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THE (n, p) REACTION AS A PROBE OF NUCLEAR STRUCTURE

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INTRODUCTION

What follows is a brief account of some of the results of studies of the (n, p) reaction on nuclear targets initiated at TRIUMF in December 1985. The close connection between studies of nucleon charge exchange reactions and spin excitations in nuclei has been a central theme of earlier conferences held here at Telluride. The emphasis at this conference is on the information uniquely accessible through measurements of spin observables in nuclear reactions at intermediate energies. The (n, p) reaction, inducing spin-flip transitions in isospin space, appears to exhibit a unique sensitivity to certain aspects of nuclear structure.

Early experiments involving nucleon scattering as a probe of nuclear structure were carried out without reference to the concept of isospin. In fact the first direct evidence that isospin is a useful quantum number in medium weight or heavy nuclei was provided by Anderson and Wong¹ utilizing the (p, n) reaction at energies high enough to involve a single scattering mechanism and with resolution sufficient to identify the isobaric analogue state in the final nucleus. This pioneering study of isospin-flip transitions involving the Fermi component ($L=0$, $S=0$, $T=1$) of the effective nucleon-nucleon interaction was followed by a period of intense theoretical and experimental activity². In many respects history was repeated more recently when the same reaction was used at higher energies to identify the Gamow-Teller resonance ($L=0$, $S=1$, $T=1$) as a simple mode of nuclear excitation prominent with targets from ^2H to ^{208}Pb .³⁻⁷

In the context of studies of the (p, n) reaction, the (n, p) reaction can be viewed as inducing "reverse" spin-flip transitions in isospin space. For a variety of reasons there are important distinctions to be drawn between the (p, n) and (n, p) reactions as probes of nuclear structure.

The most obvious difference in studies of the two charge exchange reactions is that the one is well established while the other, (n, p) , is still in its infancy. The pioneering studies of the (n, p) reaction at 152 MeV on nuclear targets by Measday and Palmieri⁸ were limited by low counting rates and an energy resolution of 6 MeV. More recently Brady *et al.*⁹ have developed an (n, p) facility utilizing a collimated neutron beam at energies up to 65 MeV. For most applications involving the distorted wave impulse approximation (DWIA) higher energies are preferred. The TRIUMF (n, p) facility is the first in operation to exploit the (n, p) reaction as a detailed probe of nuclear structure at energies above 65 MeV.¹⁰⁻¹⁴

In terms of nuclear structure the initial experiments suggest a role for the (n, p) reaction significantly different from that associated with the (p, n) studies. In isospin space all targets are 100% polarized and the majority exhibit a neutron excess with the consequence that $T_z = (N - Z)/2 > 0$. Thus for all targets but ^1H and ^3He the operator associated with the (n, p) reaction is uniquely isospin raising ($T_+ = T_x + i T_y$, $T_z = T_z + 1$). The obvious consequence of this restriction is the absence of Fermi transitions but, as is illustrated below, the impact on Gamow-Teller and other collective transitions is dramatic.

Finally there are some specific nuclear transition matrix elements which can be estimated on the basis of (n, p) measurements. Detailed discussion of these important applications of the probe lies beyond the scope of this article but brief reference will be made to two examples in the context of a specific experimental result and in the conclusions.

THE TRIUMF (n, p) FACILITY

The TRIUMF charge exchange facility utilizes the medium resolution spectrometer (MRS) in very similar configurations for the study of both the (p, n) and (n, p) reactions at forward angles in the energy range between 190 and 500 MeV. The initial (p, n) results were reported by Alford *et al.*¹⁵ and are also discussed in the following paper.¹⁶ Brief descriptions of the (p, n) mode of operation are included in Refs. 11, 15 and 16. Figure 3 of Ref. 16 illustrates many of the features common to both modes of operation. The proton beam extracted from the cyclotron is incident on the primary target located at the entrance of a dipole magnet used to deflect the emerging protons 20° to a locally shielded beam dump. For (n, p) studies the secondary beam is produced by (p, n) reactions in a ^7Li primary target. The nearly monoenergetic neutrons emitted at 0° are incident on the (n, p) target located 92 cm away, just outside the clearing magnet as is illustrated in Fig. 1. The protons emerging from the secondary target are detected in the MRS.

Two essential differences in the operation of the facility in the (n, p) mode are the use of a segmented secondary target chamber¹⁷ in place of a hydrogenous recoil scintillator and the location of the axis of rotation of the MRS near the centre of this (n, p) target chamber. This chamber, filled with counter gas, consists of alternating layers of wire chamber and target foil. The particular foil in which the (n, p) reaction takes place is identified by requiring all and only those wire chambers downstream to register the event. Correction can therefore be made for the proton energy loss in the subsequent targets, permitting the use of more secondary target material while maintaining the required energy resolution. Other advantages ensuing from the use of this design such as background reduction and the precision with which cross sections

Fig. 1. A schematic diagram of the experimental configuration in the region of the secondary target for (n, p) experiments at TRIUMF.

can be normalized are discussed in detail in Refs. 13 and 17.

