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Spin-flip strength in the continuum and effective tensor interactions via polarization transfer $D_{NN}(0°)$ for $(\vec{p},\vec{n})$ reactions at 295 MeV

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The first measurements of $D_{NN}(0°)$ for $(\vec{p},\vec{n})$ reactions at 295 MeV yield large negative values up to 50 MeV excitation for the ^{6}Li, ^{11}B, ^{12}C, ^{13}C$(\vec{p},\vec{n})$ reactions, suggesting much stronger spin-flip strength than observed at lower bombarding energies. DWIA calculations using the Franey and Love (FL) 270 MeV interaction reproduce differential cross sections and $D_{NN}(0°)$ values, while the FL 325 MeV interaction yield $D_{NN}(0°)$ values less negative than the experimental values, suggesting that its exchange tensor part is too strong at large momentum transfer ($Q\simeq 3.4$ fm^{-1}).

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Recent nucleon-nucleus experiments at intermediate energies, mostly at and below 200 MeV, and related theoretical studies have provided new information on the effective nucleon-nucleon (NN) interaction. Using a newly developed neutron polarimeter (NPOL) [1], polarization transfer coefficients $D_{NN}(0°)$ have been measured for $(\vec{p},\vec{n})$ reactions on several targets at 295 MeV. The increased energy of the present measurement more than doubles the range of energies (previously 120–200 MeV) over which the majority of $D_{NN}(0°)$ values have been measured. As such, these measurements are important for improving our understanding of the charge-exchange continuum as well as for testing the associated isovector part of the NN interaction. A comparison with similar measurements at and below 200 MeV at IUCF [2] suggest an increasing sensitivity to spin excitations with increasing bombarding energy. In addition to the intrinsic energy dependence of the NN force, the way in which it is modified in the nuclear medium is believed to change significantly between 200 and 295 MeV [3]. $D_{NN}(0°)$ values provide a useful tool for assessing the importance of the tensor interaction at large momentum transfer. The isovector central interactions (V_τ, $V_{\sigma\tau}$) have been investigated extensively by comparing their volume integrals with the relevant zero degrees differential cross section. The tensor interactions have mainly been studied by using the high spin stretched states, however, measurement of $D_{NN}(0°)$ values is a complementary tool for studying the exchange tensor interaction as may be seen by the following considerations.

In the plane-wave impulse approximation (PWIA), a nucleon-nucleus scattering amplitude is described as a product of the nuclear transition density and the NN scattering amplitude which may either be represented as [4]:

$$M(q)=A+B\sigma_{1n}\sigma_{2n}+C(\sigma_{1n}+\sigma_{2n})+E\sigma_{1q}\sigma_{2q}+F\sigma_{1Q}\sigma_{2Q}\ , \qquad (1)$$

or alternatively as a sum of central, spin-orbit, and tensor terms

$$M(q)=A+\tfrac{1}{3}(B+E+F)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2+C(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\hat{\boldsymbol{n}}+\tfrac{1}{3}(E-B)S_{12}(\hat{q})+\tfrac{1}{3}(F-B)S_{12}(\hat{\boldsymbol{Q}}), \qquad (2)$$

where S_{12} is the usual tensor operator [5] and

$$\hat{q}=\frac{\boldsymbol{k}_f-\boldsymbol{k}_i}{|\boldsymbol{k}_f-\boldsymbol{k}_i|}\ ,\quad \hat{\boldsymbol{Q}}=\frac{\boldsymbol{k}_i+\boldsymbol{k}_f}{|\boldsymbol{k}_i+\boldsymbol{k}_f|}\ \text{and}\ \hat{\boldsymbol{n}}=\hat{\boldsymbol{Q}}\times\hat{q}\ .$$

If a single ΔL transfer is dominant, the $D_{NN}(0°)$ value for the Gamow-Teller (GT) transition is given by [6]

$$D_{NN}(0°)=\frac{-F^2}{F^2+2B^2}\ . \qquad (3)$$

If there is no exchange tensor $S_{12}(\hat{\boldsymbol{Q}})$ interaction ($F=B$), then $D_{NN}(0°)=-1/3$.

