PROPOSAL FOR EXPERIMENT AT RCNP

29/10/1998

TITLE:
Measurement of Momentum Transfer Dependence of Polarization Transfer and Spin Response Functions in Quasi-Elastic ($\vec{p},\vec{n}$) Reactions

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RUNNING TIME:
Installation time without beam 4 days
Test running time for experiment 4 days
Data runs 13 days

BEAM LINE: N0 (neutron TOF facility + NPOL2)

BEAM REQUIREMENTS:
Type of particle Polarized Protons
Beam energy 346 MeV
Beam intensity 500 nA on target
Time resolution $< 500$ ps (FWHM)
Beam polarization $> 0.7$

BUDGET:
Summary of budget request 5,500,000
Experimental expenses 5,000,000
Travel plan 500,000
**TITLE:** Measurement of Momentum Transfer Dependence of Polarization Transfer and Spin Response Functions in Quasi-Elastic \((\vec{p},\vec{n})\) Reactions

**SPOKESPERSON:** Tomotsugu WAKASA

**SUMMARY OF THE PROPOSAL**

Mesonic fields in the nucleus would reveal their presence through collective effects on the quasi-elastic spin response functions. In the \(\pi+\rho+g'\) model [1] with a standard value of \(g'\), the pion exchange produces a moderately attractive spin-longitudinal interaction for \(q > 0.8\) fm\(^{-1}\), while the rho-meson exchange produces a repulsive spin-transverse interaction for the wide range of \(q\) [1]. In the quasi-elastic region for \(q > 1\) fm\(^{-1}\), an interaction with these characteristics would lead to an enhancement and a softening (shift toward lower energy transfer) of the spin-longitudinal response function \(R_L\) with respect to the free response function, and a quenching and a hardening (shift toward higher energy transfer) of the spin-transverse response function \(R_T\). The enhancement of \(R_L\) has attracted much interest in connection with both the precursor phenomena of the pion condensation [1] and the enhancement of the pion probability in the nucleus [2–6].

Our recent measurements [7] with \((\vec{p},\vec{n})\) reactions at \(T_p = 346\) MeV and \(\theta_{\text{lab}} = 22^\circ\) (\(q_{\text{lab}} \approx 1.7\) fm\(^{-1}\)) show a signature of the enhancement of \(R_L\) from the free response function. On the contrary, comparison of the experimental \(R_T\) to \((e,e')\) and random phase approximation (RPA) ones reveals a large excess of \(R_T\), which makes the spin response ratio \(R_L/R_T\) unsuitable for observing possible signatures of the pionic enhancement.

A crucial step in confirming the pionic enhancement of \(R_L\) is examination of the momentum-transfer dependence of the spin response functions. In this experiment, we measure a complete set of polarization transfer coefficients for quasi-elastic \((\vec{p},\vec{n})\) reactions on \(^2\)H, \(^{12}\)C, and \(^{40}\)Ca at \(T_p = 346\) MeV and \(\theta_{\text{lab}} = 16^\circ\) and \(27^\circ\). Combined with the previous experiment (E59), the measurement covers a wide momentum-transfer range of \(q_{\text{lab}} = 1.2–2.0\) fm\(^{-1}\) (250–400 MeV/c). The cross section is separated into spin-longitudinal and spin-transverse modes by using polarization transfer coefficients. These polarized cross sections are compared to theoretical calculations in a distorted wave impulse approximation employing RPA correlations. Such a comparison will confirm the pionic enhancement and will restrict the particle-hole residual interaction (Landau-Migdal parameter \(g'\)) used in RPA calculations.

The large excess of \(R_T\) can be understood in part by considering the spin-direction dependence of the effective neutron number and the two-step contribution. It should be noted that the two-step contribution is expected to depend on the momentum transfer. Thus our measurement will provide a ground for understanding quantitatively the large excess of \(R_T\) due to the two-step contribution.
1 Scientific motivation

The role of the pion ($\pi$) and rho-meson ($\rho$) in the nuclear spin-isospin response functions is one of the most interesting subjects of nuclear physics. The spin-isospin dependent residual interaction is often given by the $\pi+\rho+g'$ model [1]. In this model with a standard value of $g'$, the spin-longitudinal interaction becomes moderately attractive for $q > 0.8$ fm$^{-1}$, while the spin-transverse interaction remains repulsive for the wide range of $q$ [1] (see Fig. 1).

