Reaction $^{13}C(n,p)^{13}B$ at 118 MeV

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Cross sections at six angles between 0° and 19° in the center-of-mass system have been measured for the ground-state transition in the reaction $^{13}C(n,p)^{13}B$ at $E_n=118$ MeV. The 0° cross section gives a value of 186 ± 25 MeV fm^3 for the volume integral of the spin-isospin component of the central part of the effective N-N interaction. The theoretical value is 161 MeV fm^3 at 100 MeV. A distorted-wave impulse-approximation calculation for the angular distribution of the ground-state transition, $(1/2^-,1/2)$ to $(3/2^-,3/2)$, compares well with the measurement. The 0° measurement is compared with other (n,p) and (p,n) measurements on ^{6}Li, ^{12}C, and ^{13}C to test the universal proportionality of these cross sections to the inverse β decay. A falloff in the proportionality constant in going to low energy is confirmed. [S0556-2813(96)00610-3]

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Charge-exchange reactions make it possible to study the transitions to $T_z\pm1$ states built on a $|T_z|=T_0$ ground state, where T_z is the z component of the isospin T_0. These charge-exchange states have isospin equal to T_0-1, T_0, or T_0+1. Those with isospin equal to T_0 or T_0+1 are analogs of states in the parent nucleus and hence members of the isospin multiplets associated with the parent states [1]. For all stable nuclei (except ^{1}H and ^{3}He) we have $N\geqslant Z$, so that a charge-exchange reaction like (n,p) excites only T_0+1 states from these stable ground states (with lowest possibile isospin), whereas the (p,n) reaction excites T_0-1, T_0, and T_0+1 states if $N>Z+1$, the latter two if $N=Z+1$, and only the latter if $N=Z$. Thus, (n,p) reactions [2,3] provide a good means for isolating and identifying T_0+1 states and comparing them to their analogs, so identified, excited by photonuclear and (p,n) reactions [4]. In this paper we compare the $^{13}C(n,p)^{13}B$(g.s.) reaction with the analog $^{13}C(p,n)^{13}N$(15.1 MeV) reaction. A greater goal was to compare the $^{13}C(n,p)$ reaction to other well-studied (n,p) reactions in the $1p$ shell to obtain further evidence for the existence of a universal proportionality between the charge-exchange excitations of the Gamow-Teller resonances and their inverse β-decay rates [5]. The measurements on $^{13}C(n,p)^{13}B$ reported here were performed at the Indiana University Cyclotron Facility (IUCF). The setup for making (n,p) measurements is described elsewhere [6].

The neutron beam was produced by means of the reaction $^7Li(p,n)^7Be$. The target was made by pressing a piece of 99.9% pure ^{7}Li metal into a 290-mg/cm^2-thick disc with a diameter of 2.5 cm. The ^{13}C target for the (n,p) measurements was made of 99.9% pure ^{13}C powder pressed into a 217-mg/cm^2-thick slab with dimensions 3×4.5 cm^2. In order to normalize the cross-section measurements, protons produced in $^1H(n,p)n$ were measured with a polyethylene (CH_2) target 303 mg/cm^2 thick. A proton energy spectrum from $^1H(n,p)n$ is shown in Fig. 1. Measurements were also taken without a target to provide for a background subtraction. Relative yields from the (n,p) reaction were normalized either by the total neutron flux recorded in a neutron monitor [7], or by the integrated primary proton beam stopped in a Faraday cup in the proton beam dump. In the present configuration the energy resolution is dominated mainly by the thicknesses of the neutron production and the (n,p) targets, which together produce an energy width of about 2.3 MeV for the 105-MeV protons associated with production of the ^{13}B ground state.

