Reaction $^{13}C(n,p)^{13}B$ at 65 MeV

K. Wang,* C. J. Martoff,† D. Počanić,* and S. S. Hanna
Department of Physics, Stanford University, Stanford, California 94305

F. P. Brady, J. L. Romero, C. M. Castaneda, J. R. Drummond, B. McEachern, and D. S. Sorenson‡
Crocker Nuclear Laboratory, University of California-Davis, Davis, California 95616

(Received 19 October 1995)

The reaction $^{13}C(n,p)^{13}B$ has been studied at $E_n = 65$ MeV. Cross sections were measured for transitions to the ground state and excited states of ^{13}B from 0° to 40°. The 0° cross section to the ground state gives a value of 179 ± 20 MeV fm^3 for $V^c_{\sigma\tau}$, the spin-isospin central part of the volume integral of the effective *N*-*N* interaction. A theoretical calculation, 181.3 MeV fm^3, is in good agreement with this result. Distorted-wave impulse-approximation calculations are compared with the experimental angular distributions. Good agreement is obtained for the dominant Gamow-Teller transition to the ground state of ^{13}B. The evidence obtained here, together with results from the analogous reaction $^{13}C(\pi^-,\gamma)^{13}B$, suggests that transitions to states at 6.5 and 7.6 MeV are spin dipole in character and that the broad resonance at 10.2 MeV is chiefly the analog of the giant *E*1 resonance in ^{13}C.

PACS number(s): 25.40.Kv, 21.60.−n, 24.30.Cz, 27.20.+n

I. INTRODUCTION

Charge-exchange reactions have been used as probes to study nuclear structure for many years. Isobar analog transitions were discovered with the (p,n) reaction at a proton energy of 14.0 MeV in 1962 [1]. As the energy increases in a (p,n) or (n,p) reaction the spin-isospin central part of the effective *N*-*N* interaction becomes more important; hence, the (p,n) and (n,p) probes can be used to study spin and isospin changing reactions, such as the Gamow-Teller (GT) excitations, and higher multipole spin transitions. These studies will highlight the role of the one-pion-exchange potential (OPEP) in the interaction [2].

The accumulated data obtained from studying (p,n) reactions have indicated an apparent quenching of the total GT transition strength, which has led to interesting speculation on the role of the Δ-isobar excitations in nuclei [2]. It would be interesting to see to what extent this quenching effect also exists with the (n,p) probe. For this purpose it is necessary to study the excited states of a given nucleus of a given multipole order. Since the charge-exchange (n,p) reaction on stable targets only excites transitions to $T^>$ states (with very few exceptions), where $T^>$ is one unit larger than T_0, the isospin of the target state, the (n,p) reaction is a very useful probe for making isospin assignments. Moreover, the (n,p) reaction plays an important role in astrophysics since it can determine β^- decay strengths [3] of excited states which are important in nucleosynthesis [4], but unmeasurable in the laboratory by means of traditional β-decay measurements.

In this experiment we study prominent transitions to excited states in the $^{13}C(n,p)^{13}B$ reaction.

II. EXPERIMENT

This experiment was performed at the Crocker Nuclear Laboratory at U.C. Davis. A new double-target neutron facility [5–7] (see Fig. 1) has made it possible to extend measurements of (n,p) reaction cross sections to 0° which are highly desirable for these studies. The primary proton beam from the 76-in. isochronous cyclotron is used to produce a nearly monochromatic neutron beam by means of the $^7Li(p,n_0n_1)^7Be$, $^7Be^*$ reaction. The spread in the energy of the neutron beam is well within the experimental resolution. The proton beam has a maximum energy of 67.5 MeV, an energy spread of 350 keV, and a maximum current of 25