In 1982, Alberico et al. [1] theoretically pointed out that the attractive spin-longitudinal interaction should induce an enhancement and a softening (shift toward lower energy transfer) of the spin-longitudinal response function $R_L$ with respect to the free response function in the quasi-elastic region for $q > 1$ fm$^{-1}$. On the contrary, the repulsive spin-transverse interaction should induce a quenching and a hardening (shift toward higher energy transfer) of the spin-transverse response function $R_T$ in the same region. The result of theoretical calculations by Alberico et al. is presented in Fig. 2. The enhancement of $R_L$ has attracted much interest in connection with both the precursor phenomena of the pion condensation [1] and the enhancement of the pion probability in the nucleus [2–6].

Measurements of a complete set of polarization transfer coefficients for the quasi-elastic $^{12}\text{C}(\vec{p},\vec{n})$ reaction at $T_p = 494$ MeV and scattering angles of 12.5°, 18°, and 27° were performed at LAMPF [8–10]. These measurements yielded pure-isovector $R_L$ and $R_T$ separately, which shows no evidence for an enhancement of $R_L$ relative to $R_T$. The conclusion of these measurements is that there is a strong enhancement of $R_T$ which masks the effect of pionic correlations in the ratio $R_L/R_T$. However there are uncertainties in the extraction of $R_L$ and $R_T$, such as ambiguities associated with distortion effects and the free $NN$ t-matrix.

Our recent measurements [7] with $(\vec{p},\vec{n})$ reactions at $T_p = 346$ MeV and $\theta_{\text{lab}} = 22^\circ$ ($q_{\text{lab}} \approx 1.7$ fm$^{-1}$) confirm the results of the previous studies of quasi-elastic $(\vec{p},\vec{p}')$ [11,12] and $(\vec{p},\vec{n})$ [8–10] reactions which reveal no evidence for an enhancement of $R_L/R_T$ at a momentum transfer where the enhancement should be largest (see Fig. 3). However, as described below, the lack of the enhancement of $R_L/R_T$ does not necessarily mean the absence of the pionic enhancement of $R_L$.

The spin response functions for $^{12}\text{C}$ and $^{40}\text{Ca}$ are compared to random phase approximation (RPA) response functions. The result is shown in Fig. 4. In the spin-longitudinal mode, the...
Theoretically expected enhancement is clearly observed for both $^{12}$C and $^{40}$Ca. The observed enhancement of $R_L$ from the free response function is significantly large compared to the uncertainty of the experimental spin response functions of about 10%. In the spin-transverse mode, the experimental $R_T$ agrees fairly well in shape with the RPA result which predicts the hardening of $R_T$ with respect to the free response function. However it is substantially larger than the RPA calculation for both $^{12}$C and $^{40}$Ca. This apparent excess of $R_T$ is responsible for masking possible signatures of the pionic enhancement in $R_L/R_T$.

The reason of the large excess of $R_T$ is in part due to the use of the spin-direction independent effective neutron number $N_{\text{eff}}$ which was calculated in a eikonal approximation. The $N_{\text{eff}}$ values would depend on the spin direction because of both the effects of the spin-orbit potential and the difference of the radial-dependence between the spin response functions. The spin-direction dependent $N_{i\text{eff}}$ is evaluated by comparing the results of distorted wave impulse approximation (DWIA) and plane wave impulse approximation (PWIA) calculations as [13]

$$N_{i\text{eff}}(\omega_{\text{lab}}) = N \frac{ID_{i\text{DW}}(\omega_{\text{lab}})}{ID_{i\text{PW}}(\omega_{\text{lab}})} , \quad (i = q \text{ or } p) \quad (1)$$

