Quark-Meson Coupling Models for Atomic Nuclei

Honour Mid-Year Presentation

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Introduction

- The ultimate goal of nuclear physics is to predict properties of nuclear systems.
  - Nuclear mass, energy levels and half-lives
  - Superheavy and neutron rich nuclei
  - Neutron stars
  - Hypernuclei

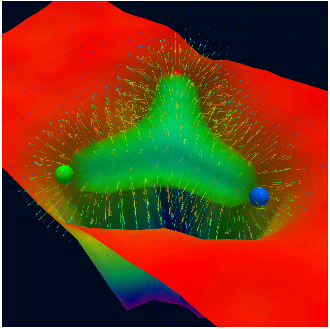
Credit: http://hubblesite.org/newscenter/archive/releases/2002/24/image/a/

Introduction

- Three ingredients are needed:
  - Nucleon interaction properties
  - A way to solve the resultant many-body problem
  - Experimental data
- Much progress has been made in solving the many-body problem
- Describing nucleon interaction in-medium is still open problem

Nucleon Interactions

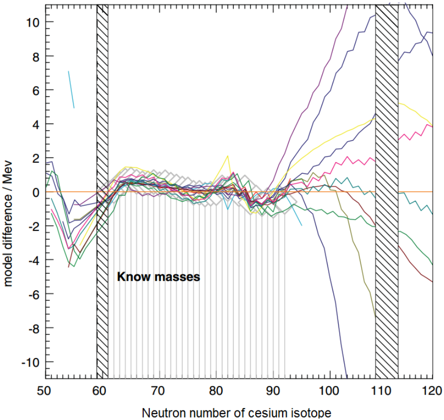
- Underlying theory is QCD
- Highly non-perturbative at low energies
- Requires supercomputers to calculate anything



Credit: http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html, see also [1]

Nucleon Interactions

- The other approach is to make up a phenomenological model
- Dozens of models and hundreds of parameterizations
- Difficult to constrain parameters
- Limited predictivity for exotic nuclei and neutron stars



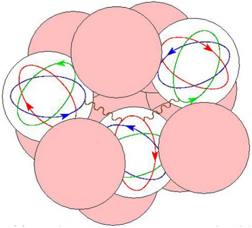
Credit: Adapted from Blaum 2006 [2]

Introducing the Quark-Meson Coupling Model

- We want a middle ground
- Treat nucleons as quarks in a bag
- The quarks interact with observed non-strange mesons
  - The scalar-isoscalar σ, attractive
  - The vector-isoscalar ω, repulsive
  - The vector-isovector ρ, isospin dependent
  - The pseudoscalar-isovector π, doesn't appear in Hartree calculations

Introducing the Quark-Meson Coupling Model

- We want a middle ground
- Treat nucleons as comprising of quarks
- The quarks interact with observed non-strange mesons
- We use the quarks and mesons in a relativistic field theory
- There are only three coupling constants, which can be determined from bulk nuclear properties



Credit: https://www.jlab.org/news/articles/quark-meson-coupling-qmc-model-american-institute-physics-bulletin-physics-news

Nucleon Mass In-Medium

- If the nucleon was point-like, the effective mass would be

$$M^* = M - g_\sigma \sigma$$

- In QMC the quarks in the nucleon can rearrange themselves, so

$$M^* = M - g_\sigma \sigma + \frac{d}{2} g_\sigma^2 \sigma^2.$$

- Analogous to polarization of atoms in an electric field

A Brief History of the Quark-Meson Coupling model

- Created by P. Guichon in 1988 [3]
- Applied by A. Thomas and K. Saito to hyperons and mesons in nuclear matter [4]
- Extended to finite nuclei in 1996 - successfully predicted properties of hypernuclei [5]
- Various versions applied to neutron star interiors
- QMC applied to nuclei only in last decade

Applying QMC to Atomic Nuclei

- From QMC an energy density functional is calculated
- Mostly approximations to QMC energy density functional are used
- In February this year, the QMC functional was for the first time directly used in nuclear code [6]

Energy Density Functionals from QMC

- Density dependence, spin-orbit interaction and isovector properties have been derived
- Other terms have not been derived
  - 'Time-odd' terms
  - Tensor term
  - Pairing term