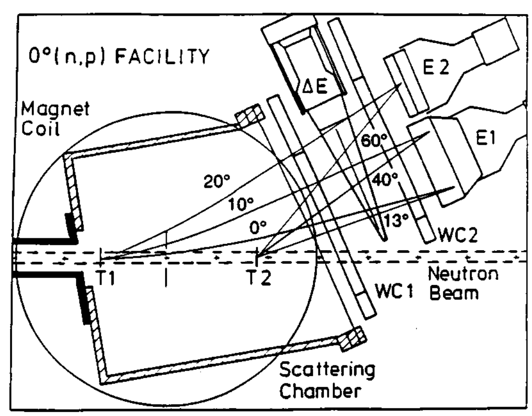

FIG. 1. The detector system of the (n,p) facility at the Crocker Laboratory. *T*1 and *T*2 indicate the two target ladders. Proton paths from *T*1 are labeled 0°, 10°, 20° and from *T*2 13°, 40°, 60°. *T*1 and *T*2 are tangent to the circular field region (not shown). *E*1 and *E*2 are the two detectors described in the text, along with the thin detector ΔE and the wire chambers WC1 and WC2.

*Present address: Department of Physics, University of Virginia, Charlottesville, VA 22901.

†Present address: Department of Physics, Temple University, Philadelphia, PA 19122.

‡Present address: P15, Los Alamos National Laboratory, Los Alamos, NM 87545.

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μA. A 3-m thick concrete wall separates the vault area into two regions: the neutron production region and the (n,p) reaction region. This wall can attenuate the neutron intensity by a factor of about 10^{-4} at 40 MeV [6]. A well-defined neutron beam is produced at 0° by a collimator embedded in the concrete wall.

At the exit of the collimator is located a scattering chamber which houses two target ladders and provides a thin Mylar window through which the protons from the (n,p) reaction can leave the chamber. One target ladder is mounted at the front edge of the field of a 10.4 kG dipole magnet; protons produced at this point will be bent away from the neutron beam to allow those emitted at or near 0° to be detected. The other target ladder is mounted at the rear edge of the magnetic field; protons produced here will not be affected by the magnet. This complete arrangement makes it possible to detect the (n,p) reaction over a range of scattering angles from 0° to 60° (see Fig. 1).

The detector system consists of two large-area E detectors: one is a 125×175 mm^2 oblong NE102 plastic scintillator and the other is a 127-mm-diam circular NaI(Tl) crystal. In front of both E detectors is a 1-mm-thick plastic scintillator sandwiched by two delay-line-type multiwire proportional chambers. The thin scintillator is used as a ΔE detector for particle identification through its characteristic values of dE/dx, whereas the two wire chambers are used for mapping the trajectories of the protons to obtain their angles of emittance. In the present experiment an angular range of 0°–40° was deemed sufficient so that the NaI(Tl) scintillator was not used.

Four different targets were used in this work: ^{13}C (powder), a "blank," CH_2 (polyethylene), and ^{12}C (graphite). The ^{13}C powder had an isotopic purity of 99.9% and was pressed into a rectangular slab 60 mg/cm^2 thick. This target was used for primary data acquisition. The "blank" target provided a background subtraction. A CH_2 (polyethylene) target 50 mg/cm^2 thick produced the ^{1}H$(n,p)n$ reaction which was used to normalize the ^{13}C$(n,p)^{13}$B cross section at each angle. As ^{12}C is a well-studied nucleus at the Crocker Laboratory, the ^{12}C target was included to provide a spectrum that could be used to check the experimental system; it could also be used to subtract the ^{12}C contribution in the CH_2 spectrum in order to obtain clean ^{1}H$(n,p)n$ scattering data.

III. SPECTRA

In Fig. 2, a ^{13}C$(n,p)^{13}$B spectrum obtained in this work at $E_n=65$ MeV is compared with a ^{13}C$(\pi^-,\gamma)^{13}$B spectrum [8]. In the former reaction at 65 MeV and 0° the momentum transfer, $q=0.19$ fm^{-1}, is much smaller than that in pion capture at rest. The GT transitions are enhanced at these small momentum transfers that approach those of the corresponding GT β decays. In the comparison in Fig. 2, the angle chosen for ^{13}C$(n,p)^{13}$B was 19° so as to match the momentum transfer in the ^{13}C$(\pi^-,\gamma)^{13}$B reaction. The two spectra are aligned at the ground state of ^{13}C and plotted to the same excitation scale. It is clear that the spectra have many features in common.

