# Measurement of the Transverse Spin-Transfer Coefficient $D_{NN}(0°)$ for $(p_{\rm pol}, n_{\rm pol})$ Reactions at 160 MeV

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The first measurements of the transverse spin-transfer coefficient $D_{NN}(0°)$ for intermediate-energy $(p,n)$ reactions to well-resolved nuclear states are reported. Results are presented for $(p_{\rm pol}, n_{\rm pol})$ reactions on $^{6,7}$Li, $^{12,13,14}$C, and $^{90}$Zr at $E_p = 160$ MeV. The average value of $D_{NN}(0°)$ for pure Gamow-Teller transitions at this energy is shown to be close to the expected value of $\simeq -\frac{1}{3}$. The utility of spin-transfer measurements for investigation of aspects of the nuclear spin-dependent response not otherwise observable is pointed out.

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The proportionality at intermediate energies between the $(p,n)$ differential cross section $\sigma(0°)$ and the corresponding $\beta$-decay transition strength[1,2] has provided a direct means of measuring Gamow-Teller (GT) transition strengths for a wide range of nuclei and has led to the discovery that a large fraction of the minimum GT sum-rule strength of $3(N-Z)$ is missing in all cases studied to date.[3] Despite the successful use of $(p,n)$ differential cross sections to identify and measure spin-flip strength, in some cases important details of the reaction are not adequately revealed by differential cross-section measurements alone. In particular, there is the continuing problem of distinguishing giant resonances excited by the $(p,n)$ reaction from the background of continuum excitations or competing giant resonances with which they are mixed.[4-8] This separation mainly depends upon distinguishing between components that have differing spin-flip characteristics.

A direct measure of the spin-flip character of a $(p,n)$ transition is provided by the transverse spin-transfer coefficient $D_{NN}(\theta)$ [or, equivalently, the transverse spin-flip probability $S_{NN} = (1 - D_{NN})/2$]. Cornelius, Moss, and Yamaya[9] and Moss[10] have shown that this quantity takes on distinctive values for transitions having a unique or single dominant value for the orbital angular momentum transfer.

In particular, GT transitions ($J=1$, $L=0,2$, $S=1$) should have $D_{NN}(0°) \simeq -\frac{1}{3}$ if $L=0$ dominates and Fermi (F) transitions ($J=0$, $L=0$, $S=0$) have $D_{NN}(0°)=1$, where $J$, $L$, and $S$ are the total, orbital, and spin angular momenta transferred in the reaction. Recent measurements and analyses of the spin-flip probability in intermediate-energy $(p,p')$ reactions have also shown that for transitions dominated by a single multipole, $D_{NN}$ (as well as other spin-transfer observables) is relatively insensitive to distortion effects and details of the transition density near the peak of the associated form factor.[11,12] Measurements of $D_{NN}(0°)$ are thus potentially important tests of the effective nucleon-nucleon interaction as well as a means of investigating the nuclear spin-dependent response.

In this Letter, we report the first measurements of the transverse spin-transfer coefficient $D_{NN}(0°)$ for intermediate-energy $(p,n)$ reactions. We have obtained data for $(p_{\text{pol}},n_{\text{pol}})$ reactions on $^{6,7}$Li and $^{12-14}$C at $E_p=160$ MeV. The bombarding energy was chosen to be as high as possible to minimize $L>0$ contributions to the transition amplitudes at 0°, while still maintaining the experimental energy resolution required. The targets chosen all exhibit GT transitions leading to well-resolved final states with minimal interfering background and thus provide suitable tests for establishing the validity of the experimental technique and the applicability of the simple predictions for $D_{NN}(0°)$. As an illustration of the type of information to be gained from measurements of spin-transfer observables, we have also obtained some preliminary data for the reaction $^{90}$Zr$(p_{\text{pol}},n_{\text{pol}})$ and interpret these data with respect to the "benchmark" measurements obtained on the light targets.