Figure 2 shows spectra of the reaction $^{13}C(n,p)^{13}B$ at $\theta_{\rm lab}=0°$ and 7.5°. The highest-energy peak in both spectra is from $^1H(n,p)n$ scattering due to hydrogen contamination in

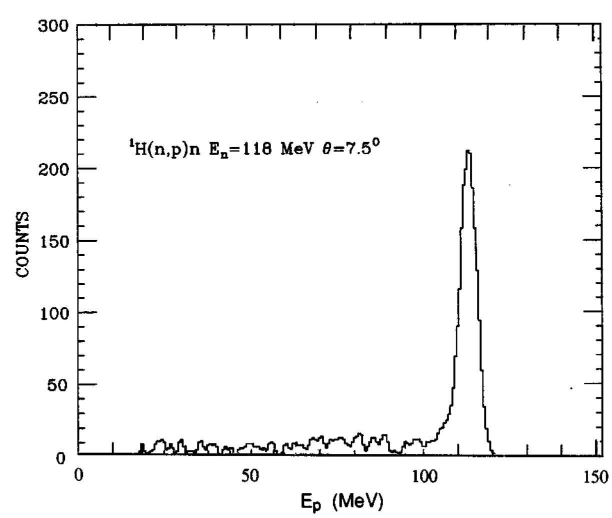

FIG. 1. Energy spectrum from $^1H(n,p)n$ at $E_n=118$ MeV and 7.5° in the laboratory system. The observed proton energy is designated as E_p and the elastic peak is at 113 MeV.

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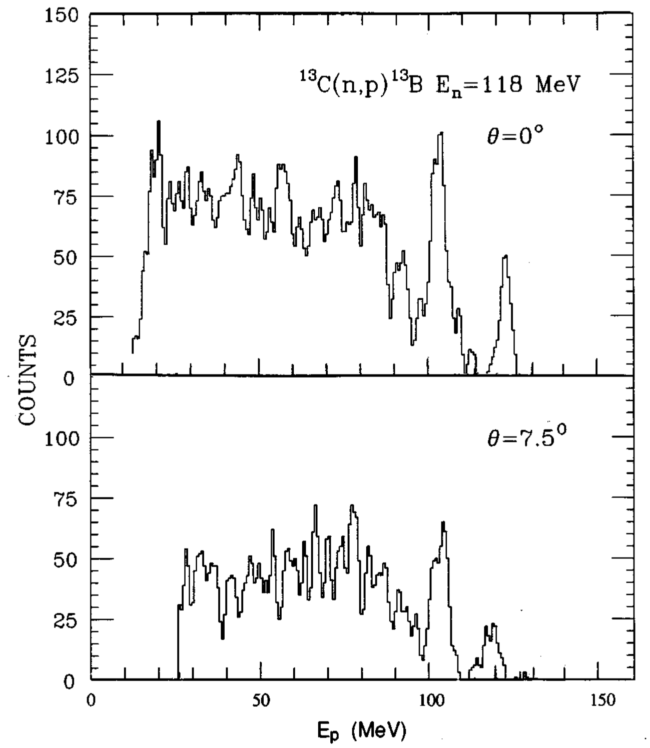

FIG. 2. Energy spectrum from $^{13}C(n,p)^{13}B$ at $E_n = 118$ MeV and 0° and 7.5° in the laboratory system. The highest-energy peak is from $^{1}H(n,p)n$. The next lower-energy peak is from $^{13}C(n,p)^{13}B$(g.s.); the proton energies E_p are 102.8 and 102.6 MeV at 0° and 7.5°, respectively.