First, it is necessary to recognize the existence of strong continua in both spectra due principally to the three-body breakup processes in the reactions

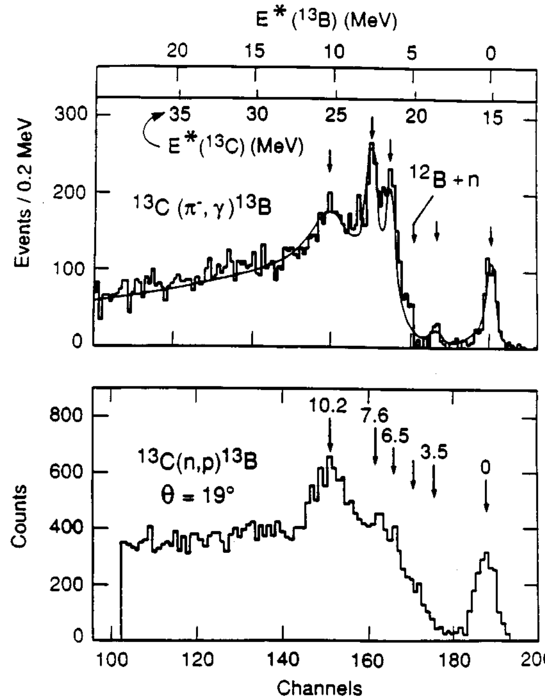

FIG. 2. Comparison of the spectra of ^{13}C$(n,p)^{13}$B and ^{13}C$(\pi^-,\gamma)^{13}$B. The features pointed out are discussed in the text.

$$^{13}\mathrm{C}(\pi^-,\gamma)^{13}\mathrm{B}^*(n)^{12}\mathrm{B},$$

$$^{13}\mathrm{C}(n,p)^{13}\mathrm{B}^*(n)^{12}\mathrm{B}.$$

Such processes have been observed for many years [9] and their continuum shapes can be related to details of the breakup processes [9,10]. The continua in the present and similar reactions have previously been attributed to such three-body breakup mechanisms and treated accordingly [8,11]. In Fig. 2 the upper ends of the continua in both proton spectra are indicated by the arrows at $E^*=4.9$ MeV [labeled ^{12}B$+n$ in the (π^-,γ) spectrum].

Superposed on the continua are peaks indicating transitions to states in ^{13}B (see Fig. 5) excited by the two-body reactions

$$^{13}\mathrm{C}(n,p)^{13}\mathrm{B}^* \text{ and } ^{13}\mathrm{C}(\pi^-,\gamma)^{13}\mathrm{B}^*.$$

At 0 MeV excitation in ^{13}B both reactions show a strong ground-state transaction. At $E_x=3.5$ MeV the (π^-,γ) reaction shows a weak transition which might also be present in the (n,p) reaction to account for the yield above the continuum observed in all the (n,p) spectra (see Figs. 2–4). The better resolution of the (π^-,γ) reaction shows a prominent doublet at 6.5 and 7.6 MeV. In Fig. 2 there is possible structure in the (n,p) yield that is consistent with this doublet, but in most other spectra the poorer resolution of the (n,p) reaction precludes positive identification of a doublet (see Figs. 3 and 4). Nevertheless, on the basis of the (π^-,γ) evidence we accept the presence of a doublet and analyze all the

