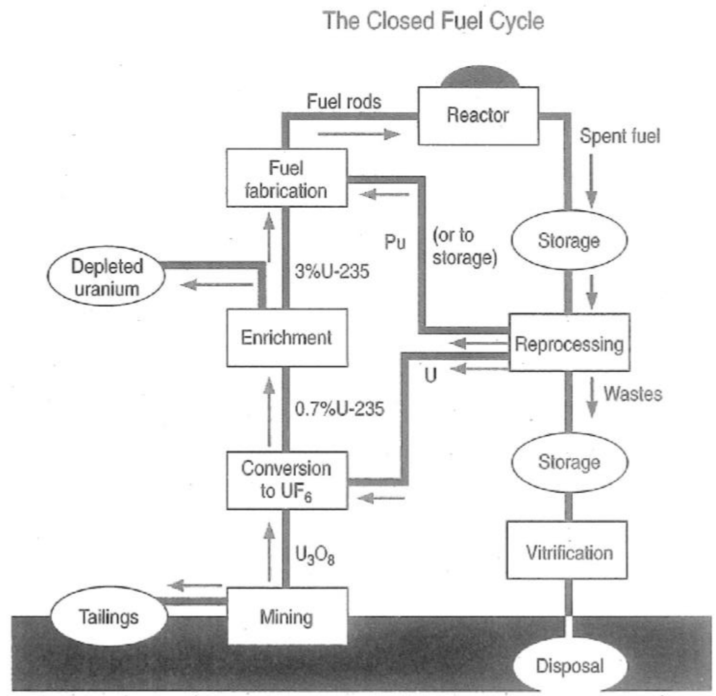


Fig. 5.5. Closing the fuel cycle with reprocessing and recycling of plutonium and uranium.

References:

Richard Garwin & Georges Charpak, Megawatts and Megatons. Alfred Knopf (2001), Chapters 5, 7, 8, 9.

National Geographic, August 2005, pp. 2-31. ("Future Power")

National Geographic, September 2009, pp. 28-53. ("Plugging into the Sun")

Renewable Energy, History Channel DVD (2006) ISBN: 1-4229-1581-6.

Richard Wolfson, Nuclear Choices, M.I.T. Press (2000), Chapter 11.

Daniel Yergin, The Quest, Penguin Press (2011).

(N) Nuclear Fusion: Magnetic Confinement

Compared to fission, a second way to extract nuclear energy is via the **fusion** of hydrogen into helium - (via the left-hand side vs. the right-hand side) of the Binding -Energy plot. (Figs. J-1, N-1 and N-2.)

$4\,(^1H) \Rightarrow {}^4He + 2\,\beta^+ + 2\,\nu + 26\text{ MeV}$

$\approx 6\text{ MeV/amu}$

(vs. $\approx 1\text{ MeV/amu}$ for fission)

Still only $\approx \dfrac{6}{1000} = 0.6\%$ of mass is converted to energy via $E = mc^2$.

Lots of hydrogen fuel available via H_2O

$\downarrow$

BUT $\Rightarrow$ **Actually** utilize $^2H + {}^3H \rightarrow n + {}^4He + 17.6\text{ MeV}$

$\approx 10^{18} \times$ larger cross section (rate)

Therefore need to

(a) Separate *deuterium* (only 0.015% in nature)

(b) Produce *tritium* via $^6Li + n \Rightarrow t + \alpha$

- **<u>Key Issue</u>** ⇒ Control and Confinement

Refs: T.K.Fowler, <u>The Fusion Quest</u>, Johns Hopkins University Press (Baltimore, 1997)
http://www.jet.efda.org/
http://www.pppl.gov/fusion_basics/
http://www.iter.org/

Temperatures ≈ 5 - 10 keV corresponding to 10^7 to 10^8 °K.

This corresponds to the center of the sun,
<u>not</u> the 6,000 °K at the surface of the sun.

- Sun ⇒ Confiined by Gravity (**!**)

Multi-Billion $$$ Facilities

- Magnetic Confinement**:** Magnetic Fields used to keep <u>high temperature</u> plasma from touching the walls.

  Tokamak = a "**Torus**" configuration.
  Its simplicity has made it the currently dominant approach to controlled-fusion research: Princeton-Penn-Plasma- Lab, (PPPL), Joint-European-Torus (JET), and International-Thermonuclear-Experimental-Reactor (ITER).

  Making progress, <u>but</u> <u>not</u> <u>yet</u> at the "Break Even" condition which is defined as more energy produced than was used to produce it.

- "Inertial" Confinement (Very different approach. See "Section O")

Check the numbers:

The JET (Joint European Torus) web-site tells us that 10 grams of deuterium (^{2}H) [which can be extracted from 500 liters of water] and 15 grams of tritium (^{3}H) [which can be produced from 30 grams of ^{6}Li (400 grams of ^{nat}Li)] can be combined to generate a lifetime of electricity for an average person in an industrialized country.

Do the algebra, and see how much energy (in Joules) this corresponds to.

For a lifetime of 100 years, what level of power usage (Joules/sec) does this correspond to?

Is the JET estimate reasonable? (See below.)

- -

$E = (\Delta M)\, c^2$

For (D+T) Fusion :

$$(\Delta M)c^2 / Mc^2 \approx (17.6 \text{ MeV}) / (5 \times 951.5 \text{ MeV}) = 3.78 \times 10^{-3}$$

$$\therefore \quad \Delta M \approx (3.78 \times 10^{-3})(10 + 15) \text{ grams}$$

$$\Rightarrow \quad \approx \quad 9.45 \times 10^{-5} \text{ kgm}$$

$$\therefore \quad E = (\Delta M)c^2 \approx 8.5 \times 10^{12} \text{ Joules}$$

Over a lifetime of 100 years ($\approx 3 \times 10^9$ sec) this corresponds to an average power of

$\approx$ 3×10^3 Joules/sec

$\approx$ 3 kWatts. (Does this sound reasonable to you?)

Fig. N-1

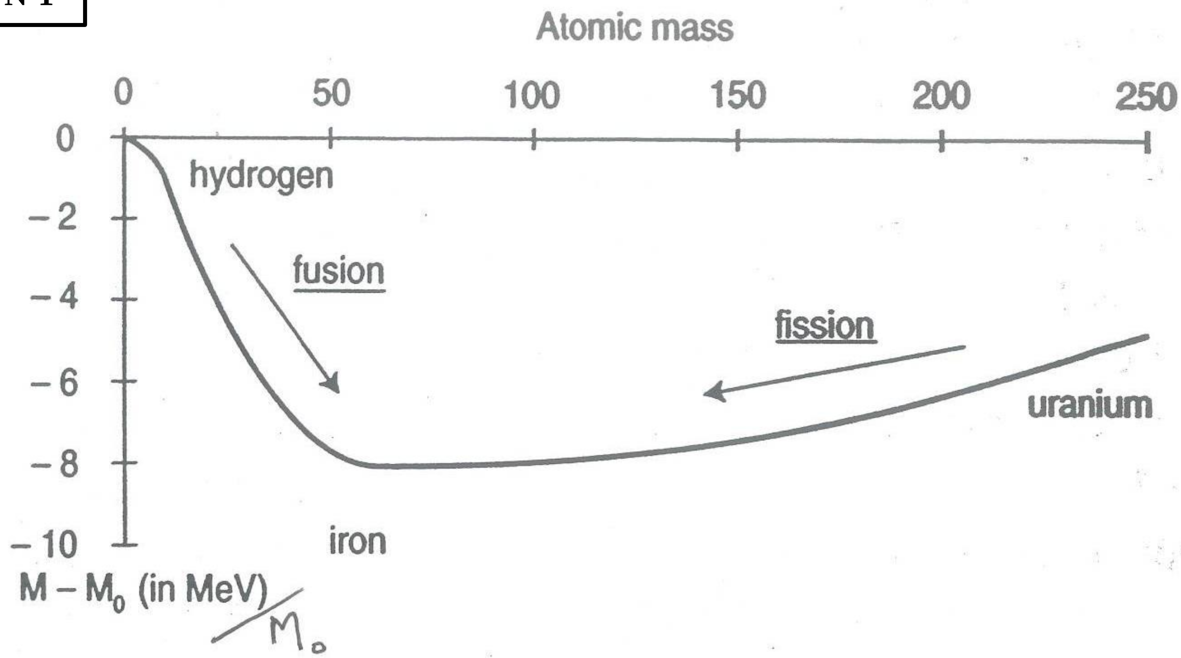


Fig. 1.2. Binding energy (BE) per nucleon as a function of mass number.

Fig. N-2

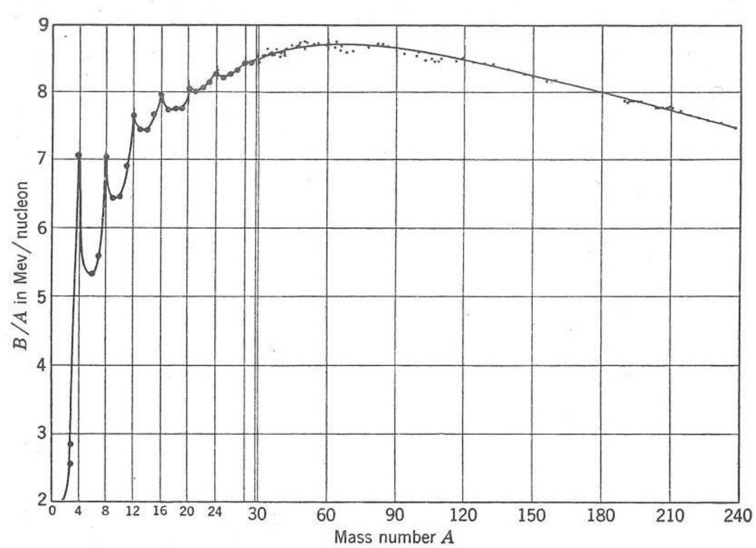
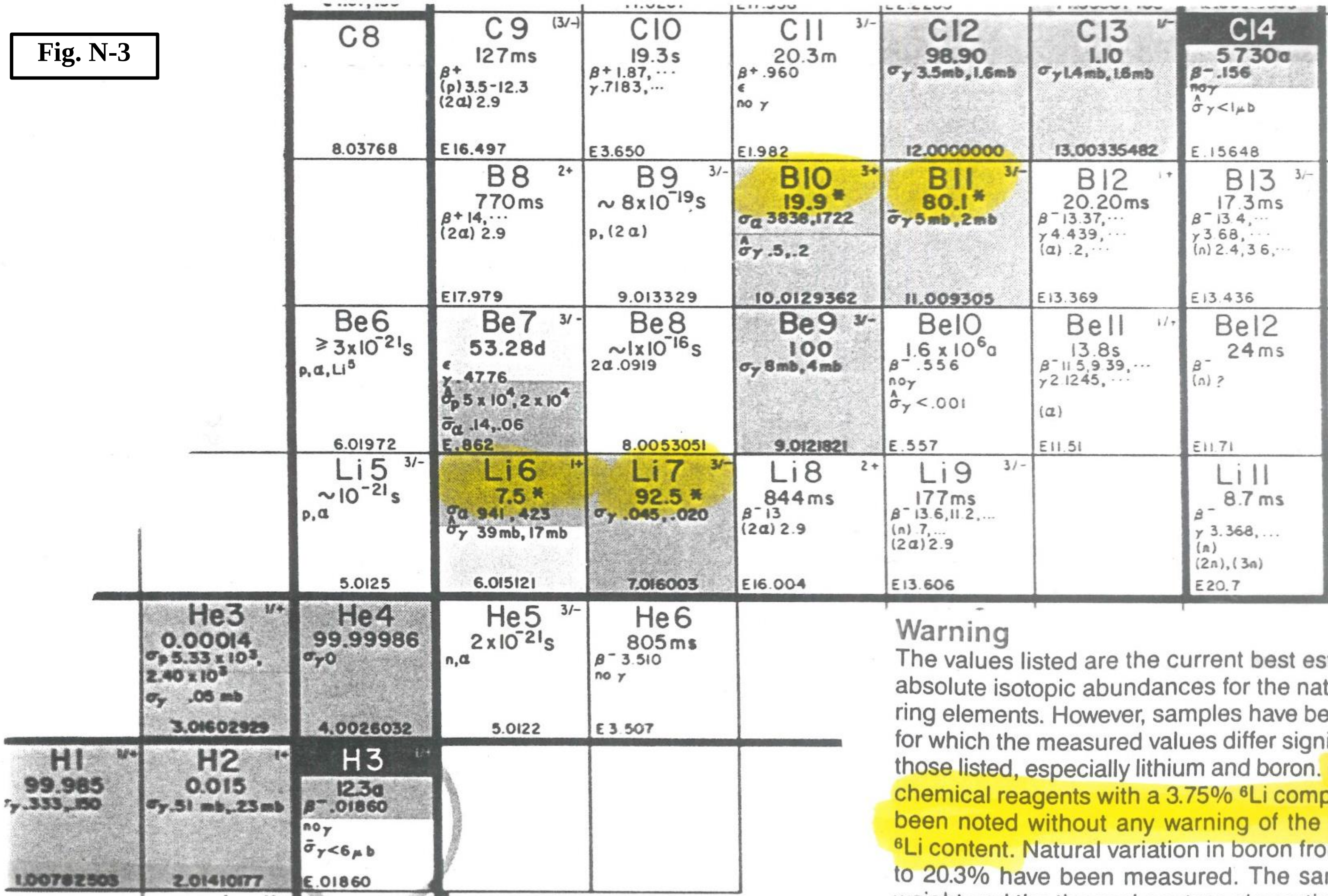


Fig. 3.1 Average binding energy B/A in Mev per nucleon for the naturally occurring nuclides (and Be^8), as a function of mass number A. Note the change of magnification in the A scale at $A = 30$. The Pauli four-shells in the lightest nuclei are evident. For $A \geq 16$, B/A is roughly constant; hence, to a first approximation, B is proportional to A.

Evans, The Atomic Nucleus, Chapter 9.3, p. 299.

Fig. N-3



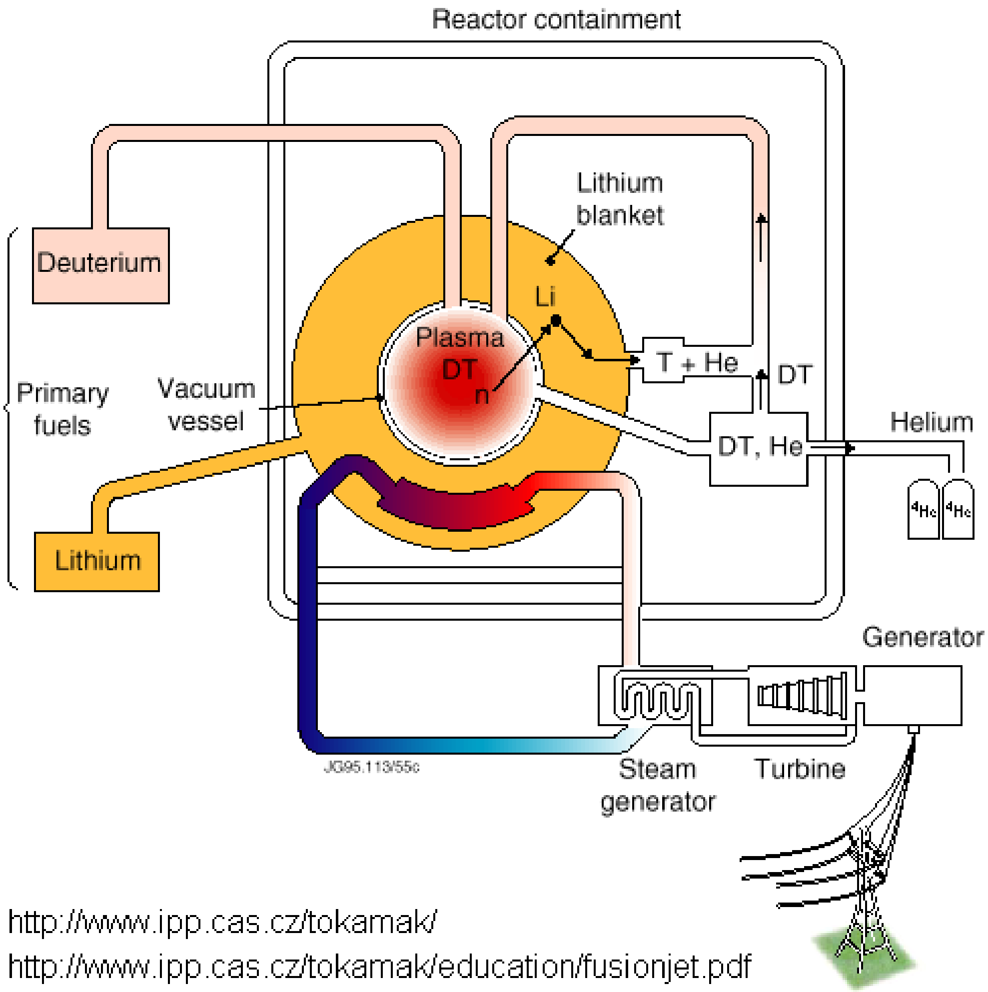
General Electric, Chart of the Nuclides.

Warning

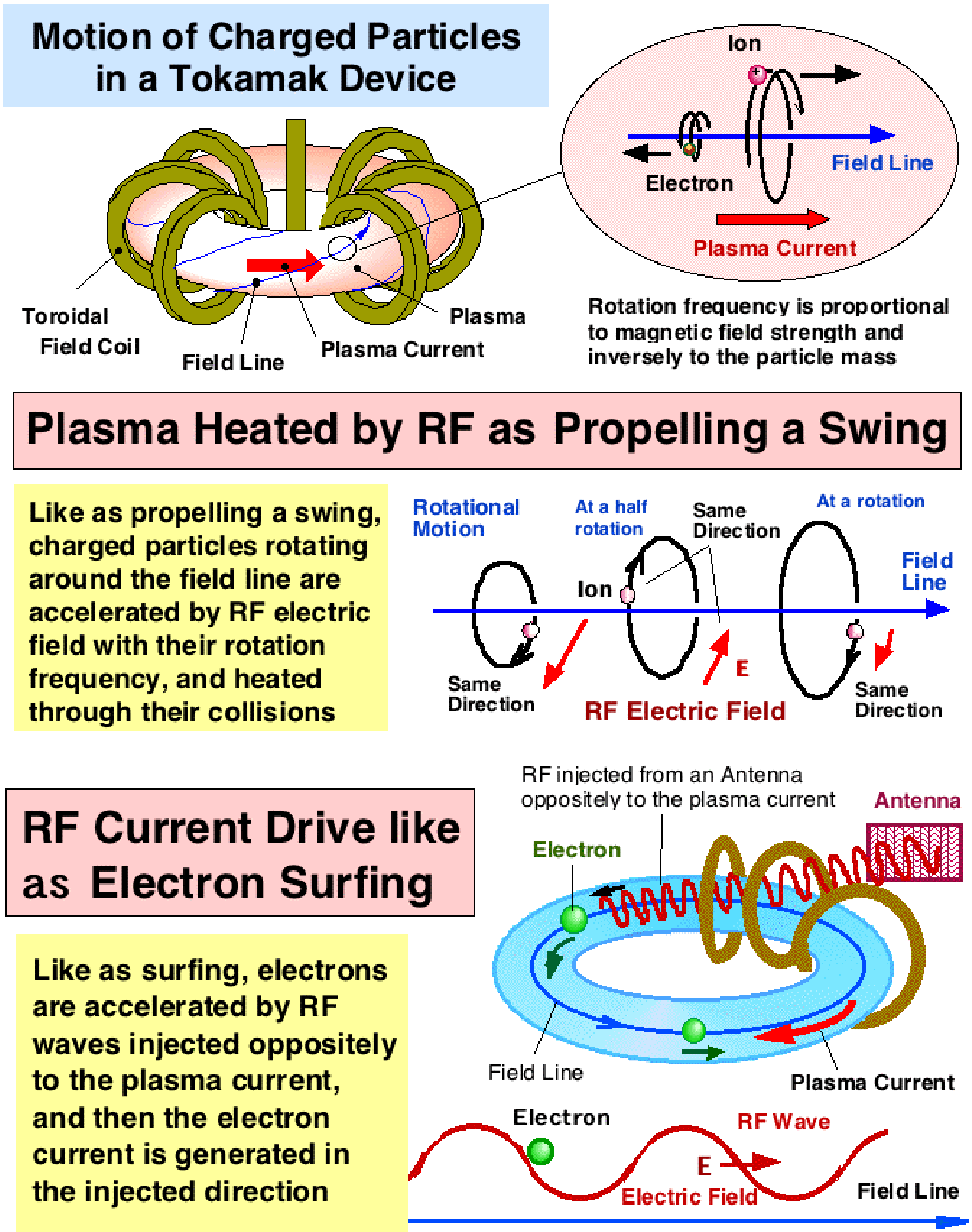
The values listed are the current best estimate of the absolute isotopic abundances for the naturally occurring elements. However, samples have been observed for which the measured values differ significantly from those listed, especially lithium and boron. On the shelf, chemical reagents with a 3.75% ^{6}Li composition have been noted without any warning of the depletion in ^{6}Li content. Natural variation in boron from 19.1% ^{10}B to 20.3% have been measured. The sample atomic weight and the thermal neutron absorption cross section will then differ significantly from the value listed. It is highly recommended that samples be checked before the listed values are assumed to apply if these values are critical to the application.

Fig. N-4

Schematic Diagram of a Tokamack Device

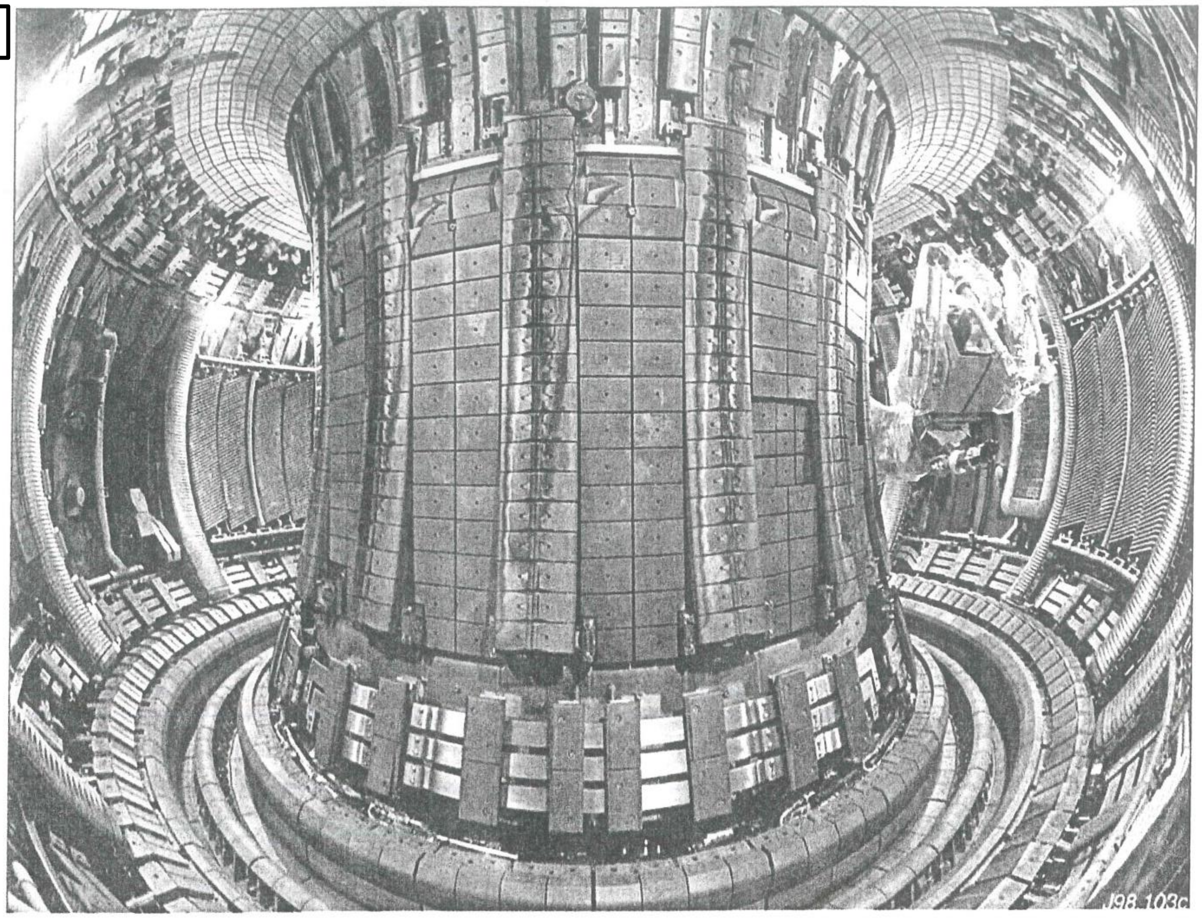


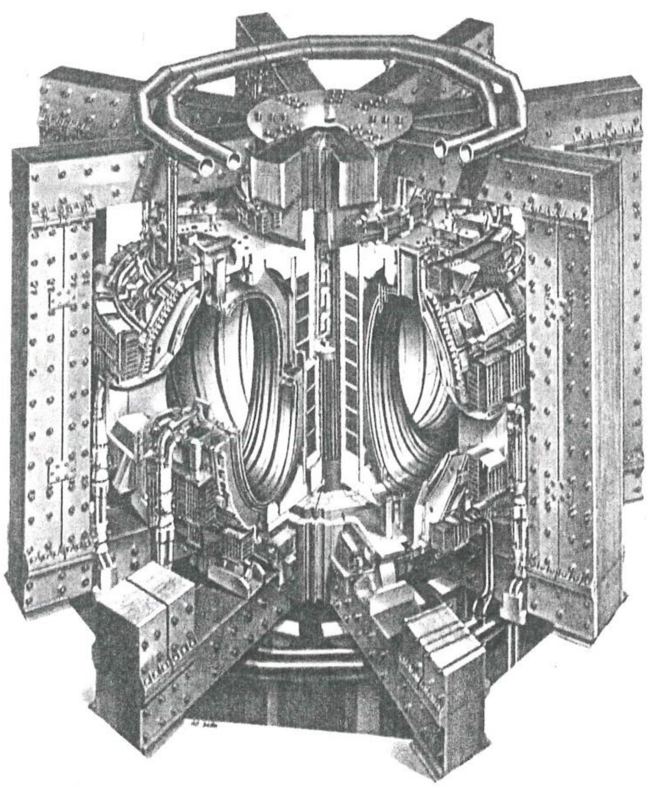
http://www.ipp.cas.cz/tokamak/
http://www.ipp.cas.cz/tokamak/education/fusionjet.pdf



http://www-jt60.naka.qst.go.jp/english/jt60/rf/html/rf2.html

Fig. N-5





JET, the Joint European Torus, is located at Culham, near Oxford in the UK. Deuterium and tritium ions, held in place by strong magnetic fields, are made to collide and fuse within the donut-shaped vacuum chamber. The cut-away shows the huge magnetic pole-pieces around the vacuum vessel. The height inside the vacuum vessel is more than 4 metres and the whole apparatus is 12 metres high. JET is just part of the long and difficult international effort to harness fusion energy for peaceful purposes on Earth.
(Photographs courtesy EFDA–JET.)

Mackintosk, <u>Nucleus</u>, Chapter 9, p. 121.

- JET (Joint European Torus)

  1978 - Project Start

  1983 - Operation Start

  1991 - 2 MW of fusion power

  1997 - Fusion-Power/ Input-Power $\rightarrow$ 65%

- Next Step $\Rightarrow$ ITER (International Thermonuclear Experimental Reactor)
  (China, Europe, Japan, Korea, Russia, U.S.)

"Projected" Time Scales for ITER: <http://www.iter.org/>
[See also Basdevant, Fundamentals in Nuclear Physics, (2005) Chapter 7, pp 344-345.]

June 2005 - Site Selection = France

2006 - Begin Site Construction

2017 - Currently under Construction

2035 - DEMO Operational

2050 - Commercial Power Plant Construction **Start*

New York Times, 29 June 2005

France Will Get Fusion Reactor To Seek a Future Energy Source

By CRAIG S. SMITH

PARIS, June 28 — An international consortium announced Tuesday that France would be the site of the world's first large-scale, sustainable nuclear fusion reactor, an estimated $10 billion project that many scientists see as crucial to solving the world's future energy needs.

"It is a great success for France, for Europe and for all the partners in ITER," President Jacques Chirac said in a statement released after the six-member consortium of the United States, Russia, China, Japan, South Korea and the European Union chose the country as the site for the International Thermonuclear Experimental Reactor.

Japan, which had lobbied hard for the project, dropped out of the bidding in the last few days and ceded to France. The consortium agreed in Moscow to build the project at Cadarache in southern France.

Nuclear fusion is the process by which atomic nuclei are forced together, releasing huge amounts of energy, as with the sun or a hydrogen bomb. The process has long been studied as a potential energy source that would be far cleaner than burning fossil fuels or even nuclear fission, which is used in nuclear reactors today but produces dangerous radioactive waste.

While the physics of nuclear fusion have long been understood, the engineering required to control the process remains difficult.

The logistics of coordinating construction in a six-member consortium has presented an even bigger challenge. The project was started in 1988 but bogged down in bickering over where the reactor's design team would be based. A compromise split the team between Japan, Germany and the United States, but the consortium struggled over where the reactor would be built.

Canada, Spain, France and Japan were originally in contention for the

Continued on Page A10

France Wins Site of Fusion Reactor to Test Future Energy

Continued From Page A1

reactor site, but a December 2003 ministerial meeting to pick a winner ended in a deadlock, with the United States, Japan and South Korea backing the Japanese site and the other three consortium members pushing for the site in France.

Recently, Japan agreed to relinquish its bid in return for the consortium's commitment to build a $1 billion materials testing center there.

The consortium also promised that any subsequent fusion reactor built by the consortium would be built in Japan. It is a significant concession, because the first reactor is only a demonstration plant meant to prove that fusion can be harnessed as an economically viable energy source. A second reactor would probably be a prototype meant for commercial power generation.

With the agreement, the consortium can now proceed with the drafting of a deal on the construction and operation of the reactor. ITER officials said they hoped that the accord would be signed by the end of the year, allowing work on the reactor to begin next year and ground to be broken at the Cadarache site in 2008. Current plans foresee the reactor operating in 2016.

Construction of the reactor is estimated to cost $5 billion, with its operation costing another estimated $5 billion over 20 years, according to ITER. The host country is expected to cover half of those costs, with the other five partners each paying 10 percent. Those numbers are based on current dollars, however, meaning the actual cost of the reactor will be much higher by the time it is completed.

Many experts also predict that construction could take much longer than now foreseen given the difficulty of coordinating multiple suppliers of costly and highly technical components in many countries. The agreement leaves open the possibility that still more countries may take part in the project. India, for example, has expressed interest.

The final agreement is expected to include provisions that would require consortium members that cause delays to pay compensation.

The fusion project has stirred controversy since it was first proposed in the 1980's, with many scientists arguing that such "big science" will rob financing from the "little science" of individual researchers who have often produced the world's most striking scientific breakthroughs.

But criticism has been drowned out by the growing recognition of fusion's potential as a solution to the world's looming energy crisis.

"We all know oil and gas depletion will start in 2030 or 2035," said Peter Haug, secretary general of the European Nuclear Society.

He said most experts agreed that because of technical difficulties, renewable energy sources like wind or solar power would never provide more than 15 or 20 percent of the world's energy needs. There is enough coal in the earth to keep the world running for centuries, but at an unacceptable environmental cost. As oil and gas fields peter out, Mr. Haug and others say, the world will be forced to turn to nuclear energy.

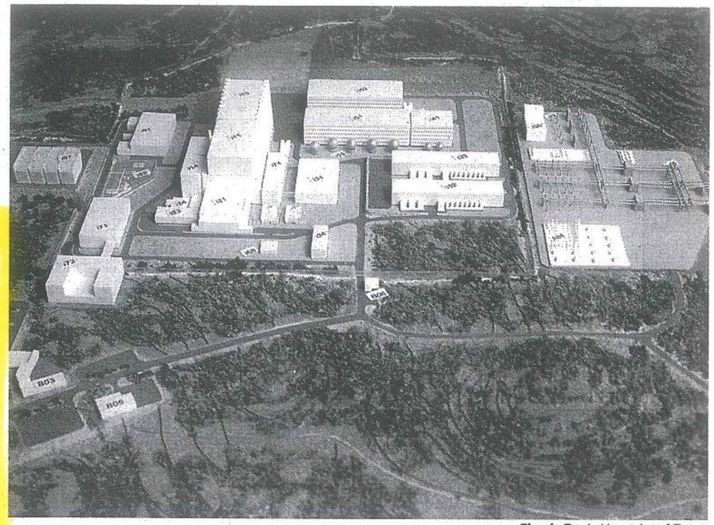
"We don't think fusion will remove fission from the production scheme," Mr. Haug said. "But it will probably be used along with fission because of the growing energy needs of man."

Still, few scientists expect a fusion reactor to generate commercially viable electricity before mid-century, if by then.

In principle, using fusion to produce energy is easy: take hydrogen atoms and press them together to form helium. The helium is a bit lighter than its constituent hydrogen pieces, and by Einstein's $E=mc^2$ equation, that tiny change in mass results in a large release of energy.

At the center of the sun, where temperatures reach nearly 30 million degrees Fahrenheit and hydrogen atoms are pushed together at ultra-high pressures, fusion generates light and heat. But turning fusion into a viable source of energy requires

Kenneth Chang contributed reporting from New York for this article.



Claude Paris/Associated Press

The model of the site of the International Thermonculear Experimental Reactor (ITER) that is to be built at Cadarache in southern France.

Comparing Fuels

As a source of energy, fusion, if a viable plant can be built, would have many advantages over coal and nuclear fission power plants.

DAILY FUEL CONSUMPTION AND WASTE PRODUCTION FOR 1,000 MEGAWATTS

	COAL PLANT	NUCLEAR FISSION PLANT	NUCLEAR FUSION PLANT
FUEL	9,000 tons coal	147 lbs. uranium	**1 lb. deuterium** **1.5 lbs. tritium**
WASTE	30,000 tons carbon dioxide 600 tons sulfur dioxide 80 tons nitric oxide	6.6 lbs. highly radioactive material	**4.0 lbs. helium**

Sources: Princeton Plasma Physics Laboratory, Energy Information Administration figuring out how to recreate on Earth the conditions at the sun's heart.

Instead of ordinary hydrogen, fusion reactors use heavier versions, known as deuterium and tritium, that fuse together more easily. Experimental fusion reactors have been able to heat gases to temperatures of hundreds of millions of degrees. The harder task, however, is confining the hot gas.

ITER follows the same approach used by most large-scale fusion experiments since the 1970's, using doughnut-shaped magnetic fields to confine the gas, but it will be the first large enough to explore how well fusion reactions can be sustained.

In order to succeed, the ITER project must demonstrate that it can create a fuel cycle in the reactor that will produce excess tritium, the reactor's fuel, from a "blanket" of lithium lining the reactor chamber. As neutrons thrown off from the fusion reaction strike lithium atoms, they produce tritium. But in order for the reactor to be viable, consortium officials say, the reactor must produce more tritium than it consumes.

Even fusion proponents concede that the process is decades away from practical use. A timeline published on ITER's Web site foresees a larger demonstration project that would begin operating around 2030. A commercial fusion reactor would follow around 2050.

ITER's interim leader, Yasuo Shimomura, said the project's next step would be to appoint a director general who could start the complicated procurement process.

The consortium has already spent $700 million on scale models of the reactor's major components, and "in this sense, there is no fundamental technical problem," Dr. Shimomura said in a phone call from ITER's offices in Garching, Germany. "But the machine is very complicated, and the procurement will be done between six parties, and this is not a small experimental device, it is a real nuclear device, so quality control will be very important."

In the meantime, the fusion project means money for the industries and scientific sectors contributing to it. Prime Minister Dominique de Villepin of France said it would create 4,000 jobs and bolster research and development there.

"It's brings us great joy and great pride," said Pascale Amenc Antoni, director of the French Atomic Energy Commission's Cadarache Center, where the reactor will be built. She said it also recognized the work the center has already carried out at its nuclear fusion research facility.

References:

Jean-Louis Basdevant, James Rich, & Michel Spiro, Fundamentals in Nuclear Physics, Springer (2005), Chapter 7.

Robley Evans, The Atomic Nucleus, McGraw-Hill (1955), Chapter 9.

Mackintosk et al., Nucleus, Johns Hopkins Univ. Press (2001), Chapter 9.

Craig Smith, New York Times, 29 June 2005.

(O) Nuclear Fusion: Inertial Confinement

"National Ignition Facility", Lawrence Livermore Nat'l Lab

<http://www.llnl.gov/nif>

D+T confined in glass spheres,
volume $\approx$ 1 mm^3, and then compressed by 192 laser beams.
delivering kiloJoules (kJ) of energy to the surface of a target pellet
on a time scale of 10–100 picoseconds (psec = 10^{-12} sec).

The resulting implosion - compresses and heats up the pellet

$\Rightarrow$ ($10^3 \times$ Density) @ 10^8 °K

Burns via $D + T \longrightarrow n + {}^4He$ reaction $\Rightarrow$ 10^4 TeraWatts

for a time scale ~ 100 psec. $\Rightarrow$ $10^{16} \times 10^{-10} = 10^6$ J

~ 10^{17} DT molecules in target $\times$ 18 MeV $\times$ 1.6×10^{-19} $\approx$ 10^6 J

Averaged over 1 shot every second,

this would correspond to ~ 1 MW.

But currently (2012) NIF is capable of ~ 1 shot per day,

so this averages out to only just a few Watts. (!)

At this stage, one of the most important questions has to be -

Can repetition rate get to 1000/sec?

The answers will have to come in ***technological*** **developments.**

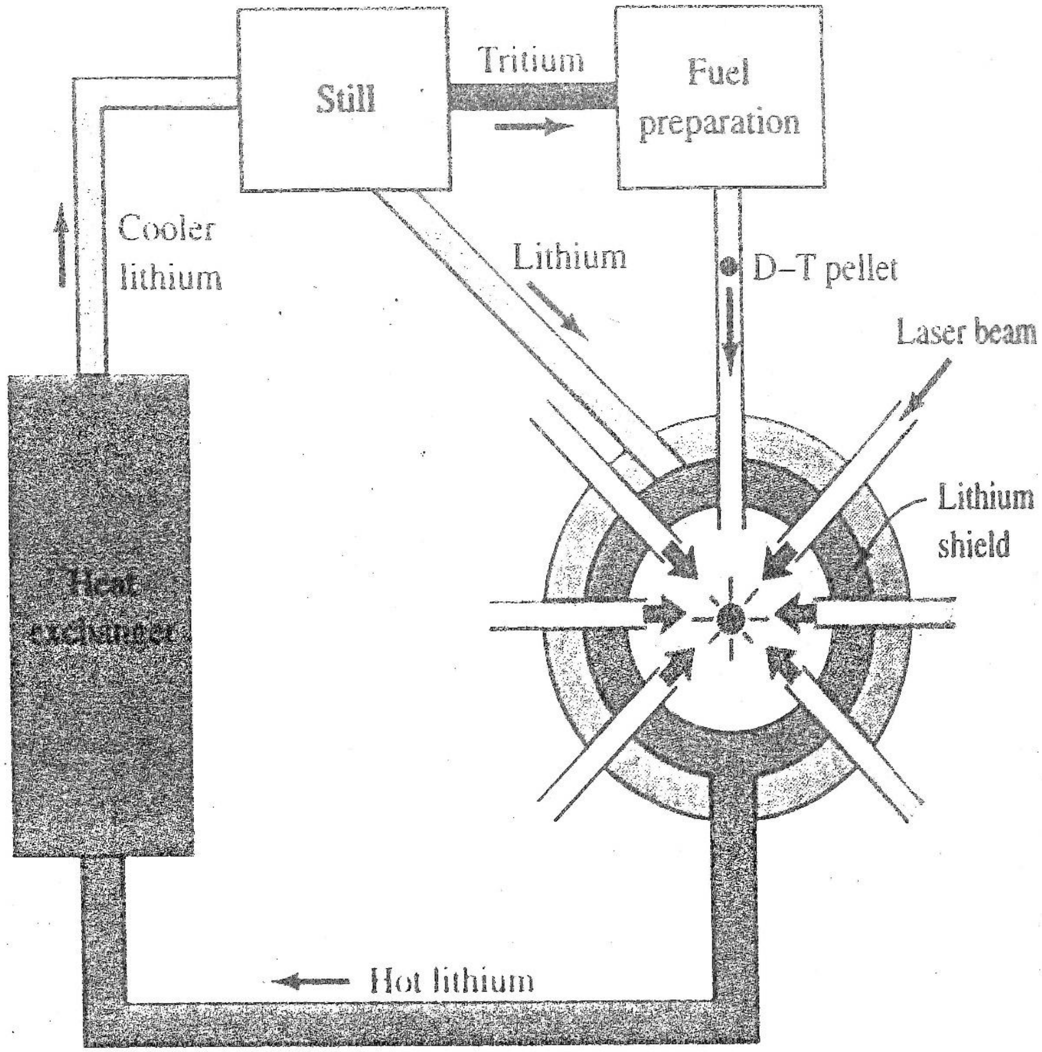
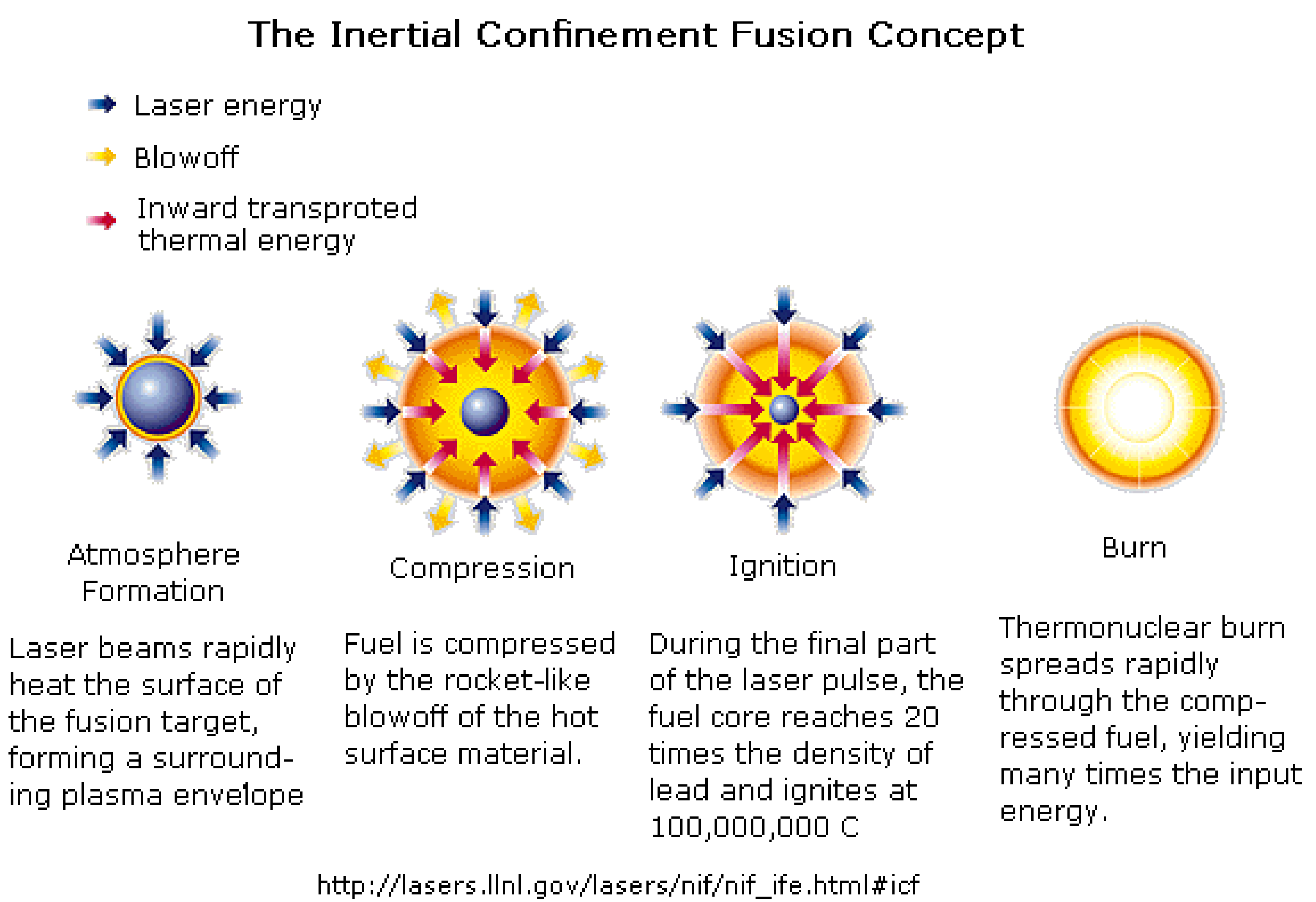


Fig. O-1

Simplified sketch of an Inertial Confinement System

Fig. O-2


The Inertial Confinement Fusion Concept
Laser energy
Blowoff
Inward transproted thermal energy
Atmosphere Formation
Compression
Ignition
Burn
Laser beams rapidly heat the surface of the fusion target, forming a surround-ing plasma envelope
Fuel is compressed by the rocket-like blowoff of the hot surface material.
During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 C
Thermonuclear burn spreads rapidly through the comp-ressed fuel, yielding many times the input energy.
http://lasers.llnl.gov/lasers/nif/nif_ife.html#icf

Jean-Louis Basdevant
James Rich
Michel Spiro

Fundamentals In Nuclear Physics

From Nuclear Structure to Cosmology

7.4 Inertial confinement by lasers

The principle of inertial confinement by lasers is to adiabatically compress a small ($\sim$ 1mg) sphere containing deuterium and tritium in order to increase its density by $\sim 10^4$, and to obtain temperatures of $\sim$ 10 keV. The core of the sphere ignites during a time of the order of 10^{-10} s and then explodes (see Fig. 7.9).

One calls *ignition* the regime where the temperature and density conditions of the core allow the burning of the d-t mixture.

Initially, this method was classified, because of its military applications. Since 1993 civilian-physicists have worked in the field.

The principle is simpler than in tokamaks. Additionally, research on this method has been funded partly owing to its importance for the understanding of thermonuclear explosions.

Principle of the method. The radiation of a set of laser beams delivering a very large power (TW) for a short time (ns) is directed toward a sphere of the order of a mm^3 of a solid deuterium-tritium mixture. There is an ablation, or sudden vaporization, of the periphery of the sphere and the formation of a corona of plasma.

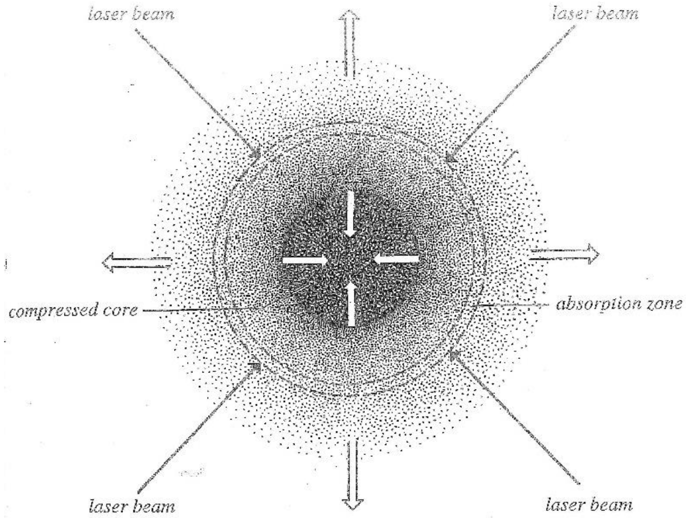


Fig. 7.9. Sketch of laser induced fusion. The d-t sphere interacts with the laser beams and it is vaporized superficially. By reaction, the corona compresses the central core.

The electrons of the medium which oscillate in the laser field transfer energy to the plasma by colliding with the ions. The energy is transfered to the cold regions of the center of the target by thermal conduction, by fast electrons and by UV and X radiation. A shock wave is created which compresses and heats the central region of the deuterium-tritium sphere, called the *core*.

Under that implosion, the core is compressed by a factor of 1000 to 10000, i.e. densities of $\sim 10^{31}\,\mathrm{m}^{-3}$, and its temperature reaches $\sim 10\,\mathrm{keV}$. Under these conditions, the fusion of the d-t nuclei occurs abundantly. The core burns for about 10^{-11}s. Its cohesion is maintained by inertia, it explodes because of the thermonuclear energy release.

The laser energy goes mainly into the compression of the d-t mixture. The energy necessary to heat the plasma comes mainly from the fusion energy release. This results in a reduction of the laser energy which is necessary to make the target burn.

In 1992, in the United States, the Lawrence Livermore National Laboratory (LLNL) declassified the principle of inertial confinement fusion. At Ann Arbor, the KMS laboratory (named after its creator, K.M. Siegel) was the first, around 1973, to achieve the implosion of glass "micro-balloons" containing gaseous deuterium-tritium. The experiment was then performed by other laboratories. The 100 kJ Nova laser of LLNL reached a production of 10^{13} neutrons per laser pulse.

Such experiments led to rapid development of computer-simulated explosions. The experimental inputs to these calculations involved the observation of X-rays and neutrons emitted by the target, the spectroscopy of tracers incorporated in the d-t mixture, such as argon and neon, and pictures of the α particles produced in the fusion reactions. Such measurements were compared with the results of computer simulations, in order to validate the assumptions entering the codes, in particular the fact that neutron emission is of thermonuclear origin.

