Nuclear Theory

Francesco Iachello

- Neutrinoless double beta decay
- Clustering in nuclei
- Quantum phase transitions

Yoram Alhassid

- Nuclear many-body physics
- Ultra-cold atoms
- Mesoscopic physics and nanoscience (condensed matter)

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We study correlated quantum systems in which the number of particles is large but still small enough for finite-size effects to be important:

-- nuclei, quantum dots, nanoparticles, and cold atoms.

• Combination of statistical and many-body methods.

• Conventional methods have to be modified in a finite-size system.

• Combination of analytical and computational methods.
Development of non-perturbative methods

Gibbs ensemble \( e^{-\beta H} \) (\( \beta = 1/T \)) can be written as a superposition of ensembles \( U_\sigma \) of non-interacting particles in external time-dependent fields \( \sigma(\tau) \)

\[
e^{-\beta H} = \int \mathcal{D}[\sigma] G_\sigma U_\sigma
\]

auxiliary fields non-interacting propagator

• Small-amplitude quantal fluctuations of \( \sigma \) can be calculated analytically

  \( \Rightarrow \) Static path plus random-phase approximation (SPA+RPA)

Large-amplitude fluctuations of \( \sigma \) can be evaluated by stochastic methods: auxiliary-field quantum Monte Carlo

I. Atomic nuclei

**The challenge:** microscopic derivations of statistical nuclear properties from the underlying effective interactions.

- Important for astrophysical processes: nucleosynthesis, supernovas, …
- Phase transitions in finite systems
- Tests of fundamental symmetries

The strong interactions make the problem difficult; conventional methods are intractable.

**Methods:** we developed quantum Monte Carlo methods to solve in much larger configuration spaces ($\sim 10^{40}$) than those that can be treated by conventional methods ($\sim 10^{11}$).
Example: exact shape distributions in nuclei without breaking of the rotational symmetry ($\beta, \gamma$ are shape parameters)

Quantum shape transition (at $T=0$) vs. neutron number
II. Ultra-cold atoms

By tuning the interaction it is possible to go continuously from a Bose-Einstein condensate (BEC) of dimers to “paired” fermionic atoms (BCS).

In the middle of the crossover from BEC to BCS is the unitary limit of strongest interaction.
Exotic behavior was conjectured at the unitary limit:

- The existence and extent of a pseudogap regime is extensively debated in the literature.

**pseudogap regime** above the critical temperature (non-Fermi liquid)

![Diagram](image_url)

- The existence and extent of a pseudogap regime is extensively debated in the literature.
The contact in the unitary Fermi gas
- A fundamental property of many-body systems with short-range interactions

Previous theory results

Many of the strong coupling theories are based on uncontrolled approximations
The contact

Previous theory results + recent experiments

C/(N_k_F) vs T/T_F
Previous theory results + recent experiments + our AFMC results

Our results provide the best quantitative agreement with the recent precision experiments.
Mesoscopic systems are intermediate between microscopic systems and macroscopic bulk matter.

**Quantum dots**: sub-micron-scale devices containing up to several thousands electrons (“artificial atom”).

- Sufficiently small to be governed by the laws of quantum mechanics.
- Finite-size effects are important.

**Statistical regime**: single-particle dynamics are chaotic.
- Interplay between one-body chaos and electron-electron interactions.
The residual two-body interaction is random and correspond to an SYK (Sachdev, Ye, Kitaev) model (describing non-Fermi liquids)

**Flake of graphene: SYK Hamiltonian?**

A. Chen et al, PRL 2018

“Quantum holography in a graphene flake with an irregular boundary”

What are the signatures of SYK in the transport properties of the device?
Nano-scale metallic grains

Discrete energy levels extracted from non-linear conductance measurements

Levels of aluminum grain vs. a magnetic field

“Superconducting” but properties are very different from bulk superconductors: conventional theory of superconductivity (BCS) breaks down.
Conclusion

• Interdisciplinary work on the interface of nuclear many-body theory, mesoscopic physics/nanoscience, and cold atoms has led to important progress in our understanding of finite-size correlated quantum systems.

• A major challenge in understanding the rich physical behavior exhibited by these systems is the inclusion of correlations beyond mean-field theory.

• Novel quantum phases.