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Isovector effective NN interaction in $^{28}\mathrm{Si}(\vec{p},\vec{n})\,^{28}\mathrm{P}(6^-)$ at 198 MeV

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Abstract

We report measurements of the cross section and a complete set of polarization observables for the $^{28}\mathrm{Si}(\vec{p},\vec{n})\,^{28}\mathrm{P}(6^-)$ reaction at a bombarding energy of 198 MeV. The data are compared with distorted wave impulse approximation calculations employing response functions normalized to inelastic electron scattering. The spin-longitudinal polarized cross section ID_q is slightly over-predicted by the calculations, while the normal spin-transverse polarized cross section ID_n is significantly under-predicted. The calculated in-plane spin-transverse ID_p and spin-scalar ID_0 polarized cross sections agree well with the experimental data. These results are consistent with those for $^{28}\mathrm{Si}(\vec{p},\vec{p}')\,^{28}\mathrm{Si}(6^-, T=1)$ scattering at the same energy, and thus it is concluded that isospin-mixing effects are not responsible for the discrepancy between theory and experiment in the $(\vec{p},\vec{p}')$ case. Energy half-off-shell effects as medium effects on the effective nucleon–nucleon interaction are also investigated and found to be too small to be responsible for the discrepancy.

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Keywords: Isovector effective interaction; Stretched 6^- state; Polarization transfer measurement

Nuclear medium effects on the effective nucleon–nucleon (NN) interaction in nuclei are of considerable interest in nuclear physics. The effective NN interaction can be substantially altered from the NN interaction in free space because the nuclear field can modify the properties of mesons exchanged between nucleons. The reduction of hadron mass and coupling constant with nuclear density has been discussed by many authors [1–3] as a signature of partial restoration of chiral symmetry in nuclear matter. Horowitz and Iqbal [4] have also studied modification of the nucleon spinor in nuclear matter in the framework of a Dirac approach. Clear evidence for these medium effects is the systematic reduction of the analyzing power for the exclusive $(\vec{p},2p)$ reactions as a function of averaged nuclear density [5]. This reduction can be explained in part as being due to the reduction of nucleon mass in the strong scalar part of the relativistic nuclear potential [6]. Other factors in the reduction can be resolved by considering modifications of meson mass and coupling constant in nuclei [7].

Polarization transfer measurements of nucleon inelastic scattering and nucleon charge-exchange reactions provide a way to investigate the effective NN interaction in nuclei [8,9]. If the transition form factor is known, comparisons between experimental data and distorted-wave impulse approximation (DWIA) calculations enable us to assess the absolute size of NN amplitudes in nuclei. Stephenson et al. [10] have reported comparisons between experimental and theoretical results for

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$^{28}\text{Si}(\vec{p},\vec{p}')\,^{28}\text{Si}(6^-, T=1)$ at $T_p = 198$ MeV, where the transition form factor is adjusted to reproduce the transverse electron scattering data [11]. For the spin-dependent interaction in nuclei, Stephenson et al. claim that the spin-longitudinal component is reduced by a factor of two whereas the normal spin-transverse component is significantly enhanced. These modifications can be accounted for in part by using a reduced medium-modified ρ-meson mass in nuclei. If the NN amplitude is modified in nuclei, the interpretations of some experimental data including quasielastic $(\vec{p},\vec{n})$ reactions [12–14] would need to be revised. However, isospin-mixing effects can also explain the modifications in part [15,16]. Thus it is very important to determine whether the observed differences are due to medium modifications of NN amplitudes in nuclei.

In this Letter, we present measurements of the cross section and a complete set of polarization observables for the excitation of the 6^-, $T=1$ state at $E_x = 4.94$ MeV in ^{28}P using the $(\vec{p},\vec{n})$ reaction at $T_p = 198$ MeV. We compare a pure isovector $(\vec{p},\vec{n})$ result with a previous $(\vec{p},\vec{p}')$ result [10,16] in order to assess isospin mixing effects on the (p,p') data. We also compare our results with DWIA calculations using the effective NN interaction based on the free NN interaction. A comparison between experimental and theoretical results reveals significant enhancement and possible quenching of the normal spin-transverse ID_n and spin-longitudinal ID_q polarized cross sections, respectively. We also compare the data with DWIA calculations employing the NN interaction based on the CD-Bonn potential [17] in order to assess energy half-off-shell effects quantitatively.