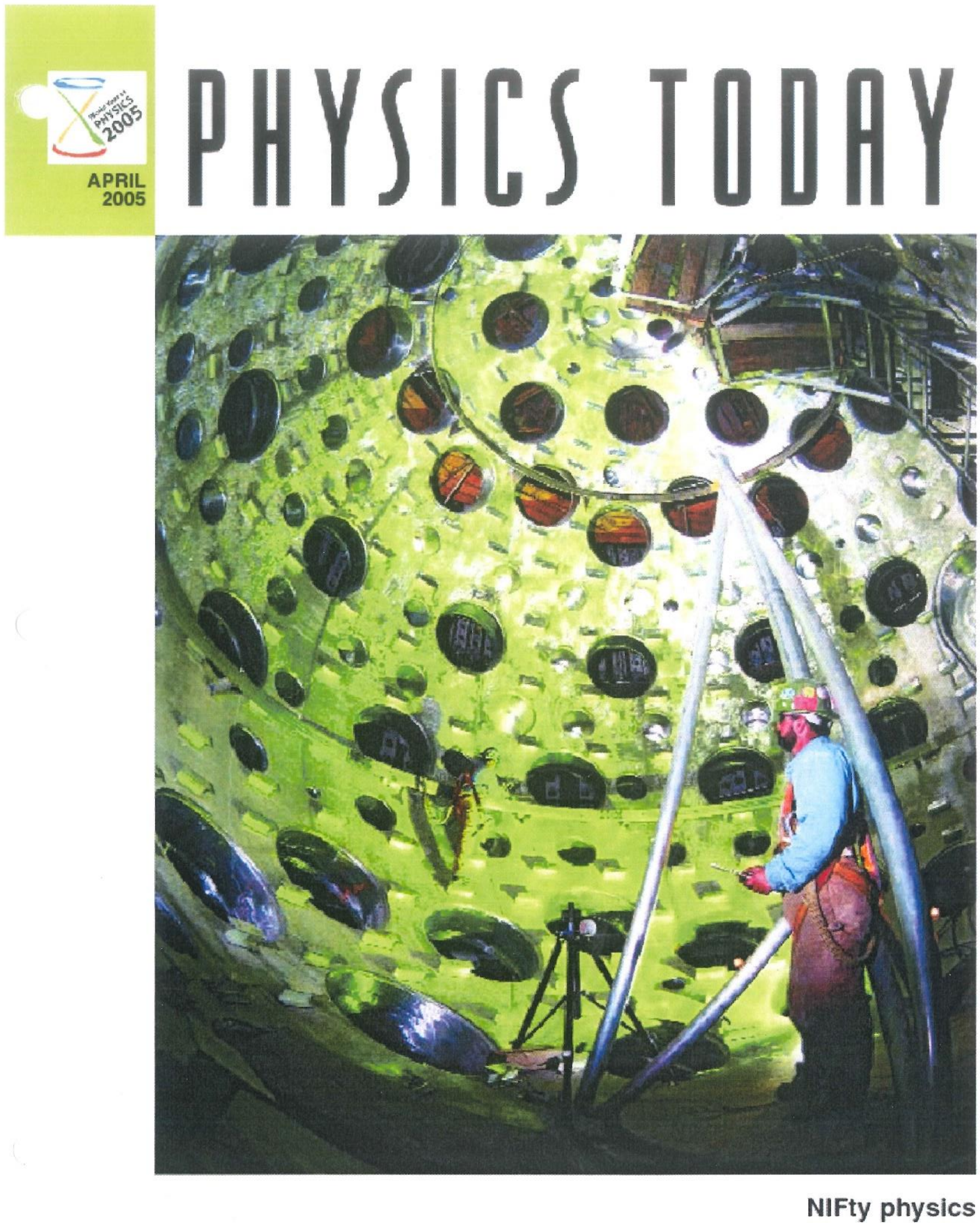


Fig. O-3

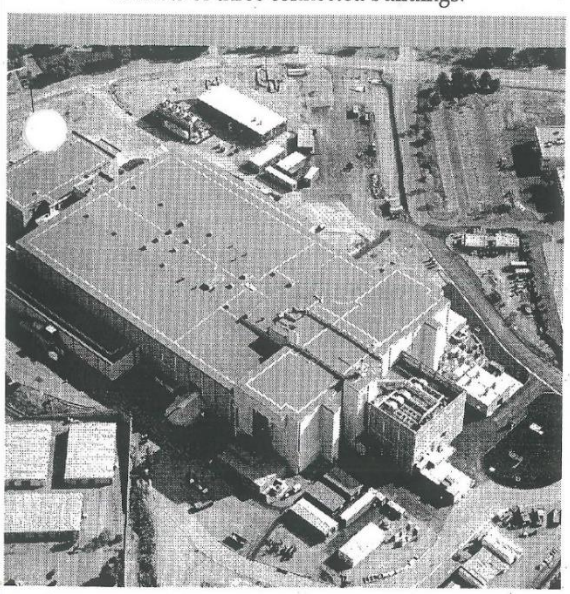
The following four pages are outdated, but provide an early overview to the National Ignition Facility at Lawrence Livermore National Laboratory. Current information is available on their website, https://lasers.llnl.gov/.

'urpose

The National Ignition Facility (NIF) will use the world's largest laser to compress and heat BB-sized capsules of fusion fuel to thermonuclear ignition. NIF experiments will produce temperatures and densities like those in the Sun or in an exploding nuclear weapon. The experiments will help scientists sustain confidence in the nuclear weapon stockpile without nuclear tests as a unique element of the National Nuclear Security Administration's Stockpile Stewardship Program and will produce additional benefits in basic science and fusion energy.

The Buildings

- NIF is 704 feet long, 403 feet wide, and 85 feet tall—about the size of a football stadium—and consists of three connected buildings:



  - Optics Assembly Building (OAB)
  - Laser Building (LB)
  - Target Area Building (TAB)
- The $260 million, 7-acre NIF building complex was completed on schedule and within its allocated budget on September 30, 2001. The OAB is undergoing commissioning of laser component assembly workstations.
  - Concrete poured: 73,000 cubic yards.
  - Steel and rebar erected: 12,700 tons.
  - Earth moved: 210,000 cubic yards.

The Laser System

- The 192 laser beams of NIF will generate
  - A peak power of 500 trillion watts, 1000 times the electric generating power of the United States.
  - A pulse energy of 1.8 million joules of ultraviolet light.
  - A pulse length of three to twenty billionths of a second.
- Optical components:
  - 7500 large optics including 3072 laser glass slabs as well as large lenses, mirrors, and crystals.
  - More than 15,000 small optical components.
- Precision optics: total area of 33,000 square feet (3/4 of an acre). More than 40 times the total precision optical surface in the world's largest telescope (Keck Observatory, Hawaii).
- Laser beams: 16-inch by 16-inch beams of infrared laser light (1-micron wavelength). The infrared beams are converted to ultraviolet beams (0.35-micron wavelength) at the target chamber.
- Laser pulse amplification:
  - In the master oscillator room, the initial 1 billionth of a joule pulse is amplified 10,000 times, then split into 48 separate laser pulses.
  - In the preamplifier module, each of the 48 pulses is further amplified 20 billion times, then split 4 ways to create 192 pulses.
  - In the main laser system, each propagated pulse is amplified another 15,000 times.
  - Total amplification = 3 quadrillion (3 million billion).

Laser and Optical System Cleanliness

- The high optical intensities of the NIF laser beams requires the laser beampath and optics to have a precision-cleaned environment for reliable operation.
- NIF cleanliness requirements for optics assembly areas are similar to those required for semiconductor fabrication.
- There are 400,000 square feet of structural surfaces

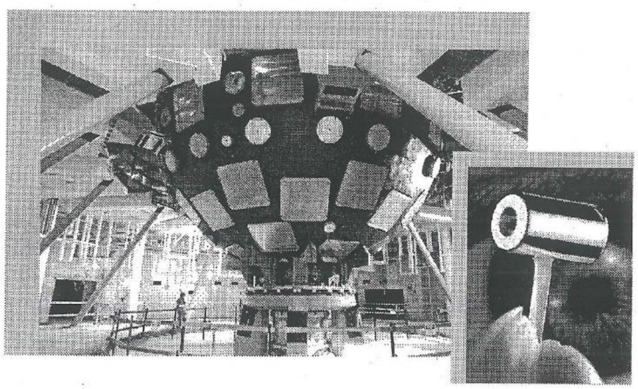
in the NIF laser and beampath that require precision cleaning.

The Target Experimental System

- Experiments consisting of laser targets and supporting systems are contained inside a 33-foot-diameter, 1 million-pound aluminum target chamber. The walls of the target chamber are 4-inches thick and coated with an additional 16 inches of concrete for radiation shielding.
- NIF scientists will conduct approximately 700 experiments each year where target materials will typically reach temperatures of 100 million degrees and densities up to 20 times that of lead.
- NIF ignition targets consist of a BB-sized plastic sphere containing frozen and gaseous fusion fuel, surrounded by a gold cylinder called a hohlraum, about the size of a cold capsule.
- NIF's 192 laser beams will be focused into 48 spots on the inner walls of the hohlraum, creating x-rays that drive the implosion of the fusion capsule, compressing it to one-thirtieth of its original size when the thermonuclear ignition process begins.

The NIF High Energy Density and Ignition Physics Program

- NIF experiments in support of the Stockpile Stewardship Program measure properties of materials and phenomena that occur at extreme temperatures and pressures, and under highly dynamic conditions. Weapons scientists will use the data generated on NIF to model, predict, and resolve problems that may be found in our aging nuclear stockpile without resorting to full-scale nuclear testing.
- Basic scientific experiments will also be performed on NIF to help astrophysicists understand the phenomena occurring deep within stars or the conditions that existed in the universe shortly after the big bang.
- Experiments will be fielded on NIF to study and understand inertial fusion energy. These experiments will help to increase the likelihood of full-scale fusion-energy-based power plants.



The NIF laser target chamber with hohlraum (inset).

Questions concerning the National Ignition Facility at LLNL should be directed to the LLNL Public

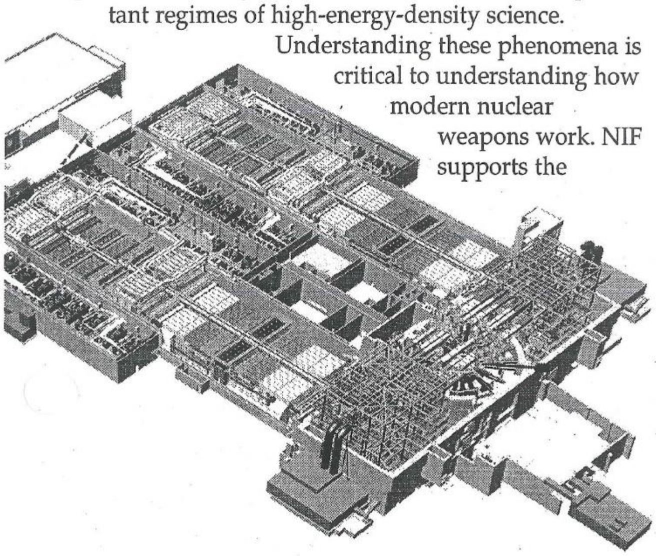
NATIONAL IGNITION FACILITY

What is stockpile stewardship?

The Stockpile Stewardship Program (SSP) is an initiative to maintain the nuclear deterrent of the United States in the post-Cold War era. It is based on the maintenance of our stockpile through an ongoing process of surveillance, assessment, refurbishment, and recertification, without nuclear testing. At the heart of the SSP is an attempt to bring advanced experimental and computational tools to bear on the evaluation and certification of the stockpile itself; these advanced scientific capabilities are necessary because of the cessation of nuclear testing. This science-based approach requires new tools: advanced computers for more detailed 3-D simulations, multi-axis hydrodynamic facilities and plutonium research facilities for physics measurements of primaries, and the National Ignition Facility for fusion burn and high-energy-density science. The science basis requires summing up the pieces we can measure and simulate, which cannot be done without a complete set of tools. Refurbishing weapons with confidence, without testing, is a difficult challenge. Only with high-quality scientists and a complete set of tools, can the U.S. accomplish this program.

What is NIF's role in stockpile stewardship?

NIF is a unique element of the Stockpile Stewardship Program because it is the only facility that will allow the experimental study of thermonuclear burn and important regimes of high-energy-density science. Understanding these phenomena is critical to understanding how modern nuclear weapons work. NIF supports the Stockpile Stewardship Program in three essential ways:



1. It permits the study of issues that can affect an aging or refurbished stockpile.
2. It permits advancement of the critical elements of the underlying science of nuclear weapons.
3. It will attract and help train the exceptional scientific and technical talent required to sustain Stockpile Stewardship over the long term.

Is NIF essential to stockpile stewardship?

Yes. NIF is a unique facility for experimental study of thermonuclear burn and high-energy-density phenomena that occur in modern nuclear weapons. Thermonuclear burn is at the very heart of how our stockpile works, and the inability to experimentally study physical phenomena in this physical regime would lead to reduced confidence in the U.S. nuclear weapons stockpile.

How would a delay in NIF affect stockpile stewardship?

Stockpile stewardship is a race against time. The oldest nuclear weapon in the stockpile was added to the stockpile in 1970. That makes the weapon 30 years old. Few people own a car or refrigerator of that vintage.

Efforts to maintain and refurbish aging nuclear weapons over the coming decade will raise questions that will require data from NIF to answer. If NIF is not on line when these questions arise, the nation will have to accept the risk of incomplete certifications or employ expensive risk mitigation strategies until the questions can be adequately answered.

Each year, the National Laboratories must evaluate the surveillance information available on each weapon system in the stockpile and recertify that the weapon system is still safe, secure, and reliable. This is the annual certification process. When surveillance data raise questions about a particular weapon's performance, the Laboratories analyze the problem/issue, conduct experiments to access the significance of the problem/issue, run complex simulations, and finally make a judgement as to their continuing confidence in the weapon system. NIF is designed to fill a critical role as a tool to use in these assessments, and its absence will reduce our ability to have high confidence in the stockpile. Although not all questions that arise will require data from NIF, many past issues would have required NIF if we had not tested, and it is inevitable that future ones will as well.

The weapons life-extension programs that are scheduled to be completed before NIF is fully operational will benefit later in the decade from NIF when their status is reviewed through the annual certification process. Post-deployment evaluations of U.S. nuclear weapons systems using newly available tools have historically been important elements of maintaining stockpile integrity and have led to a number of refurbishment actions.

Are there any NIF success stories?

Five Major Technological Breakthroughs. NIF will be 60 times more powerful than its predecessor, Nova, at one-sixth the cost per unit of energy generated. This advancement has required six major breakthroughs in technology: faster, less expensive laser glass production, large-aperture optical switches, stable high-gain preamplifiers, servo-controlled large-aperture deformable mirrors, large rapid-growth frequency-conversion crystals, and long-life final-stage optics.

Livermore Laboratory in collaboration with industry has now successfully developed five of these breakthrough technologies, and we are making good progress on the sixth— the final-stage optics. We recently grew the world's largest rapid-growth crystal, weighing 701 pounds, in 2 months. In the past, growing a crystal of this size and quality would have taken 2 years. The Livermore Lab crystals will produce twice the number of planned frequency-conversion components, decreasing the number of required crystals for NIF.

In addition, our recent pilot-production run at Schott Glass Technologies in Duryea, PA was particularly successful. The initial run yielded 200 glass slabs or 5% of the total glass required. These glass slabs meet all technical specifications. We anticipate similar success later this year with our other vendor, Hoya Optics in Fremont, CA. Before the manufacturers' technological breakthroughs, high-quality glass had not been produced in a bulk process. Previously, each piece of glass had to be individually manufactured, an expensive and lengthy process.

The Conventional Facilities Are on Schedule and Meet the Demanding Requirements of NIF. The conventional facilities were completed September 2001 on schedule and budget. The conventional facilities include the Optics Assembly Building, the Laser Building, and the Target Area Building. The demanding requirements of the NIF laser and target systems led to unusual features in these buildings. For instance, the 25,000-square-ft Optics Assembly Building has a large receiving area and three connected clean rooms. This facility receives optics and laser components, and then stores and assembles the components in rooms with stringent cleanliness controls. This building is complete, it is clean, and it has been transferred to Lawrence Livermore for outfitting of special equipment.

The Laser Building is approximately 600 ft long and 400 ft wide. It houses two laser bays that each contain 96 of the 192 beams of the NIF laser. The lasers must be pointed very precisely. This pointing requirement is equivalent to using the point of a needle to touch a single human hair from 100 yards away. This pointing precision contributes to a number of unusual requirements relating to stability and vibration for the Laser Building. For stability, the laser system is supported on concrete pedestals that are mounted on 400-ft-long by 80-ft-wide by 3-ft-thick single-pour concrete slabs. The laser building will be temperature-controlled to one-half degree Fahrenheit to maintain laser positioning. This in turn requires 15 full air changes per hour and sophisticated air-handling systems that have very low vibration. The Laser Building is now very close to completion and will start accepting large steel laser vessels later this year.

The Target Area Building contains ten-story steel structures that hold the large turning mirrors that direct the laser beams toward the target. Again, these structures must be very stable and resistant to vibration. Consequently, the steel structures are robust, and in addition, are anchored into the building, resulting in the stiffest structures of this size ever built. One of the two switchyards is now complete; the second is nearing completion. At the center of the Target Area Building is the 33-ft-diameter target chamber. For stability reasons, the target chamber is an integral part of the Target Area Building concrete structure. This concrete structure includes 6-ft-thick walls surrounding the chamber for radiation protection. The Target Area Building is complete, and the one-million pound target chamber has been set and precision-aligned to better then 1/4 millimeter.

Questions concerning the National Ignition Facility at LLNL should be directed to the LLNL Public Affairs Office, (925) 422-9919.

National Ignition Facility Prepares for Fusion Test
Next year scientists hope to trigger a fusion reaction with its 192 lasers
By Jenny Mandel
Scientific
Scientific American, August 20, 2009
https://wwtificamerican.com/article/national-ignition-facility-fusion-reaction-test-lasers/

PEA-SIZE POWER: *Within this cylinder lies the pea-size NIF fusion capsule. - Courtesy of Lawrence Livermore National Laboratory*

Federal researchers are slowly testing 192 lasers that they hope will set off the world's first controlled nuclear fusion reaction.

The lasers are housed at the National Ignition Facility (NIF), a $4 billion complex the size of three football fields that is part of the Lawrence Livermore National Laboratory in Livermore, Calif.

The facility's construction was completed this spring with tests directing more than a megajoule of energy at a target (a megajoule is the energy consumed by 10,000 100-watt light bulbs in a second). Now researchers are preparing for a first use of its full capabilities next year, when the battery of lasers will be trained on a small pellet of fuel in hopes of igniting it to trigger a brief but powerful fusion reaction.

While commercially operating nuclear fission reactors provide power -- and a host of controversy over weapons use and waste disposal -- nuclear fusion is a different process. A sustained string of uncontrolled fusion reactions can be used for military purposes such as a hydrogen bomb, and since the 1950s, scientists have chased controlled fusion reactions for potential civilian purposes.

NIF will offer them new opportunities to study the process in a laboratory setting.

Preparation for the big experiment next year involves gradually running the lasers at higher intensities. The team is wary of moving too fast for fear of seeing a dramatic flop like the one that happened with a similar project in Switzerland in September 2008.

The Large Hadron Collider, a massive European facility that runs similar experiments on superheated matter, was sidelined by engineering problems just days after it opened.

So the facility's scientists are working cautiously. "We don't want to break the world's biggest laser in its first month of operation," NIF researcher Mordecai Rosen said in an interview yesterday at the American Chemical Society's annual meeting in Washington, D.C.

Late next year, Rosen said, the full power of the lasers will be trained on a fuel capsule the size of a pea. The resultant implosion is expected to generate 10 times as much energy as was used to power the machines.

Rosen said the facility will provide new opportunities for astrophysicists to study the stars and other matter, and for nuclear scientists to run experiments that could eventually lead to fusion power production. Some classified work related to the U.S. nuclear stockpile will also be done there, according to Tom D'Agostino, administrator of the Energy Department's National Nuclear Security Administration, which runs the lab.

One unique element of the Livermore facility is that it provides a view into the behavior of hot, highly pressurized matter, whereas the Large Hadron Collider works with heat but not high density.

Rosen likens the NIF apparatus to a giant microwave with a baked potato inside.

Next year, the microwave will be heated to 3 million degrees. What happens to the potato remains to be seen.

References:

Jean-Louis Basdevant, James Rich, & Michel Spiro, Fundamentals in Nuclear Physics, Springer (2005), Chapter 7.

Lasers.llnl.gov (Lawrence Livermore National Laboratory)

http://www.llnl.gov/nif

Mandel, Jenny. National Ignition Facility Prepares for Fusion Test, *Scientific American*, August 20, 2009. https://www.scientificamerican.com/article/national-ignition-facility-fusion-reaction-test-lasers/

(P) Solar Energy Generation

As soon as "we" know the distance to the sun, the age of the solar system, the luminosity of the sun, and the mass of the sun, we can then estimate how much energy the sun must have radiated thus far over the course of its life, and that can be compared to how much would have been available from the gravitational condensation of the solar nebula to the current size of the sun or from chemical reactions such as $C+O_2 \rightarrow CO_2$, etc.

Distance to the Sun:

19^{th} Century - Transits of Venus
Modern Measurements: Radar Reflections and Space Probes

$\boxed{\text{Result} = 1.496 \times 10^{11} \text{ meters}}$

Age of the Solar System:

4N (^{232}Th), 4N+1(^{237}Np), 4N+2(^{238}U), 4N+3(^{235}U) Decay Chains

Still find the progenitors for the 4N, 4N+2, and 4N+3 chains in terrestrial ores, but NO **4N+1** progenitor (^{237}Np). Therefore we can conclude the solar system is not infinitely old but is at least several times older than the half-life of the **4N+1** progenitor (^{237}Np), 2.2×10^6 years.

$$\left.\begin{array}{l}\text{Ratio of Uranium-to-Helium in ores.}\\ {}^{235}U/{}^{238}U \text{ abundance ratio.}\\ \text{Ratio of Uranium-to-Lead in ores.}\end{array}\right\} \sim 5\times10^9 \text{ years}$$

(Leighton, Principles of Modern Physics, Chapter 15)

$\boxed{\text{Result} = 4.55 \times 10^9 \text{ years}}$

At this point we could pick the sun's energy source as Nuclear Fusion Reactions, but only by *default*. See comparisons on next page.

SOLAR ENERGY GENERATION

5×10^9 years $\times\ 3.9 \times 10^{26}$ Joules/sec $\approx 6.4 \times 10^{43}$ Joules

Gravitational Contraction $\approx \frac{1}{2} G \frac{M_\odot^2}{R_\odot} \approx 2 \times 10^{41}$ Joules

Chemical Reactions (e.g., $C + O_2 \rightarrow CO_2$) $\approx 2 \times 10^{37}$ Joules

$$\left.\begin{array}{l}\text{Nuclear Reactions:} \\ \quad 4H^1 \rightarrow He^4 + 2\beta^+ + 2\nu + 26.7\ \text{MeV}\end{array}\right\} \approx 1.6 \times 10^{45}\ \text{Joules}$$

To go further (i.e., to search for more <u>direct</u> evidence of nuclear fusion in the sun) we will have to detect some of the nuclear reaction products from such fusion.

The overall fusion of four ^{1}H nuclei to form one ^{4}He nucleus can be written as

$$\boxed{4\,(^{1}H) \Rightarrow\ ^{4}He + 2\,\beta^{+} + 2\,\nu_{e} + 26.7\ \text{MeV}}$$

where the 26.7 MeV of energy is initially in the form of high-energy gamma rays or the kinetic energy of the particles produced in this fusion reaction.

The specific reactions involved have been put together to form two sequences that are known as the **Proton-Proton Chain** and the **Carbon-Nitrogen Cycle**; see Figs P-7 and P-8.
[Ref: vonWeizsäcker (1937+1938), Bethe & Critchfield (1938), and Bethe (1939)]

On the basis of our discussions in Sections N and O we can expect this fusion will take place at the high temperature (~15 million ^{o}K), and high density (~150 g/cc) in the core of the sun. Under those conditions the mean-free-paths for any of these reaction products are orders of magnitude shorter than the size of the sun - ***except*** for the neutrinos (ν_{e}) .

See Section Q for more information on neutrinos.

4N Evans, <u>The Atomic Nucleus</u>, p. 518

Fig. P-1

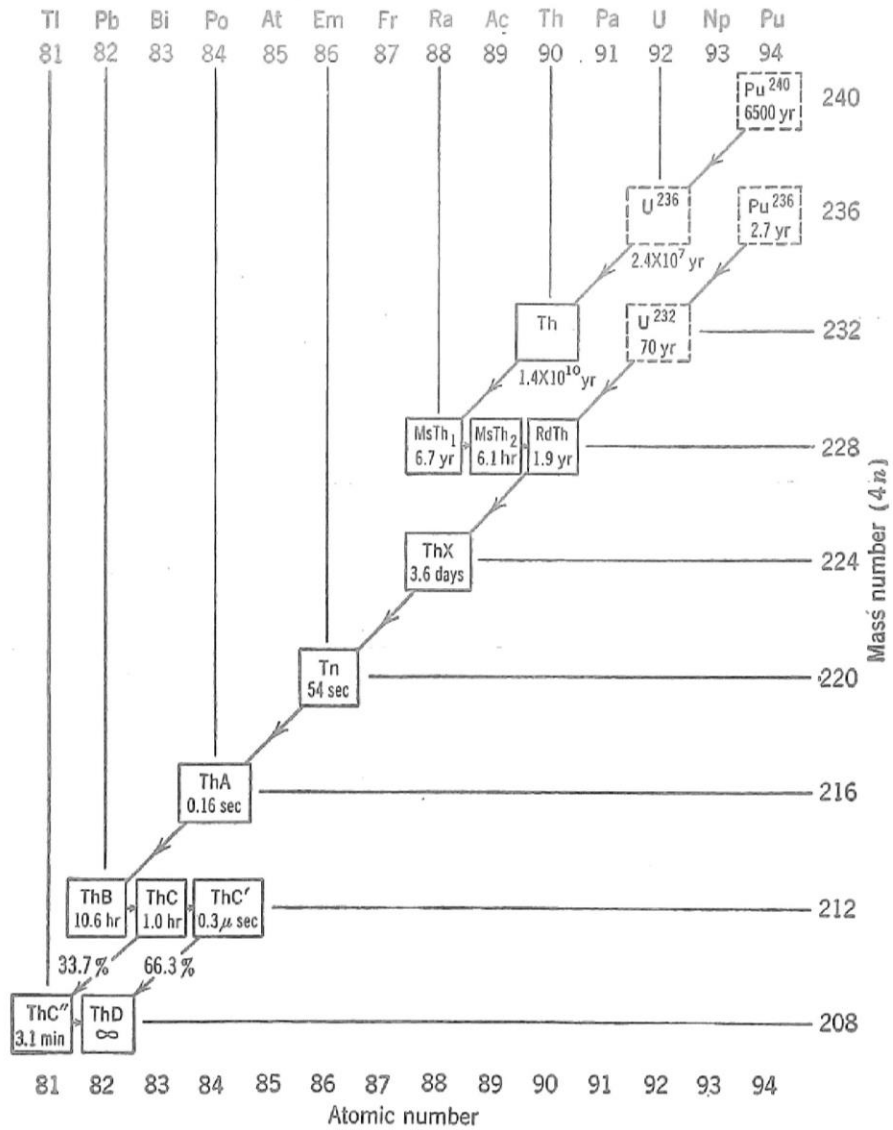


Fig. 2.1 Main line of decay for the thorium series, or $4n$ series, of heavy radioactive nuclides. Solid boxes denote nuclides which occur in nature. Diagonal arrows denote α decay; horizontal arrows indicate β decay. All artificially produced nuclides with $A = 4n$ and $A > 208$ will decay into this most stable line of descent. A few artificially produced $4n$ nuclides are shown in dotted boxes. All possible $4n$ nuclides probably were present when the universe was very young. Short-lived nuclides, such as thoron, are found in nature today only because of a genealogical accident; they have a long-lived ancestor in Th^{232}.

4N+1	Evans, <u>The Atomic Nucleus</u>, p. 520

Fig. P-2

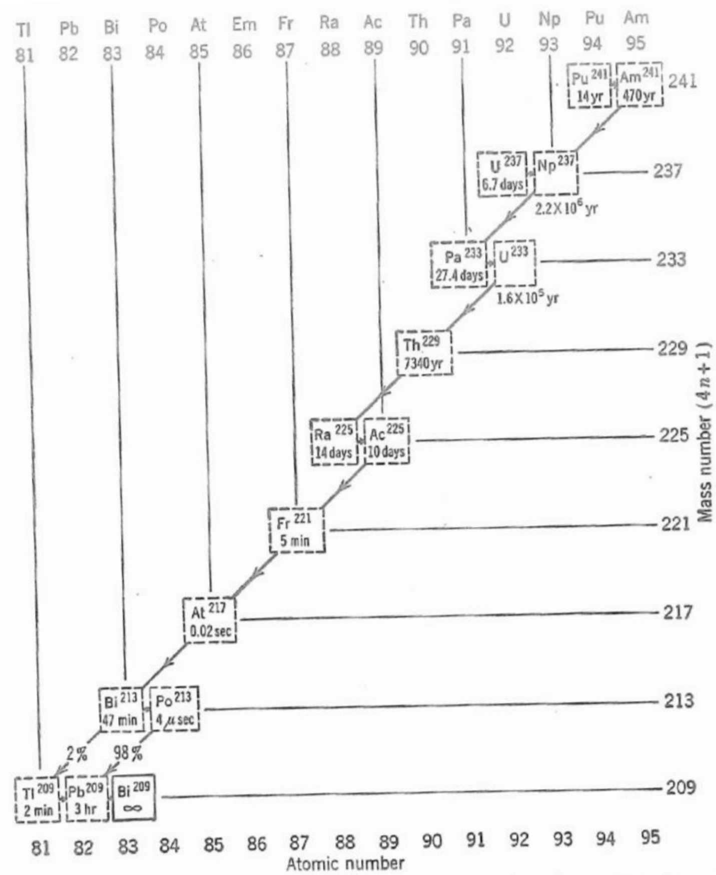


Fig. 2.2 Main line of descent for members of the neptunium $(4n + 1)$ series. Only the stable end product, Bi^{209}, is a naturally occurring nuclide.

4N+2	Evans, The Atomic Nucleus, p. 521

Fig. P-3

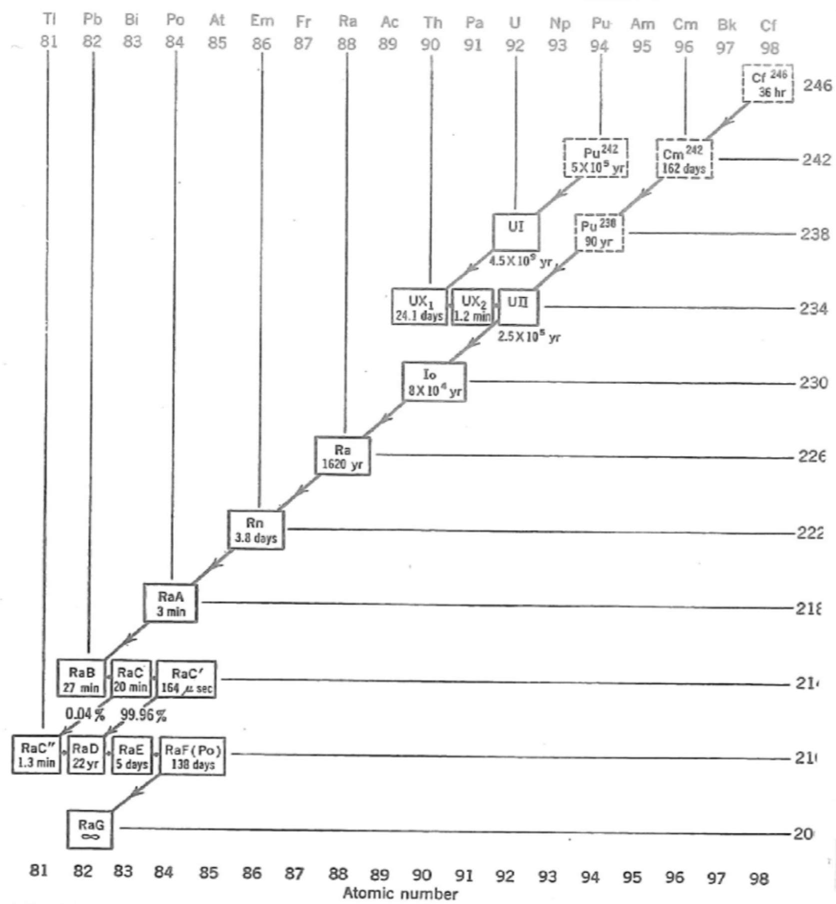


Fig. 2.3 The uranium series ($4n + 2$), shown here, is the longest-known decay cha
A few artificially produced members are shown in dotted boxes. A collateral ser
not found in nature, includes U^{230} and joins the uranium series at RaC′ ($_{84}Po^{214}$).

4N+3	Evans, <u>The Atomic Nucleus</u>, p. 522

Fig. P-4

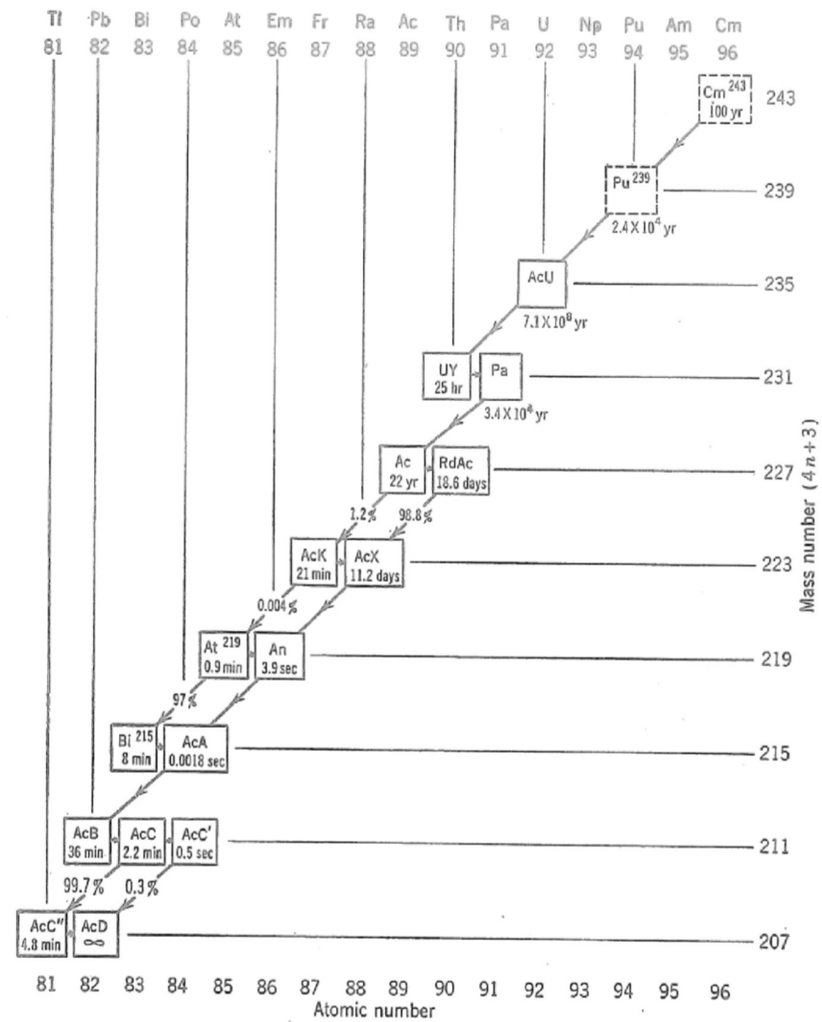


Fig. 2.4 The actinium $(4n + 3)$ series. The nuclides shown in solid boxes occur in nature. Note the weak collateral branch $Ac^{227} \xrightarrow{\alpha} AcK \xrightarrow{\alpha} At^{219} \xrightarrow{\alpha} Bi^{215} \xrightarrow{\beta} AcA$ which contains the only isotopes of francium and astatine which occur in nature. In this branch, the percentages shown refer to the fraction of each nuclide which undergoes α decay. The main line of descent is through actinium X (Ra^{223}) and actinon (Em^{219}).

($^{235}U(t) / {}^{238}U(t)$) Estimation of the Age of the Solar System:

$$({}^{235}U(t) / {}^{238}U(t)) = 1/140 = [\,235_o\,] / [\,238_o\,] \left\{ (1/2)^{\,t / 7\times10^{\wedge}8} / \ (1/2)^{\,t / 4.5\times10^{\wedge}9} \right\}$$

If the initial ratio of $[\,235_o\,] / [\,238_o\,]$ were ≈ 1 , then

$$\Rightarrow \quad \underbrace{140 = (1/2)^{(\,t / 4.5\times10^{\wedge}9\,)} / (1/2)^{(\,t / 7\times10^{\wedge}8\,)} = (1/2)^{(\,-1.2\times10^{\wedge}\text{-}9 \times t\,)}}$$

$$\longrightarrow \quad (2)^{7} \approx (2)^{(\,1.2\times10^{\wedge}\text{-}9 \times t\,)} \qquad \therefore \qquad t \sim 6 \times 10^{9} \text{ yrs.}$$

If the initial $[\,235_o\,] / [\,238_o\,]$ ratio were somewhat smaller, e.g. ≈ 0.2 ,

$$\Rightarrow \quad \underbrace{28 = (1/2)^{(\,t / 4.5\times10^{\wedge}9\,)} / (1/2)^{(\,t / 7\times10^{\wedge}8\,)} = (1/2)^{(\,-1.2\times10^{\wedge}\text{-}9 \times t\,)}}$$

$$\longrightarrow \quad (2)^{4.8} \approx (2)^{(\,1.2\times10^{\wedge}\text{-}9 \times t\,)} \qquad \therefore \qquad t \sim 4 \times 10^{9} \text{ yrs.}$$

So that the age of the solar system (depending on the initial uranium isotope ratio in the proto-solar nebula) is somewhere around:

$$\mathbf{t \sim 5 \times 10^{9} \text{ yrs.}}$$

Fig. P-5

Orion Nebula

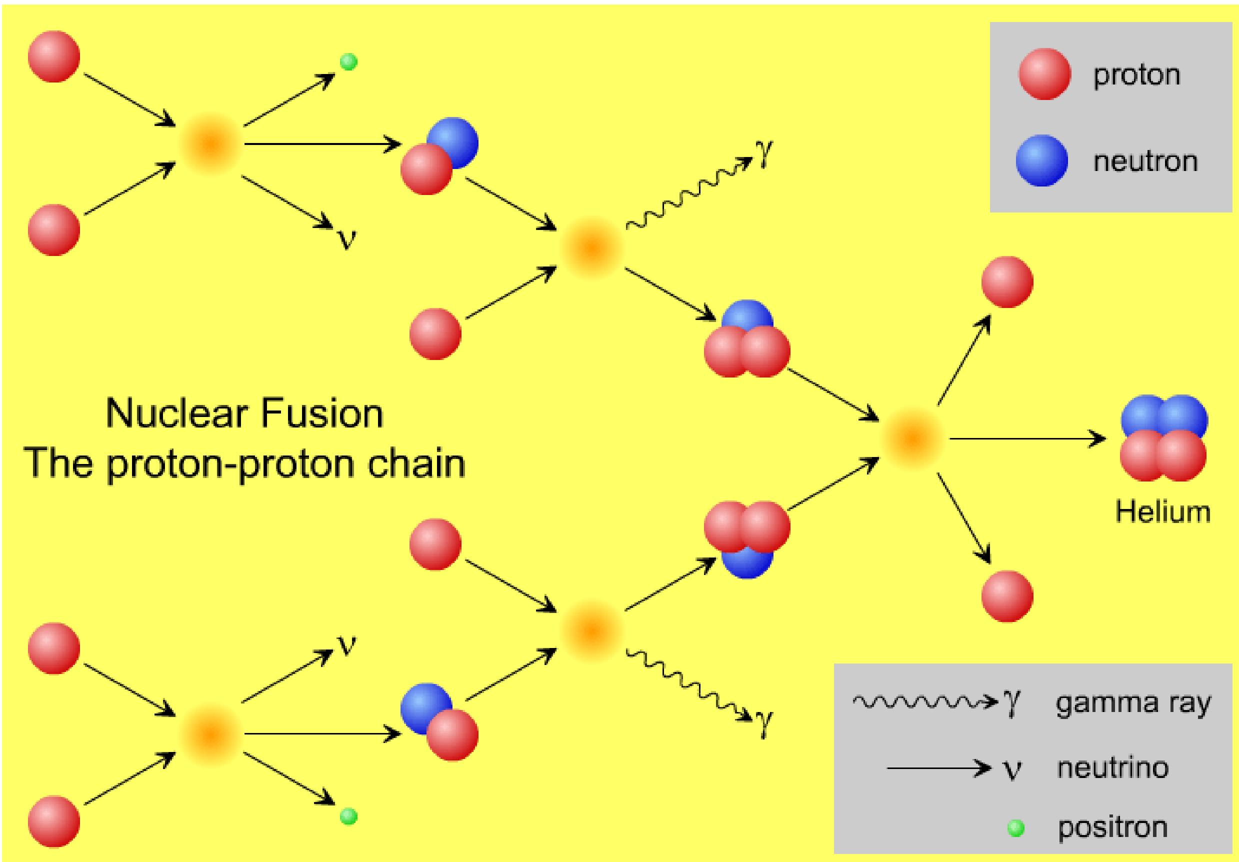
Gas clouds undergoing gravitational collapse to form stars.

Pleiades

Fig. P-6

The Pleiades, a young star cluster (10^7 to 10^8 years old). The blue nebulosity around these stars is due to light from these stars being reflected from the proto-stellar cloud (like the Orion Nebula) that is now being dispersed by light pressure from these stars.

Fig. P-7


proton
neutron
γ
ν
Nuclear Fusion
The proton-proton chain
Helium
ν
γ
γ gamma ray
ν neutrino
positron

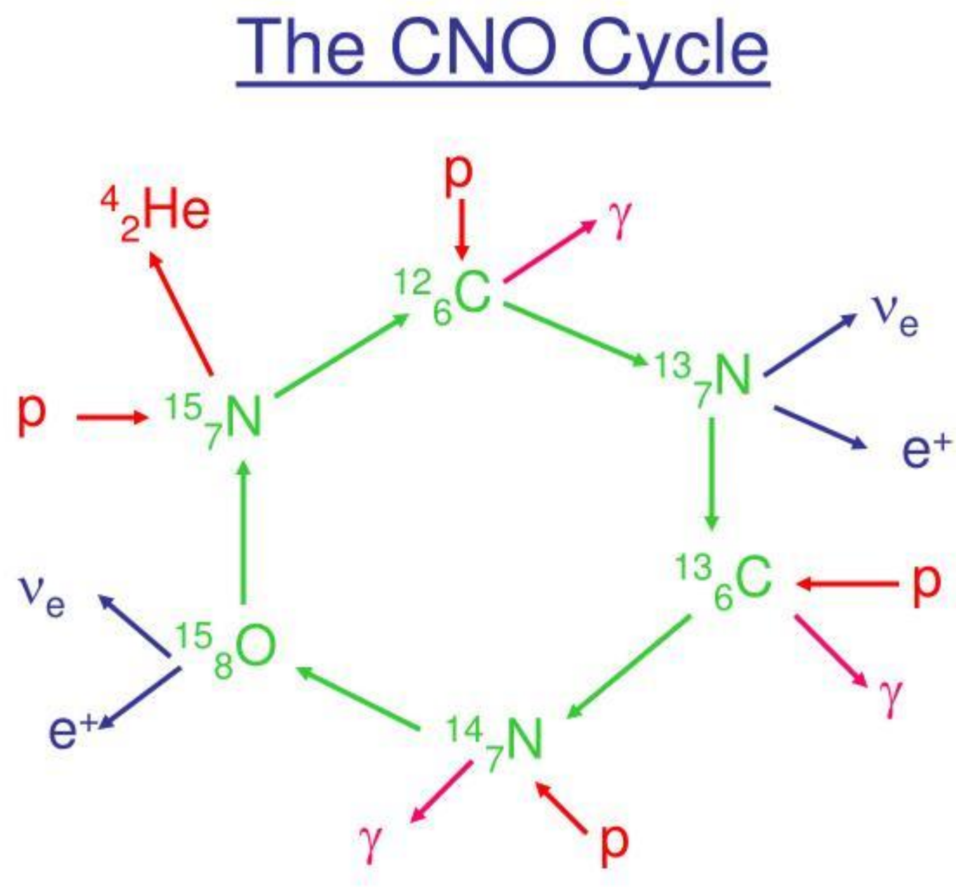


Fig. P-8

Nuclear Fusion via CNO Cycle

References:

H.A. Bethe, Physical Review **55** (1939) 434.

H.A. Bethe and C.L. Critchfield, Physical Review **54** (1938) 248.

Robley Evans, The Atomic Nucleus, McGraw-Hill (1955), Chapter 16.

Robert Leighton, Principles of Modern Physics, McGraw-Hill (1959), Chapter 15.

C.F. vonWeizsäcker, Physik.Z. **38** (1937) 176.

C.F. vonWeizsäcker, Physik.Z. **39** (1938) 663.

(Q) Neutrinos

December 1930: Hypothesis by Wolfgang Pauli at a meeting in Tubingen.

> Pauli hypothesized that a new neutral particle, the **neutrino**, ("the little neutral one") was needed in order to account for missing energy and angular momentum which couldn't be detected in beta decay, i.e., were apparently being *lost*. The neutrino was needed in order to still have the Law of Conservation of Energy (LCE) and the Law of conservation of Angular momentum (LCAM), and it was therefore *given* the specific properties (unmeasured) that were needed in order to keep LCE and LCAM.

Consider nuclear beta decay:

e.g., $^{64}Cu \rightarrow {}^{64}Zn + e^- + \bar{\nu}_e$

OR, $n \rightarrow p + e^- + \bar{\nu}_e$

Conservation Laws: [Written to describe observations!]

Conservation of
- charge
- nucleon number
- lepton number
  [e^- and ν_e are leptons (leptons vs. antileptons, which must be created or annihilated as a pair so that the **net** number doesn't change.) Later discover other types of leptons, "muons" and "tauons".]
  ∴ in beta decay when an e^- is emitted a corresponding antineutrino $\bar{\nu}_e$ must also be emitted.

Conservation of Energy:
[Compare energy spectra from β–decay vs. α–decay]
(See Fig. Q-1 vs. Fig. Q-2)

Because neutrinos could not be detected/measured in the 1930s, it was asserted that their reaction probabilities (cross sections) must be at least 20 orders of magnitude times smaller ($\sim 10^{-20}$) than typical nuclear cross sections – and this was then labeled the <u>**weak**</u> interaction.

1959: It was not until 29 years later that these hypothesized particles were finally detected by researchers (Reines & Cowan, 1959) utilizing the intense flux of 10^{13} neutrinos/cm^2/sec from the Savannah River fission reactor (built as part of the nuclear weapons program). As an indication of how weak the neutrino interaction is, we can note that this flux of neutrinos incident on a $\approx$1000 liter liquid detector produced a yield of only 36 ±4 events per hour.

Remember [Section (I)] that fission reactors produce neutron-rich radioactivities so that they decay by β^- decays which, in order to conserve lepton number, are therefore hypothesized to be accompanied by antineutrinos.

At Savannah River,

$$\therefore \qquad \bar{\nu}_e + p \rightarrow n + e^+$$

$$\text{then } e^+ + e^- \Rightarrow \gamma\text{-rays}$$

$$n + Cd \Rightarrow \gamma\text{-rays}$$

These coincident gamma-rays – separated by the 20 - 100 μsec that it took the neutron to slow down and be captured by the cadmium in the detector – were the signature for this antineutrino induced event.
Their <u>measured</u> cross section for this "neutrino reaction" was $\sim 10^{-43}$ cm^2 compared to the cross section of ~ 10 to 100×10^{-24} cm^2 for neutron capture by the Cd nucleus.

By contrast, the "neutrinos" produced in **fusion** - [i.e., in the sun in our "default" argument in Section (P)] - will be neutrinos rather than anti-neutrinos, because they accompany β^+ decay. Their detection is discussed in Section (R).

Conservation of Energy:

Comparison of β – decay *vs.* α – decay

Fig. Q-1

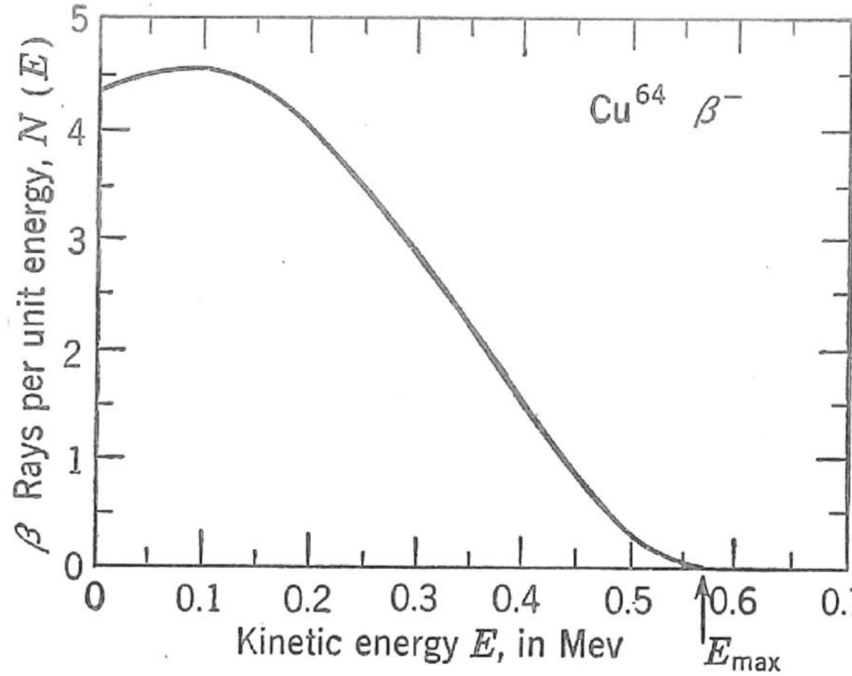


Fig. 1.4 Energy spectrum of the negatron β rays from Cu^{64}.

