Momentum Transfer Dependence of Spin Isospin Modes in the Quasielastic Region


*Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan
†Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
**Faculty of Computer and Information Sciences, Hosei University, Tokyo 184-8584, Japan
† Division of Natural Sciences, International Christian University, Tokyo 181-8585, Japan
§Department of Physics, Saitama University, Saitama 338-8570, Japan
¶Department of Information Science, Kanagawa University, Kanagawa 259-1293, Japan
∥Department of Physics, Tohoku University, Miyagi 980-8578, Japan
††Institute of Chemical and Physical Research (RIKEN), Saitama 351-0198, Japan
‡‡Center for Nuclear Study (CNS), University of Tokyo, Tokyo 113-0033, Japan
§§Department of Physics, Kyushu University, Fukuoka 812-8581, Japan

Abstract. A complete set of polarization transfer coefficients has been measured for the quasielastic $^{12}$C$(\vec{p}, \vec{n})$ reaction at a bombarding energy of 345 MeV and laboratory scattering angles of $16^\circ$, $22^\circ$, and $27^\circ$. The spin-longitudinal $ID_\rho$ and spin-transverse $ID_p$ polarized cross sections are deduced. The theoretically expected enhancement in the spin-longitudinal mode is observed. The observed $ID_\rho$ is consistent with the pionic enhanced $ID_\rho$ evaluated in a distorted wave impulse approximation (DWIA) calculation employing a random phase approximation (RPA) response function. On the contrary, the theoretically predicted quenching in the spin-transverse mode is not observed. The observed $ID_p$ is not quenched, but rather enhanced in comparison with the DWIA+RPA calculation. Two-step contributions are responsible in part for the enhancement of $ID_p$.

INTRODUCTION

Isovector spin responses to nuclear mesonic fields are expected to show an enhanced ratio of the spin-longitudinal $(\sigma \cdot \hat{q})$ to spin-transverse $(\sigma \times \hat{q})$ response functions for momentum transfer $q > 1$ fm$^{-1}$, as predicted by $\pi + \rho + g'$ meson exchange models of the nuclear mean field [1]. Recent experimental and theoretical investigations of isovector $(\vec{p}, \vec{n})$ reactions at $T_p = 346$ [2, 3] and 494 MeV [3, 4, 5, 6] show a signature of the enhancement of the spin-longitudinal cross section $ID_\rho$ relevant to the spin-longitudinal response function $R_L$ around the quasielastic peak. The enhancement of $R_L$ is attributed to the collectivity induced by the one-pion exchange interaction, and thereby 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 [7, 8, 9, 10, 11]. However the theoretical calculation in a distorted wave impulse approximation (DWIA) employing random phase approximation (RPA) response functions underpredicts $ID_\rho$ for energy
transfer greater than that for the quasielastic peak. Furthermore the DWIA+RPA calculation underestimates the spin-transverse cross section \( ID_p \) in the quasielastic region. These disagreements between experimental and theoretical results would suggest the importance of the two-step (and possibly higher step) contribution in this region [18].

In this article, we present the measurements of a complete set of polarization transfer coefficients for the quasielastic \((\vec{p},\vec{n})\) reaction on \(^{12}\text{C}\) at \(T_p = 345\, \text{MeV}\) and laboratory scattering angles of \(\theta_{\text{lab}} = 16^\circ, 22^\circ, \text{ and } 27^\circ\) which correspond to \(q_{\text{lab}} \simeq 1.2, 1.7\) and \(2.0\, \text{fm}^{-1}\) at the quasielastic peak [2]. The measured polarization transfer coefficients and cross sections are used to separate the cross sections into non-spin, spin-longitudinal, and spin-transverse polarized cross sections. The experimental polarized cross sections will be compared with theoretical calculations in frameworks of DWIA and RPA. The data will also be compared with a calculation including the two-step contribution.

**EXPERIMENTAL METHODS**

The measurement was carried out at the Neutron Time-Of-Flight (NTOF) facility [12] at the Research Center for Nuclear Physics (RCNP), Osaka University. The NTOF facility and the neutron detector/polarimeter NPOL2 system are described in detail in Refs. [12, 13, 14]. In the following, therefore, we present a brief description of the detector system and discuss experimental details relevant to the present experiment.

Natural carbon (98.9% \(^{12}\text{C}\)) targets used for the cross section and polarization observable measurements with thicknesses of 338 mg/cm\(^2\) and 682 mg/cm\(^2\), respectively, were placed in a beam swinger dipole magnet. Neutrons from the \((p,n)\) reaction traversed various distances within a 100 m time-of-flight (TOF) tunnel, and were detected with NPOL2. Protons downstream of the target were swept by the beam swinger magnet into an aluminum beam stop (Faraday cup). The integrated beam current stopped in the Faraday cup was measured. Typical beam currents were 10 and 50 nA for the cross section and polarization observable measurements, respectively.

The NPOL2 system [14] consists of six planes of two dimensionally position sensitive scintillation detectors: four detectors of liquid scintillator BC519 and two detectors of plastic scintillator BC408. The liquid scintillator BC519 has a high hydrogen-to-carbon ratio of 1.7, which is useful to analyze the neutron polarization using the \(\vec{n} + p\) scattering in the scintillator. Each of the six neutron detectors has an effective detection area of approximately 1 m\(^2\) with a thickness of 0.1 m. Thin plastic scintillation detectors are placed in front of each neutron detector in order to distinguish charged particles from neutrons.

