Structure of Atomic Nuclei

Anthony W. Thomas

JLab Users Meeting
Jefferson Lab : June 2\textsuperscript{nd} 2015
The Issues

• What lies at the heart of nuclear structure?

• Start from a QCD-inspired model of *hadron* structure

• Ask how that structure is modified in-medium

• This naturally leads to saturation + predictions for all hadrons

• Derive effective forces (Skyrme type): apply to finite nuclei

• Test predictions for structure functions and form factors in-medium
A different approach: QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl. Phys. 58 (2007) 1 for a review)

- 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
  - determine by fitting to saturation properties of nuclear matter ($\rho_0$, $E/A$ and symmetry energy)

- Must solve self-consistently for the internal structure of baryons in-medium
Effect of scalar field on quark spinor

• MIT bag model: quark spinor modified in bound nucleon

\[
\frac{N}{4\pi} \left( i\beta_q \vec{\sigma} \cdot \hat{u}' j_1(\xi u' / R_B) \right) \chi_m
\]

• Lower component enhanced by attractive scalar field

\[
\beta_q = \sqrt{\frac{\Omega_0 - m^*_q R_B}{\Omega_0 + m^*_q R_B}}
\]

• This leads to a very small (~1% at \( \rho_0 \)) increase in bag radius

• It also suppresses the scalar coupling to the nucleon as the scalar field increases

\[
\frac{\Omega_0/2 + m^*_q R_B (\Omega_0 - 1)}{\Omega_0 (\Omega_0 - 1) + m^*_q R_B / 2}
\]

• This is the “scalar polarizability”: a new saturation mechanism for nuclear matter
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

\[ M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2} (g_\sigma \sigma(\vec{R}))^2 \]

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.
Summary: Scalar Polarizability

• Can always rewrite non-linear coupling as linear coupling plus non-linear scalar self-coupling – likely physical origin of some non-linear versions of QHD

• Consequence of polarizability in atomic physics is many-body forces:

\[ V = V_{12} + V_{23} + V_{13} + V_{123} \]

– same is true in nuclear physics
Summary so far ..... 

• QMC looks superficially like QHD but it’s fundamentally different from all other approaches

• Self-consistent adjustment of hadron structure opposes applied scalar field (“scalar polarizability”)

• Naturally leads to saturation of nuclear matter – effectively because of natural 3- and 4-body forces

• Only 3 parameters: $\sigma$, $\omega$ and $\rho$ couplings to light quarks

• Fit to nuclear matter properties and then predict the interaction of any hadrons in-medium
Linking QMC to Familiar Nuclear Theory

Since early 70’s tremendous amount of work in nuclear theory is based upon effective forces

- Used for everything from nuclear astrophysics to collective excitations of nuclei

- Skyrme Force: Vautherin and Brink


explicitly obtained effective force, 2- plus 3- body, of Skyrme type

- density-dependent forces now used more widely
Physical Origin of Density Dependent Force of the Skyrme Type within the Quark Meson Coupling Model

P.A.M. Guichon¹, H.H. Matevosyan²,³, N. Sandulescu¹,⁴,⁵ and A.W. Thomas²

<table>
<thead>
<tr>
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<th>$E_B$ (MeV, exp)</th>
<th>$E_B$ (MeV, QMC)</th>
<th>$r_c$ (fm, exp)</th>
<th>$r_c$ (fm, QMC)</th>
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<tr>
<td>$^{16}\text{O}$</td>
<td>7.976</td>
<td>7.618</td>
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<td>$^{40}\text{Ca}$</td>
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<td>8.213</td>
<td>3.485</td>
<td>3.415</td>
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<td>$^{48}\text{Ca}$</td>
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<td>8.343</td>
<td>3.484</td>
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<td>$^{208}\text{Pb}$</td>
<td>7.867</td>
<td>7.515</td>
<td>5.5</td>
<td>5.42</td>
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</table>

• Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$
\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[ \frac{-3 G_\rho}{32} + \frac{G_\sigma}{8 (1 + d\rho G_\sigma)^3} - \frac{G_\sigma}{2 (1 + d\rho G_\sigma)} + \frac{3 G_\omega}{8} \right] +
$$

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

• highlights scalar polarizability

Global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

M. Dutra, O. Lourenço, J. S. S. Martins, and A. Delfino
Departamento de Física - Universidade Federal Fluminense,
Av. Litorânea s/n, 24210-150 Boa Viagem, Niterói RJ, Brazil

J. R. Stone
Department of Physics, University of Oxford,
OX1 3PU Oxford, United Kingdom and
Department of Physics and Astronomy,
University of Tennessee, Knoxville, Tennessee 37996, USA

C. Providência
Centro de Física Computacional,
Department of Physics,
University of Coimbra,
P-3004-516 Coimbra, Portugal

Furthermore, we considered weaker constraints arising from giant resonance experiments on isoscalar and isovector effective nucleon mass in SNM and BEM, Landua parameters and low-mass neutron stars. If these constraints are taken into account, the number of CSkP reduces to 9, GSkl, GSklII, KDE0v1, LNS, NRAPR, QMC700, QMC750 and SKRA, the CSkP* list.