The data were obtained with the Indiana University cyclotron and beam-swinger facility.[13] Polarized protons with energy $E_p=160$ MeV bombarded self-supporting targets with thicknesses ranging from 107 to 232 mg/cm$^2$. The beam polarization was typically $0.65 \leq |p_i| \leq 0.75$ and was cycled between up and down orientations at 2-min intervals. Typical beam currents were about 30 nA. The time of flight (TOF) of neutrons emitted at 0° was measured over a 60-m flight path. Time resolution (including beam and target contributions) varied from 0.7 to 1.1 ns depending upon the target, with corresponding energy resolution of 0.7 to 1.1 MeV.

The neutron polarimeter consisted of six 15-$\times$15-$\times$100-cm$^3$ plastic scintillators arranged in two parallel stacks of three. The long axes of the scintillators were parallel to the horizontal plane and perpendicular to the incident neutron flux. The separation between stacks was approximately 1.4 m. The polarization of incident neutrons was determined by scattering from hydrogen [$^1$H$(n_{\text{pol}},n')^1$H] and carbon [$^{12}$C$(n_{\text{pol}},n'x)$] nuclei in one of the forward scintillators. The scattered neutrons (denoted as $n'$) were subsequently detected by one of the trailing scintillators. A thin plastic scintillator between the stacks was used to veto events associated with forward-going protons. Time signals derived from each end of the detectors furnished both the TOF of the incident neutron and position information from which the event geometry was reconstructed. Neutrons that scattered at polar angles of $14° \leq \theta \leq 31°$, at azimuthal angles $\phi$ within 45° of the horizontal plane, and with velocity $v_n'/\cos\theta \geq 0.91 v_n$ were accepted as valid events. The measured instrumental analyzing power for these conditions (which includes the average value of $\cos\phi$) is $A_p = 0.34 \pm 0.02$ and is primarily due to scattering from hydrogen. The neutron-energy dependence of the analyzing power was calculated with use of the $N$-$N$ phase-shift solutions of Arndt[14] and amounts to a change of less than 5% in the magnitude of $A_p$ for 140 MeV $\leq E_n \leq 160$ MeV.

The general expression relating $D_{NN}(\theta)$ to other observables is

$$(1+p_iA)p_f = P + p_iD_{NN}, \tag{1}$$

where $p_i$ ($p_f$) is the proton (neutron) polarization, $A$ is the analyzing power, and $P$ is the polarization function. At $\theta=0°$, this expression reduces to

$$D_{NN}(0°) = p_f/p_i, \tag{2}$$

and may be defined in terms of measured quantities as

$$D_{NN}(0°) = (\bar{p}_iA_p)^{-1}(R-1)/(R+1), \tag{3}$$

where $\bar{p}_i = (p_i^+ - p_i^-)/2$ is the average magnitude of the proton polarization, $A_p$ is the instrumental analyzing power,

$$R = [(N_L^+N_R^-)/(N_L^-N_R^+)]^{1/2}, \tag{4}$$

and $N_L^+$ [$N_R^+$] is the number of neutrons that scatter to the left ($\phi = 0° \pm 45°$) [right ($\phi = 180° \pm 45°$)] for positive incident proton polarization, etc. This definition of $D_{NN}(0°)$ is largely independent of false asymmetries caused by instrumental inefficiencies and misalignments or unequal beam current for spin up and spin down. The product $\bar{p}_iA_p$, which provides the absolute normalization of $D_{NN}$, was empirically determined by measuring $R$ for the $0^+ \to 0^+$ $^{14}$C$(p,n)^{14}$N(2.31

MeV) isobaric analog state (IAS) transition for which $D_{NN}(0°) \equiv 1$. Relative changes in $\bar{p}_i$ (and thus in the product $\bar{p}_i A_p$) were monitored with a helium polarimeter in the low-energy beam line between the injector and main-stage cyclotrons and with a fixed detector that measured protons scattered from the $(p,n)$ target.

Energy spectra for the summed yields $(N_L^+ + N_L^- + N_R^+ + N_R^-)$ and difference of yields $(N_L^+ - N_L^- + N_R^- - N_R^+)$ for double-scattered neutrons produced by $(p,n)$ reactions on $^{13}$C and $^{14}$C are shown in Figs. 1 and 2. The difference spectra show positive peaks for transitions with $D_{NN}(0°) > 0$ and negative peaks for transitions with $D_{NN}(0°) < 0$. Most of the peaks in these spectra correspond to GT transitions and thus exhibit negative peaks in the difference spectra. The exceptions are the $0^+ \rightarrow 0^+$ $^{14}$C$(p,n)$ IAS transition, for which $D_{NN}(0°) = 1$, and the $\frac{1}{2}^- \rightarrow \frac{1}{2}^-$ $^{13}$C$(p,n)^{13}$N(g.s.) transition, which is a mixture of Gamow-Teller and Fermi components.