where $N$ is the target neutron number, and $ID_{i\text{DW}}$ and $ID_{i\text{PW}}$ are the polarized cross sections in DWIA and PWIA calculations, respectively. The results of DWIA+RPA calculations are shown in Fig. 5, in which our results of E59 are presented with the filled circles. The $N_{i\text{eff}}$ values obtained from Eq. (1) become $N_{q\text{eff}} = 2.4$–2.6 and $N_{p\text{eff}} = 2.7$–3.2 for $^{12}$C, and $N_{q\text{eff}} = 3.9$–4.3 and $N_{p\text{eff}} = 5.9$–7.1 for $^{40}$Ca in the energy-transfer region of $\omega_{\text{lab}} = 40$–120 MeV. These values should be compared to the spin-direction independent $N_{\text{eff}}$ in the eikonal approximation of 2.5–2.7 for $^{12}$C and 5.4–5.8 for $^{40}$Ca in the same region. The spin-direction dependence for $^{12}$C is rather small with 9–22%, while that for $^{40}$Ca is large with 31–43%. Thus, by using the spin-direction dependent $N_{i\text{eff}}$, $R_L$ for $^{40}$Ca is more enhanced by 27–48%, while $R_T$ becomes small by 2–23%.

Recently, Nakaoka [14] has pointed out that the two-step contribution for $ID_p$ would be significantly larger than that for $ID_q$. In the two-step process, the momentum transfers of the 1st- and 2nd-steps share the experimentally observed momentum transfer $q$. Thus the two-step contribution can be represented as a coherent sum of the contributions with various combinations of the 1st- and 2nd-step momentum transfers. In the momentum-transfer region from 0 to $q$, the spin-longitudinal interaction changes its sign at around 0.7 fm$^{-1}$, while the spin-transverse interaction remains positive (repulsive). Thus the coherent sum for $ID_q$ is partly destructive, while that for $ID_p$ is wholly constructive. As a result, the two-step contribution for $ID_p$ is more important than that for $ID_q$. The two-step contribution for $ID_p$ would be partly responsible for the discrepancy of the $(\vec{p}, \vec{n})$ spin-transverse response function from the corresponding RPA one.

On the base of these studies, we propose here to measure momentum-transfer dependence of polarization transfer and spin response functions in quasi-elastic $(\vec{p}, \vec{n})$ reactions. Combined with the previous experiment (E59), the measurement forms the spin response functions as
a function of momentum transfer in the range of $q = 1.2 – 2.0 \, \text{fm}^{-1}$ (250–400 MeV/c) [see Fig. 1]. The cross section is separated into spin-longitudinal and spin-transverse modes by using polarization transfer coefficients. Note that $ID_q$ and $ID_p$ are proportional to $R_q (=R_L)$ and $R_p (=R_T)$, respectively, in a framework in PWIA. These polarized cross sections are compared to DWIA+RPA calculations. The prediction of DWIA+RPA calculations is shown in Fig. 6. Due to the momentum-transfer dependence of the residual interaction shown in Fig 1, the enhancement of $ID_q$ with RPA correlations (DWIA+RPA) from that without correlations (DWIA+free) becomes large with increasing $q$ from 1.2 to 2.0 fm$^{-1}$. On the contrary, the quenching of $ID_p$ with RPA correlations from that without correlations becomes small with increasing $q$. Such a comparison will confirm the pionic enhancement and will restrict the particle-hole residual interaction (Landau-Migdal parameter $g'$) used in RPA calculations.

It should be noted that the two-step contribution is expected to depend on the momentum transfer [14]. Thus our measurement will also provide a ground for tests of models proposed for treating the two-step contribution. These tests will be helpful to understand the large excess of $R_T$ due to the two-step contribution quantitatively.

2 Experimental procedures

We measure a complete set of polarization transfer coefficients for quasi-elastic ($\vec{p}, \vec{n}$) reactions on $^2$H, $^{12}$C, and $^{40}$Ca. The cross section, analyzing power, and induced polarization for these reactions are also measured. Measurements are carried out with the neutron time-of-flight (NTOF) facility at a bombarding energy of 346 MeV and scattering angles of $\theta_{\text{lab}} = 16^\circ$ and $27^\circ$. Detailed descriptions concerning the NTOF facility and the neutron detection system can be found in Refs. [15–17]. In the following, therefore, we present a brief description about experimental procedures.

