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Energy dependence of the Gamow-Teller strength in *p*-shell nuclei observed in the (n,p) reaction

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Cross sections from 0° to 10° (lab) have been measured for ground-state Gamow-Teller transitions for the reactions ^{6}Li$(n,p)^{6}$He, ^{12}C$(n,p)^{12}$B, and ^{13}C$(n,p)^{13}$B from 60 to 260 MeV. The 90 meter station at the Weapons Neutron Research facility at Los Alamos National Laboratory was used to obtain these data. Unit cross sections $(\hat{\sigma})$ have been obtained and are compared with existing (n,p) and (p,n) data. The volume integrals $(J_{\sigma\tau})$ for the spin-flip isospin-flip part of the effective nucleon-nucleon interaction have also been obtained and are compared with theoretical predictions.

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Charge-exchange (p,n) reactions have been used extensively to study both nuclear structure and the isovector components of nucleon-nucleus interactions. In particular, it has been shown for a wide range of nuclei, that the differential cross sections for Gamow-Teller (GT) transitions, when extrapolated to zero-momentum transfer (q) and zero energy loss (ω), are proportional to the GT β-decay matrix element [1]. These studies were extended to (n,p) reactions by the groups at Davis [2], TSL [3], IUCF [4], and TRIUMF [5]. Their measurements were conducted at discrete energies between 65 and 300 MeV. The availability of the Weapons Neutron Research (WNR) "white" neutron source at the Clinton P. Anderson Meson Physics Facility (LAMPF) at Los Alamos has enabled us to study the (n,p) reaction mechanism at all neutron energies continuously between 60 and 260 MeV. For the first time differential cross sections can be measured over a wide range of bombarding energies simultaneously, thus allowing the effective N-N interaction, and unit cross sections to be studied in a systematic way. In this paper we report our results for three targets: the self-conjugate nuclei ^{6}Li and ^{12}C with known GT β-decay strengths, and ^{13}C, a nucleus for which the (p,n) results disagree with the smooth systematics found in Ref. [1].

In the framework of the impulse approximation, a simple expression [1,6] relates the GT differential cross section at $(q,\omega)=0$ to the volume integral of the central part of the effective nucleon-nucleon $(N$-$N)$ interaction, $J_{\sigma\tau}(q=0)$, and the GT matrix element for the (n,p) reaction, $B_{\rm GT}^{np}$. This expression can be written as

$$\frac{d\sigma}{d\Omega}(q=0,\omega=0)=KN^{D}|J_{\sigma\tau}(q=0)|^{2}B_{\rm GT}^{np}\,, \tag{1}$$

where K is a kinematic factor, and N^D is the distortion factor defined as the ratio of the distorted-wave cross section to the plane-wave cross section evaluated at $(q,\omega)=0$. In the present case $B_{\rm GT}^{np}$ is related to $B_{\rm GT}$, the reduced β-decay matrix element as defined by Bohr and Mottelson [7]:

$$B_{\rm GT}^{np}=\frac{2J_f+1}{2J_i+1}B_{\rm GT}\,, \tag{2}$$

where J_i (J_f) refer to the initial (final) total angular momentum in the (n,p) reaction. The $B_{\rm GT}^{np}$ values are tabulated in Table I.

The expression given in Eq. (1) can be used in two ways. First, if the distortion factors are calculated, $J_{\sigma\tau}(q=0)$ values can be obtained and compared directly to theoretical values derived from effective N-N interactions. A second approach is to define a quantity that does not involve the distortion factor, thereby eliminating the uncertainty in the calculation of this factor. This quantity, the unit cross section, is defined as [1]

$$\hat{\sigma}(E_n,A)=\left[\frac{d\sigma}{d\Omega}(q=0,\omega=0)\right]\Big/B_{\rm GT}^{np}\,. \tag{3}$$

For transitions with known β-decay transition rates this quantity essentially represents an experimental number. Assuming Eq. (1) is valid for all GT transitions, the unit cross section can be parametrized as a function of atomic mass (A) and bombarding energy (E_n), thereby enabling the determination of $B_{\rm GT}$ values for transitions in which β decay does not occur. In addition, this unit cross section is a useful observable for comparing (n,p) and (p,n) reac-

TABLE I. $B_{\rm GT}^{np}$ values.

