Recent Experimental Results and Future Plans in Few-Nucleon Systems

In Honor of Professor Sergio Rosati at the Occasion of his 80th Birthday

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Critical comparison of experimental data and theoretical predictions for N–d scattering below the breakup threshold

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Abstract

The theoretical approaches for studying N–d processes using realistic, semi-phenomenological NN potentials have matured considerably during the last few years. Accurate calculations of scattering observables are now feasible. Recently, high-quality measurements of N–d scattering at energies below the deuteron breakup threshold became available. Therefore, a detailed comparison between theory and experimental data can now be performed. In this paper the various sets of experimental data for the N–d differential cross section, and the vector and tensor analyzing powers are examined in a critical way in the incident nucleon energy range from 1 to 3 MeV. In order to identify possible inadequacies of the interaction models adopted, phase-shift analyses were performed and compared to the theoretical parameters.

\textit{PACS:} 25.10+s, 24.70.+s, 21.30+y, 21.45.+v
No evidence for large charge-symmetry breaking effects in the $^3P_J$ nucleon-nucleon interactions

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Rigorous calculations of proton-deuteron and neutron-deuteron analyzing power $A_p(\theta)$ angular distributions in the incident nucleon energy range from 1 to 3 MeV are presented. It is shown that the sizable difference in the magnitude of $A_p(\theta)$ for $p-d$ and $n-d$ scattering is caused by the Coulomb interaction in the case of $p-d$ scattering and is not due to charge-symmetry-breaking effects in the $^3P_J$ nucleon-nucleon interactions. The calculated relative difference in the angular region of the $A_p(\theta)$ maximum is in agreement with the existing experimental data. [S0556-2813(97)01901-8]

PACS number(s): 21.45.+v, 24.70.+s, 25.40.--h, 13.75.Cs
Outline

High-Intensity Gamma-ray Source (HI\(\gamma\)S) 
\(A=3,4\)
1) \(\gamma\)-\(^3\)He and \(\gamma\)-\(^4\)He two-body breakup  
2) n-n QFS in n-\(^2\)H breakup  
3) n-n QFS in \(\gamma\)-\(^3\)H three-body breakup  
4) Elastic scattering N-A\(_\gamma\)(\(\theta\)) in the 4N systems 
\(A=2\)

Gerasimov-Drell-Hearn Sum Rule of the deuteron  
What is next at HI\(\gamma\)S?
Compton scattering off the proton, deuteron and \(^3\)He

Future Upgrade
High-Intensity Gamma-ray Source (HIγS) @ TUNL

γ-ray beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1 – 100 MeV</td>
</tr>
<tr>
<td>Linear &amp; circular polarization</td>
<td>&gt; 97%</td>
</tr>
<tr>
<td>Spatial distribution after collimation (diameter)</td>
<td>10 – 25 mm</td>
</tr>
<tr>
<td>Pulse width (FWHM)</td>
<td>0.5 – 0.8 ns</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>5.58 MHz</td>
</tr>
<tr>
<td>Flux with 2% $\Delta E / E_\gamma$ (2 MeV &lt; $E_\gamma$ &lt; 5 MeV)</td>
<td>$&gt; 3 \times 10^6 \gamma$/s</td>
</tr>
<tr>
<td>Flux with 5% $\Delta E / E_\gamma$ (5 MeV &lt; $E_\gamma$ &lt; 20 MeV)</td>
<td>$&gt; 7 \times 10^7 \gamma$/s</td>
</tr>
<tr>
<td>Flux on with 5% $\Delta E / E_\gamma$ (20 MeV &lt; $E_\gamma$ &lt; 100 MeV)</td>
<td>$&gt; 1 \times 10^7 \gamma$/s</td>
</tr>
</tbody>
</table>

World’s most intense accelerator-driven γ-ray source
Intensity $10^3 \gamma$/s/eV on target
HlγS: Intracavity Compton-Back Scattering

Example:

\[ E_e = 500 \text{ MeV} \Rightarrow \gamma = 978 \]

\[ \lambda_{\text{FEL}} = 400 \text{ nm} \]
\[ \hbar \omega = 3.11 \text{ eV} \]
\[ E_\gamma = 11.9 \text{ MeV} \]
$A=3$

World Data

HI$\gamma$S Data

A=4

World Data

$$^{4}\text{He}(\gamma,p)^3\text{H}$$

$E_\gamma$ (MeV)

$\sigma$ (mb)

HI$\gamma$S Data

$$^{4}\text{He}(\gamma,p)^3\text{H}$$

$E_\gamma$ (MeV)

$\sigma$ (mb)

- Present data
- T. Shima et al. (2005)
- S. Quaglioni et al.