Fig. Q-2

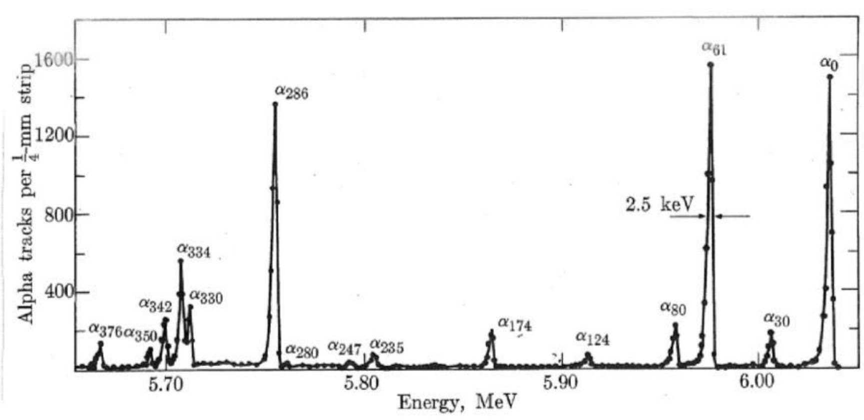


Fig. 10–4. Alpha-particle spectrum of Th^{227} taken by Pilger *et al.* [R. C. Pilger, Ph.D. thesis, University of California Radiation Laboratory Report UCRL-3877 (1957)]. The subscripts on the alpha peaks indicate the excitation energies of the corresponding levels in the daughter nucleus Ra^{223}.

Free Antineutrino Absorption Cross Section. I. Measurement of the Free Antineutrino Absorption Cross Section by Protons*

FREDERICK REINES AND CLYDE L. COWAN, JR.†
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received September 8, 1958)

The cross section for the reaction $p(\bar{\nu},\beta^+)n$ was measured using antineutrinos ($\bar{\nu}$) from a powerful fission reactor at the Savannah River Plant of the United States Atomic Energy Commission. Target protons were provided by a 1.4×10^3 liter liquid scintillation detector in which the scintillator solution (triethylbenzene, terphyenyl, and POPOP) was loaded with a cadmium compound (cadmium octoate) to allow the detection of the reaction by means of the delayed coincidence technique. The first pulse of the pair was caused by the slowing down and annihilation of the positron (β^+), the second by the capture of the neutron (n) in cadmium following its moderation by the scintillator protons. A second giant scintillation detector without cadmium loading was used above the first to provide an anticoincidence signal against events induced by cosmic rays. The antineutrino signal was related to the reactor by means of runs taken while the reactor was on and off. Reactor radiations other than antineutrinos were ruled out as the cause of the signal by a differential shielding experiment. The signal rate was 36 ± 4 events/hr and the signal-to-noise ratio was $\frac{1}{5}$, where half the noise was correlated and cosmic-ray associated and about half was due to non-reactor-associated accidental coincidences. The cross section per fission $\bar{\nu}$ (assuming 6.1 $\bar{\nu}$ per fission) for the inverse beta decay of the proton was measured to be $(11\pm2.6)\times10^{-44}$ cm^2/$\bar{\nu}$ or $(6.7\pm1.5)\times10^{-43}$ cm^2/fission. These values are consistent with prediction based on the two-component theory of the neutrino.

I. INTRODUCTION

A DETERMINATION of the cross section for the reaction: antineutrino ($\bar{\nu}$) on a proton (p^+) to yield a positron (β^+) and a neutron (n),

$$\bar{\nu}+p^+\rightarrow\beta^++n, \tag{1}$$

permits a check to be made on the combination of fundamental parameters on which the cross section depends. Implicit in a theoretical prediction of the cross section are (1) the principle of microscopic reversibility, (2) the spin of the $\bar{\nu}$, (3) the particular neutrino theory employed: e.g., two- or four-component, (4) the neutron half-life and its decay electron spectrum, and (5) the spectrum of the incident $\bar{\nu}$'s.

An experiment which was performed to identify antineutrinos from a fission reactor[1] yielded an approximate value for this cross section. Following this work, however (and prior to the parity developments involved in point 3), the equipment was modified in order to obtain a better value of the cross section. The modification consisted in the addition of a cadmium salt of 2-ethylhexanoic acid to the scintillator solution[2] of one of the detectors of reference 1, utilizing the protons of the solution as targets for antineutrinos, and making the necessary changes in circuitry to observe both positrons and neutron captures in the detector resulting from antineutrino-induced beta decay in the detector. In addition, a second detector used in the experiment of reference 1 was now used as an anticoincidence shield against cosmic-ray-induced backgrounds, and static shielding was increased by provision of a water tank about 12-inches thick below the target detector. The delayed-coincidence count rate resulting from the positron pulse followed by the capture of the neutron was observed as a function of reactor power, and an analysis of the reactor-associated signal yielded, in addition to an independent identification of the free antineutrino, a measure of the cross section for the reaction and a spectrum of first-pulse (or $\bar{\nu}$) energies. Since the antineutrino spectrum is simply related to the β^+ spectrum, the measurement yields an antineutrino spectrum above the 1.8-Mev reaction threshold. The spectrum is, however, seriously degraded by edge effects in the detector.

This experiment was identical in principle with that performed at Hanford in 1953.[3] It was, however, definitive from the point of view of antineutrino identification (whereas the Hanford experiment was not) because of a series of technical improvements, coupled with the better shielding against cosmic rays achieved by going underground. The improvements consisted in the use of an isolated power supply to diminish electrical noise from nearby machinery, better shielding from the reactor gamma-ray and neutron background, a more complete anticoincidence shield against charged cosmic rays through the use of a liquid scintillation detector, and use of a large detector containing 6.5 times as many proton targets.[4] In addition, oscilloscopic presentation and photographic recording of the data assisted materially in analyzing the signals and rejecting electrical noise.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at the Department of Physics, George Washington University, Washington, D. C.
[1] Cowan, Reines, Harrison, Kruse, and McGuire, Science 124, 103 (1956).
[2] Ronzio, Cowan, and Reines, Rev. Sci. Instr. 29, 146 (1958), describe the preparation and handling of liquid scintillators developed for the Los Alamos neutrino program.
[3] F. Reines and C. L. Cowan, Jr., Phys. Rev. 90, 492 (1953).
[4] The gain, times 6.5, due to the increase in target protons was largely balanced by a decrease in the neutron detection efficiency, times $\frac{1}{5}$, made necessary by other experimental considerations.

Detection of the Free Antineutrino*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

INTRODUCTION

THE importance of a direct verification of the Pauli-Fermi neutrino hypothesis[1] has long been recognized. The experiment reported in this paper was designed to show that the neutrino has an independent existence, i.e., that it can be detected away from the site of its creation, by means of the effect it produces on a counter. In this work, carried out at the Savannah River Plant of the U. S. Atomic Energy Commission, we investigated the reaction[2]

$$\bar{\nu}+p\rightarrow\beta^++n, \tag{1}$$

which is the antineutrino-induced inversion of neutron decay.

The detection scheme is shown schematically in Fig. 1. An antineutrino ($\bar{\nu}$) from the fission products in a powerful production reactor is incident on a water target in which $CdCl_2$ has been dissolved. By reaction (1), the incident $\bar{\nu}$ produces a positron (β^+) and a neutron (n). The positron slows down and annihilates with an electron in a time short compared with the 0.2-μsec resolving time characteristic of our system, and the resulting two 0.5-Mev annihilation gamma rays penetrate the target and are detected in prompt coincidence by the two large scintillation detectors placed on opposite sides of the target. The neutron is moderated by the water and then captured by cadmium in a time dependent on the cadmium concentration (in our experiments practically all neutrons are captured within 10 μsec of their production). The multiple cadmium-capture gammas are detected in prompt coincidence by the two scintillation detectors, yielding a characteristic delayed-coincidence count with the preceding β^+ gammas. The experiment consisted in showing that:

1. Reactor-associated delayed coincidences of the kind described above were observable at a rate consistent with that calculated from the $\bar{\nu}$ flux and the detector efficiency, on the basis of the two-component neutrino theory.
2. The first prompt-coincidence pulse of the delayed-coincidence pair was due to positron-annihilation radiation.
3. The second prompt-coincidence pulse of the delayed-coincidence pair was due to cadmium capture of a neutron.
4. The signal was a function of the number of target protons.
5. The reactor-associated signal was not caused by gamma rays or neutrons from the reactor.

Throughout the experiment an effort was made to provide redundant checks of these several points. Since it may not be easy to repeat the experiment because of the elaborate equipment required, the results are given

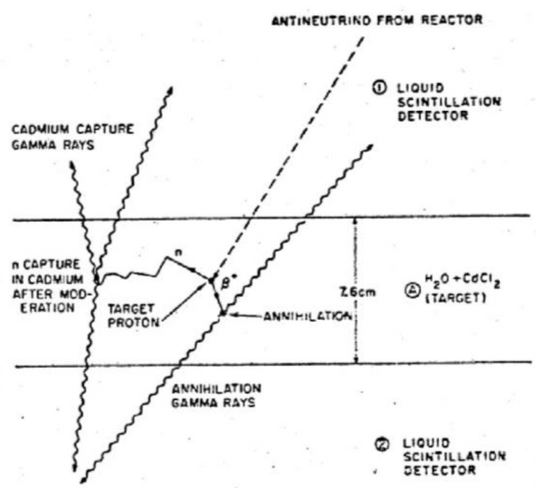


FIG. 1. Schematic diagram of antineutrino experiment.

* Work performed under the auspices of the U. S. Atomic Energy Commission. A preliminary account of the present work appeared in Science **124**, 103 (1956). The antineutrino is generally understood to be associated with negative beta decay.

† Now at the Department of Physics, Case Institute of Technology, Cleveland, Ohio.

‡ Now at the Department of Physics, Catholic University of America, Washington, D. C.

[1] W. Pauli, Jr., address to Group on Radioactivity of Tübingen, December 4, 1930 (unpublished); E. Fermi, Z. Physik **88**, 161 (1934). A discussion of the historical development of the neutrino concept and some pictures of the apparatus used in the present experiment may be found in an article by F. Reines and C. L. Cowan, Jr., Phys. Today **10**, 12 (1957).

[2] A first attempt to study this reaction was made at the Hanford Engineering Works in 1953; F. Reines and C. L. Cowan, Jr., Phys. Rev. **92**, 830 (1953).

References:

Robley Evans, The Atomic Nucleus, McGraw-Hill (1955), Chapters 16, 17.

Wolfgang Pauli – See ref. #1 in Reines et al. (1960). (reference below)

F. Reines and C.L. Cowan, Physical Review **113** (1959) 273.

F. Reines, C.L. Cowan, F.B. Harrison, A.D. McGuire, and HG.W. Kruse, Physical Review **117** (1960) 159.

(R) Solar Neutrinos

The direct detection of neutrinos from the core of the sun (solar neutrinos) would do away with the need for the "default" argument in determining the energy source for the sun.

How many solar neutrinos are expected per cm^2 at the earth's orbit?

$$4\,(^1H) \Rightarrow {}^4He + 2\,\beta^+ + 2\,\nu_e + 26.7\text{ MeV}$$

Solar Luminosity =

$$3.9\times10^{26}\text{ Joules/sec} = 2.4\times10^{45}\text{ eV/sec} = 2.4\times10^{39}\text{ MeV/sec}$$
$$\Rightarrow 1.8\times10^{38}\ \nu_e/\text{sec}$$

At the earth's orbit, i.e., @ 1.5×10^{13} cm Area $\Rightarrow$ $2.8\times10^{27}cm^2$

$$\boxed{\Rightarrow \quad 6.4\times10^{10}\ \nu_e/cm^2/sec}$$

Example of Solar Neutrino Detection**:**

(^{37}Ar decay) $\longrightarrow$ $^{37}Ar + e^- \Rightarrow {}^{37}Cl + \nu_e + 0.8\text{ MeV}$

$\therefore$ The inverse reaction,

$$^{37}Cl + \nu_e + 0.8\text{ MeV} \Rightarrow {}^{37}Ar + e^-$$

can serve as a neutrino detection process for neutrinos as long as $E_\nu > 800$ keV. (But note that the flux is ≈1000 times smaller than what was used by Reines and Cowan at Savannah River, so one would need a much larger detector.)

Such a detector was built by Ray Davis - 390,000 liters of C_2Cl_4 in which the radioactive ^{37}Ar (as a noble gas atom) could be extracted from the liquid C_2Cl_4 and its decay counted as the signature for this neutrino interaction and a direct measure of the solar neutrino flux. To reduce the background from cosmic-ray produced ^{37}Ar, the detector was built 4850 feet below the surface, in the Homestake gold mine in South Dakota. [See: Ray Davis et al. (1968).]
Other examples of neutrino detectors (all underground) include the Sudbury Neutrino Observatory (SNO) in Canada and Superkamiokande (SuperK) in Japan.

Sudbury Neutrino Observatory:
1000 metric tonnes of D_2O, 6800 feet deep in the Creighton nickel mine in Ontario, Canada, detecting neutrinos via the reactions

$$\nu_e + {}^2D \rightarrow p + p + e^-$$

$$\nu_z + {}^2D \rightarrow \nu_z + p + n$$

$$\nu_z + e^- \rightarrow \nu_z + e^-$$

[The latter two reactions are sensitive to neutrinos of all 3 lepton families (ν_e , ν_μ , ν_τ) and thereby measure the neutrino flux independent of neutrino oscillations between the various families.]

SuperKamiokande:
50,000 m^3 of H_2O, 1000 meters deep in the Kamiokande tin mine in Japan,

- Detecting neutrinos via elastic scattering of neutrinos by electrons, by detecting the Cherenkov radiation from each recoiling electron.

So we now have **direct** evidence (neutrinos coming from the sun) and that the source of solar energy (solar luminosity) is Nuclear Fusion.

Fig. R-1

The site of the Homestake gold mine in Lead, SD. The open pit of the initial mining operation, about 500 feet deep, before the tunneling began which eventually reached down to about 6000 feet.

Fig. R-2

Ray Davis (top) providing a comparison scale for his detector (~100' long x 50' in diameter).

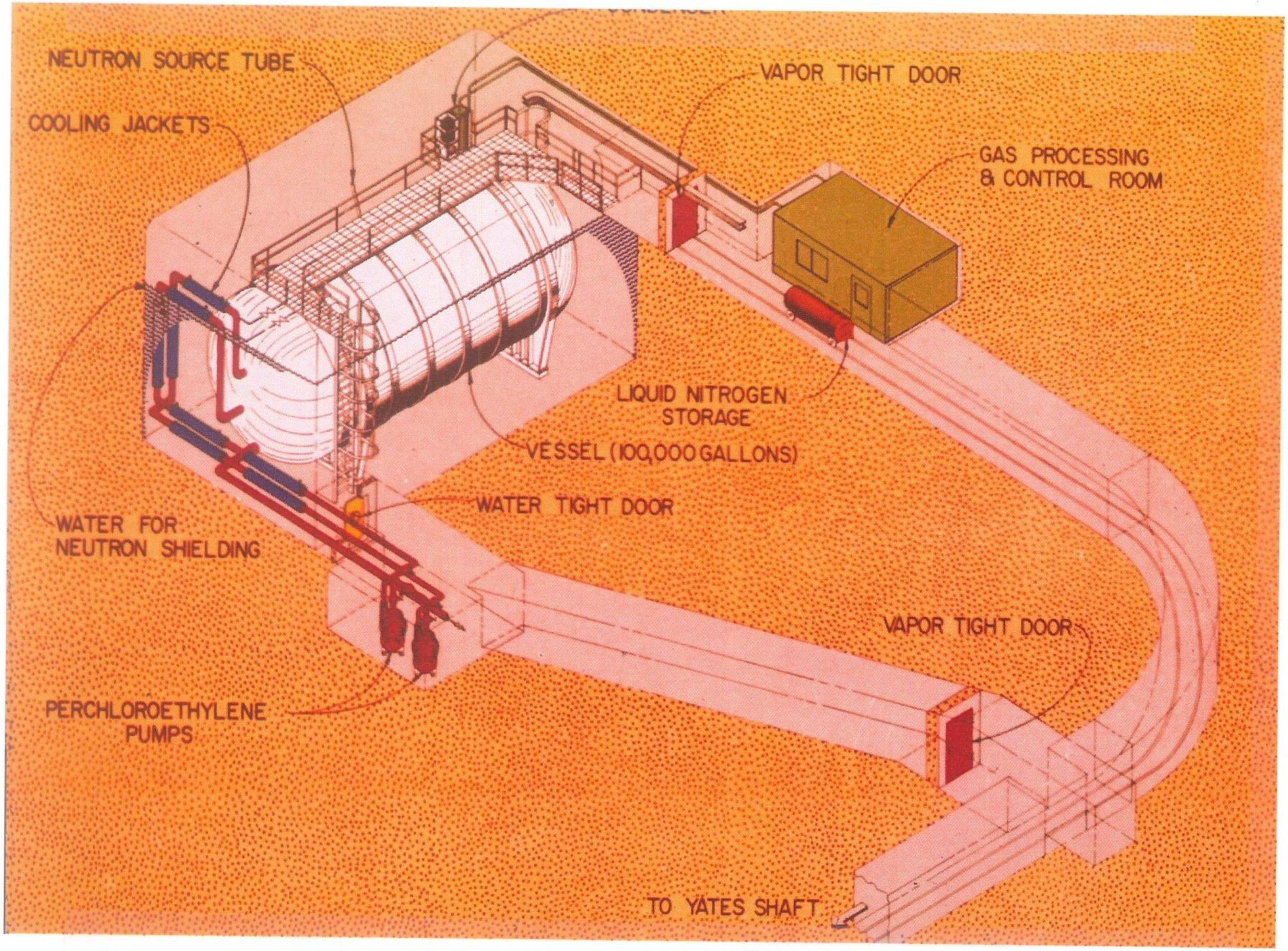
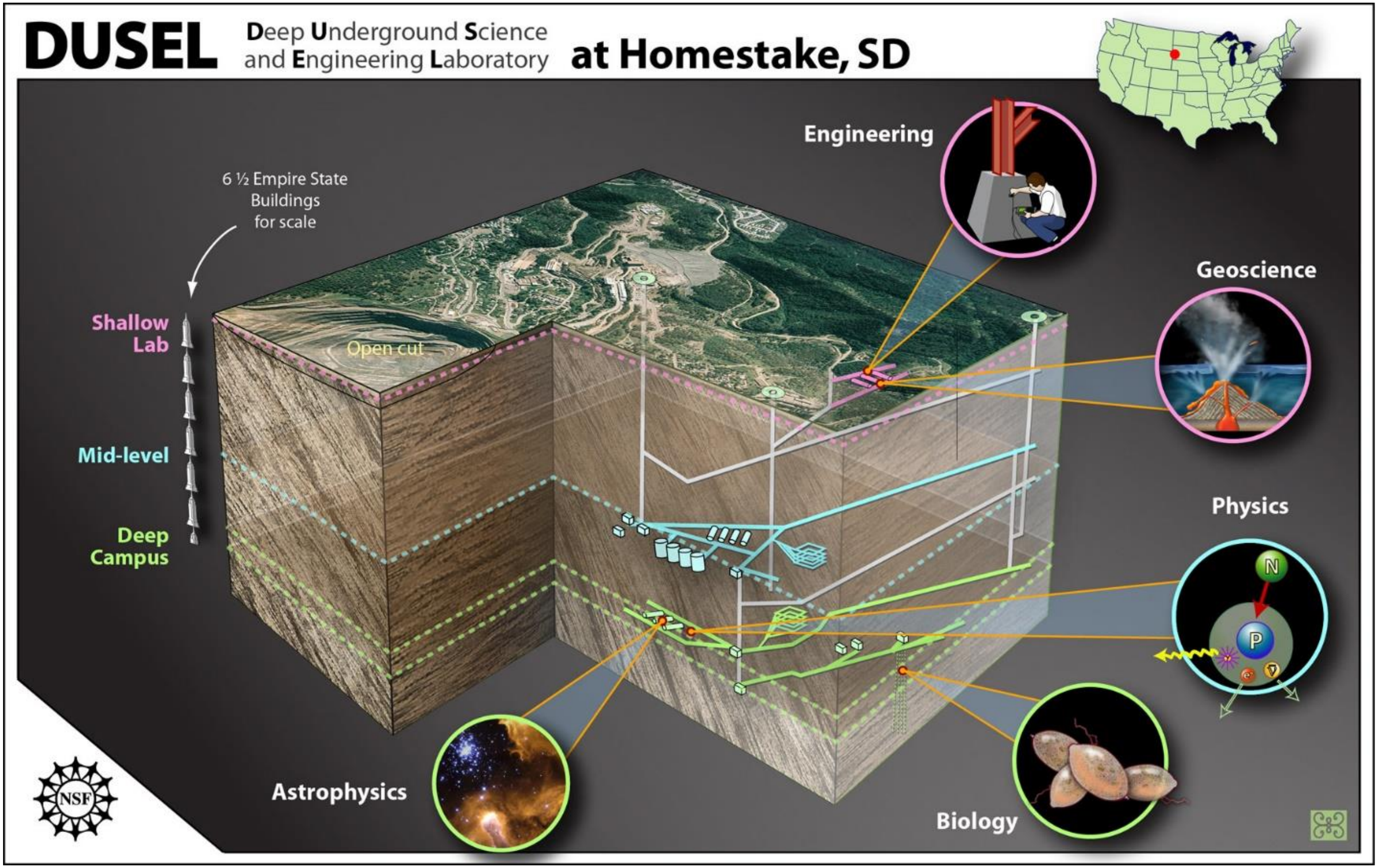


Fig. R-3

One of Ray Davis's favorite pictures, an artist's "view" of what his detector looked like, located in a *GOLD* mine.

Fig. R-4


DUSEL
Deep Underground Science
and Engineering Laboratory
at Homestake, SD
6 ½ Empire State
Buildings
for scale
Shallow
Lab
Mid-level
Deep
Campus
Open cut
Engineering
Geoscience
Physics
Astrophysics
Biology
N
P
NSF

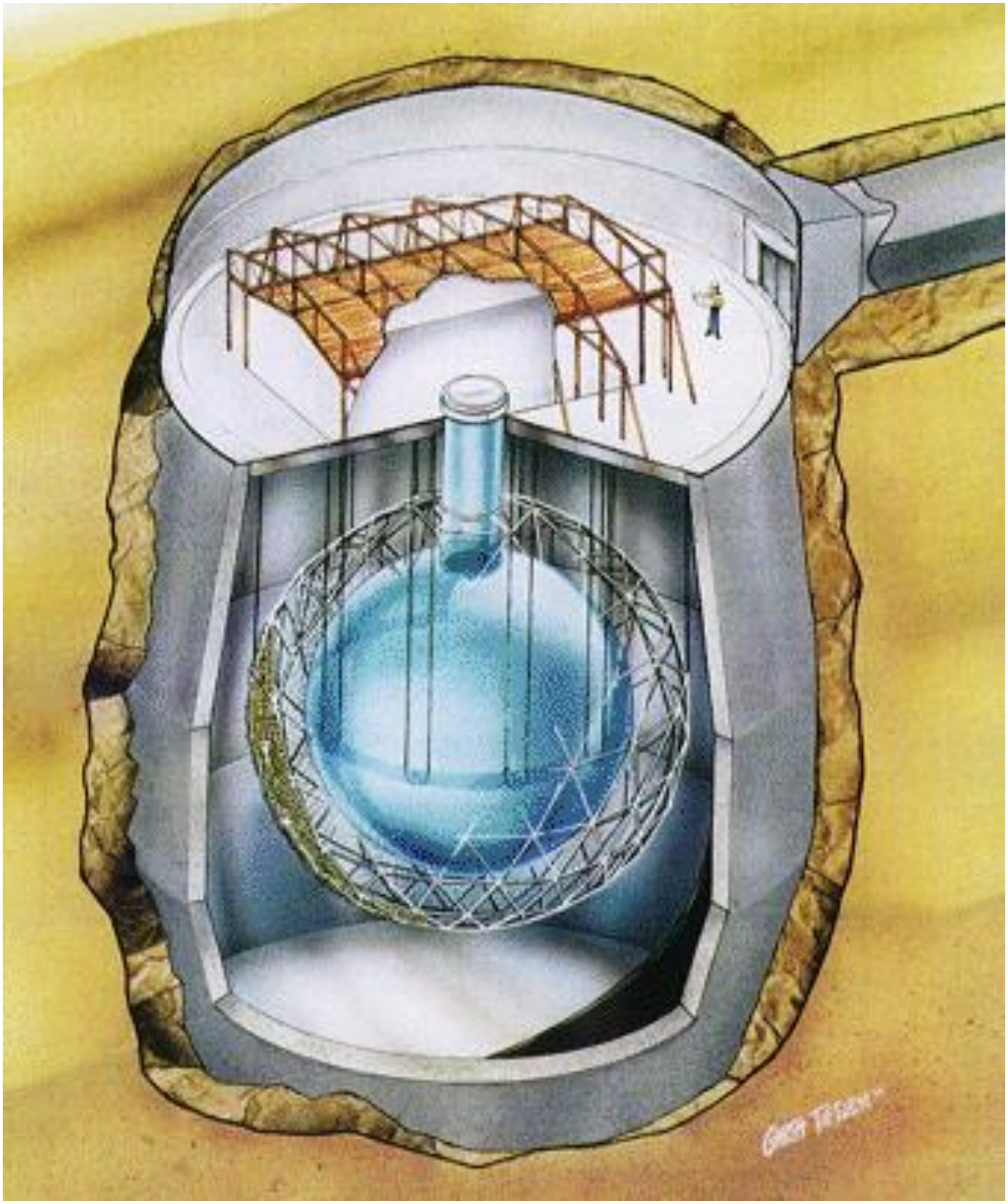


Fig. R-5

Sudbury Neutrino Detector
http://www.sno.phy.queensu.ca

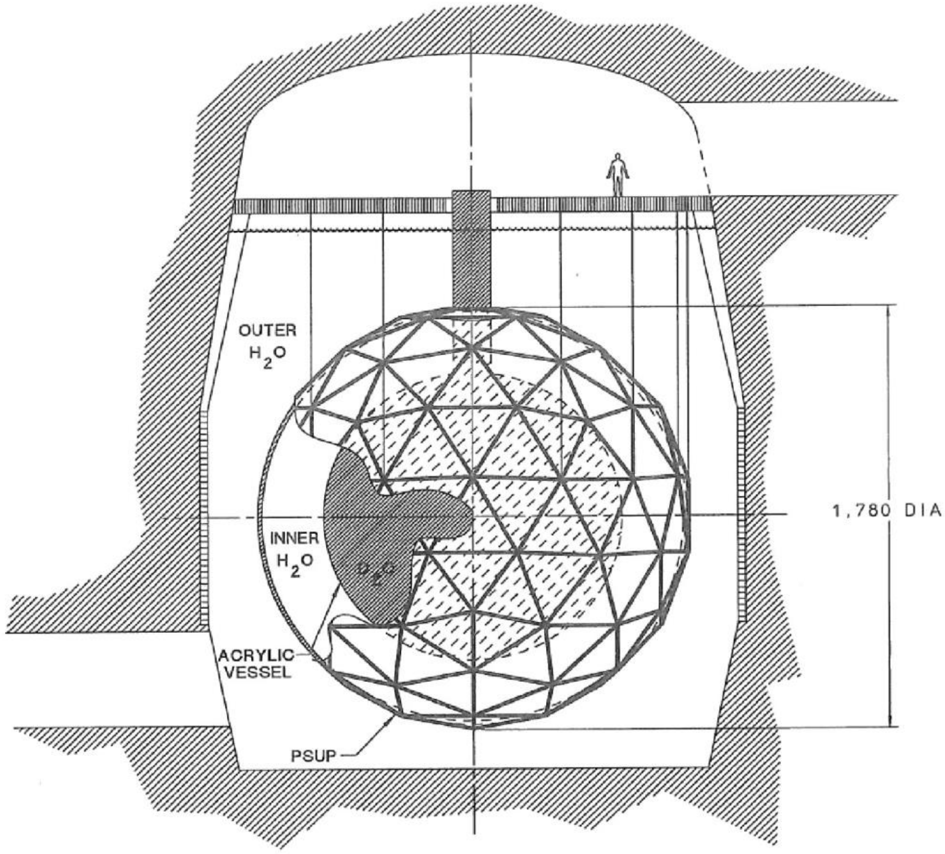
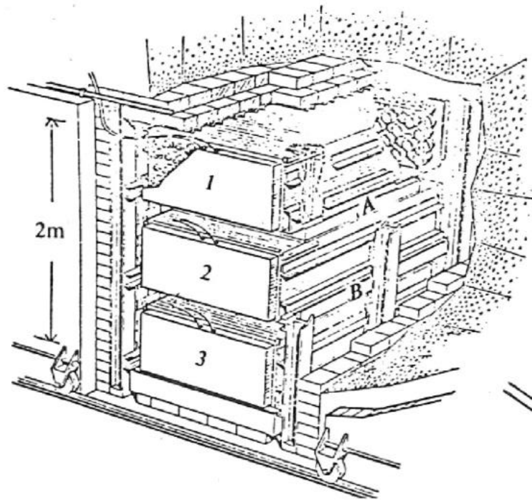


Fig. R-6 Schematic view of the SNO detector. The PMT support structure (PSUP) shown inside the SNO cavity, surrounding the acrylic vessel, with light- and heavy-water volumes located as indicated.

Schematic View of the SNO Detector

Karsten M. Heeger – PhD Thesis (Univ. Wash.)

Reines & Cowan - 1959

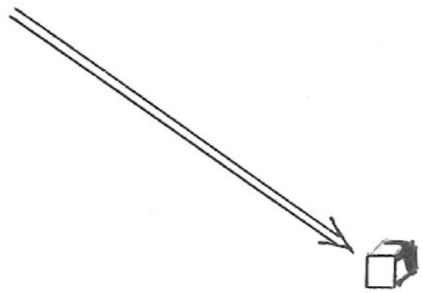


Depth: A few meters of earth and water

Dimensions: $\approx 2m\times2m\times2m$

PMTs: 110

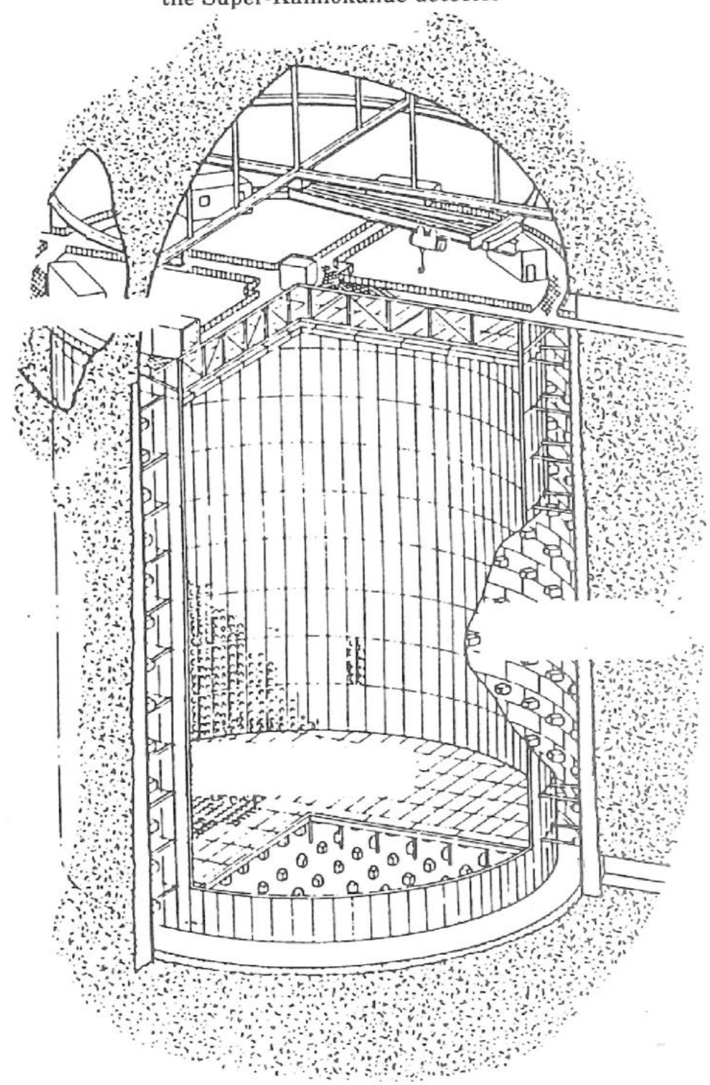
Fig. R-7



Super-K

Fig. R-8

the Super-Kamiokande detector



Depth: 1000 meters

Dimensions: 38-m diam. $\times$ 40-m high

PMTs: 11,000

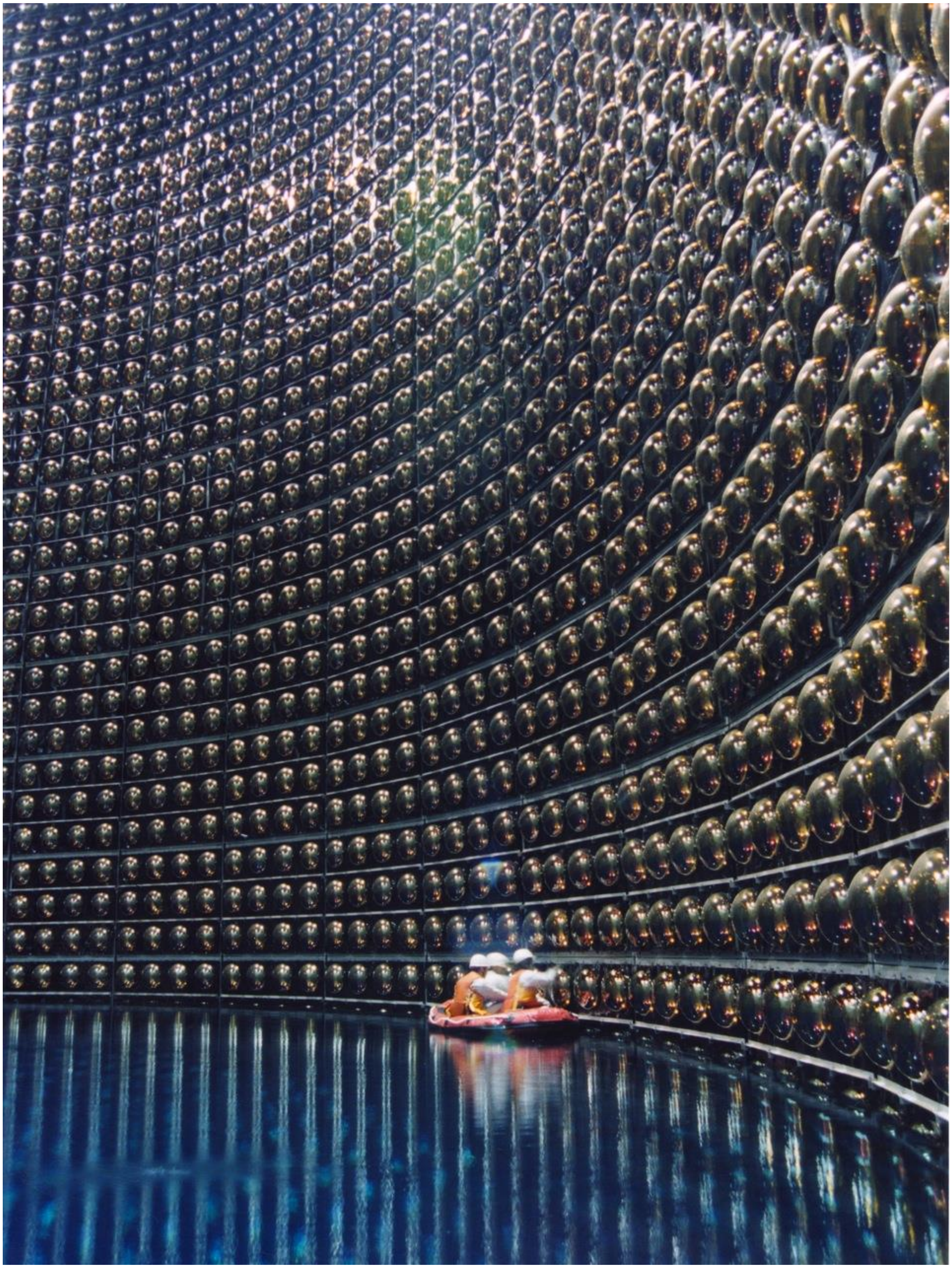


Fig. R-9

Technicians on a rubber raft inside the SuperK detector, cleaning the surfaces of the 11,000 PMTs (24" diameter) as the tank is filled with water.

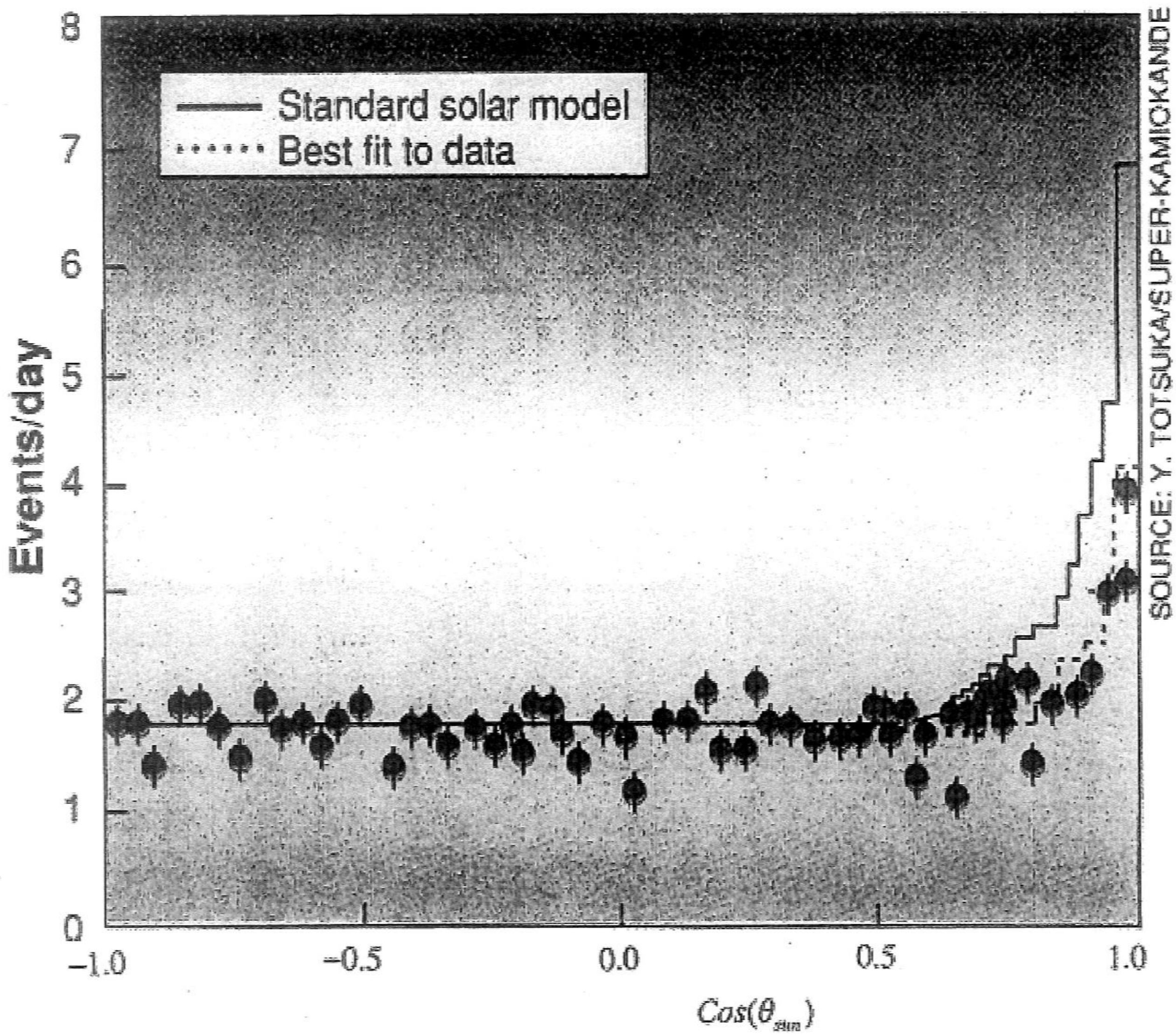


Fig. R-10

Plot of the angle of incidence of the neutrinos detected at SuperK, showing the peak at 0º (the direction of the sun), and the uniform background due to all others sources distributed randomly on the sky.

References:

R. Davis, D. Harmer and K. Hoffman, Phys.Rev.Letts. **20** (1968) 1205.

Karsten M. Heeger, Ph.D. Thesis, University of Washington (2002).

K.S. Hirata, et al., Phys. Rev. Letts. **65** (1990) 1297.

A New Eye on the Universe, SNO Official Opening (1998).
http://www.sno.phy.queensu.ca

(S) Stars and Stellar Evolution

Now that we know the source of solar/stellar energy generation, we can try to make sense of observations of the properties of stars.

Observations: Surface Temperature $\Rightarrow$ (color)

Brightness, Luminosity

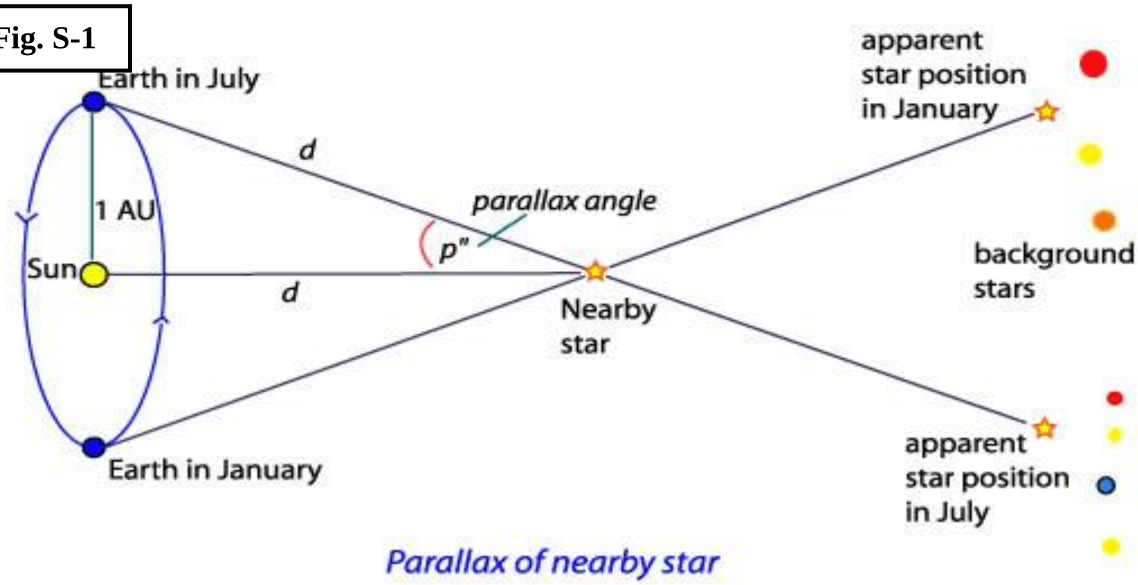
$\Rightarrow$ depends on - <u>distance</u>, <u>size</u>, <u>temperature</u>

Need to factor out the distance dependence, and <u>then</u> ask if there is any correlation.

$\therefore$ Need to measure the distance to some of these stars !

Measure this distance relative to the size of the earth's orbit around the sun, by measuring (i.e., Fig. S-1) the change in angle towards a nearby star <u>relative</u> to further-away stars (background stars which do not appear to move). This is defined as the star's "parallax".

Fig. S-1



Parallax : Geometry Due to Earth's Orbit (and proof of orbit)

1838 - First Observation

(by the 1980s, several hundred stars)

1990s - Hipparcos satellite (ESA)

(More that 100,000 stars)

We can make a scatter plot of these stars on the basis of :

"**Absolute** Magnitude" *vs.* Color (temperature)

⇕

"Luminosity @ 10 parsecs"

("parsec" is defined as the distance for a parallax of 1 arcsec.)

Fig. S-7 (Abell, 1969,) shows what such a scatter-plot would look like if the stars were all at the same distance from earth.

NOTE: This scatter plot is **not** random **!** This correlation must mean something about the nature of stars**!**

As stars convert (burn) their initial hydrogen into helium (see Section P), we might expect that their luminosity would gradually change. To investigate this, one can make computer models of the internal structure of a star using all the physics we know about gravity and thermodynamics and nuclear physics. Such a model (e.g., Fig. S-2) can then be tracked as the hydrogen is converted to helium to determine the evolution of the distributions of H and He in the internal regions of the star and the resulting changes in the star's radius and luminosity. As an example of what can be seen in such an evolving model, Fig. S-3 shows a comparison of the hydrogen and helium relative abundances in a model of our initial sun vs. a model of the current sun, indicating in yellow the degree to which the hydrogen has been consumed in the central core of the sun.

To see how stars evolve, it wold be useful to find and study a "group" of stars of the same age - i.e., all formed at roughly the same time. Conveniently, nature provides such groups in the form of globular clusters (gravitationally bound star clusters which can be observed orbiting galaxies - e.g., the fuzzy spots visible in the attached images of NGC 4594 and M87, Figures S-4 and S-5, respectively. A plot of the location of the globular clusters observed around our own Milky Way galaxy is shown in an attached plot (Fig. S-6), together with a table of some of the properties of a dozen of the globular clusters orbiting our galaxy.

Compared to the plot Fig. S-7 (Abell, Fig. 23.3), which shows stars at a variety of ages, the plot of the stars in any specific globular cluster (e.g., **M3**, Figs. S-8 and S-9) show stars all at the same age, but with a variety of masses. In the plot for M3, we see the stars above ~ 6000º K (M3's "turn-off point" along the Main Sequence) have evolved away from the Main Sequence into the "Giant" region of this plot. For different globular clusters, the turn-off point occurs at different temperatures related to the age of the globular cluster.