The measurements were carried out using the neutron time-of-flight (NTOF) system [18] and the neutron detector and polarimeter NPOL3 system [19] at the Research Center for Nuclear Physics, Osaka University. The NTOF system consists of a beam-swinger dipole magnet, a neutron spin-rotation (NSR) magnet, and a 100-m tunnel. The beam polarization was continuously monitored using two $\vec{p}+p$ scattering polarimeters. The typical magnitude was found to be about 0.65. The beam energy was determined to be 198 ± 1 MeV from the kinematic energy shift between two peaks from $^7\text{Li}(p,n)\,^7\text{Be(g.s.)}$ and $^{12}\text{C}(p,n)\,^{12}\text{N(g.s.)}$. The beam was incident on a self-supporting $^{\text{nat}}$Si (92.2% ^{28}Si) target in the beam-swinger magnet of thickness 123 mg/cm^2. Neutrons from the target passed through the NSR magnet and were measured by the NPOL3 system in the 100-m TOF tunnel with a resolution of about 480 keV FWHM. The neutron detection efficiency of NPOL3 was determined using $^7\text{Li}(p,n)\,^7\text{Be(g.s.} + 0.43\text{ MeV)}$ at 0° whose cross section is known for $T_p = 80$–795 MeV [20]. The uncertainty was estimated to be about 6%. The neutron polarimetry of NPOL3 was calibrated using $^{12}\text{C}(\vec{p},\vec{n})\,^{12}\text{N(g.s.)}$ at 0° to an accuracy of about 6%.

Fig. 1 shows the excitation energy spectrum of $^{28}\text{Si}(p,n)\,^{28}\text{P}$ at momentum transfer $q_{\text{c.m.}} = 1.8\text{ fm}^{-1}$. The stretched 6^- state at $E_x = 4.94$ MeV forms a pronounced peak, though it is not clearly resolved from the neighboring states. Therefore, we performed peak fitting for $E_x = 3$–6 MeV to extract the yield of the 6^- state. Seven states including the 6^- state were considered in the peak fitting, listed in Table 1. The positions, apart from that of the peak at $E_x = 5.82$ MeV, were taken from Ref. [21]. The peak at $E_x = 5.82$ MeV might correspond to

