Direct effect of Tensor Force by (p,d) reaction

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RCNP-E314/E396/E443/E457, GSI-S436/S437 collaboration

The 9th Japan-China Joint Nuclear Physics Symposium
Tensor Interactions in Nucleus

Effective nucleon-nucleon potential (e.g. Hamada-Johnston):

\[ V(r) = \begin{cases} 
V_C(r) + V_{LS} \frac{(L \cdot S)}{\hbar^2} + V_T(r)S_{12} + V_{L^2} \frac{(L_{12})}{\hbar^2}, & r > r_c \\
+\infty, & r < r_c 
\end{cases} \]

Tensor force: \( V_T(r)S_{12} \)

\[ S_{12} = \frac{3(\sigma_1 \cdot r)(\sigma_2 \cdot r)}{r^2} - (\sigma_1 \cdot \sigma_2) \]

\[ = \sqrt{24\pi / 5} \left( [\vec{\sigma}_1 \times \vec{\sigma}_2]^{(2)} \cdot Y^{(2)} \right) \]

Originated mainly from One-Pion Exchange Potential:

\[ S_{12} \frac{q^2}{m^2_\pi + q^2} \]

High-momentum components in nuclei

\( \Delta S = 2, \Delta L = 2 \)
Deuteron

\[ L=2 \quad S=1 \]

Figures, theoretical data courtesy of T. Myo

\[ \text{Energy} \quad -2.24 \text{ MeV} \]

- Kinetic: 19.88
- Central: -4.46
- Tensor: -16.64
- LS: -1.02
- \( P(L=2) \): 5.77%
- Radius: 1.96 fm

\( d \)-wave is "spatially compact"

\( R_m(s)=2.00 \text{ fm} \)
\( R_m(d)=1.22 \text{ fm} \)

\[ \dagger \text{ Figures, theoretical data courtesy of T. Myo} \]
## Alpha Particles

<table>
<thead>
<tr>
<th></th>
<th>Faddeev-Yakubovsky†</th>
<th>TOSM + UCOM‡</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>-25.94</td>
<td>-22.30</td>
<td>-28.2957† †</td>
</tr>
<tr>
<td>Kinetic (MeV)</td>
<td>102.39</td>
<td>90.50</td>
<td></td>
</tr>
<tr>
<td>Central (MeV)</td>
<td>-55.26</td>
<td>-55.71</td>
<td></td>
</tr>
<tr>
<td>Tensor (MeV)</td>
<td>-68.35</td>
<td>-54.55</td>
<td></td>
</tr>
<tr>
<td>LS (MeV)</td>
<td>-4.72</td>
<td>-2.53</td>
<td></td>
</tr>
<tr>
<td>Radius (fm)</td>
<td>1.49</td>
<td>1.55</td>
<td>1.6755(28)§</td>
</tr>
</tbody>
</table>

† H.Kamada et al. PRC 64 (’01) 044001
‡ T.Myo et al. PTP 121 (’09) 511
¶ AME2012
§ I. Angeli et al. ADNDT 99 (’13) 69
Independent Particle Model

• Nuclear Shell Model (1949)
• developed by Mayer, Jensen, Wigner
• complex many-body nucleon-nucleon interactions
  ⇒ average potential:
  i) 3 dimensional harmonic oscillator
  ii) spin-orbit interactions
• reproduces nuclear magic numbers
• enhances understanding of nuclear structures, predicts energy levels and other observables
• helps to understand/predict (direct) nuclear reactions
  • spectroscopic factor
Limitation of IPM

• Underestimates (direct) nuclear reactions, especially those that involve transfer/knockout of high momentum nucleons
  ⇒ the need to consider explicitly tensor and short-range correlations.

But how?

Wanted: Experiment data

\[ \text{\^{12}C}(e,e'pp[n]) \]

at TJLAB

Can we measure/observe directly an effect of tensor interactions in nuclei heavier than the alpha particle?

YES!