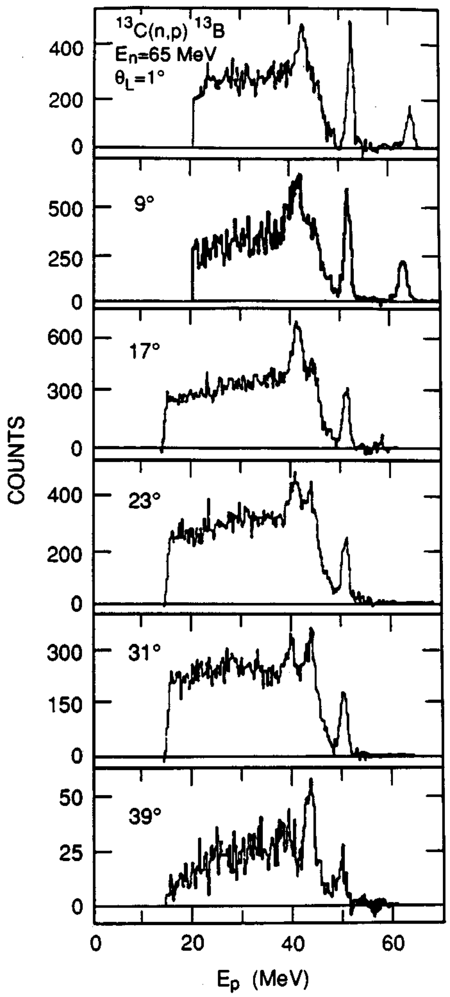

FIG. 3. The spectrum of $^{13}C(n,p)^{13}B$ at 65 MeV and at six angles between 0° and 40°. The three peaks seen at $E_p=51$, 44, and 50 MeV in the 31° spectrum are seen in most other spectra and attributed to levels in ^{13}B; see text.

(n,p) spectra by fitting a doublet to the yield in the region (see Fig. 4), but we present results only for the combined yield of the doublet. The final structure that is identified in all the spectra of both reactions is the dominant broad peak at 10.2 MeV (see Figs. 2–4).

Figure 3 shows the proton spectrum from $^{13}C(n,p)^{13}B$ at $E_n=65$ MeV and angles from 1° to 39°. The prominent peak at $E_p=52$ MeV and $\theta=1°$ corresponds to the ground state of ^{13}B. The smaller peak at higher energy is due to a small hydrogen impurity in the ^{13}C target. (Recall the very high cross section for $n+p$ scattering.) No CH_2 was used in preparing the target. At small angles the hydrogen peak is well separated from the ground state, but at angles larger than 23° this hydrogen peak moves kinematically into the ^{13}B spectrum and it is necessary to subtract it out (as has been done for 17° and above). The ground-state peak is observed prominently at all angles in these spectra. The prominent peak at $E_x=10.2$ MeV ($E_p\cong 42$ MeV and $\theta=1°$) is strong at small angles in Fig. 3, but becomes very weak at larger angles, whereas for the peak at 7.0 MeV, corresponding to the presumed doublet (see Fig. 2), the angle dependence is just reversed. These spectra clearly establish the

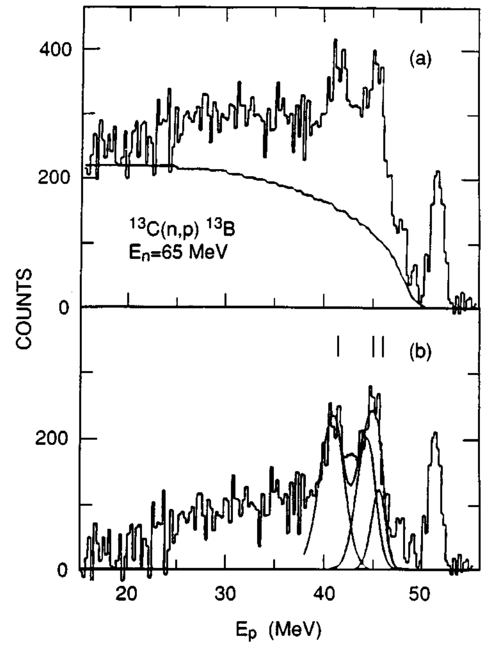

FIG. 4. Spectrum at $E_n=65$ MeV and $\theta=21°$, illustrating the removal of the calculated continuum and the resolution of the excited-state structures into three peaks. In the discussion the two members of the doublet are added together and treated as a single resonance.

existence of the structure at 7.0 MeV and a marked difference in its angular distribution compared to the 10.2 MeV resonance.

