Isovector and Gamow-Teller Strength from Small-Angle (n,p) Reactions at 60 MeV

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(Received 20 August 1981)

The (n,p) reactions to the analog giant magnetic dipole states, the inverse of the transitions in allowed Gamow-Teller β decay, have been measured for ^{6}Li, ^{12}C, and ^{28}Si for forward angles using 59.6-MeV neutrons. With use of a relation between $\sigma(0°)$ and the β-decay matrix elements, there results $v_{\sigma\tau}^c(0) = 157 \pm 11$ MeV fm^3 for the $l=0$, isovector part of the effective spin-flip nucleon-nucleon interaction. Comparison with 120-MeV (p,n) reactions indicates that $v_{\sigma\tau}^c$ has a small energy dependence in the range 60 to 120 MeV.

PACS numbers: 24.50.+g, 25.40.Fq, 27.20.+n, 27.30.+t

Direct charge-exchange reactions[1-3] are important tools for the study of transitions which are induced by isovector interactions, which involve a transfer of one unit of isospin to the target nucleus. Charge-exchange reactions excite states in the target isobars and allow the isovector modes to be isolated from the isoscalar.[4] This can be particularly important in the study of giant-resonance excitations where the width of the resonances often causes the overlapping of isoscalar and isovector modes in the target nucleus. Furthermore, direct reactions between nuclear states of definite spin and parity provide selectivity to particular components of the nucleon-nucleon interaction. This is an important feature of charge-exchange reactions which can provide information to supplement that obtained from free n-p scattering.

Of particular interest here is the fact that these charge-exchange reactions can produce transitions which are the inverse of those in Fermi (F) and Gamow-Teller (GT) β decay. In earlier experimental work[5,6] with the (p,n) reaction at lower energies, the relation between the $l=0$ contribution to the cross sections and the F and GT matrix elements for the corresponding weak-interaction transitions was used to establish that the ratio of $v_{\sigma\tau}^c$ to v_τ^c, the volume integrals of the $l=0$ isovector components of the effective central nucleon-nucleon interaction for spin-flip and spin-nonflip, respectively, was nearly independent of energy.

More recent (p,n) work[7] at 120 MeV has led to a theoretical relation[8-10] between the 0° (p,n) cross section and the F and GT matrix elements and showed that the ratio $v_{\sigma\tau}^c/v_\sigma^c$ was considerably larger than at low energies. This relation allowed the determination of values for $v_{\sigma\tau}^c(q)$ and $v_\tau^c(q)$ at $q \cong 0$ for 120-MeV incident energy.

In this paper we present for the first time results from the (n,p) reaction of ^{6}Li, ^{12}C, and ^{28}Si at neutron beam energy of 59.6 ± 0.3 MeV, which provide a measure of the strength of the spin-flip part of the isovector interaction at small momentum transfer. The (n,p) reaction, even at 60 MeV, because of its less negative Q value, has as small momentum transfer as (p,n) at higher energies, or smaller, thus fulfilling the assumptions of the theoretical analysis.[8-10] In addition, the (n,p) reaction for $N > Z$ has the feature of being very selective in that it excites only T_0+1 states for T_0 targets. The (p,n) reaction favors T_0-1, and (p,p') favors T_0 states. The present results for $N=Z$ ($T_0=0$) targets provide simpler test cases to see if the n-p interaction strength obtained is reasonable. If so, (n,p) reactions can be used to investigate T_0+1 components in cases of astrophysical interest and in connection with GT strength not reached in β decay or (p,n) reactions.

The experiments were performed using the monoenergetic neutron production facility of the Crocker Nuclear Laboratory of the University of California at Davis.[2] The ^{6}Li and ^{12}C results[11] were obtained using a new detection system consisting of two multiwire proportional chambers (MWC) and a large area ΔE-E telescope. The MWC determined the trajectories of the charged particles thereby providing improved angular resolution and, via detector response mapping, improved energy resolution in the large-area plastic-scintillator ΔE and the NaI E detectors. The overall energy resolution in this system was typically ~1 MeV full width at half maximum. The ^{28}Si data[12] were obtained with an array of Si ΔE and NaI E telescopes. In both cases the cross-section normalization was provided by the n-p scattering cross section, via a CH_2 target.

