Measurement of analyzing powers for $p - {^3\text{He}}$ scattering with polarized $^3\text{He}$ target

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Introduction

2-Nucleon Forces

first formulated by H. Yukawa ➔ meson exchange picture

1960’s~ performed many NN scattering exp. throughout the world
1990’s realistic NN potentials (AV18, CD-Bonn, Nijmegen I&II)
→ precisely reproduced many NN scattering data ($N_{\text{data}} \sim 4000$, $\chi^2 \sim 1$)

$A \geq 3$ system

- scattering observables ($d+p$)
- binding energies ($^3\text{H}$, $^3\text{He}$)
- equation of state of nuclear matter

only NN potential

reproduced by Three-Nucleon Forces (3NFs)
Experimental study of 3NFs

Property of Nuclear Force
- momentum dependence
- spin dependence
- isospin dependence

Few-Nucleon Scattering is a good approach
- direct comparison
- precise data ↔ rigorous theoretical calc.
- quantitative discussion of 3NFs

$d+p$ elastic scattering at 70~300 MeV/A

\[ \frac{d\sigma}{d\Omega}, A_{ij} \]

precise data

The first signatures of 3NFs in 3-nucleon scattering system (at intermediate energy)

K. Sekiguchi et al., PRC 65, 034003 (2002)
3NFs effect in 4-nucleon system

Our Next Step

- 3NFs effects in the $A \geq 4$ system
- Isospin dependence of 3NFs

→ we focus on $p + ^3\text{He}$ system
  - Theoretical calculation (at low energy)
  - The appearance of 3NFs at intermediate energy...

Planning the measurement in

$p + ^3\text{He}$ scattering system (at 70 MeV)

$\frac{d\sigma}{d\Omega}$, $A_y(^3\text{He}$ and $p)$

$^3\text{He}$ analyzing power (spin observable)

$A_y{^3\text{He}}$ calculation at $E_p = 5.54$ MeV

M. Viviani et al., PRL 111, 172302 (2013)

Need to develop

the polarized $^3\text{He}$ target
Polarized $^3$He target

Requirement for our exp.
- high polarization (> 20%)
- high density (~3 atm at room temp.)
- measuring polarization during scattering exp.

How to polarize $^3$He gas

Method: **Spin Exchange Optical Pumping (SEOP)**

1. Polarization of Rb atom
   - Static magnetic field (~3 mT)
   - circularly polarized laser $\sigma^+$
     - $\lambda=795$ nm (Rb $D_1$ transition)

2. Spin-Exchange
   - Rb
     - electron spin
   - $^3$He
     - nuclear spin
   - Fermi interaction
   - polarize $^3$He nuclei

$^3$He, Rb, N$_2$ target glass cell
3He polarization measurement

**AFP-NMR method**

- RF + sweeping magnetic field → reverse 3He nuclear spin
- detect induced voltage by pick-up coil

NMR signal is proportional to 3He polarization

This method does not give the absolute 3He polarization
Calibration of NMR signal

**Rb-ESR**

- in the presence of magnetic field, energy levels of Rb are split (Zeeman effect)
- because of the presence of polarized $^3$He, ESR frequency shift comes about
- ESR freq. shift is proportional to $^3$He polarization


Energy levels of $^{85}$Rb

**Hyper fine structure**

**Zeeman splitting**
in the presence of magnetic field, energy levels of Rb are split (Zeeman effect)

because of the presence of polarized $^3$He, ESR frequency shift comes about

ESR freq. shift is proportional to $^3$He polarization

obtaining the absolute $^3$He polarization and calibration of NMR signal are possible

Calibration of NMR signal


- in the presence of magnetic field, energy levels of Rb are split (Zeeman effect)
- because of the presence of polarized $^3$He, ESR frequency shift comes about
- ESR freq. shift is proportional to $^3$He polarization

obtaining the absolute $^3$He polarization and calibration of NMR signal are possible

- measure ESR freq. in $^3$He nuclear spin-up and down
- ESR freq. shift between spin-up and down is a few kHz

as a result...

the value of $^3$He polarization is $\sim 10\%$

Typical result of ESR freq. measurement
**p-^3^He elastic scattering exp.**

**Setup**

- beam: 70 MeV proton (~5 nA)
- target: polarized $^3$He gas (~3 atm, 2.98 mg/cm$^2$)
- detector: $\Delta E$-$E$ detector (PID by $\Delta E$-$E$ coincidence)
- measured angles: 50°, 70°, 90°, 110° (lab. system)

**Solid Angle:** ~0.4 msr

**Schematic view of exp. setup**

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@CYRIC, Tohoku Univ.
- beam intensity is measured by Faraday Cup and Beam Monitor
- reverse $^3$He nuclear spin direction by AFP-NMR method
- detect protons scattered by $^3$He nuclei
- and compare yields before and after reverse $^3$He nuclear spin direction

\[ p_y A_y^{3\text{He}} = \frac{N_+ - N_-}{N_+ + N_-} \]

$N_\pm$: Yield ($\pm$: spin-up or down)

$p_y$: $^3$He polarization

$A_y^{3\text{He}}$: $^3$He analyzing power

“asymmetry” of yields $\propto$ $^3$He analyzing power
Results of exp.

PID spectrum (ΔE vs. E)

$p^+^3$He elastic event

Yield of elastic proton event

asymmetry of yield/B.I. was confirmed at forward angles (50°, 70°)

at left-side 50° detector

Preliminary

Spin down

Spin up
Results of exp.