The pertinent energy levels of ^{12}B and ^{13}B are compared in Fig. 5 [8,12]. As indicated, one can relate levels in ^{13}B to those in ^{12}B by recognizing shifts in the ^{12}B core states and splittings due to the "valence" neutron in ^{13}B [13]. In addition, the Q values of the reactions $^{12}C(n,p)^{12}B$ and

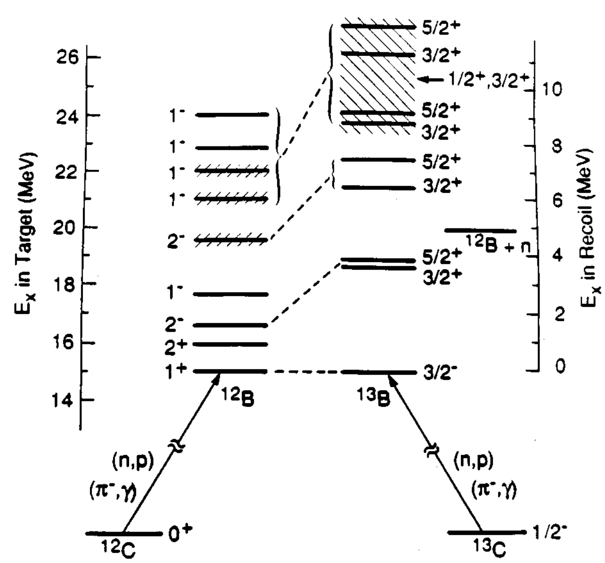

FIG. 5. Comparison of levels of ^{12}B and ^{13}B, chosen and arranged to illustrate the spectator model used to describe the levels and transitions; see text.

$^{13}C(n,p)^{13}B$ are very nearly the same, -12.59 MeV and -12.65 MeV, respectively, as are the β-decay $\log(ft)$ values of ^{12}B and ^{13}B, 4.10 and 4.01, respectively [14]. These properties, as well as others, suggest that the valence neutron in ^{13}C is loosely attached to the even-even ^{12}C core and the observed (π^-,γ) and (n,p) reactions interact mainly with the core to produce excited ^{12}B core states while the valence neutron remains a spectator [13], its spin coupling to the core to produce doublets.

In Fig. 5 the levels given for ^{12}B are all experimentally observed [14] and identified; the lower five are well identified and studied, whereas the upper four are more tentative. The excited states shown for ^{13}B as sharp levels are from a calculation for radiative pion capture [12]. The $3/2^+$, $5/2^+$ doublets are assumed to arise from a coupling between the ^{12}B core, excited into a 2^- state, and the $p_{1/2}$ spectator neutron. The excitation of such a doublet in ^{13}B from ^{13}C by a charge-exchange reaction is thus assumed to be primarily an excitation from the 0^+ ground state of the ^{12}C to a 2^- state in the ^{12}B core. These 2^- states in ^{12}B are analogs of the 2^- states in ^{12}C that could make up the giant $M2$ resonance [15] excited by electromagnetic transitions from the ground state of ^{12}C. The charge-exchange transitions, $0^+\rightarrow 2^-$ in the cores or $1/2^-\rightarrow 3/2^+$, $5/2^+$ in the whole nuclei, have been called charge-exchange spin-dipole excitations. In Figs. 2–4 the possible structure observed at 3.5 MeV is believed to correspond with the lowest doublet [unresolved in both the (π^-,γ) and (n,p) reactions] in ^{13}B, and the structure around 7.0 MeV to the next higher (resolved in the pion capture reaction) doublet. The peak at 10.2 MeV is believed to be the ^{13}B analog of the $T=1$ giant resonance (GDR) in ^{13}C, as discussed below.

