Measurement of spin correlation coefficients in $p-^3\text{He}$ scattering at 65 MeV

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**Introduction**

**Nucleon-Nucleon force**

In 1935, the first theoretical insight was given as meson exchange theory by Yukawa. In 1990’s, the Nucleon-Nucleon potentials have achieved to realistic ones.

(e.g. CD Bonn, AV18, Nijmegen)

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But in $A \geq 3$ system, some aspects are not explained by the NN potential only.

(e.g. few nucleon system, nucleon binding energies, equation of state of nucleon matter)

**Three-nucleon force**

The force acting between three-nucleons is considered to be essential for fully understanding nucleon phenomena.

(e.g. Fujita-Miyazawa, Urbana IX, Tucson-Melbourne)
Introduction

**Few nucleon scattering**
It is a good probe to study the dynamical aspects of nuclear forces.
- momentum dependence
- spin dependence
- isospin dependence

Nucleon-deuteron scattering …

K. Sekiguchi et al., PRC 65 034003 (2002).

3NFs are necessary to explain the data for $N$-$d$ elastic scattering.
Introduction

Energy dependence of $N$-$d$ elastic scattering

3NFs effects are clearly seen in the cross section minimum at intermediate energies ($E > 60$ MeV).

It is interesting to study 3NFs at intermediate energies.

In $d$-$p$ scattering system, the total isospin is limited to $T = 1/2$. 
Introduction

We have a strong interest in the isospin dependence of 3NFs. (e.g. neutron-rich nuclei and neutron matter)

\textit{p-}^3\text{He scattering system}
\begin{itemize}
  \item Approaching the effects of 3NFs in 4N scattering system
  \item The simplest system to approach the $T = 3/2$ channel
\end{itemize}

We performed \textit{p-}^3\text{He scattering at intermediate energies and measured spin observables.}
This work

- By using the 65 MeV polarized proton beam and the polarized $^3\text{He}$ target, the experiment of $p$-$^3\text{He}$ elastic scattering was performed.
- The measured angles were $\theta_{\text{Lab.}} = 35^\circ, 70^\circ, 115^\circ$. ($\theta_{\text{C.M.}} = 47^\circ, 89^\circ, 133^\circ$)
- The observables were $A_y, A_y^T, C_{yy}$.

Spin correlation coefficient $C_{yy}$ is obtained by bombarding the polarized proton beam on the polarized $^3\text{He}$ target and measuring the asymmetry of the scattered particles.
$p-^3\text{He}$ scattering at 65 MeV

RCNP (Research Center for Nuclear Physics), Osaka University, Japan
- Polarized proton beams were provided by the polarized ion source.
- The beam was accelerated by the AVF cyclotron up to 65 MeV.
- The beam bombarded the polarized $^3\text{He}$ target.
- Scattered protons were detected by the $dE-E$ scintillators.
- The beam polarization was measured by using $p-d$ elastic scattering.
ENN course

**Beam**
- Beam energy $E_p = 65$ MeV
- Beam intensity $\sim 10$ nA
- Beam polarization $p_y^\uparrow \sim 50\%$, $p_y^\downarrow \sim 20\%$

**Target**
- Polarized $^3$He gas, polarization $\sim 40\%$

**Detectors**
- $dE-E$ detectors

**Measured angles**
- $\theta_{\text{Lab.}} = 35^\circ, 70^\circ, 115^\circ$
- $(\theta_{\text{C.M.}} = 47^\circ, 89^\circ, 133^\circ)$

**Observables**
- $A_y, A_y^T, C_{yy}$

**Polarized Proton Beams**

**Beam Line Polarimeter (BLP)**
**Beam Line Polarimeter**

- The beam polarization was measured by using the reaction of $p-d$ elastic scattering.
- Scattered protons and recoiled deuterons were detected in a kinematical coincidence condition.

$A_y = -0.539, \quad dA_y = 0.025$

<table>
<thead>
<tr>
<th>Target</th>
<th>Thin film of CD$_2$(14.8 mg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>plastic (20 mm$^t$×35 mm$^H$×20 mm$^w$) + PMT(H7415)</td>
</tr>
<tr>
<td>Measured angles</td>
<td>$\theta_p = 70^\circ, \theta_d = 40^\circ$</td>
</tr>
</tbody>
</table>

$Y_L^u = \frac{d\sigma}{d\Omega} n I^u (1 + A_y p_{N}^u) \Delta \Omega_L$

$Y_L^d = \frac{d\sigma}{d\Omega} n I^d (1 + A_y p_{N}^d) \Delta \Omega_L$

$Y_R^u = \frac{d\sigma}{d\Omega} n I^u (1 - A_y p_{N}^u) \Delta \Omega_R$

$Y_R^d = \frac{d\sigma}{d\Omega} n I^d (1 - A_y p_{N}^d) \Delta \Omega_R$

$n$ : the number of targets

$I$ : the beam current
The beam polarization

Detector’s solid angle is time independently constant.

\[ \frac{\Delta \Omega_L}{\Delta \Omega_R} = \frac{I^d Y_L^u - I^u Y_L^d}{I^u Y_R^d - I^d Y_R^u} = \text{const.} \]