110° detector

- energy of scattered proton is low
- thus, PID spectrum spread (right figure)
  - need to develop detector
- low statistics for elastic events
  - need to improve $^3$He polarization

Statistical error: $\delta A_{y}^{3\text{He}} = \frac{1}{\sqrt{N_{p_y}}}$

- $N$: Yield of detected protons
- $p_y$: $^3$He polarization
- $A_{y}^{3\text{He}}$: $^3$He analyzing power

<table>
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<tr>
<th>$\theta_{\text{lab}}$ [deg]</th>
<th>$\theta_{\text{c.m.}}$ [deg]</th>
<th>$E_{p}^*$ [MeV]</th>
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<tr>
<td>110</td>
<td>128.9</td>
<td>25.1</td>
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Energies of scattered proton

PID spectrum ($\Delta E$ vs. $E$) at 110°
**Summary**

- Recently, importance of $^3$NFs has been indicated

- In order to explore $^3$NFs, we are planning the measurement in $p-^3$He system at intermediate energy

- We have performed the measurement of $^3$He analyzing power for $p-^3$He scattering at CYRIC, Tohoku Univ.

- Future plan
  
  - **improve $^3$He polarization**
  
  - **improve process of gas-filling and glass cell cleaning**

  - **develop detectors** for measurement at backward angles

  - measure $^3$He analyzing power **at the other angles**
Collaborators

Department of Physics, Tohoku Univ.


CYRIC, Tohoku Univ.
M. Itoh

RIKEN, Nishina Center
T. Uesaka

NIRS
T. Wakui

KEK
T. Ino

Thank you for your attention.
$p^+{^3He}$ theoretical calc. @70 MeV

by A. Deltuva (private communication)

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differential cross section

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$^3$He analyzing power
Rotating system (freq. = $\omega$)

sweeping magnetic field

$B_\text{eff} = \left( B + \frac{\omega}{\gamma_3^{\text{He}}} \right) e_z + B_1 e'_x$

$B$ : static magnetic field
$B_1$ : RF magnetic field
$B_{\text{eff}}$ : effective magnetic field
ESR frequency shift

\[ \Delta \nu (m_F = \pm F) = \frac{2\mu_0}{3} \frac{\mu_B g_e}{\hbar (2I + 1)} \left( 1 + \frac{8I}{(2I + 1)^2} \frac{\mu_B g_e B_0}{\hbar A_{\text{hfs}}} \right) \kappa_0 \mu_K [^3\text{He}] P_{^3\text{He}} \]

constant

(\kappa_0 \text{ is coefficient depending on temp.})

energy levels of $^{85}\text{Rb}$

\begin{align*}
5^2S_{1/2} & \quad F = 3 \\
F = 2 & \quad -2 \quad -1 \quad 0 \quad +1 \quad +2 \quad +3 \quad m_F
\end{align*}


ESR

\[ \nu = \Delta E / \hbar \]

\[ \nu \sim 6 \text{ MHz} \]

@\[ B_0 \sim 1.20 \text{ mT} \]

\[ \Delta \nu \sim \text{ few kHz} \]
Setup of ESR measurement

- Main Coils
- Drive Coils
- Oven
- ESR Coil
- Laser Light
- VCO
- Freq. Counter
- I-V Converter
- Lock in Amp.
- Ref. Target Glass Cell
- Function Generator
- D₂ Filter
- Photo Diode
- PI-Feedback
- Mixer
Our target system design

**Pumping laser**
- Power: 40 W
- Wavelength: 794.7 nm (FWHM: 0.2 nm)

**Target glass cell**
- Structure: double-cell
- Material: GE180
- Gas pressure: $^3$He gas -> 3 atm, $N_2$ gas -> 100 torr
- Typical relax. time: ~8 hour (@160°C), ~10 hour (@room temp.)

**NMR**
- Static magnetic field: ~3 mT
- RF magnetic field: ~5 μT, 87 kHz
Detector design

50°, 70°, 90° detector

- plastic + NaI(Tl) + PMT
- $\Delta E$ detector: plastic (1 mm)
- $E$ detector: NaI(Tl) (50 mm)
- solid angle: 0.4 msr

110° detector

- plastic + PMT
- $\Delta E$ detector: plastic (1 mm)
- $E$ detector: plastic (50 mm)
- solid angle: 0.5 msr

Beam Monitor

- plastic + PMT
- $\Delta E$ detector: plastic (2 mm)
- $E$ detector: plastic (35 mm)
- solid angle: 4.3 msr
- target: CH$_2$ (20 µm)
For improvement of $^3\text{He}$ polarization

\[ P_{^3\text{He}} = \bar{P}_{\text{Rb}} \frac{\gamma_{\text{SE}}}{\gamma_{\text{SE}} + \Gamma_{^3\text{He}}} \]

$P_{^3\text{He}}$ : $^3\text{He}$ polarization
$P_{\text{Rb}}$ : average of Rb polarization
$\gamma_{\text{SE}}$ : spin-exchange rate between $^3\text{He}$ nucleus and Rb atoms
$\Gamma_{^3\text{He}}$ : relaxation rate of $^3\text{He}$ polarization

- impurities in the $^3\text{He}$ gas
- inhomogeneity of magnetic field
- dipole interaction between two $^3\text{He}$ nucleus

we focused on

develop the vacuum system for cell-construction