Truly remarkable – force derived from quark level does a better job of fitting nuclear structure constraints than phenomenological fits with many times # parameters!
Systematic Study of Finite Nuclei
Systematic approach to finite nuclei

(This work is in preparation for publication: collaborators are J.R. Stone, P.A.M. Guichon and P. G. Reinhard)

• Allow 3 basic quark-meson couplings to vary so that nuclear matter properties reproduced within errors

-17 < E/A < -15 MeV
0.15 < ρ₀ < 0.17 fm⁻³
28 < J < 34 MeV
L > 25 MeV
250 < K₀ < 350 MeV

• Fix at overall best description of finite nuclei
Overview of Nuclei Studied – Across Periodic Table

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>N</th>
<th>Element</th>
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<td>6 -16</td>
<td>Pb</td>
<td>82</td>
<td>116 - 132</td>
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<td>16 – 32</td>
<td>Fm</td>
<td>100</td>
<td>148 - 156</td>
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<tr>
<td>Ni</td>
<td>28</td>
<td>24 – 50</td>
<td>No</td>
<td>102</td>
<td>152 - 154</td>
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<tr>
<td>Sr</td>
<td>38</td>
<td>36 – 64</td>
<td>Rf</td>
<td>104</td>
<td>152 - 154</td>
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<tr>
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<td>40</td>
<td>44 -64</td>
<td>Sg</td>
<td>106</td>
<td>154 - 156</td>
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<tr>
<td>Sn</td>
<td>50</td>
<td>50 – 86</td>
<td>Hs</td>
<td>108</td>
<td>156 - 158</td>
</tr>
<tr>
<td>Sm</td>
<td>62</td>
<td>74 – 98</td>
<td>Ds</td>
<td>110</td>
<td>160</td>
</tr>
<tr>
<td>Gd</td>
<td>64</td>
<td>74 -100</td>
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<table>
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<th>N</th>
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<tr>
<td>20</td>
<td>10 – 24</td>
<td>64</td>
<td>36 - 58</td>
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<td>12 – 32</td>
<td>82</td>
<td>46 - 72</td>
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<td>40</td>
<td>22 – 40</td>
<td>126</td>
<td>76 - 92</td>
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<tr>
<td>50</td>
<td>28 – 50</td>
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</table>

i.e. We look at most challenging cases of p- or n-rich nuclei.
Binding Energies: Isotopes & Isotones

Typically better than 0.5%
Deformation Impressive

FDRM: P. Moller et al., ADNDT, 59, 185 (1995)
Superheavies
Summary: Finite Nuclei

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

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

• The force involves δ-functions
  − i.e. looks superficially like point-like nucleons

• BUT underlying theory also predicts modified
  − structure functions
  − form factors
Modified Structure Functions
The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 30 years ago

- Nearly 1,000 papers have been generated.....

- What is it that alters the quark momentum in the nucleus?

![Graph](image)

Calculations for Finite Nuclei

(Spin dependent EMC effect TWICE 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].

Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët, W. Bentz, and A. W. Thomas

\[ A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[ a_2(x_A) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3(x_A) \right] \]

\[ Z/N = 82/126 \text{ (lead)} \]

Ideally tested at EIC with CC reactions

Parity violating EMC will be tested at Jlab 12 GeV
Modified Electromagnetic Form Factors In-Medium
In-medium electron-nucleon scattering

D.H. Lu, A.W. Thomas, K. Tsushima, A.G. Williams, K. Saito

Jefferson Lab & Mainz: more from S. Strauch

Polarized $^4$He(e,e’p) measuring recoil p polarization (T/L : $G_E/G_M$)

STRAUCH ET AL., EPJ WEB OF CONF. 36 (2012) 00016

QMC medium effect predicted more than a decade years before the experiment
Longitudinal response function
– revisited in expectation of new results from JLab, Meziani et al.

Horikawa and Bentz, nucl-th/0506021
Recent Calculations Motivated by:

E01-015, PR-04-015 – Chen, Choi & Meziani

• Using NJL model with nucleon structure self-consistently solved in-medium

• Same model describing free nucleon form factors, structure functions and EMC effect
Modification of Proton Form Factors

Free nucleon form factors
Bentz et al.
Phys Rec C90, 045202 (2014)

Cloët et al., 2015
Response Function

RPA correlations repulsive
Significant reduction in Response Function from modification of bound-nucleon

\[ \frac{d^2 \sigma}{d \Omega \ d \omega} = \sigma_{\text{Max}} \left[ \frac{q}{|q|} R_L(\omega, |q|) + \left( \frac{q^2}{2 |q|^2} + \tan^2 \frac{\beta}{2} \right) R_\sigma(\omega, |q|) \right] \]

Cloët, Bentz & Thomas (arXiv: this week)
Comparison with Unmodified Nucleon & Data

Data: Morgenstern & Meziani
Calculations: Cloët, Bentz & Thomas (arXiv: this week)
Summary

• Relativity is essential

• Intermediate attraction in NN force is STRONG 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 force/density dependence of effective forces
  – clear physical interpretation

• Derived, density-dependent effective force gives results better than most phenomenological Skyrme forces
Summary

• Initial systematic study of finite nuclei very promising
  − Binding energies typically within 0.5% or better across periodic table

• Super-heavies (Z > 100) especially good (typically better than 0.25%)!

• Deformation, spin-orbit splitting and charge distributions all look good (NOT fit – only binding)

• Await new data:
  − Response Functions & Coulomb sum rule (soon)
  − Isovector EMC effect; spin EMC etc....
Special Mentions......

Guichon

Stone

Saito

Tsushima

Bentz

Cloët
We look forward to welcoming delegates to Adelaide, Australia for INPC 2016

September 11-16 2016

Key papers on QMC

• Two major, recent papers:

• Built on earlier work on QMC: e.g.

• Major review of applications of QMC to many nuclear systems:
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:
  

Most recent nuclear structure results

- Results obtained using SKYAX code of P. G. Reinhard
- 2 BCS pairing parameters (density dependent, contact pairing force) fitted from pairing gaps in Sn isotopes