Lorentz Integral Transform
Trento Group

Giant Dipole Resonance
Wataru Horiuchi

from W. Tornow et al., PR C85, 061001R (2012)
Return to A=3
PHYSICAL REVIEW C 85, 064003 (2012)

Di-neutron and the three-nucleon continuum observables

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We investigate how strongly a hypothetical $^1\!S_0$ bound state of two neutrons would affect observables in neutron-deuteron reactions. To that aim we extend our momentum-space scheme of solving the three-nucleon Faddeev equations and incorporate in addition to the deuteron also a $^1\!S_0$ di-neutron bound state. We discuss effects induced by a di-neutron on the angular distributions of the neutron-deuteron elastic scattering and deuteron breakup cross sections. A comparison to the available data for the neutron-deuteron total cross section and elastic scattering angular distributions cannot decisively exclude the possibility that two neutrons can form a $^1\!S_0$ bound state. However, strong modifications of the final-state-interaction peaks in the neutron-deuteron breakup reaction seem to disallow the existence of a di-neutron.
\( E_n = 26 \, \text{MeV} \quad n + d \rightarrow n + n + p \)

\(^2\text{H}(d,n)^3\text{He}\)

For \textit{n-n QFS} the proton detector is replaced by a neutron detector.

W. von Witsch, A. Siepe \textit{et al.}, 2002
$^2\text{H}(n,\text{np})n$ np QFS

$^2\text{H}(n,\text{nn})p$ nn-QFS

$E_n = 26$ MeV

FIG. 2. Data for $n$-$p$ QFS, projected onto the $E_n$ axis. The solid line is the finite-geometry Monte Carlo prediction, using CD-Bonn for the $N$-$N$ interaction.

FIG. 4. HE data of Fig. 3, projected onto the $E_{n1}$ axis. The solid curve represents the finite-geometry Monte Carlo prediction using CD-Bonn, the dotted line is the MC result normalized to the experiment by multiplication with a factor of 1.18. Only events with $E_{n1}$ and $E_{n2} > 6$ MeV have been included in the analysis.
$E_n = 25$ MeV

X.C. Ruan (CIAE) & W. von Witsch (Bonn), 2007

China Institute of Atomic Energy

$^2\text{H}(n,nn)p$ nn-QFS

$^3\text{H}(d,n)^4\text{He}$

FIG. 5. (Color online) Measured neutron energy spectrum from QFS compared with the theoretical prediction by Monte Carlo simulation based on CD-Bonn. The solid squares show the measured data, and the solid curve is the theoretical prediction, whereas the dotted line gives the theoretical prediction multiplied by a factor of 1.16. The error bars denote the statistical uncertainty only.
nn-Quasi-Free Scattering (QFS) & Search for a di-neutron bound state

**2H(n, np)n**  np-QFS  \( E_n = 26 \text{ MeV} \)

**2H(n, nn)p**  nn-QFS

Witała: Must increase the nn \( ^1S_0 \) strength to fit data

**Consequence:** shallow nn \( ^1S_0 \) bound state

A shallow nn \( ^1S_0 \) bound state is not in contradiction to few-nucleon observables in the continuum, except for nn-FSI data obtained at TUNL by Gonzalez-Trotter

**Two-pronged approach**

- Remeasure nn-QFS
- Search for di-neutron bound state via \( \gamma + ^3\text{H} \rightarrow \text{nn} + \text{p} \)
R&D for nn QFS measurement in nd breakup

Faculty: C.R. Howell and W. Tornow
Thesis Student: Ron Malone
Facility: Tandem Lab

Experiment setup

Neutron source:
\(^2\text{H}(d, n)\)

Signal-to-background ratio acceptable will move on to first Phase of measurements
Pulsed Deuteron Beam
Deuterium Gas Cell

Collimator & Shielding Wall

1.5 m

Proton Recoil Telescope

Transmission Foil Detector

CD$_2$ Target

Proton Detector

Neutron Detector

C$_6$D$_{12}$ Target

Neutron Detector

Neutron Detector

np QFS setup

nn QFS setup
\[ n+d = n + n + p \]

versus

\[ \gamma + ^{3}\text{H} = n + n + p \]
Photon-induced Three-body Breakup of $^3\text{H}$: $\gamma + ^3\text{H} \rightarrow n + n + p$

Proton Energy Spectrum at $\theta_p = 15^\circ$ and $\theta_p = 75^\circ$

- **AV18**: $a_{nn} = -18.8$ fm, $r_{\text{eff}} = 2.83$ fm, $\varepsilon_{nn} = 0$ keV
- Mod. AV18, $^1S_0$ nn force increased by $\lambda = 1.16$: $a_{nn} = +20.8$ fm, $r_{\text{eff}} = 2.36$ fm, $\varepsilon_{nn} = -108$ keV
- Mod. AV18, $^1S_0$ nn force increased by $\lambda = 1.22$: $a_{nn} = +12.6$ fm, $r_{\text{eff}} = 2.23$ fm, $\varepsilon_{nn} = -323$ keV

