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The (n,p) reaction as a probe of Gamow-Teller strength

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Abstract

The ground state differential cross sections for the (n,p) reaction at 0° on ^{6}Li, ^{12}C and ^{13}C have been measured for 198 MeV neutrons with a precision of about 4%. These data, together with the accurately known ft values for the β^- decay of ^{6}He, ^{12}B and ^{13}B provide three calibrations of the (n,p) reaction as a probe of Gamow–Teller strength for isospin raising transitions.

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Studies of the (p,n) reaction at intermediate energies and forward angles have revealed much about simple isovector modes of nuclear excitation, particularly the Gamow-Teller resonance prominent in most nuclei from ^{2}H to ^{208}Pb [1-6]. An essential first step in the quantitative analysis of the (p,n) data was a systematic series of measurements of the cross sections at 0° for transitions for which the Gamow-Teller strength, B_{GT}, was already known from β decay [1].

For some time it has been realized that the (n,p) reaction could provide crucial information complementary to the (p,n) results [7-9]. In particular, this reaction offers unique potential as a quantitative probe of B^+_{GT}, the distribution of Gamow-Teller strength for isospin raising transitions. We report here results of the first facility in operation to exploit the (n,p) reaction as a detailed probe of nuclear structure at energies above 70 MeV [10-13]. Given the interest in measurements of B^+_{GT}, the precise calibration of the probe was an early priority of the program. The accurately known ft values for the β^- decay of ^{6}He [14], ^{12}B [15] and ^{13}B [16] to the ground states of the daughter nuclei provide ideal opportunities for this calibration. Consequently the results presented here are for the (n,p) reaction at 0° on ^{6}Li, ^{12}C and ^{13}C. The incident neutron energy, E_n = 198 MeV, was chosen to permit direct comparison with the most recent results for the corresponding (p,n) analogue transitions at E_p = 200 MeV [17].

The TRIUMF charge exchange facility utilizes the Medium Resolution Spectrometer (MRS) in the study of both (p,n) and (n,p) reactions at forward angles in the energy range between 190 and 500 MeV [10,12]. Fig. 1 of ref. [18] illustrates many of the features common to both modes of operation. For (n,p) studies, a nearly monoenergetic neutron beam is produced by the (p,n) reaction in a ^{7}Li primary target.

This beam is incident on a series of six targets centered on the axis of rotation of the MRS. The origin of an (n,p) event is identified by the hit pattern in multiwire proportional chambers (MWPC) separating each of the targets. This segmented target chamber, described in detail in ref. [19], permits the use of more (n,p) target material while maintaining the required energy resolution. Another advantage, important in the results presented below, is the precision with which (n,p) cross sections can be normalized.

Fig. 1a illustrates the spectrum obtained for the $^{12}C(n,p)^{12}B$ reaction at 0°. Natural carbon targets (each 5 cm high, 2 cm wide and 92 mg/cm^2 thick) were mounted in the central 4 positions of the segmented chamber. The spectrum shown is the sum for all 4 targets with suitable energy loss corrections. The spectrum is dominated by the peak resulting from the (n,p) reaction populating the ground state of ^{12}B ($Q_0 = -12.6$ MeV). The observed energy resolution results from comparable contributions from energy spread of the incident proton beam, energy loss in the 110 mg/cm^2 ^7Li target, the difference in energy of neutrons populating the lowest 2 states in ^7Be and energy loss in the carbon targets. The smaller peak at $Q = 0$ is associated with the (n,p) reaction on hydrogen mainly in the mylar foils of the MWPC's and in the counter gas (50% isobutane, 50% argon in this case). This background and a very small contribution at lower energies can adequately be accounted for with an 'empty spectrum' recorded with the carbon targets removed.

Fig. 1b is an (n,p) spectrum recorded simultaneously with that in 1a for CH_2 located in the first and last target positions. The $^{12}C(n,p)$ cross section is measured relative to that for the $H(n,p)$ peak that dominates this spectrum. The observed ratio of these cross sections, R, is completely insensitive to the incident neutron flux,

to computer dead time and to the efficiencies of all wire chambers except those in the target chamber. Any small differences associated with individual target locations are monitored by a separate measurement with CH_2 located in all target positions.

The value $R_0 = 0.188 \pm 0.005$ is the ratio of counts in the dominant peaks in fig. 1a and 1b divided by the ratio of C and H nuclei in the C and CH_2 targets respectively. Corrections to this result are made to account for subtraction of the empty target spectra and for inefficiencies in individual wire planes of the (n,p) target chamber. A measured difference in the angular distributions for the (n,p) reactions on ^{12}C and H combined with the finite spectrometer acceptance results in a 2.5% correction to obtain the true ratio at 0°. Estimates are also made of small contributions to the C spectrum from the (n,p) reaction populating the 0.95 MeV state in ^{12}B and on the 1.1% ^{13}C present in the target. Finally, a correction is made for the measured dependence of the spectrometer acceptance on the focal plane coordinate. None of these corrections exceeds 6%. Including all of the above corrections and all reasonable uncertainties, one obtains the value $R = 0.183 \pm 0.008$.