Ground state of $^{16}$O

High Momentum Nucleons

Ground-state of $^{16}$O: mixing of 2p-2h configuration
Predicted Momentum Distribution of Nucleons

Unitary Correlation Operator Method

R. Schiavilla et al., PRL 98, 132501 (2007)

Large effect by tensor around 2 fm\(^{-1}\)

Probe internal momentum of nucleon by \((p,d)\) reaction

- taking advantage of the momentum selectivity

\(d-p\) at 135 MeV/A

G. W. Bennett et al., PRL19, 387(1967)
K. Sekiguchi et al., PRL95, 162301(2004)

\(P_d - P_p = P_F\)

\((p,d)\) is a good probe to study high momentum component

\[
\sigma_F = K \frac{P_d}{p} N(P_F) \left[ B_D + \frac{\hbar^2}{M} (p - P_{d/2})^2 \right]^2 \phi(r) \epsilon \left(p - P_d + r/2\right)\]

K: phase space constant, \(B_D\): deuteron binding energy, M: nucleon mass
Momentum Transfer

$^{16}\text{O}(p,d)$

- $\theta_d = 30^\circ$
- $\theta_d = 10^\circ$
- $\theta_d = 0^\circ$

RCNP

GSI

Momentum Transfer (fm$^{-1}$)

Proton Energy (MeV)
[RCNP-E314] Experiment Setup

RCNP Grand RAIDEN
(p/Δp ~ 37000)

M. Fujiwara et al., NIMA 422, 484 (1999)

- 198, 295, 392 MeV
- ~2 nA
**[RCNP-E314] Missing-mass Spectra**

15° level scheme

1d_{5/2}, 2s_{1/2}

Ground-state of $^{16}$O: mixing of 2p-2h configuration

Selection Rule: $\Delta J=0$, $\Delta L=\Delta S=2$

T. Myo, private communication
• CDCC-BA calculation with known spectroscopic factors:
  ✓ qualitatively agree with ratios for the neutron-hole states (3/2- to 1/2-)
  ✓ cannot explain the ratios for the positive-parity state (1/2+ or 5/2+ to 1/2-)

• Two(Multi)-step process does not help

• TOSCOM-type momentum wave functions that include high-momentum components due to the tensor forces “fit” the data well.


Issues to be addressed...

- (p,d) at finite (≥10 deg) scattering angle in RCNP-E314 (Apr, 2009)

reaction mechanism effect at finite angle

⇒ 0 degree measurement

ambiguity of contributions from p-n and/or n-n pairs

⇒ (p,dp) and (p,dn) measurements

- (p,d) at 0 deg with 400-MeV proton -> RCNP-E396 (Nov. 2013)

- (p,d) at 0 deg with 400〜1200-MeV proton to cover 2 fm⁻¹ -> GSI-S436/S437 (July, 2014)

- (p,dp), (p,dn) at finite angles with 400-MeV proton to study p-n and n-n correlations -> RCNP-E443 (Nov. 2015)

- (p,dp), (p,dn) at higher energy to cover 2 fm⁻¹ is being planned at the future SuperFRS at FAIR/GSI, Germany.
What is unique and what is new observable about (p,d) 

Energy [LOG] 

Also mass($^{16}$O, $^{12}$C) and $J^\pi$ dependence 

RCNP-E314 

2 fm$^{-1}$ Line 

GSI-s436 

Past experiment till 1980’s
Effect of reaction mechanism is negligible
[GSI-S436/S437] Pilot Experiment of Super-FRS Collaboration

$^{16}\text{O}(p,d)$ at forward angles & large p transfer

- Proton beam with energies: 400, 600, 900, 1200 MeV/u
- Good excitation-energy resolution (< 400 keV) sufficient to separate $3/2^-$ and $5/2^+$ (and/or $1/2^+$) states with special large dispersion mode $R/\delta R=10^4$.
- Moderate beam intensity $\sim 10^{10}$: To access sub $\mu$b/sr.
- Successfully performed in July, 2014
[GSI-S436]

$^{16}\text{O}(p,d), ^{12}\text{C}(p,d)$ reactions at forward angles with 400 - 1200 MeV/u proton beams

Proton beam @400 MeV/u, with 107 mg/cm$^2$ natC target

$^{12}\text{C}(p,d)$

Sufficient resolution achieved
Preliminary Results for $^{16}\text{O}(p,d)@400\text{ MeV/u in CH}_2\text{O}$

- (Angular) acceptance not uniform
  - e.g. $^{15}\text{O}$ excited states ↔ ground state
  - ~40% difference
- Ratios consistent with RCNP data

STAY TUNE for higher energy
(more) exclusive data in $X(p,dN)$

NEW DATA last week at RCNP
[RCNP-E443] (p,dp) and (p,dn) Experiments

Experiment was completed 2015/10/31-11/4

400 MeV proton
20 pnA
60 mg/cm²

θ_{GR}=8.7°, 15.0°
θ_{BAND}=112°, 135°
Previous experiment with triple coincidence

$^{12}\text{C}(p,ppn)$ at BNL
PRL90(03),042301

$^{12}\text{C},^{16}\text{O}(e,e'pp)$ at NIKEF
PRL74(95), 1712, PRL81(98), 2213

$^{12}\text{C}(e,e'pp[or n])$ at TJlab
PRL99(07)072501

FIG. 1. The ninefold-differential cross section as a function of the excitation energy, averaged over missing momenta between 50 and 350 MeV/c and over $\gamma$, between $10^\circ$ and $40^\circ$ ($d\sigma/d\Omega = d^5\sigma / dE_2 d\Omega / dE_1 d\Omega_2 dE_2 d\Omega_3$). The measured cross sections are indicated with the solid circles. The error bars represent the statistical uncertainty. The curves correspond to results of a microscopic calculation (see text).

FIG. 2 (color online). Plots of $\cos \gamma$, where $\gamma$ is the angle between $p_\gamma$ and $p_{\nu}$, for $^{12}\text{C}(p,2p+n)$ events. Panel (a) is for events with $p_\gamma > 0.22 \text{ GeV/c}$, and panel (b) is for events with $p_\gamma < 0.22 \text{ GeV/c}$; $0.22 \text{ GeV/c} = k_F$, the Fermi momentum for $^{12}\text{C}$.

High statistics measurement is needed
=> (p,dN) reaction
New Beam transporting for low-background environment for Coincidence measurement GRAF (Grand-RAiden Forward mode)

First Physics RUN with GRAF in 2015/Nov

400 MeV Proton Beam

Dedicated beam dump design is really important from beginning.
Before GRAF

\[ V_{th} = 2 \text{ MeV}_{\text{proton}} \]

\[ V_{th} = 14 \text{ MeV}_{\text{proton}} \]

\[ \theta_{GR} = 5.0^\circ, \ Q1FC, \ 8 \text{ nA} \]

Continuum background from beam stopper[FC]
With GRAF

\[ V_{\text{th}} = 2 \text{ MeV} \]

\[ \theta_{\text{GR}} = 8.7^\circ, \text{ WallFC, 20 nA} \]

Now ready for neutron coincidence measurement at finite angle
Snapshot

**True+Accidental**

**Accidental**

\[ \text{GR} \_ \text{Pos} \left( \theta_{\text{GR}} = 15 \right) \]

\[ \text{BAND} \_ \text{E} \left( \theta_{\text{BAND}} = 112 \right) \]

3% in \( \sigma \) of Pla-QDC

150 psec in \( \sigma \) of RF-Pla-TDC
Cont.

\[ ^{12}\text{C}(p,dp)^{10}\text{B}(\text{g.s.}) \]

\[ \text{nat}\, ^{12}\text{C}(p,dn) \text{ in } 30 \text{ min} \]

\text{Estimated resolution } \sim 4\text{MeV} [\sigma]

\[ \text{nat}\, ^{12}\text{C}(p,dp) \text{ in } 30 \text{ min} \]

\text{Estimated resolution } \sim 2\text{MeV} [\sigma]

1-2\% of total data set
Extension to future study

- Higher energy proton is preferable up to 800A MeV.
- Extended unstable nuclei for \((p,d)\) and \((p,dN)\) \(g.e\) \(6\)He, \(6,8,9,11\)Li
  => Unique choice at GSI-FRS/FAIR-SuperFRS

- Moderate energy resolution and enough space around target
  => started to discuss in preparation phase.
- Smaller cross section
  => extremely higher rate detector and thick target
extension to exotic nuclei in $p(X,d[N])$
Study for nucleon correlation in nuclei $^6\text{He}$

FOR nucleon correlation
- $p(\text{He}, d)n\alpha$ or $^5\text{He}$ : n-n pair
- $p(\text{Li}, d)p\alpha$ or $^5\text{Li}$ : p-n pair

Sideward detector is necessary and suitable.
We need high intensity thick target wide dynamic range.

