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The ^{13}C$(p,n)^{13}$N reaction to the $3/2^{-}T=3/2$ state at 15.06 MeV

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Abstract

The zero degree cross section for the ^{13}C$(p,n)^{13}$N reaction has been measured at 200 MeV incident energy, with an energy resolution of 800 keV. Of particular interest is the transition to the ^{13}N$(15.06\text{ MeV}, 3/2^{-}T=3/2)$ level, since a previous measurement of this cross section is inconsistent with that for the isobaric analog level excited in the ^{13}C$(n,p)^{13}$B$_{g.s.}$ reaction. The present measurement yields a cross section significantly less than that previously reported, and in agreement with that for the (n,p) reaction.

Keywords: Nuclear reaction ^{13}C(p,n), 200 MeV measured $\sigma(E_x, 0°)^{13}$N.
Deduced $\sigma(p,n)$, $B(GT)$ proportionality.
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I. INTRODUCTION

The relation of the transition matrix elements involving the isovector components of the nucleon-nucleon interaction to weak-decay matrix elements has received much attention, both theoretically and experimentally. Specifically, the similarities of the operators for the spin-flip and non-spin-flip central isovector terms of the effective nucleon-nucleon interaction to those for Gamow-Teller (GT) and Fermi (F) β decay, respectively, led to the suggestion that there should be a proportionality between (p,n) cross sections and β decay transition strengths.[1-4] Such a relationship, if it could be reliably demonstrated, would permit the investigation of weak-interaction matrix elements in regions energetically forbidden in beta decay, as well as leading to a greater understanding of nuclear reaction mechanisms themselves.[5]

A recent careful study[5] of the relationship of (p,n) cross sections at small angles to the corresponding β-decay transition rates showed that for L=0 spin-flip transitions in the Distorted Wave Impulse Approximation (DWIA) model the cross section could be expressed as:

$$\sigma_{pn}(q,\omega,A,\alpha) = \hat{\sigma}_{\mathrm{GT}}^{-}(A)F(q,\omega)B_{\mathrm{GT}}^{-}(A,\alpha)\ , \qquad (1)$$

where q is the momentum transfer, ω is the energy loss and α specifies the final state of the recoil nucleus of mass A. $F(q,\omega)$ is a form factor, calculable in the DWIA model, which approaches unity as q and ω approach zero. Since $\hat{\sigma}_{\mathrm{GT}}^{-}$ (referred to as the "unit cross section") can also be calculated in the DWIA model, direct comparisons can be made between experimental measurements and theoretical predictions. It was found that a proportionality between σ_{pn} and B_{GT}^{-} does indeed exist, although the ratios for specific nuclei may show significant deviations from the smooth A dependence predicted by DWIA.

For the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction, the ratio $\sigma_{pn}/B^{-}_{\mathrm{GT}}$ was found[5] to be ≈40–50% higher than for either $^{12}\mathrm{C}$ or $^{14}\mathrm{C}$. Consistent values of the ratio $\sigma_{pn}/B^{-}_{\mathrm{GT}}$ were found for transitions to the $1/2^{-}; T=1/2$ ground state and the $3/2^{-}; T=3/2$ 15.06 MeV state of $^{13}\mathrm{N}$. From this and similar observations for other nuclei, it was concluded that a single proportionality constant characterized $\hat{\sigma}$ for all GT transitions originating from the *same* target nucleus, although the constant might differ for different nuclei.

The (n,p) reaction bears the same relation to β^{-} decay that the (p,n) reaction does to β^{+} decay. Measurements of (n,p) reaction cross sections to members of the same isospin multiplet as those reached through the (p,n) reaction permit comparisons to be made between the two reactions, whose cross sections are related (except for kinematic factors) by isospin symmetry considerations. Measurements of the $^{13}\mathrm{C}(n,p)^{13}\mathrm{B}$ reaction[6] at 200 MeV show a significant discrepancy between values of the ratios for transitions to the analogue states $^{13}\mathrm{B}_{g.s.}$ and $^{13}\mathrm{N}(15.06)$:

