Latest Developments in the Quark-Meson Coupling model

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Outline

I. Nuclei from Quarks
   − start from a QCD-inspired model of hadron structure
   − develop a quantitative theory of nuclear structure

   NOT COVERED

II. Search for observable effects of the change in hadron structure in-medium
   − EMC effect (including spin)

III. Neutron Stars
   − role of hyperons and insights from GW170817
I. Insights into nuclear structure

− what is the atomic nucleus?

There are two very different extremes....
Quark Structure matters/doesn’t matter

• Nuclear Femtography: the science of mapping the quark and gluon structure of atomic nuclei is just beginning

• “Considering quarks is in contrast to our modern understanding of nuclear physics... the basic degrees of freedom of QCD (quarks and gluons) have to be considered only at higher energies. The energies relevant for nuclear physics are only a few MeV”
What do we know?

• Since 1970s: Dispersion relations $\rightarrow$ intermediate range
  NN attraction is a strong Lorentz scalar

• In relativistic treatments (RHF, RBHF, QHD...) this
  leads to mean scalar field on a nucleon $\sim$300 to 500 MeV!!

  - This is not small – up to half the nucleon mass
  - death of “wrong energy scale” arguments

• Largely cancelled by large vector mean field BUT these
  have totally different dynamics: $\omega^0$ just shifts energies,
  $\sigma$ seriously modifies internal hadron dynamics

• Latter cannot be accurately captured by EFT with N and $\pi$
Suggests a different approach: QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl. Phys. 58 (2007) 1 and
  Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

• Start with quark model (MIT bag/NJL...) for all hadrons

• Introduce a relativistic Lagrangian with $\sigma$, $\omega$ and $\rho$ mesons coupling to non-strange quarks

• Hence **only 3 parameters** (4 if $\sigma$ mass not fixed)

  - determine by fitting to:
    - $\rho_0$, $E/A$ and symmetry energy
    - same in dense matter & finite nuclei

• Must solve **self-consistently** for the internal structure of baryons in-medium
Quark-Meson Coupling Model (QMC): Role of the Scalar Polarizability of the Nucleon

The response of the nucleon internal structure to the scalar field is of great interest... and importance

\[ M^* (r) = M - g_\sigma \sigma (r) + \frac{d}{2} \left( g_\sigma \sigma (r) \right)^2 \]

Non-linear dependence through the scalar polarizability \( d \sim 0.22 \, R \) in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the ONLY place the response of the internal structure of the nucleon enters.
Application to nuclear structure
Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon a,*, H.H. Matevosyan b,c, N. Sandulescu a,d,e, A.W. Thomas b

Nuclear Physics A 772 (2006) 1–19

- Start with classical theory of MIT-bag nucleons with structure modified in medium to give $M_{\text{eff}}(\sigma)$.

- Quantise nucleon motion (non-relativistic), expand in powers of derivatives

- Derive equivalent, local energy density functional:

$$\langle H(\vec{r}) \rangle = \rho M + \frac{\tau}{2M} + H_0 + H_3 + H_{\text{eff}} + H_{\text{fin}} + H_{\text{so}}$$
Derivation of EDF (cont.)

\[ H_0 + H_3 = \rho^2 \left[ \frac{-3G_\rho}{32} + \frac{G_\sigma}{8(1 + d\rho G_\sigma)^3} - \frac{G_\sigma}{2(1 + d\rho G_\sigma)} + \frac{3G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[ \frac{5G_\rho}{32} + \frac{G_\sigma}{8(1 + d\rho G_\sigma)^3} - \frac{G_\omega}{8} \right], \]

\[ H_{\text{eff}} = \left[ \left( \frac{G_\rho}{8m_\rho^2} - \frac{G_\sigma}{2m_\sigma^2} + \frac{G_\omega}{4M_N^2} \right) \rho_n + \left( \frac{G_\rho}{4m_\rho^2} + \frac{G_\sigma}{2M_N^2} \right) \rho_p \right] \tau_n + p \leftrightarrow n, \]

\[ H_{\text{fin}} = \left[ \left( \frac{3G_\rho}{32m_\rho^2} - \frac{3G_\sigma}{8m_\omega^2} + \frac{3G_\omega}{8m_\omega^2} - \frac{G_\sigma}{8M_N^2} \right) \rho_n + \left( \frac{-3G_\rho}{16m_\rho^2} - \frac{G_\sigma}{2m_\sigma^2} + \frac{G_\omega}{2m_\omega^2} - \frac{G_\sigma}{4M_N^2} \right) \rho_p \right] \nabla^2 (\rho_n) + p \leftrightarrow n, \]

\[ H_{\text{so}} = \nabla \cdot J_n \left[ \left( \frac{-3G_\sigma}{8M_N^2} - \frac{3G_\omega(-1 + 2\mu_s)}{8M_N^2} - \frac{3G_\rho(-1 + 2\mu_\omega)}{32M_N^2} \right) \rho_n + \left( \frac{-G_\sigma}{4M_N^2} + \frac{G_\omega(1 - 2\mu_s)}{4M_N^2} \right) \rho_p \right] + p \leftrightarrow n. \]