H. Witała
Return to A=4
Goal: Obtain n-$^3$H $A_y(\theta)$ data at $E_n=2.26$ MeV and $E_n=5.54$ MeV.
Return to HIγS
$A=2$

$\gamma + ^2H$ breakup
Gerasimov-Drell-Hearn Sum Rule on the Deuteron

\[ I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu} [\sigma_N^P(\nu) - \sigma_N^A(\nu)] = \frac{4\pi^2 \alpha}{M_N^2} \kappa_N^2 I \]

\[ I_p = 204.8 \ \mu b \quad I_n = 232.5 \ \mu b \quad I_d = 0.652 \ \mu b \]

Above pion production threshold: Large positive value

Below pion production threshold: Large negative value
H\_i\_\gamma\_S: Intracavity Compton-Back Scattering

Example: \( E_e = 500 \text{ MeV} \Rightarrow \gamma = 978 \)

\( \lambda_{\text{FEL}} = 400 \text{ nm} \)
\( \hbar \omega = 3.11 \text{ eV} \)
\( E_\gamma = 11.9 \text{ MeV} \)
- HIGS is currently mounting the GDH experiment on the deuteron
- Installation of the HIGS Frozen Spin Target (HIFROST) is ongoing
- The majority of data taking will be completed by the end of 2014 between 4 and 16 MeV

Setup for GDH Measurement on Deuteron

Frozen-spin polarized target
HIFROST
Outlook

What’s next at HIGS?
Compton Scattering: \( A=1, A=2, A=3 \)
Compton Scattering

The T-matrix for the Compton scattering of incoming photon of energy $\omega$ with a spin ($\sigma$) ½ target is described by six structure functions

$$T(\omega, z) = A_1(\omega, z)(\vec{\epsilon}'^* \cdot \vec{\epsilon}) + A_2(\omega, z)(\vec{\epsilon}'^* \cdot \hat{k})(\vec{\epsilon} \cdot \hat{k}')$$

$$+ iA_3(\omega, z) \bar{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) + iA_4(\omega, z) \bar{\sigma} \cdot (\hat{k}' \times \hat{k})(\vec{\epsilon}'^* \cdot \vec{\epsilon})$$

$$+ iA_5(\omega, z) \bar{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{k})(\vec{\epsilon} \cdot \hat{k}') - (\vec{\epsilon} \times \hat{k}')(\vec{\epsilon}'^* \cdot \hat{k})]$$

$$+ iA_6(\omega, z) \bar{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{k}')(\vec{\epsilon} \cdot \hat{k}') - (\vec{\epsilon} \times \hat{k})(\vec{\epsilon}'^* \cdot \hat{k})],$$

$\vec{\epsilon} = \text{photon polarization}, \ k = \text{the momentum}$

HIGS Results on $^{16}\text{O}$ and $^6\text{Li}$ Compton Scattering

Phenomenological Model

- Giant Resonances
- Quasi-Deuteron
- Modified Thompson
Predictive powers of chiral perturbation theory in Compton scattering off protons

BχPT with Δ Prediction
\( \alpha = 10.7 \pm 0.7 \)
\( \beta = 4.0 \pm 0.7 \)

PDG Accepted Value
\( \alpha = 12.7 \pm 0.6 \)
\( \beta = 1.9 \pm 0.5 \)

Polarizabilities

Using Effective Field Theory to analyse low-energy Compton scattering data from protons and light nuclei

H.W. Grießhammer\textsuperscript{a,*}, J.A. McGovern\textsuperscript{b}, D.R. Phillips\textsuperscript{c}, G. Feldman\textsuperscript{a}
Upgrade of HI$\gamma$S: HI$\gamma$S2
HI$\gamma$S2 Layout

Collaborators: Jun Ye, JILA and U. of Colorado at Boulder

Mirrors of FP optical cavity
$L_{\text{cav}} = 1.679\, \text{m}$
$P_{FB} \text{ (avg)} > 10\, \text{kW}, 90\, \text{MHz}$
Major physics drivers

1. $\gamma + ^{16}\text{O} = ^{12}\text{C} + \alpha$
   (Holy Grail of Nuclear Astrophysics)

2. $\gamma + d = n + p$
   (Parity violation)
Comparison of HI\$\gamma\$S2 to ELI

ELI: Extreme Light Infrastructure
Bucharest, Prague, Szeged