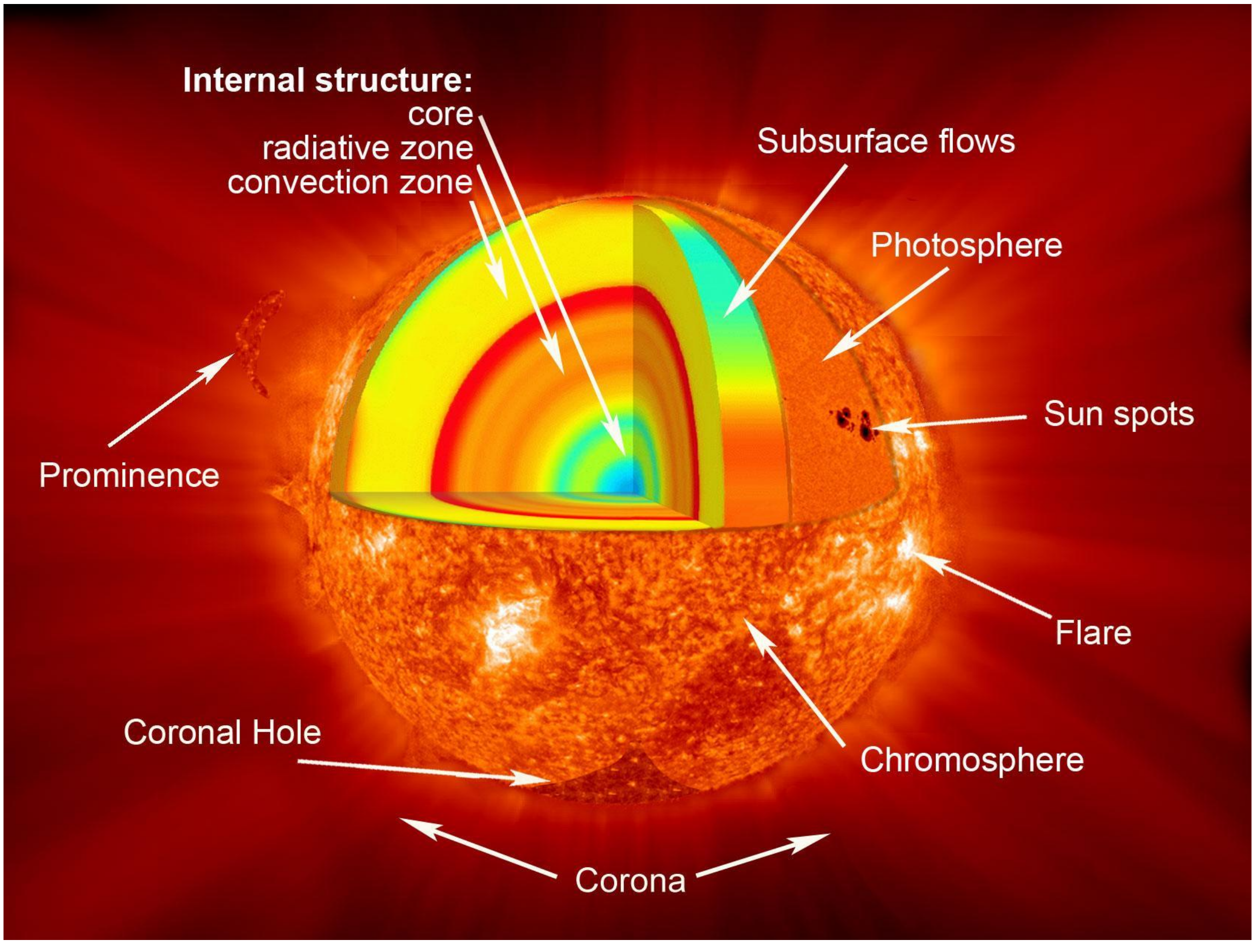


Fig. S-2

Cutaway View of a Stellar Interior

https://www.nasa.gov/mission_pages/sunearth/science/plasma-flow.html

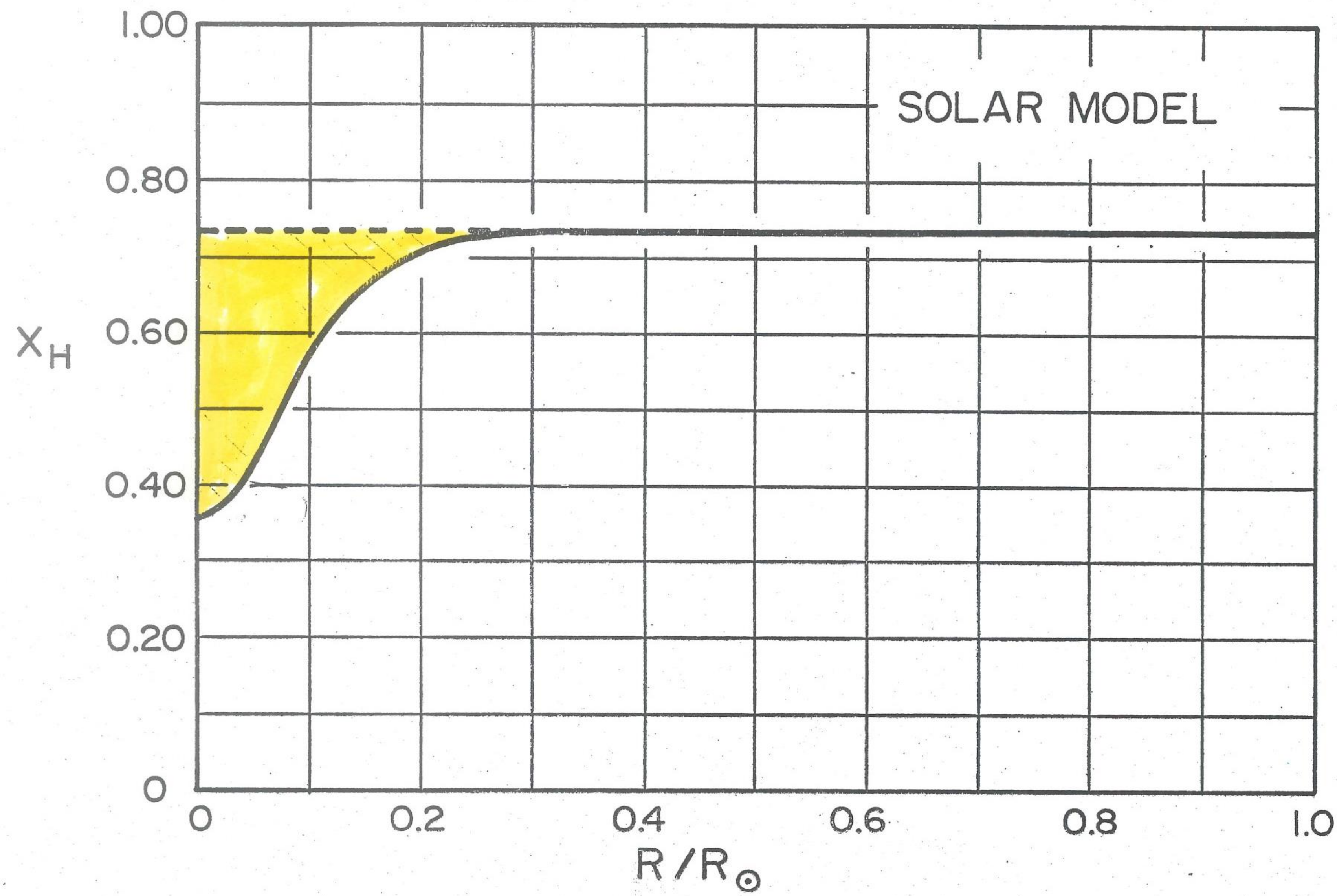
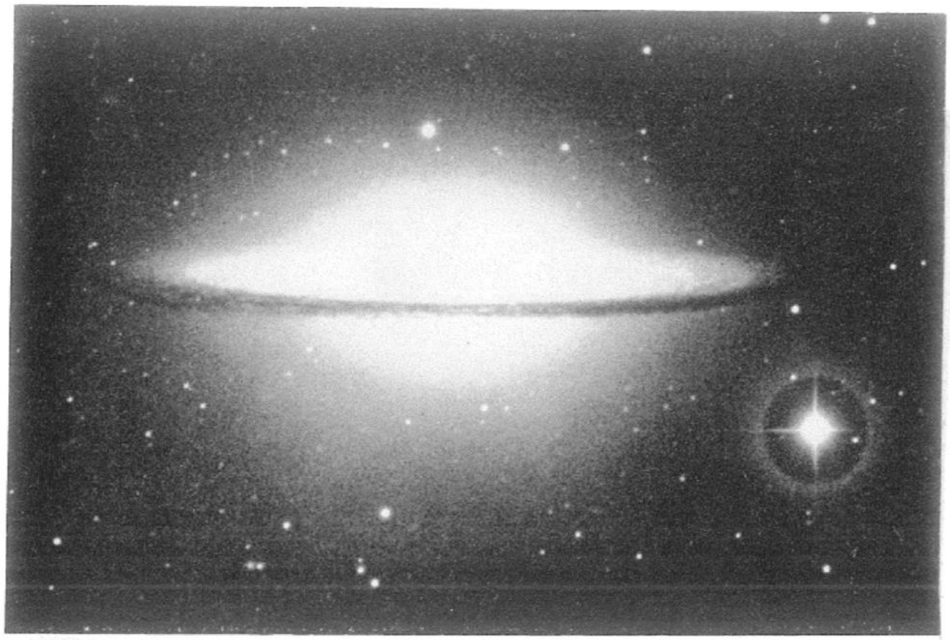


Fig. S-3 Proportion of Hydrogen fused into Helium (yellow) in the Solar Interior

Fig. S-4



Mt. Wilson and Palomar Observatories

XXVI—THE GALAXY NGC 4594, THE 'SOMBRERO HAT'

This galaxy possesses hundreds of associated globular clusters. They can be distinguished by a softness of outline from the hard circular star images. The latter are of course just local stars of the Milky Way. The globular clusters each contain perhaps 100,000 separate stars, while NGC 4594 itself probably contains upwards of 100,000,000,000 stars. Its distance must be approaching 10 million parsecs. The dark band of the 'Sombrero' is due to the obscuring effect of huge dust clouds.

XXVII—THE GLOBULAR GALAXY M 87, A MONSTER MEMBER OF THE VIRGO CLOUD

This galaxy has three outstanding peculiarities: it possesses about a thousand associated globular clusters; it contains near its centre a blue jet of gas (not visible in this picture); and it is an intensely powerful transmitter of radio-waves.

Mt. Wilson and Palomar Observatories

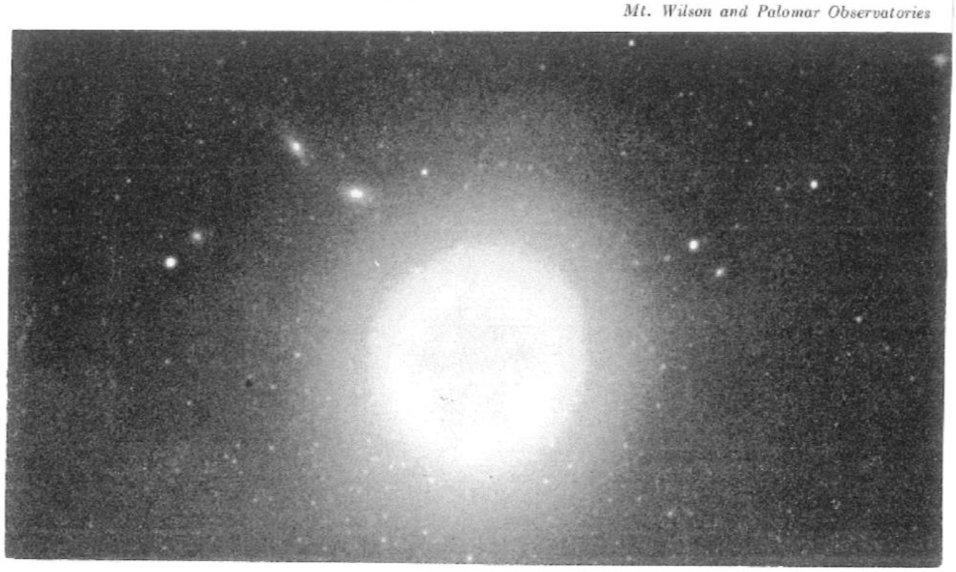


Fig. S-5

Fig. S-6 **Globular Clusters Associated with the Milky Way Galaxy**

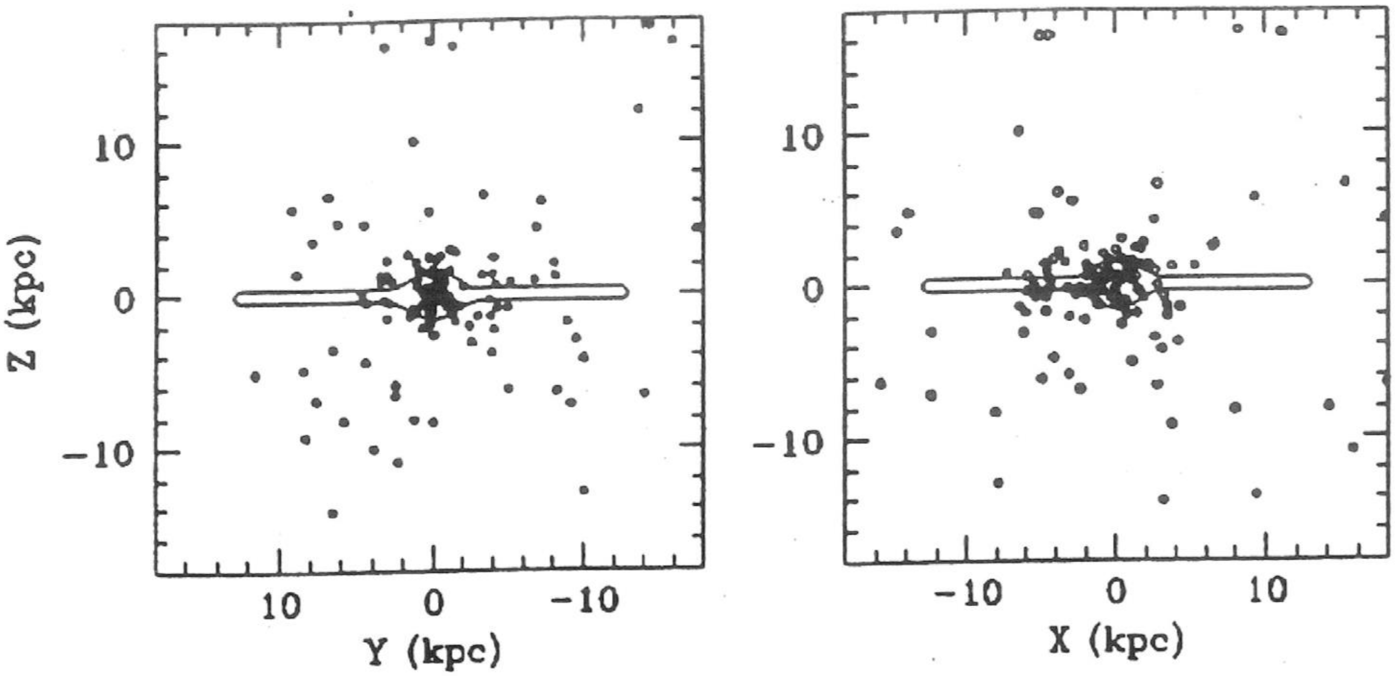


TABLE 27.8
SELECTED GLOBULAR CLUSTERS

Cluster	NGC	Galactic coordinates l^{II}	Galactic coordinates b^{II}	Representative diameter angular	Representative diameter linear	Distance	Visual magnitude	Visual absorption	Observed no. of variables	Radial velocity in km/sec	Mass
					psc	kpsc					$10^4 \mathscr{M}_\odot$
47 Tuc	104	306	−45	7.6	10	4.6	4.01	0.2	11		
	2419	180	+25	1.9	32	58	10.7	0.3	36	+ 14	
ω Cen	5139	309	+15	14.2	20	4.8	3.57	1.1	164		
M 3	5272	42	+79	3.4	13	13	6.38	0.2	187	−150	21
M 5	5904	4	+47	4.5	12	9.2	5.93	0.0	97	+ 45	6
M 4	6121	351	+16	9.8	9	3.0	5.91	1.3	43		6
M 13	6205	59	+41	4.8	11	8.2	5.87	0.2	10	−228	30
M 19	6273	357	+10	3.5	7	7.3	6.88	1.3	4	+102	
M 22	6656	10	− 8	10	9	3.1	5.09	1.3	24	−148	700
Δ 295	6752	336	−26	15	24	5.6	6.2	0.6	1	− 3	
	7006	64	−19	1.2	17	48	10.68	0.3	40	−348	
M 15	7078	65	−27	2.8	11	13	6.36	0.2	93	−114	600

Fig. S-7

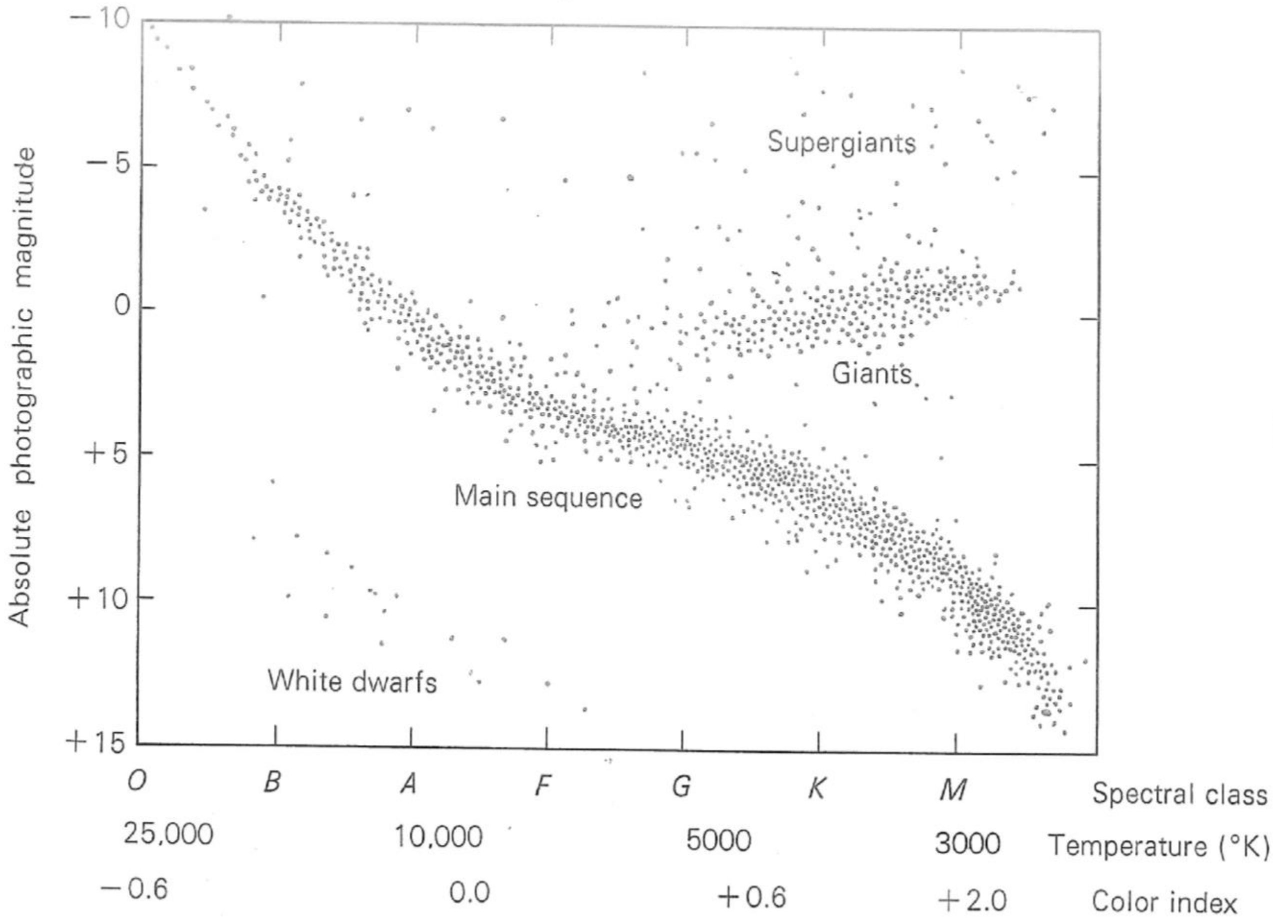


FIG. 23-3 Hertzsprung-Russell diagram for stars of known distance.

"Absolute Magnitude" is defined as the magnitude @ 10 parsecs (32.5 light years)

Note: a magnitude change of -5 corresponds to a luminosity change of 100×

Note that stars of the same color (i.e., the same surface temperature) can vary by many factors of 10 in their luminosity – which then must correspond to many factors of $10^{1/2}$ in their radius.
Hence, the designations dwarfs and giants and even supergiants.

Some examples:

	M_{ABS}		M_{VIS}	mass ($m_\odot$)	radius($R_\odot$)	T_{surf} (°K)
Rigel	-7.0	B9	+0.14	18. ×	78. ×	11,000
Betelgeuse	-5.5	M2	+0.41	8. ×	1,200. ×	3,500
Sirius	+1.4	A1	-1.4	2.0 ×	1.7 ×	9,900
Sun	+4.7	G2		1.0 ×	1.0 ×	5,800

Fig. S-8

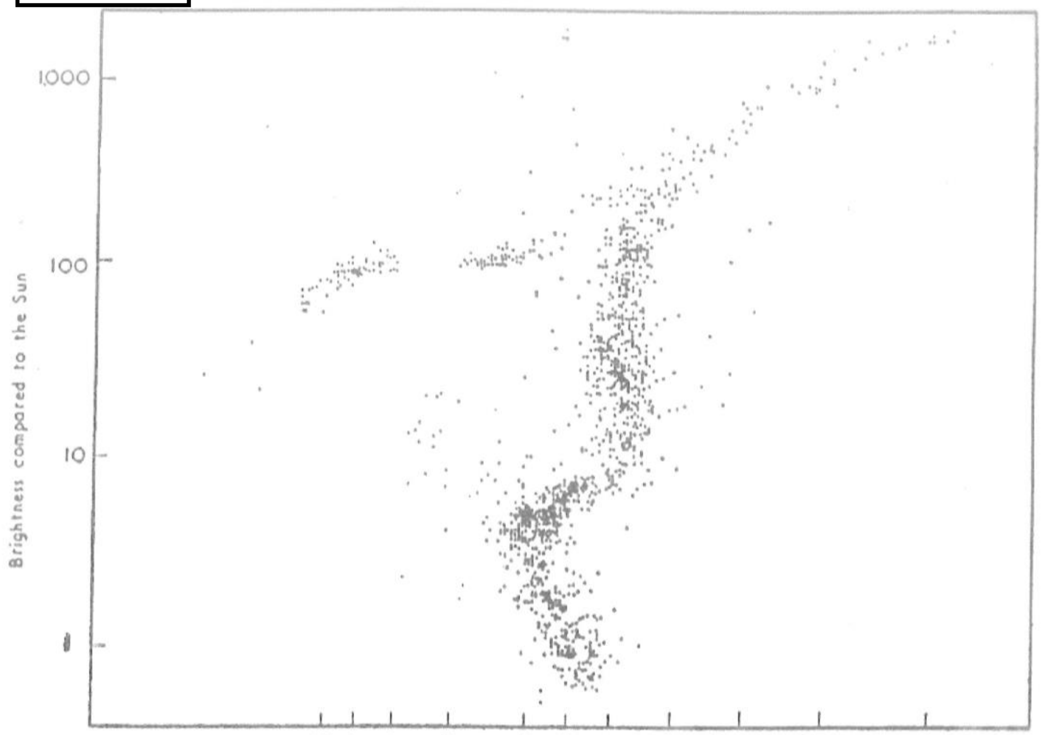


FIG. 17. The stars of the globular cluster M 3 ((Hoyle, 1955)

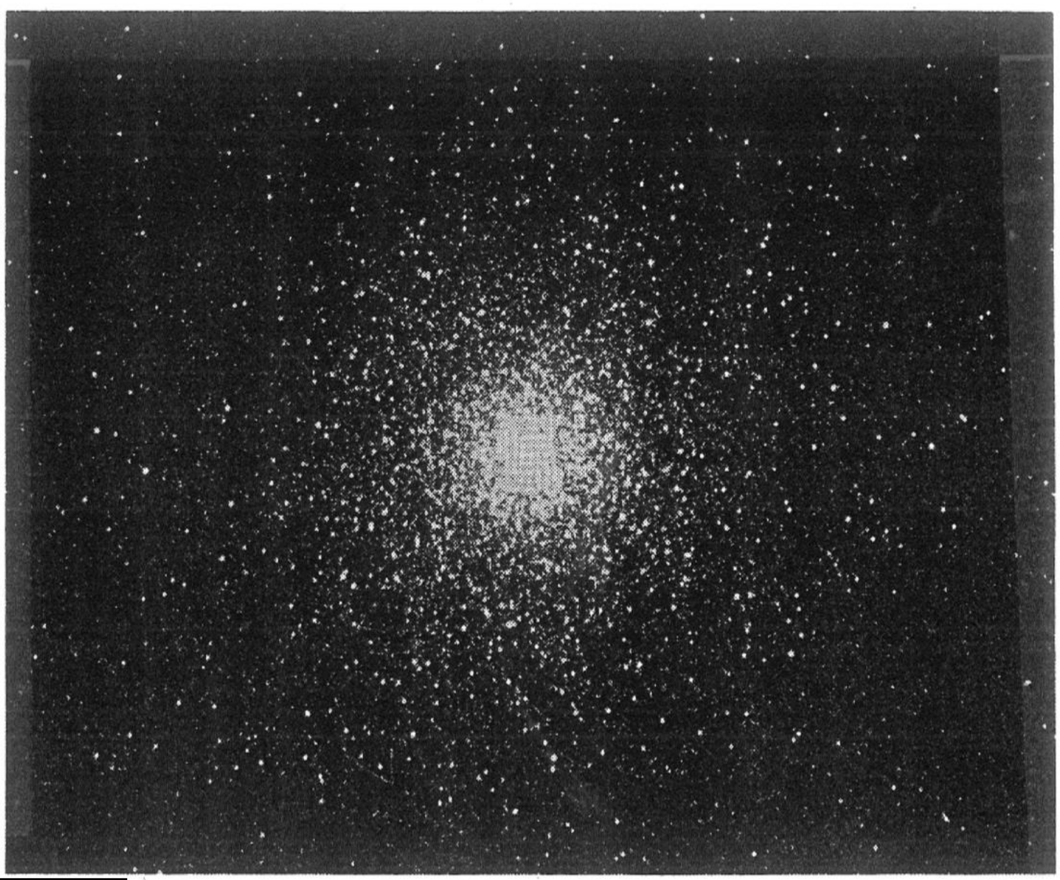


Fig. S-9

The globular cluster, M3.

Our “Milky Way” galaxy was initially (conveniently?) thought to have an **Sb** structure – a “twin” of M31, the Andromeda Galaxy in Fig. S-10) below – but is now thought to, in fact, be a barred spiral **SBb** as shown in the image Fig. S-11, though still of comparable size to M31. We do not yet know how to get outside our galaxy, so that for the foreseeable future we will not be able to look back and get a real image of the Milky Way. ☺

Fig. S-10

Andromeda Galaxy M31

Andromeda is the nearest major galaxy to our own Milky Way Galaxy. Our Galaxy was thought to look much like Andromeda. Together these two galaxies dominate the Local Group of galaxies. The diffuse light from Andromeda is caused by the hundreds of billions of stars that compose it. The several distinct stars that surround Andromeda's image are actually stars in our Galaxy that are well in front of the background object. Andromeda is frequently referred to as M31 since it is the 31st object on Messier's list of diffuse sky objects. M31 is so distant it takes about two million years for light to reach us from there. Although visible without aid, the above image of M31 was taken with a standard camera through a small telescope. Much about M31 remains unknown, including how it acquired its unusual double-peaked center.

https://apod.nasa.gov/apod/ap140730.html

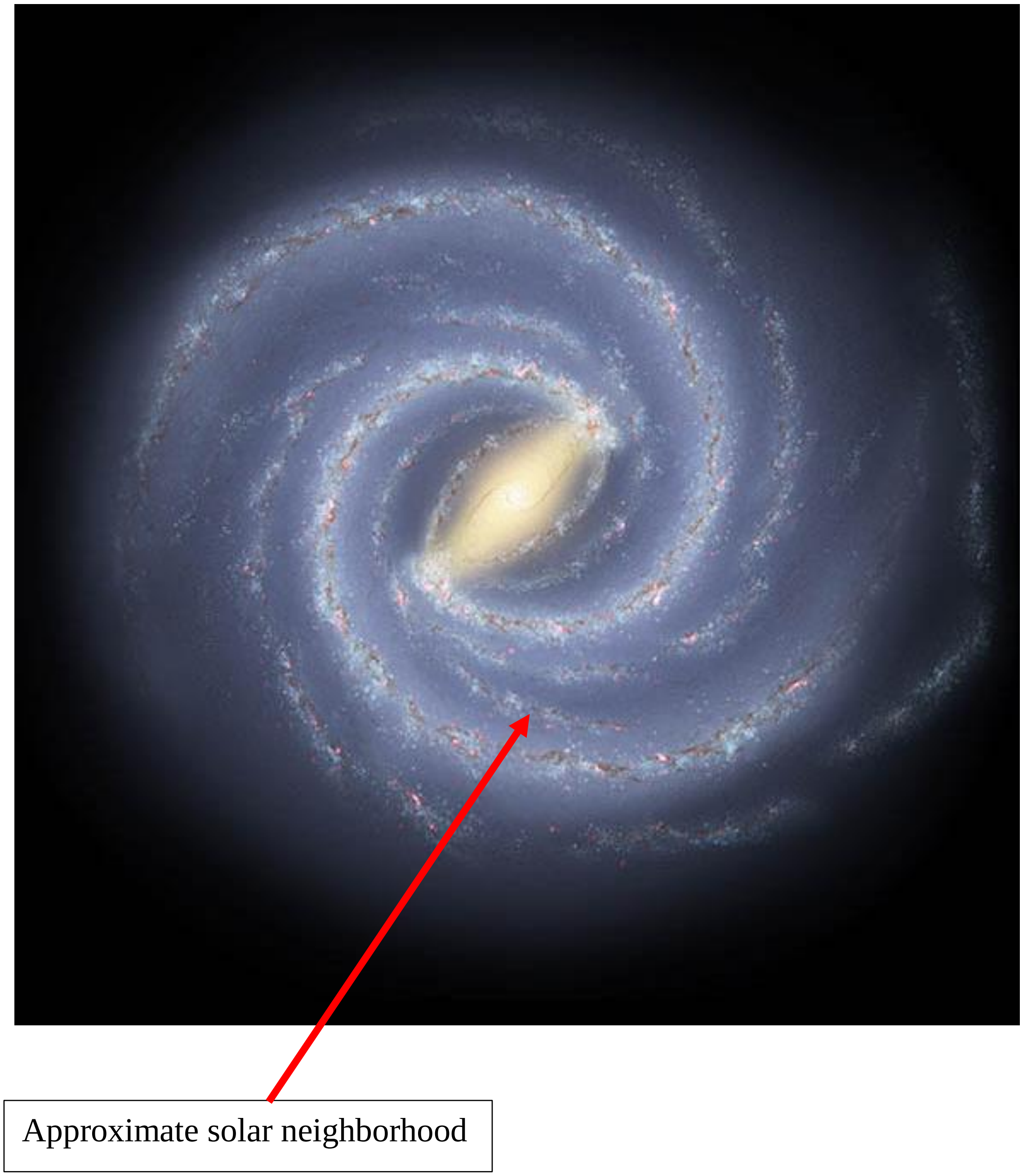
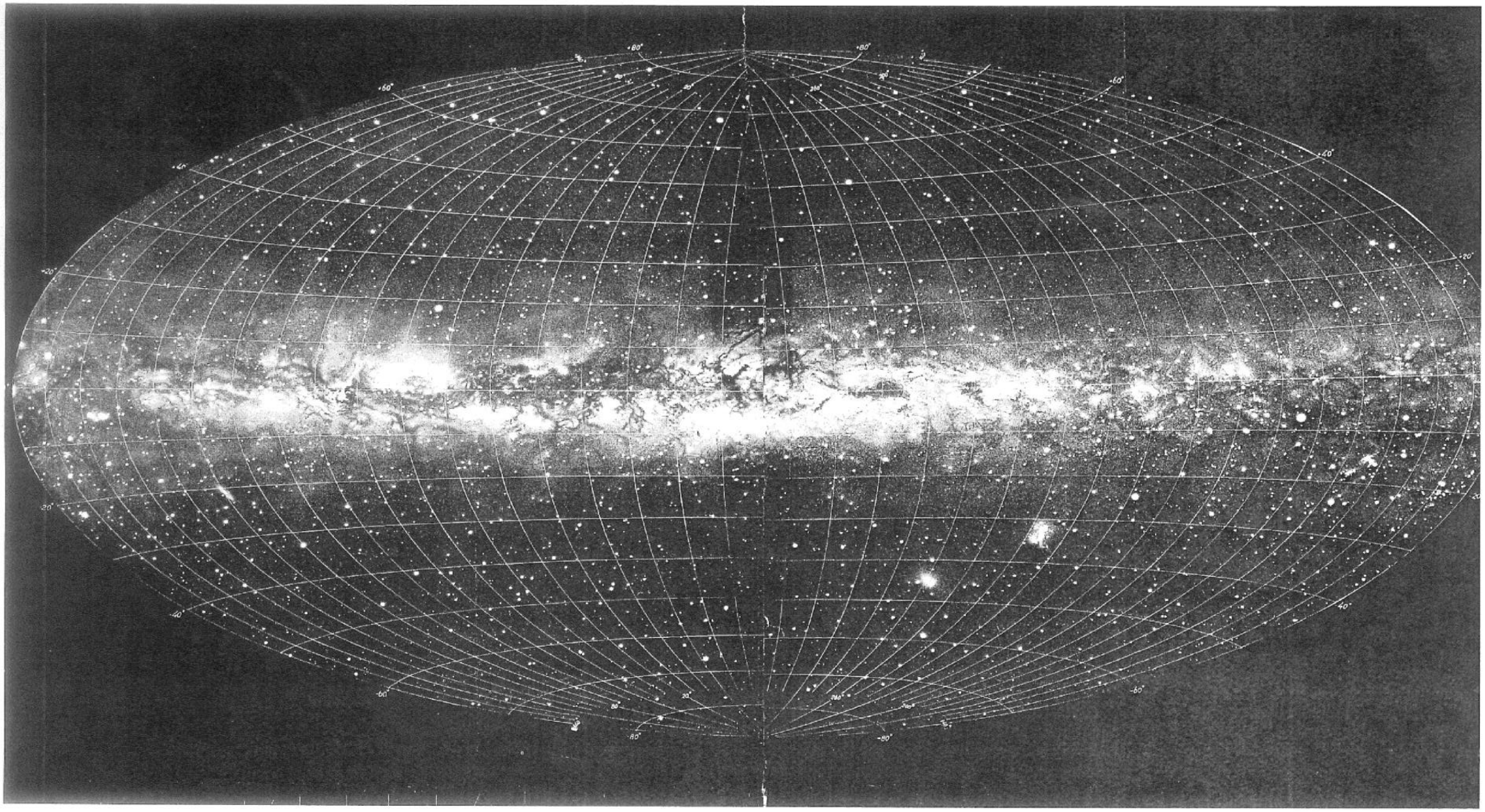


Fig. S-11

Milky Way Image
ref.: NASA/JPL-Caltech/EOF/R. Hurt (SSC-Caltech)
Artist's concept, based on data from the ESO VISTA Telescope
at the Paranal Observatory. Looking from the inside out,
the Milky Way as seen on the next page, Fig. S-12; this is all we can do.
(#SSC2008-10a and #ESO-1339g)

Fig. S-12

A wrap-around view of our galaxy (the Milky Way) as viewed from our location in the disc of our galaxy, about 28,000 ly from its center (at the center of this image).The Large Magellenic and Small Magellenic Clouds are located below the disc, in the lower right-hand quadrant of this optical image.



Having introduced pictures of galaxies at the beginning of this section, one should add a few words about the range in the structure (types) of galaxies observed in our universe. **Elliptical** galaxies are mostly featureless and are only classified on the basis of the apparent ellipticity of their image [from E0 (spherical, e.g., M87, Fig. S-13) to E7 or E8]. **Spiral** galaxies have a much more complex classification system, starting with whether or not they have a "bar" in their central region and then an abc system depending on how dominant their spirals are compared to their central region; "c" having very dominant spiral structure. In addition, Figs. S-14 and S-15 show a useful comparison of the variety of spiral galaxies.

Fig. S-13

XXVII—THE GLOBULAR GALAXY M 87, A MONSTER MEMBER OF THE VIRGO CLOUD

This galaxy has three outstanding peculiarities: it possesses about a thousand associated globular clusters; it contains near its centre a blue jet of gas (not visible in this picture); and it is an intensely powerful transmitter of radio-waves.

Mt. Wilson and Palomar Observatories

Fig. S-14

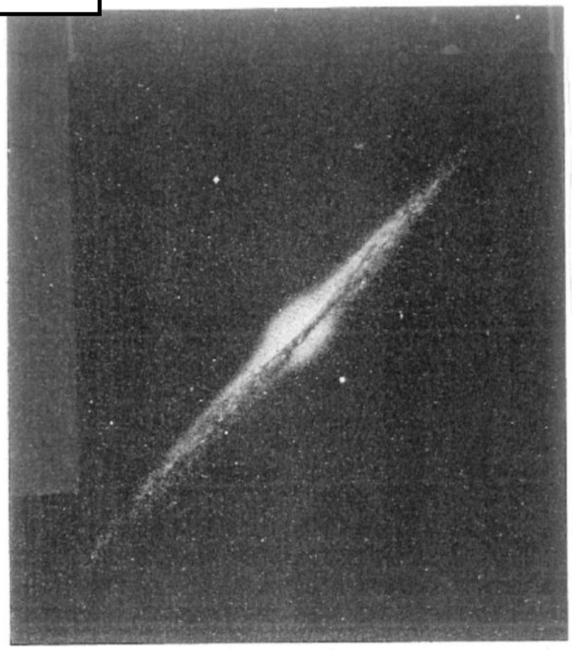


FIG. 32-9 NGC 4565, a spiral galaxy in Coma Berenices, seen edge on. Photographed in red light with the 200-inch telescope. *(Mount Wilson and Palomar Observatories.)*

FIG. 32-10 The Sc galaxy NGC 5194 (M51) and its irregular II companion, NGC 5195. 200-inch telescope. *(Mount Wilson and Palomar Observatories.)*

FIG. 32-12 NGC 3031 (M81), spiral galaxy in Ursa Major. Photographed with the 200-inch telescope. *(Mount Wilson and Palomar Observatories.)*

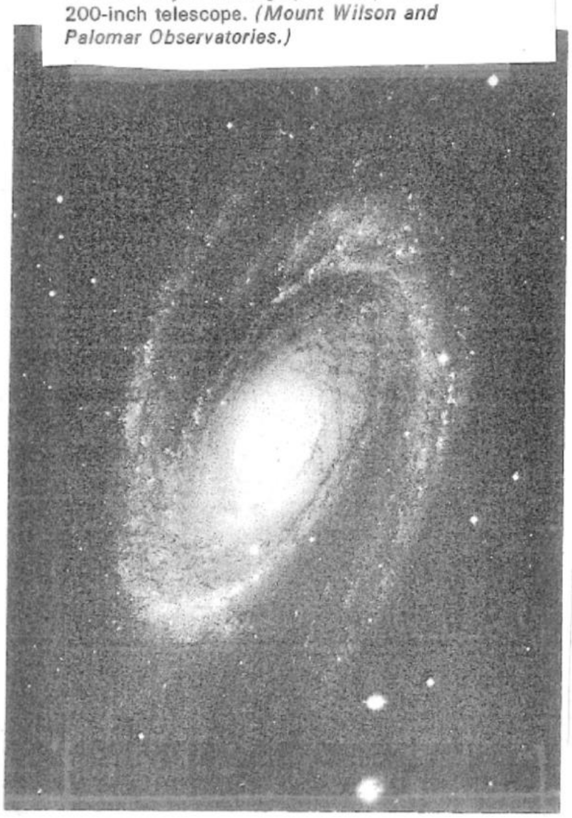


FIG. 32-13 NGC 1300, barred spiral galaxy in Eridanus, photographed with the 200-inch telescope. *(Mount Wilson and Palomar Observatories.)*

Fig. S-15

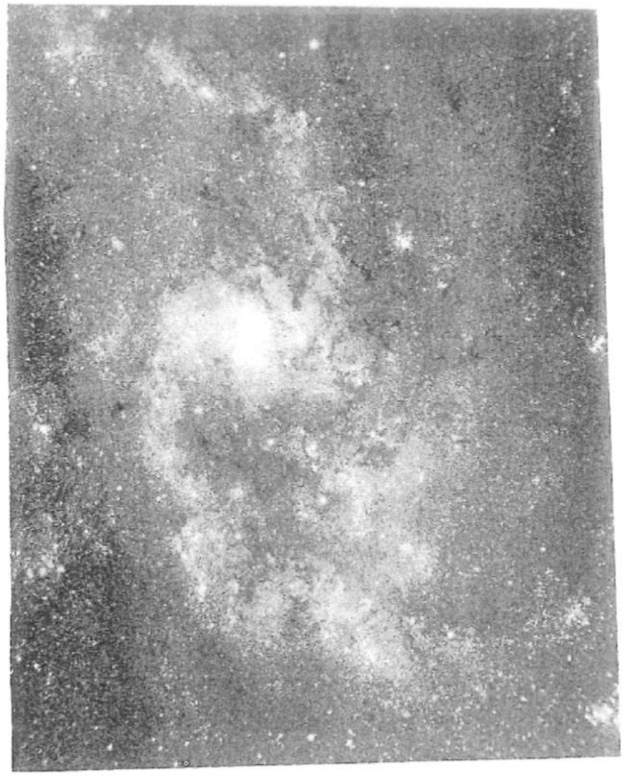


FIG. 30–9 (*a*) *Spiral galaxy in Triangulum (central region). Messier 33. This is a member of our Local Group and the nearest Sc galaxy. Its distance modulus is 24.5 according to Sandage. Stars down to $M_{ph} = -1.5$ can be detected. The spiral arms are completely resolved into bright stars, most of which are blue supergiants. In addition there are in the spiral arms, Cepheid variables, open clusters, novae, irregular variables, HII regions, and at least 3 000 red supergiants of $M_v = -5$ similar to those in the open cluster h and χ Persei. Globular clusters are also present. The integrated color index is 0.40. (200-inch photograph from Mount Wilson and Palomar Observatories)*

FIG. 30–9 (*b*) *NGC 598 Spiral nebula in Triangulum. Messier 33. Photographed in red light. (48-inch Schmidt photograph from Mount Wilson and Palomar Observatories. Caption material reprinted from* The Hubble Atlas of Galaxies, *by Alan Sandage (1961), by permission of the Carnegie Institution of Washington and the California Institute of Technology.)*

Fig. S-16

Large Magellanic Cloud

The Large Magellanic Cloud (LMC) is the nearest galaxy to the Milky Way but less than one tenth as massive; even so it contains the equivalent of over ten billion solar masses of material in the form of stars, gas and dust. The LMC is at a distance of 170,000 light years and is visible to the unaided eye from southern latitudes, with an appearance rather like a detached piece of the Milky Way, in the otherwise barren constellation of Dorado.

http://oldweb.aao.gov.au/images/captions/uks014.html

References:

George Abell, Exploration of the Universe, Holt, Reinhardt, Winston, (1969), Chapters 23, 32.

Fred Hoyle, Frontiers of Astronomy, Harper & Brothers (1955), Chapters 8, 11.

Lloyd Motz and Anneta Duveen, Essentials of Astronomy, Wadsworth, (1966), Chapters 27, 30.

(T) Heavy Element Production

In addition to the conversion of hydrogen to helium in stars, by the 1950s, it became apparent that still heavier elements were also being produced in stars.

1952: P.W. Merrill, Science **15** (1952), 484.

Observation ⇒ **Technetium**: The atomic spectra from the element technetium was observed (Fig. T-1) from the surfaces of red-giant stars, although there are no stable isotopes of **Tc**. The most likely isotope is ^{99}Tc which has a $t_{1/2} = 2{\times}10^5$ years. (The Tc isotope with the longest $t_{1/2}$ is ^{98}Tc with $t_{1/2} = 4{\times}10^6$ years. Fig. T-2.)

⇒ Therefore, we must be seeing evidence for nuclear activity to make these Tc atoms in these stars and then bring them up to the surface with a time-scale $\approx 10^6$ yrs.

1952: First Thermonuclear Weapon (Hydrogen Bomb)Test - (nicknamed "Mike")

A. Ghiorso, et al., Physical Review **99** (1955), 1048(L)

P.R. Fields, et al., Physical Review **102** (1956), 180.

Observation ⇒ **Cf** (Z=98), **Es** (Z=99), **Fm** (Z=100): Since the heaviest element that was initially in the weapon was U (Z=92), these observations indicate the occurrence of **multiple** neutron captures on the time scale of approximately a **few** nanoseconds. The observation of the spontaneous fission of ^{254}Cf in this debris indicates that at least 16 neutrons must have been captured in that few nanosecond time scale (See Fig. T-3.)

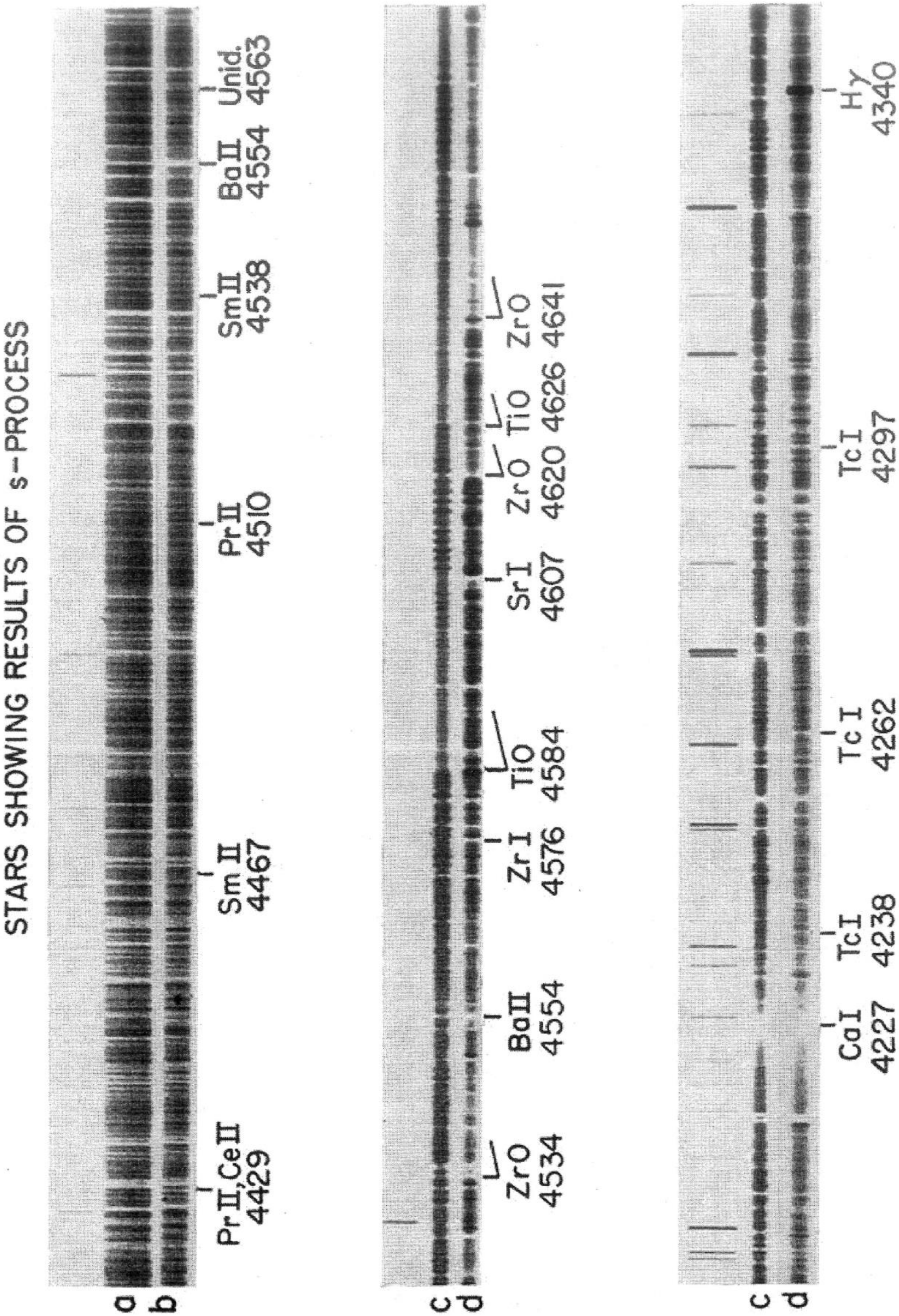
These two 1952 observations then served to define *slow* and *rapid* neutron capture (neutrons, because of their lack of a Coulomb barrier): the **s-Process** and the **r-Process** as discussed in the seminal papers in this field - Burbidge, Burbidge, Fowler, Hoyle (1957), (B^{2}FH) and Cameron (1957).

We see in Fig. T-4, (Z vs. N for stable isotopes), the slow cooking and β-decay along (right next to) the line of stable isotopes via the s-Process (since the subsequent neutron capture happens on a time scale which is slow compared to the β-decay lifetime). This produces many/most of the stable isotopes we find in nature. But there also needs to be the r-Process in an explosive environment (along a path well to the right of the stable nuclei), in order to produce the most neutron-rich stable isotopes – sometimes referred to as “r-only” isotopes. These latter sites are now shown to be in neutron-star mergers (see Section X).

The isotopes formed along each of these two paths will β-decay back to the region of stable nuclei when the process is terminated. For example, looking at the N=82 (more stable and relatively more durable) nuclei, it can be seen in the diagram that the β-decay for the N=82 s-process nuclei will contribute to higher Z stable nuclei than the N=82 r-process nuclei. The resulting abundance plot (as a function of A) through this region would be expected to show two peaks - one due to the s-process nuclei and one, at a somewhat lower A, due to the r-process nuclei. And this is indeed seen in the observed (Seuss and Urey, 1956) abundance plot in Fig. T-6.

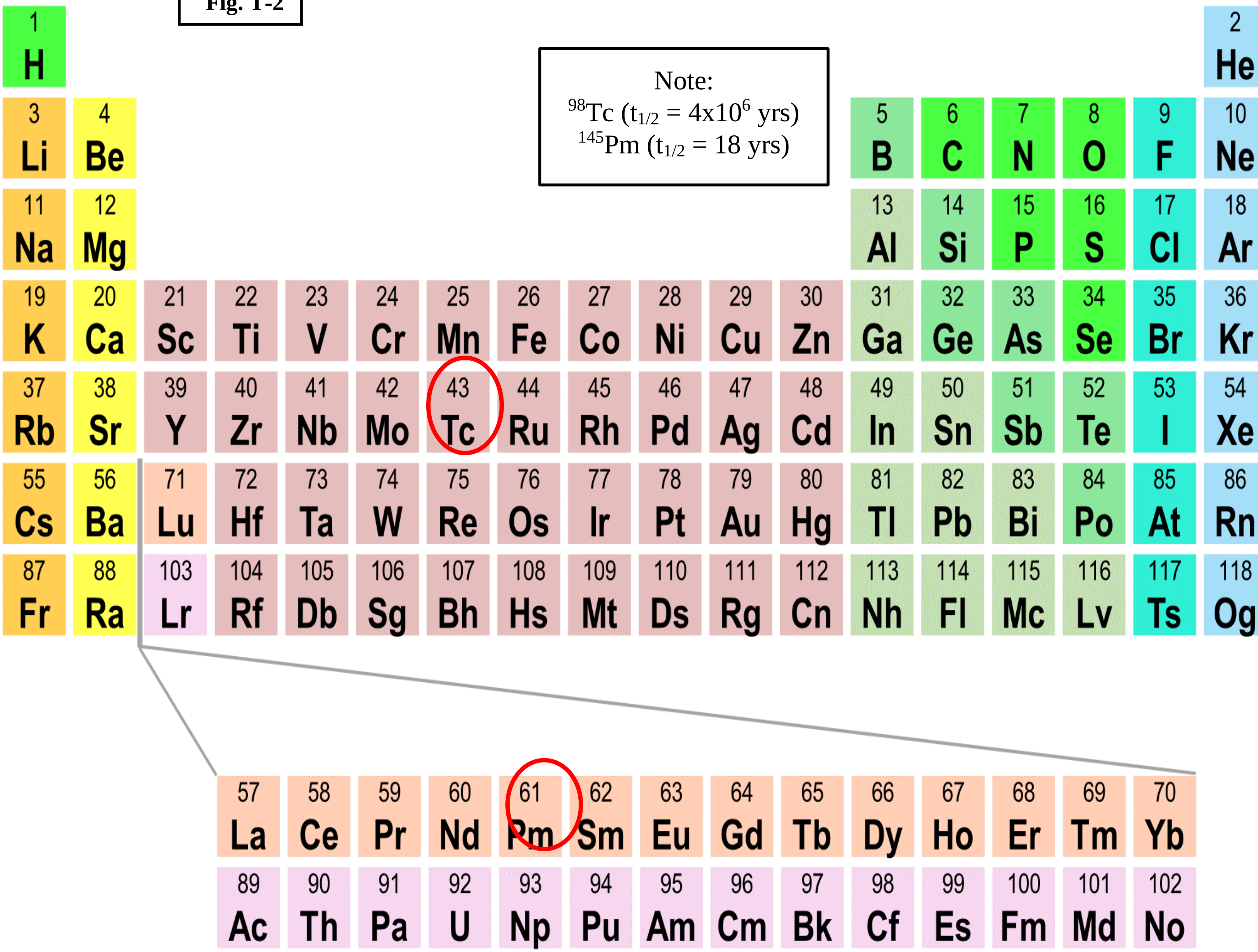
The heavy elements made in these two processes are scattered into the interstellar space by the stellar wind and the planetary nebulae associated with the s-Process giant stars and in the debris-nebulae associated with the SN explosions, (e.g., the “SN-Remnants” illustrated in the images in Section U) and this enriched (or **contaminated**) material is then available for inclusion in subsequent proto-stellar nebulae as they condense into stars, planetary systems, and even humans and their environments.