The direction of the polarization axis of incident protons is controlled by using two sets of superconducting solenoid magnets SOL1 and SOL2 installed in the injection line from AVF to ring cyclotrons. The beam polarization (magnitude and direction) is monitored with two beam line polarimeters BLP1 and BLP2 by using the proton elastic scattering on $^1$H. The targets (CD$_2$, $^{12}$C, and $^{40}$Ca) are positioned in the beam swinger magnets. The reaction angle of the ($\vec{p}, \vec{n}$) reaction can be varied by repositioning a target along the beam trajectory. The polarization of outgoing neutrons is measured with the neutron polarimeter NPOL2. The neutron spin rotation (NSR) magnet positioned at the entrance of the 100 m TOF tunnel is used to rotate the neutron polarization from longitudinal to normal direction, which enables us to measure the longitudinal component of the neutron polarization.
3 Beam time and Beam requirements

In E59, the count rate (event rate accepted by the data acquisition (DAQ) system) was limited by the speed of the DAQ system. The net count rate was 500 cps, which was about 30% of the total event rate. The upgrade of the DAQ system is now in progress. The new system with high-speed memory (HSM) modules and VME will improve the speed by a factor of 2, which means that about 60% of the total event can be accepted.

cross section and analyzing power

From the following conditions:

<table>
<thead>
<tr>
<th></th>
<th>CD$_2$</th>
<th>$^{12}$C</th>
<th>$^{40}$Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target thickness (mg/cm$^2$)</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Target thickness (1/cm$^2$)</td>
<td>$1.1 \times 10^{22}$</td>
<td>$1.5 \times 10^{22}$</td>
<td>$4.5 \times 10^{21}$</td>
</tr>
<tr>
<td>$\sigma$ at QES peak at $\theta_{lab}=16^\circ$ (mb/sr/5-MeV)</td>
<td>9.0</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>$\sigma$ at QES peak at $\theta_{lab}=27^\circ$ (mb/sr/5-MeV)</td>
<td>3.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

and

- Solid angle: 0.1 msr
- Beam intensity: 50 nA (after 1/9 pulsing)
- Beam polarization: 0.70
- Efficiency of NPOL2: 0.12
- Accept/Event: 0.75

One data point at $\theta_{lab}=16^\circ$ ($\theta_{lab}=27^\circ$) with the statistical uncertainty for $A_y$ of 0.2% (1.4% for CD$_2$ which corresponds to the statistical uncertainty of 2% for $^2$H) around the quasi-elastic peak will be obtained as follows.

<table>
<thead>
<tr>
<th></th>
<th>CD$_2$</th>
<th>$^{12}$C</th>
<th>$^{40}$Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 h (9 h)</td>
<td>3 h (9 h)</td>
<td>6 h (18 h)</td>
<td></td>
</tr>
</tbody>
</table>

polarization transfer coefficients

From the following conditions:

<table>
<thead>
<tr>
<th></th>
<th>CD$_2$</th>
<th>$^{12}$C</th>
<th>$^{40}$Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target thickness (mg/cm$^2$)</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Target thickness (1/cm$^2$)</td>
<td>$2.2 \times 10^{22}$</td>
<td>$3.0 \times 10^{22}$</td>
<td>$9.0 \times 10^{21}$</td>
</tr>
<tr>
<td>$\sigma$ at QES peak at $\theta_{lab}=16^\circ$ (mb/sr/5-MeV)</td>
<td>9.0</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>$\sigma$ at QES peak at $\theta_{lab}=27^\circ$ (mb/sr/5-MeV)</td>
<td>3.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

and

- Solid angle: 0.1 msr
- Beam intensity: 50 nA (after 1/9 pulsing)
- Beam polarization: 0.70
- Efficiency of NPOL2: 0.02
- Analyzing power of NPOL2: 0.12
- Accept/Event: 0.75
one data point at $\theta_{\text{lab}} = 16^\circ$ ($\theta_{\text{lab}} = 27^\circ$) with the statistical uncertainty of 2\% (1.4\% for CD$_2$ which corresponds to the statistical uncertainty of 2\% for $^2$H) around the quasi-elastic peak will be obtained as follows.

