Polarized experiment with medium energy hadron beam

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What do we learn from polarized experiment?

unpolarized  polarized
Outline

• Three-body Nuclear Force (TNF) in polarized scattering
• Polarized charge exchange reaction with inverse kinematics
• R&D of polarized $^3$He target in Lanzhou Univ.
Three-body Nuclear Force (TNF) in polarized scattering
Effect of TNF—spectrum of light nucleus


![Graph showing the spectrum of light nucleus with energy levels and transitions indicated.]
Phenomenological NN potential

• Two body interaction (AV18, CD-Bonn...)
  \[ O_{ij}^p = [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S, L^2, L^2(\sigma_i \cdot \sigma_j), (L \cdot S)^2] \]
  \[ + [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S, L^2, L^2(\sigma_i \cdot \sigma_j), (L \cdot S)^2] \otimes \tau_i \cdot \tau_j \]
  \[ + [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes T_{ij} \]
  \[ + [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes (\tau_i + \tau_j)_z \]

• Three body interaction (TM’, IL7, NJIM...)
  Illinois \[ V_{ijk} = V_i^{2\pi P} + V_i^{2\pi S} + V_i^{3\pi \Delta R} + V_i^R \]

• Global fitting of (un)polarized scattering data
Description of chiral EFT

**LO**
\[(Q/\Lambda_\chi)^0\]
- Approximation of QCD in low energy

**NLO**
\[(Q/\Lambda_\chi)^2\]
- Uniform framework

**NNLO**
\[(Q/\Lambda_\chi)^3\]
- Fair description of data

**N^3LO**
\[(Q/\Lambda_\chi)^4\]

\[N^5L: \text{ PRL 115, 122301 (2015)}\]
Polarized scattering on light nuclei

• Experimental observable
  – \( a^\uparrow(b, c) d \): Analyzing power
  – \( a^\uparrow(b^\uparrow, c) d \): Spin correlation
  – \( a^\uparrow(b, c^\uparrow) d \): Polarization transfer
  – \( a (b, c^\uparrow) d \): Polarization
  – \( a (b, c^\uparrow) d^\uparrow \): Spin correlation

• Theoretical analysis tools
  – Faddeev-Yakubovsky (FY) equation (3N)
  – AGS equation (4N)
  – hyperspherical harmonics expansion method
Experiments over the world

RIKEN

$m + p$

magnetic spectrograph
SMART

IUCF

The Cooler Ring

CIPOS

Cold Neutron Facility

PINTEX

BINA & SALAD

KVI

$p + d$

$p + d$

BBS

RCNP

$ar{n} + d$

NTOF

Grand Raiden & LAS

Cooler Ring + PINTEX

$p + d$

0 5 m

0 50 m

Ring Cyclotron Facility

2017/7/28
3-N system scattering

<table>
<thead>
<tr>
<th>Nd elastic scattering</th>
<th>Nd break-up</th>
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<tr>
<td>( \frac{d\sigma}{d\Omega} )</td>
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<td>( \vec{p} \rightarrow \vec{p} )</td>
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<td>(</td>
<td>A_{xz} )</td>
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<td>(</td>
<td>C_{ij} )</td>
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- Elastic scattering
- Low energy
- Ay puzzle
\[
\vec{p} + d \rightarrow p + d
\]

\[
\sigma = \sigma_0 (1 + pA_y \cos \varphi)
\]

\[
\Rightarrow A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}
\]

p(d)+d in medium energy since 2010

• Complete set of deuteron analyzing powers for dp elastic scattering at 250–294 MeV/nucleon and the three-nucleon force

• Vector analyzing powers of the deuteron-proton elastic scattering and breakup at 100 MeV

• Measurement of the vector and tensor analyzing powers for dp-elastic scattering at 880 MeV

• Three nucleon force effects in intermediate-energy deuteron analyzing powers for dp elastic scattering

• Vector and tensor analyzing powers in deuteron-proton breakup at 130 MeV

• Spin observables in the three-body break-up process near the quasi-free limit in deuteron–deuteron scattering

• Angular distributions of the vector $A_{y}$ and tensor $A_{yy}, A_{xx}, A_{xz}$ analyzing powers in the dd→$^{3}$Hp reaction at 200 MeV