$$\sigma(n,p)/B^{+}_{\mathrm{GT}} = 10.96 \pm 0.56$$

$$\sigma(p,n)/B^{-}_{\mathrm{GT}} = 14.7 \pm 1.1 \quad .$$

Measurements of $\sigma(p,n)/B^{-}_{\mathrm{GT}}$ for $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ have been reported at other energies,[5,7] but all are consistent with the 200 MeV result, and not in agreement with that for $\sigma(n,p)/B^{+}_{\mathrm{GT}}$ at 200 MeV. Some uncertainty in this comparison arises from the fact that while the (n,p) result uses the experimental value of the comparative half-life, (ft), for the $^{13}\mathrm{B} \rightarrow {}^{13}\mathrm{C}_{g.s.}$ beta decay in order to determine B^{+}_{GT}, the analog decay from the $^{13}\mathrm{N}(15.06\ \mathrm{MeV})$ state cannot be measured directly. The estimate of B^{-}_{GT} used in reported measurements of $\sigma(p,n)/B^{-}_{\mathrm{GT}}$ was obtained from the $^{13}\mathrm{B}$ decay modified by the measured decay rate asymmetry between $^{12}\mathrm{B} \rightarrow {}^{12}\mathrm{C}_{g.s.}$ and $^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C}_{g.s.}$. It was argued that this should give a reasonable estimate, given the similarity in structure amplitudes and transition energies in the $^{13}\mathrm{N}(15.06\ \mathrm{MeV}) \rightarrow {}^{13}\mathrm{C}_{g.s.}$ and $^{12}\mathrm{N} \rightarrow {}^{12}\mathrm{C}_{g.s.}$ transitions. From this approach, it is found that $B^{-}_{\mathrm{GT}} = 0.23 \pm 0.01$, the uncertainty being due to the difference in the asymmetry parameters for the A=12 and A=13 systems.

Since isospin symmetry would require that $\hat{\sigma}_{pn}$ and $\hat{\sigma}_{np}$ should be equal for transitions to isobaric analog states, it is of considerable interest to remeasure the (p,n) result. At the same time this measurement will serve to test the conjecture of "specific proportionality" for (p,n) reactions,[5] i.e. the suggestion that $\sigma(p,n)/B^{-}_{\mathrm{GT}}$ is a constant for all transitions originating in a given target nucleus.

II. EXPERIMENTAL

Measurements of the zero degree cross section for the $^{13}\mathrm{C}(p,n)^{13}\mathrm{N}$ reaction were carried out at incident beam energy of 200 MeV, using the TRIUMF charge exchange facility in the standard (p,n) configuration.[8] The recoil proton radiator was a liquid scintillator (Bicron BC 513) $2.5 \times 2.5 \times 7\ \mathrm{cm}^3$. In order to achieve a well-defined beam energy spread, the incident beam was momentum dispersed across a strip target which intercepted only part of the beam. The $^{13}\mathrm{C}$ target was a self-supporting strip, 4.5 mm wide with thickness 63.5 mg/cm^2. It was made by wetting $^{13}\mathrm{C}$ powder (isotopic enrichment 99.1%) with ether and pressing the resulting paste to the required shape. Such targets were rather fragile, but proved satisfactory for these measurements. The isotopic purity of the final target was confirmed by observation of the $^{12}\mathrm{C}(p,p')^{12}\mathrm{C}$ (4.44 MeV) reaction. The count rate for this reaction relative to elastic scattering from $^{13}\mathrm{C}$ indicated that the target contained 1±0.2% $^{12}\mathrm{C}$.

The cross section for the 15.06 MeV state of primary interest was determined relative to that for the summed cross section to the ground and 3.51 MeV states of

^{13}N. The cross section for the latter states had been determined relative to that for ^{7}Li$(p,n)^7$Be (ground + 0.43 MeV) reaction in an earlier measurement.[9] This indirect procedure was required since the dispersed beam tune used to obtain good energy resolution in the present measurement made it impossible to obtain an accurate measurement of integrated beam intensity on target.

Because of the relatively large difference in Q values between the reference groups and the group of interest, it was also necessary to determine the acceptance of the spectrometer as a function of focal plane position, using the ^{7}Li(p,n) reaction with a non-dispersed beam tune.

