QCD and a New Paradigm for Nuclear Structure

Anthony W. Thomas

New Directions in Subatomic Physics
Adelaide : March 10th 2016
QCD and a New Paradigm for Nuclear Structure
More than 50 joint publications 1985+

Tony
Governor Eric Neil at NITP
The path to CSSM and CoEPP : 1995
Japan-Australia Workshop 1995
Centre for the Subatomic Structure of Matter formed as an ARC Special Research Centre in 1997

To understand the quark structure of matter from protons and neutrons to atomic nuclei and neutron stars (pulsars)
CSSM early this millennium
Who has a new computer?
No Tony but still a good photo
Same Workshop – QCD Down Under
ARC Centre of Excellence for Particle Physics at the Tera-Scale

The University of Adelaide
The University of Melbourne
The University of Sydney
Monash University
Stawell Underground Physics Laboratory

SUPL will be Australia's first underground integrated laboratory within the Stawell Gold Mine in Victoria, hosting Australia's first-ever direct detection dark matter experiment.

In the Southern Hemisphere, we have a crucial advantage in measuring the true nature of dark matter, allowing us to address one of the most important unsolved problems of contemporary science.

SUPL will be a national underground research facility, with its dedicated infrastructure for dark matter direct detection, for wide-area gamma-ray and neutrino searches, for ultra-cold dark matter characterization as well as a multi-science low-background underground laboratory, providing new experimental evidence for new physics well beyond the Standard Model.

SUPL will ensure Australia's leadership in the worldwide effort to directly detect and characterize dark matter.

Collaborating Organizations:
The University of Adelaide • Monash University • The University of Melbourne • Macquarie University • Swinburne University of Technology • The University of Western Australia • The University of Sydney • The University of Tasmania • The University of Technology, Sydney

Adelaide University Australia
A decade ago.....

PLANS FOR A NATIONAL DUMP DITCHED

July 14, 2004

**Photo:** South Australian Premier Mike Rann spent years fighting the Federal Government's nuclear waste plans. (ABC News)

The Federal Government **abandons its plan to build a single national radioactive waste dump in South Australia.**

The Commonwealth wants each state and territory to build its own waste storage site.

The premier, Mr Rann, describes the decision as a great victory.
and now.....

SA nuclear waste dump would deliver $257b

February 18, 2016

Total revenue from a proposed nuclear waste facility in SA would reach $257 billion. Photo: Glenn Campbell

Momentum is growing for the construction of a nuclear waste facility in Australia to store and dispose of spent nuclear fuel rods and other waste from around the world in a project which would deliver $257 billion in revenue with signs of a bipartisan approach from the major federal political parties on the issue.

Kevin Scarce, a former South Australian governor who spent almost 12 months taking evidence from 128 witnesses, handed down his preliminary findings on Monday from The Nuclear Fuel Cycle Royal Commission which examined if South Australia should expand from being a uranium miner into enrichment, waste storage and power generation.

So let’s discuss nuclear physics
Beginning of the 20th Century

Knew about the proton and the electron – tried to build all atoms from these

In Adelaide William Henry Bragg was trying to understand the nature of X-rays – concluded they were particles
Rutherford

Discovered that alpha particles went straight through matter – most of the time

Occasionally scatter very hard – back the way they came!

Concludes **mater is mainly empty space**!

There is a heavy nucleus surrounded at a (comparatively great distance by electrons)
1930’s the Discoveries Accelerate

1932 Chadwick the n ; the positron – or “anti-electron”

1940’s the muon and pion (predicted by Yukawa in 1935);
then in the 50’s an “explosion” of new
particles – 100’s of them generated by
new particle accelerators at national or
international laboratories
• From that time forward nuclei have been built from neutrons and protons, with exactly the same properties in-medium as outside, interacting through the exchange of pions and other mesons

• BUT is that the whole story?

• After all along came QCD in the 1970s!

• BUT regarded as irrelevant to nuclear structure............
“Stan, you have to understand -- in nuclear physics we are only interested in how protons and neutrons make up a nucleus. We are not interested in what is inside of a proton.”
Fundamental Question for Nuclear Physics

• Is the nucleon immutable?

• i.e. When immersed in a nuclear medium with applied scalar field strength of order half its mass is it really unchanged??

• When looked at in the context of QCD as the theory of the strong force clearly **NO**

• Is this irrelevant to nuclear structure? **NO**

• Indeed, we argue it is of fundamental importance.....
Relativity really matters

- Once we realize that a nucleon has internal structure, the effects of a Lorentz scalar mean field and Lorentz vector mean field are totally different.