Figure 2(a) illustrates the spectrum obtained for the $^{12}\text{C}(n, p)^{12}\text{B}$ reaction at 0° with $E_n = 198$ MeV in the first experiment performed with this facility. Natural carbon targets each 5 cm high, 2 cm wide and 92 mg/cm² thick were mounted in positions T2 to T5 in the segmented chamber. The spectrum shown is the sum of all four 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 ($Q_0 = -12.59$ MeV). The observed energy resolution results from comparable contributions from

- 1) the energy spread of the incident proton beam,
- 2) energy loss in the 110 mg/cm² ^7Li target,
- 3) secondary neutrons populating both the g.s. and 0.43 MeV states in ^7Be , and
- 4) energy loss and straggling in the carbon targets.

The smaller peak at $\omega=0$ is associated with the $\text{H}(n, p)$ reaction primarily on hydrogen in the mylar foils of the wire chambers and in the counter gas (50% isobutane, 50% argon in this case). This background and a very small contribution at higher excitation energies can adequately be accounted for with an "empty spectrum" recorded with the carbon targets removed.

Figure 2(b) is an (n, p) spectrum recorded simultaneously with that in 2(a) for CH_2 targets located in positions T1 and T6. The $^{12}\text{C}(n, p)$ cross section is measured relative to that for the $\text{H}(n, p)$ peak that dominates this spectrum. This ratio is completely insensitive to the incident neutron flux, to computer dead time and to

Fig. 2. (a) The (n, p) spectrum at 0° with 4 carbon targets and $E_n = 198$ MeV; ω is the kinetic energy lost by the nucleon, (b) the (n, p) spectrum recorded simultaneously with (a) for two CH_2 targets, (c) the spectrum used to infer the distribution of incident neutron energies [(a) and (b) are reprinted from Ref. 13, (c) from Ref. 11].

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. Such spectra recorded with different settings of the MRS magnetic field are also used to measure the acceptance of the spectrometer as a function of the coordinate on the focal plane.

A novel feature of this (n, p) facility is the short uncollimated neutron beam. Figure 2(c) shows the spectrum obtained by subtracting the contribution of the C from a CH_2 spectrum and correcting for the variation with energy of the spectrometer acceptance. The peak arises from the $\text{H}(n, p)$ reaction induced by neutrons from the $^7\text{Li}(p, n)$ reaction populating the lowest two states in ^7Be . Lower-energy neutrons resulting from the population of unbound levels in ^7Be will give rise to a continuum at $\omega > 3$ MeV. Data from the time-of-flight facility at IUCF for the $^7\text{Li}(p, n)$ reaction at 200 MeV¹⁸ indicate that this source accounts for the continuum present in Fig. 2(c). Estimates of the contribution of this continuum are subtracted from the (n, p) spectra recorded with the targets of interest by performing a simple deconvolution of the neutron line shape.

EXPERIMENTAL RESULTS

Below is a sample of the results acquired to date with the TRIUMF (n, p) facility. These are generally ordered by increasing target mass and are chosen to illustrate the trends in the data. Detailed discussion is avoided; in most cases reference is made to more complete accounts of these results.

${}^6\text{Li}(n, p){}^6\text{He}$

Figures 3(a) and 3(b) illustrate spectra at two angles recorded with neutrons incident at 198 MeV on ${}^6\text{Li}$. The value $\theta_{c.m.} = 2.1^\circ$ in Fig. 3(a) is an estimate of the rms scattering angle accounting for the finite acceptance of the MRS, which was centred at $\theta = 0^\circ$. The dominant feature of these data is the strong transition to the ${}^6\text{He}_{g.s.}$ ($J^\pi=0^+$) at forward angles. At 2.1° the strength of the transition to the 2^+ state at 1.80 MeV is $<2\%$ of that to the 0^+ state despite the possible contribution of Gamow-Teller transitions from the ${}^6\text{Li}_{g.s.}$ ($1^+ T=0$) in both cases.

Figure 3(a) is a simple illustration of the sensitivity of the (n, p) reaction to the influence of space symmetry on nuclear wave functions. If the nuclear Hamiltonian was independent of both total spin S and isospin T , the energy levels would be eigenfunctions of SU_4 :

$$\psi_n \{ [f](\lambda\mu\dots)LSJT \}$$

with eigenvalues:

$$E_n \{ [f](\lambda\mu\dots)L \}$$

exhibiting the $(2S+1) \times (2T+1)$ degeneracy of a Wigner supermultiplet.¹⁹ In this classification $[f]$ specifies the spatial permutation symmetry and $\lambda\mu\dots$ any additional quantum numbers. In general the attractive nature of the long-range part of the nucleon-nucleon interaction tends to lead to states of maximum orbital symmetry dominating the low-lying eigenfunctions. The operator responsible for Gamow-Teller transitions is particularly sensitive to the influence of space symmetry (SU_4) since it connects only states of the same $[f](\lambda\mu\dots)L$ (i.e., states within the same supermultiplet).

