Three-nucleon forces: From neutron-rich nuclei to matter in astrophysics

Achim Schwenk

ARIS 2014 – Tokyo, Japan
June 3, 2014
Main message

3N forces and neutron-rich nuclei

Masses of exotic calcium isotopes pin down nuclear forces

Evidence for a new nuclear ‘magic number’ from the level structure of $^{54}$Ca

3N forces and neutron stars

based on same strong interactions
Chiral effective field theory for nuclear forces see also talk by Ulf Meißner

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale $\sim 500$ MeV

include long-range pion physics

few short-range couplings, fit to experiment once

systematic: can work to desired accuracy and obtain error estimates

consistent electroweak interactions and matching to lattice QCD
Chiral effective field theory and **many-body forces**

Separation of scales: low momenta \( \frac{1}{\lambda} = Q \ll \Lambda_b \) breakdown scale \( \sim 500 \text{ MeV} \)

consistent **NN-3N-4N** interactions

3N,4N: 2 new couplings to N\(^3\)LO
+ no new couplings for neutrons

<table>
<thead>
<tr>
<th></th>
<th>LO</th>
<th>NLO</th>
<th>N(^2)LO</th>
<th>N(^3)LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td></td>
<td></td>
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<tr>
<td>3N</td>
<td>( \mathcal{O}(Q^0/\Lambda^0) )</td>
<td>( \mathcal{O}(Q^2/\Lambda^2) )</td>
<td>( \mathcal{O}(Q^3/\Lambda^3) )</td>
<td>derived in (2002)</td>
</tr>
<tr>
<td>4N</td>
<td></td>
<td></td>
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</tbody>
</table>

\( c_i \) from \( \pi N \) and NN

Meissner et al. (2007)

\[
\begin{align*}
    c_1 &= -0.9^{+0.2}_{-0.5}, \\
    c_3 &= -4.7^{+1.2}_{-1.0}, \\
    c_4 &= 3.5^{+0.5}_{-0.2}
\end{align*}
\]

c\(_D\), c\(_E\) fit to light nuclei only

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,...
The oxygen anomaly


without 3N forces, NN interactions too attractive

3N forces crucial for location of neutron dripline
New ab initio methods extend reach impact of 3N forces confirmed in large-space calculations:
Coupled Cluster theory with phenomenological 3N Hagen et al., PRL (2012)
In-Medium Similarity RG based on chiral NN+3N Hergert et al., PRL (2013)
Green’s function methods based on chiral NN+3N Cipollone et al., PRL (2013)
first results with 3N forces for ground and excited states of N=8, 20

prediction for $^{20}\text{Mg}$ agrees with new state observed at GSI  

Holt, Menendez, AS, PRL (2013)

Mukha, private comm.
Ab initio calculations going open shell: SM interactions

In-Medium Similarity RG to derive valence-shell interactions

Bogner, Hergert, Holt, AS et al., 1402.1407
Ab initio calculations going open shell: SM interactions

In-Medium Similarity RG to derive valence-shell interactions
Bogner, Hergert, Holt, AS et al., 1402.1407

Coupled Cluster calculations for effective interactions
Jansen et al., arXiv:1402.2563
Towards theoretical uncertainties see talk by Javier Menéndez
based on NN+3N interactions that predict nuclear matter saturation within uncertainties

Preliminary

![Graphs showing dependence of $S_{2n}$ on mass number for different isotopes (O, F, Ne, Na, Mg, Al, Si)]

- $S_{2n}$ (MeV) vs Mass number $A$
- Preliminary results
- Isotopes: O, F, Ne, Na, Mg, Al, Si
- Lines and markers indicate data from AME 2012
- Various fits: 1.8/2.0, 2.0/2.0, 2.2/2.0, 2.8/2.0, 2.0/2.5
new $^{51,52}$Ca TITAN measurements

$^{52}$Ca is 1.74 MeV more bound compared to atomic mass evaluation

Gallant et al., PRL (2012)

behavior of 2n separation energy $S_{2n}$ agrees with NN+3N predictions
Masses of exotic calcium isotopes pin down nuclear forces

53,54Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer
see talk by Susanne Kreim

establish prominent N=32 shell closure in calcium

excellent agreement with theoretical NN+3N prediction
Frontier of ab initio calculations at $A \sim 50$

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz$^1$, D. Beck$^2$, K. Blaum$^3$, Ch. Borngmann$^3$, M. Breitenfeldt$^4$, R. B. Cakirli$^3,5$, S. George$^1$, F. Herfurth$^2$, J. D. Holt$^6,7$, M. Kowalska$^8$, S. Kreim$^3,8$, D. Lunney$^9$, V. Manea$^9$, J. Menéndez$^6,7$, D. Neidherr$^2$, M. Rosenbusch$^1$, L. Schweikhard$^1$, A. Schwenk$^7,6$, J. Simonis$^6,7$, J. Stanja$^{10}$, R. N. Wolf$^1$ & K. Zuber$^{19}$