Note the totally new, subtle density dependence

Spin-orbit force predicted!
Systematic approach to finite nuclei

J.R. Stone, P.A.M. Guichon, P. G. Reinhard & A.W. Thomas:
( Phys Rev Lett, 116 (2016) 092501 )

• Constrain 3 basic quark-meson couplings \((g_{\sigma}^q, g_{\omega}^q, g_{\rho}^q)\) so that nuclear matter properties are reproduced within errors

\[-17 < E/A < -15 \text{ MeV} \]
\[0.14 < \rho_0 < 0.18 \text{ fm}^{-3}\]
\[28 < S_0 < 34 \text{ MeV}\]
\[L > 20 \text{ MeV}\]
\[230 < K_0 < 320 \text{ MeV}\]

• Fix at overall best description of 106 finite nuclei with 5 parameters (3 for the EDF +2 pairing pars)

• Benchmark comparison: SV-min 16 parameters (11+5 pairing)
## Overview

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<th>rms error %</th>
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Stone et al., PRL 116 (2016) 092501
Superheavy Binding: 0.1% accuracy

Stone et al., PRL 116 (2016) 092501
For detailed study of SHE see: arXiv:1901.06064
Drip line predictions

Table 1. Neutron numbers corresponding to proton and neutron drip lines, derived from the Fermi energy for isotopes of elements $96 < Z < 136$

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<th>$Z$</th>
<th>$N(p)$</th>
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Most recent development

• Includes pion Fock terms

• Includes $\sigma^3$ term – now EDF has 5 free parameters
Overview of 739 even-even nuclei

Martinez et al., arXiv:1811.06628
Systematics of two-neutron separation energy

Martinez et al., arXiv:1811.06628
Giant Monopole Resonance

Martinez et al., arXiv:1811.06628
Summary: Finite Nuclei

• The effective force was derived at the quark level based upon the changing structure of a bound nucleon

• Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces

• Looks like standard nuclear force

• BUT underlying theory also predicts modified internal structure and hence modified
  – DIS structure functions (EMC effect)
  – elastic form factors......
I. Summary

• Intermediate range NN attraction is STRONG Lorentz scalar

• This modifies the intrinsic structure of the bound nucleon
  – profound change in shell model:
    what occupies shell model states are NOT free nucleons

• Scalar polarizability is a natural source of three-body forces (NNN, HNN, HHN…)
  – clear physical interpretation

• Naturally generates effective HN and HNN forces with no new parameters and predicts heavy neutron stars
II. Summary

- Initial systematic study of finite nuclei very promising
  - Binding energies typically within 0.3% across periodic table
  - Super-heavies (Z > 100) especially good

- Need empirical confirmation:
  - Response Functions & Coulomb sum rule (soon?)
  - Isovector EMC effect; spin EMC (not too long?)

- Yields neutron stars at $2M_\odot$ with hyperons
  - Consistent with the tidal deformability deduced from GW170817
Special Mentions……

Guichon  Tsushima  Saito  Stone  Krein  
Matevosyan  Cloët  Whittenbury  Simenel  Bentz  
Martinez  Motta  Kalaitzis
Recent Study Motivated by GW170817

• Includes isovector scalar meson

Species Fractions: in $\beta$-equilibrium

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

FIG. 7: The EMC and polarized EMC effect in $^{11}$B. The empirical data is from Ref. [31].

FIG. 9: The EMC and polarized EMC effect in $^{27}$Al. The empirical data is from Ref. [31].

Approved JLab Experiment

- Effect in $^7$Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)

- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of $^7$Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)

Spin EMC measurement is critical as the proposed explanation in terms of SRC through the tensor force gives NO spin EMC effect (arXiv:1809.06622)
Latest papers

• Review:
  Guichon et al., PPNP 100 (2018) 262

• SHE:
  Stone et al., arXiv: 1901.06064

• Systematic application to finite nuclei:

• Neutron Stars
  Stone et al., arXiv:1906.11100
Key papers on QMC

• Many-body forces:
  1. Guichon, Matevosyan, Sandulescu, Thomas,

• Built on earlier work on QMC: e.g.
  4. Guichon, Saito, Rodionov, Thomas,

• Major review of applications of QMC to many nuclear systems:
  5. Saito, Tsushima, Thomas,
References to: Covariant Version of QMC

• Basic Model: (Covariant, chiral, confining version of NJL)

• Applications to DIS:
  • Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302

• Applications to neutron stars – including SQM: