Probing effect of tensor interactions in nuclei via (p, d) reaction

Guo Chenlei
(On behalf of RCNP-E396)
Research Center of Nuclear Science and Technology (RCNST)
Beihang University
Contents

- Physics Motivation (Already talked a lot in this symposium…)
- Experiments in RCNP, Osaka
- Preliminary results & Discussion
- Summary & Acknowledgments
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\) ) @ RCNP, Osaka
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) \& \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

---

**Abstract**

We have measured the \(^{16}\text{O}(p,d)\) reaction using 198-, 295- and 392-MeV proton beams to search for a direct evidence on an effect of the tensor interactions in light nucleus. Differential cross sections of the one-neutron transfer reaction populating the ground states and several low-lying excited states in \(^{15}\text{O}\) were measured. Comparing the ratios of the cross sections for each excited state to the one for the ground state over a wide range of momentum transfer, we found a marked enhancement of the ratio for the positive-parity state(s). The observation is consistent with large components of high-momentum neutrons in the initial ground-state configurations due to the tensor interactions.
Further question has been asked: reaction mechanism effect at finite angle
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka
Nucleon pick-up reaction ($^{12}$C(p,d) & $^{16}$O(p,d)) @ RCNP, Osaka

Configuration difference for $^{16}$O & $^{12}$C

$^{16}$O
- $2s_{1/2}$
- $1d_{5/2}$
- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

$^{12}$C
- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

proton  neutron  proton  neutron
Nucleon pick-up reaction (\( ^{12}\text{C}(p,d) \) & \( ^{16}\text{O}(p,d) \)) @ RCNP, Osaka

Configuration difference for \( ^{16}\text{O} \) & \( ^{12}\text{C} \)

\( ^{15}\text{O} \)

- 2s\(_{1/2} \)
- 1d\(_{5/2} \)

\( ^{12}\text{C} \)

- 1p\(_{1/2} \)
- 1p\(_{3/2} \)
- 1s\(_{1/2} \)

\( ^{15}\text{O} \): negative parity ground state (\( J^\pi = 1/2^- \))
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\) ) @ RCNP, Osaka

Configuration difference for \(^{16}\text{O} \& ^{12}\text{C}\)

\(^{15}\text{O}\)
- \(2s_{1/2}\)
- \(1d_{5/2}\)

\(^{12}\text{C}\)
- \(1p_{1/2}\)
- \(1p_{3/2}\)
- \(1s_{1/2}\)

\(^{15}\text{O}\): negative parity ground state (\(J^\pi=1/2^-\))
- negative parity excited state (\(J^\pi=3/2^-\))

proton

neutron

C.L. Guo

Experiments in RCNP
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

Configuration difference for \(^{16}\text{O}\) & \(^{12}\text{C}\)

\(^{15}\text{O}\)

- 2s\(_{1/2}\)
- 1d\(_{5/2}\)

\(^{11}\text{C}\)

- 1p\(_{1/2}\)
- 1p\(_{3/2}\)
- 1s\(_{1/2}\)

\(^{15}\text{O}\): negative parity ground state (\(J^\pi=1/2^-\))

\(^{15}\text{O}\): negative parity excited state (\(J^\pi=3/2^-\))

\(^{11}\text{C}\): negative parity ground state (\(J^\pi=3/2^-\))
Nucleon pick-up reaction ($^{12}\text{C}(p,d)$ & $^{16}\text{O}(p,d)$) @ RCNP, Osaka

Configuration difference for $^{16}\text{O}$ & $^{12}\text{C}$

$^{15}\text{O}$

- $2s_{1/2}$
- $1d_{5/2}$
- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

$^{11}\text{C}$

- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

Proton

Neutron

$^{15}\text{O}$: negative parity ground state ($J^{\pi}=1/2^-$)

Negative parity excited state ($J^{\pi}=3/2^-$)

$^{11}\text{C}$: negative parity ground state ($J^{\pi}=3/2^-$)

Negative parity excited state ($J^{\pi}=1/2^-$)
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

Configuration difference for \(^{16}\text{O} \) & \(^{12}\text{C} \)

\(^{16}\text{O} \)
- \(2s_{1/2} \)
- \(1d_{5/2} \)
- \(1p_{1/2} \)
- \(1p_{3/2} \)
- \(1s_{1/2} \)

\(^{12}\text{C} \)
- \(1p_{1/2} \)
- \(1p_{3/2} \)
- \(1s_{1/2} \)

Tensor selection rule:
\(\Delta L=2, \Delta s=2, \Delta J=0\)

Proton

Neutron
Nucleon pick-up reaction ($^{12}\text{C}(p,d)$ & $^{16}\text{O}(p,d)$) @ RCNP, Osaka

Configuration difference for $^{16}\text{O}$ & $^{12}\text{C}$

$^{16}\text{O}$
- $2s_{1/2}$
- $1d_{5/2}$
- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

Ground state of $^{16}\text{O}$ ($J^{\pi}=0^+$):
mixing of 2p-2h configuration

$^{12}\text{C}$
- $1p_{1/2}$
- $1p_{3/2}$
- $1s_{1/2}$

Ground state of $^{12}\text{C}$ ($J^{\pi}=0^+$):
mixing of 2p-2h configuration

Tensor selection rule:
- $\Delta L=2$
- $\Delta s=2$
- $\Delta J=0$
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

Configuration difference for \(^{16}\text{O}\) & \(^{12}\text{C}\)

\[^{15}\text{O}\]

- \(2s_{1/2}\)
- \(1d_{5/2}\)

\[^{12}\text{C}\]

- \(1p_{1/2}\)
- \(1p_{3/2}\)
- \(1s_{1/2}\)

Ground state of \(^{16}\text{O}\) (\(J^\pi=0^+\)): mixing of 2p-2h configuration → \(^{15}\text{O}\): positive parity excited state (\(J^\pi=5/2^+\))

Tensor selection rule:
\(\Delta L=2, \Delta s=2, \Delta J=0\)

Ground state of \(^{12}\text{C}\) (\(J^\pi=0^+\)): mixing of 2p-2h configuration
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

**Configuration difference for \(^{16}\text{O}\) & \(^{12}\text{C}\)**

\[^{15}\text{O}\]

- 2s\(^{1/2}\)
- 1d\(^{5/2}\)
- 1p\(^{1/2}\)
- 1p\(^{3/2}\)
- 1s\(^{1/2}\)

\[^{11}\text{C}\]

- 1p\(^{1/2}\)
- 1p\(^{3/2}\)
- 1s\(^{1/2}\)

**Ground state of \(^{16}\text{O}\) (J\(^{\pi}\)=0\(^{+}\)):

mixing of 2p-2h configuration

\(^{15}\text{O}\): positive parity excited state (J\(^{\pi}\)=5/2\(^{+}\))

**Ground state of \(^{12}\text{C}\) (J\(^{\pi}\)=0\(^{+}\)):

mixing of 2p-2h configuration

\(^{11}\text{C}\): ground state (J\(^{\pi}\)=3/2\(^{-}\))

**Tensor selection rule:**

\(\Delta L=2, \Delta s=2, \Delta J=0\)
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

Configuration difference for \(^{16}\text{O}\) & \(^{12}\text{C}\)

- **\(^{15}\text{O}\)**
  - \(2s_{1/2}\)
  - \(1d_{5/2}\)
  - \(1p_{1/2}\)
  - \(1p_{3/2}\)
  - \(1s_{1/2}\)

- **\(^{11}\text{C}\)**
  - \(1p_{1/2}\)
  - \(1p_{3/2}\)
  - \(1s_{1/2}\)

Tensor selection rule: \(\Delta L=2, \Delta s=2, \Delta J=0\)

Ground state of \(^{16}\text{O}\) \((J^\pi=0^+):\) mixing of 2p-2h configuration

\(\rightarrow \) \(^{15}\text{O}\): positive parity excited state \((J^\pi=5/2^+))\)

Ground state of \(^{12}\text{C}\) \((J^\pi=0^+):\) mixing of 2p-2h configuration

\(\rightarrow \) \(^{11}\text{C}\): ground state \((J^\pi=3/2^-)\) excited state \((J^\pi=1/2^-)\)
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

Grand RAIDEN Spectrometer \(\frac{p}{\Delta p} \sim 37000\)

Scattering angle: \(0^\circ \sim 10^\circ\)

\(^{16}\text{O}\) target: Mylar (\(\text{C}_{10}\text{H}_8\text{O}_4\))
\(^{12}\text{C}\) target: \(\text{CD}_2\)

Focal Plane Detector:
Two Plastic scintillator for \(\Delta E\) & TOF
Two VDCs (drift chamber) for position and angle \((x, dx, y, dy)\)

Beam energy: 392 MeV/nucleon
Beam Intensity: 10 nA
Energy resolution \(\leq 150\text{keV}\) (Achromatic mode)
Nucleon pick-up reaction (12C(p,d) & 16O(p,d)) @ RCNP, Osaka

Beam energy: 392 MeV/nucleon
Beam Intensity: 10 nA
Energy resolution ≤ 150keV (Achromatic mode)

Focal Plane Detector:
Two Plastic scintillator for ΔE & TOF
Two VDCs (drift chamber) for position and angle (x,dx,y,dy)

16O target: Mylar (C10H8O4)
12C target: CD2

Scattering angle: 0° ~ 10°
Nucleon pick-up reaction (\(^{12}\text{C}(p,d)\) & \(^{16}\text{O}(p,d)\)) @ RCNP, Osaka

- **Beam energy**: 392 MeV/nucleon
- **Beam Intensity**: 10 nA
- **Energy resolution**: \(\leq 150\text{keV (Achromatic mode)}\)

**Focal Plane Detector:**
- Two Plastic scintillator for \(\Delta E\) & TOF
- Two VDCs (drift chamber) for position and angle \((x, dx, y, dy)\)

**Scattering angle**: \(0^\circ \sim 10^\circ\)

**16O target**: Mylar \((\text{C}_{10}\text{H}_8\text{O}_4)\)

**12C target**: \(\text{CD}_2\)
$^{16}\text{O}(p,d)^{15}\text{O}: 1/2^-$

C.L. Guo

Preliminary results and discussion

18.5MeV: Phys. Rev. 129, 272 (1963)
100MeV: Nucl. Phys. A 106, 357 (1968)
Preliminary results and discussion

$^{16}\text{O}(p,d)^{15}\text{O}: 1/2^-$

$^{16}\text{O}(p,d)^{15}\text{O}: 5/2^+$

18.5 MeV: Phys. Rev. 129, 272 (1963)


100 MeV: Nucl. Phys. A 106, 357 (1968)


C.L. Guo
\[ ^{16}\text{O}(p,d)^{15}\text{O}: 1/2^- \]

\[ ^{16}\text{O}(p,d)^{15}\text{O}: 5/2^+ \]

\[ ^{16}\text{O}(p,d)^{15}\text{O}: 3/2^- \]

18.5 MeV: Phys. Rev. 129, 272 (1963)
100 MeV: Nucl. Phys. A 106, 357 (1968)

Preliminary results and discussion
$^{12}\text{C}(p,d)^{11}\text{C}: 3/2^-$

100MeV: Nucl. Phys. A 106, 357 (1968)  
Preliminary results and discussion

$^{12}$C(p,d)$^{11}$C: 3/2-

$^{12}$C(p,d)$^{11}$C: 1/2-

100MeV: Nucl. Phys. A 106, 357 (1968)
Preliminary results and discussion

$^{12}\text{C}(p,d)^{11}\text{C}: \frac{3}{2}^-$

$^{12}\text{C}(p,d)^{11}\text{C}: \frac{1}{2}^-$

$^{12}\text{C}(p,d)^{11}\text{C}: \frac{5}{2}^-$

100MeV: Nucl. Phys. A 106, 357 (1968)
$^{12}\text{C}(p,d)^{11}\text{C}$:
- $3/2^-$
- $1/2^-$
- $5/2^-$
- $3/2^-$

Preliminary results and discussion:

- $^{12}\text{C}(p,d)^{11}\text{C}$: $3/2^-$
- $^{12}\text{C}(p,d)^{11}\text{C}$: $1/2^-$
- $^{12}\text{C}(p,d)^{11}\text{C}$: $5/2^-$
- $^{12}\text{C}(p,d)^{11}\text{C}$: $3/2^-$
As long as ratio is concerned, $0^\circ$ data and finite angle data are consistent with each other. Therefore reaction mechanism effect is negligible and we obtain the conclusion same as Ong, et. al.

---

**Preliminary results and discussion**

100MeV: Nucl. Phys. A 106, 357 (1968)  
Preliminary results and discussion

CDCC-BA

- 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 (5/2+ to 1/2-)

- Two(Multi)-step process does not help

- TOSCOM-type momentum wave functions that include high-momentum components “fit” the data well.

Among the ratio of cross sections of excited states (5/2+ & 3/2-) to ground state of $^{15}$O, stronger momentum dependence is observed for the 5/2+ state, which is indicated to be consistent with the effect of tensor interaction.

- 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 (5/2+ to 1/2-)

- Two(Multi)-step process does not help

- TOSCOM-type momentum wave functions that include high-momentum components “fit” the data well.


Preliminary results and discussion

By comparing the ratio of cross sections of ground state (3/2-) and excited state (1/2-) of $^{11}$C to ground state of $^{15}$O, respectively, we observed a difference in the momentum transfer dependence in $^{11}$C and $^{15}$O ground state, which is also indicated to be consistent with the effect of tensor interaction.
Tensor force is the important part of nuclear force.

Nucleon pick-up reaction is a good tool to probe the high-momentum component.

We have studied the high-momentum neutrons in the initial gs-configuration by (p,d) reactions.

- Among the ratio of cross sections of excited states (5/2+ & 3/2-) to ground state of $^{15}$O, stronger momentum dependence is observed for the 5/2+ state, which is indicated to be consistent with the effect of tensor interaction.
- As long as ratio is concerned, 0° data and finite angle data are consistent with each other. Therefore reaction mechanism effect is negligible and we obtain the conclusion same as Ong, et. al..
- By comparing the ratio of cross sections of ground state (3/2-) and excited state (1/2-) of $^{11}$C to ground state of $^{15}$O, respectively, we observed a difference in the momentum transfer dependence in $^{11}$C and $^{15}$O ground state, which is also indicated to be consistent with the effect of tensor interaction.
## RCNP-E396 Collaboration

<table>
<thead>
<tr>
<th>Institution</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osaka Inst. of Tech.</td>
<td>T. Myo</td>
</tr>
<tr>
<td>Osaka Univ.</td>
<td>M. Fukuda, K. Matsuta, M. Mihara</td>
</tr>
<tr>
<td>Tsukuba Univ.</td>
<td>A. Ozawa</td>
</tr>
<tr>
<td>RIKEN Nishina Center</td>
<td>J. Zenihiro</td>
</tr>
<tr>
<td>Kyoto Univ.</td>
<td>T. Kawabata, Y. Matsude</td>
</tr>
</tbody>
</table>
RCNP-E396 Collaboration

RCNP


Beihang Univ.


Osaka Inst. of Tech.

M. Fukuda, K. Matsuta, M. Mihara

Osaka Univ.

A. Ozawa

Tsukuba Univ.

RIKEN Nishina Center

J. Zenihiro

Kyoto Univ.

T. Kawabata, Y. Matsude
The most important origin of the momentum distribution is the movement of nucleons in a nuclear potential and typically expressed by Fermi momentum (mainly momentum below 1 fm\(^{-1}\)).

The momentum distributions are also affected by the n–n correlations. One of the well-known origins is the short-range repulsion of the central forces.

The tensor forces also give a characteristic range in the n–n interaction and make a large contribution at momentum at around 2 fm\(^{-1}\).