Values of $D_{NN}(0°)$ extracted from these spectra are given in Table I along with results for $^6$Li, $^7$Li, $^{12}$C, and $^{90}$Zr. Significantly, the values of $D_{NN}(0°)$ for the pure GT transitions are evenly distributed around the expected value of $-\frac{1}{3}$. The average for six strong transitions from $^6$Li, $^{12}$C, $^{13}$C, and $^{14}$C is $D_{NN}(0°) = -0.32 \pm 0.05$. Large systematic deviations from this value would be indicative of unexpectedly large $L = 2$ (or tensor) amplitudes at 0° or failure of the assumed single-step direct-reaction mechanism.

The $^{90}$Zr results lead to some interesting conclusions, in spite of the low statistical accuracy of the present data. The values of $D_{NN}(0°)$ listed in Table I for $^{90}$Zr$(p,n)$ represent the summed strength in the energy regions indicated, i.e., no "background" has been subtracted. The value obtained for the IAS + background is consistent with $D_{NN}(0°) = 1$ for the IAS and $D_{NN}(0°) \simeq -\frac{1}{3}$ for the background. The value obtained for the giant GT resonance is consistent with the "pure GT" average and thus indicates that most of the strength observed in this region has the same GT-type spin-transfer signature. There is also significant spin-flip strength in the $15.0 \leq E_x \leq 25.0$-MeV continuum region. The spin-flip probability for this region is $S_{NN} = 0.58 \pm 0.05$. This situation should be contrasted to that in $(p,p')$, where the spin-flip probability for the equivalent region of excitation energy in $^{90}$Zr is found to be[15] $S_{NN} \simeq 0.15$ at 319 MeV and 3.5°. This comparison points out the advantage that the $(p,n)$ reaction has over $(p,p')$ for investigation of the nuclear spin-dependent response. The latter reaction is dominated by strong scalar-isoscalar transitions that are not present for $(p,n)$.

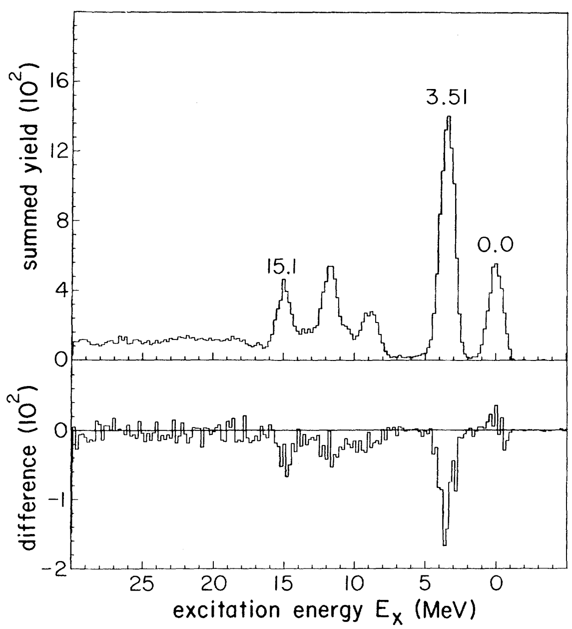


FIG. 1. Energy spectra for the sum $(N_L^+ + N_L^- + N_R^+ + N_R^-)$ and difference $(N_L^+ - N_L^- + N_R^- - N_R^+)$ of yields of double-scattered neutrons produced by the reaction $^{13}$C$(p,n)^{13}$N at $E_p = 160$ MeV and $\theta = 0°$. The neutron energy is given by $E_n = 157.0\ \text{MeV} - E_x$.