Fig. T-1

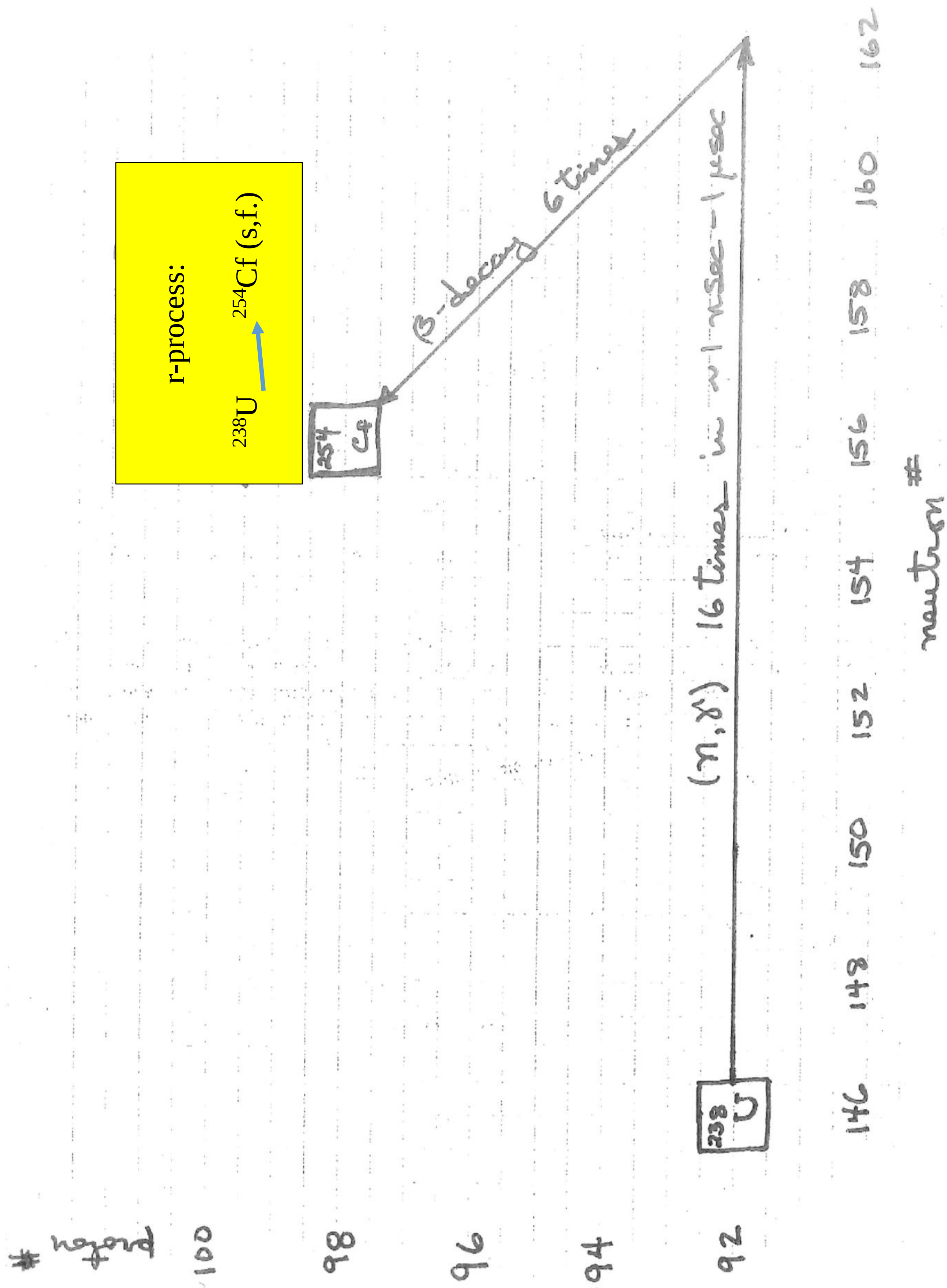


STARS SHOWING RESULTS OF s-PROCESS
a
b
Pr II, Ce II 4429
Sm II 4467
Pr II 4510
Sm II 4538
Ba II 4554
Unid. 4563
c
d
ZrO 4534
Ba II 4554
Zr I 4576
TiO 4584
Sr I 4607
ZrO 4620
TiO 4626
ZrO 4641
c
d
Ca I 4227
Tc I 4238
Tc I 4262
Tc I 4297
Hγ 4340

Fig. T-2



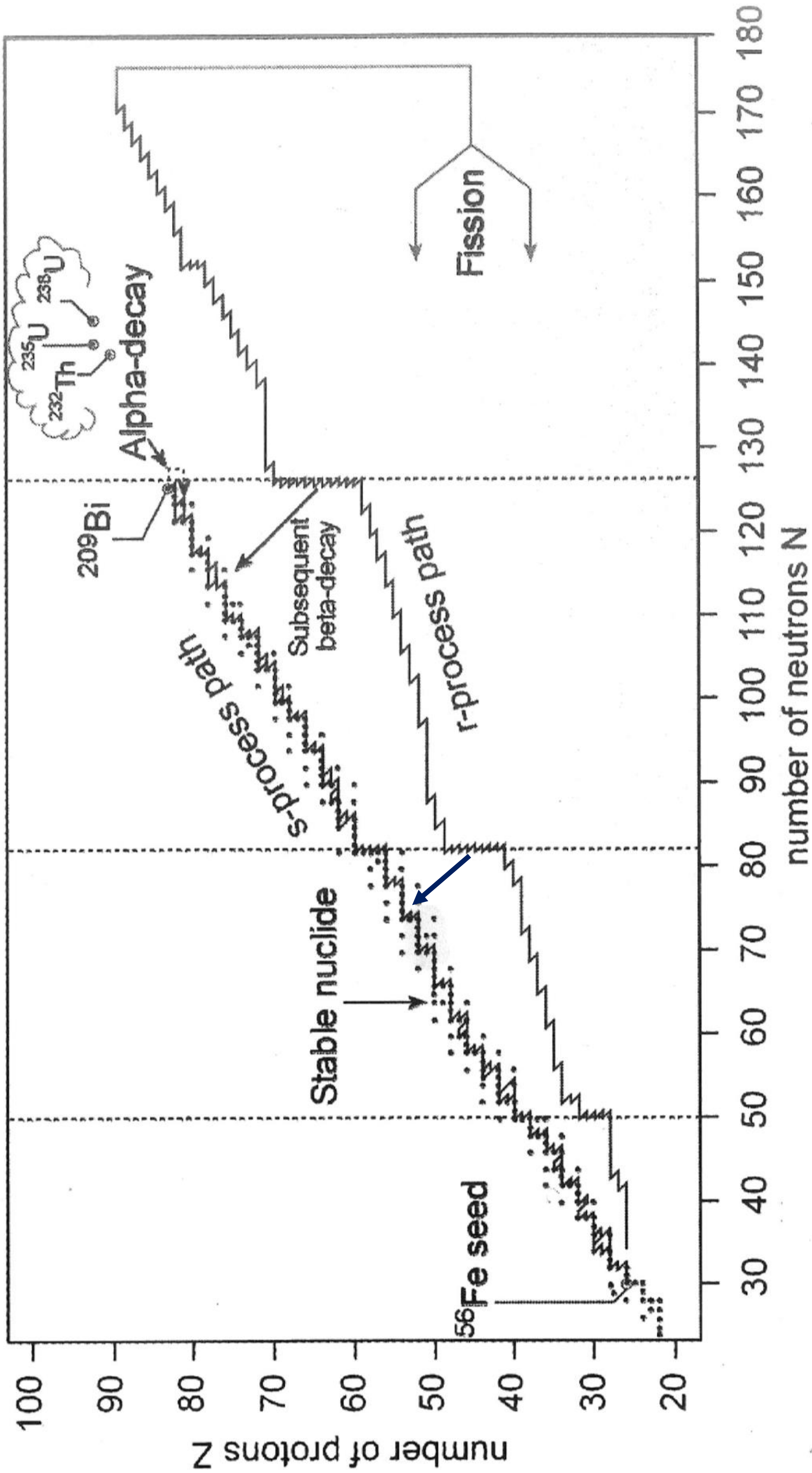
Note:
^{98}Tc ($t_{1/2}$ = 4x10^6 yrs)
^{145}Pm ($t_{1/2}$ = 18 yrs)
1 H
2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Nh 114 Fl 115 Mc 116 Lv 117 Ts 118 Og
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No



r-process:
$^{238}U \rightarrow {}^{254}Cf$ (s,f.)
proton
100
98
96
94
92
238 U
254 Cf
(n,γ) 16 times in ~1 nsec – 1 μsec
β-decay 6 times
146
148
150
152
154
156
158
160
162
neutron #

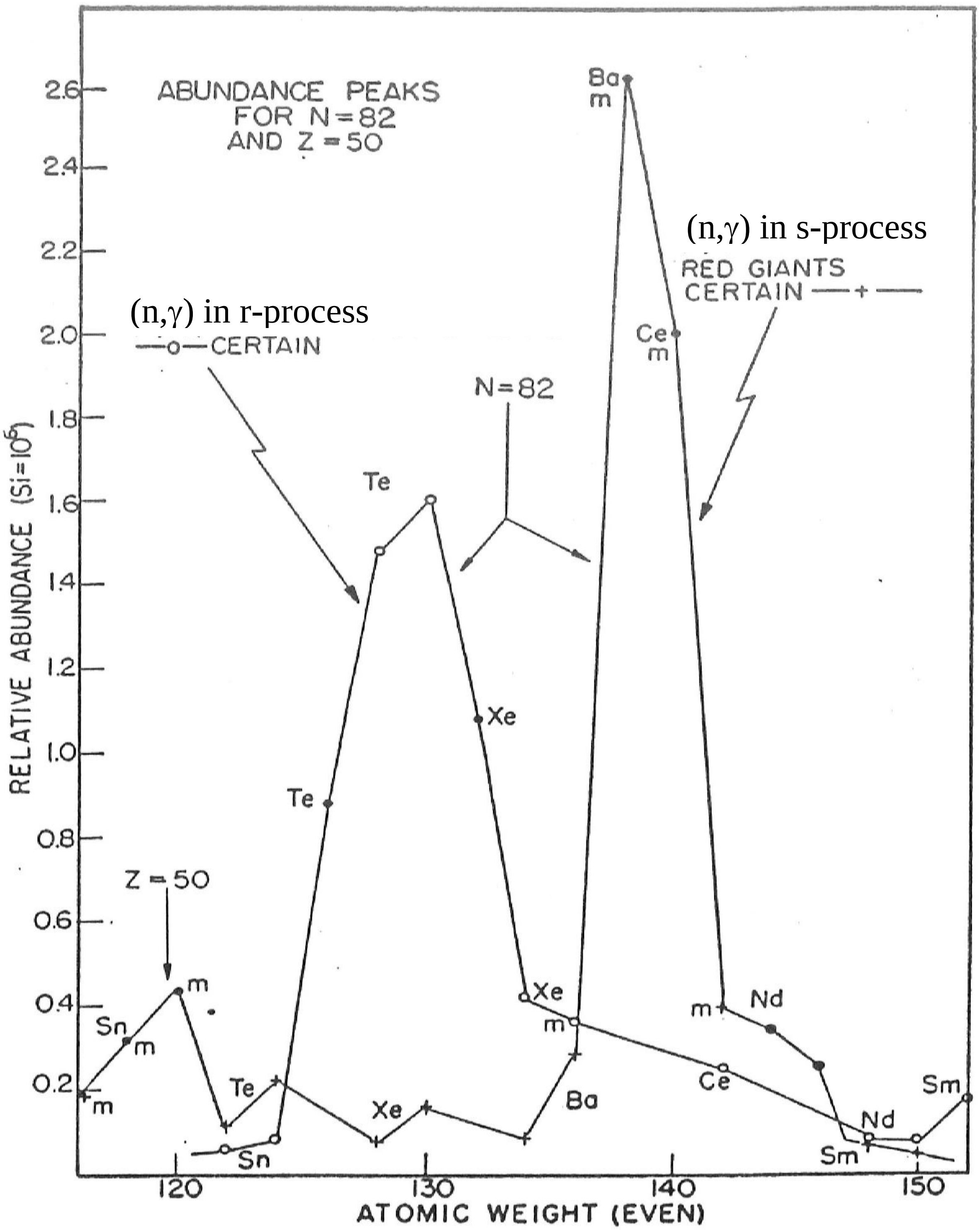
Fig. T-3

Fig. T-4



number of protons Z
number of neutrons N
100
90
80
70
60
50
40
30
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
56Fe seed
Stable nuclide
s-process path
Subsequent beta-decay
r-process path
209Bi
Alpha-decay
232Th
235U
238U
Fission

Fig. T-5


ABUNDANCE PEAKS
FOR N=82
AND Z=50
(n,γ) in s-process
RED GIANTS
CERTAIN —+—
(n,γ) in r-process
—o—CERTAIN
N=82
Z=50
RELATIVE ABUNDANCE (Si=10^6)
ATOMIC WEIGHT (EVEN)
Ba
m
Ce
m
Te
Xe
Te
m
Sn
m
m
Te
Sn
Xe
Xe
m
Ba
Ce
m
Nd
Nd
Sm
Sm
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
120
130
140
150

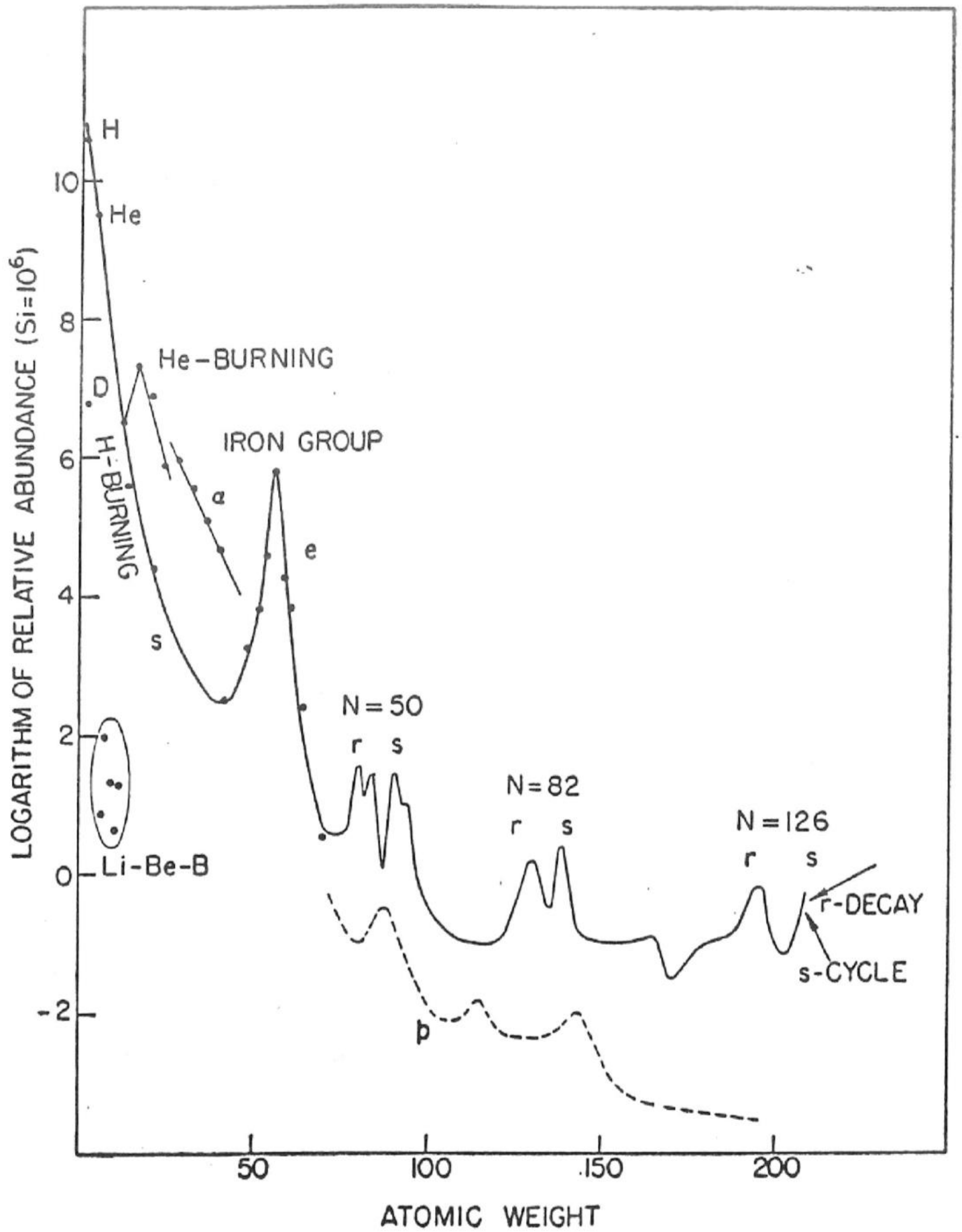
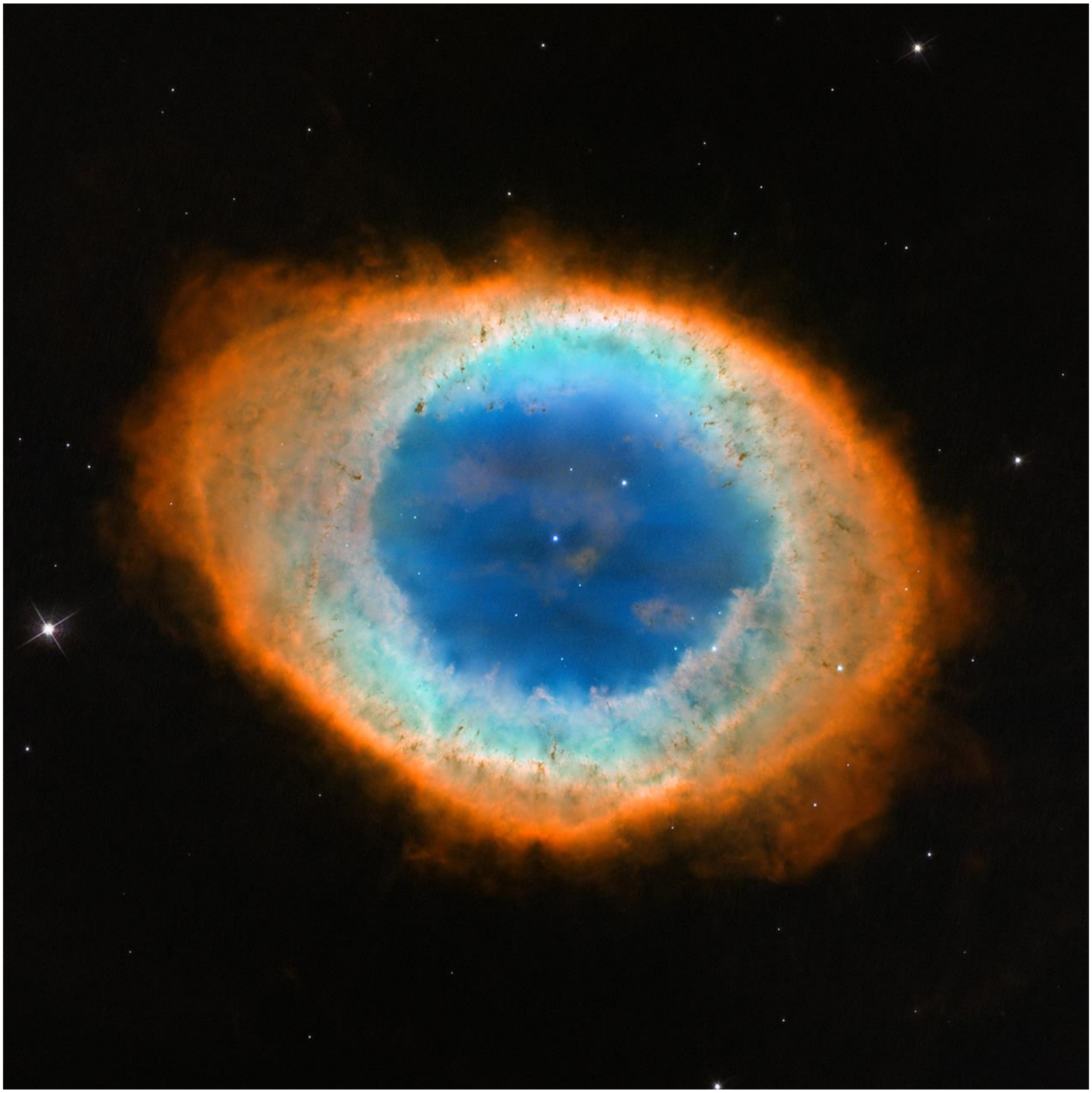


FIG. I,1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (Su56).

Fig. T-6

Fig. T-7



M57: The Ring Nebula

Except for the rings of Saturn, the Ring Nebula (M57) is probably the most famous celestial band. Its classic appearance is understood to be due to our own perspective, though. The recent mapping of the expanding nebula's 3-D structure, based in part on this clear Hubble image, indicates that the nebula is a relatively dense, donut-like ring wrapped around the middle of a football-shaped cloud of glowing gas. The view from planet Earth looks down the long axis of the football, face-on to the ring. Of course, in this well-studied example of a planetary nebula, the glowing material does not come from planets. Instead, the gaseous shroud represents outer layers expelled from the dying, once sun-like star, now a tiny pinprick of light seen at the nebula's center. Intense ultraviolet light from the hot central star ionizes atoms in the gas. In the picture, the blue color in the center is ionized helium, the cyan color of the inner ring is the glow of hydrogen and oxygen, and the reddish color of the outer ring is from nitrogen and sulfur. The Ring Nebula is about one light-year across and 2,000 light-years away.

https://apod.nasa.gov/apod/ap130605.html

References:

"B^{2}FH": E.M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, Reviews of Modern Physics **29** (1957), 347.

A.G.W.Cameron, Astro. J. **62** (1957), 9.

P.R. Fields, et al., Physical Review 1**02** (1956), 180.

A. Ghiorso, et al., Physical Review **99** (1955), 1048(L).

P.W. Merrill, Science **15** (1952), 484.

Lloyd Motz and Anneta Duveen, Essentials of Astronomy, Wadsworth, (1966), Chapter 24.

H.E. Suess and H.C. Urey, Reviews of Modern Physics **28** (1956), 53.

(U) Supernova Explosions

Supernova (SN) explosions are interesting and dramatic enough to deserve their own Section. A supernova explosive collapse produces:

a) an optical outburst which, for a SN in our own galaxy, can be visible in the daytime for weeks or months.
b) a total energy outburst equivalent to $10^{19} \times L_{\odot}$ for a few seconds.
c) a highly condensed remnant in the form of a black hole, or a neutron star which can be observed as a rapidly spinning pulsar.
d) a burst of neutrinos that has been detected from as far as 169,000 light-years (ly) away in the Large Magellanic Cloud (LMC).
e) a gamma-ray flux from decaying radioactivities that has been detected from as far as 169,000 ly away in the LMC.
f) a set of "standard candles" that can be used to measure the expansion of our universe and led to the discovery of "Dark Energy".

Supernovae were observed and recorded as "guest stars" and regarded as potent portents of good or evil as early as 3000 years ago. While supernovae are observed to occur in galaxies like our own about once or twice every century, the last one observed in our galaxy was over 300 years ago (in 1680 by Flamsteed in the constellation Cassiopeia). However, this is not inconsistent with the statistics of small numbers (3 were observed in the period from 1572-1680) and the small fraction of the galactic disk that we can observe optically, buried as we are in the gas and dust of this disk. See the wrap-around image of our galaxy, Fig. S-12, in Section S. Also, see the "cartoon" sketch (Fig. U-1) of the location of the historical SNe for which we have observed/recorded positions and/or subsequently identified residual nebulae.

Three of the most notable examples are SN-1054, SN-1987a, and SN-1680**:**

(A) **SN-1054** was recorded by Chinese astrologers, appearing as a "guest star" in the constellation Taurus, on the night of July 4th (corrected to the modern calendar) in the year 1054. It became as bright as the planet Venus, visible in daylight for more than 3 weeks and was followed for 650 nights until it was no longer visible to the naked eye at night. See the plot in Fig. U-7 of the decay of the luminosity of this and other supernovae. See also the comparison images (Fig. U-6) of the SN observed in the galaxy IC-4182 in 1937 (Walter Baade).

Then in the late 19th century it was recognized that the "Crab Nebula" (in Taurus) corresponded to the location of the SN-1054 and was measured to be expanding at a rate such that, following it backwards in time, brought it to a point "source" in

1054. Subsequently more detailed observations revealed a star in the nebula which was suspiciously like a neutron star and which was then observed (Jan. 1969) to be a radio and optical pulsar, rotating with a period of 30 millisec. Also see the optical images obtained by a telescope arranged to store data, blinking on-and-off 30x per second in Fig. U-5 This rapid rotation is the result the law of conservation of angular momentum (LCAM: the spinning ice-skater effect) when a normal star, like the sun (rotating ~ once a month) collapses from a radius of 500,000 miles to <50 miles. Such a reduction in its moment of inertia by a factor of 10^8 results in an increase in its rotation rate by 10^8, decreasing its period from 3 x10^6 sec to 3 x10^{-2} sec.

TABLE 5

CHINESE OBSERVATIONS ON THE CRAB NEBULA*

(9.5 mag = 12 half-lives in 627 days. "Half-life" ≈ 52 days)

			App. mag.	*Abs. mag*
First observed	July 4, 1054	"Guest star visible by day like Venus"	-5	-16.5
Daylight visibility	July 27, 1054	23 days	-3.5	-15
Visible until	Apr. 17, 1056	650 days	6.0	- 5.5

*Duyvendak, Publ. Astro.SocPacific54(1942(,p.91. Mayall and Oort, ibid p.95

Fowler (1967) p.66.

An interesting side-light is that although this SN was observed and recorded by Chinese and other Asian astronomers, it was NOT observed or recorded by any European astronomers; however, it was possibly observed and recorded by native Americans inhabiting areas in what is now northern Arizona - seen in the petroglyph shown in Fig. U-2. (Running a sky chart backwards shows that on the morning of July 5th SN-1054 would have appeared just 2º below the crescent moon.) Similarly, the sunburst at the foot of the "rabbit in the moon" (Fig. U-3), a Native American constellation is in the "right" location and is suggested to possibly represent SN-1054 on this piece of Mimbres Indian pottery.

<u>The Crab Nebula</u> (Simon Mitton) is a very thorough historical description of the various stages in the observations and interpretations of the SN-1054, from guest star to pulsar.

(B) **<u>SN-1987a</u>** was first observed (serendipitously) optically in a photograph of the Large Magellanic Cloud, (LMC, a dwarf, satellite galaxy orbiting our own galaxy, on the night of February 23, 1987. [See the "life history" of this star on the page at the end of the text for this section.] This SN was subsequently studied in numerous optical telescopes **but,** perhaps most interestingly, was also detected (a) "simultaneously" as a neutrino flash passing through terrestrial neutrino detectors [i.e., at Kamiokande in Japan (Fig. U-8) and at the Irvine-Michigan-Brookhaven (IMB) underground detector facility in the Morton Salt mine near Lake Erie, Ohio] and (b) several months later as an emitter of gamma rays from the decay of ^{56}Co (Fig. U-9). [All of this from the LMC, ≈169,000 ly away.] (Note that, of course, this SN occurred 169,000 years before anybody on earth was aware of it.)

The neutrino burst in the Kamiokande data shows a net 12 neutrinos arriving in a lapse-time interval of 10 to 15 seconds. Based on the weak interaction of these neutrinos with the detector (Section Q) these 12 "events" correspond to ~ $\mathbf{10^{16}}$ neutrinos passing through the detector during this time interval. This weak interaction with matter allows these neutrinos to escape from the SN "simultaneously" with the collapse-explosion.

In tracking down some urban legends regarding the status of the Kamiokande detector at this time, the e-mail exchange below is strong verification.

From: Mark Vagins <vagins@markie.ps.uci.edu>
To: Peter Parker <peter@mirage.physics.yale.edu>
Subject: Re: 1987a ??

On Mon, 22 Aug 2005, Peter Parker wrote:

Mark -
There has been an "urban legend" circulating for some time (and I thought that maybe I should check it out before I repeat it one more time) that just prior to 1987a, Kamiokande II had been down for maintenance(?) and recalibration, etc. and that it had just come back on line half and hour before the famous burst of neutrinos arrived.

Fact or fiction ?? Is this story actually written down anywhere or just transmitted by word of mouth?

Thanks - Peter

Hey Peter,

Well, as it happens you have asked the right person...

As with many Urban Legend-like stories, this one has been transmitted by word of mouth for many years. As far as I know there is nothing officially written down anywhere which is publicly available, at least not in English!

However, I can tell you authoritatively that this particular story is absolutely, 100% true. No urban (or subterranean) legend, this. How can I be so sure?

I had also heard many stories about SN1987A, so in 1998, shortly before all of the old Kamiokande stuff was removed from the Kamioka mine (in order to make room for the KamLAND experiment), I walked down the tunnel from Super-Kamiokande, went into the Kamiokande counting house, and read through the original logbooks. Indeed, on the fateful date there had been hardware servicing and calibration work performed - it had concluded and the detector was restarted less than an hour before the neutrino wave swept past. As there was no GPS timing or Simple Network Time Protocol (SNTP) in those days, the times in the book were based upon the watch worn by that day's shiftworker, and hence are not accurate to the second or even to the minute.

At the same moment, on the other side of the world, the IMB detector had a faulty high voltage power supply, and hence one entire side of that cube-shaped detector was turned off. Luckily, they were still running with what was left, and so were able to observe the neutrino burst as well. That power supply was later, and with considerable ceremony (as part of a collaboration meeting), heaved over the side of a ship and into the depths of the ocean.

So, needless to say, I am always very, very uneasy whenever I need to turn off Super-Kamiokande's data-taking for any reason. At any given moment there are approximately 1,000 "local" supernova neutrino waves propagating through our galaxy, getting closer and closer each and every second. We must do everything we can to be ready when the next one arrives!

Later,
-Mark

However, we have to wait for the SN-remnant nebula to expand and its density to correspondingly decrease before the gamma rays from the decay of ^{56}Ni (the most tightly bound heavy nucleus - e.g., the Binding Energy Plots in Section N) at the core of the SN core can escape and travel to earth. In December 1987, the gamma rays from the decay ^{56}Co (847-keV and 1238-keV) were detected in NaI detectors mounted in satellites above the earth's atmosphere. This was 10 months after the SN explosion, so that given the 78-day half-life of ^{56}Co, these gamma rays would have been $2^4 = 16\times$ more intense if we could have detected them in February. Given the intensity of these gamma rays, this observation measures that the SN-1987a explosion produced ~ 0.3 $M_\odot$ of ^{56}Ni,

Although SN-1987a occurred in a galaxy which seems far, far away, it is worth noting that the next nearest galaxy (other than even smaller dwarf galaxies orbiting our galaxy) is more than 10× farther away (e.g., the Andromeda Galaxy), and therefore, at this time, detecting supernova neutrinos and gamma rays from the Andromeda Galaxy would be more than 100× harder.

(C) **<u>SN-1680</u>** (Flamsteed) has become better known as CasA (an intense radio source) and was the first target (Aug. 26, 1999) looked at by the Chandra X-ray Satellite. (That image of SN-1680 (Fig. U-10) has become an icon for explosive nucleosynthesis.) Because of its location in the disk of our galaxy, the SN-1680 remnant shows almost no optical image, but it is clearly seen in x-rays and gamma rays (Fig. U-10), which are more energetic and therefore more penetrating. The white dot in the middle of this x-ray image is the neutron-star remnant.
A measurement by the NASA gamma-ray telescope (COMPTEL) of the energy spectrum of the gamma rays from CasA shows a clear peak at 1.16 MeV, corresponding to the decay of ^{44}Ti. Given the 60-year half-life of ^{44}Ti, this peak would have been **42**× more intense if Flamsteed had had COMPTEL at his disposal to study his supernova 320 years ago. ☺

<u>SN generated **^{26}Al** Gamma Rays:</u>
When NASA first put a gamma-ray detector into a satellite (HEAO-3) in 1979, Maloney *et al.* (Ap.J. <u>262</u> (1982) 742) discovered the gamma-ray line associated with the decay of ^{26}Al coming from the interstellar medium (Fig. U-12). Since ^{26}Al has a half-life of only 720,000 years, this indicates that this ^{26}Al is not primordial (i.e., not produced in the Big Bang or in the formation of our galaxy or the solar system) but must still be being produced in our galaxy. More recent surveys using this 1.8-MeV γ-ray line to map out an image (Fig. U-13) of our galaxy [what our eyes would see as the Milky Way if they were sensitive to these energetic gamma rays] shows a concentration in the central region of its disk together with a number of identifiable SN remnants.

Life History of SN-1987a (Sanduleak -69º 202)

[7:36 a.m. UT, 23 February 1987]

11 million years ago: $(M \approx 18\times M_{\odot})$ H $\Rightarrow$ He $L \approx 40{,}000 \times L_{\odot}$

1 Million years ago: Switched to Helium burning

Compare to our sun which will burn its H $\Rightarrow$ He for 10 to 20 billion years.

45,000 years ago: Switch to Carbon burning

At this time the successive burning stages had less and less available energy and so the sequence proceeded at an ever accelerating pace, until the final, silicon-burning stage lasted only about a week.

By that time the central temperature of the star had risen from 4×10^{7} ºK to 4×10^{9} ºK, and its central density had risen to about 5×10^{7} grams/cc. But its core had run out of nuclear energy to oppose gravity and support its massive external layers.

The internal structure of this star then went into free-fall, and in a few tenths of a second its iron core (formed in the silicon-burning stage) collapsed to nuclear density ($\approx10^{14}$ grams/cc) forming a "neutron star" with a radius of only ≈20 miles, whereas it had earlier had a radius of $\approx200\times10^{6}$ miles as a red giant (~ twice the radius of the earth's orbit around the sun). And so, like an ice-skating ballerina pulling in her arms, this star increased its rotation rate from once a month (like our sun) to about once every millisecond – just by having to conserve its angular momentum.

In this collapse an enormous amount of gravitational and nuclear energy was released, resulting in a **burst** of neutrinos carrying away energy at a rate which for about 10 seconds is more than $10^{19} \times L_{\odot}$. During that time interval, this neutrino burst nearly outshone the visible radiation from the rest of our universe.

The shell of this supernova neutrino burst is only about 10 light-sec thick and expands spherically at essentially the velocity of light and (in the case of SN1987a) 169,000 years later reached the earth, leaving its mark for its "10 seconds of fame", and kept on going!

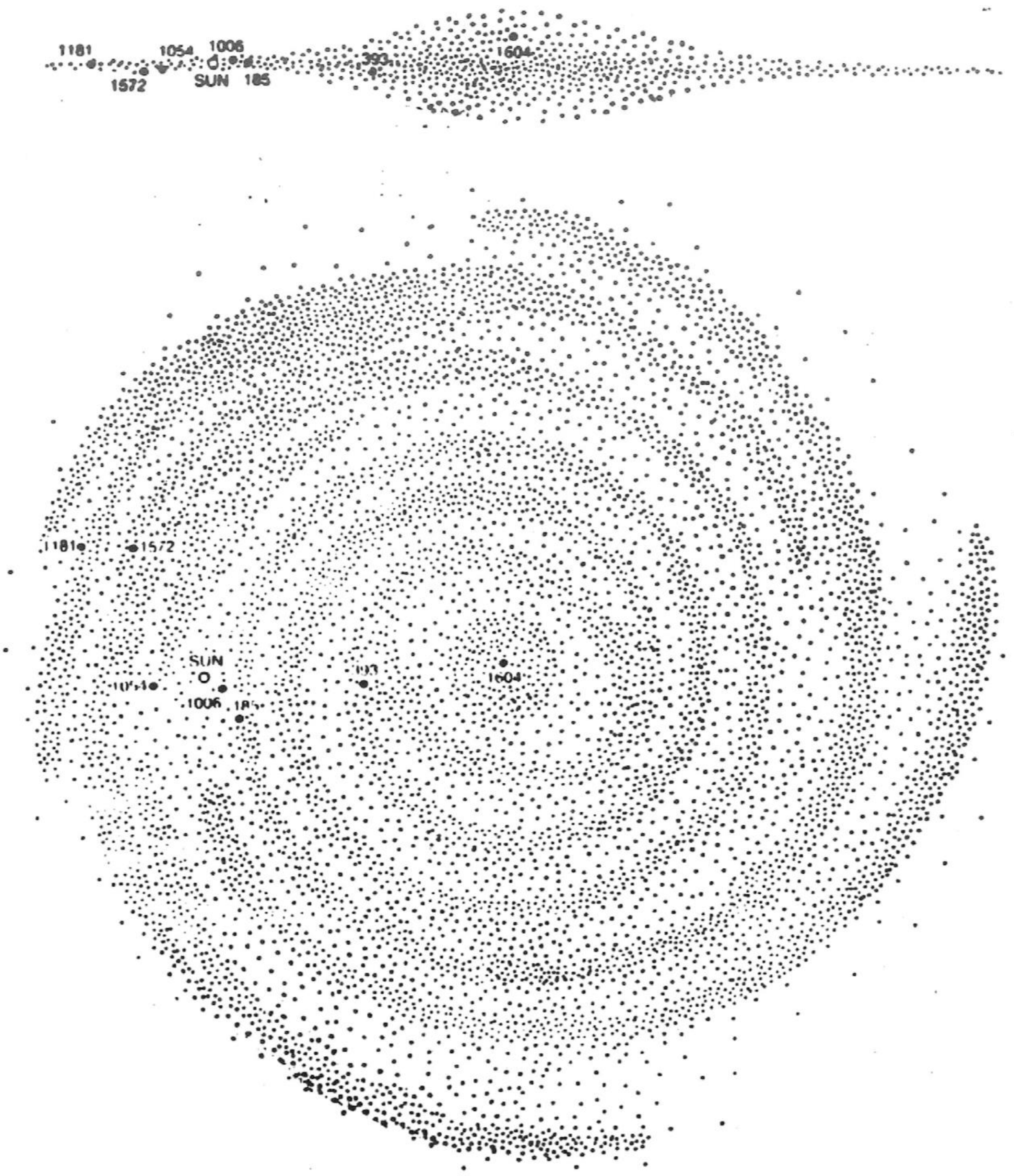


Fig. U-1	A "cartoon" sketch of location of the historical supernovae for which we have observed/recorded positions and/or subsequently identified residual nebulae. Note the small piece of our galaxy where we can observe its supernovae.

Fig. U-2

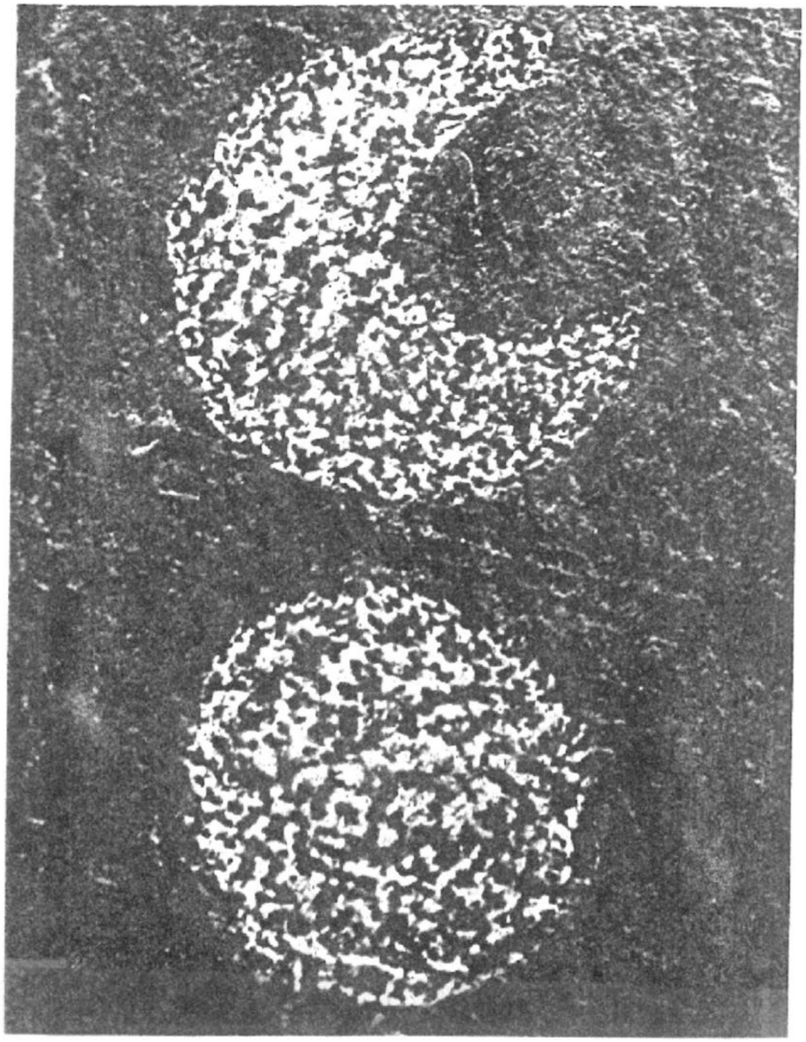
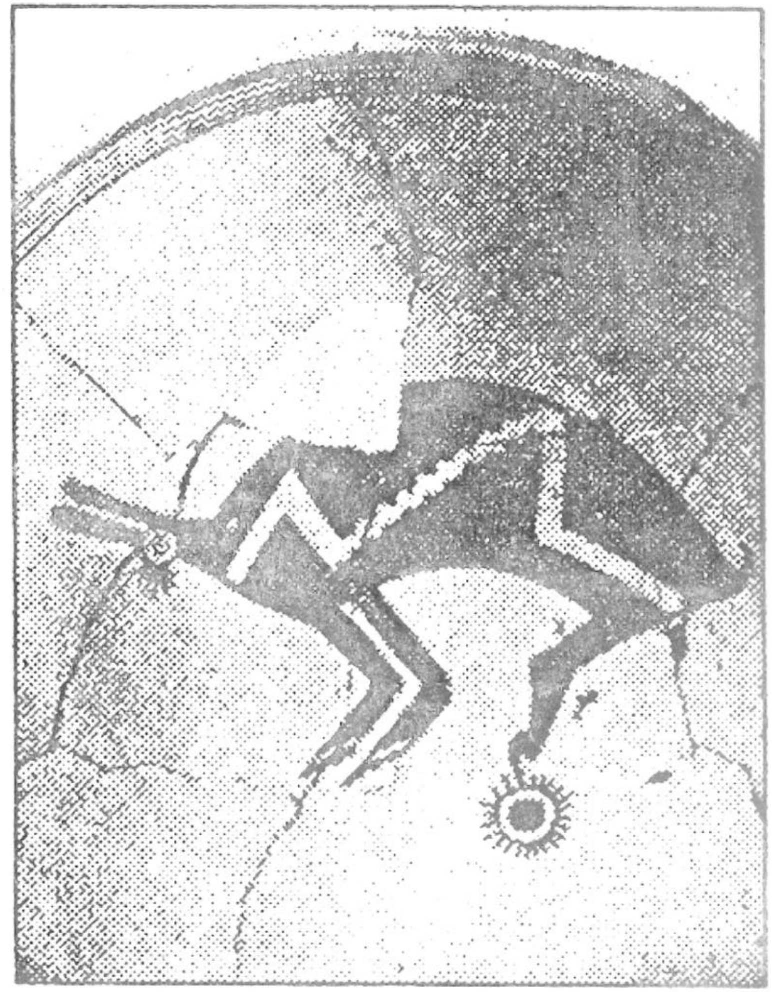


FIG. 16. Petroglyph found on the wall of a cliff in Navajo Canyon in northern Arizona. The object below the crescent moon may well be the supernova observed by Chinese astronomers in 1054. There is substantial evidence that the Pueblo people inhabited the canyon at that time. (*Reproduced by courtesy of William C. Miller and the Museum of Northern*

[Fowler (1967) p. 67.]

Fig. U-3



University of Minnesota Museum

Sunburst at foot of "rabbit in the moon" on Mimbres Indian pot is believed to depict 1054 supernova.

Fig. U-4

Crab Nebula
Remnant of SN-1054

Of the four stars near the center of this image, one of them (as seen in the next figure) is observed to be an optical pulsar.

Fig. U-5

Crab Nebula optical pulsar

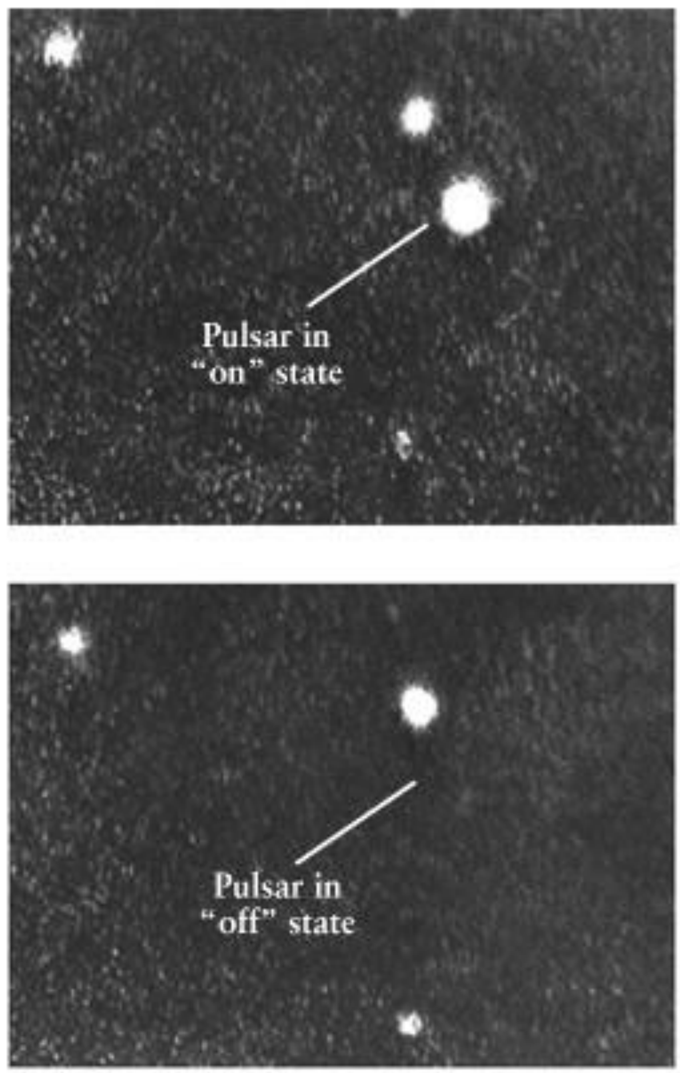


Fig. U-6

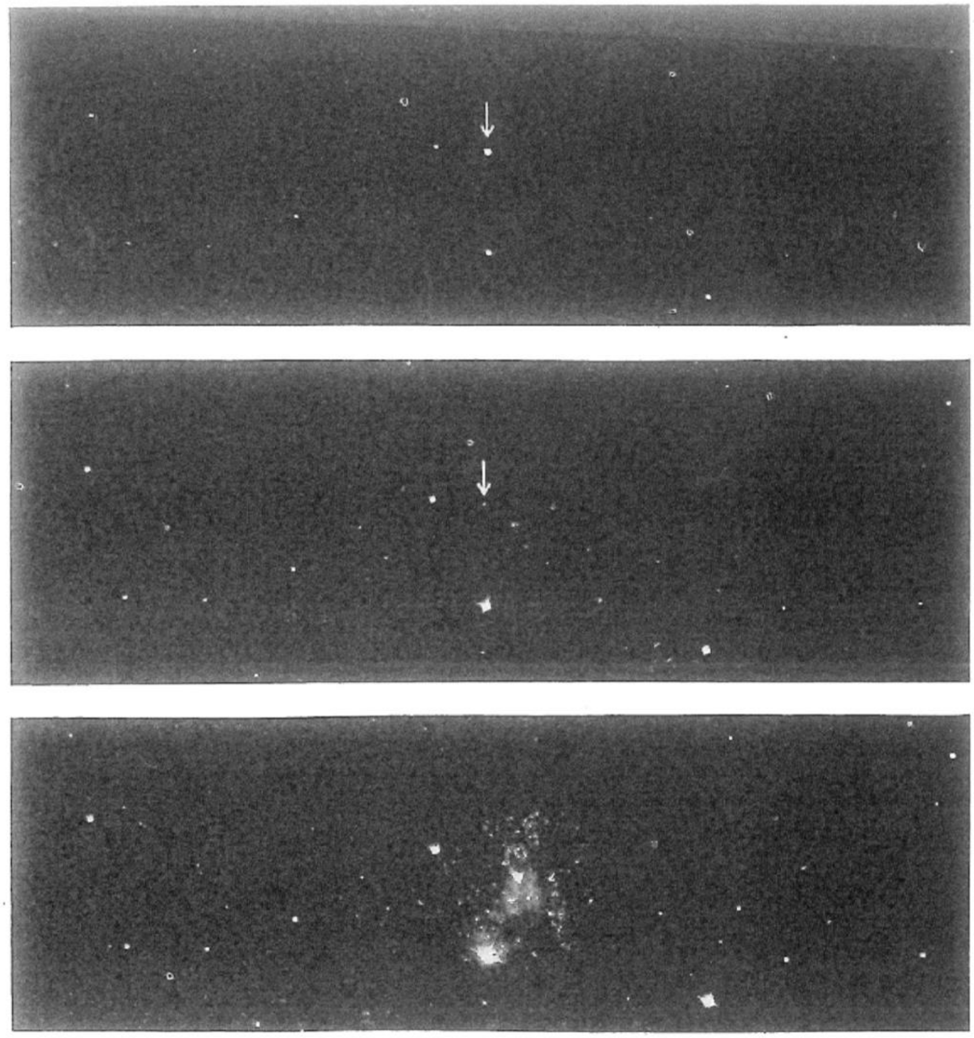
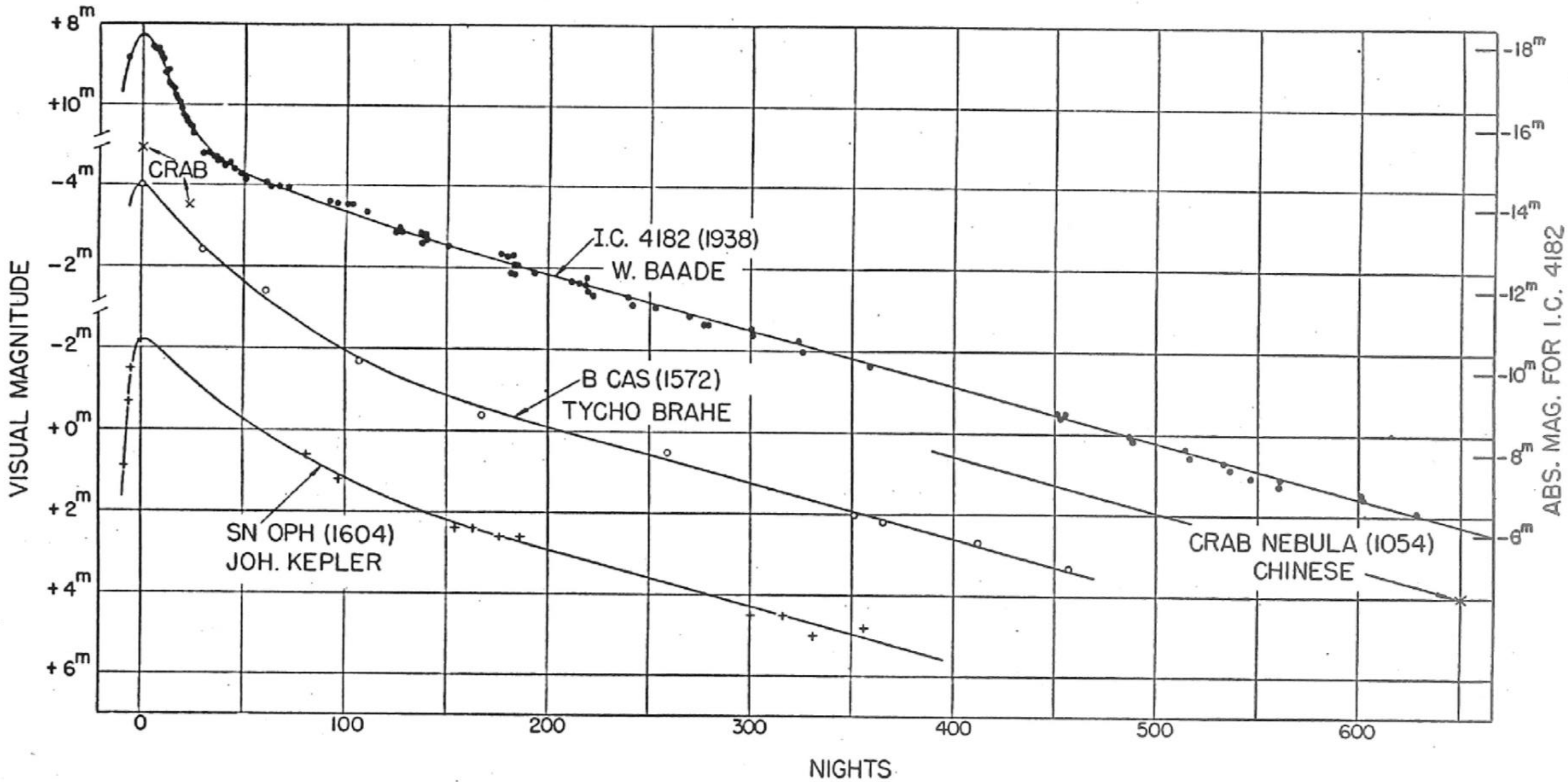


FIG. 14. The supernova in IC 4182, photographed (top) September 10, 1937, at maximum brightness—exposure 20 minutes; (middle) November 24, 1938, about 400 days after maximum—exposure 45 minutes; (bottom) January 19, 1942, about 1,600 days after maximum, when the supernova was too faint to be detected—exposure 85 minutes. Note that the time intervals of the three exposures are different. The galaxy in which the supernova occurred is clearly seen in the bottom photograph. It is not apparent in the two top photographs for which the exposure time was too short. (*Mount Wilson and Palomar Observatories*.)