<table>
<thead>
<tr>
<th>observables</th>
<th>CD$_2$</th>
<th>$^{12}$C</th>
<th>$^{40}$Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{NN}$ and $P$</td>
<td>8 h (24 h)</td>
<td>8 h (24 h)</td>
<td>16 h (48 h)</td>
</tr>
<tr>
<td>$D_{S^*S}$ and $D_{L^*S}$</td>
<td>4 h (12 h)</td>
<td>4 h (12 h)</td>
<td>8 h (24 h)</td>
</tr>
<tr>
<td>$D_{L^*L}$ and $D_{S^*L}$</td>
<td>4 h (12 h)</td>
<td>4 h (12 h)</td>
<td>8 h (24 h)</td>
</tr>
<tr>
<td>total</td>
<td>16 h (48 h)</td>
<td>16 h (48 h)</td>
<td>32 h (96 h)</td>
</tr>
</tbody>
</table>

**summary**

In summary, requirements for the beam time are as follows.

<table>
<thead>
<tr>
<th>observables</th>
<th>CD$_2$</th>
<th>$^{12}$C</th>
<th>$^{40}$Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ and $A_y$</td>
<td>3 h (9 h)</td>
<td>3 h (9 h)</td>
<td>6 h (18 h)</td>
</tr>
<tr>
<td>$D_{NN}$ and $P$</td>
<td>8 h (24 h)</td>
<td>8 h (24 h)</td>
<td>16 h (48 h)</td>
</tr>
<tr>
<td>$D_{S^*S}$ and $D_{L^*S}$</td>
<td>4 h (12 h)</td>
<td>4 h (12 h)</td>
<td>8 h (24 h)</td>
</tr>
<tr>
<td>$D_{L^*L}$ and $D_{S^*L}$</td>
<td>4 h (12 h)</td>
<td>4 h (12 h)</td>
<td>8 h (24 h)</td>
</tr>
<tr>
<td>total</td>
<td>19 h (57 h)</td>
<td>19 h (57 h)</td>
<td>38 h (114 h)</td>
</tr>
<tr>
<td>grand total</td>
<td>304 h (~13 days)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The measurements of

1. $\sigma$ and $A_y$
2. $D_{NN}$ and $P$
3. $D_{S^*S}$ and $D_{L^*S}$
4. $D_{L^*L}$ and $D_{S^*L}$

will be performed in the separated beam time, and one additional day for setting-up is required for each beam time.

**beam requirement**

The requirements for the beam are following:

- Type of particle: Polarized Protons
- Beam energy: 346 MeV
- Beam intensity: 500 nA on target
- Time resolution: $< 500$ ps (FWHM)
- Beam polarization: $> 0.7$

**4 Budget**

The new DAQ system is now under construction. To complete this system, the following equipments are needed.
Travel expenses (500,000 yen) for all of the members for the beam time as well as for preparation are also required.

5 Schedule

The installation of the new DAQ system will be completed on March 1999. We can start our measurement after April 1999.

6 Other commitment of group members

Most of our group member has a commitment of our own experiments performed with N0 beam line (neutron TOF facility + NPOL2).

7 References

8 Recent publications on the related works

   Polarization Transfer and Spin Response Functions in Quasi-Elastic ($\vec{p}, \vec{n}$) Reactions at 346 MeV

   Cross Sections and Complete Polarization Transfer Measurements for the $^2$H($\vec{p}, \vec{n}$)pp Reaction at 346 MeV

   Nuclear Spin Responses from Polarization Transfer in Quasi-Free ($p, n$) Reactions at 346 MeV

   in Proceedings of the International Symposium on New Facet of Spin Giant Resonances
Study of Reaction Mechanisms for $(p,n)$ and $(p,p')$ quasi elastic scattering

Isovector Nuclear Spin Responses from Polarization Transfer in Quasi-Free $(p,n)$ Reactions at 346 MeV

Cross Section and Analyzing Power of the $(p,n)$ and $(p,p')$ Quasi Elastic Scattering at 400 MeV

Spin-Isospin Modes in Nuclei