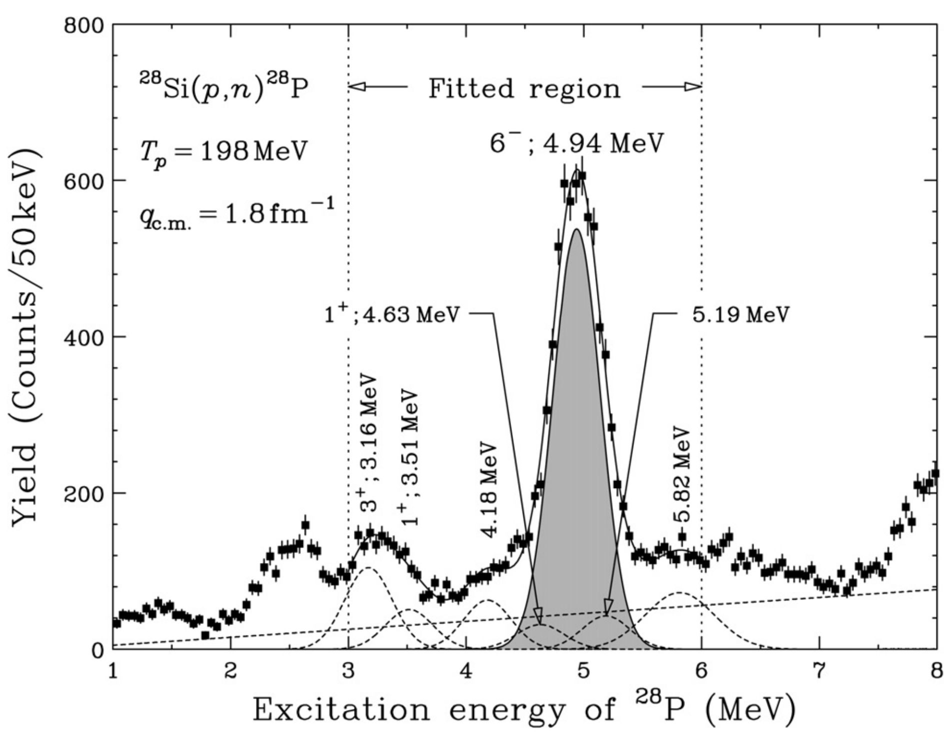

Fig. 1. Excitation energy spectrum for $^{28}\text{Si}(p,n)\,^{28}\text{P}$ at $T_p = 198$ MeV and $q_{\text{c.m.}} = 1.8\text{ fm}^{-1}$. The curves show the reproduction of the spectrum with Gaussian peaks and a continuum.

Table 1
^{28}P levels used in the peak fitting to extract the 6^- state

E_x (MeV)	J^π
3.164	3^+
3.512	1^+
4.180	
4.630	1^+
4.940	6^-
5.190	
5.820	

the peak at $E_x = 5.90$ MeV in Ref. [21]; however, we used a value of 5.82 MeV to improve the quality of the peak fitting. The dashed curves in Fig. 1 represent the fits to the individual peaks, while the straight dashed line and solid curve represent the background and the sum of the peak fitting, respectively. The peak fittings at all momentum transfers were satisfactory for extracting the 6^- yield.

Fig. 2 shows the cross section for $^{28}\mathrm{Si}(p,n)^{28}\mathrm{P}(6^-)$ at $T_p = 198$ MeV. The momentum-transfer dependence was measured in the range $q_{\mathrm{c.m.}} = 1.0$–$2.4\ \mathrm{fm}^{-1}$, covering the maximum at $q_{\mathrm{c.m.}} \simeq 1.5\ \mathrm{fm}^{-1}$. The data at $T_p = 200$ MeV [22] are also displayed as open circles. Both data are consistent with each other taking into account the systematic uncertainties.

We performed DWIA calculations using the computer code DW81 [23], which treats the knock-on exchange amplitude exactly. The one-particle one-hole configuration for $^{28}\mathrm{P}(6^-)$ was assumed to be a pure stretched combination of a $1f_{7/2}$ proton–particle and a $1d_{5/2}^{-1}$ neutron–hole. The single-particle wave functions were generated by a Woods–Saxon potential with $r_0 = 1.27$ fm, $a_0 = 0.67$ fm, and $\lambda = 25.0$ [24], the depth of which was adjusted to reproduce the separation energies of the $1d_{5/2}$ orbitals. The unbound single-particle $1f_{7/2}$ state was assumed to have a very small binding energy of 0.01 MeV to simplify the calculations. In the calculations, we used a spectroscopic factor of 0.33 [25], which was determined to reproduce the transverse electron scattering data of Yen et al. [11]. The NN t-matrix parameterized by Franey and Love [26] at 210 MeV was used. The distorted waves were generated using the optical model parameter (OMP) used in previous DWIA analysis for the $(\vec{p},\vec{p}\,')$ data [10]. This OMP reproduces the proton elastic scattering for ^{28}Si at the same energy. The solid curve in Fig. 2 denotes the DWIA result. The result underestimates at the small momentum-transfer region and overestimates at the large momentum-transfer region. Willis et al. [27] claim that the DWIA result is sensitive to the choice of the OMP. Therefore, we performed DWIA calculations using four other OMPs at the same energy [28–31]. The OMP dependence is shown by the band in Fig. 2. By considering the uncertainties of both the experimental and theoretical results, we conclude that there is no significant discrepancy between the experimental and theoretical results for the cross section.