Fig. 3. (a) The cross section deduced from the observation of the (n, p) reaction on ${}^6\text{Li}$ with $E_n = 198$ MeV and θ (MRS) $= 0^\circ$. (b) The corresponding result with θ_{lab} (MRS) $= 15^\circ$.

SU_4 is at best an approximate nuclear symmetry broken by, amongst other terms, a one-body spin-orbit interaction. The low-lying levels of the $A=6$ nuclei may exhibit the best examples of the influence of space symmetry in which the ground states of ${}^6\text{Li}$ and ${}^6\text{He}$ are predominantly 3_1 and 1_5 , respectively, while the ${}^6\text{He}$ (1.80 MeV) is largely $1D_2$.²⁰⁻²⁴ The strong GT transition to the ${}^6\text{He}_{g.s.}$ and the almost pure $L=2$ transition to the 2^+ state seen in Fig. 3 reflect these assignments. The complete (n, p) data set (including data at other angles) is being analyzed in terms of detailed nuclear wave functions and the abundant data available for the $A=6$ nuclei from other probes of nuclear structure.

Calibration of the Probe: $\hat{\sigma}_{\text{GT}}^+$

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.⁴ The result of a recent analysis by Tadducci *et al.*²⁵ of $L=0$ spin-flip transitions within the framework of the DWIA is expressed in terms of $\hat{\sigma}_{\text{GT}}^-$, the cross section per unit GT strength extrapolated to $q = \omega = 0$.

An important objective in taking the data shown in Figs. 2, 3, and 4 was to obtain a similar calibration of the (n, p) reaction as a probe of B_{GT}^+ , the distribution of Gamow-Teller strength for isospin-raising transitions. The accurately known f_1 values for the β^- decay of ${}^6\text{He}$, ${}^{12}\text{B}$ and ${}^{13}\text{B}$ to the ground states of the daughter nuclei provide ideal opportunities for this task. 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.²⁵ The details of this investigation have recently been published.¹³ The results are summarized in Table I.

Table I. A summary of the cross sections (c.m.) per unit Gamow-Teller strength for analogous (n, p) and (p, n) transitions at 200 MeV. For definitions of the symbols please see the text (reprinted from Ref. 13).

Target	B_{GT}^+	$\hat{\sigma}_{\text{GT}}^+$ mb/sr	$\hat{\sigma}_{\text{GT}}^-$ mb/sr
${}^6\text{Li}$	1.593 ± 0.007	9.90 ± 0.36	9.1 ± 0.5
${}^{12}\text{C}$	0.999 ± 0.005	9.42 ± 0.31	9.2 ± 0.9
${}^{13}\text{C}$	0.759 ± 0.018	10.97 ± 0.56	14.7 ± 1.1

For the (n, p) measurements the use of the segmented target chamber provides a natural normalization for cross sections in terms of the elementary $\text{H}(n, p)n$ reaction. This point was made with reference to Fig. 2 and is discussed in detail in Ref. 13. To derive the values for $\hat{\sigma}_{\text{GT}}^+$ the $\text{H}(n, p)$ cross section at 198 MeV and 0° was assumed to be 12.5 mb/sr (c.m.), the value given in a recent phase-shift analysis.²⁶ The values for $\hat{\sigma}_{\text{GT}}^-$ were derived²⁵ from (p, n) cross sections at 0° measured relative to that for the ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction. The uncertainties quoted for $\hat{\sigma}_{\text{GT}}^+$ and $\hat{\sigma}_{\text{GT}}^-$ do not include

Fig. 4. The (n, p) cross section for ^{13}C with $E_n = 198$ MeV and θ (MRS) = 0° . The prominent peak at " $E_x = -12.6$ MeV" results primarily from hydrogen in the mylar windows of the ^{13}C target container.

in either case the uncertainty in the cross section used for normalization.

As is discussed in Ref. 13, the values for the cross sections per unit strength given in Table I for $A=6$ and 12 are in reasonable accord with expectations. In contrast to these results there is a substantial discrepancy between the measured values of $\hat{\sigma}_{GT}^+$ and $\hat{\sigma}_{GT}^-$ for $A=13$. The latter value is based on the measured $\sigma_{pn}(0^\circ)$ for the transition to the lowest $T = 3/2$ state at 15.1 MeV in ^{13}N and an estimate of $B_{GT}^- = 0.23 \pm 0.01$.²⁵ Considering the results for $A=6$ and 12, the 34% discrepancy in the two values for $A=13$ cannot reasonably be attributed to uncertainties in the overall normalizations. 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 (see Fig. 4).