A second largely independent estimate of R is derived from a single spectrum similar to that shown in fig. 1b with CH_2 targets in all 6 secondary target locations. One obtains $R = 0.178 \pm 0.008$ where the uncertainty is dominated by that associated with estimating the area of the $^{12}C(n,p)$ peak. Averaging these two consistent results and accounting for common systematic error leads to the value of R given in Table 1.

The spectra shown in Fig. 2a and 2b are those for the (n,p) reaction on ^6Li and ^{13}C, respectively. For ^{13}C the secondary target material was in the form of fine powder (99% ^{13}C) contained in 4 copper frames covered with thin (3.5 mg/cm^2) mylar foils. The average thickness of ^{13}C in each target was 81 mg/cm^2. Care was taken in the analysis to exclude events originating in the copper frames by raytracing [12] and to subtract an $(8.4 \pm 2.0)\%$ contribution from ^{12}C in the mylar containment windows and in the materials of the target box. The ^{6}Li and ^{13}C cross sections were also measured relative to that for the $H(n,p)$ reaction and the corresponding values of R quoted in Table 1 include all corrections and estimates of both statistical and systematic errors.

The values of R given in Table 1 are the most direct expressions of the results of this experiment. They represent in each case the ratio in the lab frame of the cross section of interest to that for the $H(n,p)$ reaction. In order to obtain absolute cross sections from the ratios listed in Table 1 the value for the $H(n,p)$ reaction at 0° and 198 MeV was assumed to be 12.5 mb/sr (c.m.) which corresponds to 55.3 mb/sr (lab). This value is the result of a recent phase shift analysis [20]. The errors quoted for σ_{np}(c.m.) include those assigned to R but none associated with the $H(n,p)$ cross section.

Taddeucci *et al.* have recently completed a detailed analysis of the relationship between (p,n) cross sections at small angles and the corresponding β decay transition strengths [17]. The result of their analysis of $L = 0$ spin flip transitions within the framework of the DWIA is the following:

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

where q is the momentum transfer, ω is the energy loss and α specifies the final state of the recoil nucleus. $F(q,\omega)$ is a form factor which approaches 1 as $(q,\omega) \rightarrow (0,0)$ and can be reliably calculated in the DWIA. The unit cross section $\hat{\sigma}_{\rm GT}^{-}(A)$ is a proportionality factor which can also be predicted within the framework of the DWIA. One prefers, however, to determine $\hat{\sigma}$ experimentally by relating known transition

strengths and measured (p,n) cross sections.

The analysis of ref. [17] is extended to the results of the present experiment in the last 4 columns of Table 1. The values of $F(q,\omega)$ were calculated with the reaction code DW81 [21]. As in ref. [17] , the values of $B_{\rm GT}$ were obtained from the known ft values for decay using $B_{\rm GT} = 6166/(1.26)^2$ft. The values of the unit cross section for this experiment are then $\hat{\sigma}_{\rm GT}^{+} = \sigma_{np}(0°)/F(q,\omega)B_{\rm GT}^{+}$. These values are compared with the corresponding values of $\hat{\sigma}_{\rm GT}^{-}$ given in ref. [17] for the isobaric analogue (p,n) transitions.

For A = 12 the values of $B_{\rm GT}^{+}$ and $B_{\rm GT}^{-}$ are individually known from the decays of ^{12}B and ^{12}N respectively. In this case the two values of the unit cross section are in excellent agreement. The ground state of ^{6}Be, however, is unbound and the quoted value of $\hat{\sigma}_{GT}^{-}$ is based on the assumption that for these transitions $B_{\rm GT}^{-}$ is identical to the value of $B_{\rm GT}^{+}$ known from the β^{-} decay of ^{6}He. Noting the 12% difference in the actual values of $B_{\rm GT}^{+}$ and $B_{\rm GT}^{-}$ for the transitions in A = 12 nuclei [17], one might expect a slight discrepancy in the quoted values of $\hat{\sigma}_{\rm GT}$ for A = 6 arising from a value of $B_{\rm GT}^{-}$ smaller than that assumed. The comparison of the cross sections for the (n,p) and (p,n) reactions on ^{6}Li reported here is consistent with a similar comparison reported recently by Počanić *et al.* at 120 MeV.

In contrast to the results for A = 12 and 6, there is a substantial discrepancy between the measured values of $\hat{\sigma}_{\rm GT}^{+}$ and $\hat{\sigma}_{\rm GT}^{-}$ for A = 13. The latter value is based on the measured $\sigma_{pn}(0°)$ for the transition to the lowest T = 3/2 state at 15.1 MeV in ^{13}N and an estimate of $B_{\rm GT}^{-} = 0.23 \pm 0.01$ [17]. Considering the results for A = 12, the 34% discrepancy in the two values of the unit cross section for A = 13 cannot reasonably be attributed to uncertainties in the overall normalization of either the

(p,n) or (n,p) cross sections. It should be pointed out that, in contrast to the (p,n) case, the (n,p) result involves a substantially stronger transition to the well-isolated ground state of ^{13}B. Taddeucci *et al.* have drawn attention to the value of $\hat{\sigma}^{-}_{GT}$ for A = 13 as one of a few that are anomalously high and difficult to accommodate within the framework of the DWIA [17]. The present result for $\hat{\sigma}^{+}_{GT}$ suggests further study of this question.