Extensive measurements of $D_{NN}(0°)$ values for bombarding energies at and below 200 MeV on various targets [7] yield $D_{NN}(0°)$ values for the GT transitions consistent with $-1/3$, which clearly suggests the dominance of the central interaction in this energy range. At higher energies, PWIA calculations predict deviations from $-1/3$ due to the tensor interaction. In particular, at zero degrees when Q is large (~ 3 fm^{-1}), the exchange tensor interaction is important. Therefore, in addition to providing a pivotal role in explaining the spin composition of the charge-exchange continuum, measurements of $D_{NN}(0°)$ should provide a window on the exchange tensor interaction at large momentum transfer.

$D_{NN}(0°)$ values at 295 MeV using NPOL were obtained for $(\vec{p},\vec{n})$ reactions on ^{6}Li, ^{7}Li, ^{11}B, ^{12}C, and ^{13}C at the neutron time-of-flight facility [8] of the Research Center for Nuclear Physics (RCNP), Osaka University. One of four beam pulses was selected yielding an effective separation between beam pulses of about 260 ns. The average beam

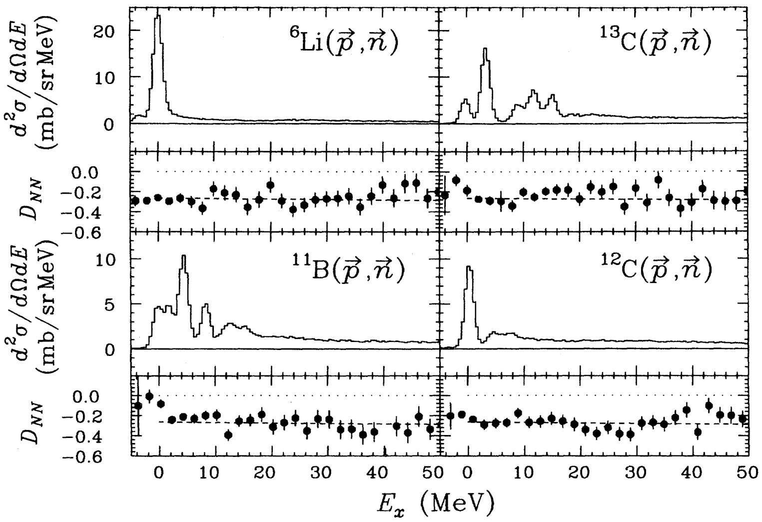

FIG. 1. The double differential cross sections and the polarization transfer coefficients $D_{NN}(0°)$ as a function of the excitation energy. The dashed lines represent the values of $D_{NN}(0°)$ for free NN scattering.

intensity was 2 nA with an average polarization of 73%. Targets with thicknesses ranging from 150 to 396 mg/cm^2 and from 155 to 703 mg/cm^2 were placed for the differential cross section measurement and the $D_{NN}(0°)$ measurement, respectively, in a beam-swinger dipole magnet. NPOL was positioned at a distance between 53 and 100 m for the differential cross sections, and at 100 m for the $D_{NN}(0°)$ measurements. Typical energy resolution was 1.7 MeV at 100 m.

The NPOL system consists of four planes of two-dimensional position-sensitive scintillation detectors, each with an effective detection area of approximately 1 m^2. The first two planes of liquid scintillation (BC519) detectors act as scatterers, and the two plastic scintillation (BC408) detectors downstream of the scatterer plane can serve as catchers of doubly scattered neutrons or recoiled protons. Thin plastic scintillation detectors placed in front of each detector serve to distinguish charged particles from neutrons. The neutron polarization can be determined via the ^{1}H($\vec{n}$,n)^{1}H and ^{1}H($\vec{n}$,p)n reactions. The $n+p$ events were discriminated kinematically from the $n+$C events by using time and position information.