$(J_i^\pi,T_i)\rightarrow(J_f^\pi,T_f)$	$B_{\rm GT}^{np}$
^{6}Li$(1^+,0)\rightarrow{}^{6}$He$(0^+,1)$	1.59 ± 0.02 [a]
^{12}C$(0^+,0)\rightarrow{}^{12}B(1^+,1)$	1.00 ± 0.01 [b]
^{12}C$(0^+,0)\rightarrow{}^{12}B(2^+,1)$	
^{13}C$(\frac{1}{2}^-,\frac{1}{2})\rightarrow{}^{13}B(\frac{3}{2}^-,\frac{3}{2})$	0.72 ± 0.01 [c]

[a] Reference [8].
[b] Reference [9].
[c] Reference [10].

tions on nuclei with the same A. A study related to this recently has been performed by Mildenberger *et al.* [11] where they report tests of isospin symmetry in (n,p), (p,n), and (p,p') reactions at 280 MeV which populate the GT $T=1$ isospin triplets in $A=6$ and $A=12$ nuclei. They found excellent agreement for all three reactions for the $A=12$ nuclei; however, for ^{6}Li$(n,p)^6$He and ^{6}Li$(p,p')^6$Li they find a difference at finite q, which goes away at $q=0$. Similar results are reported in Ref. [12].

The experiment reported here was conducted at the WNR neutron spallation source [13] at a detector station located 87.5 m from the neutron production target on the 15° left flight path. The current of the 800-MeV proton beam on the neutron production target was typically 800 nA with a micropulse spacing of 1.8 μsec, yielding 1.1×10^3 n/MeV sec at 100 MeV on our 100-cm^2 target. The neutron energy was determined by time of flight, with energy resolutions ranging from 0.3% to 0.7% [full width at half maximum (FWHM)] over the 60- to 260-MeV energy range.

A multiple-target array such as described in Ref. [14] was used with as many as four targets separated by multiwire proportional chambers. Two chambers were used ahead of the target array to veto charged particles in the beam. The rest of the detection system is similar to that developed at Davis (see Ref. [15]) and includes four drift chambers to give scattering-angle information, a 0.63-T magnet to sweep the zero degree protons out of the neutron beam, a thin plastic scintillator ($30.5\times50.8\times0.5$ cm^3) to provide timing and particle identification information, and a calorimeter array of 15 ($8.9\times8.9\times15.2$ cm^3) CsI(Tl) detectors. The CsI(Tl) detectors were thick enough to stop protons with energies up to 260 MeV and had intrinsic resolutions ranging from 1.2% to 0.6% over the energy range of interest. The system could simultaneously measure proton scattering angles from 0° to 12° (laboratory) with a total solid angle of 50 msr at one setting. A more detailed account of the detection system is given in Ref. [16].

Three separate targets were used in this experiment. The ^{6}Li foil was 102 mg/cm^2 thick. It was enclosed in an argon atmosphere by a frame with a 0.0127-mm-thick stainless steel upstream window on the side of the target facing the incident neutron beam and a 0.0064-mm-thick Mylar window on the downstream side. The ^{13}C target (97% enriched [17]) had an areal density of 209 mg/cm^2. The ^{12}C data were obtained with a 76.1-mg/cm^2 CH_2 target, which also provided hydrogen for normalization of our cross-section data. All data were normalized to the H(n,p) cross sections given by the SM88 phase-shift solution of Arndt and Roper [18].

The major source of background was protons from the H(n,p) and ^{12}C(n,p) reactions occurring in the wire chamber gas and Mylar windows. In the case of ^{6}Li, the target holder windows created another source of background. "Target empty" runs were taken for background subtraction. For ^{6}Li, the background under the ground-state (GS) peak ($Q=-2.73$ MeV) was 10% or less and for ^{13}C, the background under the GS peak ($Q=-12.65$ MeV) was 6% or less. For ^{12}C, however, the background under the GS peak ($Q=-12.59$ MeV) was as much as 20% and was mainly due to the tail of the n-p elastic scattering from the hydrogen in the CH_2 target.

Sample background-subtracted excitation spectra for each target are shown in Fig. 1. The spectra are for neutron energy bins of 70 to 80 MeV and 200 to 220 MeV. The GS GT transitions produce sharp peaks and are therefore easily visible in the spectrum. The overall resolution observed in the figure ranges from 1 to 2.5 MeV (FWHM) depending on the bombarding energy and target thickness.

Differential cross sections were obtained with average angles of 1.4°, 3.2°, 5.1°, 7.1°, and 9.1° (laboratory). Neutron energies were binned in 10 MeV intervals from 60 to 100 MeV and in 20 MeV intervals from 100 to 260 MeV.