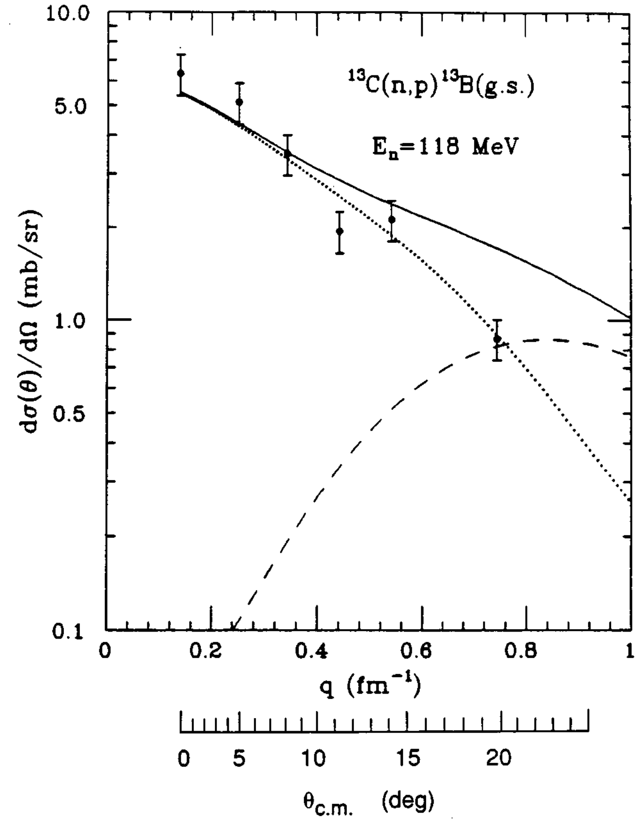

FIG. 3. Angular distribution in the c.m. system of $^{13}C(n,p)^{13}B$(g.s.) at $E_n = 118$ MeV. The dotted and dashed curves are contributions from GT(1^+) and $E2$ (2^+) transitions, respectively, as given by a DWIA calculation, and the solid curve is the sum of the GT and $E2$ contributions, without normalization.

the ^{13}C powder. This peak is easily recognized by the large kinematic shift observed as the scattering angle is changed. The next lower-energy peak corresponds to the population of the ground state of ^{13}B, a transition in which (J^{π},T) changes from ($1/2^-$,1/2) to ($3/2^-$,3/2). Thus, the isospin change is limited to unity, and the angular momentum change to one or two. In the first case we have an isovector $\Delta J = 1^+$, $\Delta S = 1$, and $\Delta L = 0,2$ transition; at the reaction energy used, the $\Delta L = 0$ mode dominates to give chiefly a $\Delta S = 1$, $\Delta L = 0$ transition, often called a Gamow-Teller (GT) transition. In the second case we have $\Delta J = 2^+$, $\Delta S = 0,1$ and $\Delta L = 2$, a quadrupole-type transition, which turns out to be weak compared to the GT component. Above the ground state of ^{13}B, transitions to excited states are observed (Fig. 2), as discussed in earlier papers [8,9]. No attempt has been made in this work to study these transitions in detail.

Figure 3 shows the measured cross sections of the ground-state transition at $\theta_{\mathrm{c.m.}} = 0°$, 5.5°, 8.2°, 10.9°, 13.6°, and 19.1°; the corresponding momentum transfer at each angle is also given on the horizontal axis. The cross sections were obtained by comparing the background-subtracted yield from ^{13}C with that from $^{1}H(n,p)n$ at each angle. The dotted and dashed curves in Fig. 3 show the calculations based on the distorted-wave impulse approximation (DWIA) for the GT and $E2$ transitions obtained with the code DW81 [10]. At small angles the GT transition dominates, but at larger angles the $E2$ excitation becomes comparable to the GT transition. The solid curve gives the sum of the two transitions. The data appear to favor a fairly pure GT transition, but this result is not definitive since it depends essentially on one point. In the calculation, the effective N-N interaction is taken from Franey and Love [11], the transition strengths from Lee and Kurath [12], and the optical potential from Comfort and Karp [13].

The volume integral of the spin-isospin component of the effective N-N interaction, as extracted from the measured cross section at 0° [14,15], is

$$V^{c}_{\sigma\tau} = 186 \pm 25 \ \ \mathrm{MeV\ fm}^3.$$

The theoretical value of 161 MeV fm^3 at $E_p = 100$ MeV and $A = 13$ is consistent with but below this result. This theoretical value was calculated with the method of [15] and the N-N t-matrix interaction strength given in [11]. In extracting the experimental value of the volume integral, a value of 0.20 was used for the distortion factor as obtained from the procedure in [5].