The effective analyzing powers ($A_{y;\mathrm{eff}}$) of NPOL were calibrated by using polarized neutrons from the ^{2}H($\vec{p}$,$\vec{n}$)pp reaction at zero degrees. Its $D_{NN}(0°)$ value at 295 MeV was derived as -0.297 ± 0.004 from the previously measured $D_{LL}(0°)$ values [9–11]. The resulting $A_{y;\mathrm{eff}}$ are $0.290\pm0.012\pm0.009$ for the ($\vec{n}$,n) channel and $0.114\pm0.003\pm0.003$ for the ($\vec{n}$,p) channel, where the first and second uncertainties are statistical and systematic uncertainties, respectively. The total systematic uncertainties are mainly from uncertainties in the incident proton polarization and $D_{NN}(0°)$.

Figure 1 shows the double differential cross sections and the $D_{NN}(0°)$ values. The continuum region shows surprisingly large negative $D_{NN}(0°)$ values up to 50 MeV excitation indicative of strong spin-flip excitation not typically observed at lower bombarding energies [2]. The dashed lines in Fig. 1 correspond to the free NN values of $D_{NN}(0°)$ at the appropriate q, taken from the Arndt phase-shift solution [12], which are in good agreement with the $D_{NN}(0°)$ data over the entire range of E_x. The same features in the continuum are also observed for ($\vec{p}$,$\vec{n}$) reactions on ^{27}Al, ^{90}Zr, and ^{208}Pb at 295 MeV [13] and for ($\vec{p}$,$\vec{n}$) reactions on ^{40}Ca, ^{48}Ca, and ^{208}Pb at 135 MeV [14], indicating little target and energy dependence. It is interesting to note that the measurement of the spin-flip probabilities S_{NN} [$S_{NN}=(1-D_{NN})/2$] for inelastic proton scattering around 300 MeV from nuclei between ^{12}C and ^{90}Zr show the enhancement of the S_{NN} values near 40 MeV excitation at $q\sim100$ MeV/c compared with the free NN values of S_{NN} [15,16]. Further measurement of spin-transfer coefficients for (p,n) reactions at finite angles should also provide valuable information about the nuclear response which should be critical in the separation of $\Delta T=0$ and $\Delta T=1$ contributions.

The measured differential cross sections for transitions to the ground and some excited states of ^{6,7}Be, ^{11}C, and ^{12,13}N are shown in Fig. 2. We performed the full microscopic distorted-wave impulse approximation (DWIA) calculations by using the computer code DW81 which treats the knock-on exchange amplitude exactly [17]. The transition amplitudes were calculated from Cohen-Kurath wave functions (CKWF) [18] assuming harmonic oscillator radial dependence. We used the effective NN t-matrix interactions parametrized by Franey and Love (FL) at 270 MeV [19]. As discussed in detail below, since both DWIA calculations and associated $D_{NN}(0°)$ values were relatively insensitive to appropriate changes in the radial shape of the wave functions and choice of optical potentials, the wave functions with a harmonic oscillator (HO) radial dependence and optical potential parameters obtained from proton elastic scattering on ^{12}C at 318 MeV [20] were used for all targets studied.

The dashed curves in Fig. 2 are the DWIA calculations using CKWF. The solid curves in Fig. 2 are the calculations in which the GT $\Delta J^\pi=1^+$ components were normalized to give the experimentally determined B(GT) values [21–25]. The harmonic oscillator range parameters $b=2.15$, 1.73, 1.50, 1.87, and 1.82 fm were used for ^{6}Li [26], ^{7}Li [21], ^{11}B [27], ^{12}C [21], and ^{13}C [28], respectively. Both the original and normalized DWIA calculations are roughly comparable in their ability to reproduce the experimental