Fig. 3 shows four polarized cross sections as a function of momentum transfer. The open circles are the $(\vec{p},\vec{p}\,')$ results of Stephenson et al. [10,16]. These data are multipled by a factor of two to take into account the difference of the isospin Clebsch–Gordan (CG) coefficients for (p,n) and (p,p'). The

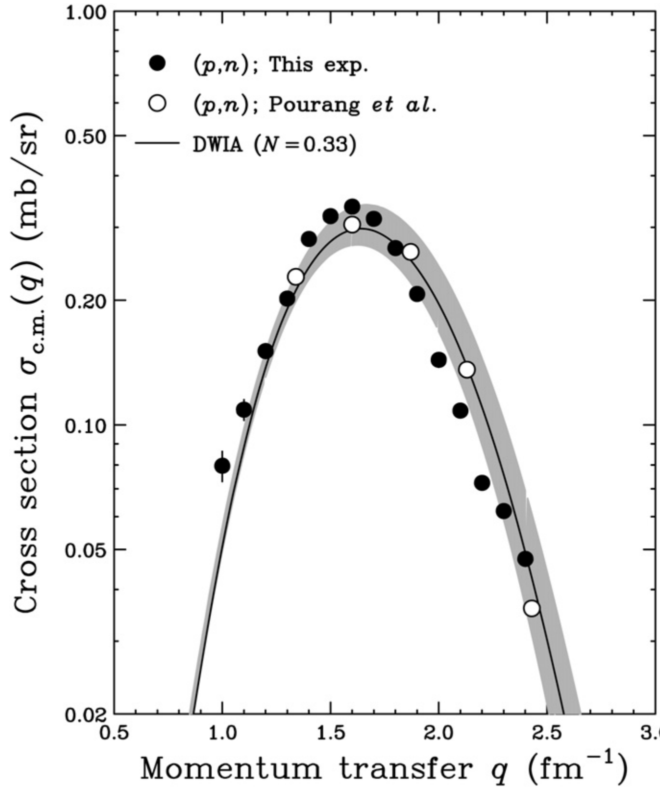

Fig. 2. Measured cross section for $^{28}\mathrm{Si}(p,n)^{28}\mathrm{P}(6^-)$ at $T_p = 198$ MeV (closed circles). The solid curve shows the theoretical prediction using the OMP in Ref. [10]. The band represents the OMP dependence, as explained in the text. The open circles are data taken from Ref. [22].

$(\vec{p},\vec{n})$ and $(\vec{p},\vec{p}\,')$ results are in good agreement with each other within uncertainties. Thus we can exclude the possibility of isospin mixing effects [15] which might be responsible for the discrepancy between experimental and theoretical results observed in the $(\vec{p},\vec{p}\,')$ case.

The solid curves in Fig. 3 denote the DWIA calculations with the same parameters for the cross section, and the bands represent the OMP dependence of the calculations. The calculations are very similar to those for the $(\vec{p},\vec{p}\,')$ case taking into account the isospin CG coefficients. The results in Fig. 3 show significant differences between the data and the calculations based on the free NN t-matrix. The spin-longitudinal ID_q is slightly over-predicted while the normal spin-transverse ID_n is significantly under-predicted. The in-plane spin-transverse ID_p is reasonably well reproduced. The spin-scalar ID_0, which is significantly smaller than other three polarized cross sections, is fairly well predicted. These conclusions quantitatively coincide with those for $^{28}\mathrm{Si}(\vec{p},\vec{p}\,')^{28}\mathrm{Si}(6^-, T=1)$ at the same energy [10,16] and for $^{28}\mathrm{Si}(\vec{p},\vec{n})^{28}\mathrm{P}(6^-)$ at $T_p = 295$ MeV [32].