III. RESULTS AND ANALYSIS

A typical raw spectrum for the ^{13}C$(p,n)^{13}$N reaction is shown in Fig. 1(a). The energy resolution of the data is about 800 keV, with most of the spread arising from the scintillator signal. This spectrum requires correction for the effect of ^{12}C in the recoil scintillator, which gives rise to protons from the ^{12}C$(n,p)^{12}$B reaction.[8] In the spectrum shown, neutrons leading to the ground and 3.51 MeV states in ^{13}N give rise to protons from the ^{12}C$(n,p)^{12}$B$_{\rm g.s.}$ reaction with energies indicated by the arrows. The location and intensity of these groups relative to the corresponding groups from the ^{1}H$(n,p)n$ reaction are reliably established from observation of the spectrum produced by neutrons from the ^{7}Li(p,n) reaction. These are show as the dashed peaks in Fig. 1(a). The second correction is for the variation in acceptance over the region of interest in the spectrum. A spectrum corrected for both effects is shown in Fig. 1(b).

In order to estimate the cross section for the neutron group to the 15.06 MeV state, the spectrum was fitted with peaks having a skewed Gaussian shape, after subtraction

of a continuum background. It is the estimation of this background which introduces the largest uncertainty in the final result.

As an estimate of plausible background, it was assumed that the continuum cross section had a quadratic energy dependence in the region from about 6.8 MeV to 17.3 MeV, as shown by the dashed curve in Fig. 2. The remaining cross section was then fitted by peaks at the location of known states of $J^\pi = 1/2^-$ or $3/2^-$, plus a broad peak centred near 13.5 MeV. This assumption yields an estimate of the cross section of 1.85 ± 0.11 mb/sr.

IV. DISCUSSION

The motivation for this measurement comes from the observation of the apparent lack of isospin symmetry between the two reactions ^{13}C$(n,p)^{13}$B(g.s.) and ^{13}C$(p,n)^{13}$N (15.06 MeV,T=3/2) which populate analog states in ^{13}B and ^{13}N. In the (n,p) reaction, the cross section is normalized directly to the ^{1}H$(n,p)n$ reaction cross section. Furthermore, since the transition is to the ground state of the final nucleus, possible interference from other states is expected to be small. As a result, the cross section is reported as 10.96±0.56 mb/sr at zero degrees, with an overall uncertainty of 6% in the measurement. In contrast to this, the (p,n) measurement requires normalization to the ^{7}Li$(p,n)^7$Be (g.s. + 0.43 MeV) cross section in a separate measurement, with possible uncertainties arising from beam focus on the target and from current integration. At an excitation energy of 15 MeV, there is also a significant continuum in the spectrum, so that background subtraction introduces significant uncertainty in the cross section for the group of interest.

It should be noted that ^{12}C contamination in the target is a problem in either measurement, since the reactions ^{12}C$(n,p)^{12}$B$_{\rm g.s.}$ and ^{13}C$(n,p)^{13}$B$_{\rm g.s.}$ have almost equal

Q values, as do the reactions $^{12}C(p,n)^{12}N_{g.s.}$ and $^{13}C(p,n)^{13}N(15.06\text{ MeV})$. It was for this reason that the ^{12}C content in the ^{13}C target was measured in this experiment, in order to confirm the isotopic composition of the target material which was used both in this and in the (n,p) measurement.

The most important source of uncertainty in this measurement arises from the subtraction of the continuum background in the region of the peak of interest, with a cross section of 1.85 mb/sr for the 15.06 MeV state resulting from our assumption about the magnitude of the background. This value is significantly less than that in Ref. 5, and with the value of $B^-_{\rm GT}$ given in Ref. 5 yields a value $\hat{\sigma}_{pn} = 9.81 \pm 0.8$, in good agreement with the reported value of $\hat{\sigma}_{np} = 10.96 \pm 0.56$.

A further problem in comparing $\hat{\sigma}_{pn}$ and $\hat{\sigma}_{np}$ arises from the fact that $B^+_{\rm GT}$ is known from the ^{13}B beta decay while $B^-_{\rm GT}$ corresponding to the $^{13}N(15.06\text{ MeV}) \rightarrow {}^{13}C(\text{g.s.})$ beta decay cannot be measured directly. In Ref. 5 it is assumed that $B^-_{\rm GT}$ may be related to $B^+_{\rm GT}$ using the value of the beta decay asymmetry parameter[11] $\delta = (B^-_{\rm GT}/B^+_{\rm GT}) - 1$ measured for the A=12 triad ^{12}B, ^{12}C, and ^{12}N. While there is some plausibility in this approach, it is difficult to estimate what the resulting uncertainty in $B^-_{\rm GT}$ might be. It may be expected, however, that this approach yields an upper limit for $B^-_{\rm GT}$. Theoretical studies of the asymmetry[12] have shown that it is very sensitive to the difference in binding energies of the neutron or proton undergoing beta decay. Since the proton in ^{12}N is bound by 0.60 MeV while that in ^{13}N is unbound, it would be expected that the matrix element for the $^{13}N(15.06\text{ MeV})$ decay will be smaller than that for the $^{12}N_{g.s.}$ decay.