- Of course, they largely cancel to give ~8 MeV binding per nucleon: BUT this is very misleading.

- Time component of $\omega$ mean field just shifts the energy scale – no effect on internal structure.

- The $\sigma$ field changes the (very light) quark mass and hence changes the internal dynamics!

  Strength of the $\sigma$ field is the real measure of how far off-shell the nucleon is in-medium!
Relevance of QCD to Nuclear Structure

• Insight into origin of saturation – unexpected!

• Behaviour at very high density (neutron star) – transition from hadronic to quark matter

• EFT *assumes* relevant degrees of freedom (d.o.f): beware lesson of drunk looking for keys under lamp post
  
  – i.e. EFT has symmetries of QCD .......
  
  BUT we need to know the relevant d.o.f. too

• Working at quark level can provide guidance
Outline

• Start from a QCD-inspired model of hadron structure

• Ask how that internal structure is modified in-medium

• This naturally leads to saturation + predictions for all hadrons (e.g. hypernuclei...)

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

• Test predictions for quantities sensitive to internal structure: DIS structure functions, form factors in-medium....
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 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
  \[ \frac{N}{4\pi} \left( i\beta_q \hat{\sigma} \cdot \hat{u}' j_1(xu'/R_B) \right) \chi_m \]

- 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

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

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.
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.
Explicit Demonstration of Origin of 3-Body Force

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

\[
H_{QMC} = \sum_i \frac{\nabla_i \cdot \nabla_i \rho_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \nabla_i \delta(\vec{r}_{ij}) \cdot \nabla_i
\]
\[
+ \frac{1}{2} \sum_{i \neq j} \left[ \nabla_i^2 \delta(\vec{r}_{ij}) \right] \left[ \frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{T}_i \cdot \vec{T}_j}{4} \right]
\]
\[
+ \frac{1}{2} \sum_{i \neq j} \delta(\vec{r}_{ij}) \left[ G_\omega - G_\sigma + G_\rho \frac{\vec{T}_i \cdot \vec{T}_j}{4} \right]
\]
\[
+ \frac{dG_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{dG_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl)
\]
\[
+ \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \nabla_i \delta(\vec{r}_{ij}) \times \nabla_i \hat{\sigma}_i ,
\]

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 functional:

$$\langle H(\vec{r}) \rangle = \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\text{eff}} + \mathcal{H}_{\text{fin}} + \mathcal{H}_{\text{so}}$$
Derivation of effective Force (cont.)

\[ \mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[ -\frac{3G_\rho}{32} + \frac{G_\sigma}{8(1 + d\rho G_\sigma)^3} - \frac{G_\sigma}{2(1 + d\rho G_\sigma)} + \frac{3G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[ \frac{5G_\rho}{32} + \frac{G_\sigma}{8(1 + d\rho G_\sigma)^3} - \frac{G_\omega}{8} \right] , \]

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

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

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

Note the totally new, subtle density dependence

Spin-orbit force predicted!
Global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

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Furthermore, we considered weaker constraints arising from giant resonance experiments on isoscalar and isovector effective nucleon mass in SNM and BEM, Landau parameters and low-mass neutron stars. If these constraints are taken into account, the number of CSkP reduces to 9, GSki, GSkII, 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!
Important observation

- Simenel and McRae (ANU) noticed that the ratio of iso-vector to iso-scalar spin-orbit force in purely phenomenological UNDEF1 agrees with that predicted by QMC approach within 3%.

- This may well be one part of the explanation of why it works so well for finite nuclei. ....... see next
Systematic Study of Finite Nuclei
Systematic approach to finite nuclei

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

• Vary 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 MeV
0.14 < $\rho_0$ < 0.18 fm$^{-3}$
28 < $S_0$ < 34 MeV
L > 20 MeV
250 < $K_0$ < 350 MeV

• Fix at overall best description of finite nuclei (+2 pairing pars)

• Benchmark comparison: SV-min 16 parameters (11+5)
Overview of Allowed Parameters

![Graph showing the overview of allowed parameters with labels A to R and corresponding values of G in fm².]
Overview of 106 Nuclei Studied – Across Periodic Table

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<th>Element</th>
<th>Z</th>
<th>N</th>
<th>Element</th>
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<td>Ca</td>
<td>20</td>
<td>16-32</td>
<td>Fm</td>
<td>100</td>
<td>148-156</td>
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<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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<td>44-64</td>
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<td>106</td>
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<td>62</td>
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<tr>
<td>Gd</td>
<td>64</td>
<td>74-100</td>
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<table>
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<tr>
<td>50</td>
<td>28-50</td>
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</table>

i.e. Challenging cases of p- or n-rich nuclei across Periodic Table
"I think you should be more explicit here in step two."
## Overview