$^9\text{Be}(n, p)^9\text{Li}$

Figure 5 presents the $^9\text{Be}(n, p)^9\text{Li}$ spectrum measured at $E_n = 198$ MeV with the MRS centred at 0° . The peak near $\omega = 0$ corresponds to the incomplete subtraction of the contribution of hydrogen in the segmented target chamber. Two relatively weak peaks are identified with transitions to the lowest known states in ^9Li .²⁷ The measured angular distribution for the transition to the $^9\text{Li}_{g.s.}$ is consistent with DWIA calculations²⁸ based on the wave functions of Cohen and Kurath.²² These calculations indicate that even for this weak transition $\sigma_{np}(0^\circ)$ is dominated by the $L=0$ GT component. The value $B_{GT}^+ = 0.019$ is known from the decay of ^9Li ,²⁷ and when combined with the measured $\sigma_{np}(0^\circ)$ gives $\hat{\sigma}_{GT}^+(^9\text{Li}_{g.s.}) = 16$ mb/sr. The deviation between this value and the generally more consistent values of $\hat{\sigma}_{GT}^+$ given in Table I can probably be attributed to the fact that the $A=9$ transition is nearly

Fig. 5. The (n, p) cross section for ^9Be . Also shown are the expected locations of the 2 peaks corresponding to the lowest known states in ^9Li .

two orders of magnitude weaker than those chosen for the calibration of the probe.

A comparison between the (n, p) spectra recorded at 0° for ^{13}C (Fig. 4) and ^9Be (Fig. 5) reveals much more Gamow-Teller strength concentrated in the $^{13}\text{B}_{g.s.}$ than is seen at low excitation energy in the final nucleus ^9Li . Reasonable wave functions calculated²² for these nuclei account for this difference. It should be noted that if SU_4 is an exact symmetry for these nuclei there is no $T=3/2$ state of the same $[f]$ as the maximum orbital symmetry of the $T=1/2$ ground state. In general, in the SU_4 limit, $B_{GT}^+ = 0$ for any target with a neutron excess. Figure 5, like Fig. 3(a), dramatically illustrates the influence of spatial symmetry on these light nuclei. The much stronger B_{GT}^+ noted for ^{13}C can be attributed to the larger effect of the one-body spin-orbit interaction near the end of the $1p$ shell.

$^{54}\text{Fe}(n, p)^{54}\text{Mn}$

Results of measurements of the $^{54}\text{Fe}(n, p)^{54}\text{Mn}$ cross sections at 298 MeV have been reported by Vetterli *et al.*¹⁰ and are shown in Fig. 6. There is a strongly forward peaked concentration of strength at excitation energies below 10 MeV. The shell model calculations of Bloom and Fuller²⁹ predict a distribution of GT strength with a shape shown for comparison with the 0° data. It is important to note that, although the predicted shape coincides reasonably well with the data for $E_x < 8$ MeV, the predicted magnitude of the cross section exceeds the data by more than a factor of 2.

To confirm the $L=0$ assignment for the peak at 0° in Fig. 6, Vetterli *et al.* used the measured angular distributions to perform a limited multipole decomposition of the data involving orbital angular momentum transfer $L=0, 1$ and 2. The results of this analysis for the 0° data are shown in Fig. 7. The measured cross section at 0° integrated to $E_x = 10$ MeV is 16.9 mb/sr of which 12.9 mb/sr is identified as $L=0$.

The most prominent feature at higher excitations in Fig. 7 is the broad spin dipole resonance ($L=1, S=1, T=1$). The analysis of Fig. 7 suggests an $L=0$ contribution of 8.5 mb/sr in the range $10 < E_x < 40$ MeV. It is not clear however

Fig. 6. Cross sections for the (n, p) reaction on ^{54}Fe at 298 MeV for five angles between 0° and 12° . The dashed curve in the 0° spectrum is the calculation of Bloom and Fuller (Ref. 29) normalized by a factor of 0.45 (reprinted from Ref. 10).

Fig. 7. A multipole decomposition of the $^{54}\text{Fe}(n, p)^{54}\text{Mn}$ spectrum at 0° . The top graph is a plot of the data with the total fitted curve, as well as the $L=0$ component shown hatched. The bottom graph shows the $L=1$ component (cross-hatched) and the $L=2$ (shaded) (reprinted from Ref. 10).

what fraction of this strength can properly be attributed to B_{GT}^+ . As is mentioned in Ref. 10, this result is very sensitive to a possible uncertainty in the DWIA estimate of the angular distribution of the $L=1$ strength. Moreover, Auerbach *et al.*³⁰ have identified this region of excitation as the location of a spin isovector monopole resonance with the same quantum numbers as the GT resonance but involving a radial $(2\hbar\omega)$ excitation.