Forward-angle unsubtracted spectra are shown in Fig. 1 along with the continuum background (solid line). The transitions which are of interest here, those corresponding to allowed GT transitions, are shown by the arrows. The peak energy uncertainties are ≲0.3 MeV. The underlying continuum background for ^{6}Li and ^{12}C was assumed to be due to three-body breakup. For ^{28}Si, the continuum was estimated from calculations of the emission of preequilibrium protons using the exciton model and a phenomenological angular parametrization.[13]

Figure 2 shows the angular distributions obtained over the range of angles from about 5° to 70°. A spray of neutrons and photons does not allow measurements at 0°. The continuous line in Fig. 2 is the result of distorted-wave calculations with the computer code[14] DWBA70 using wave functions of Cohen and Kurath[15] and Wildenthal,[16] the G-matrix interaction of Bertsch *et al.*,[17] and optical model parameters of Fulmer *et al.*[18] and Bray.[19] The indicated N factors correspond to the normalization of the interaction after normalizing the wave functions to the experimental $B(M1\uparrow)$. These values are consistent with (p,n) calculations at 61 MeV.[9]

The 0° c.m. cross sections needed for the present analysis were extrapolated from these graphs with distorted-wave Born approximation predictions as a guide. Uncertainties in $\sigma(0°)$ due to

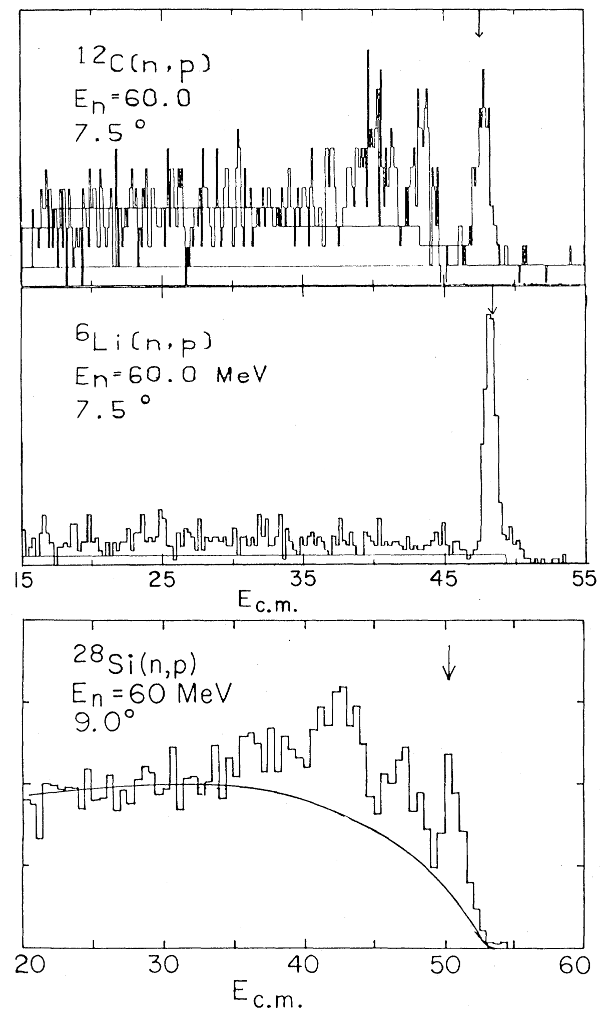

FIG. 1. Forward-angle (n,p) energy spectra with "GT transitions" shown by arrows.

extrapolation are estimated to be ≅7%. The results are given in Table I along with the initial and final J^π, and the excitation energies, E_x, of the GT transitions studied. The uncertainties quoted for $\sigma(0°)$ include also an absolute normalization uncertainty in the data ≅7% (due largely to n-p cross-section uncertainties), and for ^{28}Si an additional uncertainty of ≅10% due to continuum background subtraction.