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<th>data</th>
<th>rms error %</th>
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<td>QMC</td>
<td>SV-min</td>
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<td><strong>fit nuclei:</strong></td>
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<td>binding energies</td>
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<td>diffraction radii</td>
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<td>pairing gap (p)</td>
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<tr>
<td>other</td>
<td>0.35</td>
<td>0.26</td>
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</table>

Not fit
Superheavies: 0.1% accuracy

Stone et al., PRL (2016)
Quadrupole Deformation of Superheavies

Stone et al., PRL 116 (2016) 092501
Deformation in Gd (Z=64) Isotopes
### Spin-orbit splitting

<table>
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<td>7.2 b)</td>
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<td>Pb208</td>
<td>proton</td>
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<td></td>
<td>0.91</td>
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<tr>
<td></td>
<td>neutron</td>
<td>$3p_{1/2} - 3p_{3/2}$</td>
<td>0.90(18)a</td>
<td>1.11</td>
</tr>
</tbody>
</table>
Shape evolution of Zr (Z=40) Isotopes

- Shape co-existence sets in at N=60 – Sotty et al., PRL115 (2015) 172501
- Usually difficult to describe
  – e.g. Mei et al., PRC85, 034321 (2012)

Stone et al., PRL 116 (2016) 092501
"Hot off the press"

Traditionally very hard to describe
Summary: Finite Nuclei

• The effective force was derived at the quark level based upon changing structure of 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
  − elastic form factors......
Nuclear DIS Structure Functions

To address questions like this one MUST start with a theory that quantitatively describes nuclear structure – very, very few examples.....

Indeed, the approach described here is unique!
The EMC Effect: Nuclear PDFs

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

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


Theoretical Understanding

• Still numerous proposals but few consistent theories

• Initial studies used MIT bag\textsuperscript{1} to estimate effect of self-consistent change of structure in-medium – but better to use a covariant theory

• For that Bentz and Thomas\textsuperscript{2} re-derived change of nucleon structure in-medium in the NJL model

• This set the framework for sophisticated studies by Cloët and collaborators over the last decade

\textsuperscript{1} Thomas, Michels, Schreiber and Guichon, Phys. Lett. B233 (1989) 43
\textsuperscript{2} Bentz and Thomas, Nucl. Phys. A696 (2001) 138
Approved JLab Experiment

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

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

- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in $^7\text{Li}$*

![Graph showing EMC ratios for $^7\text{Li}$ with data points and fitted curves for unpolarized and polarized EMC effects.](image)

Other tests (e.g. Isovector EMC effect) – see Ian Cloet
Modified Electromagnetic Form Factors In-Medium
In-medium electron-nucleon scattering

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

a Department of Physics and Mathematical Physics and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Australia 5005
b Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan

In-medium nucleon electromagnetic form factors are calculated in the quark meson coupling model. The form factors are typically found to be suppressed as the density increases. For example, at normal nuclear density and $Q^2 \sim 0.3$ GeV$^2$, the nucleon electric form factors are reduced by approximately 8% while the magnetic form factors are reduced by only 1–2%. These variations are consistent with current experimental limits but should be tested by more precise experiments in the near future. ©1998 Elsevier Science B.V.
In-medium electron-nucleon scattering

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

![Graph showing the ratio of coupled channel amplitudes to free amplitudes as a function of momentum transfer squared (Q^2). The graphs display the effects of different nuclear densities (n=0.5n_0, n=1n_0, n=1.5n_0, n=2n_0) on the electron-nucleon scattering.](image)

Electromagnetic form factors of the bound nucleon

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

Department of Physics, National Taiwan University, Taipei 10617, Taiwan
Department of Physics and Mathematical Physics and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide, Australia 5005
Physics Division, Tohoku College of Pharmacy, Sendai 981-8558, Japan

(Received 24 July 1998; revised manuscript received 19 July 1999; published 5 November 1999)

We calculate electromagnetic form factors of the proton bound in specified orbits for several closed-shell nuclei. The shell structure of the finite nuclei, together with the internal quark substructure of the nucleon, are self-consistently described by the quark-meson-coupling model. We find that the medium-modified electric and magnetic form factors of the bound nucleon deviate considerably from those of the free nucleon. Our results suggest that this medium correction on the nucleon’s quark substructure may be detectable in forthcoming quasielastic electron-nucleus scattering. [S0556-2813(99)00511-7]
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
Response Function

