The atomic nucleus: A natural laboratory of complexity

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Definitions

The atomic nucleus

Complexity

Description(s)

Generalities

Many-body techniques

Interactions

State-of-the-art descriptions

Problems

Beyond Mean Field

Approaches

Conclusions

We are still there

Outlook
Definitions
Is it a nucleus?

A **building** block of matter

- Small and dense region at the center of the Atom
- Inferred by Rutherford
- "Made" of protons and neutrons
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What are the correct d.o.f to describe it?
What is a nucleus?

A quantum-many-body system:

- Sensitive to 3 fundamental interactions (EM,W,S)
- Composed of non-elementary fermions
- Strongly correlated system of finite size
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The nucleus is a complex system
Consequences:

- No systematic analytical treatment of the problem.
- A wide variety of phenomena.
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Deformation:
Complexity – A challenging description

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Clustering:
Complexity – A challenging description

Consequences:

- No systematic analytical treatment of the problem.
- A wide variety of phenomena.

Superfluidity:

\[ E_{\text{pair}} = 0 \text{ MeV} \]
What can one measure?

Some observables

Ground-State:

- Energy (Separation)
- Radii
What can one measure?

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Excited-states:

- Energies (Spectroscopy)
- Electric moments
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Description(s)
Nuclear "Philosophy" – A complicated compromise

- First Principles
  - A scaling problem
- Universality
- Accuracy
  - Treatment of the many-body problem
  - Description of the interaction
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We need a compromise!
The quantum Many-body problem

- Exact
- Ab-initio
- EDF

Summary: Explicit treatment of the total wave-function

- $\hat{H}\Psi = E\Psi$
- Very accurate with a true interaction.
- Extremly costly and heavy (Power-law scaling)
The quantum Many-body problem

- **Exact**
- **Ab-initio**
- **EDF**

**Summary:** Explicit treatment of truncated total wave-function

- \( \Psi = \sum_I c_I \Phi_I \)
- Predictive with an effective interaction
- Very costly and heavy (Combinatorial scaling)
The quantum Many-body problem

- Exact
- Ab-initio
- EDF

**Summary:** Mean-field like treatment of the wave-function

- $[\hat{H}, \hat{\rho}] = 0$
- Almost universal, but uses a phenomenological interaction
- Quite computationally easy (Polynomial scaling)
From QCD to strong-force

From the "true" non-abelian gauge theory...

\[ \mathcal{L} = -\frac{1}{4} F^A_{\alpha\beta} F_A^{\alpha\beta} + \sum_f \bar{q}_A (i\gamma^\mu D_\mu - m)_{AB} q_B + \mathcal{L}_{\text{gauge-fixing}} + \mathcal{L}_{\text{ghost}} \]
From QCD to strong-force

From the "true" non-abelian gauge theory...

To a realistic N-N interaction
Establish a direct link between QCD and an effective strong force

**The Holy Grail**

**Courtesy M. Drissi**
Establish a direct link between QCD and an effective strong force

Still a lot of work...
Energy Functionals – A Phenomenological approach

An example Relativistic Mean Field Theory (RMF)
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Interpretation in term of mesons exchange
A brief summary

\[
L_{\text{int}} = g_\sigma \bar{\psi} \sigma \psi + g_\omega \bar{\psi} \gamma_\mu \omega^\mu \psi + \g_\rho \bar{\psi} \gamma_\mu \rho^\mu \cdot \vec{\tau} \psi + g_\pi \bar{\psi} \gamma_5 \pi \cdot \vec{\tau} \psi
\]

\[
\mathcal{H} = \hat{T}_{i,j} + \hat{V}_{\text{eff}}
\]

- Mesons: \((\partial_\mu \partial^\mu + M^2)\phi^\nu = j^\nu\)
- Nucleons: \((\rho - m_{\text{eff}} + \Sigma)\psi = 0\)
State-of-the-art descriptions
Correlations

Some "observable" problems

![Graph showing correlations between Sn-isotopes and energy levels](image)
Correlations

Some "observable" problems

Odd-even staggering ⇒ Pairing correlations
Explicit fields expansion truncated at a given order

Bogoliubov-Many-Body-Perturbation-Theory (BMBPT) diagrams
Correlations (1)

Explicit fields expansion truncated at a given order

Results:

![Graph showing energy levels (E_a) against mass number (A) for HFB and BMBPT(2) methods.](image)
Correlations (2)

Symmetry breaking:

- Capture additional correlations
- For any sym. group. (U(1), O(3), etc...)
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And restoration: Generator Coordinate Method

- Pick a generating coordinate
- Sum over symmetry broken states
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And restoration:
Conclusions
Nuclear physics is an active research field!

Major intrinsic open subjects:

- Theoretical link between QCD and N-N Interaction
- Systematic and simultaneous restorations
- New (non-spurious) many-body techniques.
- Hybrid approaches (EDF/EFT, EDF/CI,...)
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Cross-fertilizing topics

Detection of Majorana neutrinos

- Precise study of double-beta decays
- Dependence on nuclear reactions knowledge
Lorentz-symmetry breaking\textsuperscript{1}

- Very strong dependence on nuclear structure knowledge
- Major cosmological impact

\textsuperscript{1}H.Pians-Le Bars, C. Guerlin, R-D.L, J-P. Ebran, Q.G. Baily, S.Bize, E.Khan, P.Wolf \textit{Phys. Rev. D} 95, 075026
Thank you!