The incident neutron energies were determined from the TOF between the target and a given neutron detector. Flight times are measured relative to the cyclotron rf signal. Prominent \(\gamma\)-rays from \(\pi^0\) -decays and prompt de-excitation of inelastically excited states in the target provide a time reference for the absolute timing calibration. Then the transitions to discrete states with known reaction \(Q\) values were used to determine the incident beam energy. The beam energy was thus determined to be \(T_p = 345 \pm 1\, \text{MeV}\). The total full width at half maximum energy resolutions are about 2 and 3 MeV for the cross section and polarization observable measurements, respectively.
DATA REDUCTION

The spin-longitudinal $I_{D_q}$ and spin-transverse $I_{D_p}$ polarized cross sections are related to the unpolarized cross section $I$ and the laboratory-frame polarization transfer coefficients $D_{ij}$ according to [16]

$$I_{D_q} = \frac{I}{4} [1 - D_{NN} + (D_{S'S} - D_{L'L}) \cos \alpha_2 - (D_{L'S} + D_{S'L}) \sin \alpha_2],$$

$$I_{D_p} = \frac{I}{4} [1 - D_{NN} - (D_{S'S} - D_{L'L}) \cos \alpha_2 + (D_{L'S} + D_{S'L}) \sin \alpha_2],$$

where $\alpha_2 \equiv 2 \theta_p - \theta_{lab} - \Omega$. The angle $\theta_p$ represents the angle between the incident beam direction and the transverse direction $\hat{p}$, and the relativistic spin rotation angle $\Omega$ is given by [15]

$$\tan(\theta_{cm} - \theta_{lab} - \Omega) = \frac{\sin \theta_{cm}}{\gamma (\cos \theta_{cm} + \beta / \beta_{cm})},$$

where $\beta_{cm}$ is the velocity of the center-of-mass (cm) frame relative to that of the laboratory frame, $\beta$ is the velocity of the outgoing nucleon in the cm frame, and $\gamma \equiv 1/\sqrt{1 - \beta^2}$.

RESULTS AND DISCUSSIONS

In Fig. 1 the experimental polarized cross sections $I_{D_q}$ and $I_{D_p}$ for $^{12}$C are compared with DWIA+RPA calculations. The RPA calculations are performed without the commonly used universality ansatz ($g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta}$), namely all of the $g'$s are treated independently [17]. The nonlocality of the mean field is treated by an effective mass $m^*$ with radial dependence of

$$m^*(r) = m_N - \frac{f_{WS}(r)}{f_{WS}(0)} [m_N - m^*(0)],$$

where $f_{WS}$ is the Woods-Saxon radial form factor. The formalism of DWIA calculations is described in Ref. [3].

The dashed curves are the results of DWIA calculations with the RPA response functions employing ($g'_{NN}$, $g'_{N\Delta}$, $g'_{\Delta\Delta}$) = (0.6, 0.4, 0.5) and $m^*(0) = 0.7m_N$. The dotted curves are the DWIA results with the free response functions employing $m^*(0) = m_N$. The calculations reasonably reproduce the observed $I_{D_q}$ at the larger angles of $22^\circ$ and $27^\circ$. This result is consistent with the predicted enhancement of $R_L$ in this momentum-transfer region. It should be noted that the present calculations prefer the smaller $g'_{N\Delta}$ ($\sim 0.4$) compared with $g'_{NN}$ ($\sim 0.6$) and the smaller effective mass at the center ($m^* \sim 0.7m_N$). The calculation at $16^\circ$ is slightly larger than the observed data. This might mean that the effective interaction in this momentum-transfer region is not so attractive as is expected in the $\pi + \rho + g'$ model.

In the spin-transverse mode, the calculations underestimate $I_{D_p}$ in the quasielastic region by a factor of approximately 2 at all three angles. The RPA correlation quenches
**FIGURE 1.** The spin-longitudinal $ID_q$ (left panels) and spin-transverse $ID_p$ (right panels) polarized cross sections for the $^{12}\text{C}(p,n)$ reaction at $T_p = 345$ MeV and $\theta_{\text{lab}} = 16^\circ$, $22^\circ$, and $27^\circ$. The dotted and dashed curves represent the results of DWIA calculations with RPA and free response functions, respectively. The dotted-dashed curve are the two-step cross sections. The solid curves are the sum of one- and two-step contributions employing RPA correlations.

$ID_p$ as is predicted, while the experimental results are significantly enhanced. Recently, Nakaoka and Ichimura [18] have pointed out that the two-step contribution for $ID_p$ would be significantly larger than that for $ID_q$ in the present momentum-transfer region. They showed that the 1st- and 2nd-step contributions for $ID_q$ are partly destructive, while those for $ID_p$ are wholly constructive. As a result, the two-step contribution for $ID_p$ is more important than that for $ID_q$. 

The dotted-dashed curves in Fig. 1 are the two-step cross sections calculated by Nakaoka [19]. The solid curves are the sum of one- and two-step contributions employing RPA correlations. Relatively small two-step contributions for $ID_q$ at large angles of $22^\circ$ and $27^\circ$ do not affect the agreement between the experimental and theoretical results. On the contrary, the two-step contribution at $16^\circ$ is fairly large, and the inclusion of this overestimates the experimental $ID_q$ at large energy transfers.

In the spin-transverse mode, at all three angles, two-step contributions relative to one-step ones are significantly large compared with those for $ID_q$. Two-step contributions account for the underestimation of $ID_p$ in DWIA+RPA calculations at large energy transfers beyond the quasielastic peak. However they are insufficient to explain the underestimation of $ID_p$ around the quasielastic peak. This discrepancy in $ID_p$ might be due to the effects of the higher order (such as $2p2h$) configuration mixing which are not included in the present RPA calculations.

ACKNOWLEDGMENTS

We are grateful to K. Nishida and A. Itabashi for their helpful correspondence. This work is supported in part by the Grants-in-Aid for Scientific Research Nos. 6342007, 12740151, and 14702005 of the Ministry of Education, Science, Sports and Culture of Japan.

REFERENCES