Fowler (1967) p. 62

Fig. U-7



Light-Curves for Supernovae

SN 1987 a

(23 February 1987, LMC)

Fig. U-8

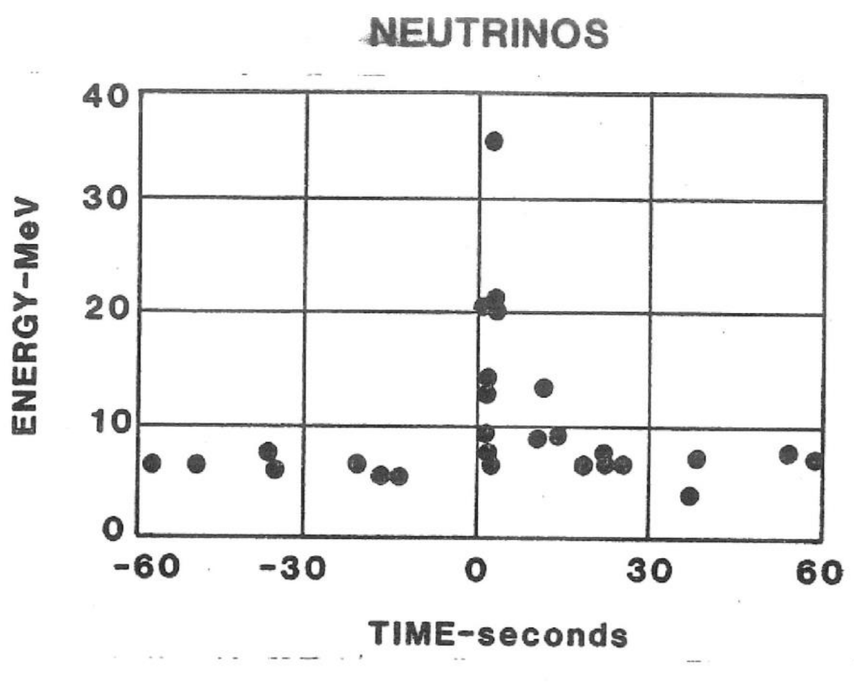


Fig. U-9

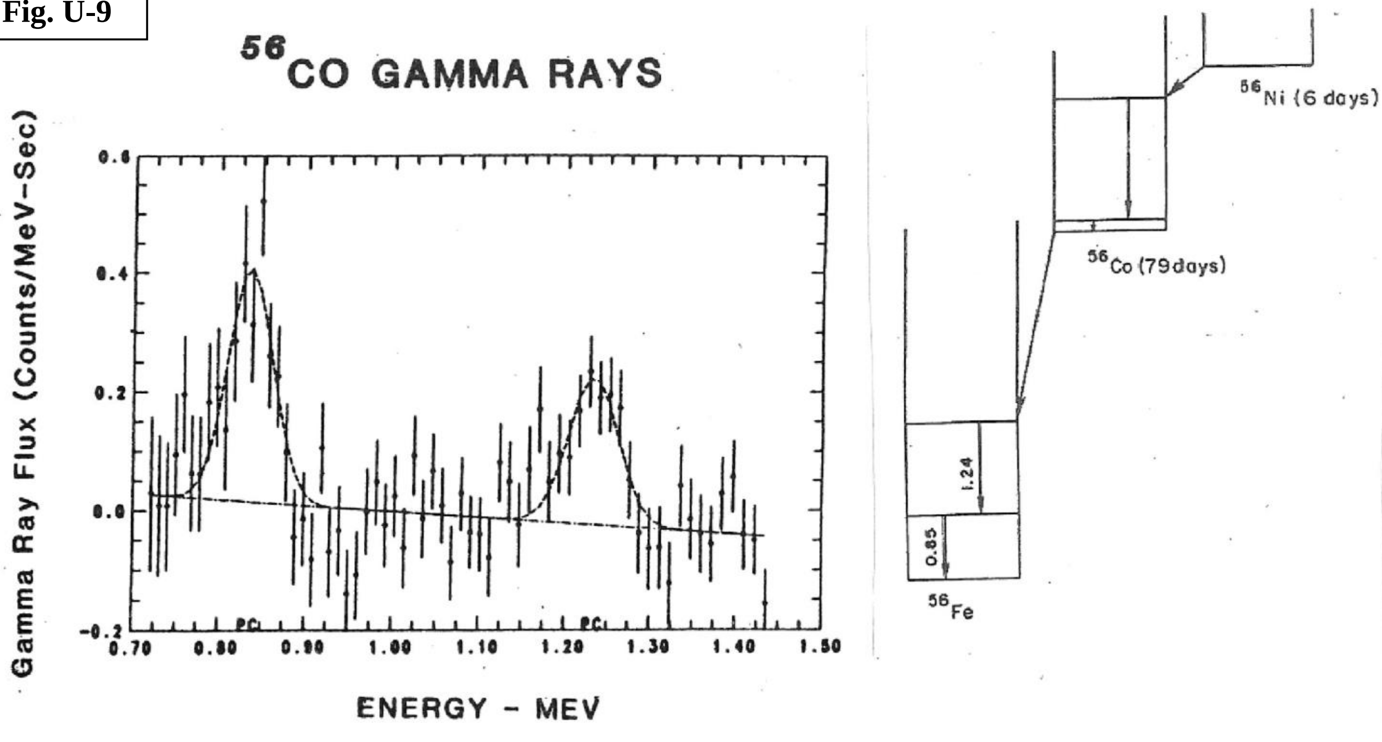
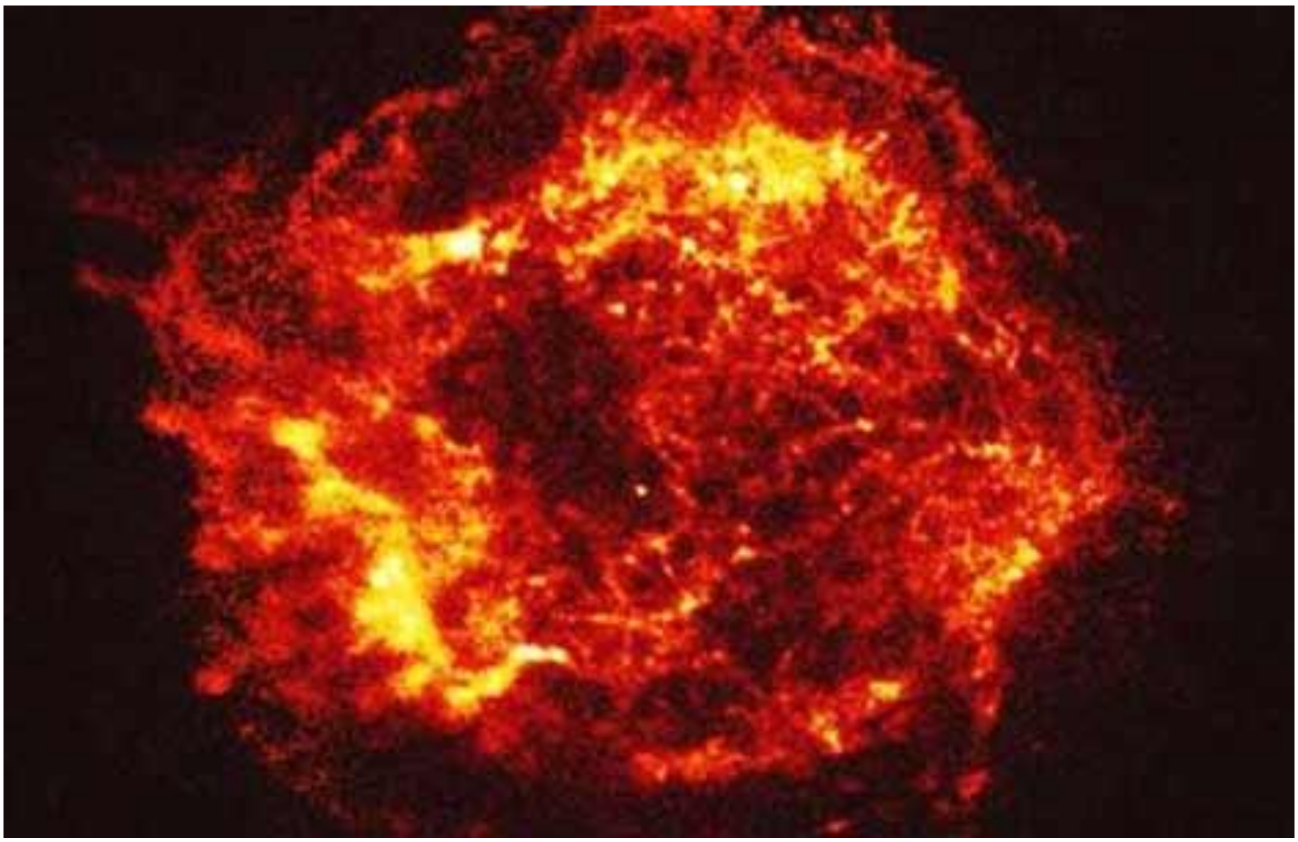
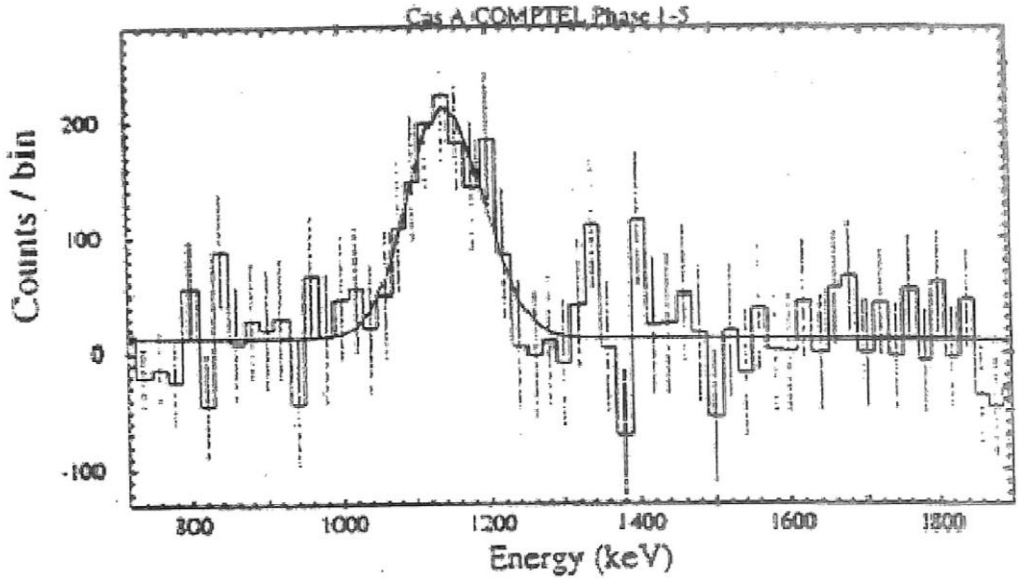


Fig. U-10

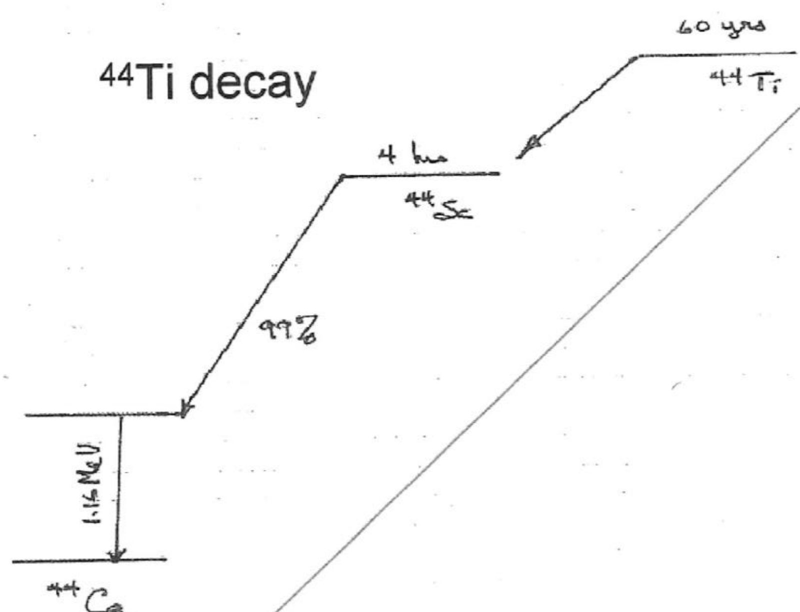


Cas-A SN-1680
Chandra satellite x-ray image of Cas-A

Fig. U-11



^{44}Ti decay



1.157-MeV Gamma Rays ($t_{1/2}$ = 60 yrs)

320 years after SN explosion
≈ 5.4 half-lives (× 42)

CasA is at 10,000, light-years
∴ sensistive out to about 65,000 ly
-- IF look early.

Fig. U-12

HEAO-3 (1979) :

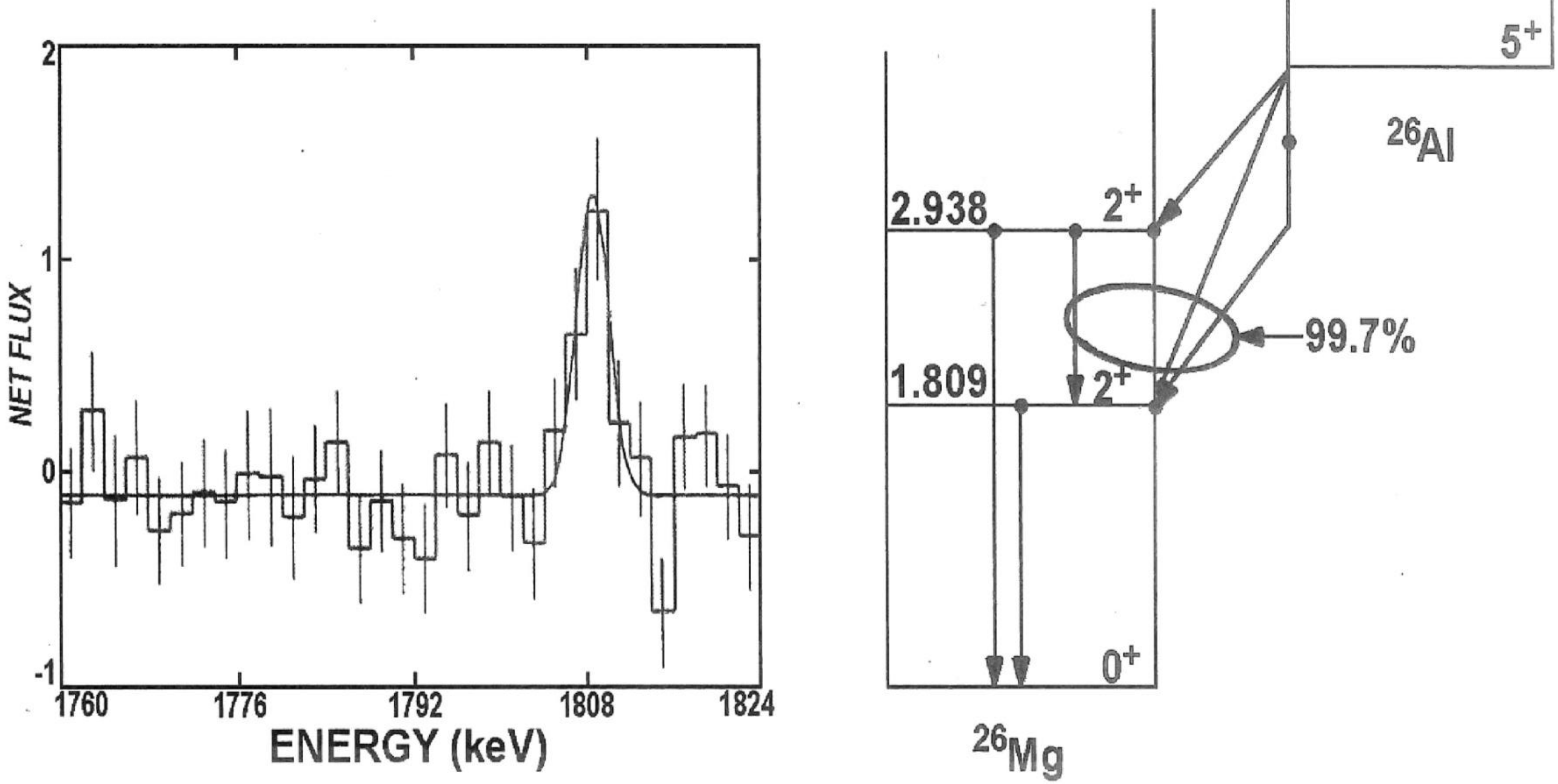
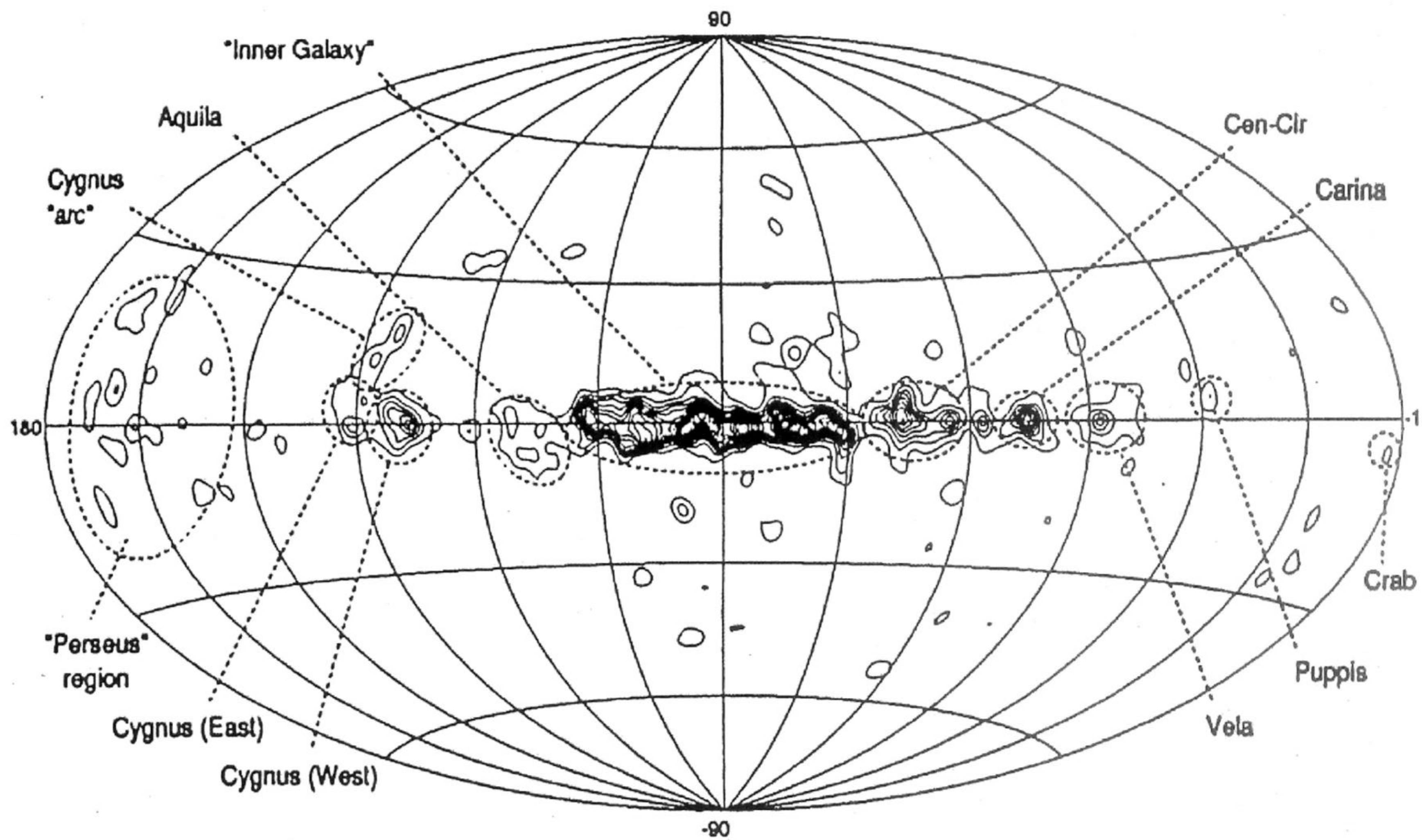


Fig. U-13

^{26}Al (1809 keV) map of our Galaxy

GRO-Comptel



References:

"B^{2}FH": E.M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, Reviews of Modern Physics **29** (1957), 347.

William Fowler, Nuclear Astrophysics, American Philosophical Society, (1967), Chapter II.

David Helfand, Bang: The Supernova of 1987, Physics Today (August 1987), p 24 (and references therein).

Fred Hoyle, Frontiers of Astronomy, Harper & Brothers, (1955), Chapter 12.

W.A. Maloney, et al., Ap.J. **262** (1982), 742.

Simon Mitton, The Crab Nebula, Charles Scribner's Sons, (1978).

Lloyd Motz and Anneta Duveen, Essentials of Astronomy, Wadsworth, (1966), Chapter 24.

F.R. Stephenson and D.H. Clark, Historical Supernovas, Scientific American **234** (June 1976), p. 100.

Virginia Trimble, Visit to a Small Universe, A.I.P., (1992), "Deaths of Stars".

(V) Gravity and Light

The discovery of the interaction of gravity and light - first in Einstein's theory of General Relativity and then in observations of the bending of light by the sun (Fig. V-2) in the total solar eclipse of 1919 - is another of the unexpected and **dramatic** shifts in the study of Physics andAstrophysics at the transition from the 19^{th} to the 20^{th} century. [From the discovery of x-rays and radioactivity and photons, to $E = mc^2$, to quantum mechanics, to the recognition of nebulae as galaxies of stars, etc.]

Shortly after publishing (1905) his results for what became known as his theory of Special Relativity, Einstein was working on the problem of how to expand this theory to include gravity. His initial derivation/calculation predicted a deviation angle for light passing close to the sun (at $r = R_\odot$) of ≈ 0.85 seconds of arc, and an expedition was planned and mounted to measure such an effect for an eclipse at a site which was near the German-Russian frontier in the summer of 1914; however, World War I intervened so that the measurement could not be carried out. Subsequently, in November 1915 Einstein was called upon to present a series of three lectures on his theoretical results at sessions of the Prussian Academy of Sciences. In his preparation for these lectures he uncovered an error and corrected his calculations which now predicted a limiting angle of deviation of 1.75 seconds of arc.

During a total solar eclipse May 29, 1919, expeditions at Sobral (Brazil) and on Principe Island (off the west coast of Africa) were able to obtain photographs of stars surrounding the sun which could then be compared with photographs of the same area of sky at a different time of year, when the sun was in a very different part of the sky. When the analysis and comparison was completed at the end of September, 1919, the observations:

Sobral - 1.98 ± 0.12 sec of arc
Principe - 1.61 ± 0.30 sec of arc

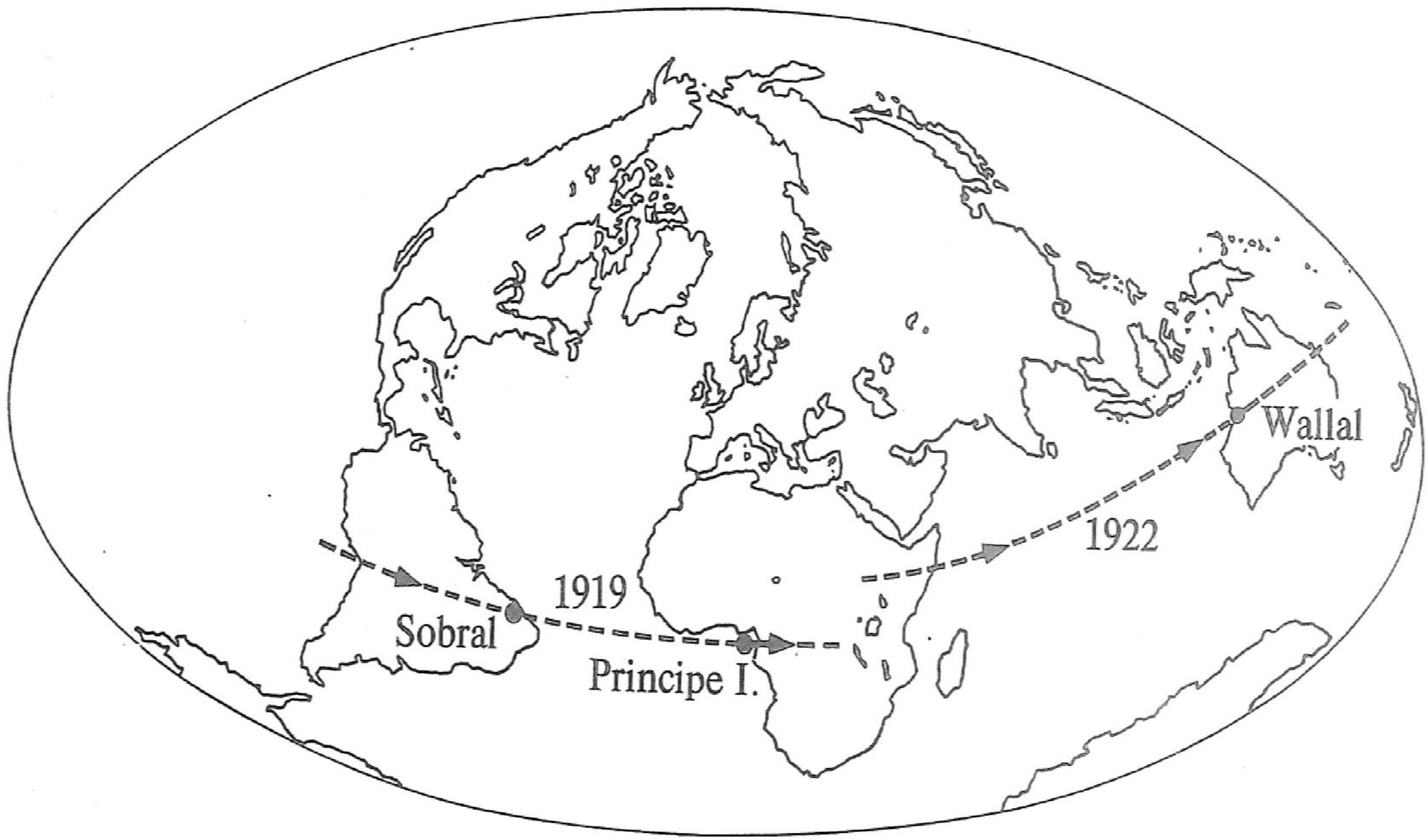
were in good agreement with Einstein's prediction of 1.7 sec of arc. (See the plot of the data, compared to Einstein's theory. (Fig. V-3)) And, on that same day, he reported this success to his mother on a post card, shown in Fig. V-4.

In addition to reporting these data to Einstein, Eddington waxed poetic, expressing the results as (The Glass Universe, p.185, Dava Sobel):

> Oh leave the Wise our measures to collate
> One thing at least is certain, light has weight.
> One thing is certain and the rest debate
> Light rays, when near the Sun, do not go straight.

In 1922, at Wallal, Australia, Campbell and Trumpler confirmed this result with a measurement of 1.72 ± 0.11 sec of arc.

Fig. V-1



Solar Eclipse Paths, 1919 and 1922
See A.P. French reference, 1979

Fig. V-2

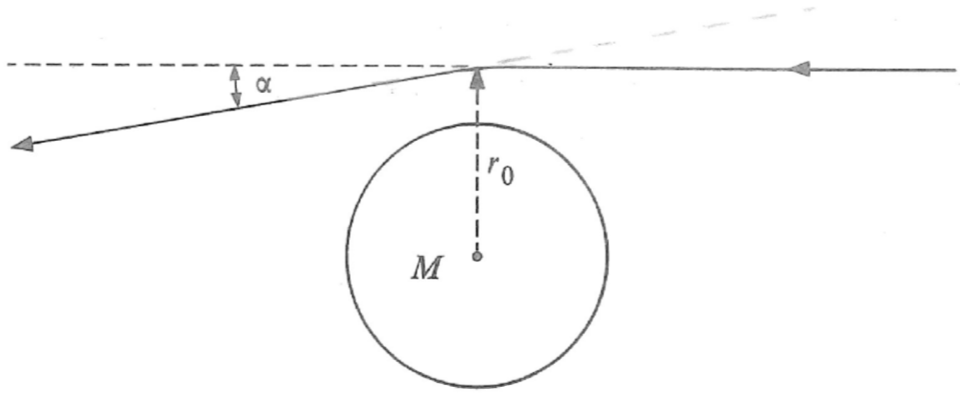
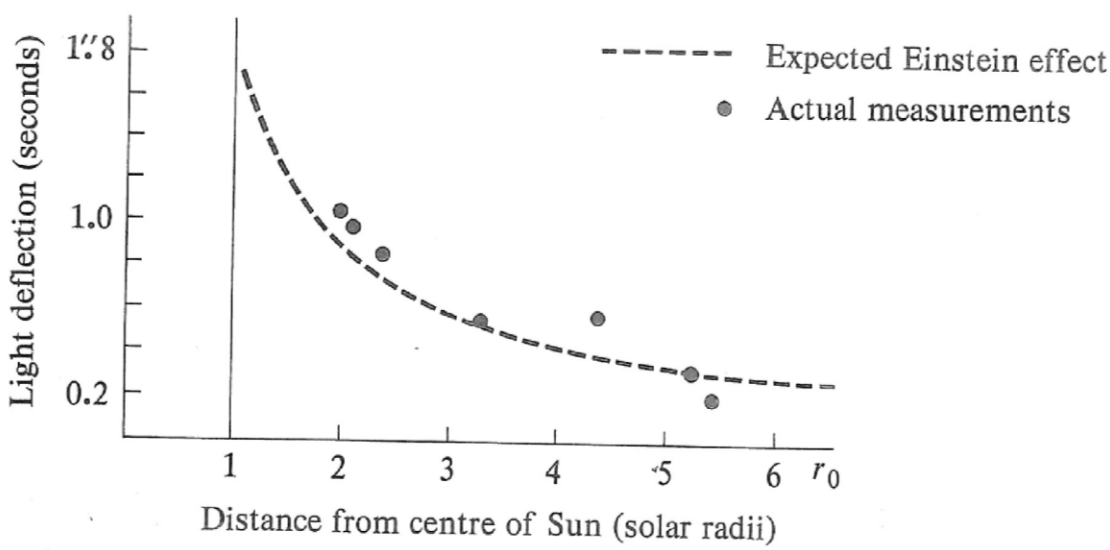


Diagram 3.3
Deflection of a ray of light by a star (greatly exaggerated).

$$\alpha = (4\,G\,M)/(c^2\,r_o)$$

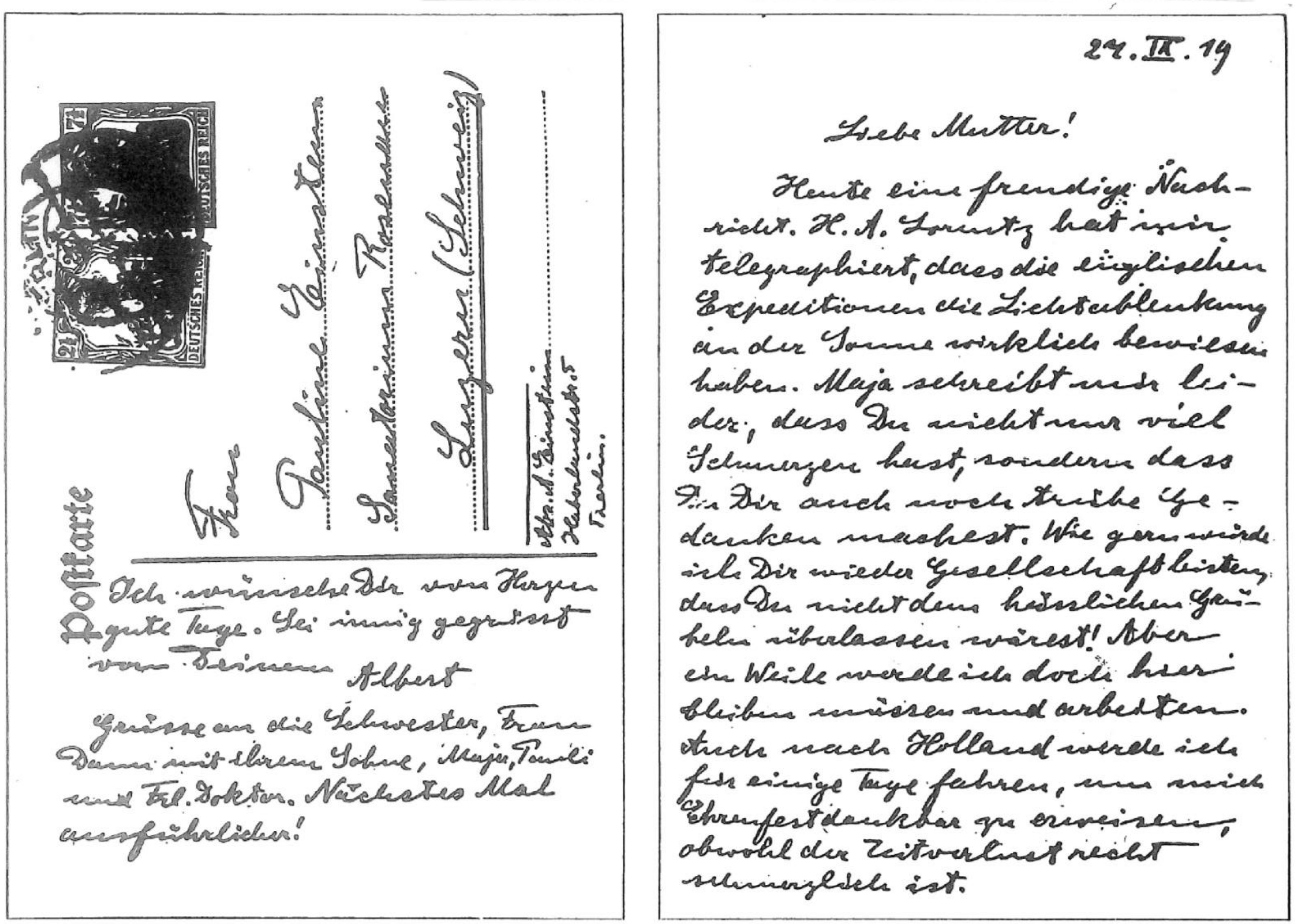
Fig. V-3



A test of the relation between the angle of deflection and the distance between the light ray and the centre of the Sun (theoretically $\alpha \sim 1/r_0$).

Fig. V-4

A postcard from Albert Einstein to his mother, dated 27 September 1919. The first sentences read 'Good news today. H. A. Lorentz has telegraphed me that the British expeditions have definitely confirmed the deflection of light by the Sun'



Postkarte

Frau Pauline Einstein
Sanatorium Rosenau
Luzern (Schweiz)

Abs. A. Einstein
Haberlandstr. 5
Berlin.

Ich wünsche Dir von Herzen gute Tage. Sei innig gegrüsst von Deinem Albert

Grüsse an die Schwester, Frau Dann mit ihrem Sohne, Maja, Pauli und Frl. Doktor. Nächstes Mal ausführlicher!

27. IX. 19

Liebe Mutter!

Heute eine freudige Nachricht. H. A. Lorentz hat mir telegraphiert, dass die englischen Expeditionen die Lichtablenkung an der Sonne wirklich bewiesen haben. Maja schreibt mir leider, dass Du nicht nur viel Schmerzen hast, sondern dass Du Dir auch noch trübe Gedanken machest. Wie gern würde ich Dir wieder Gesellschaft leisten, dass Du nicht dem hässlichen Grübeln überlassen wärest! Aber eine Weile werde ich doch hier bleiben müssen und arbeiten. Auch nach Holland werde ich für einige Tage fahren, um mich Ehrenfest dankbar zu erweisen, obwohl der Zeitverlust recht schmerzlich ist.

Gravitational Lensing

Once it had been demonstrated that light is bent by the gravitational distortion of space, it would follow that large accumulations of mass should behave as a *lens*.
[Comments by jcohn@berkeley.edu - last updated Dec. 13, 2010.]

In general relativity, the presence of matter (energy density) can curve spacetime, and the path of a light ray will be deflected as a result. This process is called gravitational lensing and in many cases can be described in analogy to the deflection of light by (e.g. glass) lenses in optics. Many useful results for cosmology have come out of using this property of matter and light. For many of the cases of interest one does not need to fully solve the general relativistic equations of motion for the coupled spacetime and matter, because the bending of spacetime by matter is small. (Quantitatively the matter bending space is moving slowly relative to c, the speed of light and the "gravitational potential" Phi induced by the matter obeys $|Phi|/c^2 << 1$.)

A sketch of the paradigm of a lensed system is below:).

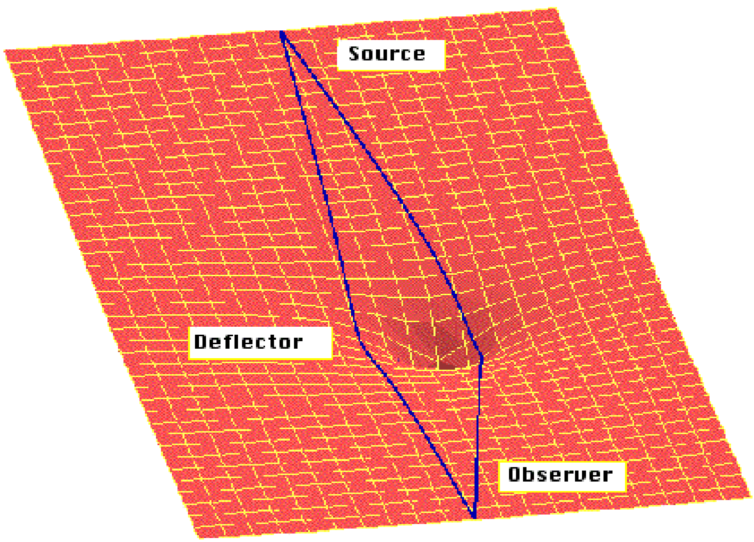


Fig. V-5

In a system where lensing occurs there is a

- *source: where the light comes from, can be a quasar, the cosmic microwave background, a galaxy, etc.*
- *lens(es): which deflect(s) the light by an amount related to its quantity of mass/energy, can be anything with mass/energy*
- *observer: who sees a different amount of light than otherwise because the lens has bent spacetime and thus the travel paths of the light*
- *image or images: what the observer sees*

The light is not only visible light, but more generally any radiation.
As a consequence of lensing, light rays that would have otherwise not reached the observer are bent from their paths and towards the observer. (Light can also be bent away from an observer but that is not the case of interest.) There are different regimes: strong lensing, weak lensing, *and microlensing. The distinction between these regimes depends on the positions of the source, lens and observer, and the mass and shape of the lens (which controls how much light is deflected and where.)*

Gravitational Lensing

Imagine a bright object such as a **star**, a **galaxy**, or a **quasar**, that is very far away from Earth (say...10 billion **light years**). For our discussion, let us imagine we have a quasar. If there is nothing between it and us, we see one image of the quasar. Yet, if a **massive** galaxy (or **cluster of galaxies**) is blocking the direct view to the quasar, the light will be bent by the **gravitational** field around the galaxy [see figure below]. This is called "gravitational lensing," since the gravity of the intervening galaxy acts like a lens to redirect the light rays. But rather than creating a single image of the quasar, the gravitational lens creates multiple images. We follow the light rays from the Earth to the apparent locations of the quasar. If the galaxy were perfectly symmetric with respect to the line between the quasar and the Earth, then we would see a ring of quasars!

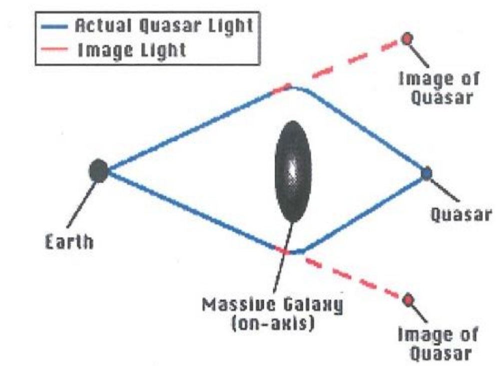


Fig. V-6

Now, if the massive galaxy is off-center (as might be expected) with respect to the line between the quasar and the Earth, then the two light paths would be different distances around the galaxy. This makes the twin images be formed at different distances away from the actual quasar.

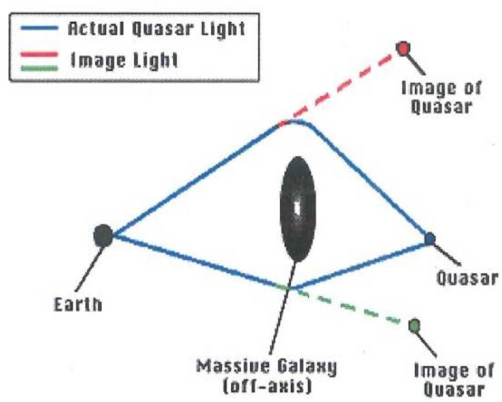


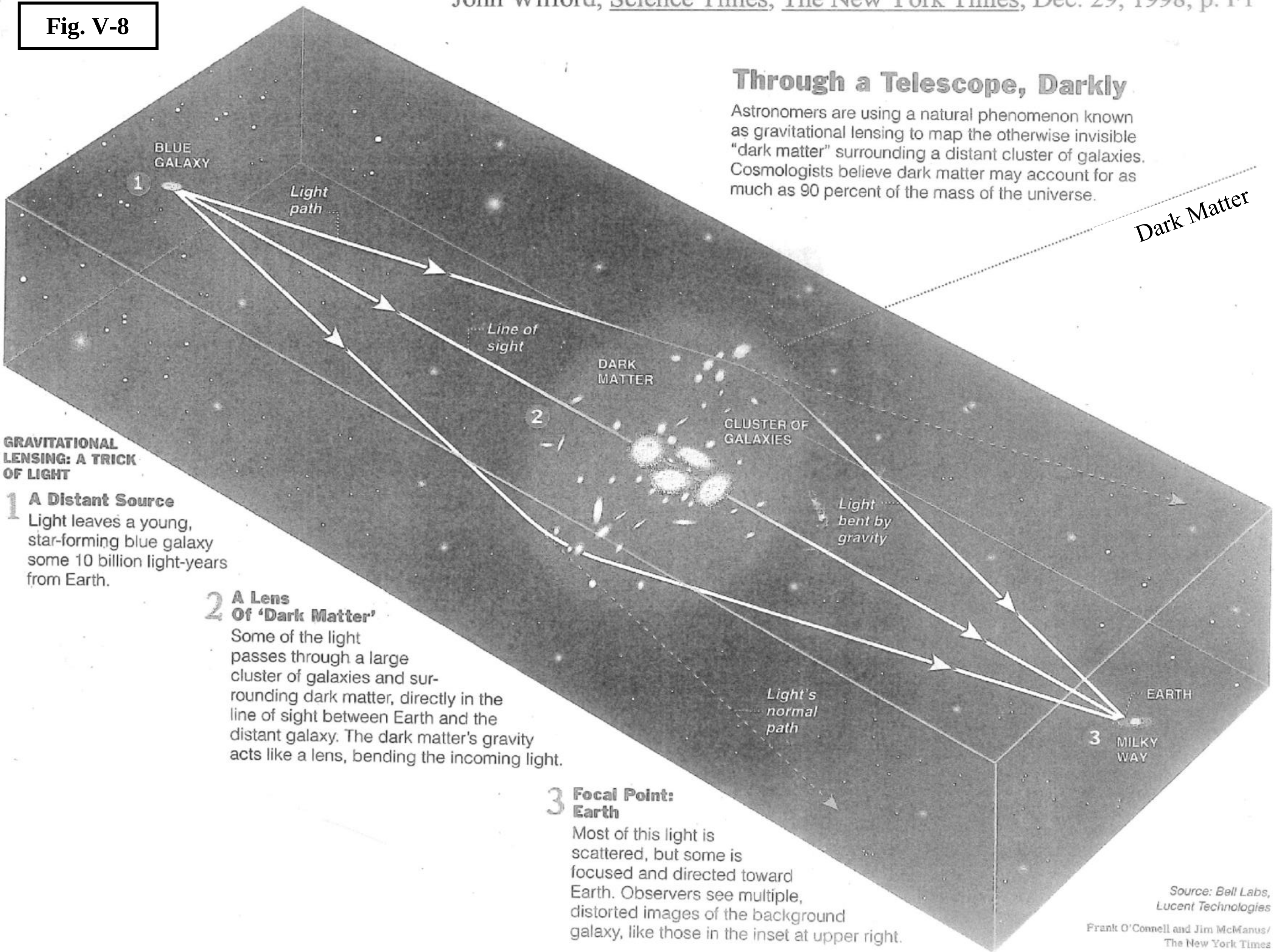
Fig. V-7

Finally, since the distances between each of the objects is so great, the radius of the galaxy and the mass distribution of the galaxy are well approximated by point masses (the error is small). Thus, one can use simple geometry (knowing the mass of the galaxy, the distance of the galaxy and the two images) to estimate the distance to the actual quasar.

http://imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html 11/18/2008

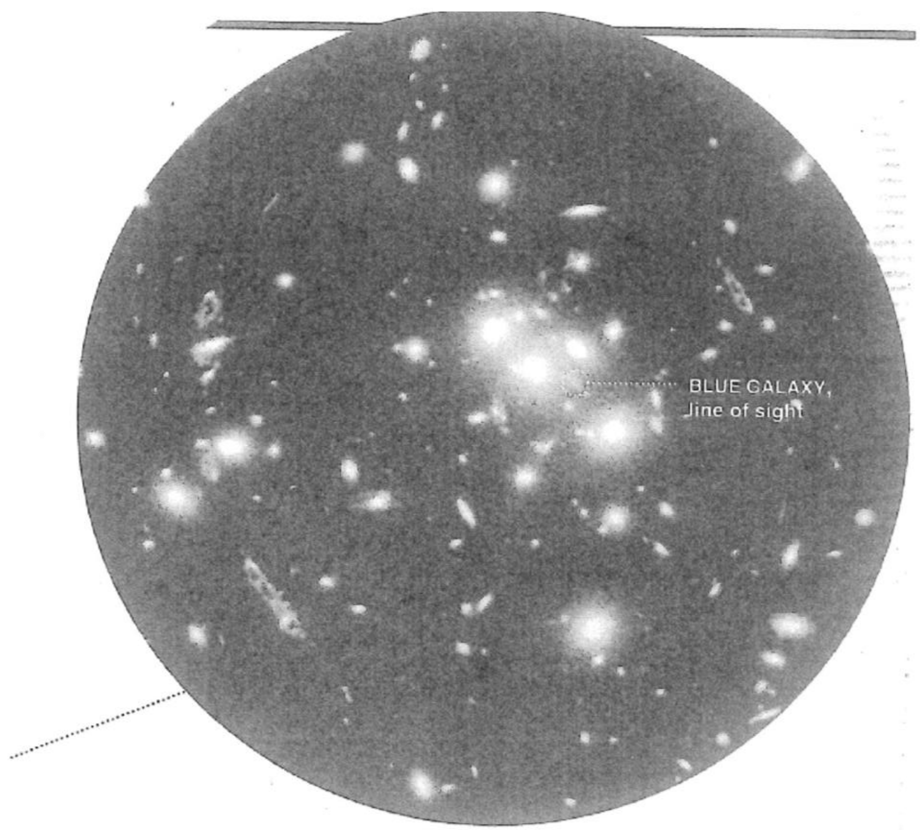
Fig. V-8

John Wilford, Science Times, The New York Times, Dec. 29, 1998, p. F1



John Wilford, Science Times, The New York Times, Dec. 29, 1998, p. F1

Fig. V-9



THE VISIBLE UNIVERSE

The visual result of the lensing is the appearance of blue "mirage" galaxies around the cluster. These are multiple images of the same galaxy.