In conclusion, we have found that the zero degree cross section for the $^{13}C(p,n)^{13}N$ (15.06 MeV) reaction is at least 30% smaller than reported in earlier measurements.

This result is then consistent with equality of the reduced cross sections $\hat{\sigma}_{pn}$ and $\hat{\sigma}_{np}$, although this is the strongest conclusion that can be reached in the absence of further information about $B^-_{\rm GT}$.

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Table I. Comparison of reduced cross sections for transitions to analogue states in ^{13}B, ^{13}N.

$^{13}C(n,p)^{13}B_{g.s.}$ [a]				$^{13}C(p,n)^{13}N$(15.06 MeV)			
B^{+}_{GT}	$F(\omega,q)$	$\sigma(0°)$ mb/sr	$\hat{\sigma}_{np}$ mb/sr	B^{-}_{GT} [b]	$F(\omega,q)$	$\sigma(0°)$ mb/sr	$\hat{\sigma}_{pn}$ mb/sr
0.759 ±0.018	0.87	7.24 ±0.33	10.96 ±0.56	0.23 ±0.01	0.82	1.85 ±0.11	9.81 ±0.8

[a] Ref. 7.
[b] Ref. 5.

Figure captions

1. (a) Spectrum of the $^{13}C(p,n)^{13}N$ reaction at 200 MeV and zero degrees. The peaks arising from the $^{12}C(n,p)^{12}B_{g.s.}$ reaction in the liquid scintillator of the neutron detector are shown dotted at locations indicated by arrows.
(b) Spectrum (a) corrected for spectrometer acceptance and contributions from the $^{12}C(n,p)$ reaction.
2. High-energy portion of spectrum 1(b) showing assumed background (dashed curve) and fitted peaks. The indicated excitation energies and spins are for known levels in ^{13}N.

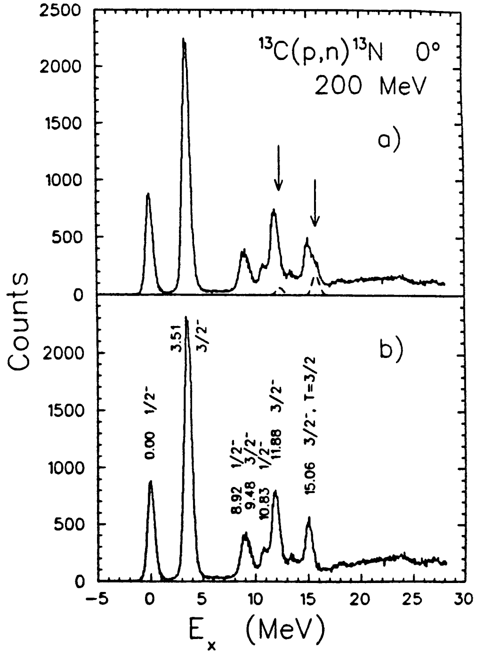

Fig. 1

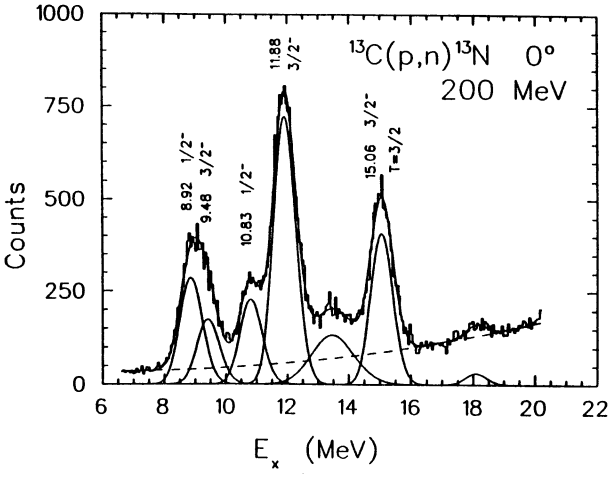

Fig. 2