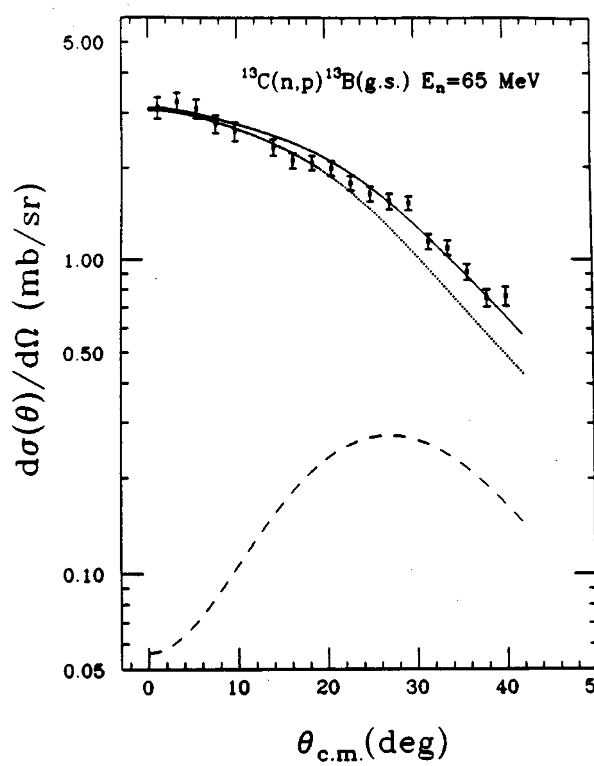

FIG. 6. Angular distribution of the reaction $^{13}C(n,p)^{13}B$ (g.s.) at 65 MeV. For the $1/2^-$ to $3/2^-$ transition, $\Delta J^\pi=1^+$ or 2^+. The dotted curve is the calculation for the former value, normalized by $N=0.6$ and the dashed curve for the latter value, normalized by $N=0.3$. The solid curve is the sum of these contributions shown for comparison with the data.

IV. ANGULAR DISTRIBUTIONS

The angular distributions for exciting these states in the (n,p) reaction can help in determining the ΔJ^π values of the transitions. (See the characteristic angular distributions for the various transitions in Figs. 6–8.) The ΔJ^π values in turn aid in assigning or confirming the J^π quantum numbers of the states involved.

A. The transition to the ground state

The ground-state transition in $^{13}C(n,p)^{13}B$ is the reverse process of the β^- decay from ^{13}B to ^{13}C. The ΔJ^π value for the transition $(1/2^-,1/2)$ to $(3/2^-,3/2)$ can be 1^+ or 2^+. However, the dominant mode is the spin-isospin flip transition with $\Delta J^\pi=1^+$, $\Delta T=1$, $\Delta L=0$, $\Delta S=1$, namely, a GT transition. The other three modes ($\Delta J=1^+$, $\Delta L=2$, $\Delta S=1$; $\Delta J=2^+$, $\Delta L=2$, $\Delta S=0$; and $\Delta J^+=2^+$, $\Delta L=2$, $\Delta S=1$) are quadrupole in nature and expected to be much less intense. Indeed, the observed angular distribution of the ground state transition, shown in Fig. 6, is strongly peaked at forward angles as is typical of a GT transition. The curves in Fig. 6 are calculated in a distorted-wave impulse approximation (DWIA) with the code DW81 [16]. The experimental $Q=-12.65$ MeV was used. The transition strength was taken from [17] (after transformation from L-S to j-j coupling) and the optical potential from [18]. The N-N effective interaction was obtained by interpolating between the Franey-Love [19] t-matrix interactions at 50 and at 100 MeV. In the radial wave functions the harmonic-oscillator size parameter was taken as 1.82 fm. At 0° the 1^+ and the 2^+ transitions are calculated to contribute 96.5 and 3.5 %, respectively. In addition, the 1^+ transition is predicted to be dominated by the GT transition amplitude as mentioned above. With the chosen normalizations noted in the figure caption, the theoretical curve provides a very good fit to the data.

Using the measured 0° cross section $d\sigma/d\Omega=3.11\pm0.24$ mb/sr and its dependence on the known β-decay strength and the effective N-N interaction [20], we find that the spin-isospin central part of the volume integral of the effective N-N interaction is $V^c_{\sigma\tau}=179\pm20$ MeV fm^3. The theoretical value of 181.3 MeV fm^3 at $E_p=50$ MeV is in good agreement. This theoretical value was calculated with the procedure of [21] and the N-N t-matrix interaction strength given in [19]. In extracting the experimental value of the volume integral, a value of 0.28 was used for the distortion factor as obtained from the procedure in [22]. The measured 0° unit cross section [23,24] for the ground-state transition at 65 MeV is smaller than the value 7.24 ± 0.33 mb/sr obtained at 200 MeV [25]. This result is discussed in [24].