According to the description and in the notation of Petrovich, Love, and McCarthy,[9] the direct local, microscopic, plane-wave Born approximation for the cross section at small momentum transfer ($q \cong 0$) is

$$\frac{d\sigma}{d\Omega}(\theta \approx 0°) = \left(\frac{\mu}{2\pi\hbar^2}\right)^2 \frac{k_f}{k_i} \frac{2J_f+1}{2J_i+1} \times 8\pi N^D |\rho_{10}{}^{11}(q)|^2 |v_{\sigma\tau}{}^c(q)|^2 \quad (1)$$

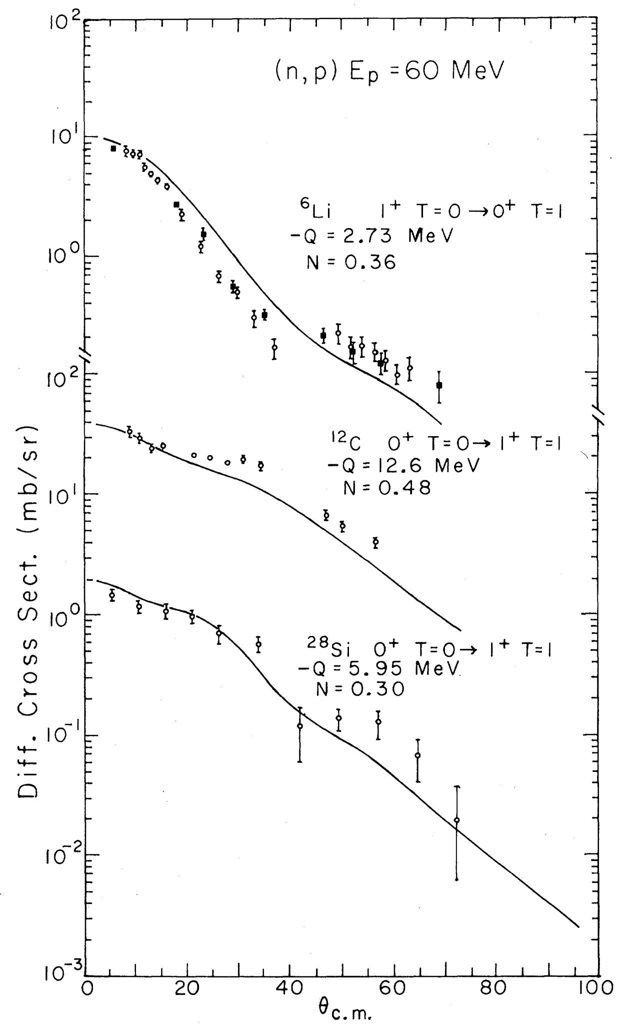

FIG. 2. c.m. angular distributions. The solid line is a distorted-wave Born-approximation calculation as indicated in text. For the ^{6}Li data, the squares are experimental points obtained with a detector system similar to the one used in the ^{28}Si experiment.

and $v_{\sigma\tau}{}^c(q)$ is the Bessel transform of the central spin-isospin ($\sigma\tau$) component of the effective nucleon-nucleon interaction. In Eq. (1) use has been made of the fact that near $q=0$ the $l=2$ transition densities and the tensor and spin-orbit interactions, v^{ls} and v^T, are very small compared to the central components, v^c, and have been neglected.[9] In Eq. (1) $\rho_{10}{}^{11}(q)=\rho_{jl}{}^{st}(q)$ is the spin-isospin transition density for the transfer of $l=0$ and $s=t=j=1$ to the target, which is the case of interest here. N^D is a distortion factor[21] to account for the use of plane rather than distorted waves. The spin transition density for the isovector spin flip, in this case, is related to the reduced matrix element of the allowed GT β decay via

$$\rho_{10}{}^{11}(0)^2 = |M_{GT}|^2/2\pi, \qquad (2)$$

where

$$|M_{GT}|^2 = (2J_i{}^\beta+1)^{-1}|\langle J_f{}^\beta \| \textstyle\sum_k t_+(k)\sigma(k) \| J_i{}^\beta\rangle|^2. \qquad (3)$$

The reduced matrix element and notation are defined as by Bohr and Mottelson,[22] wherein the following expression for allowed transitions is given:

$$D/ft = |M_F|^2 + (g_A/g_V)^2 |M_{GT}|^2, \qquad (4)$$

with $D = 6163.4 \pm 3.8$ sec and $g_A/g_V = 1.250 \pm 0.009$.[23]

Table I summarizes the results for the transitions considered. The reduced matrix element in the cases of Li and C was obtained from Eq. (4) using current ft values.[20] For the case of Si, the matrix element quoted was obtained from the values of $B(M1)$ measured in (e,e') reactions[25] and corrected for orbital contributions[9] (< 1%). The two dominant $M1$ transitions to states at 10.90

TABLE I. Parameters for transitions observed in (n,p) reactions at 60 MeV.