The differences observed in Fig. 3 are likely to be due to medium modifications of the effective NN interaction because the nuclear responses are constrained by inelastic electron scattering. In a Kerman–MacManus–Thaler (KMT) representation [33], the over-prediction for ID_q indicates reduction of the spin-longitudinal amplitude E, whereas the under-prediction for ID_n indicates an increase of the normal spin-transverse amplitude B. These modifications might have implications for

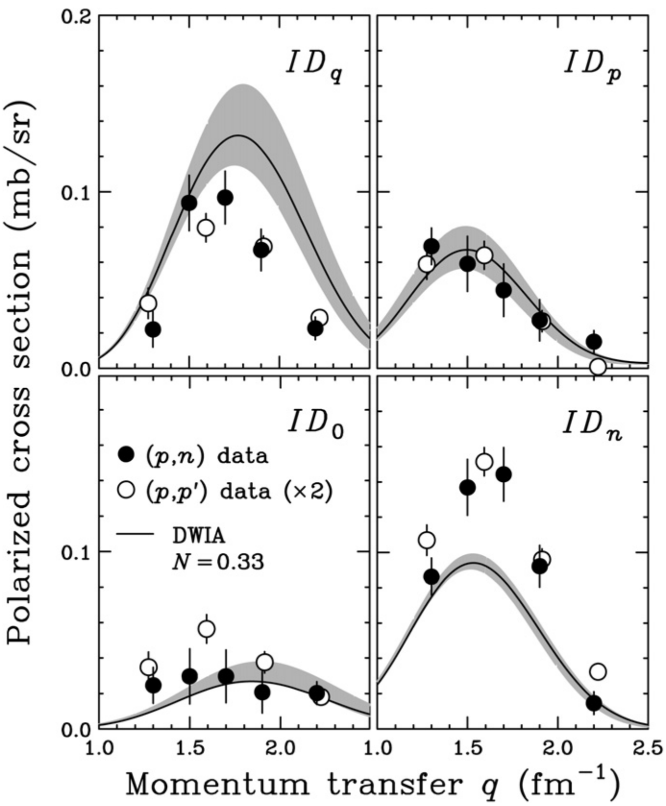

Fig. 3. Measured polarized cross sections for ^{28}Si$(p,n)^{28}$P(6^-) at $T_p = 198$ MeV (closed circles). The solid curves are DWIA calculations with the free t-matrix parameterized at 210 MeV. The band represents the OMP dependence of the DWIA calculations. The open circles are (p,p') results [10, 16], multiplied by a factor of two, as explained in the text.

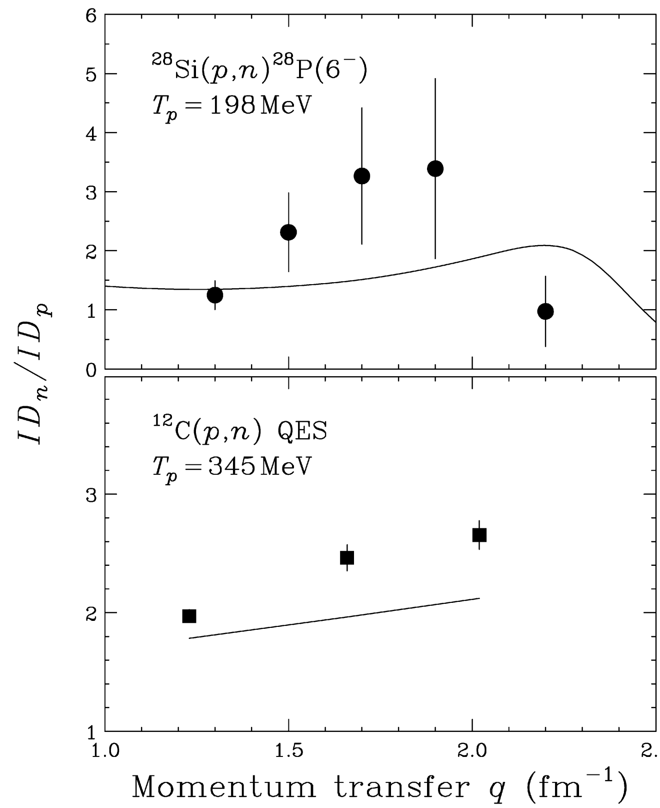

Fig. 4. Ratios of ID_n/ID_p for ^{28}Si$(\vec{p},\vec{n})^{28}$P(6^-) at $T_p = 198$ MeV (upper panel) and quasielastic ^{12}C$(\vec{p},\vec{n})$ at $T_p = 345$ MeV (lower panel). The solid curves are DWIA calculations with the free NN interaction, as described in the text.