Using this constant, we extract spin observables without using the information of beam intensity.

\[ p_N^u = \frac{1}{A_y} \frac{Y_L^u / Y_R^u - \Delta \Omega_L / \Delta \Omega_R}{Y_L^u / Y_R^u + \Delta \Omega_L / \Delta \Omega_R} , \]

\[ p_N^d = \frac{1}{A_y} \frac{Y_L^d / Y_R^d - \Delta \Omega_L / \Delta \Omega_R}{Y_L^d / Y_R^d + \Delta \Omega_L / \Delta \Omega_R} . \]

- Typical polarizations are \( p_y^\uparrow \sim 50\% , p_y^\downarrow \sim 20\% \).
- Statistical uncertainties of each run are \( \sim 0.07 \) at most.
Polarized $^3$He target

- **Main coil** (static field ~1.2 mT)
- **Drive coil** (RF field ~ 85 kHz)
- **$^3$He target cell**
- **Pick up coil**

**Optical system**
- **Laser**
  - power: 60 W
  - wavelength: 795 nm
Polarized $^3$He target

**AH-SEOP method**: to polarize $^3$He

i. Circularly polarized laser polarizes Rb atoms by optical pumping under the static magnetic field.

ii. K atoms are polarized by spin exchange collision with Rb atoms.

iii. $^3$He nucleus are polarized by hyper-fine interactions with K atoms.

**Target Cell**
- **Proton beam**: 150 mm
- **Circularly polarized laser**
- **Spin exchange**
- **Optical pumping**

**Glass Thickness**
- sides 1 mm, windows 0.5 mm

**Material**
- GE180 glass

**Contents**
- $^3$He (3 atm, ~2 mg/cm$^2$), N$_2$ (~0.1 atm), A small amount of Rb, K
Polarized $^3$He target

**AFP-NMR method**: to measure $^3$He polarization

**Rb-EPR method**: to calibrate $^3$He polarization

For more details, see talk by A. Watanabe

Typical polarization is $p_y^{^3\text{He}} \sim 40\%$. 
Detector system for $p$-$^3$He scattering

Scattered protons were detected by $dE$–$TE$ detectors which are consisted of NaI(Tl) and plastic scintillators.

Double slit collimators were adopted.

<table>
<thead>
<tr>
<th>$\theta_{lab}$ [deg.]</th>
<th>$dE$ [mm$^4$]</th>
<th>$TE$ [mm$^4$]</th>
<th>$\Delta\Omega$ [msr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>1.0</td>
<td>50</td>
<td>0.11</td>
</tr>
<tr>
<td>70</td>
<td>0.5</td>
<td>50</td>
<td>0.20</td>
</tr>
<tr>
<td>115</td>
<td>0.2</td>
<td>50</td>
<td>0.43</td>
</tr>
</tbody>
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Events for $p^{-3}\text{He}$ elastic scattering are clearly seen.
To estimate the ambiguity of background subtraction, the integrating range of an elastic scattering peak was changed from $\pm 1\sigma$ to $\pm 3\sigma$.

Values of spin observables were changed less than 0.02.
Extraction of spin observables

Polarized cross sections for the left side are expressed as,

\[ L_{\uparrow \uparrow} = L_0 (1 + p_y A_y + p_y T A_y^T + p_y p_y T C_{yy}) \]
\[ L_{\uparrow \downarrow} = L_0 (1 + p_y A_y - p_y T A_y^T - p_y p_y T C_{yy}) \]
\[ L_{\downarrow \uparrow} = L_0 (1 - p_y A_y + p_y T A_y^T - p_y p_y T C_{yy}) \]
\[ L_{\downarrow \downarrow} = L_0 (1 - p_y A_y - p_y T A_y^T + p_y p_y T C_{yy}) \]

The way of extraction for right side is same.
Spin observables

$A_y^{(p)}$

- Statistical errors are only shown.
- Overall agreements are good.

$A_y^{(^3\text{He})}$

- Statistical errors are only shown.
- Large difference is found at backward two angles.

*Calculations by A. Deltuva, private communication
Spin observables

Statistical errors are only shown.

Large difference is found at backward two angles.

Sizable effects of Δ-isobar (3NFs) are predicted.

*Calculations by A. Deltuva, private communication
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Summary

- 3NF plays important roles to understand various nuclear phenomena.

- For study of 3NF properties, we have measured $p - ^{3}\text{He}$ scattering at 65 MeV by using the polarized proton beam and the polarized $^{3}\text{He}$ target. (@RCNP, Osaka Univ., Japan)

- Measured angles were $\theta_{\text{Lab}} = 35^\circ, 70^\circ, 115^\circ$. ($\theta_{\text{C.M.}} = 47^\circ, 89^\circ, 133^\circ$)

- By comparing the data with the theoretical calculations, large discrepancies are found at the backward angles for $A_y^T$ and $C_{yy}$.

- As the next step, we are planning to measure a complete set of spin correlation coefficients in a wide angular range.