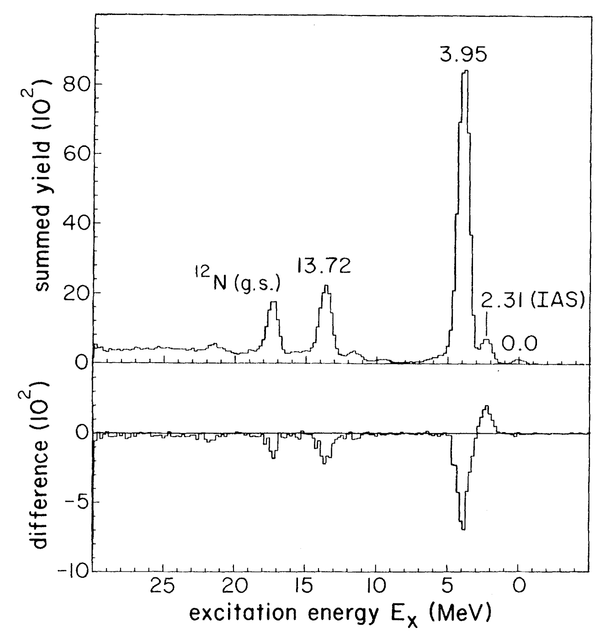


FIG. 2. Energy spectra for the sum and difference of yields of double-scattered neutrons produced by the reaction $^{14}$C$(p,n)^{14}$N at 160 MeV and $\theta = 0°$. The neutron energy given by $E_n = 159.4\ \text{MeV} - E_x$.

TABLE I. Transverse spin-transfer coefficient $D_{NN}(0°)$ for $(p,n)$ reactions at 160 MeV. The quoted uncertainties are absolute and arise from the statistical uncertainty in the yields of double-scattered neutrons for each transition plus an uncertainty of about 6% due to the statistical uncertainty in the yields for the calibration reaction $^{14}C(p,n)^{14}N(2.31$ MeV).

| Reaction | $E_x$ (MeV) | $D_{NN}(0°)$ | Transition type |
|---|---|---|---|
| $^6Li(p,n)^6Be$ | 0.0 | $-0.37\pm0.04$ | GT |
| $^7Li(p,n)^7Be$ | 0.0 + 0.43 | $-0.28\pm0.06$ | GT + F |
| $^{12}C(p,n)^{12}N$ | 0.0 | $-0.24\pm0.03$ | GT |
| $^{13}C(p,n)^{13}N$ | 0.0 | $0.05\pm0.06$ | GT + F |
| | 3.51 | $-0.33\pm0.05$ | GT |
| | 15.1 | $-0.36\pm0.08$ | GT |
| $^{14}C(p,n)^{14}N$ | 0.0 | $-0.29\pm0.17$ | GT |
| | 2.31 | 1.0 | F |
| | 3.95 | $-0.29\pm0.02$ | GT |
| | 13.72 | $-0.33\pm0.04$ | GT |
| $^{90}Zr(p,n)^{90}Nb$ | 4.3–6.3 | $0.24\pm0.17$ | F + GT background |
| | 6.4–13.1 | $-0.28\pm0.08$ | GT (Giant $1^+$) |
| | 15.0–25.0 | $-0.17\pm0.09$ | ? |

In summary, measurements of the transverse spin-transfer coefficient $D_{NN}(0°)$ have been made for $(p,n)$ reactions on $^{6,7}Li$, $^{12-14}C$, and $^{90}Zr$ at $E_p = 160$ MeV. These measurements reveal that the average value of $D_{NN}(0°)$ for GT transitions is close to the value of $-\frac{1}{3}$ expected for pure $L=0$ transitions. Calculations indicate that the relatively small deviations from the average value of $D_{NN}(0°)$ that are observed for individual transitions can be associated primarily with the tensor component of the effective nucleon-nucleon interaction.[10,11] Detailed analyses of individual transitions should therefore reveal important information about the strength of the tensor interaction near zero momentum transfer. Initial results obtained for $^{90}Zr(p,n)$ suggest that there is very little non-GT background in the region of the giant Gamow-Teller resonance. In addition, significant spin transfer is observed in the continuum region of the $^{90}Zr(p,n)$ spectrum, in contrast to the situation for the analogous region observed in $^{90}Zr(p,p')$ measurements.[15] In general, the measurement of $(p,n)$ polarization-transfer observables appears to be a promising technique for investigating new features of the spin-dependent nuclear response, especially in the continuum region.

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