Target	J_i^π	J_f^π	E_x (MeV)[a]	$\frac{d\sigma}{d\Omega}(0°)$ (mb/sr)	$\frac{2J_f+1}{2J_i+1}M_{GT}^2$	N^D	$v_{\sigma\tau}{}^c(0°)$ (MeV fm^3)
^{6}Li	1^+	0^+	GS	9.5 ± 1.0[b]	1.61 ± 0.02[c]	0.59	155 ± 18
^{12}C	0^+	1^+	GS	4.0 ± 0.4[b]	1.00 ± 0.02[d]	0.28	182 ± 20
^{28}Si	0^+	1^+	2.1[e]	1.9 ± 0.3[b]	1.80 ± 0.09[f]	0.11	138 ± 20

[a] Excitation energy in the final nucleus.
[b] Extrapolated 0° from angular distribution.
[c] Values obtained by use of expression (4) in text and $\log ft = 2.911 \pm 0.003$ from Ref. 20.
[d] Same as c, with $\log ft = 4.072 \pm 0.002$.
[e] Based on our energy calibration, consistent with analogs in ^{28}Si (see text).
[f] Based on $B(M1)$ values from (e,e') reactions; see text.

and 11.44 MeV in ^{28}Si have analogs to 2.20 and 1.62 MeV in ^{28}Al.[26] On the basis of the $B(M1)$ values, the energy centroid is expected to be at 2.1 MeV, while we observe 2.0 ± 0.3 MeV. The distortion factors shown (column 7) have been calculated with the prescription of Ref. 7 using the code DWBA70[14] and we estimate that they have an uncertainty of 20%.

Using Eqs. (1) and (4) one obtains the values of the volume integrals shown in column 8, Table I. The uncertainties include those from $\sigma(0°)$, $|M_{\rm GT}|^2$, and N^D. From these data, the mean value of the volume integral, $v_{\sigma\tau}{}^c(0°)$, is 157± 11 MeV fm^3.

This value is lower by a factor of about 0.6 than the predictions of $v_{\sigma\tau}{}^c(0)$ at 65 MeV based on a G matrix interaction for two nucleons interacting in nuclear matter.[17,24] The one-pion-exchange potential $\sigma\tau$ value is ≅ 122 MeV fm^3 at 60 MeV and increases slowly with energy.[10] At 120 MeV the $v_{\sigma\tau}{}^c(0)$ value derived from forward-angle (p,n) data is 168 MeV fm^3. This small energy dependence of $v_{\sigma\tau}{}^c$ has recently been explained[24] in terms of a nucleon-nucleon interaction model based on meson exchange. In this model the energy independence of $v_{\sigma\tau}{}^c$ arises because it is given mainly by first-order one-pion and one-rho exchange terms, while the energy dependence of v_τ is mainly due to second-order terms whose contributions decrease with increasing nucleon energy.

In summary, it has been shown that the selectivity of the (n,p) reaction can be used to study in nuclei components of GT strength and the isovector spin-flip component of the nucleon-nucleon effective interaction. In particular it appears that $v_{\sigma\tau}{}^c$ is nearly energy independent in the region from 60 to 120 MeV. This small energy dependence is in contrast to that of $v_\tau{}^c$ which in a series of (p,n) measurements has been found to decrease monotonically with energy. As noted above the physical explanation for these behaviors with energy has recently been given.[24]

We thank Claudio Zanelli and also the Crocker Nuclear Laboratory staff for assistance during stages of this work. This work was supported in part by the U. S. National Science Foundation under Grants No. 77-PHY-05301 and No. 79-PHY-26282.

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