B. The transition to the 7.0 MeV structure

If we use the spectator model to describe the resonance at 7.0 MeV, the transitions from the ground state of ^{13}C to the

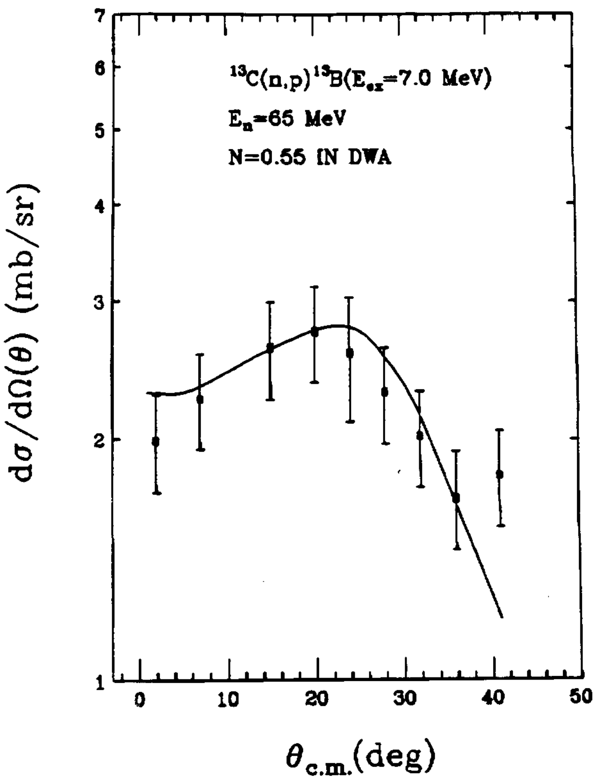

FIG. 7. Angular distribution of the reaction $^{13}C(n,p)^{13}B$ (7.0 MeV) at 65 MeV. The data and the theory (solid curve) are summed over the two members of the doublet at 7.0 MeV. The theory is normalized so as to facilitate comparisons of the shapes of the angular distributions. The resonance is primarily spin-dipole in nature. See text.

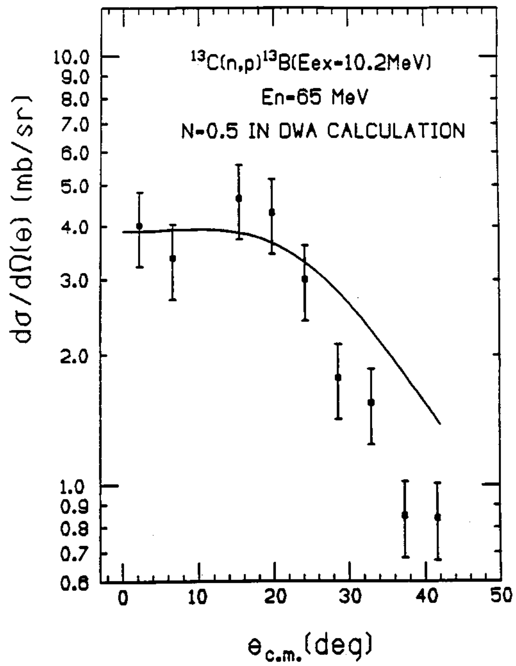

FIG. 8. Angular distribution of the reaction $^{13}C(n,p)^{13}B$ (10.2 MeV) at 65 MeV. The theory is normalized so as to facilitate comparisons of the shapes of the angular distributions. The resonance is primarily GDR in nature. See text.

doublet states, $1/2^- \rightarrow \{5/2^+, 3/2^+\}$, reduce to simply the $0^+ \rightarrow 2^-$, charge-exchange transition in the ^{12}C core. Thus we have

$$\Delta J^{\pi} = 2^-, \quad \Delta L = 1,3, \quad \Delta S = 1.$$

In a shell-model description the $\Delta L = 3$ excitation would be very small compared to the $\Delta L = 1$ choice. Thus we are led to the spin-dipole excitation

$$\Delta J^{\pi} = 2^-, \quad \Delta L = \Delta S = 1.$$

The angular distribution shown in Fig. 7 was calculated in DWIA [16], as for the ground-state transition. Separate angular distributions were obtained for each member of the doublet in ^{13}B, $1/2^- \rightarrow 3/2^+$ and $1/2^- \rightarrow 5/2^+$, with the shell-model transition strengths given by Millener [26]. The spin angular distributions obtained were very similar to each other, as they should be if the core transition is dominant. Thus, the calculated angular distributions were summed for comparison with the summed data in Fig. 7. We see that the fit is very reasonable.