In Table I we compare 0° cross sections for $^{13}C(n,p)^{13}B$(g.s.) and the analog transition in the $^{13}C(p,n)^{13}N$ reaction. The significant comparison is between the unit cross sections $\hat{\sigma}^{+}_{\mathrm{GT}}$ and $\hat{\sigma}^{-}_{\mathrm{GT}}$ [5], derived on the assumption that all the 0° strength is GT in character. The experimental quantities in Table I are related through [5]

$$\sigma^{\pm}(q,\omega,A,\alpha) = \hat{\sigma}^{\pm}_{\mathrm{GT}}(A) F(q,\omega) B^{\pm}_{\mathrm{GT}}(A,\alpha), \qquad (1)$$

where q is the momentum transfer, ω the energy loss, and α specifies the particular state of the transition. The + and − signs designate the (n,p) and (p,n) reactions or β^- and β^+ decays, respectively. $F(q,\omega)$ is a form factor which accounts

TABLE I. Comparison of 0° cross sections for the $^{13}C(n,p)^{13}B$(g.s.) and $^{13}C(p,n)^{13}N$(15.1 MeV) reactions. The unit cross sections $\hat{\sigma}^{\pm}_{GT}$ are obtained from Eq. (1). The values $B^{+}_{GT}=0.72\pm0.02$ [16] and $B^{-}_{GT}=0.23\pm0.01$ [5] are used. This is a new value of B^{+}_{GT} [16], differing from the old value of 0.759±0.018. All experimental values of $\hat{\sigma}^{+}_{GT}$ listed are based on this new value of B^{+}_{GT}. The DWIA values are obtained from Eq. (2). The + and − signs refer to (n,p) and (p,n) reactions or β^- and β^+ decays, respectively.

Reaction	E^a (MeV)	$(d\sigma/d\Omega)$ c.m. (mb/sr)	$F(q,\omega)$	$\hat{\sigma}^{\pm}_{GT}$ (mb/sr)	DWIA $\hat{\sigma}^{\pm}_{GT}(1^+)$ (mb/sr)	DWIA $\hat{\sigma}^{\pm}_{E2}(2^+)$ (mb/sr)	Reference
$^{13}C(n,p)^{13}B$	65	3.11±0.24	0.70	6.2±0.7			[8]
$^{13}C(n,p)^{13}B$	118	6.32±0.60	0.83	10.6±1.2	8.53	0.088	This work
$^{13}C(n,p)^{13}B$	198	7.24±0.33	0.87	11.6±0.6	10.76	0.020	[17]
$^{13}C(p,n)^{13}N$	200	1.85±0.11	0.82	9.8±0.8	9.08	0.003	[18]

[a]Projectile energy.

for the dependence of the cross sections on q and ω. $B^{\pm}_{GT}$ is the inverse β-decay transition strength in the usual form. Also given in Table I are DWIA values of the unit cross sections for the GT(1^+) and $E2(2^+)$ transitions obtained from Eq. (2) below. We note in Table I that the experimental value of $\hat{\sigma}^{-}_{GT}$ at 200 MeV agrees fairly well with the (n,p) values at 118 and 198 MeV. However, the (n,p) value at 65 MeV is well below these values.

To investigate this feature further we present the pertinent (p,n) and (n,p) data in Fig. 4 where they are compared with the seemingly definitive data from $^{12}C(p,n)^{12}B$ (very many data from several laboratories, all agreeing well with each other [19]). For ^{12}C and ^{13}C, we see that all the data (four sets) show a decrease on going to low energy. In particular, the agreement is excellent between the $^{13}C(n,p)$ data depicted by the square symbols and that shown by the dotted curve which represents the detailed work of Sorenson *et al.* [20]. We believe this falloff is well established for these light nuclei, although there are differences in detail, such as the shape of the curves and the fact that the (n,p) unit cross sections generally lie somewhat above the (p,n) values.