One of the important objectives of this study of the $^{54}\text{Fe}(n, p)$ reaction was to test the Gamow-Teller sum rule relating the strengths B_{GT}^- and B_{GT}^+ integrated over all excitation energies:

$$S_{\text{GT}} - S_{\text{GT}}^+ = 3(N - Z). \quad (1)$$

As is mentioned above, there is significant uncertainty associated with possible B_{GT}^+ strength at $E_x > 10$ MeV. Also, the value of the total strength S_{GT} estimated by

Rapaport *et al.*³¹ from studies of the $^{54}\text{Fe}(p, n)^{54}\text{Co}$ reaction has an estimated uncertainty of 25%. Detailed analysis of the data in terms of the sum rule has been reported both by Vetterli *et al.*¹⁰ and by Auerbach.³² Given the uncertainties, no firm conclusions can be drawn in this regard at this time.

Despite the absence of a definitive test of the sum rule there are important implications of the comparison of the detailed distribution of strength B_{GT}^+ predicted by Bloom and Fuller²⁹ and measured by Vetterli *et al.*¹⁰ The primary motivation of the theoretical calculations was to obtain estimates of electron capture rates on nuclei in this mass range during the gravitational collapse of a massive star prior to a supernova explosion. The results of the (n, p) experiment suggest that these calculations accurately give the relative distribution of the strength at $E_x < 10$ MeV but overestimate the total strength in this region by a factor of 2.4. The corresponding reduction in the predicted electron capture rates would tend to increase estimates of the electron/baryon ratio Y_e in the stellar interior. In terms of nuclear structure, Auerbach³² has discussed the quenching of both B_{GT}^+ and B_{GT}^- for ^{54}Fe , with emphasis on the influence of RPA correlations. This analysis would suggest that these correlations are probably responsible for a major fraction of the rescaling necessary to fit the results of a limited-space shell model calculation to the (n, p) data. In terms of fractional changes in the total strengths, the influence of RPA correlations on B_{GT}^+ is much greater than on B_{GT}^- .

Much of the emphasis in the early (n, p) experiments at TRIUMF has been on B_{GT}^+ and hence data at the most forward angles. However, the somewhat featureless data at larger angles illustrated in Fig. 6 have also received attention. Smith and Wambach³³ have compared the $^{54}\text{Fe}(n, p)$ data at $\theta = 5^\circ, 8^\circ$ and 12° with predictions of a semi-infinite slab model of the response of the nuclear surface. The predictions including significant $2p\text{-}2h$ damping of the $T=1, S=1$ response agree well with the data.

$^{90}\text{Zr}(n, p)^{90}\text{Y}$

Studies of the $^{90}\text{Zr}(p, n)^{90}\text{Nb}$ reaction have played a very prominent role in the consideration of isovector excitations in nuclei. Figure 8 illustrates both the data of Gaarde *et al.*⁶ at $E_p = 200$ MeV, $\theta = 0^\circ$ and one of the most recent calculations of this cross section by Smith and Wambach.³⁴ This calculation, based on the eikonal approximation, explicitly includes an estimate in the second random phase approximation of the $2p\text{-}2h$ spreading of the single scattering response and an estimate of the two-step contribution to the cross section. The results of this calculation are similar to earlier ones by Osterfeld *et al.*³⁵ and Klein *et al.*³⁶ The general conclusion based on these calculations is that for the (p, n) reaction at these energies the nuclear response can be accounted for in detail over a wide range of q and ω without invoking isobar-hole mixing in the nuclear wave functions.

The $^{90}\text{Zr}(n, p)^{90}\text{Y}$ reaction provides the opportunity for a critical test of the conclusions based on the analysis of the (p, n) data. The B_{GT} strength dominates the data of Fig. 8 at $\omega < 20$ MeV. However, to the extent that $Z=40$ is a closed proton shell in the $^{90}\text{Zr}_{\text{gs}}$, the B_{GT}^+ strength is totally Pauli blocked. It is therefore very important to see whether the theoretical formalism apparently successful in accounting for (p, n) data can also correctly predict a dramatically different (n, p)

Fig. 8. The full 0° cross section calculated by Smith and Wambach (Ref. 34) for the (p,n) reaction on ^{90}Zr (thinner smooth line) compared to the data of Gaarde *et al.* (Ref. 6, heavier irregular line). The calculated two-step contribution is also given separately by the dotted line (reprinted from Ref. 34).

response. Results of studies of the $^{90}\text{Zr}(n,p)^{90}\text{Y}$ reaction at $E_n = 198$ MeV have recently been reported by Yen *et al.*¹⁴

Figure 9 is a comparison of the (n,p) data¹⁴ at 6.4° and the results of a calculation by Smith and Wambach³⁴ carried out with the same formalism used to explain the (p,n) data in Fig. 8. The calculation gives a reasonable account of the location of the two peaks in the data which are attributed to concentrations of isovector spin dipole strength. The quantitative agreement between data and prediction exhibited in Fig. 8 is, however, notably absent in Fig. 9.