$^{53,54}$Ca masses measured at ISOLTRAP using new MR-TOF mass spectrometer

see talk by Susanne Kreim

interesting continuum effects for very neutron-rich Ca

see Forssen et al., Physica Scripta (2013)
Masses of exotic calcium isotopes pin down nuclear forces

overall good agreement with density functional predictions

but DF’s do not reproduce shell closures

cf. N=50, 82, 126 “arches”

Bender et al. (2005)
3N forces and magic numbers

Hagen et al., PRL (2012)

Holt et al., JPG (2012, 2013)

Energy measured at RIBF suggests magic number N=34

Steppenbeck et al., Nature (2013)
see talk by David Steppenback
Ab initio calculations going open shell: around Ca

Gorkov Green’s function methods based on chiral NN+3N
Somà, Cipollone, Barbieri, Navratil, Duguet, PRC (2014)
see talk by Carlo Barbieri

multi-reference IM-SRG
Hergert et al., PRL (2013)

shell model based on NN+3N

### Chart

- **55 Ca**
  - 1/2
  - 7/2
  - 3/2
  - 9/2
  - 5/2

### Graph

- **S2n [MeV]**
- **N**
- **Ca**
- **Sc**
- **Ti**
- **K**
- **Ar**

### Table

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>NN+3N</th>
<th>pfg(_{9/2})</th>
<th>Expt.</th>
<th>GXPF1A</th>
<th>KB3G</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2</td>
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<td>9/2</td>
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<td>7/2</td>
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<td>5/2</td>
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<td>3/2</td>
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<tr>
<td>1/2</td>
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<td>(5/2)</td>
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Notes:
- (5/2) is indicated in red.
Chiral EFT for electroweak currents

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<th>( \mathcal{O} \left( \frac{Q^0}{\Lambda^0} \right) )</th>
<th>NN</th>
<th>3N</th>
<th>4N</th>
<th>one-body currents at ( Q^0 ) and ( Q^2 )</th>
</tr>
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<tbody>
<tr>
<td>NLO</td>
<td>( \mathcal{O} \left( \frac{Q^2}{\Lambda^2} \right) )</td>
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<td></td>
<td></td>
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<tr>
<td>N^2LO</td>
<td>( \mathcal{O} \left( \frac{Q^3}{\Lambda^3} \right) )</td>
<td></td>
<td></td>
<td></td>
<td>+ two-body currents at ( Q^3 )</td>
</tr>
<tr>
<td>N^3LO</td>
<td>( \mathcal{O} \left( \frac{Q^4}{\Lambda^4} \right) )</td>
<td></td>
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</tbody>
</table>

same couplings in forces and currents!
Chiral EFT currents and electroweak interactions predicts consistent 1- and 2-body currents

GFMC calcs of magnetic moments in light nuclei Pastore et al., PRC (2012)
2-body currents (meson-exchange currents) are key!
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A=$10^{57}$

(PSR J0348+0432)
Chiral effective field theory and many-body forces

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consistent NN-3N-4N interactions

3N,4N: 2 new couplings to N$^3$LO
+ no new couplings for neutrons

$c_i$ from $\pi N$ and NN Meissner et al. (2007)
$c_1 = -0.9^{+0.2}_{-0.5}$, $c_3 = -4.7^{+1.2}_{-1.0}$, $c_4 = 3.5^{+0.5}_{-0.2}$

c$D$, c$E$ fit to light nuclei only

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meissner,…
Complete $N^3\text{LO}$ calculation of neutron matter

first complete $N^3\text{LO}$ result Tews, Krüger, Hebeler, AS, PRL (2013)

includes uncertainties from NN, 3N (dominates), 4N
Quantum Monte Carlo for neutron matter based on new local chiral EFT potentials, order-by-order convergence up to saturation density

Quantum Monte Carlo for neutron matter based on new local chiral EFT potentials, order-by-order convergence up to saturation density, excellent agreement with perturbative calculations for low cutoffs (~400 MeV)
Quantum Monte Carlo for neutron matter based on new local chiral EFT potentials, order-by-order convergence up to saturation density.

Excellent agreement with perturbative calculations for low cutoffs (~400 MeV).

Light nuclei based on GFMC.