the interpretation of $(\vec{p},\vec{n})$ quasielastic scattering (QES) data at 494 MeV [12] and at 345 MeV [13,14]. If we take into account the reduction of E, the enhancement of ID_q in QES, which is relevant to pionic correlations and enhancement in nuclei, becomes larger than the prediction using Landau–Migdal (LM) parameters $g'_{NN} = 0.7$ and $g'_{N\Delta} = 0.3$ [34]. This difference can be corrected by using smaller LM parameters, $g'_{NN} \simeq 0.6$ and $g'_{N\Delta} \simeq 0.2$ [35]. For both spin-transverse polarized cross sections ID_p and ID_n, theoretically unexpected enhancement has been observed in QES. The enhancement of the normal spin-transverse amplitude B might be responsible for the enhancement of the corresponding spin-transverse cross section ID_n. However, since no modification of the spin-transverse amplitude F is observed, the enhancement of the in-plane spin-transverse ID_p cannot be explained by modifications of the NN interaction. We note that the enhancement of ID_n in QES is substantially larger than that of ID_p. Since the spin-transverse response is common for both ID_n and ID_p, the ratio ID_n/ID_p is predominantly sensitive to the ratio B^2/F^2. The upper panel of Fig. 4 shows the ratio ID_n/ID_p for ^{28}Si$(\vec{p},\vec{n})^{28}$P(6^-), where both the experimental and theoretical data are the same as those in Fig. 3. The lower panel shows the same ratio for ^{12}C$(\vec{p},\vec{n})$ QES at 345 MeV [14], with the calculation data taken from Ref. [34]. In both cases, significant enhancement is observed at $q \simeq 1.8$ fm^{-1}. Thus the enhancement of B seems to be common at large momentum transfers, and this enhancement is responsible in part for the enhancement of ID_n in QES.

Modifications of the effective NN interaction have been discussed [16,36,37] in connection with nuclear binding, Pauli blocking, and relativistic mean field effects. Sammarruca et al. [16] performed calculations including these conventional medium effects systematically, and they found that the effects are too small to explain the $(\vec{p},\vec{p}')$ results. Another preliminary attempt to explain the results has been made by Stephenson et al. [10] in terms of scaling of the ρ-meson mass in nuclei. They employed density-independent DWIA calculations under the assumption that any effect would correspond to some average density for the transition. The reduction of the mass has the effects of reducing the spin-longitudinal amplitude E, and increasing the spin–orbit amplitude C. Both effects explain the observed modifications qualitatively; however, the changes suggested by the data do not correspond to the same reduced ρ-meson mass for each amplitude. Furthermore, later comprehensive density-dependent DWIA calculations [16] show that the effect is too small to account for the discrepancies. Since the transition probability to the stretched 6^- state peaks near the nuclear surface with low nuclear density, the effect of the partial restoration of chiral symmetry including the ρ-meson mass reduction would be masked due to its density dependence. Thus, in the following, we discuss another mechanism, energy half-off-shell effects, which might be re-