RPA correlations repulsive

Significant reduction in Response Function from modification of bound-nucleon

\[
\frac{d^2\sigma}{d\Omega \, d\omega} = \sigma_{\text{Mol}} \left[ \frac{q^4}{|q|^4} R_L(\omega, |q|) \right.
\]
\[
+ \left( \frac{q^2}{2|q|^2} + \tan^2 \frac{\beta}{2} \right) R_\sigma(\omega, |q|) \right]
\]

Cloët, Bentz & Thomas (PRL 116 (2016) 032701)
Comparison with Unmodified Nucleon & Data

Data: Morgenstern & Meziani
Calculations: Cloët, Bentz & Thomas (PRL 116 (2016) 032701)
and these predictions are stable!

\[ S_L(|q|) = \int_{\omega^+} |q| \frac{R_L(\omega, |q|)}{Z G_{Ep}^2(Q^2) + N G_{En}^2(Q^2)} \ |q| \ [\text{GeV}] \]

Data: Morgenstern & Meziani
Calculations: Cloët, Bentz & Thomas (arXiv:1506.05875)

\( ^{12}\text{C} \) current – RPA

\( ^{208}\text{Pb} \) – experiment

\( ^{12}\text{C} \) – experiment

\( ^{12}\text{C} \) – GFMC

\( \star \) Saito et al., QMC 1999 (op cit)
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 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 0.3% across periodic table

• Super-heavies (Z > 100) especially good
  (average difference 0.1%)

• Deformation, spin-orbit splitting and charge distributions all look good

• BUT need empirical confirmation:
  - Response Functions & Coulomb sum rule (soon)
  - Isovector EMC effect; spin EMC
  - Your idea here.....................
We look forward to welcoming delegates to Adelaide, Australia for INPC 2016

September 11-16 2016
best wishes tony
Key papers on QMC

- **Two major, recent papers:**
  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:

Hyperons

• Derive \( \Lambda N, \Sigma N, \Lambda \Lambda \) ... effective forces in-medium with no additional free parameters

• Attractive and repulsive forces (\( \sigma \) and \( \omega \) mean fields) both decrease as # light quarks decreases

• NO \( \Sigma \) hypernuclei are bound!

• \( \Lambda \) bound by about 30 MeV in nuclear matter (~Pb)

• Nothing known about \( \Xi \) hypernuclei – JPARC!
### Λ- and Ξ-Hypernuclei in QMC

<table>
<thead>
<tr>
<th></th>
<th>$^{89}$Yb (Expt.)</th>
<th>$^91 \Lambda$Zr</th>
<th>$^91 \Xi_0$Zr</th>
<th>$^{208}$Pb (Expt.)</th>
<th>$^{209}$Pb</th>
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<td>-16.0 (1p)</td>
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<td>-7.2</td>
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<td>-4.3</td>
</tr>
</tbody>
</table>

Predicts Ξ – hypernuclei bound by 10-15 MeV to be tested soon at J-PARC
$\Sigma$ – hypernuclei

$\Sigma$-hypernuclei unbound:
because of increase of hyperfine interaction with density
– e.g. for $\Sigma^0$ in $^{40}\text{Ca}$:
central potential +30 MeV and few MeV attraction in surface (-10 MeV at 4 fm)

Consequences for Neutron Star

Rikovska-Stone et al., NP A792 (2007) 341
A two-solar-mass neutron star measured using Shapiro delay

Report a very accurate pulsar mass much larger than seen before: $1.97 \pm 0.04$ solar mass

Claim it rules out hyperons (particles with strange quarks - ignored our published work!)
Experimental Test of QMC at Mainz & JLab

Capacity to measure polarization in coincidence:

\[ \sigma_T / \sigma_L \sim G_E / G_M : \text{Compare ratio in } ^4\text{He and in free space} \]

Super-ratio – in-medium to free space

\( \frac{G_E^*}{G_M^*} / \frac{G_E}{G_M} \)

Neutron

Proton

Nambu–Jona-Lasinio

(Bentz et al.)

Relativistic light front constituent quark

(Smith & Miller)

\( Q^2 \) (GeV\(^2\))

from - Cloet, Miller et al., arXiv:0903.1312
Jefferson Lab & Mainz: more from S. Strauch

Polarized $^4\text{He}(e,e'p)$ measuring recoil $p$ polarization ($T/L: G_E/G_M$)

Strauch et al., EPJ Web of Conf. 36 (2012) 00016