• Three-body break-up in deuteron-deuteron scattering at 65 MeV/nucleon
4-N system scattering (p+\(^{3}\)He)

Unpolarized case: theory consists with measurement

4-N system scattering \((d \uparrow +d)\)


IUCF: \(d \uparrow +d\) elastic @241MeV

KVI : \(d \uparrow +d\) elastic @135MeV (BBS)

\(d \uparrow +d\) -> \(d+p+n\) @135MeV (BINA)

\(d +d\) -> \(d+p+n\) @160MeV (BINA)
4-N system scattering (p+$^3$He)

Polarized case: Ay puzzle

Lack of data in medium energy region

p + $^3$He -> d + p + p ?

CSR External target Experiment (CEE)
Planned measurement in CEE

- Put the $^3$He target between T0 detector and the diple

  Target parameters:
  - Coil radii: 50 cm
  - Cell geometry: 22.5 cm long, φ 1.67 cm cylinder
  - Density: 4 amagt $^3$He
  - Window: 0.2 mm Pyrex glass

- Both elastic and break-up channel are studied

2017/7/28
Planned measurement in CEE

- Put the 3He target between T0 detector and the dipole

Target parameters:
- Coil radii: 50 cm
- Cell geometry: 22.5 cm long, \( \phi 1.67 \) cm cylinder
- Density: 4 amagat
- Window: 0.2 mm

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Missing mass spectrum in different channels

300 MeV

600 MeV
Proton track in Elastic events ($E_{\text{beam}} = 300\text{MeV}$)

- Only $<5\%$ proton track with $\theta_p > 30^\circ$
Other types of events in break-up channel

300 MeV

600 MeV

Single deuteron

\( p + d \)
Proton tracks in Break-up events ($E_{\text{beam}}=300\text{MeV}$)
Simulation summary

- For elastic channel: most tracks can be covered within the acceptance of CEE spectrometer

- For break-up channel \((p + {^3}\text{He} \rightarrow p + p + d)\):
  - \(p+p\) and \(p+d\) events can be identified, while single \(d\) event cannot
  - Large angle detection is necessary
Polarized charge exchange reaction with inverse kinematics
• Measures strength of GT transition in β decay
• Access to the matrix element of 2νββ decay
• Gain information of electron capture process in core collapse of supernova
$\Delta R_{np}$ measured in ($^3$He, t)

Compared with ($p$, $n$), ($^3$He, t) is more sensitive to the surface of nuclei

$\Delta R_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$
Isovector multipole giant resonance

M. Scott et al
Phys. Rev. Lett. 118, 172501 – April 28 2017

\[ \Delta L=0 \text{ MDA} \]
\[ \text{IVGMR (NM)} / 3 \]
\[ \text{IVGMR (pn-RTBA) x 2} \]
Inverse kinematics
EXL project in NUSTAR collaboration, GSI

- small momentum transfer
- detection of low energy recoil particles
- high luminosities
- windowless $^1,^2\text{H}$, $^3,^4\text{He}$, etc. targets.
Meson exchange in $^3\text{He} \uparrow (zA, z+1A)t$

$^3\text{He}$

$^3\text{H}$

$\rho^+ \times \pi^+$

$\hat{\sigma} \times \hat{q}$

$\hat{\sigma} \cdot \hat{q}$

$^A_Z X$

$^A_{Z+1} Y$
charge exchange reaction: $^3\text{He} \uparrow_{(zX, \ z+1Y)t}$

$^3\text{He} \approx S \sim 90\% \quad S' \sim 1.5\% \quad D \sim 8\%$
charge exchange reaction: $^3\text{He} \uparrow (z\text{X}, z+1\text{Y}) \downarrow$
charge exchange reaction: $^3\text{He} \uparrow _{S, S', D} (zX, z+1Y) t$
charge exchange reaction: $^3\text{He} \uparrow (z \ X, \ z+1 \ Y) \ \downarrow$