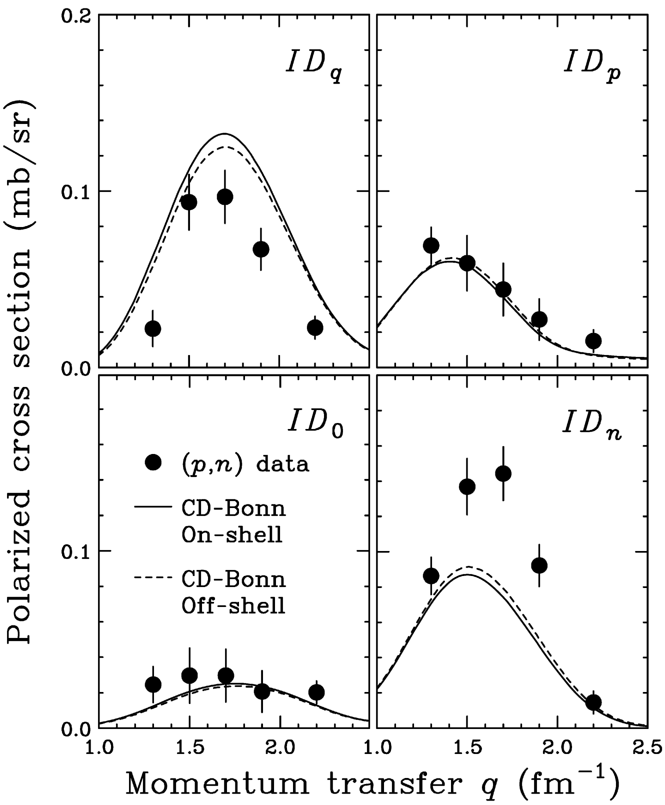

Fig. 5. Energy half-off-shell effects in DWIA calculations. The solid and dashed curves represent DWIA results with on-shell and half-off-shell ($Q = -20.6$ MeV) t-matrices, respectively. The experimental data are the same as in Fig. 3.

sponsible for the observed difference between experiment and theory.

Energy half-off-shell effects are expected to be significant in $^{28}\mathrm{Si}(\vec{p},\vec{n})\,^{28}\mathrm{P}(6^-)$ because the reaction Q value of -20.6 MeV is large. We investigated these effects on ID_i by using the computer code CRDW [38]. We deduced both energy on-shell and half-off-shell NN t-matrices from the CD-Bonn potential [17]. The OMP and single-particle wave functions used were the same as those used in the previous calculations. The solid and dashed curves in Fig. 5 show the DWIA results for energy on-shell and half-off-shell NN t-matrices, respectively. Energy half-off-shell effects are seen in ID_q and ID_n, and they partly explain the discrepancies observed in ID_i. However, these effects are too small to reproduce the experimental data. Here, for simplicity, the energy difference between initial and final states in the half-off-shell t-matrix has been chosen to be the same as the reaction Q value. Therefore further detailed and comprehensive theoretical studies without this assumption would be helpful to explain the discrepancy.

In conclusion, we have made high-resolution measurements of $^{28}\mathrm{Si}(\vec{p},\vec{n})\,^{28}\mathrm{P}$, which have enabled us to investigate the effective NN interaction on the stretched 6^- excitation where the spin-transverse response function is known from inelastic electron scattering. The data are consistent with those for $^{28}\mathrm{Si}(\vec{p},\vec{p}')\,^{28}\mathrm{Si}(6^-, T = 1)$ at the same energy taking into account the isospin CG coefficients. Thus we conclude that isospin-mixing effects are not responsible for the discrepancy between experimental and theoretical results observed for $(\vec{p},\vec{p}')$. Small quenching and significant enhancement are observed for spin-longitudinal ID_q and normal spin-transverse ID_n polarized cross sections, respectively. The significant enhancement in ID_n indicates enhancement of the normal spin-transverse amplitude B in the KMT representation. This enhancement is likely to be partly responsible for the enhancement of ID_n in QES at similar momentum transfers. We investigated energy half-off-shell effects by using the CD-Bonn potential. These effects alter the calculated values of ID_q and ID_n to make them closer in value to the experimental data, but are too small to fully reproduce the experimental data. More comprehensive and detailed theoretical analyses are needed to explain medium modifications of the effective NN interaction inside nuclei.