Fritz Zwicky posited in 1937 that the effect could allow galaxy clusters to act as gravitational lenses. It was not until 1979 that this effect was confirmed by observation of the so-called "Twin Quasar" **Q0957+561**.

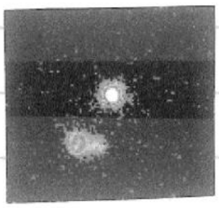
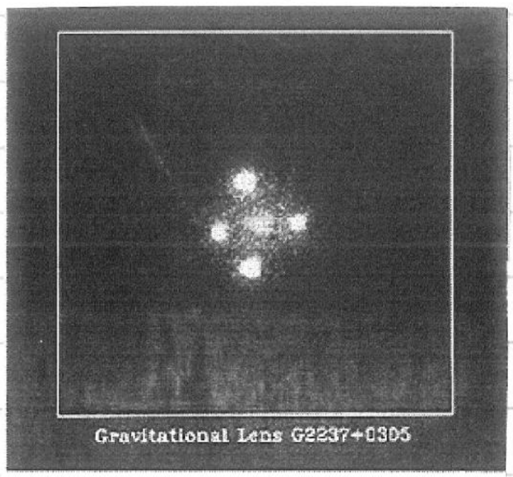
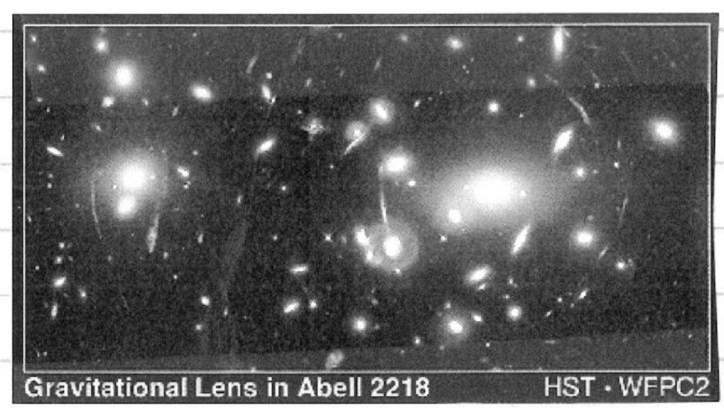


Fig. V-10



In the formation known as Einstein's Cross four images of the same distant quasar appears around a foreground galaxy due to strong gravitational lensing

Fig. V-11



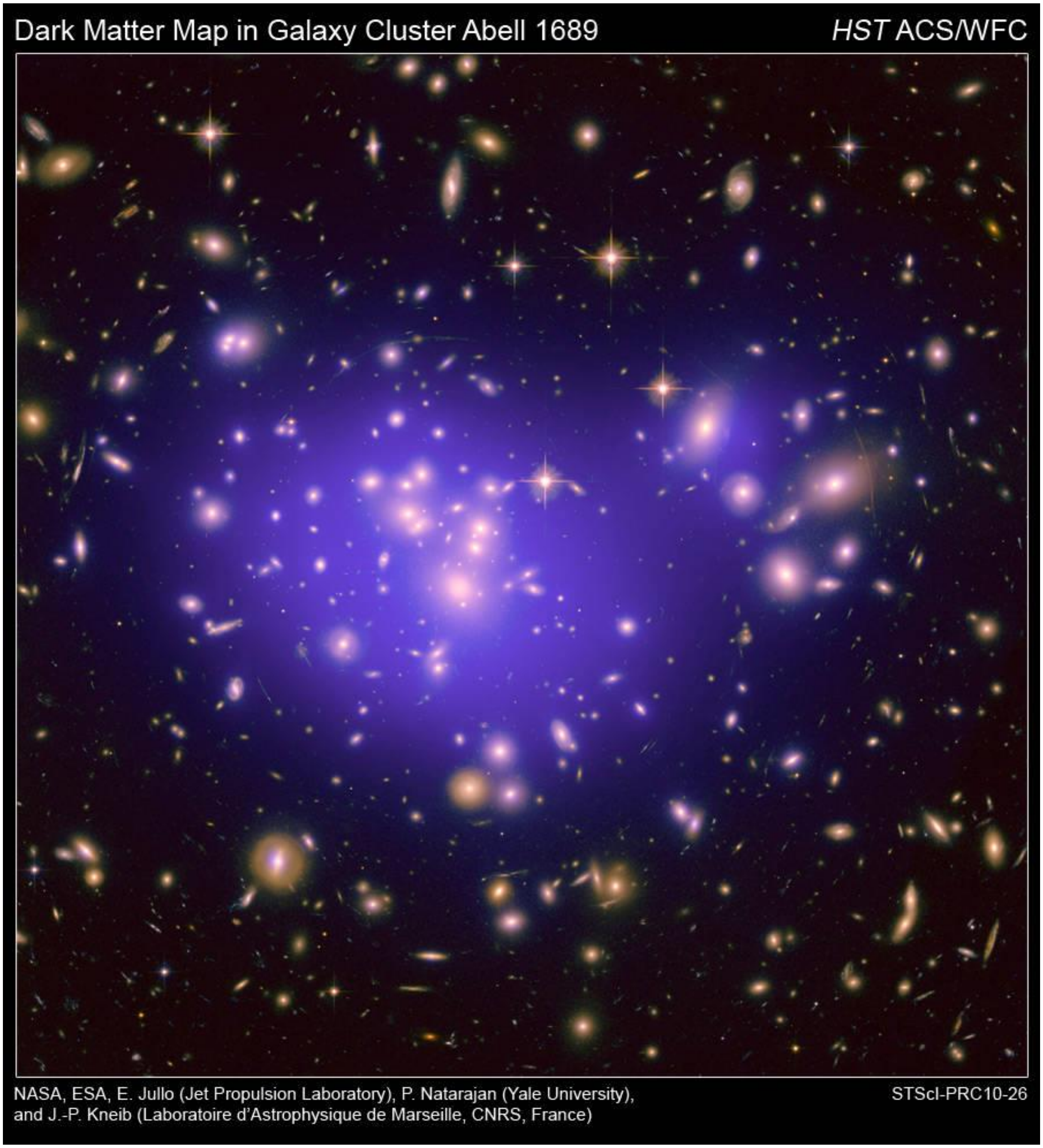


Fig. V-12

The blue haze added to this image **represents** the extracted location and density of "dark matter" associated with this galactic cluster, based on the observed distortion of the galaxy images shining through the cluster to the Hubble Space Telescope. (See the discussion of the Pandora's Cluster on Fig. W-5.)

References:

A.P. French, *The Story of General Relativity* in Einstein, a Centenary Volume, Harvard University Press (1979), p.91.

History Channel, Einstein, A&E Television Network (2008), #7, 8, 9, 10. ISBN: 1-4229-2102-6.

Dava Sobel, The Glass Universe, Viking Press (2016), Chapter 11.

John Wilford, *Science Times*, The New York Times, Dec. 29, 1998, p. F1.

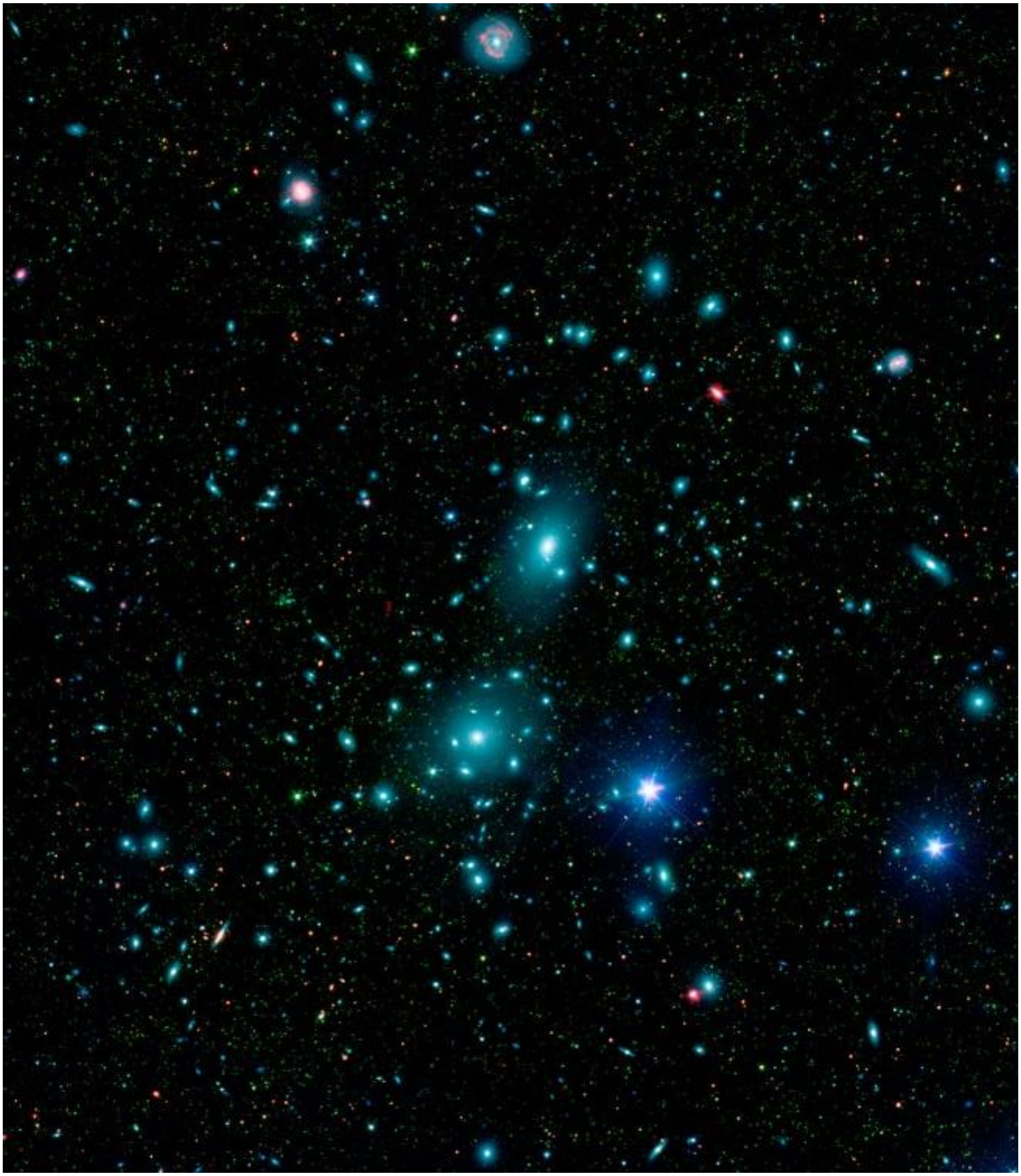
(W) Missing Mass → Dark Matter

In the 1930s, in studying the Coma Cluster of galaxies (Fig. W-1), Fritz Zwicky recognized and drew attention to the fact that, based on the integrated light from the cluster, there was not enough mass in the cluster to make it stable, given the measured velocities of the individual galaxies orbiting in the cluster. He referred to this as the "Missing Mass" problem, which we now refer to it as **Dark Matter**.

With increasingly better observations of the velocities of stars and gas clouds orbiting in galaxies (e.g., M31, the Andromeda Galaxy), it also turned out that the same "missing mass" problem existed in trying to account for the stability/binding of these objects (with their measured velocities) by the visible mass in these galaxies. (e.g., Rubin and Ford, Ap.J. **159** (1970) 379.)

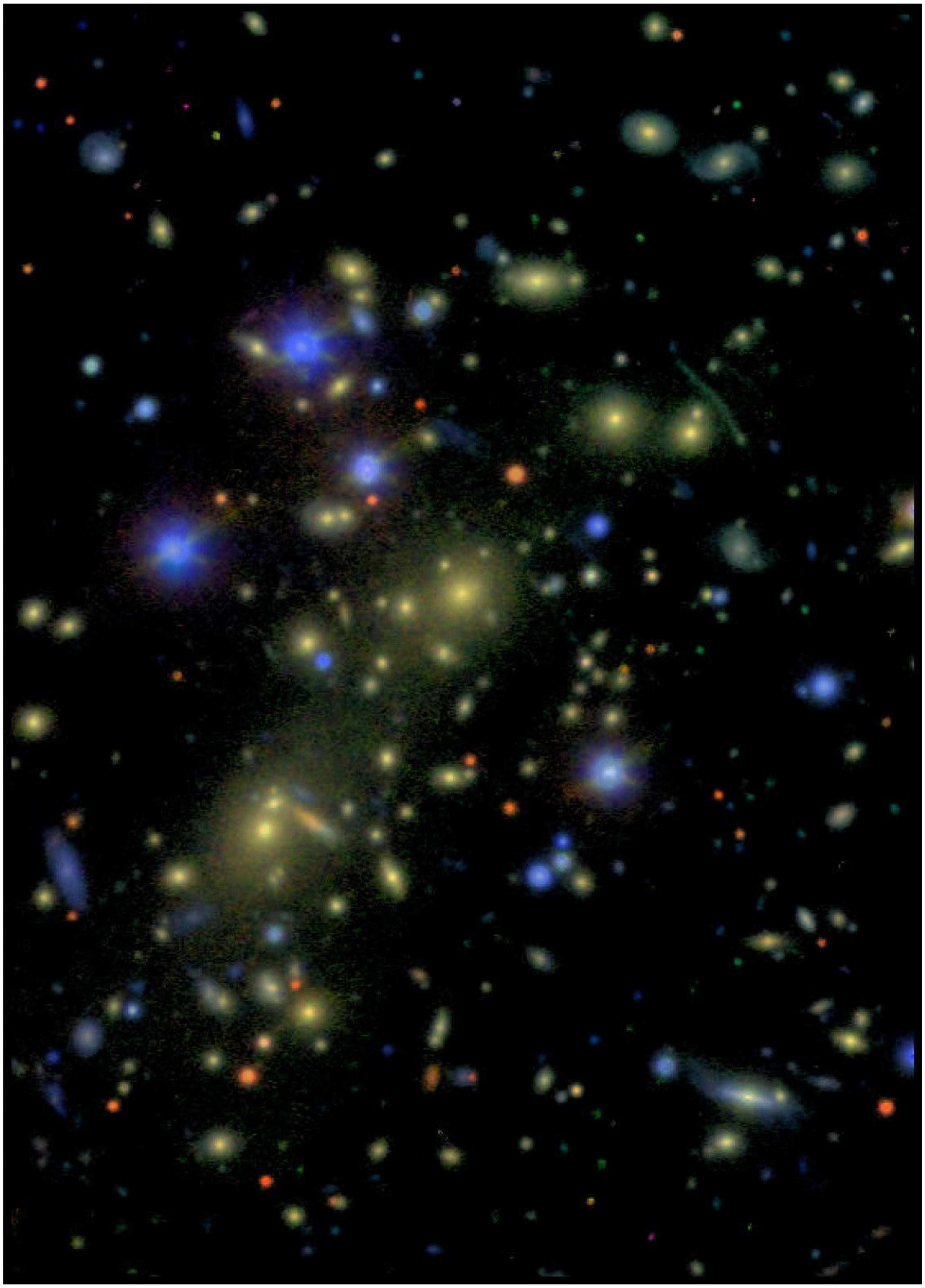
See Fig. W-3, from Vera Rubin, *Seeing Dark Matter in the Andromeda Galaxy* in Physics Today (Dec. 2006) p. 8 of the orbital motion of stars in M31 compared to their positions in the galactic image.

Fig. W-1



Coma Cluster: 1000^{+} to 10,000 (?) galaxies
≈ 300 M light years away

Fig. W-2



Color composite image of the galaxy cluster 1ES 0657-558, based on data taken in the B (blue; exposure 900 sec), V (green; 600 sec), R (red; 500 sec) and I (near-infrared; 600 sec) filters with FORS1 in the standard observing mode at the VLT UT1. A few of the brighter stars in the field saturated the CCD during the exposure; their images have been cleaned in this reproduction. North is up and East is left.
https://www.eso.org/public/usa/images/eso9920u/

reference frame

Seeing dark matter in the Andromeda galaxy

Vera Rubin

Vera Rubin is an observational astronomer who has studied motions of stars and gas in galaxies for 75% of her life. She is at the Department of Terrestrial Magnetism, Carnegie Institution of Washington in Washington, DC.

This is a story of why and how Kent Ford and I studied the orbital velocities of stars in the Andromeda galaxy 40 years ago. Our study was influential in the later conclusion that most of the matter in the universe is dark.

In January 1965 I walked into the Department of Terrestrial Magnetism (affectionately known as DTM), and asked for a job. I had been working at Georgetown University since obtaining my PhD there a decade earlier. But teaching, doing research, and traveling to observatories complicated a busy family life that included a physicist husband and four active children.

It was typical of DTM's unconventional ways that I was not handed a job application. Instead, I was handed a new 2 in. × 2 in. glass plate containing a spectrum of a star, and asked if I could measure its velocity. Back at Georgetown I measured it, and I got the job.

Kent Ford, a DTM physicist, had recently built an image tube spectrograph. It incorporated a two-stage magnetically focused RCA cascaded image tube at the focus of a Cassegrain Schmidt camera. Baked II-aO plates photographed the image tube's final phosphor screen. Using this device on a telescope reduced the exposure time to 1/10th that of an unaided photographic plate. It was a major step forward in telescope instrumentation.

The next year Kent and I embarked on a program to measure rotation velocities in the Andromeda galaxy, M31. We hoped to determine the rotation curve—the velocity relative to the M31 nucleus as a function of nuclear distance—as far out as possible, and thus deduce M31's mass. In our solar system, the orbital velocity of each planet is determined by its distance from the Sun. In a disk galaxy, the disk stars all orbit in the same direction; each star's velocity is determined by the total mass interior to its orbit.

In M31 we hoped to detect the Hα spectral line emitted by hydrogen gas clouds that had been ionized by nearby hot stars. Spectral lines shift blueward (redward) as the star's orbit carries it toward (away from) the observer. I had long been interested in orbital motions of stars at the outer parts of galaxies, a subject little studied. Kent was interested in using the spectrograph at the limits of its capabilities.

It was not simple to work at Lowell Observatory in the 1960s. I would arrive several days before the allotted nights to cut photographic plates into 2 in. × 2 in. squares in total darkness. Baking a plate in an oven for 72 hours magically increased its sensitivity. At the telescope, Kent and I would each guide an exposure in turn, making tiny adjustments to the telescope to keep the guide star exactly on the cross wires. I thought I guided best, and would not relinquish my turn; Kent behaved the same way. We worked in almost total darkness, for a light leak in the telescope or spectrograph could ruin the exposure. I developed the plates.

At the telescope

In December 1967 we took our first spectrum. It was one of 688 Hα regions in M31 that Carnegie astronomer Walter Baade photographed and identified[1] in the 1940s, using the Mt. Wilson 100-in. telescope. The regions were too faint to be visible at the 72-in. Lowell or the 84-in. Kitt Peak telescopes, so we set the telescope by "blind offsets" using exact distances calculated from bright stars on Baade's charts. We also had to account for any slight rotation of the telescope field. A hard task in a cold dark dome with freezing fingers inside heavy gloves.

After completing our first 70-minute exposure, Kent and I and a visiting astronomer (observers love to visit other observers at a telescope) went to the darkroom. I developed the plate and turned on the lights while the plate was washing. We were excited to see a lovely spectrum, and knew then that the program could succeed. Our guest offered to finish the washing so we could start offsetting for the next region. In a few minutes he returned to the dome, leaving the plate washing in running water. When we returned to the darkroom after the next exposure, we found a clear 2 in. × 2 in. piece of glass washing in a basin of hot water! Our guest had mistakenly washed the plate in hot water, causing the emulsion to slither off. Our logbook reads: PLATE DESTROYED IN WASHING. But it didn't matter. I was euphoric! We had proved that we could measure velocities of individual regions in M31, 2.5 million light years from our telescope.

During 1968 and 1969, we observed M31 at Lowell and Kitt Peak whenever we had telescope time. To observe at Kitt Peak, we loaded a van with the spectrograph, power supply, tools, boxes for plate baking, and log books, and drove 300 miles from Flagstaff to Kitt Peak.

Once, the crane in the Lowell dome failed, so Kent and I carried the heavy spectrograph down the dome stairs and headed for Kitt Peak. Dirt roads on arid Native American lands were a visual contrast to the Japanese flower farms south of Phoenix. At the observatory loading dock, three or four Tohono O'odham Native American workmen helped us unload. I never knew if their comment, "There must be an easier way to make a living," referred to them or to us.

Regulations required that a telescope operator stay at the 84-in. telescope all night. Operators hated our arrival, for after setting the telescope on M31 at the twilight start, they had no duties until dawn. They even covered the luminous clock dial, knowing that I objected to any lights. Standing at the telescope in a black dome during a many-hour exposure, guiding by a nearby star, I found the greenish glow of the M31 nucleus exhilarating and a little spooky. Often I wondered if an astronomer in M31 was observing us. Always I wished we could exchange views.

From 1967 to 1969, Kent and I obtained spectra and derived orbital velocities for 67 regions whose distances from M31's center range out to 120 arcmin (89 light years), the farthest region identified by Baade. Interior to 16 arcmin, no regions were found, so we used a long spectrograph slit placed across the M31 nucleus, and detected and measured a weak nitrogen emission line. Exposures ranged from one to several hours. During the long exposures, I would flash my faint red light periodically to identify my surroundings. After our observing run, we carried the plates to DTM. Kent, the consummate instrumentalist, constructed an aluminum can to carry wet plates developed the last night. At DTM, I measured the spectra on a two-dimensional measuring microscope, punched cards manually, and calculated velocities using an early IBM computer.

In my talk at the American Astronomical Society meeting in Austin, Texas, in December 1968, I showed our preliminary rotation curve for M31. The result attracted attention because it represented the largest extent of an optical galaxy rotation curve.[2] Earlier attempts to derive extended rotation curves for galaxies failed[3] because spectrographs were not stable over the tens of hours (3 months for M31 in 1917) for a single exposure. Even spectra obtained by others in the 1960s failed to yield velocities beyond the visibly bright galaxy.

After my talk, the esteemed Rudolph Minkowski asked when we would publish the paper. I replied, "There are hundreds more regions that we could observe." He looked at me sternly and said, emphatically, "I think you should publish the paper now." We did.

'Tis a puzzlement

Our 1970 paper included optical observations out to 120 arcmin[4] but did not include the superposed image of M31, or the 1975 radio observations[5] shown in the figure. This composite of the galaxy and velocities emphasizes the extent of the optical image and the "flatness" of the velocities. We found it puzzling that stars far from the center traveled as fast as those much closer to the center. However, we chose not to extend the curve beyond the final measurement by using a decreasing Newtonian inverse square velocity, the common practice at that time. Instead, we wrote "extrapolation beyond that point is clearly a matter of taste."

Isaac Newton showed that the force on a mass at radius r from the center of a symmetrical mass distribution is proportional to the mass interior to that r. High-school students learn that in a gravitationally bound system like our solar system, a planet moves in a closed orbit, such that $M/G = V^2r$ where M is the mass of the Sun, G is the gravitational constant, and V and r are the velocity of a planet and its distance from the Sun. In M31, the same relation between mass, velocity, and distance holds. A flat rotation curve (V = constant) implies that mass increases linearly with distance from the center. (I leave this as an exercise for the reader.) Enormous amounts of nonluminous matter extend far beyond the optical image of M31.

Although in the 1930s Fritz Zwicky and Sinclair Smith had suggested that dark matter stabilizes clusters of galaxies,[6] their ideas were largely ignored. Our M31 study offered new evidence for dark matter in the universe. After our 1970 paper, it would take a decade of more observations of flat rotation curves and brilliant theoretical ideas[7] for the scientific community to embrace the concept that most matter in the universe is dark.[8]

Early on, I had discussed M31 with Mort Roberts, a near neighbor at the National Radio Astronomy Observatory in Charlottesville, Virginia. In 1975 Roberts and Robert Whitehurst published their survey of the southern end of M31, observed with the 300-ft. Green Bank radio telescope.[5] They traced the extent and velocity of neutral hydrogen gas, using the 21-cm hyperfine transition (a spin flip in the H atom). To the limits of their detection, 150 arcmin, the velocities remain flat. It was Mort who first showed me a superposition of the M31 velocities and the optical image. That composite is a wonderful illustration of the concept of dark matter. The figure raises the questions: What's spinning the stars and gas around so fast beyond the optical galaxy? What's keeping them from flying out into space? The current answer is, "Gravity, from matter that has no light."

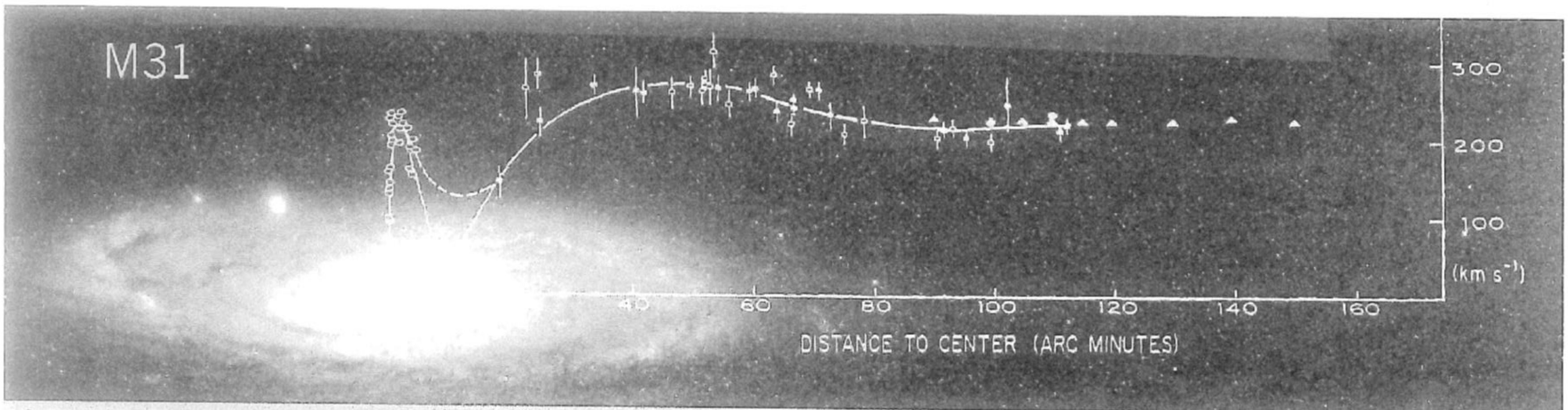
Now, 40 years after Kent and I started studying M31, astronomers know that more than 90% of the matter in the universe is dark, but we only have theories about its composition. The simplicity of our M31 optical observing contrasts with the sophistication of current dark-matter galaxy models and with the experiments planned by particle physicists. A few brave, smart cosmologists work to modify Newton's laws to account for the observations. But no one can predict the surprises that surely lie ahead as we attempt to shed light on nature's dark secret.

References

1. W. Baade, H. C. Arp, *Astrophys. J.* **139**, 1027 (1964).
2. *Sky Telesc.* **27**, 147 (1969).
3. V. M. Slipher, *Lowell Obs. Bull.* **62** (1914). F. G. Pease, *Proc. Natl. Acad. Sci. USA* **4**, 21 (1918); H. W. Babcock, *Lick Obs. Bull.* **498**, 41 (1939); E. M. Burbidge, G. R. Burbidge, K. H. Prendergast, *Astrophys. J.* **138**, 375 (1963).
4. V. C. Rubin, W. K. Ford, *Astrophys. J.* **159**, 379 (1970).
5. M. S. Roberts, R. N. Whitehurst, *Astrophys. J.* **201**, 327 (1975).
6. F. Zwicky, *Helv. Phys. Acta* **6**, 110 (1933); S. Smith, *Astrophys. J.* **83**, 23 (1936).
7. J. P. Ostriker, P. J. E. Peebles, A. Yahil, *Astrophys. J. Lett.* **193**, L1 (1974).
8. S. M. Faber, J. S. Gallagher, *Annu. Rev. Astron. Astrophys.* **17**, 135 (1979).

[Grab your reader's attention with a great quote from the document or use this space to emphasize a key point. To place this text box anywhere on the page, just drag it.]

Fig. W-3



The M31 major axis mean optical radial velocities and the rotation curve,[4] $r < 120$ arcmin, superposed on the M31 image from the Palomar Sky Survey. Velocities from radio observations[5] are indicated by triangles, $90 < r < 150$ arcmin. Rotation velocities remain flat well beyond the optical galaxy, implying that the M31 cumulative mass rises linearly with radius. (Image by Rubin and Janice Dunlap.)

Dark Energy, Dark Matter

https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy

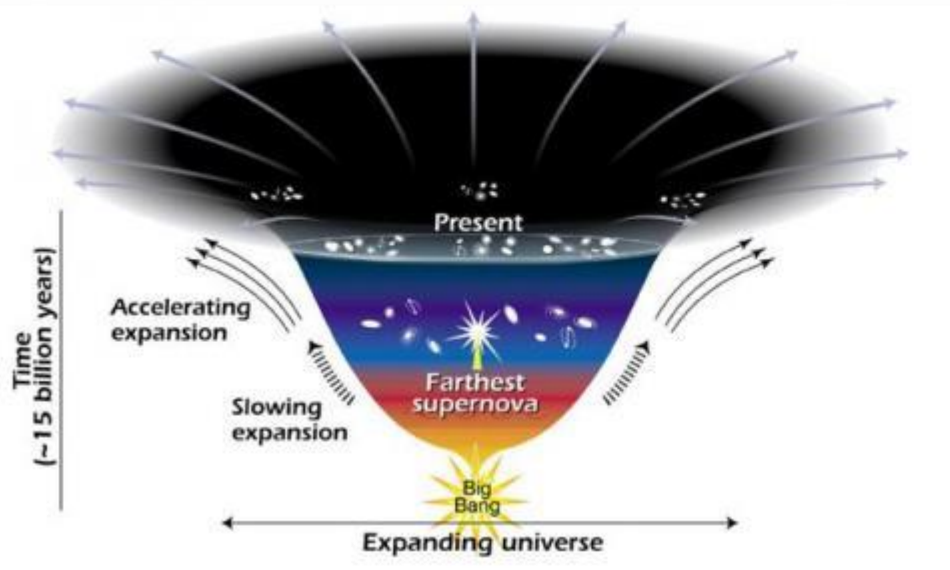
In the early 1990s, one thing was fairly certain about the expansion of the universe. It might have enough energy density to stop its expansion and recollapse, it might have so little energy density that it would never stop expanding, but gravity was certain to slow the expansion as time went on. Granted, the slowing had not been observed, but, theoretically, the universe had to slow. The universe is full of matter and the attractive force of gravity pulls all matter together. Then came 1998 and the Hubble Space Telescope (HST) observations of very distant supernovae that showed that, a long time ago, the universe was actually expanding more slowly than it is today. So the expansion of the universe has not been slowing due to gravity, as everyone thought, it has been accelerating. No one expected this, no one knew how to explain it. But something was causing it.

Eventually theorists came up with three sorts of explanations. Maybe it was a result of a long-discarded version of Einstein's theory of gravity, one that contained what was called a "cosmological constant." Maybe there was some strange kind of energy-fluid that filled space. Maybe there is something wrong with Einstein's theory of gravity and a new theory could include some kind of field that creates this cosmic acceleration. Theorists still don't know what the correct explanation is, but they have given the solution a name. It is called dark energy.

What Is Dark Energy?

More is unknown than is known. We know how much dark energy there is because we know how it affects the universe's expansion. Other than that, it is a complete mystery. But it is an important mystery. It turns out that roughly 68% of the universe is dark energy. Dark matter makes up about 27%. The rest - everything on Earth, everything ever observed with all of our instruments, all normal matter - adds up to less than 5% of the universe. Come to think of it, maybe it shouldn't be called "normal" matter at all, since it is such a small fraction of the universe.

Fig. W-3



Universe Dark Energy-1 Expanding Universe
This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart as a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pulling galaxies apart.
Credit: NASA/STSci/Ann Feild

One explanation for dark energy is that it is a property of space. Albert Einstein was the first person to realize that empty space is not nothing. Space has amazing properties, many of which are just beginning to be understood. The first property that Einstein discovered is that it is possible for more space to come into existence. Then one version of Einstein's gravity theory, the version that contains a <u>cosmological constant</u>, makes a second prediction: "empty space" can possess its own energy. Because this energy is a property of space itself, it would not be diluted as space expands. As more space comes into existence, more of this energy-of-space would appear. As a result, this form of energy would cause the universe to expand faster and faster. Unfortunately, no one understands why the cosmological constant should even be there, much less why it would have exactly the right value to cause the observed acceleration of the universe.
Another explanation for how space acquires energy comes from the quantum theory of matter. In this theory, "empty space" is actually full of temporary ("virtual") particles that continually form and then disappear. But when physicists tried to calculate how much energy this would give empty space, the answer came out wrong - wrong by a lot. The number came out 10^{120} times too big. That's a 1 with 120 zeros after it. It's hard to get an answer that bad. So the mystery continues.

Another explanation for dark energy is that it is a new kind of dynamical energy fluid or field, something that fills all of space but something whose effect on the expansion of the universe is the opposite of that of matter and normal energy. Some theorists have named this "quintessence," after the fifth element of the Greek philosophers. But, if quintessence is the answer, we still don't know what it is like, what it interacts with, or why it exists. So the mystery continues.

A last possibility is that Einstein's theory of gravity is not correct. That would not only affect the expansion of the universe, but it would also affect the way that normal matter in galaxies and clusters of galaxies behaved. This fact would provide a way to decide if the solution to the dark energy problem is a new gravity theory or not: we could observe how galaxies come together in clusters. But if it does turn out that a new theory of gravity is needed, what kind of theory would it be? How could it correctly describe the motion of the bodies in the Solar System, as Einstein's theory is known to do, and still give us the different prediction for the universe that we need? There are candidate theories, but none are compelling. So the mystery continues.

The thing that is needed to decide between dark energy possibilities - a property of space, a new dynamic fluid, or a new theory of gravity - is more data, better data.

By fitting a theoretical model of the composition of the universe to the combined set of cosmological observations, scientists have come up with the composition that we described above, ***~68% dark energy, ~27% dark matter, ~5% normal matter.***

What Is Dark Matter?

Dark Matter Core Defies Explanation
This image shows the distribution of dark matter, galaxies, and hot gas in the core of the merging galaxy cluster Abell 520. The result could present a challenge to basic theories of dark matter.

We are much more certain what dark matter is not than we are what it is. First, it is dark, meaning that it is not in the form of stars and planets that we see. Observations show that there is far too little visible matter in the universe to make up the 27% required by the observations. Second, it is not in the form of dark clouds of normal matter, matter made up of particles called baryons. We know this because we would be able to detect baryonic clouds by their absorption of radiation passing through them. Third, dark matter is not antimatter, because we do not see the unique gamma rays that are produced when antimatter annihilates with matter. Finally, we can rule out large galaxy-sized black holes on the basis of how many gravitational lenses we see. High concentrations of matter bend light passing near them from objects further away, but we do not see enough lensing events to suggest that such objects to make up the required 25% dark matter contribution.

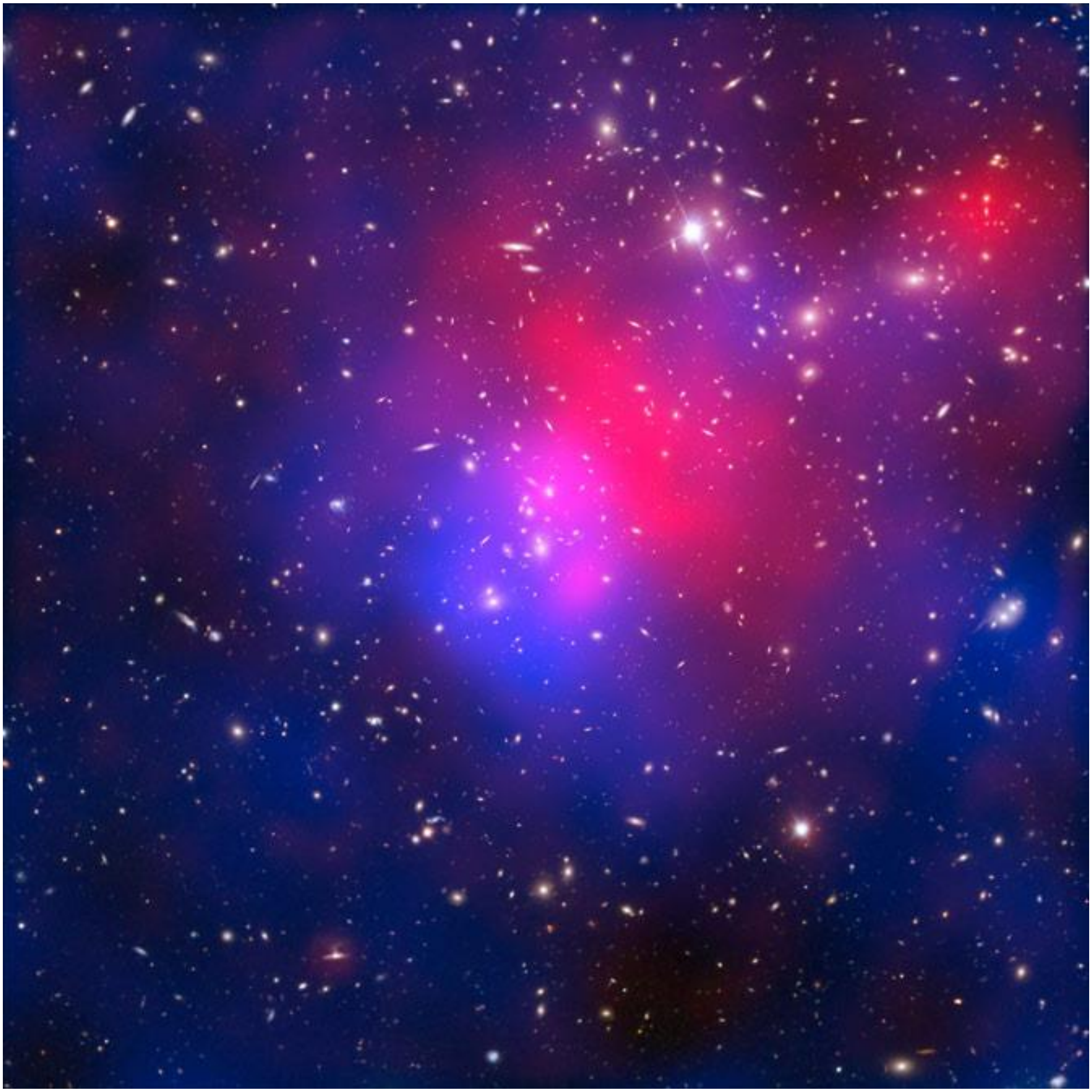
However, at this point, there are still a few dark matter possibilities that are viable. Baryonic matter could still make up the dark matter if it were all tied up in brown dwarfs or in small, dense chunks of heavy elements. These possibilities are known as massive compact halo objects, or "MACHOs". But the most common view is that dark matter is not baryonic at all, but that it is made up of other, more exotic particles like axions or WIMPS (Weakly Interacting Massive Particles).

https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy

Fig. W-5

Pandora's Cluster — Clash of the Titans

https://www.nasa.gov/mission_pages/hubble/science/pandora-cluster.html
06.22.11



A team of scientists studying the galaxy cluster Abell 2744, nicknamed Pandora's Cluster, have pieced together the cluster's complex and violent history using telescopes in space and on the ground, including the Hubble Space Telescope, the European Southern Observatory's Very Large Telescope, the Japanese Subaru telescope, and NASA's Chandra X-ray Observatory. The giant galaxy cluster appears to be the result of a simultaneous pile-up of at least four separate, smaller galaxy clusters. The crash took place over a span of 350 million years.

The galaxies in the cluster make up less than 5 percent of its mass. The gas (around 20 percent) is so hot that it shines only in X-rays (colored red in this image). The distribution of invisible dark matter (making up around 75 percent of the cluster's mass) is colored here in blue.

Dark matter does not emit, absorb, or reflect light, but it makes itself apparent through its gravitational attraction. To pinpoint the location of this elusive substance the team exploited a phenomenon known as gravitational lensing. This is the bending of light rays from distant galaxies as they pass through the gravitational field created by the cluster. The result is a series of telltale distortions in the images of galaxies in the background of the Hubble and VLT observations. By carefully analyzing the way that these images are distorted, it is possible to accurately map where the dark matter lies. Chandra mapped the distribution of hot gas in the cluster.

The data suggest that the complex collision has separated out some of the hot gas (which interacts upon collision) and the dark matter (which does not) so that they now lie apart from each other, and from the visible galaxies. Near the core of the cluster there is a "bullet" shape where the gas of one cluster collided with that of another to create a shock wave. The dark matter passed through the collision unaffected.

In another part of the cluster, galaxies and dark matter can be found, but no hot gas. The gas may have been stripped away during the collision, leaving behind no more than a faint trail.

The Hubble Space Telescope is a project of international cooperation between NASA and the European Space Agency. NASA's Goddard Space Flight Center manages the telescope. The Space Telescope Science Institute (STScI) conducts Hubble science operations. STScI is operated for NASA by the Association of Universities for Research in Astronomy, Inc., in Washington, D.C.

https://www.nasa.gov/mission_pages/hubble/science/pandora-cluster.html

Related Links:
http://www.nasa.gov/hubble
http://hubblesite.org/news/2011/17
http://www.spacetelescope.org/news/heic1111

References:

Dark Energy, Dark Matter
https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy.

Pandora's Cluster — Clash of the Titans
https://www.nasa.gov/mission_pages/hubble/science/pandora-cluster.html.

V.C. Rubin and W.K. Ford, Ap. J.**159** (1970), 379.

Vera Rubin, *Seeing Dark Matter in the Andromeda Galaxy*, Physics Today (December 2006), p. 8.

Fritz Zwicky, Helv. Phys. Acta **6** (1933), 110.

(X) Gravitational Radiation - LIGO

Gravitational radiation (gravity waves and gravitons), first predicted by Einstein's theory of General Relativity in 1916, were detected indirectly in the 1970s in observations of the decaying orbit of a binary pulsar (two orbiting neutron stars) using the Arecibo Radio Telescope on Puerto Rico (see Figs. X-1 and X-2) for which (Hulse and Taylor, 1975) won the Nobel Prize in 1993.)

At the time that this seminar was most recently held at Yale (fall 2012), the most that one could say about the *direct* detection of gravitational waves was to describe the techniques involved in the interferometer, LIGO, that was being built and upgraded (and then further upgraded) at that time. (e.g., Barish and Weiss, 1999)

BUT, three years later on Sept. 14, 2015, along came LIGO's ***direct* detection** of the pulse of gravity waves from a binary black-hole merger (two black holes with a masses of 36× and 29× the mass of the sun, respectively) published in Phys.Rev.Letts. in February, 2016 [A Classic Discovery Paper!] . (Nobel Prize – 2017.) This was followed by the subsequent detection of similar events on Dec. 26, 2015, and on Jan. 04, 2017, etc. The labeling system for these events is GW150914, GW151226, GW170104, GW170814. [GW=Gravity Wave; the number correspond to 150914 = 2015 Sept 14; and so on.] GW170814 was also confirmed by the recently completed interferometer, Virgo, near Pisa, Italy, and the additional Virgo data provided a much tighter location for this event as can be seen in Fig. X-3.

These first 4 events were each an example of the merger of two large black holes (each ~40 solar masses). Then just 3 days after GW170814, GW170817 provided an example of a very different event - the merger of two neutron stars (each ~1.4 solar masses) with a completely different time pattern for the squeezing and stretching of space-time (Fig. X-4). Not involving black holes,this event produced a simultaneous **visible** signal in the electromagnetic spectrum from gamma-rays (Fermi-GRB and INTEGRAL satellites) to radio waves (the VLA, in New Mexico) and included dozens of visible-light telescopes, world-wide. These emissions have been interpreted as indicating that such binary-neutron-star merger events are the primary sites for the production of r-process heavy elements. (Look back at Section T,)

As the sensitive range for studies of our universe extends further out in distance and correspondingly further back in time, it is interesting and important to note that we find that the physical laws and constants remain unchanged.

Fig. X-1

Arecibo Observatory

Movies:

<u>Golden Eye</u> – James Bond Film
<u>Contact</u> – Starring Jodie Foster (Yale ’85)

Role Reversal:

1974 – In addition to receiving signals, Arecibo was also used to send out a message to anyone who might be listening - in the direction of Globular Cluster M13, ≈25,000 light-years away.

Fig. X-2

Arecibo Radio Telescope, Puerto Rico

Spherical Diameter = 305 meters
Bottom to Upper Platform ≈ 150 meters
Towers ≈ 100 meters

LIGO AND THE DETECTION OF GRAVITATIONAL WAVES

Large detectors on opposite sides of the country are about to start monitoring the cosmos for the gravitational waves that general relativity tells us should be emanating from catastrophic astrophysical events.

Barry C. Barish and Rainer Weiss

The idea of gravitational waves was already implicit in the 1905 special theory of relativity, with its finite limiting speed for information transfer. The explicit formulation for gravitational waves in general relativity was put forward by Einstein[1,2] in 1916 and 1918. He showed that the acceleration of masses generates time-dependent gravitational fields that propagate away from their sources at the speed of light as warpages of spacetime. Such a propagating warpage is called a gravitational wave.

The best empirical evidence we have of the existence of gravitational radiation is indirect. It comes from the 1974 discovery and beautiful observations, by Russell Hulse and Joseph Taylor,[3] of the first binary pulsar ever found. (See PHYSICS TODAY, December 1993, page 17.) Exploiting the clockwork pulsar signal from the neutron star, they were able to monitor the orbital period of the binary star system with exquisite precision and confirm that it was indeed gradually speeding up at just the rate predicted for the general-relativistic emission of gravitational waves.

The *direct* detection of gravitational waves will mark the opening of a new window on the near and far reaches of the cosmos. For physics, its most important promise is the direct observation of gravitation in highly relativistic settings, so that one can test general relativity in the strong-field limit, where it is not merely a small correction to Newtonian gravity. (See the companion article in this issue by Clifford Will, on page 38.) In that limit, the strong curvature of the spacetime geometry should show us fundamentally new physics.

By the time they reach us, the gravitational waves are, of course, only very weak perturbations on our local flat space. But they will provide information about the strong-field regions where they began. The detection of the waves will also allow us to determine the wave properties of the gravitational radiation—for example, their propagation velocity and polarization states.

For the astrophysicist, the observation of gravitational waves will provide a new and very different view of the universe. These waves arise from motions of large aggregates of matter, rather than from the particulate sources that produce electromagnetic waves. Because gravitational waves are not scattered as they propagate between source and observer, they should provide information about what's happening in the innermost and densest regions of the astrophysical source. Probing the universe in this very different way, gravitational radiation is likely to bring us exciting surprises and unanticipated new astrophysics.

A new generation of detectors based on suspended mass interferometry promises to attain the requisite sensitivity for observing gravitational waves. (See figure 1.) These new detectors are the fruit of a quarter-century of worldwide technology development, design, and construction. The US effort, called LIGO (Laser Interferometer Gravitational-Wave Observatory), is a joint Caltech–MIT project, supported by the National Science Foundation. LIGO is a pair of L-shaped laser interferometers: one in Hanford, Washington, the other, some 3000 km away, in Livingston, Louisiana. (See figure 2.) Each evacuated interferometer arm is 4 km long.