Other predictions of the $^{90}\text{Zr}(n,p)$ strength exist^{36,37} but none appears to account in detail for the data. Until the discrepancy between theory and experiment

Fig. 9. The cross section for the (n,p) reaction on ^{90}Zr at 6.4° (solid histogram, Ref. 14) is compared with the full calculations of Smith and Wambach (dashed line, Ref. 34). This full calculation includes the contribution of the two-step processes also shown separately by the dotted line (reprinted from Ref. 14).

Fig. 10. The histogram represents the data of Yen *et al.* (Ref. 14) for the (n,p) reaction on ^{90}Zr at 1.8° . Shown dotted for comparison is the cross section predicted for B_{GT}^+ by the calculation of Bloom *et al.* (Ref. 38) on the basis of their model A (reprinted from Ref. 14).

for the $^{90}\text{Zr}(n,p)$ data can be resolved, conclusions based on the apparent success of theoretical predictions of the (p,n) data must be viewed with caution.

The possible contribution of B_{GT}^+ to the $^{90}\text{Zr}(n,p)$ data at forward angles is of particular importance. The RPA calculations of the full nuclear response reported in Refs. 34–37 do not include the effects of $2p\text{--}2h$ correlations in the $^{90}\text{Zr}_{\text{g.s.}}$ and therefore give $S_{\text{GT}}^+ = 0$. Bloom *et al.*³⁸ have calculated B_{GT}^+ on the basis of a shell model including g.s. correlations involving the excitation of 2 protons from the $2p$ shell to the $1g_{7/2}$ shell. Figure 10 illustrates the results of this calculation when single nucleon transfer data are used to fix the corresponding $1g_{7/2}$ occupation probability (model A of Ref. 38). The $^{90}\text{Zr}(n,p)$ data at 1.8° are also shown and are clearly inconsistent with this prediction.

We have noted earlier the sensitivity of B_{GT}^+ to the influence of space symmetry (SU_4) in light nuclei and RPA correlations in ^{54}Fe . Detailed calculations by Townner³⁹ for the $N=50$ isotones suggest that one can expect very substantial quenching of the strength predicted with a shell model with a restricted set of basis states. In particular core polarization and higher-order effects are estimated to reduce B_{GT}^+ at low E_x for ^{92}Mo by a factor of ~ 9 compared to the result expected if the wave function of the $^{92}\text{Mo}_{\text{g.s.}}$ involved simply 2 protons in $1g_{7/2}$ coupled to an $A=90$ closed shell. It seems plausible that these effects could also account for the substantial overestimate of B_{GT}^+ at $E_x < 5$ MeV shown in Fig. 10.

CONCLUSIONS

The (n,p) data presented and discussed above are a representative sample of the initial experimental program undertaken at TRIUMF. A number of simple conclusions can already be drawn.

The calibration of the (n,p) reaction as a probe of the Gamow-Teller strength B_{GT}^+ has been achieved for the three targets best suited to this purpose. Features

of the design of the TRIUMF (n, p) facility lead to a precision which in these cases exceeds that achieved in analogous (p, n) measurements.

A comparison of the cross sections per unit strength $\sigma_{G^+}^+$ and $\sigma_{G^-}^-$ deduced for analogous transitions on ^{13}C reveals a substantial discrepancy. There is at present no adequate explanation of this result.

Detailed theoretical calculations appear to be remarkably successful in accounting in detail for the nuclear response of ^{90}Zr to the (p, n) reaction. The same procedures, however, are not nearly so successful in predicting the $^{90}\text{Zr}(n, p)$ data. A comprehensive understanding of the isovector nuclear response is an important objective which will certainly require further experiments and refinement of the theoretical approach.

Several examples have been given of the sensitivity of the measured distributions of $B_{G^+}^+$ to the detailed nature of the nuclear wave functions. This situation may be contrasted with that for $B_{G^-}^-$ where all nuclei with $N > Z$ exhibit a reasonably compact Gamow-Teller resonance located in the vicinity of the isobaric analogue state with a total strength $5\bar{g}_T$ given by $3(N-Z)$ to within a factor of 2. In light nuclei the sensitivity of $B_{G^+}^+$ is connected with the influence of spatial symmetry (SU_4) on the nuclear wave functions. It is interesting to note that in a very early assessment of limited experimental data on $B_{G^+}^+$ for $A \sim 120$ Fujita and Ikeda⁴⁰ proposed a model invoking a "persistent supermultiplet structure" broken in perturbation theory by the spin-orbit interaction. More recent theoretical analyses of this problem in medium and heavy nuclei (such as in Refs. 32, 39 and 41) do not make this connection with SU_4 symmetry but arrive at similar conclusions regarding the substantial quenching of $B_{G^+}^+$ strength.

