3 Nucleon Interactions
Beyond A=4

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+ many others
Goal: Understand Nuclear Properties & Reactions from 'Realistic' Interactions & Currents

Relative Momenta beyond 2 x Fermi Momenta
CM Energies up to ~ 100 MeV

\[ E \sim \frac{k^2}{2\mu} \sim 100 \text{ MeV} \]
Concerns on EFT in many-body systems

**Binding Energy Differences Small:**
\[ E(6\text{Li}) - ( E(4\text{He}) + E(D) ) = 1.5 \text{ MeV} \]
\[ E(7\text{Li}) - E_{\text{th}} = 2.4 \text{ MeV} \]
yielding concerns about counting schemes that require perturbation theory

**Interaction Terms in Many-Body systems** can add coherently (L.S splittings) or cancel strongly (TNI in n-rich systems).

What are we sensitive to in light nuclear spectra?
Argonne v18
with Illinois-2
GFMC Calculations
19 June 2002

Pieper, Wiringa, & Varga
Can we understand forces from Spectra?

Pieper & Wiringa, PRL 2003
Central Interaction

Expt
V1'
VX'
V4'
+tensor
+LS
+ q^2 (AV18)
+ III - TNI

3He 4He 5He 6He 6Li 7Li 8He 8Be 10B
+ Space Exchange Interaction
+ spin-spin, tensor, L.S
AV18 w/o TNI

Expt
V1'
VX'
V4'
+ tensor
+ L_S
+ q^2 (AV18)
+ III - TNI
Urbana/ Illinois Models of TNI:

A(PW)

UIX: -0.0293
IL2: -0.037

'Short-range' Spin-Indep.

UIX: 0.00480 (0.00291)
IL2: 0.00705 (0.00493)
2-pion TNI terms in various interactions

<table>
<thead>
<tr>
<th></th>
<th>A'</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujita-Miyazawa</td>
<td>0</td>
<td>-1.15</td>
<td>0</td>
<td>-0.29</td>
</tr>
<tr>
<td>TM</td>
<td>-1.03</td>
<td>-2.62</td>
<td>1.03</td>
<td>-0.60</td>
</tr>
<tr>
<td>Brazil</td>
<td>-1.05</td>
<td>-2.29</td>
<td>(1.05)</td>
<td>-0.77</td>
</tr>
<tr>
<td>UIX</td>
<td>0</td>
<td>-1.20</td>
<td>0</td>
<td>-0.30</td>
</tr>
<tr>
<td>Texas</td>
<td>-1.87</td>
<td>-3.82</td>
<td>0</td>
<td>-1.12</td>
</tr>
<tr>
<td>Ill-2</td>
<td>-1</td>
<td>-1.52</td>
<td>0</td>
<td>-0.38</td>
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</tbody>
</table>

Huber, Friar, Nogga, Witala, van Kolck
Additional Terms in Illinois

S-wave Pion Term:

\[ A_{(SW)} [IL2] = -1.0 \]
(as in chiral potentials)

3-Pion Terms:

Quantum Numbers give large
\[ T = 3/2 \] contribution
Strength adjusted to \( A < 9 \)
Additional Chiral TNI terms:

Contact term:
For short-range, acts only in T=1/2

Pion-range – short-range Term
\[ V_4^{(1)} = -\frac{d_2}{(2\pi)^6} \frac{g_A}{4f_{\pi}^2} \sigma_1 \times \sigma_3 \cdot \vec{Q} \, \sigma_2 \cdot \vec{Q}' \, \frac{1}{Q'^2 + m_{\pi}^2} \, \tau_1 \cdot \tau_2 \times \tau_3 \]
\[ -\frac{d_2}{(2\pi)^6} \frac{g_A}{4f_{\pi}^2} \sigma_1 \times \sigma_2 \cdot \vec{Q} \, \sigma_3 \cdot \vec{Q} \, \frac{1}{Q^2 + m_{\pi}^2} \, \tau_1 \cdot \tau_2 \times \tau_3 \]

Triple-product structure:
Acts only in T=1/2 (& S=1/2)
Argonne v18
with Illinois-2
GFMC Calculations
19 June 2002
### Expectation Values:

<table>
<thead>
<tr>
<th>Nucleus:</th>
<th>AV18/UIX</th>
<th>IL2</th>
<th>$\langle TNI \rangle/\langle VNN \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4He</td>
<td>-6.35(5)</td>
<td>-8.38(7)</td>
<td>0.06</td>
</tr>
<tr>
<td>7Li</td>
<td>-9.1(2)</td>
<td>-14.5(4)</td>
<td>0.07</td>
</tr>
<tr>
<td>8He</td>
<td>-8.0(2)</td>
<td>-16.3(5)</td>
<td>0.07</td>
</tr>
<tr>
<td>12C</td>
<td>-40.8(2.)</td>
<td></td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nucleus:</th>
<th>2Pi(AC)</th>
<th>2Pi(C)</th>
<th>S-wv</th>
<th>VSR</th>
<th>3Pi(SS)</th>
<th>3Pi(AA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C</td>
<td>-40.</td>
<td>-24</td>
<td>-2</td>
<td>+30</td>
<td>-7</td>
<td>+2</td>
</tr>
<tr>
<td>8He</td>
<td>-16</td>
<td>-9</td>
<td>-1</td>
<td>+13</td>
<td>-5</td>
<td>+1</td>
</tr>
<tr>
<td>4He</td>
<td>-10</td>
<td>-6</td>
<td>-1</td>
<td>+7</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>
Additional Information (Beyond A=3,4)

- Nuclear / Neutron Matter
- Neutron Drops
- Scattering Processes
Symmetric Nuclear Matter
AV18 + UIX
Akmal, Pandharipande

Variational Method using Integral Eqn Techniques

“Simple” Wavefunction, cluster expansion slowly convergent w/ IL2
Neutron Matter (AV18 + UIX)

Supports 1.8 Solar mass neutron star

Cluster Expansion much more difficult for Illinois models of TNI
Neutron Drops
(N>8; mimicks Oxygen Isotopes)

Ext. well: $V=-35.5$, $R=3$, $a=1.1$
Without & with Argonne $v_{18}$ & $V_{ijk}$
23 June 2003
Expectation Values in Neutron Drops

<table>
<thead>
<tr>
<th></th>
<th>V1</th>
<th>VNN</th>
<th>VSR</th>
<th>V-2pi</th>
<th>V-sw</th>
<th>V-3pi</th>
<th>&lt;TNI/VNN&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=8</td>
<td>-173</td>
<td>-88</td>
<td>4</td>
<td>-0.</td>
<td>0.2</td>
<td>-10</td>
<td>7%</td>
</tr>
<tr>
<td>n=14</td>
<td>-260</td>
<td>-176</td>
<td>9</td>
<td>0.</td>
<td>0.5</td>
<td>-25</td>
<td>9%</td>
</tr>
</tbody>
</table>
A great deal of additional data in low-energy scattering:

**Example: n-alpha scattering**

![Graph showing neutron-alpha phase shifts](image)

Same information can be represented as $E$ vs. log derivative
n-α Log Derivative from R-matrix data
n-alpha Scattering - $P_{1/2}$ channel

Strong Correlations – Energy Differences Preliminary
1/2(-) p-wave results --- AV18 + UIX

$n$-$\alpha$ Log Derivative from R-matrix data

3/2(-) results will be worse

PRELIMINARY
Conclusions:

Nuclear spectra provide a valuable, if limited, set of constraints on nuclear interactions.

Additional Information can be provided by neutron-rich systems nuclear/neutron matter (potentially) scattering