The LIGO facilities at both sites have now been completed, and detector installation is under way. Following a two-year commissioning program, we expect the first sensitive searches for astrophysical gravitational waves to begin in 2002. This initial search, sensitive to changes (strains) as small as a part in 10^{21} in the lengths of the interferometer arms, will be the first attempt to detect gravitational waves at a sensitivity that reaches plausible estimates for astrophysical source strengths. It will mark a 100- to 1000-fold improvement over previous searches—both in sensitivity and bandwidth.

The two LIGO interferometers will operate in coincidence, so as to filter out local noise. In fact, to provide additional coincidence surety, a third independent interferometer, half as long as the other two, will share the vacuum system of the full-size interferometer at Hanford. Also, one determines the direction and polarization of a gravitational wave by measuring arrival-time differences between geographically dispersed detectors. At the Hanford and Livingston support facilities, efforts will continue on the development of improved and special-purpose detectors of increased search and follow-up sensitivity.

Gravitational radiation

The gravitational wave plays a role in gravitation similar to that of the electromagnetic wave in electricity and magnetism. But because mass, unlike charge, comes in only one sign and the momentum of a free system must be conserved, the lowest-order source of gravitational radiation is quadrupolar.

The radiation field causes a strain in space itself, transverse to the propagation direction. The strain pattern contracts space along one transverse dimension while expanding it along the orthogonal direction in the transverse plane. One way of imagining this distortion of space

BARRY BARISH *is a professor of physics at the California Institute of Technology in Pasadena and director of the LIGO laboratory.* **RAINER WEISS** *is a professor of physics at the Massachusetts Institute of Technology in Cambridge and the LIGO project's integration scientist.*

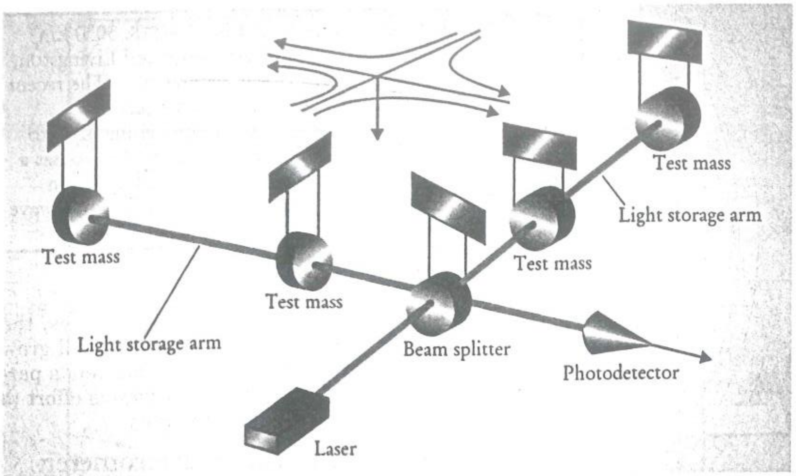


FIGURE 1. THE LIGO GRAVITATIONAL-WAVE DETECTORS are equal-arm Michelson laser interferometers whose hanging mirrors serve as the gravitational test masses. An incident gravitational wave, indicated in red by the stress pattern coming down from above, stretches one interferometer arm and compresses the other, causing a difference between light travel times in the two orthogonal arms. This time difference is manifested in the interference pattern when the two laser beams recombine on the way to the photodetector, which can measure phase shifts to a few ten-billionths of an interference fringe.

is to look at the weave in a piece of cloth when it's pulled along one dimension. The little squares of the weave distort in just this way. Furthermore the strain is quite uniform, so that the relative motion of points in the cloth depends linearly on their separation.

It is this linear increase in the relative motion that provides the motivation for LIGO's 4 km interferometer arms. Such ambitious length is intended to provide adequate sensitivity to passing gravitational waves in the face of inevitable local perturbations. The tensor character of gravity (the putative graviton is a spin-2 particle) means that the push/pull pattern of the strain field for a plane gravitational wave has two orthogonal polarizations. If a candidate signal really is a gravitational wave, and not just noise, the half-length auxiliary interferometer at the Hanford site should see a coincident displacement half as large as that experienced by its full-length neighbor.

One can also think of the gravitational wave as producing a tidal force field such that the relative force between masses grows as their separation. The field will pull masses together along one transverse direction while pushing them apart along the orthogonal direction. How one chooses to view the wave–matter interaction is really a matter of taste. But one must be careful to maintain consistency in one's view and not mix the geometric and tidal representations.

The strength of the gravitational field is expressed by the dimensionless strain

$$h \approx \left(\frac{GM}{Rc^2}\right)\left(\frac{v^2}{c^2}\right)$$

where the factor in the first pair of brackets is the Newtonian potential due to a source mass M at a distance R, divided by the square of the speed of light. On the surface of the Earth, that comes to 10^{-8}, a very weak field. But, at the surface of a neutron star, it can be as large as 10^{-1}. And at the horizon of a black hole, it is close to unity—the ultrarelativistic limit of a strong gravitational field. The factor in the second bracket pair—an estimate of the system's kinetic energy in asymmetric motion relative to its rest energy—is a measure of the strength of the relativistic dynamics.

This expression gives us an immediate estimate of the scale of the strains we might encounter. Consider, for example, a solar-mass source at a Galactic distance, moving at about 10% of the speed of light. In such a case, the strain we would observe halfway across the Galaxy would not exceed a part in 10^{18}. This simple estimate explains why we have to take such heroic measures to detect the strains. Even over the 4 km span of a LIGO arm, the relative displacement of two objects would be only a few times 10^{-13} cm, just about the size of an atomic nucleus! It's even worse than that. As discussed below, plausible sources typically lead to strains of only 10^{-21}, corresponding to LIGO displacements a thousand times smaller than the width of a nucleus.

Candidate sources

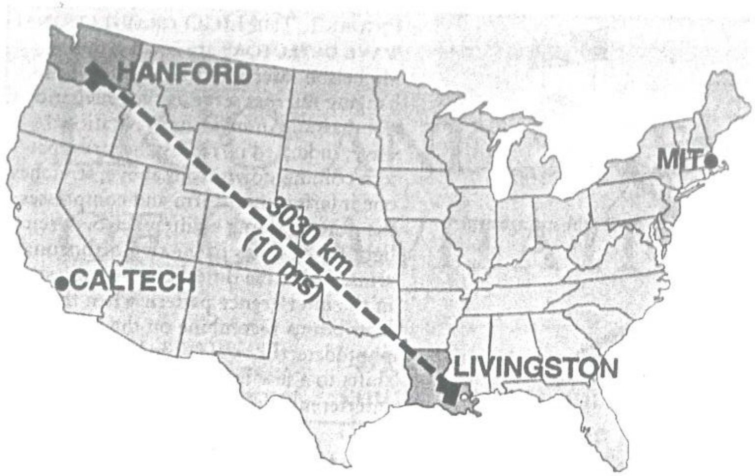
There is a large range of processes in the universe that should produce detectible gravitational waves.[4] Terrestrial interferometers like LIGO will search in the frequency range from 10 Hz to 10 kHz for characteristic signals from a variety of astrophysical sources for which one might hope to discern the signatures of gravitational radiation over the background noise. (See figure 3.)

▷ **Chirp signals.** The terminal spiraling of a star into a "compact" binary partner (a neutron star or a black hole) will produce radiation that increases in amplitude and frequency as the two move toward final coalescence. This chirp signal can be well characterized, depending on parameters such as the mass, separation, and orbital eccentricity. That makes it possible to formulate efficient detection templates.

▷ **Burst signals.** The collapse of a supernova may produce gravitational radiation. Type II supernova collapses can generate strong gravitational radiation, *if* the core collapse departs sufficiently from axial symmetry. Estimates suggest that detection might be possible for such collapses as far out as the Virgo Cluster of galaxies, some 50 million

Initial parameters for the LIGO detectors

Arm length	4000 m
Arm cavity storage time	880 μs
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power at recycling cavity	6 W
Power recycling gain	30
Mirror mass	10.7 kg
Mirror diameter	25 cm
Mirror loss	$<1\times10^{-4}$
Mirror internal Q	1×10^{6}
Cavity input mirror transmission	3×10^{-2}
Pendulum Q (structure damping)	1×10^{5}
Pendulum period (single)	1 s
Seismic isolation system	-110 dB at 100 Hz



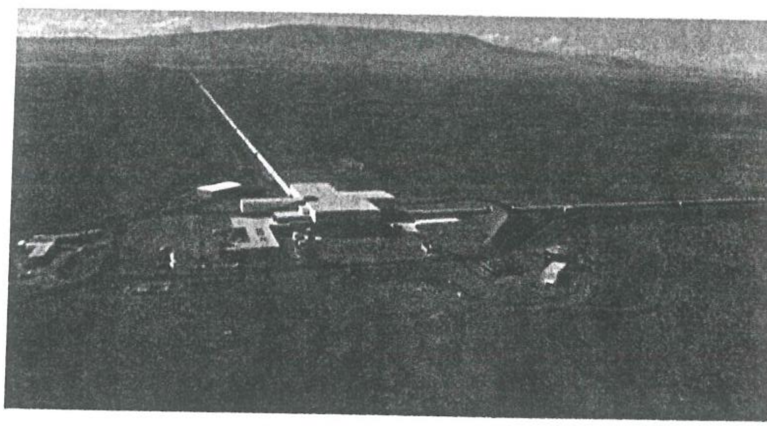


FIGURE 2. THE TWO LIGO SITES, 3030 km apart, in Hanford, Washington and Livingston, Louisiana, will work in coincidence. The recent photo of the Hanford site shows the two orthogonal 4 km vacuum pipes going off into the distance. The vacuum system also houses a smaller auxiliary interferometer, with 2 km arms to help distinguish true gravitational wave signals from noise.

light-years away. That would yield type II supernova observation rates of one or more per year. Another possible burst source accessible to LIGO is the brief, burplike oscillation of a black hole's event horizon just after it swallows a star. The detection of supernova or postprandial black hole events will require coincident observation of burst signals in several geographically dispersed interferometers.

▷ **Periodic signals.** Radiation from the nonaxisymmetric motion of a neutron star, or of the nuclear fluid on its surface might produce periodic signals in the detectors. Happily, for many known pulsars the frequency of such periodic signals lies within LIGO's sensitivity band. The searches for periodic gravitational signals from identified neutron stars will be facilitated by the fact that one can track the system continually over very many cycles, taking account of the gradual slowing of the pulsar's spin and the Doppler shifts and amplitude variation due to the Earth's diurnal and annual motions. We expect to perform general sky searches as well as targeted searches of known pulsars.

▷ **Stochastic signals.** Signals from gravitational waves emitted in the first instants of the early universe—as far back as the Planck epoch at 10^{-43} seconds—can be detected by way of correlations of background signals from two or more detectors. Some models of the early universe predict detectable signals. Such relic gravitational radiation would provide us with an exciting new cosmological probe.

The initial parameters for the LIGO interferometers have been chosen to provide a sensitivity with a reasonable chance for detecting gravitational waves. (See the table on page 45.) The anticipated rates for the various sources, however, are burdened with large uncertainties. As future advances in detector sensitivity increase the distance over which one can find sources, the rate at which events are observed will grow *as the cube* of LIGO's reach. That lends particularly high priority to a vigorous effort to improve the system's sensitivity.

Basic idea of the interferometer

A Michelson interferometer operating between freely suspended masses is ideally suited to detect the antisymmetric compression and distension of space induced by gravitational waves.[6] Figure 1 is a schematic drawing of the LIGO equal-arm Michelson interferometer. The two interferometer arms, each 4 km long in the full-length detectors, have identical light-storage times. Light sent from the laser light source to the beam splitter is divided evenly between the two arms.

Having traversed the arms, the light is reflected back to the splitter by mirrors at their far ends. On the return journeys to the photodetector, the roles of reflection and transmission in the splitter are interchanged for the two beams and, furthermore, the phase of the reflected beam is inverted by 180°. Therefore the recombined beams heading toward the photodetector interfere destructively, while the beams heading back to the laser source interfere constructively. If the interferometer arms are of precisely equal length, the photodetector ideally sees no light, all of it having been diverted, by perfect interference, back to its source.

One would get this kind of perfect interference if the beam geometry provides a single phase over the propagating wavefront. An idealized uniphase plane wave has this property, as does the Gaussian wavefront in the lowest-order spatial mode of a laser. Then, provided the arms are equal in length (or their length difference is a multiple of half the wavelength of the monochromatic beam), the photodetector sees no light at all. The destructive interference over the entire beam wavefront is complete.

If, in the absence of any disturbance, the interferometer is carefully balanced so that no light appears at the photodetector, a sufficiently strong gravitational wave passing though the interferometer can disturb this balance and cause light to fall on the detector. That, in essence, is how LIGO will sense gravitational waves. To obtain the required sensitivity, we have made the arms 4 km long, and we have included two refinements:

▷ First, the intensity change at the photodetector due to a gravitational wave depends on the interaction time of the wave with the light in the arms. The longer this interaction time—up to half the period of the gravitational wave—the larger is the resulting optical phase shift and the consequent change of the light intensity at the photodetector. To gain further interaction time, beyond what one gets simply from the 4 km arm length, the initial

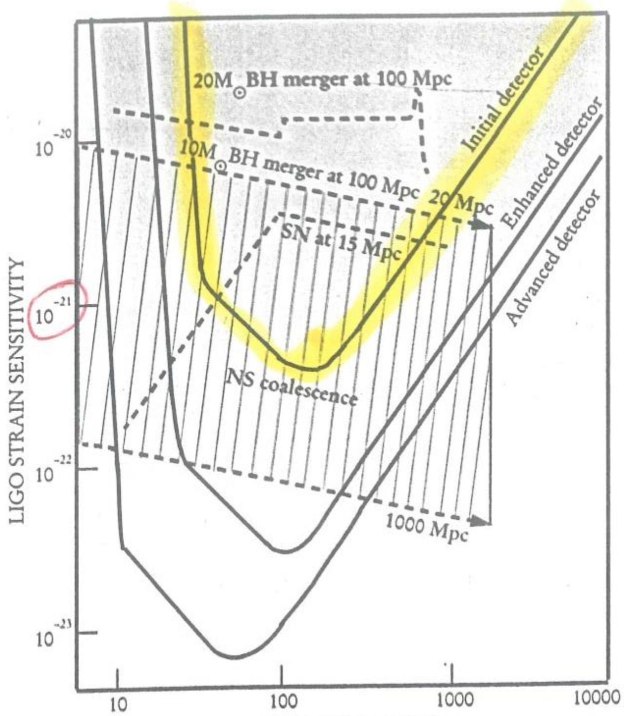


FIGURE 3. RMS STRAIN SENSITIVITY LIMITS as a function of signal frequency, for three LIGO generations indicated by the U-shaped black curves, are compared with signal estimates for various astrophysical sources. The "enhanced" detector is anticipated for 2006, and the "advanced" detector four years later. The shaded red region indicates the strain signal expected from the coalescence of two neutron stars at distances from 20 to 1000 megaparsecs (1 Mpc = 3×10^6 light-years), and from the merger of two 10 $M_\odot$ black holes at least 100 Mpc away. The larger and more structured signal expected from the merger of two 20 $M_\odot$ black holes at 100 Mpc is indicated by the purple dashed curve. The green dashed curve indicates the signal expected from an asymmetric supernova 15 Mpc away. One expects a few events per year within the red parallelogram.

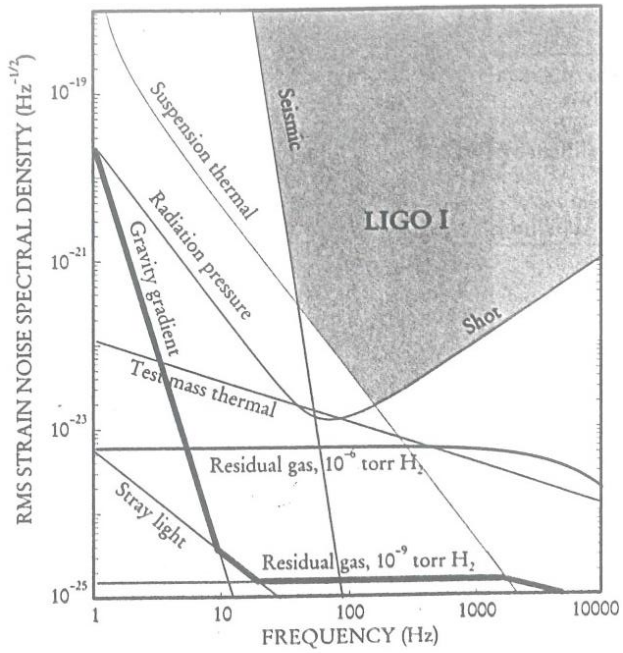


FIGURE 4. LIMITING NOISE SOURCES for the initial LIGO interferometers are shown on a plot of frequency against spectral noise density. The vertical axis denotes the RMS strain noise in 1 Hz of bandwidth. The noise increases as the square root of bandwidth, so that the noise in a typical 100 Hz window would be 10 times that shown on the axis. At the lowest frequencies, sensitivity is limited by geophysical and man-made seismic noise; at intermediate frequencies by thermal noise; and at the highest frequencies by the shot noise of photon statistics. The green line represents the minimum noise at the present LIGO facilities, irrespective of eventual detector upgrades.

LIGO interferometers will also fold the optical beams within the arms by means of optical cavities. This trick results in a light-storage time of about 1 millisecond. That's about 50 times longer than a simple straight transit through a 4 km arm.

▷ A second refinement increases the interfering light intensity by making the entire interferometer a resonant optical storage cavity. Most of the light interferometrically diverted from the photodetector direction—when the arms are unstrained—returns toward the light source. That makes it possible to achieve a significant gain by placing another mirror between the laser and the beam splitter. By properly choosing this extra mirror's position and making its transmission equal to the optical losses inside the interferometer, one can match the losses so that no light at all is reflected back to the laser. This is equivalent to increasing the laser power by about a factor of 30, without adversely affecting the frequency response of the interferometer to a gravitational wave.

Sensitivity limits

The success of the detector will ultimately depend on how well we can control the noise in the measurement of the exceedingly small strains we have been discussing. That has been the prime technological challenge in this field for the past several decades, and it is the central focus of our development of the technology for LIGO. The noise we have to contend with is broadly divided into sensing noise, random force noise and, ultimately, quantum noise. Sensing noise involves the various phenomena that limit our ability to sense and register the small motions in question. Random force noise, on the other hand, results from disturbances that cause small motions of the suspended masses. Eventually one confronts the ultimate quantum noise limit. This orderly classification presumes that one is careful enough in the design and execution of the experiment to reach the fundamental limits. The quantum limit will not be an issue for the first or second generation of LIGO detectors. So we do not address it in this article. There is, however, important ongoing work that seeks to understand the quantum noise limit and develop techniques to circumvent it in measuring the strain.

In order to approach the fundamental limits, we have made extensive use of two concepts in experimental physics promoted by Robert Dicke (1916–97) of Princeton University. The first is the technique of modulating the signal to be detected at frequencies far above the $1/f$ noise due to the drift and gain experienced by all instruments. For example, we measure the optical phase to determine the motion of an interference fringe at radio frequency rather than near DC.

A second concept is to apply feedback to physical vari-

FIGURE 5. LIGO'S SEISMIC ISOLATION SYSTEM consists of four layers of masses and springs. Each of the coil springs seen here is made by lining the inside of a straight metal tube with rubbery damping material and then filling the lined tube with a line of metal slugs strung on a rubber core. The tube is then coiled and sealed.

ables in the experiment in order to control and damp large excursions at low frequencies. The variable is measured by way of the control signal required to hold it stationary. A good example is the position of the interferometer mirrors. At low frequencies, we maintain the interferometer fringe at a fixed phase by holding the mirrors at fixed positions with coil/magnet actuators.

Sensing noise

Our ability to determine the relative motions of the mirrors at the ends of the arms interferometrically is limited by the smallest change in optical phase that we can measure. The light emitted by a conventional laser is in a coherent state in which the photon occupation number n obeys a Poisson distribution with variance

$$\Delta n = \sqrt{n} = \sqrt{\dot{n}\tau}$$

where is the rate at which photons encounter the beam splitter and τ is the integration or observation time. Because the phase and photon occupation number are conjugate variables obeying an uncertainty relation, one gets

$$\Delta\phi = 1/\sqrt{\dot{n}\tau}$$

for the variance in the interferometric measurement of the relative phase of the recombining beams at the photodetector. We expect the optical-phase variance in the initial LIGO detector to be about 3×10^{-10} radians, corresponding to a strain variance in a 10-millisecond measurement of about 2×10^{-22}. That would be the fundamental Poisson limit. It is sometimes called the shot-noise limit, because it can also be derived from the statistics of photon counting in the photodetection. This shot noise determines LIGO's sensitivity limit for frequencies above 300 Hz. (See figure 4.)

Before one reaches this limit, however, one has to deal with a host of practical problems, such as laser frequency fluctuations, laser amplitude noise, and stabilization of the beam geometry. We must also reduce additional sensing noise terms that can occur in the beam propagation—for example, scattering by residual gas molecules and scattering off the vacuum tube walls driven by seismic and acoustical noise. We limit these effects by using baffling and low-scatter optics in the evacuated beam tubes. But even if one controls these noise terms and achieves the fundamental Poisson noise limit, one cannot easily reduce the noise any further by simply increasing the laser power to get more photons. That remedy raises problems of optical heating in the mirrors and coatings and, finally, radiation pressure fluctuations.

Random force noise

At lower frequencies, the sensitivity limit is set by how well the motions of our test masses—the hanging mirrors—are controlled. At the lowest frequencies (about 10–100 Hz), the largest disturbances come from "seismic noise"—the motion of the Earth's surface driven by wind, water flow, and human activities, as well as by low-level earthquakes. At intermediate frequencies (100 Hz), the principal culprit is thermal noise—that is, Brownian motion driven by thermal excitations. Less important for the initial LIGO interferometers, but increasingly significant as the detectors are upgraded, will be fluctuations in the Newtonian gravitational forces on the mirrors resulting from density fluctuations in the ground and the atmosphere and, ultimately, the radiation pressure fluctuations.

In general, these random forces are not correlated at the different mirrors, and they are independent of the length of the interferometer arms. By contrast, displacements due to gravitational waves grow linearly with the arm length. That's our principal motivation for going to the expense and trouble of having 4 km arms.

The LIGO suspended mirrors, which serve as the test masses, are isolated from motions of the Earth by cascaded stages of vibration isolation. The first level of isolation, consisting of four stages of springs and masses, reduces the seismic motion a millionfold at frequencies around 100

FIGURE 6. A LIGO MIRROR, 25 cm in diameter and 10 cm thick, is made of ultrapure fused silica. Its purple coating is a highly reflective multilayer stack of dielectric materials. Absorption and scattering losses must not exceed a few parts per million.

Hz, and progressively more at higher frequencies. (See figure 5.) This isolation works much like the suspension in a car. The final stage of the isolation system is the hanging mirror itself. Each test mass is, in effect, a pendulum suspended by flexures. The pendulum provides another stage of vibration isolation. But, more important, it also serves to reduce the influence of thermal noise.

Mechanical thermal noise enters the system by exciting the pendulum, causing the test mass to move, and by exciting acoustic waves that disturb the mirror surface. The acoustic noise can be represented as a superposition of the motions induced in the normal modes of the mass. The strength of the perturbation is estimated by taking the overlap of the acoustic-mode shape with the optical wavefront. The equilibrium thermal excitation of each normal mode at temperature T is $kT/2$, yielding significant motion at the principal resonant frequencies. Therefore we choose these frequencies to be outside LIGO's detection band for gravitational waves.

The thermal noise is a more fundamental and difficult problem than the seismic noise. Our primary techniques for reducing the thermal noise are to cool specific modes and to design systems with low dissipation. The seismic noise, by contrast, is motion relative to the inertial frame. So one can use the inertial frame as a reference to reduce the driving accelerations.

Detection strategies and confidence

In developing LIGO's search techniques, statistical tests, and detection criteria, we seek to minimize false observations. Within the statistics associated with the instrument noise, a viable gravitational wave signal from a distant astrophysical source must appear in the data streams of all three LIGO interferometers in the US, and of any other detectors in a worldwide network of comparably sensitive instruments.

For specific astrophysical searches, we will require signals consistent with calculated expectations of how the frequency varies with time. For the terminal in-spiraling of a binary system with a neutron star, for example, one can calculate the waveform as a function of the system parameters. So we can compare a candidate chirp signal over thousands of cycles, as it crosses LIGO's sensitivity band, with detailed templates of calculated waveforms.

Futhermore, the geographically dispersed detectors will have to exhibit consistent waveforms in proper coincidence. There will also be anticoincidence vetoes to weed out environmental effects. The hardest problem in a burst search is the elimination of false signals associated with non-Gaussian noise in the individual interferometers. By requiring multiple-detector coincidence, we can reduce the rate of such spurious events to less than one per decade.

Periodic sources will have to satisfy a very special set of criteria. The observed signal must exhibit amplitude modulation and Doppler frequency modulation consistent with the effects of the Earth's rotation and revolution around the Sun.

A stochastic background of gravitational waves can be detected by searching for a common "noise" in a set of interferometers. The detection requires the cross-correlation of two or more interferometers. In the LIGO geographic configuration, the cross correlation will be made between the Washington and Louisiana interferometers, with some penalty in bandwidth due to the large separation. We will also be able to correlate the two interferometers at the Washington site, assuming that their independence is not overly compromised by correlated perturbations at the same location.

Plans for the future

At first, LIGO will carry out a broadband search, because we do not know what kinds of astrophysical or cosmological sources we are most likely to see first. The LIGO facilities have been designed for a lifetime of 30 years, during which time, we expect, there will be a continuing and active program of detector development. The facilities can accommodate detectors operating at the quantum limit of a 1 ton mass and at the Newtonian limits imposed by the terrestrial environment. The vacuum and optical systems have been designed so as not to compromise eventual operation at these ultimate limits. It should be possible eventually to operate improved LIGO detectors that are several hundred times more sensitive than what we will start with next year.

Our initial detector design is a compromise between performance and technical risk. It incorporates some educated guesses as to what directions we should take to arrive at a reasonable probability for finding gravitational waves. It is a broadband system with modest optical power in the interferometer arms and a low-risk vibration isolation system. The mirror suspensions have been well tested in prototype interferometers.

We expect to make improvements in the LIGO interferometers following the first scientific data run, which is scheduled to end in 2004. These improvements will include a new suspension system, provided by the collaborating GEO project, to further reduce the thermal noise. We may also, at that point, change to sapphire test masses. We also expect that significant improvement in the seismic isolation of the test masses will extend LIGO's sensitive observation band down to 10Hz.

We plan to reduce the sensing noise by going to a new interferometer configuration and by applying higher-power lasers in conjunction with improved optical materials and techniques to handle the higher power.

We expect that LIGO's sensitivity at 100 Hz will be improved by about a factor of 15, and that the overall high-sensitivity band will be expanded significantly to both lower and higher frequencies. That should expand the cosmic volume LIGO can search at a given sensitivity—and hence the discovery rate—by a factor close to 3000. (15)

In the longer run, greater changes in the detector might use still newer interferometer configurations to drive the system to the ultimate limits dictated by quantum fluctuations and fluctuations in terrestrial gravity. It will be particularly interesting to improve LIGO's sensitivity for detecting periodic sources and possibly even a stochastic background of primordial gravitational waves. Searching for this speculative primordial background at high frequencies, where stochastic noise is tolerable, can be accomplished by using interferometers that greatly reduce the phase noise of the interference fringes at the cost of reduced bandwidth.

The scientific collaboration

As we enter LIGO's commissioning phase, we have expanded the scientific community's involvement by creating the LIGO Scientific Collaboration. It presently consists of about 30 research groups comprising more than 200 physicists and astrophysicists. We expect the collaboration to continue to grow and become the scientific center of LIGO as it develops over the next decade.

It is, of course, difficult to predict how LIGO will really evolve. But we believe we have set out on a course that has bright prospects for the early detection of gravitational waves. We plan a flexible approach toward improvements that will either let us follow up sources that have been detected or, if we find nothing at first, undertake more sensitive searches.

There are plenty of opportunities for new technical ideas and search methods. We look forward to developing an international collaboration with other gravitational-wave detectors to form a world-wide network. After LIGO's first data run, we plan to interleave subsequent searches with a series of detector upgrades that promise to lead to ever-enhanced sensitivity, making the direct detection of gravitational waves a reality within the next decade.

References

1. A. Einstein, Reports of the Physical–Mathematical Session of the Royal Prussian Academy of Sciences (1916), p. 688.
2. A. Einstein, Reports of the Physical–Mathematical Session of the Royal Prussian Academy of Sciences (1918), p. 154.
3. R. A. Hulse, J. H. Taylor, Astrophys. J. **195**, L51 (1975).
4. K. S. Thorne, in *300 Years of Gravitation*, S. Hawking, W. Israel, eds., Cambridge U. P., Cambridge, England (1987), chap. 9.
5. P. R. Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors*, World Scientific, Singapore (1994).

Comments on excerpts from the "Gravity Wave" discovery paper, **GW150914:** [B.P. Abbott et al., Phys.Rev.Letts. **116** (2016), 061102] and the neutron star merger **GW170817** papers, Abbott et al., Phys.Rev.Letts. **119** (2017) 161101, as well as Frebel and Beers, in Physics Today (January, 2018):

a) In the top row of Figure 1, (for the final ≈*150 milliseconds* of the orbiting of these black-holes before their collision), note the essentially identical signal patterns for the Hanford detector (left-hand column) and the Livingston detector (right-hand column). Also note the agreement of these measured data with the numerical general-relativistic calculations plotted in the second row based on the extracted parameters for this collision in Table 1.

b) In Figure 3, showing the lay-out and location of the LIGO interferometer, note that the scale of the interferometer components is not at all the same as the scale of the length of the two arms.

c) In Figure 2, the top row shows the orbiting of the black holes as they orbit and finally collide, in the same time scale as in Figure 1. In the same time scale, in the bottom row of this figure, are plotted the relative orbital velocities of the two black holes (thicker line) and their separation (thinner line).

d) In Fig. X-4, compare the time-dependence (~20-30 sec) of the Binary-Neutron-Star merger **GW 170817** to the time-dependence (~100 msec) for Binary-Black-Hole mergers, e.g., **GW 150914** (Fig. 1, of PRL **116** (2016) 061102). Frebel & Beers (2018) presents more details of the deduction that "The rapid-neutron capture process needed to build up many of the elements heavier than iron seems to take place in neutron-star mergers, not supernova explosions."

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$, and the final black hole mass is $62^{+4}_{-4}M_{\odot}$, with $3.0^{+0.5}_{-0.5}M_{\odot}c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [8–10], and in the 1990s higher-order post-Newtonian calculations [11] preceded extensive analytical studies of relativistic two-body dynamics [12,13]. These advances, together with numerical relativity breakthroughs in the past decade [14–16], have enabled modeling of binary black hole mergers and accurate predictions of their gravitational waveforms. While numerous black hole candidates have now been identified through electromagnetic observations [17–19], black hole mergers have not previously been observed.

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new tests of general relativity, especially in the dynamic strong-field regime.

Experiments to detect gravitational waves began with Weber and his resonant mass detectors in the 1960s [23], followed by an international network of cryogenic resonant detectors [24]. Interferometric detectors were first suggested in the early 1960s [25] and the 1970s [26]. A study of the noise and performance of such detectors [27], and further concepts to improve them [28], led to proposals for long-baseline broadband laser interferometers with the potential for significantly increased sensitivity [29–32]. By the early 2000s, a set of initial detectors was completed, including TAMA 300 in Japan, GEO 600 in Germany, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, and Virgo in Italy. Combinations of these detectors made joint observations from 2002 through 2011, setting upper limits on a variety of gravitational-wave sources while evolving into a global network. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations [33–36].

A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the

[*]Full author list given at the end of the article.

properties of space-time in the strong-field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

II. OBSERVATION

On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914 shown in Fig. 1. The initial detection was made by low-latency searches for generic gravitational-wave transients [41] and was reported within three minutes of data acquisition [43]. Subsequently, matched-filter analyses that use relativistic models of compact binary waveforms [44] recovered GW150914 as the most significant event from each detector for the observations reported here. Occurring within the 10-ms intersite

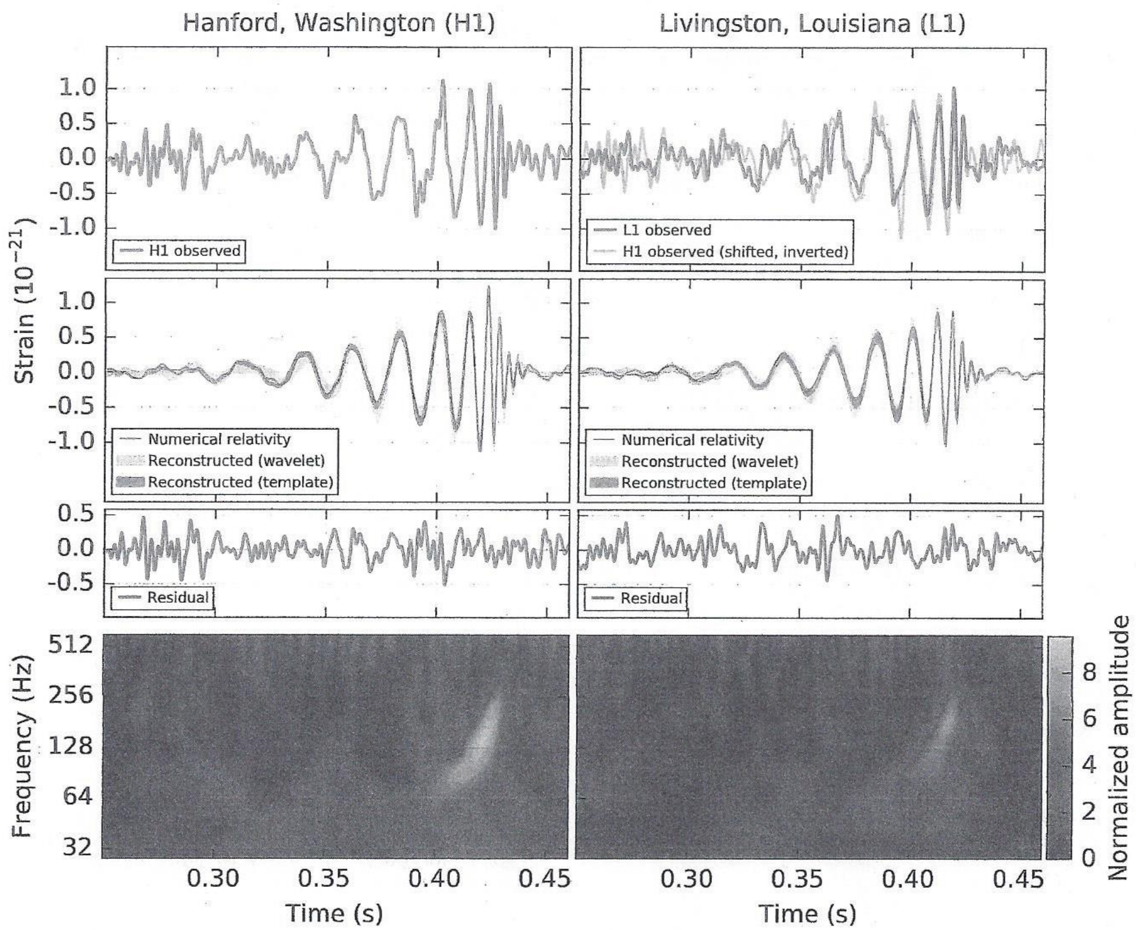


FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row:* A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.

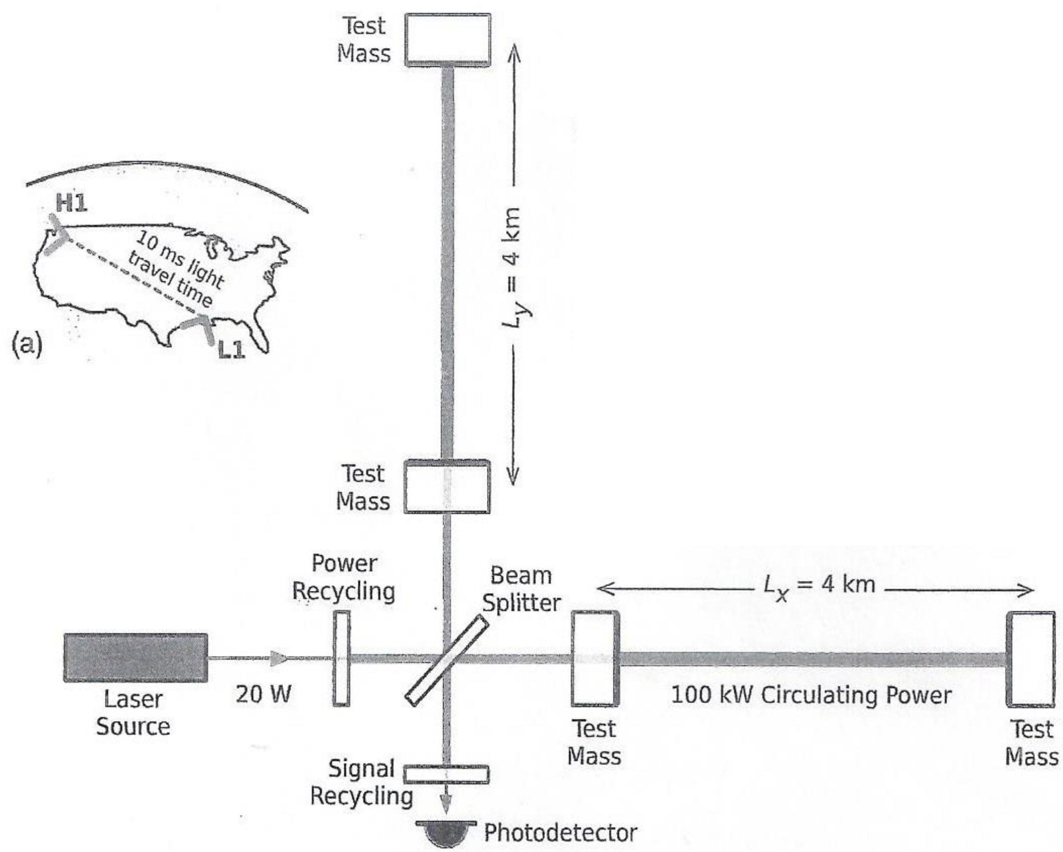


FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). *Inset (a):* Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1).

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

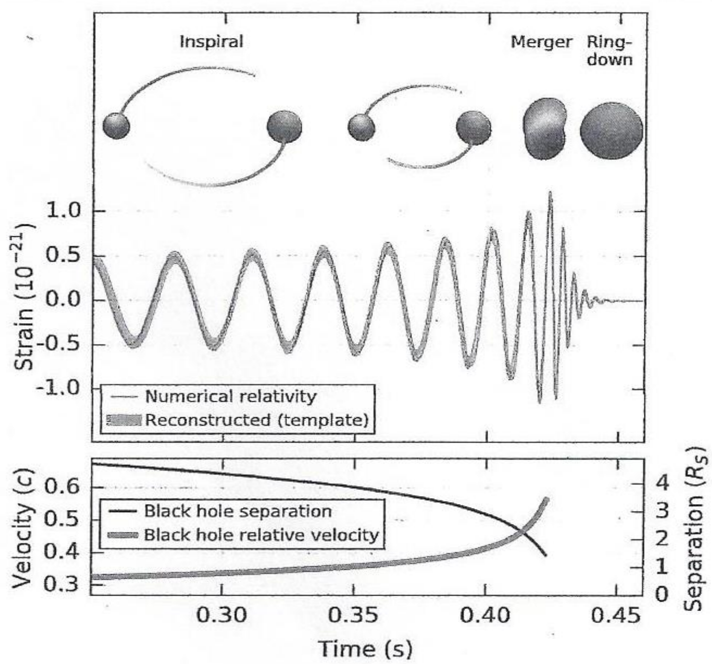
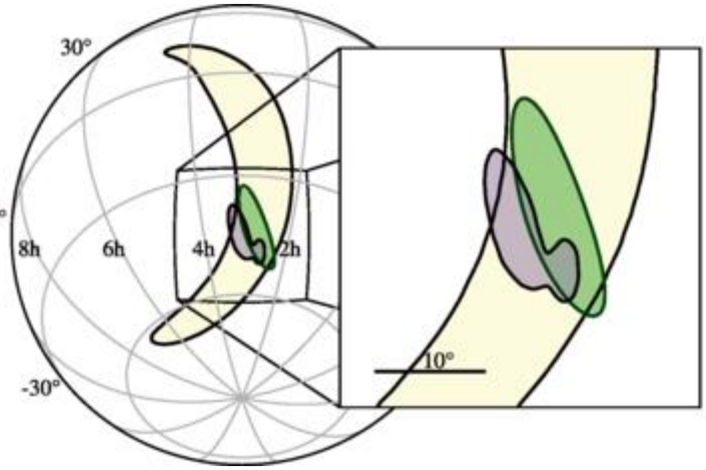


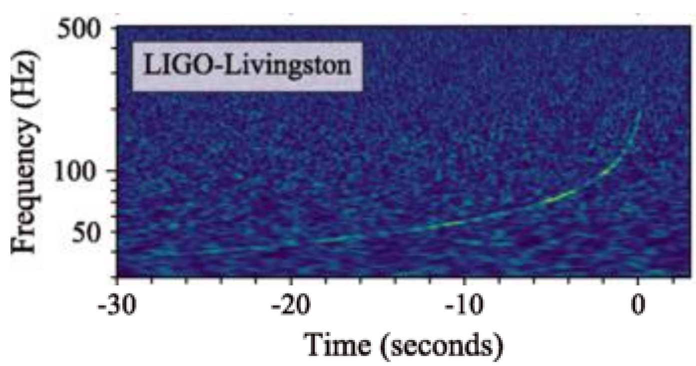
FIG. 2. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

Fig. X-3



Comparison of the localizability of **GW 170814**:
(yellow) - based on just the two LIGO detectors)
(green) - based on the two LIGO detectors plus the Virgo detector.

Fig. X-4



The time-dependence (~20-30 sec) of the Binary-Neutron-Star merger **GW170817.** Compare to the time-dependence (~100 msec) for Binary-Black-Hole mergers, e.g., **GW150914** (Fig. 1, of PRL **116** (2016) 061102).

An interesting sidelight of this discovery is the way in which it was kept under wraps while its announcement was being peer-reviewed.

Commentary

How gravitational waves went from a whisper to a shout

On 11 February 2016, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and its sister collaboration, Virgo, announced their earthshaking observation of Albert Einstein's ripples in spacetime. LIGO had seen the death dance of a pair of massive black holes. As the behemoths circled each other faster and faster, the frequency and amplitude of the spacetime waves they produced grew into a crescendo as the black holes became one. Then the new doubly massive black hole began to ring softer and softer like a quieting bell. The escalating chirp and ringdown is also a metaphor for public information flow about the discovery. It could have unfolded differently.

When scientists make a discovery, they must choose how to disseminate it. A big decision they must make is whether to reveal the results before or after peer review. Reveal before peer review—sometimes even before the paper is written—and the community can use the results right away, but there is an increased risk that problems will be found in a very public way. Reveal after peer review, and the chance of such problems decreases, but there is more time for a competitor to announce first or for rumors to leak. At *Physical Review Letters* (*PRL*), where I am an editor, we allow authors to choose when they want to reveal their results. The LIGO collaborators chose to wait.

Just before LIGO's experimental run began in September 2015, the team held a vote on which journal they would pick if they made a discovery. They picked *PRL*. Five days after the vote, LIGO's detectors seemed to hear the universe sing out for the first time.

Had LIGO just confirmed a 100-year-old prediction made by Einstein? Had they discovered the first black hole binary? Had they opened a new era of astrophysics? With the stakes so high, the collaborators wanted to keep their results secret while they determined if the results were real. It was unfortunate that some onlookers chose to publicize vague rumors when the internal vetting had just begun.

By early December the collaboration was convinced that the results were real, and LIGO spokesperson Gabriela "Gaby" González let me know that we would be receiving a paper from the group in mid- to late January. When she told me that they had convincingly observed gravitational waves, that it was not a test, and that the source was the merger of two huge black holes, my jaw dropped.

Gaby stressed LIGO's desire for strict confidentiality, so for a month I told only one other person in the world: my fellow editor Abhishek Agarwal. By mid-January we had to bring others into the loop to prepare for the paper's arrival, to review it, and eventually to publish it. To avoid information slipping out from a casual conversation or a glance at a screen, we used the code name "Big Paper." (The code name for the second LIGO, announced in June, discovery was "Big Two.") To the best of my knowledge no information leaked from us. Inside the LIGO team, for similar reasons, the discovery was referred to as "The Event."

Big Paper on The Event arrived at *PRL* on the evening of 21 January 2016, and we immediately sent it out to experts for anonymous peer review. The referees, like everyone involved, were sworn to secrecy. Informed, unbiased advice is central to picking which papers are published and to improving those that are. In this case it was clear that the paper was important and interesting enough for *PRL*. As expected, the reviews were very favorable and conveyed the message that the paper would be an inspiration to physicists and astronomers alike.

As the time for the announcement drew closer, the rumors increased. In one case, a preprint was spotted on a printer, then a physicist emailed his whole department about the results, one tweet quoted the email, and a science reporter based an entire story on that tweet. The information was incomplete, though correct—except for the journal where the paper would be published. That reporter learned at the press conference that *PRL* would publish the paper and sheepishly congratulated me.

Meanwhile, we continued to protect the information from leaking. My son, who is a budding science reporter, texted me a few days before the announcement, asking if I'd seen the rumors. That led to an awkward phone call—I still couldn't tell him about the discovery. When we ordered a celebratory cake for the editorial office, we avoided any mention of the result on the frosting, lest it lead to an information leak. It turned out that we were not being overly cautious: A tweet containing a picture of a cake at NASA's Goddard Space Flight Center on the morning of the announcement *did* leak news of the discovery![1] Confidentiality requires vigilance.

Everyone at LIGO's press conference was given access to the *PRL* paper hours beforehand, on condition that they not publish their stories until after the announcement was made and the news embargo lifted. Actually, it might have been better in some ways had the press had access to the paper a little earlier, but that also would have increased the risk of the paper leaking prior to the announcement.

We had an agreement with the LIGO team to publish the paper online on 11 February at 10:45am Eastern Time, 15 minutes after the press conference was to begin. But I learned that morning from the reporters around me that the embargo was being lifted at 10:30am, and they planned to publish their stories then, which would create 15 minutes of pent-up demand for the *PRL* paper. So I found the spokesperson minutes before she went to the microphones and asked her if we could publish at 10:30. Gaby smiled and simply said yes.

After a few frantic emails, all the plans were changed, and at 10:30 we published the LIGO paper.[2] It didn't help: The demand for the paper was still so great that our site crashed under a load of 10 000 hits per minute.[3] After we added a slew of servers, our site came back up, and the paper was downloaded an unprecedented quarter of a million times on the first day.

The LIGO researchers had chosen to maintain confidentiality because they wanted their results carefully vetted before they went public. They also wanted the information to come from them, not from rumors. Although some of the information leaked before the announcement, they still did get the glory of presenting the full results to the world. And the ringdown phase has been impressive, as news of the result continues to spread far and wide.

Authors may have good reasons to announce their results prior to the completion of peer review—reasons that include competition from other groups, hope for informal community feedback, and desire to control the announcement and avoid weeks of rumors. But if authors choose that path, they should consider the possibility that peer review will turn up problems they did not think of, and they should tailor their announcement accordingly. Authors may instead choose to wait for the completion of peer review, especially when they have no concerns about competition. In such cases it is an even greater pity when rumors leak, because the leakers provide disincentive for such patience.

For LIGO, although much of the information leaked before the press conference, the researchers still had much to announce, probably in part because they had emphasized confidentiality. Announcing early makes sense in some cases, but the LIGO group made the right choice to wait.

References

1. R. Feltman, "Thursday's massive gravitational wave news was broken by a sheet cake (really)," *Washington Post*, 11 February 2016.
2. B. P. Abbott et al. (LIGO scientific collaboration and Virgo collaboration), *Phys. Rev. Lett.* **116**, 061102 (2016).
3. C. Straumsheim, "Riding the Wave," *Inside Higher Ed*, 24 February 2016.

Robert Garisto
Physical Review Letters
Ridge, New York

References:

B.P. Abbott et al., Phys.Rev.Letts. **116** (2016), 061102. [GW-150914]

B.P. Abbott et al., Phys.Rev.Letts. **119** (2017), 141101. [GW-170814]

B.P. Abbott et al., Phys.Rev.Letts. **119** (2017), 161101. [GW-170817]

B.C. Barish and J.R. Weiss, *LIGO and the Detection of Gravitational Waves*, Physics Today (October 1999), p. 44.

Anna Frebel and Timothy C, Beers, *The Formation of the Heaviest Elements*, Physics Today (January 2018), p. 30.

Robert Garisto, *How Gravitational Waves Went from a Whisper to a Shout*, Physics Today (August 2016), p. 10.

R.A. Hulse and J.H. Taylor, Ap.J. **195** (1975) L51.

(Y) Term Paper

The final exam for this seminar was a term paper (20 – 30 pages) on any subject relevant to the “Radiation and the Universe” title of this seminar - quite possibly some topic which we had mentioned “in passing” but did not have time to pursue in detail.

Topics that have frequently been researched and discussed include the “usual suspects” such as:

- Long-Term Space Travel and Cosmic Rays
- The Manhattan Project
- Waste Storage
- Therapeutic Radiology
- Chernobyl
- Low-Level Radiation Effects
- Ripples in Space Time; Gravitation Waves
- German Atomic Bomb Program
- etc.

But also more singular topics have included:

- Thyroid Cancers in Idaho “Down Winders”
- Radon Dangers
- Cellphone Radiation
- Dark Matter
- Food Preservation via Irradiation
- Deinococus Radiodurans – an extremophile listed in the Guinness Book of Records as the world’s toughest bacterium - whose most impressive feat is its extreme resistance to radiation.
- etc.