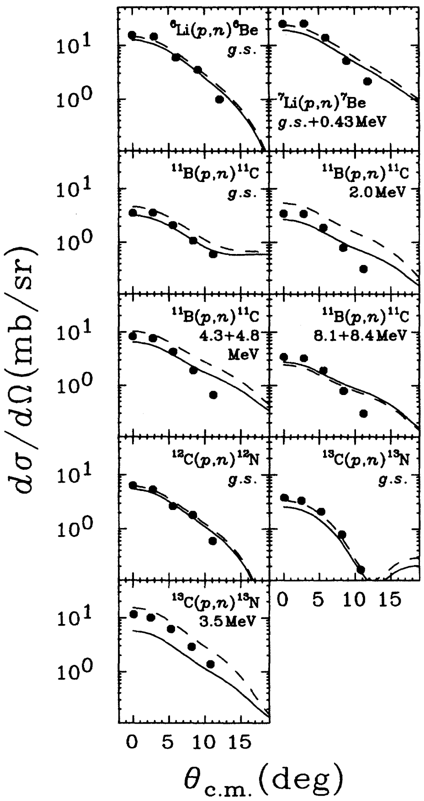

FIG. 2. Differential cross sections at 295 MeV. The curves are described in the text. The statistical uncertainties are smaller than the size of the data points.

data except for some excited states observed in the ^{11}B(p,n) and ^{13}C(p,n) reactions. It has been suggested that the discrepancy in the ^{13}C(p,n) case is particularly pronounced because its transition density has a dominant $p_{1/2}p_{1/2}^{-1}$ configuration which is sensitive to the $\Delta L=2$ part of the more general GT operator [29]. However, this interpretation is still controversial [30], and the final resolution of this as well as the discrepancy in the ^{11}B(p,n) case must await future studies.

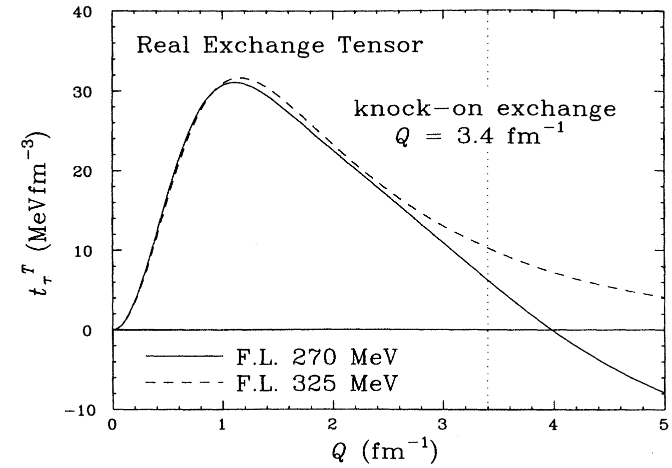

FIG. 3. The real parts of the isovector exchange tensor interactions as a function of momentum transfer. The dotted vertical line marks the exchange momentum transfer for the ^{6}Li$(p,n)^6$Be(g.s.) reaction at 295 MeV and 0°.

The measured $D_{NN}(0°)$ values obtained at 295 MeV along with previously measured values at 160 MeV [7,24] for low-lying excitations are listed in Table I where the uncertainties indicated at 295 MeV are statistical. The tabulated DWIA results are in fairly good agreement with the experimental values obtained for all transitions. The sensitivity of the DWIA calculations both to the wave functions and to the optical potential parameters was examined by using the ^{6}Li$(\vec{p},\vec{n})^6$Be(g.s.) and ^{12}C$(\vec{p},\vec{n})^{12}$N(g.s.) reactions which have isolated pure GT transition peaks.

The dependence of the DWIA calculations on the radial shape of the wave functions generated from Woods-Saxon (WS) potentials, the depths of which were adjusted to reproduce the binding energies, was studied. The $D_{NN}(0°)$ values calculated using the WS single-particle orbitals tend to be less negative by about 0.01 than those using the HO single-particle orbitals. The values of $D_{NN}(0°)$ using the optical potential parameters of Ref. [20] differed by less than 0.01 from those obtained using parameters which fit the elastic scattering on ^{12}C at 300 MeV by Meyer *et al.* [31]. Since there is no phenomenological optical potential for ^{6}Li at this

TABLE I. Polarization transfer coefficients $D_{NN}(0°)$ for (p,n) reactions. Data at 295 MeV are from this experiment. Data at 160 MeV are taken from Refs. [7] and [24]. The DWIA results are the calculations using CKWF.