This assignment of the doublet to a spin-dipole transition is nicely corroborated by the observation [27] of a strong transition in the parent reaction $^{12}C(d,^2He)^{12}B$ to the parent 2^- level in ^{12}B at $E_x = 4.5$ MeV (see Fig. 5). This reaction is expected to pick out states of the spin-flip type and thus supports the model in which the core of this doublet in ^{13}B is in a spin-flip 2^- state. The reaction $^{12}C(p,n)^{12}N$ also indicates [28] a spin-dipole transition to the mirror 4.5 level in ^{12}N.

C. The transition to the 10.2 MeV state

In the region of 10.2 MeV in ^{13}B a broad peak is seen in the spectra in Figs. 2 and 3, which corresponds to the hatched area in Fig. 5. Some spin-dipole doublets are possible in this region, as shown, but the corresponding 2^- core levels have not been positively identified in ^{12}B. On the other hand, this is the region in ^{13}B in which the analog of the giant isovector dipole $E1$ resonance (GDR) based on the ground state of ^{13}C should be found. This analog GDR is to be clearly distinguished from the photonuclear GDR based on the ground state of ^{13}B. The observed width of this analog resonance also helps to identify it as the expected GDR. This resonance would be the $T_z = 3/2$ analog of the photonuclear GDR in ^{13}C ($T_z = 1/2$) and it has recently been observed [29] clearly isolated in the charge-exchange reaction $^{13}C(\pi^-,\pi^0)^{13}B$.

In the spectator model this analog GDR could be formed by coupling appropriate 1^- levels of ^{12}B to the $p_{1/2}$ spectator neutron to give the broad $1/2^+, 3/2^+$ dipole structure shown by the hatched area in ^{13}B (Fig. 5). Such 1^- levels in ^{12}B should be at the correct position to be identified as contributing to the GDR analog of the photonuclear GDR in ^{12}C. This ^{12}B analog GDR has also been clearly seen [29] via the charge-exchange reaction $^{12}C(\pi^-,\pi^0)^{12}B$ and it has been identified theoretically in pion capture on ^{12}C [30].

If the resonance at 10.2 MeV in ^{13}B is $E1$ in nature it should consist chiefly of non-spin-flip $1/2^+$ and/or $3/2^+$ states. Then for transitions from the $1/2^-$ ground state of ^{13}C:

$$\Delta J^\pi = 1^-, \quad \Delta L = 1, \quad \Delta S = 0,$$

for either state. In the spectator model we would have the same quantum numbers, which would give an angular distribution quite distinct from that of the spin-flip case found for the doublet at 7.0 MeV. The angular distribution shown by the curve in Fig. 8 was calculated with the transition strength given by Millener. Where the analysis and statistics are reasonably good, out to about $\theta = 20°$, the data in Fig. 8 are in reasonable agreement with the DWIA calculation. Beyond 20° the data fall off faster than the calculation, indicating a possible mixture of spin-flip strength (see Fig. 7) which could come from the excitation of other 1^- or 2^- core states. However, we note that the reaction $^{12}C(d,{}^2He)^{12}B$ does not show spin-flip strength in this region.

In conclusion we have found that for the (n,p) ground-state transition the theoretical value of the volume integral of the spin-isospin part of the N-N effective interaction is in good agreement with experiment. We have obtained plausible assignments that the (n,p) transitions to the 0, 7.0, and 10.2 MeV resonances in ^{13}B are principally of the GT, spin-dipole, and GDR types, respectively. We note that the shapes of the three angular distributions in Figs. 6–8 are all quite dissimilar, providing the basis on which the assignments are made. Figure 5 summarizes the spectator model which we have used to discuss the (n,p) reactions on $^{12,13}C$ targets in comparison with the (π^-,γ) capture reaction.

We are very grateful to D. Kurath and D. J. Millener for discussions and for providing us with the results of their calculations. This work was supported by grants of the National Science Foundation.

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