Production Section
- Identification
- Momentum

Excitation Energy
- Decay identification

Analyzing Section
- Sideward Telescope

TA/PF4
- D1
- D2

FiberTracker S1
- FiberTracker S2

LP-MWDC
- Plastic

TPC
- Plastic
\[ p(^6X,d[\alpha])N \quad @FRS \]

- **Production/ID/momentum**
- **Reactin:** Ex@S2 at finite degrees
- **Reactin:** Ex@S3 at zero degrees
- **Reactin:** Ex@S4 at zero degrees

\[ p(^6He,d) : \quad d@S3 \quad 0 \text{ degree} \]
\[ p(^6He,d) : \quad d@S2 \quad 2-5 \text{ degree} \]
\[ p(^6He,d\alpha) : d@S2, \quad \alpha@S3 \]

We need:
- high intensity secondary beam \(10^{7-8}/\text{sec}\)
- Fiber tracker with MPPC
- thick proton target \(\sim g/cm^2\)
- Cryogenic or stack-active target
- wide dynamic range
- Use S3 instead of S4.

Also with \(^6\text{Li}\)

Late > 2018
Even FAIR completed > 2025
Requirement sideward telescope at S2

- High counting rate environment under $10^7$/spill.
- Moderate resolution less than 1.0 % for 100 MeV deuteron.
- Particle identification by TOF-E or dE-E

- Position sensitive plastic + 2 inch-CsI(Tl) array (+ veto plastic)
extension to higher energy for nucleon correlations in $X(p,d[N])$
Super-FRS as 0-degree Spectrometer

Try to use ultra high resolving power $10^4$

$D_x/M_x = 15 \text{ cm/\% at S436}$

$D_x/M_x = 10 \text{ cm/\%}$

$D_x/M_x = 6 \text{ cm/\% from PF4}$

Preseparator as BeamSwinger

MainSeparator as Spectrometer

H. Geissel et al. NIM B 204 (2003) 71
Detector array for correlated proton and neutron covers from -158.5 to -177.5 degrees
## RCNP-E314 collaboration

<table>
<thead>
<tr>
<th>Institution</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyoto Univ.</td>
<td>T. Kawabata</td>
</tr>
<tr>
<td>Tsukuba Univ.</td>
<td>A. Ozawa</td>
</tr>
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<td>RIKEN Nishina Center</td>
<td>K. Sekiguchi, K. Ikeda</td>
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<tr>
<td>Nara Women’s Univ.</td>
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</tr>
<tr>
<td>Beihang Univ.</td>
<td>S. Terashima, D.Y. Pang</td>
</tr>
</tbody>
</table>
RCNP-E396 Collaboration

RCNP  
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Univ. of Tokyo  
Y.N. Watanabe
GSI-S436/S437 SuperFRS collaboration


Osaka University, Universidade de Santiago de Compostela, Universitaet Giessen, Kyoto University, GSI, University of Groningen, Beihang University, The University of Tokyo, Nara Women's University, KEK, RIKEN, Tokyo Metropolitan University, Technische Universitaet Darmstadt, TRIUMF and Saint Mary’s University, Stefan Meyer Institut, Niigata University
Summary

- We have observed large component of high-momentum neutrons in the ground state of $^{16}$O via (p,d) reaction.

- The results indicate possible evidence of the effect of tensor forces.

- Further experiments have been performed/planned at RCNP (Osaka) and FAIR-GSI (Darmstadt) to confirm the results, and to provide more experimental data.

- New data of short-range partner via (p,dN) is presented.

- Combined theoretical studies with reaction and structure models that include tensor forces are called for.

  - 0 degree scattering
    - RCNP-E396 in Autumn 2013 ANALYSIS
    - GSI-s436 in Summer 2014 ANALYSIS
  - Coincidence Study
    - RCNP-E443 in Autumn 2015 ANALYSIS
    - FAIR-SuperFRS after 2025 Planned
  - $^6$He/$^6$Li => Inverse kinematics
    - At GSI-FRS also coincidence study after 2018 Prepared
  - $^{11,9,8}$Li => Inverse kinematics
    - At FAIR-SuperFRS after 2025 Planned
Thank you for your attention
Backup Slides
1. Better S/N with GRAF beamline
2. Larger efficiency for neutron: $x\ 4+\alpha$ with n-γ separation
3. Wider angular acceptance: $x\ 2$ to study out of plane events
4. More beam time