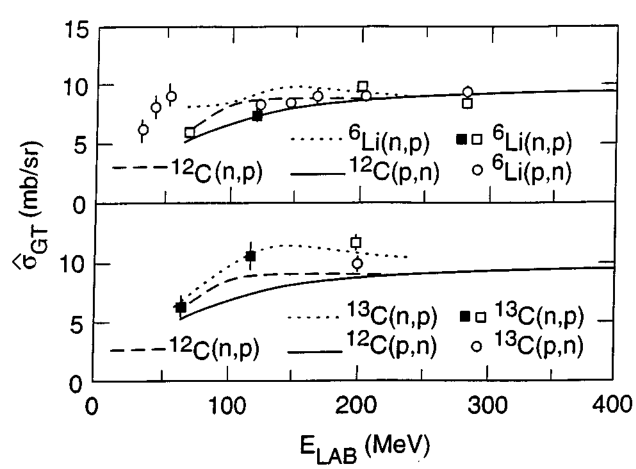

FIG. 4. Comparison of unit GT cross sections for $^{12}C(n,p)$, $^{12}C(p,n)$, $^{6}Li(n,p)$, $^{6}Li(p,n)$, $^{13}C(n,p)$, and $^{13}C(p,n)$. The $^{12}C(p,n)$ curve represents the consensus of many data that agree very well [5], [19], [22–25]. The $^{12}C(n,p)$, $^{6}Li(n,p)$, and $^{13}C(n,p)$ curves are consensus (present authors') curves of the many data of [20]. For $^{6}Li(n,p)$, see [3], [14], [17], [19]; for $^{6}Li(p,n)$, [17], [19], [21], [25]; for $^{13}C(n,p)$, [8], [17], the present work; and for $^{13}C(p,n)$, [18]. The data from [3], [8], the present work are shown by solid squares.

There is better agreement between (p,n) and (n,p) values for the ^{6}Li and ^{12}C cross sections shown in the upper part of Fig. 1, except for the low-energy $^{6}Li(p,n)$ data, taken from a graph in [21], which do not seem to fit the trends of the other results. On the other hand, the $^{6}Li(n,p)$ data shown by the square symbols agree rather well with the $^{12}C(p,n)$ curve rather than the $^{6}Li(n,p)$ curve which shows only a mild falloff. We believe the questions raised by Fig. 4 need further study.

We can understand the interest in the behavior of the unit cross section as a function of energy if we examine the expression [5]

$$\hat{\sigma}(E_p,A)=K(E_p,0)|V^c_{ST}|^2N_D, \qquad (2)$$

where ST stands for $\sigma\tau$ or τ for a GT or Fermi transition, respectively, $K(E_p,0)$ is a kinematic factor, and A represents the number and type of nucleons inside the target nucleus. The distortion decreases with increasing energy which causes the value of the distortion factor N_D to increase toward unity. On the other hand, the quantity $|V^c_{ST}|^2$ decreases with increasing energy in the region below 200 MeV. Therefore, the trend in the unit cross section is the result of a competition between N_D and $|V^c_{ST}|^2$. The value of N_D can be taken to be the same for GT and Fermi transitions [5]. Other groups [15,26] have determined that in the energy region approaching 200 MeV, $|V^c_F|^2$ decreases more rapidly than does $|V^c_{GT}|^2$. Therefore, an observed increasing trend in $\hat{\sigma}_{GT}$ would be due to the trend in N_D overcoming the trend in $|V^c_{GT}|^2$, whereas for a decreasing trend in $\hat{\sigma}_F$, as is observed [5], the situation would be just reversed. In any event, a reliable measurement of the trend with energy of $\hat{\sigma}_{GT}$ should provide valuable information on V^c_{GT}.

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