The transition to the 2^+ excited state in ^{12}B at 0.95 MeV could not be resolved from the GS transition. However, calculations for this excited state at small q show that its contribution is about an order of magnitude smaller than that for the 1^+ GS at our lowest bombarding energies and several orders of magnitude smaller at the higher energies. Brady *et al.* [19] were able to resolve the 2^+ and 1^+ states in their ^{12}C(n,p) measurements at 60 MeV, and their results are in good agreement with our calculations of the relative strengths of the transitions to the 2^+ excited state and the 1^+ GS. The ^{13}C$(n,p)^{13}$B GS transition region also included a $\Delta J=2^+$ contribution. From distorted-wave calculations, the $\Delta J=2^+$ transition for $q<0.2$ fm^{-1} was found to be an order of magnitude weaker than the $\Delta J=1^+$ transition at 75 MeV and about 3 orders of magnitude smaller at 210 MeV.

In order to evaluate $\hat{\sigma}(E_n,A)$ and $J_{\sigma\tau}(0)$, an extrapolation of the differential cross section to $(q,\omega)=0$ was

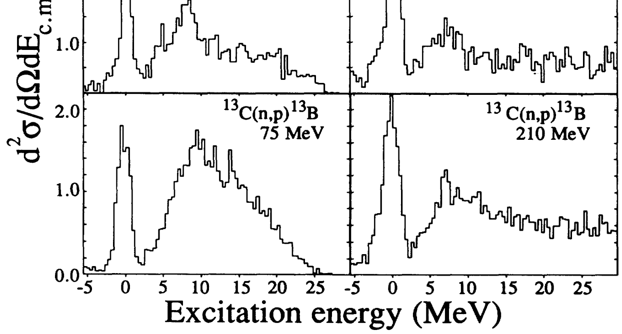

FIG. 1. Typical excitation spectra for the ^{6}Li$(n,p)^6$He, ^{12}C$(n,p)^{12}$B, and ^{13}C$(n,p)^{13}$B reactions at bombarding energies of 75 and 210 MeV after background subtraction. The angular range subtended is 0°–4° (laboratory). In all cases the GT transition is the large peak at $E_x=0.0$ MeV.

necessary. To do this extrapolation, angular distributions were calculated using the code DW81 [20]. The details are described in Ref. [21]. The unit cross section was calculated by

$$\hat{\sigma}(E_n,A)=N\frac{\sigma_{\rm DW}(q=0,Q=0)}{B_{\rm GT}^{np}}\ , \tag{4}$$

where $\sigma_{\rm DW}$ in the numerator is the differential cross section calculated at $q=0$ and Q value set to zero and N is the normalization found from fitting the calculated DW81 curve (using the correct Q value for the reaction of interest) to the data points at 1.4° and 3.2°. Figure 2 displays the unit cross sections for the three targets from 65 to 250 MeV calculated from Eq. (4). The error bars reflect the statistical uncertainty in the fit to the data points used to normalize the DW81 curves. Uncertainties in the reference ^{1}H(n,p) cross sections are not included.

Our data show a smooth energy dependence for all three targets. At the lower energies the unit cross sections fall off more rapidly for the carbon isotopes than for ^{6}Li. This is because distortion effects increase with increasing A [1]. The figure shows excellent agreement between this work and other measurements of the (n,p) reaction. Data not included in the figure are (n,p) and (p,n) reaction measurements at 280 and 300 MeV (see Refs. [11, 28] for the targets ^{6}Li and ^{12}C. We have estimated the unit cross sections from the quoted differential cross sections of those references. The results follow the trend of the present data.

For ^{6}Li and ^{12}C the (p,n) and (n,p) reactions yield very similar values for the unit cross sections. However, ^{12}C(p,n) unit cross sections between 90 and 160 MeV are not all consistent, and some appear to be about 10% lower than those observed in the ^{12}C(n,p) reaction. The unit cross sections from the ^{13}C(p,n) GS reaction are also shown. While the unit cross sections for the analog state excitation in (n,p) and (p,n) are in good agreement, they are only about two-thirds of the GT unit cross sections found for the ^{13}C(p,n) GS reaction. This breakdown of the postulated "specific proportionality" was first noted in Ref. [30] and is not understood.