Total sensitivity for $(p, dn)$: $> x10$
# BAND (BAckward Nucleon Detector)

- The BAND consists of three types of detectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness</th>
<th>Area Size</th>
<th>Length from target</th>
<th>Acceptance (Hor.)</th>
<th>Acceptance of proton* (Kinetic)</th>
<th>n-γ separation</th>
<th>Num. of readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic telescope</td>
<td>3 mm + 60 mm</td>
<td>240 x 90 mm</td>
<td>50 cm</td>
<td>+-14 deg.</td>
<td>12-92 MeV</td>
<td>only β</td>
<td>1+8</td>
</tr>
<tr>
<td>Stack Plastic</td>
<td>80 mm (5 x16)</td>
<td>320 x 160 mm</td>
<td>70 cm</td>
<td>+-13 deg.</td>
<td>92-145 MeV</td>
<td>Range</td>
<td>12</td>
</tr>
<tr>
<td>Liquid</td>
<td>50 mm</td>
<td>φ200 x2 mm</td>
<td>90 cm</td>
<td>+-13 deg.</td>
<td>145-168 MeV</td>
<td>Pulse shape</td>
<td>2</td>
</tr>
</tbody>
</table>

**Status:**

- Telescope: demonstrated, to be made
- Stack: finished design, under making
- Liquid: existing, under testing

* Region of our interest is 30 – 80 MeV.
We plan to use three targets $^{\text{nat}}\text{C}$ and $\text{H}_2\text{O(Ice)}$ and $\text{CD}_2$ [calibration].

Configuration dependence from difference of nuclear structures can be studied.
(p,dN) reaction layout (e.g. feasibility test in E396 layout)

Angular acceptance: 146 – 160 deg.
- 5 - + 5 deg.
Distance from target: 42 cm (δE)
50 cm (E)
$^{12}\text{C}(p,dp)$ and $^{12}\text{C}(p,dn)$

“Accidental negligibly small”

Missing Energy of $^{12}\text{C}(p,dp)^{10}\text{B}$ (MeV)

1.7 MeV in $\sigma$

“Accidental subtracted”

2 MeV$_{th}$

6 MeV$_{th}$

10 MeV$_{th}$

14 MeV$_{th}$

Missing Energy of $^{12}\text{C}(p,dn)^{10}\text{C}$ (MeV)

3.5 MeV in $\sigma$
Comparison \((p,d[p-n-]p)\) and \((p,d[p-n-]n)\)

\[
\sigma(p,dp) / \sigma(p,dn) = 7(4)\% \text{ for g.s.}
\]

Preliminary

Back Ground Free environment is necessary!
Many-body Finite Quantum Systems (constituents: proton(s) and neutron(s))

Purpose: To describe nuclei from NN interactions and extract information from nuclear reactions.

Nuclear chart

Stable Nuclei: ~250
Unstable Nuclei: Known ~3000
Predicted ~10000
How much understanding of (p,d) scattering at forward angle

- p+d elastic scattering at 180 degree
- \( \leftrightarrow \) d(p,d)p: Simplest process of (p,d) scattering. at zero degree.

Effort based on Faddeev calculation at intermediate energy region including spin observable.

Small discrepancy still remain at backward region at higher energies more than 200A MeV

K. Sekiguchi et al, RIKEN&RCNP Data

Now ready to study again (p,d) reaction at higher energy
Perspective

• For study tensor force in nuclei, \( (p,d) \) reaction is a good probe to measure high momentum component in nucleus.

• We had been performed and prepare several experiments at RCNP in Japan and GSI in Germany at intermediate energies region from 400 MeV/u up to 1 GeV/u.

  o 0 degree scattering
    • RCNP-E396 in Autumn 2013 ANALYSIS
    • GSI-s436 in Summer 2014 ANALYSIS

  o Coincidence Study
    • RCNP-E443 in Autumn 2015 ANALYSIS
    • FAIR-SuperFRS after 2025 Planed

  o \(^6\)He/\(^6\)Li => Inverse kinematics
    • At GSI-FRS also coincidence study after 2018 Prepared

  o \(^{11,9,8}\)Li => Inverse kinematics
    • At FAIR-SuperFRS after 2025 Planed
More optimization

<Example; Negative Swing>

By +/-5%, enough to achieve to tilt incidence beam on FMF2.

Positive tilt is similar behavior.

Bρ: -1.6%