There are two important reasons for an interest in measurements of $B_{G^+}^+$ that extend beyond the field of nuclear structure. One, concerning the rates of electron capture in the collapse of a massive star, has been mentioned in connection with the $^{54}\text{Fe}(n, p)$ data. The other involves critical tests of the nuclear structure calculations used in the analysis of double β decay.⁴²⁻⁴⁵ In general those models which are successful in accounting for the measured suppression of the 2ν transition probabilities also predict strong quenching of $B_{G^+}^+$ for the daughter nucleus and for other nuclei in the same mass region. Measurements of $L=0$ strength in the (n, p) reaction are being used to test the adequacy of such predictions and hence provide additional constraints on the models. ^{48}Ti and ^{76}Se are the first two targets being investigated for this purpose.

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References

1. J.D. Anderson and C. Wong, Phys. Rev. Lett. **7**, 250 (1961).
2. D.H. Wilkinson, ed., *Isospin in Nuclear Physics* (North-Holland, Amsterdam, 1969).
3. R.R. Doering, A. Galonsky, D.M. Patterson, and G.F. Bertsch, Phys. Rev. Lett. **35**, 1691 (1975).
4. C.D. Goodman, C.A. Goulding, M.B. Greenfield, J. Rapaport, D.E. Bainum, C.C. Foster, W.G. Love, and F. Petrovich, Phys. Rev. Lett. **44**, 1755 (1980).
5. B.D. Anderson, J.N. Knudson, P.C. Tandy, J.W. Watson, R. Madey, and C.C. Foster, Phys. Rev. Lett. **45**, 699 (1980).
6. C. Gaarde, J. Rapaport, T.N. Tadducci, C.D. Goodman, C.C. Foster, D.E. Bainum, C.A. Goulding, M.B. Greenfield, D.J. Horen, and E. Sugarbaker, Nucl. Phys. **A369**, 258 (1981).
7. H. Sakai, T.A. Carey, J.B. McClelland, T.N. Tadducci, R.C. Byrd, C.D. Goodman, D. Krofcheck, L.J. Rybarczyk, E. Sugarbaker, A.J. Wagner, and J. Rapaport, Phys. Rev. C **35**, 344 (1987).
8. D.F. Meesday and J.N. Palmieri, Phys. Rev. **161**, 1071 (1967).
9. F.P. Brady and G.A. Needham, in *The (p, n) reaction and the nucleon-nucleon force*, eds. C.D. Goodman, S.M. Austin, S.D. Bloom, J. Rapaport, and G.R. Satchler (Plenum, New York, 1980), p. 357; F.P. Brady, G.A. Needham, J.L. Ullmann, C.M. Castaneda, T.D. Ford, N.S.P. King, J.L. Romero, M.L. Webb, V.R. Brown, and C.H. Poppe, J. Phys. G **10**, 363 (1984); F.P. Brady, Can. J. Phys. **65**, 578 (1987).
10. M.C. Vetterli, O. Häusser, W.P. Alford, D. Frekers, R. Helmer, R. Henderson, K. Hicks, K.P. Jackson, R.G. Jeppesen, C.A. Miller, M.A. Moenster, K. Raywood, and S. Yen, Phys. Rev. Lett. **59**, 439 (1987).
11. R. Helmer, Can. J. Phys. **65**, 588 (1987).
12. S. Yen, Can. J. Phys. **65**, 595 (1987).
13. K.P. Jackson, A. Celler, W.P. Alford, K. Raywood, R. Abegg, R.E. Azuma, C.K. Campbell, S. El-Kateb, D. Frekers, P.W. Green, O. Häusser, R.L. Helmer, R.S. Henderson, K.H. Hicks, R. Jeppesen, P. Lewis, C.A. Miller, A. Moalem, M.A. Moenster, R.B. Schubank, G.G. Shute, B.M. Spicer, M.C. Vetterli, A.I. Yavin, and S. Yen, Phys. Lett. **B201**, 25 (1988).
14. S. Yen, B.M. Spicer, M.A. Moenster, K. Raywood, R. Abegg, W.P. Alford, A. Celler, T.E. Drake, D. Frekers, O. Häusser, R.L. Helmer, R.S. Henderson, K.H. Hicks, K.P. Jackson, R. Jeppesen, J.D. King, N.S.P. King, K. Lin, S. Long, C.A. Miller, V.C. Officer, R. Schubank, G.G. Shute, M.C. Vetterli, and A.I. Yavin, Phys. Lett. **B206**, 597 (1988).