See talk by Ulf Meißner.
direct measurement of neutron star mass from increase in signal travel time near companion J1614-2230 most edge-on binary pulsar known (89.17°) + massive white dwarf companion (0.5 $M_{\text{sun}}$) heaviest neutron star with $1.97\pm0.04$ $M_{\text{sun}}$
A Massive Pulsar in a Compact Relativistic Binary


Introduction: Neutron stars with masses above 1.8 solar masses ($M_{\odot}$), possess extreme gravitational fields, which may give rise to phenomena outside general relativity. Hitherto, these strong-field deviations have not been probed by experiment, because they become observable only in tight binaries containing a high-mass pulsar and where orbital decay resulting from emission of gravitational waves can be tested. Understanding the origin of such a system would also help to answer fundamental questions of close-binary evolution.

Methods: We report on radio-timing observations of the pulsar J0348+0432 and phase-resolved optical spectroscopy of its white-dwarf companion, which is in a 2.46-hour orbit. We used these to derive the component masses and orbital parameters, infer the system's motion, and constrain its age.

Results: We find that the white dwarf has a mass of $0.172 \pm 0.003 M_{\odot}$, which, combined with orbital velocity measurements, yields a pulsar mass of $2.01 \pm 0.04 M_{\odot}$. Additionally, over a span of 2 years, we observed a significant decrease in the orbital period, $\dot{P}_b = -8.6 \pm 1.4 \mu s \text{ year}^{-1}$ in our radio-timing data.
Equation of state/pressure for neutron-star matter (includes small $Y_{e,p}$)

- Pressure below nuclear densities agrees with standard crust equation of state only after 3N forces are included.
- Extend uncertainty band to higher densities using piecewise polytropes.
- Allow for soft regions at higher densities.


Constrain high-density EOS by causality, require to support $2 \, M_{\text{sun}}$ star

Low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

constrain high-density EOS by causality, require to support $2 \, M_{\text{sun}}$ star

low-density pressure sets scale, chiral EFT interactions provide strong constraints, ruling out many model equations of state

predicts neutron star radius: $9.7-13.9 \, \text{km for } M=1.4 \, M_{\text{sun}}$ ($\pm 18\%$ !)

constrain high-density EOS by causality, require to support 2 $M_{\odot}$ star

<table>
<thead>
<tr>
<th>$\tilde{M} = 1.97 M_{\odot}$</th>
<th>$\tilde{M} = 2.4 M_{\odot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>$\rho_c/\rho_0$ (1.4 $M_{\odot}$)</td>
<td>1.8</td>
</tr>
<tr>
<td>$\rho_c/\rho_0$ (1.97 $M_{\odot}$)</td>
<td>2.0</td>
</tr>
<tr>
<td>$\rho_c/\rho_0$ (2.4 $M_{\odot}$)</td>
<td>2.0</td>
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</table>

central densities for 1.4 $M_{\odot}$ star: 1.8-4.4 $\rho_0$

not very high momenta!
Neutron-star mergers and gravitational waves explore sensitivity to neutron-rich matter in neutron-star merger predictions for gravitational-wave signal, including NP uncertainties.

Bauswein, Janka, PRL (2012)
Bauswein, Janka, Hebeler, AS, PRD (2012)

FIG. 10: Peak frequency of the postmerger GW emission versus the radius of a nonrotating NS with 1.6 $M_\odot$ for different EoSs. Symbols have the same meaning as in Fig. 8.
Calculations of asymmetric matter Drischler, Soma, AS, PRD (2014)

$E_{\text{sym}}$ comparison with extraction from isobaric analogue states (IAS)
3N forces fit to $^3\text{H}$, $^4\text{He}$ properties only

![Graph showing $E_{\text{sym}}$ vs. $n$ for different models: this work, Akmal et al. (1998), BHF, AV18+UIX, Danielewicz & Lee (2013) IAS, Danielewicz & Lee (2013) IAS + skins.](image)
Symmetry energy and pressure of neutron matter

neutron matter band predicts symmetry energy $S_v$ and its density derivative $L$

generates comparison to experimental and observational constraints

neutron matter constraints
H: Hebeler et al. (2010)
G: Gandolfi et al. (2011)
provide tight constraints!

combined with Skyrme EDFs predicts neutron skin
$^{208}$Pb: 0.182(10) fm
$^{48}$Ca: 0.173(5) fm
Brown, AS, PRC (2014)
Summary and perspectives

3N forces are an exciting frontier for nuclei and astrophysics

ab initio calculations are going open shell: O to Ca/Ni/Sn region

need to quantify uncertainties, dominated by uncertainties in 3N forces

see talk by Javier Menéndez

nuclear structure with N^3LO 3N forces breakthrough: 3N matrix elements by Kai Hebeler + N^3LO 4N perturbatively

impact of chiral EFT two-body currents (meson-exchange currents) on electroweak transitions, provide new tests

provide ab initio constraints to powerful density functional theory

see talks by Jacek Dobaczewski and Witek Nazarewicz