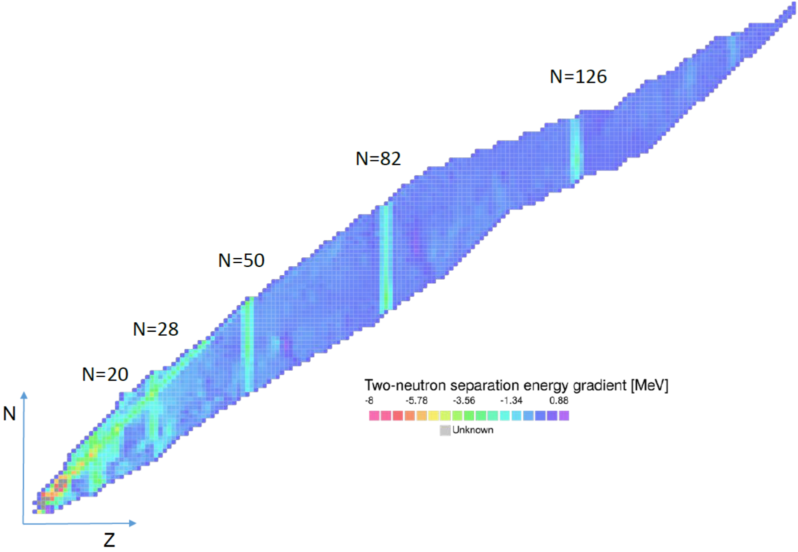
The Tensor Term

- Term of the form

$$V_T = f(r)\left[\frac{3(\vec{\sigma}_1 \cdot \vec{r})(\vec{\sigma}_2 \cdot \vec{r})}{r^2} - \vec{\sigma}_1 \cdot \vec{\sigma}_2\right]$$

- Many important observables in structure and reactions are sensitive to the tensor term

The Tensor Term



Credit: Edward Simpson

Research Plan

- Isolate from the QMC model the physics relevant to the tensor term - pion exchange
- Derive from QMC the density-dependent nucleon interaction
- Take non-relativistic limit and implement as a zero-ranged interaction
- Perform nuclear calculations to test the implications of the derived term

Summary

- QMC is a promising approach to nuclear physics
- Tensor term important but not well understood
- Deriving the tensor term from QMC should help us understand both

References

[1] Bissey *et al.*
Gluon flux-tube distribution and linear confinement in baryons.
PHYSICAL REVIEW D **76** (2007)

[2] Blaum, K.
High-accuracy mass spectrometry with stored ions.
Physics Reports **425** (2006)

[3] Guichon
A Possible Quark Mechanism for the Saturation of Nuclear Matter
Phys. Lett. B bo200 (1988).

[4] Saito *et al.*
Nucleon and hadron structure changes in the nuclear medium and impact on observables
Prog.Part.Nucl.Phys. **58** (2007).

[5] Guichon *et al.*
The role of nucleon structure in finite nuclei
Nucl. Phys. A **601** A (1996).

[6] Stone, J., Guichon, P., Reinhard, P., and Thomas, A.
Finite Nuclei in the Quark-Meson Coupling Model.
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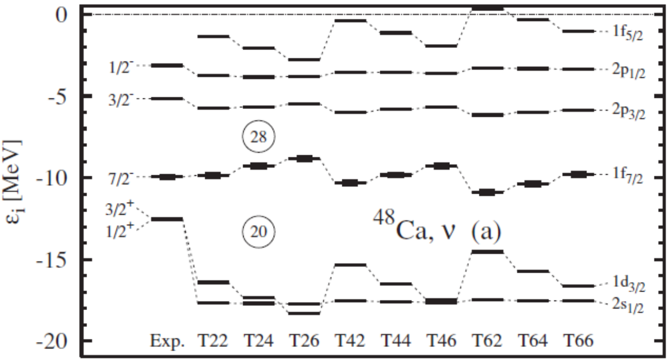
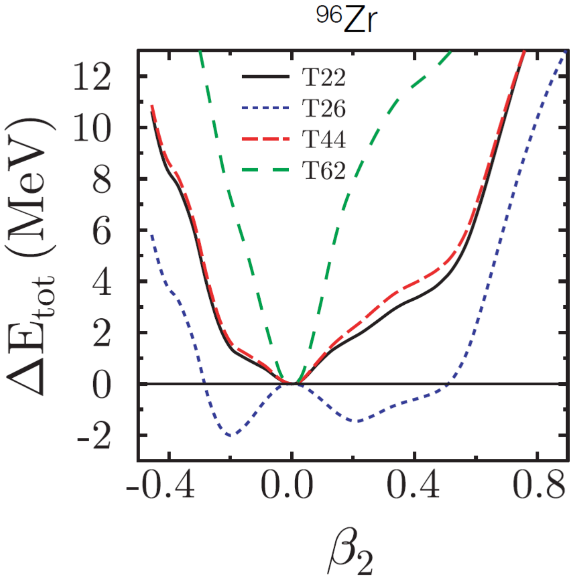


Credit: From Lensinki *et al* (2009)



Credit: From Bender *et al* (2009)

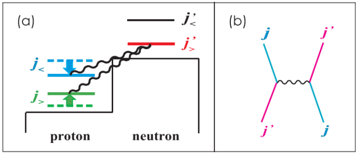


FIG. 1 (color). (a) Schematic picture of the monopole interaction produced by the tensor force between a proton in $j_{>,<} = l \pm 1/2$ and a neutron in $j'_{>,<} = l' \pm 1/2$. (b) Exchange processes contributing to the monopole interaction of the tensor force.

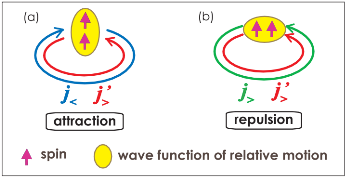


FIG. 2 (color). Intuitive picture of the tensor force acting two nucleons on orbits j and j'.

Credit: From Otsuka *et al* (2005)