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References

[1] G.E. Brown, M. Rho, Phys. Rev. Lett. 66 (1991) 2720.
[2] R.J. Furnstahl, D.K. Griegel, T.D. Cohen, Phys. Rev. C 46 (1992) 1507.
[3] T. Hatsuda, Nucl. Phys. A 544 (1992) 27c.
[4] C.J. Horowitz, M.J. Iqbal, Phys. Rev. C 33 (1986) 2059.
[5] K. Hatanaka, et al., Phys. Rev. Lett. 78 (1997) 1014.
[6] T. Noro, et al., Nucl. Phys. A 629 (1998) 324c.
[7] T. Noro, et al., Nucl. Phys. A 663–664 (2000) 517c.
[8] J.M. Moss, Phys. Rev. C 26 (1982) 727.
[9] E. Bleszynski, M. Bleszynski, C.A. Whitten Jr., Phys. Rev. C 26 (1982) 2063.
[10] E.J. Stephenson, et al., Phys. Rev. Lett. 78 (1997) 1636.
[11] S. Yen, et al., Phys. Lett. B 289 (1992) 22.
[12] T.N. Taddeucci, et al., Phys. Rev. Lett. 73 (1994) 3516.
[13] T. Wakasa, et al., Phys. Rev. C 59 (1999) 3177.
[14] T. Wakasa, et al., Phys. Rev. C 69 (2004) 054609.
[15] E.J. Stephenson, F. Sammarruca, in: H. Sakai, H. Okamura, T. Wakasa (Eds.), Proceedings of the International Symposium on New Facet of Spin Giant Resonances in Nuclei, World Scientific, Singapore, 1998, p. 369.
[16] F. Sammarruca, et al., Phys. Rev. C 61 (1999) 014309.
[17] R. Machleidt, F. Sammarruca, Y. Song, Phys. Rev. C 53 (1996) R1483.
[18] H. Sakai, et al., Nucl. Instrum. Methods A Phys. Res. 369 (1996) 120.
[19] T. Wakasa, et al., Nucl. Instrum. Methods A Phys. Res. 547 (2005) 569.
[20] T.N. Taddeucci, et al., Phys. Rev. C 41 (1990) 2548.
[21] http://www.nndc.bnl.gov/nudat2.
[22] R. Pourang, et al., Phys. Rev. C 44 (1991) 689.
[23] R. Schaeffer, J. Raynal, Program dw70, unpublished;
J. Raynal, Nucl. Phys. A 97 (1967) 572;
J.R. Comfort, Extended version dw81, unpublished.
[24] A. Bohr, B.R. Mottelson, Nuclear Structure, vol. I: Single-Particle Motion, Benjamin, New York, 1969.
[25] B.L. Clausen, R.J. Peterson, R.A. Lindgren, Phys. Rev. C 38 (1988) 589, http://galileo.phys.virginia.edu/research/groups/stretch_state/.
[26] M.A. Franey, W.G. Love, Phys. Rev. C 31 (1985) 488.
[27] A. Willis, et al., Phys. Rev. C 43 (1991) 2177.
[28] C. Olmer, et al., Phys. Rev. C 29 (1984) 361.
[29] R. Sawafta, PhD thesis, University of Alberta, 1987.

[30] O. Häusser, et al., Phys. Rev. C 37 (1988) 1119.
[31] G.M. Crawley, et al., Phys. Rev. C 39 (1989) 311.
[32] K. Yako, et al., in: T. Noro, H. Sakaguchi, H. Sakai, T. Wakasa (Eds.), Proceedings of the RCNP International Symposium on Nuclear Reactions and Medium Effects, University Academy Press, Tokyo, 1999, p. 135.
[33] A.K. Kerman, H. McManus, R.M. Thaler, Ann. Phys. 8 (1969) 551.
[34] T. Wakasa, M. Ichimura, H. Sakai, Phys. Rev. C 72 (2005) 067303.
[35] M. Ichimura, H. Sakai, T. Wakasa, Prog. Part. Nucl. Phys. 56 (2006) 446.
[36] F. Sammarruca, E.J. Stephenson, K. Jiang, Phys. Rev. C 60 (1999) 064610.
[37] F. Sammarruca, X. Meng, E.J. Stephenson, Phys. Rev. C 62 (2000) 014614.
[38] K. Kawahigashi, et al., Phys. Rev. C 63 (2001) 044609.