Finally, distortion factors were calculated [see Eq. (1)] using the ^{12}C optical-model parameters of Comfort and Karp [21,31] and values of the volume integrals were obtained. The $J_{\sigma\tau}(0)$ values for all three targets shown in Fig. 3 are in reasonable agreement with each other. The volume integrals from G-matrix calculations of Nakayama and Love [33] are shown for Fermi momenta (k_f) of

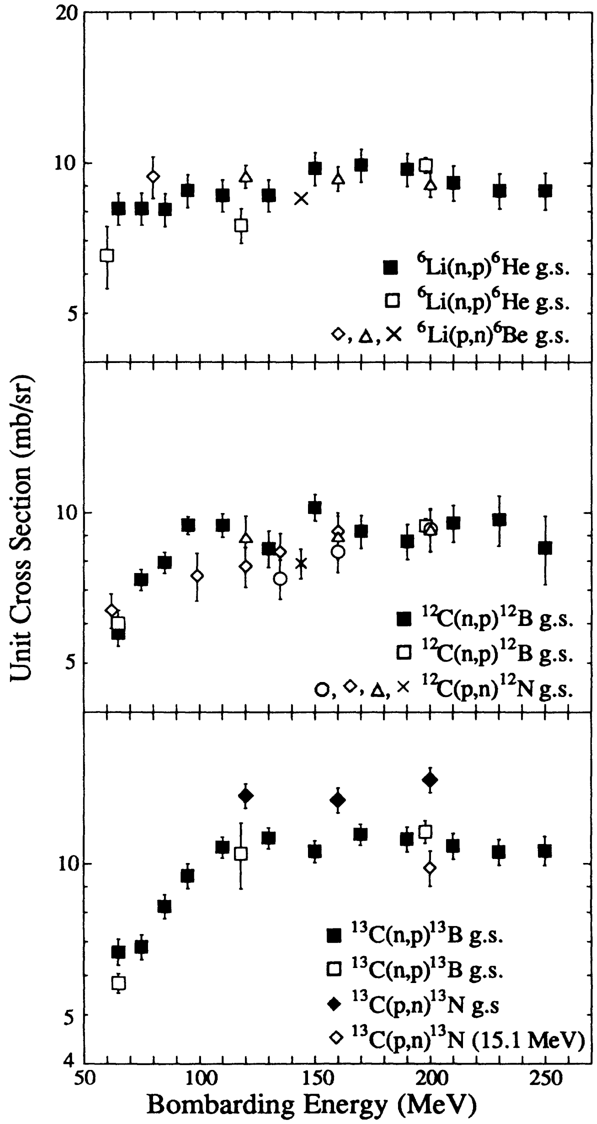

FIG. 2. Unit cross sections as a function of bombarding energy for ^{6}Li, ^{12}C, and ^{13}C GT transitions. Note the truncated log scale which extends between 4 and 20 mb/sr. The present data are shown as the solid squares. Other (n,p) unit cross sections are represented by the open squares (Refs. [22–24] for ^{6}Li, Refs. [19,24] for ^{12}C, and Refs. [24–26] for ^{13}C). Also shown are the unit cross sections as obtained from (p,n) data (Refs. [1,12,27] for ^{6}Li, Refs. [1,27–29] for ^{12}C, and Refs. [1,30] for ^{13}C). Unit cross sections which are not quoted in Refs. [19,22,25,28,29] have been extrapolated according to Eq. (4).

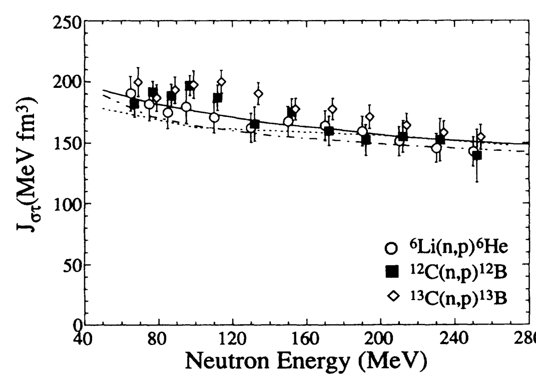

FIG. 3. Volume integrals for the spin-flip isospin-flip part of the effective N-N interaction derived from the present data. The ^{12}C points are shifted to the right by 2 MeV and the ^{13}C points by 4 MeV for clarity. Theoretical values of the volume integrals derived from the free Franey-Love t-matrix (Ref. [32]) (dotted curve) and the Nakayama-Love G-matrix (Ref. [33]) at $k_f=1.36$ (solid curve) and $k_f=0.0$ fm^{-1} (dot-dashed curve) are shown.

1.36 and 0.0 fm^{-1} as the solid curve and dot-dashed curve, respectively. Also shown are the volume integrals derived from the Franey-Love free t matrix [32] (dotted curve).

To summarize, we present for the first time (n,p) differential cross sections measured simultaneously in the 60–260 MeV energy interval. The (n,p) GS transitions on ^{6}Li and ^{12,13}C targets are used to obtain unit cross sections and empirical values of the volume integral of the spin-isospin term of the effective N-N interaction as a function of energy. These results are in very good agreement with theoretical values obtained by Nakayama and Love [33].

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