Unpolarized case:

$$O^p_{ij} = [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S, L^2, L^2(\sigma_i \cdot \sigma_j), (L \cdot S)^2]$$

$$+ \ [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S, L^2, L^2(\sigma_i \cdot \sigma_j), (L \cdot S)^2] \otimes \tau_i \cdot \tau_j$$

$$+ \ [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes T_{ij}$$

$$+ \ [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes (\tau_i + \tau_j) z$$
charge exchange reaction: $^3\text{He} \uparrow (z\, X, \, z+1\, Y) t$

$^3\text{He} \approx \begin{array}{c} \approx \frac{3}{15} \left( z \right) X, z+1 Y t \end{array}$

$^3\text{He} \rightarrow ^3\text{H}$

Polarized case:

$$O^p_{ij} = [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S, L^2, L^2(\sigma_i \cdot \sigma_j), (L \cdot S)^2]$$

$$+ [1, \boxed{\sigma_i \cdot \sigma_j}, S_{ij}, L \cdot S, L^2, L^2(\boxed{\sigma_i \cdot \sigma_j}), (L \cdot S)^2] \otimes \tau_i \cdot \tau_j$$

$$+ [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes T_{ij}$$

$$+ [1, \sigma_i \cdot \sigma_j, S_{ij}, L \cdot S] \otimes (\tau_i + \tau_j)_z$$
Utilizing Polarized $^3$He taget in Lanzhou University
Principle of polarizing $^3$He

- polarized laser $\rightarrow$ polarized Alkali atom $\rightarrow$ polarized $^3$He

$\downarrow$ optical pumping $\downarrow$ spin exchange

- Density of each piece (in cm$^{-3}$)
  - $[\text{Rb}] \sim 10^{18}$ at 230 °C
  - $[\text{He}] \sim 2.69 \times 10^{20}$
  - $[\text{N}_2] \sim 2.15 \times 10^{18}$
Pumping hybrid alkali

Spin-Exchange

³He ≈ S
~90%

S’
~1.5%

D
~8%

2017/7/28
Pumping hybrid alkali

\[ P_{He}(t) = \langle P_{Rb} \rangle \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma} \left( 1 - e^{-(\gamma_{SE} + \Gamma)t} \right) \]

\[ \gamma_{SE} = k_{SE}[\text{Rb}] \]

\[ k_{SE} = (6.1 \pm 0.2) \times 10^{-20} \text{ [cm}^3/\text{s}] \]

\[ ^3\text{He} \approx S \approx S' \approx D \]

\[ \sim 90\% \quad \sim 1.5\% \quad \sim 8\% \]
Pumping hybrid alkali

\[ \chi^2 / \text{ndf} = 0.4097 / 11 \]

- Expected Max NMR: 4.675 ± 0.0046
- Spin-Up Time (h): 3.555 ± 0.1797
- Fitting constant: 0.6821 ± 0.00786

\[ ^3\text{He} \approx S \approx S' \approx D \]

- Approximately 90% of \(^3\text{He}\) becomes \(S\)
- Approximately 1.5% of \(S\) becomes \(S'\)
- Approximately 8% of \(S'\) becomes \(D\)
Polarized $^3$He target build in LZU

- Gas filling system
- Hybrid pumping
- Polarization (~60%)
- 0.9 Amg.
  - plan: ~3 Amg.
- Only 1 chamber
  - Plan: 2 chamber
Energy loss in the glass wall

![Graph showing energy loss of \(^3\text{H}\) through Pyrex glass](graph.png)
Summary

Polarized target in hadron beam is more like a unique probe rather than an object.

- In few-nucleon system, polarization is important
  - Role of $\Delta(1232)$ and $\Delta(1440^*)$
  - Tensor force
- In CE process, polarization is crucial
  - Nuclear structure
  - Propagation of $\Delta$ in nuclear matter
  - Other applications
- For various types of experiments, technical R&D is still challenging
Thank you !
Backup slides
Simulation detail

- Physics model:
  - EM model: G4EmStandardPhysics_option3
  - Hadron physics model: G4HadronPhysicsINCLXX

- Beam energy: 240MeV~600MeV

- Tracks $E_{\text{kine}} > 1\text{MeV}, \theta > 2^\circ$, energy, momentum, position, time…
Missing mass of proton in p+d event

Red line showing Proton mass

Only has ¼ stat. of 2-p event
Energy-Angular distribution of proton (300MeV)
Angular correlation of proton (300MeV)