15. W.P. Alford, R.L. Helmer, R. Abegg, A. Celler, O. Häusser, K.H. Hicks, K.P. Jackson, C.A. Miller, S. Yen, R.E. Azuma, D. Frekers, R.S. Henderson, H. Baer, and C.D. Zafiratos, *Phys. Lett.* **B179**, 20 (1986).
16. R.G. Jeppesen, these proceedings.
17. R.S. Henderson, W.P. Alford, D. Frekers, O. Häusser, R.L. Helmer, K.H. Hicks, K.P. Jackson, C.A. Miller, M.C. Vetterli, and S. Yen, *Nucl. Instrum. Methods* **A257**, 97 (1987).
18. J. Rapaport, private communication.
19. E.P. Wigner, *Phys. Rev.* **56**, 519 (1939).
20. D.R. Inglis, *Phys. Rev.* **87**, 915 (1952).
21. D. Kurath, *Phys. Rev.* **101**, 216 (1956); *Phys. Rev.* **106**, 975 (1957).
22. S. Cohen and D. Kurath, *Nucl. Phys.* **73**, 1 (1965).
23. J.C. Bergstrom, U. Deutschmann, and R. Neuhausen, *Nucl. Phys.* **A327**, 439 (1979).
24. J.P. Perroud, A. Perrenoud, J.C. Alder, B. Gabioud, C. Joseph, J.F. Loude, N. Morel, M.T. Tran, E. Winkelmann, H. von Fellenberg, G. Strassner, P. Trüöl, W. Dahme, H. Panke, and D. Renker, *Nucl. Phys.* **A453**, 542 (1986).
25. T.N. Taddeucci, C.A. Goulding, T.A. Carey, R.C. Byrd, C.D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport and E. Sugarbaker, *Nucl. Phys.* **A469**, 125 (1987).
26. R.A. Arndt and L.D. Soper, Scattering analysis interactive dial-in (SAID) program (June 1987) (unpublished).
27. F. Ajzenberg-Selove, *Nucl. Phys.* **A413**, 1 (1984).
28. R. Schaeffer and J. Raynal, Program DWBA70 (unpublished); J.R. Comfort, extended version DW81 (unpublished).
29. S.D. Bloom and G.M. Fuller, *Nucl. Phys.* **A440**, 511 (1985).
30. N. Auerbach and A. Klein, *Phys. Rev. C* **30**, 1032 (1984); N. Auerbach, A. Klein, and W.G. Love, in *Antinucleon and Nucleon-Nucleus Interactions*, ed. G.E. Walker, C.D. Goodman, and C. Olmer (Plenum, New York, 1985), p. 323.
31. J. Rapaport, T. Taddeucci, T.P. Welch, C. Gaarde, J. Larsen, D.J. Horen, E. Sugarbaker, P. Konec, C.C. Foster, C.D. Goodman, C.A. Goulding, and T. Masterson, *Nucl. Phys.* **A410**, 371 (1983).
32. N. Auerbach, *Phys. Rev. C* **36**, 2694 (1987).
33. R.D. Smith and J. Wambach, *Phys. Rev. C* **38**, 100 (1988).
34. R.D. Smith and J. Wambach, *Phys. Rev. C* **36**, 2704 (1987) and private communication.

35. F. Osterfeld, D. Cha, and J. Speth, *Phys. Rev. C* **31**, 372 (1985).
36. A. Klein, W.G. Love, and N. Auerbach, *Phys. Rev. C* **31**, 710 (1985); A. Klein, W.G. Love, M.A. Franey, and N. Auerbach, in *Antinucleon and Nucleon-Nucleus Interactions*, ed. G.E. Walker, C.D. Goodman, and C. Olmer (Plenum, New York, 1985), p. 351.
37. M. Yabe, *Phys. Rev. C* **36**, 858 (1987).
38. S.D. Bloom, G.J. Mathews, and J.A. Becker, *Can. J. Phys.* **65**, 684 (1987).
39. I.S. Towner, *Nucl. Phys.* **A444**, 402 (1985).
40. J.I. Fujita and K. Ikeda, *Nucl. Phys.* **67**, 145 (1965).
41. D. Cha, *Phys. Rev. C* **27**, 2269 (1983).
42. B.A. Brown, in *Nuclear Shell Models*, ed. M. Vallieres and B.H. Wildenthal (World Scientific, Singapore, 1985), p. 42.
43. K. Grotz and H.V. Klapdor, *Nucl. Phys.* **A460**, 395 (1986).
44. T. Tomoda and A. Faessler, *Phys. Lett.* **B199**, 475 (1987).
45. J. Engel, P. Vogel, and M.R. Zirnbauer, *Phys. Rev. C* **37**, 731 (1988).