Reaction	Transition	E_x (MeV)	$D_{NN}(0°)$ at 160 MeV Expt.	$D_{NN}(0°)$ at 295 MeV Expt.	DWIA
^{6}Li$(p,n)^6$Be	GT	0.0	−0.37±0.04	−0.28±0.01	−0.27
^{7}Li$(p,n)^7$Be	GT+F	0.0+0.43	−0.28±0.06	−0.28±0.05	−0.23
^{11}B$(p,n)^{11}$C	GT+F	0.0	−0.02±0.04	−0.03±0.04	−0.11
	GT	2.0	−0.26±0.06	−0.30±0.05	−0.27
	GT	4.3+4.8	−0.34±0.04	−0.21±0.03	−0.27
	GT	8.1+8.4	−0.34±0.06	−0.18±0.04	−0.26
^{12}C$(p,n)^{12}$N	GT	0.0	−0.24±0.03	−0.22±0.02	−0.26
^{13}C$(p,n)^{13}$N	GT+F	0.0	0.05±0.06	−0.13±0.04	−0.04
	GT	3.51	−0.33±0.05	−0.27±0.03	−0.28

energy in the literature, folded optical potential parameters were calculated using ground-state densities derived from the electron elastic scattering [32] and the effective *NN* interaction by Love and Franey [5]. The $D_{NN}(0°)$ value thus obtained differed from that using the optical potential of Ref. [20] by only 0.01, demonstrating the insensitivity of the DWIA calculations to different sets of optical potentials.

Because of the insensitivity and relative reliability for $D_{NN}(0°)$ of the ^{6}Li$(\vec{p},\vec{n})^6$Be(g.s.) reaction, this value was used as a standard for checking the effective interactions. Even though DWIA cross sections are insensitive to changes in the effective interaction, the calculated $D_{NN}(0°)$ values were -0.24 and -0.27 for the FL 325 and 270 MeV interactions, respectively, as compared with the experimental value of -0.28 ± 0.01. This difference is mainly due to the exchange tensor interaction with a relevant exchange momentum transfer of around 3.4 fm^{-1}. The isovector tensor interaction for this process is described as [5],

$$\tilde{V}_\tau^{\mathrm{TN}} = -\tfrac{1}{4}(V^{\mathrm{TNE}} + V^{\mathrm{TNO}}) \ , \tag{4}$$

where V^{TNE} and V^{TNO} are the tensor-even and tensor-odd interactions, respectively. Figure 3 shows the strength of the real part of the exchange tensor interactions of the FL 270 and 325 MeV as a function of the exchange momentum transfer (Q), the imaginary parts being small. As is clear from the figure, the tensor interaction of the FL 325 MeV interaction is about 50% larger than that of the FL 270 MeV interaction at $Q \simeq 3.4$ fm^{-1}.

In summary, the cross sections and the polarization transfer coefficients $D_{NN}(0°)$ for $(\vec{p},\vec{n})$ reactions in p-shell nuclei have been measured at 295 MeV. Large negative $D_{NN}(0°)$ values at high excitation suggest significant spin-flip strength in the continuum. DWIA calculations were performed using Cohen and Kurath wave functions and the *NN* t-matrix interaction parametrized by Franey and Love (FL) at 270 MeV. With the exception of some excited states in the ^{11}B and ^{13}C$(\vec{p},\vec{n})$ reactions, the calculated angular distributions of the differential cross sections are in very good agreement with the data. The DWIA calculations of $D_{NN}(0°)$ with the FL 270 MeV interaction reproduced the experimental values reasonably well, but those using the FL 325 MeV interaction for the ^{6}Li$(p,n)^6$Be(g.s.) reaction do not. The exchange tensor part of the parametrized FL 325 MeV interaction is too strong at large momentum transfer ($Q \simeq 3.4$ fm^{-1}), such that measurement of $D_{NN}(0°)$ values is an excellent tool for not only the study of spin-flip strength at high excitation but the tensor interactions at large momentum transfer as well. The sensitivity of $D_{NN}(0°)$ values, at the higher energies considered here, to the exchange tensor part of the *NN* interaction call for an updated version of the interaction given in Ref. [19] which incorporates the most recent properties of the *NN* data base.

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