In conclusion, one should note that calibration of the (n,p) reaction as a probe of Gamow-Teller strength has been achieved for the three targets best suited to this purpose. Features of the design of the TRIUMF (n,p) facility provide a precision which, in these three cases, exceeds that achieved in analogous (p,n) measurements. The (n,p) results for A = 12 and 6 are generally consistent with those obtained from (p,n) measurements but a substantial discrepancy is noted in the case of A = 13.

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Table 1.

The (n,p) cross sections at 0° measured in the present experiment compared with the corresponding (p,n) results of ref. [17]. For definitions of symbols see text.

Target	R (lab)[a]	$\sigma_{n,p}$(c.m.)[a] mb/sr	$F(q,w)$[a]	B^{+}_{GT}	$\hat{\sigma}^{+}_{GT}$[a] mb/sr	$\hat{\sigma}^{-}_{GT}$[b] mb/sr
^{12}C	0.180 ± 0.006	8.19 ± 0.27	0.870	0.999 ± 0.005[c]	9.42 ± 0.31	9.2 ± 0.9
^{6}Li	0.403 ± 0.015	15.51 ± 0.55	0.983	1.593 ± 0.007[d]	9.90 ± 0.36	9.1 ± 0.5
^{13}C	0.157 ± 0.007	7.24 ± 0.33	0.870	0.759 ± 0.018[e]	10.97 ± 0.56	14.7 ± 1.1

[a]Present result, $E_n = 198$ Mev.

[b]Ref. [17], $E_p = 200$ MeV.

[c]Ref. [15].

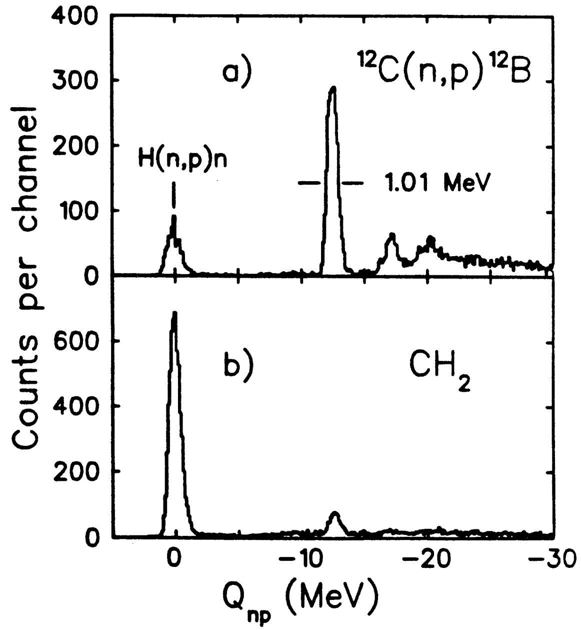
[d]Ref. [14].

[e]Ref. [16].

Figure Captions

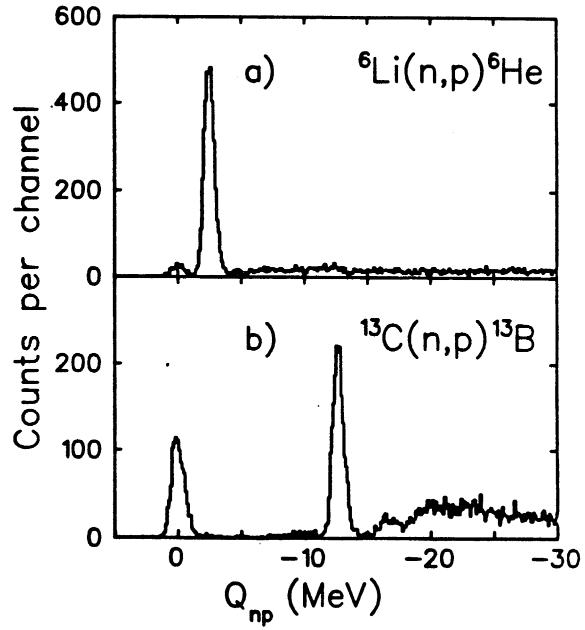
1. (a) The (n,p) spectrum at 0° with 4 carbon targets and $E_n = 198$ MeV. (b) The (n,p) spectrum recorded simultaneously for two CH_2 targets.

2. (a) The (n,p) spectrum at 0° with 4 Li targets (99% ^{6}Li); (b) The $^{13}C(n,p)$ spectrum at 0°. The prominent peak at $Q = 0$ results primarily from hydrogen in the mylar windows containing the ^{13}C target material.



a)
$^{12}C(n,p)^{12}B$
H(n,p)n
1.01 MeV
b)
CH_2
Counts per channel
Q_{np} (MeV)

Fig. 1



a)
$^{6}Li(n,p)^{6}He$
b)
$^{13}C(n,p)^{13}B$
Counts per channel
Q_{np} (MeV)

Fig. 2