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Gamow-Teller strength and giant resonances in ^{90}Zr(n,p) at 198 MeV

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Abstract

The ^{90}Zr$(n,p)^{90}$Y reaction has been studied at a bombarding energy of 198 MeV. Significant GT$^+$ strength would indicate a role for the Δ–isobar in quenching the GT$^-$ strength in (p,n) reactions. Up to an excitation energy of 10 MeV in the residual nucleus, we obtain a firm upper limit of $S_{\beta^+} \leq 3.6$ and a tighter, but model–dependent upper limit of $S_{\beta^+} \leq 1.6$. In conjunction with the existing ^{90}Zr(p,n) data, this indicates that the Ikeda sum rule is satisfied to within 12%, if there is no extra GT$^+$ strength at higher excitations. The spin giant dipole resonance is identified.

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The study of the (p,n) reaction at intermediate energies by Goodman *et al.* [1] has shown that the forward angle cross section provides a quantitative measure of Gamow-Teller (GT) strength. This has led to identification of the GT giant resonance and thence to the problem of the missing GT strength. If it is assumed that only nucleonic degrees of freedom are excited, then the Ikeda sum rule is easily derived [2]:

$$S_{\beta^-} - S_{\beta^+} = 3(N-Z)\ , \tag{1}$$

where

$$S_{\beta^-} = \sum_f |< f \mid \sum_{i=1}^{A} \sum_{\mu} \sigma_\mu^i t_-^i \mid 0 >|^2\ , \tag{2}$$

is the total GT$^-$ strength observed in (p,n) reactions, and S_{β^+} is analogously the total GT$^+$ strength observed in (n,p) reactions. One can therefore get a lower limit for S_{β^-}:

$$S_{\beta^-} \geq 3(N-Z)\ . \tag{3}$$

For heavy nuclei, S_{β^+} is expected to be close to zero because of Pauli blocking, and the equality is expected to hold. Instead, it is found that by integrating over the prominent peaks in the spectrum, only about 60% of this sum rule limit is observed [3]. This is the case in a wide range of nuclei. The cause of this apparent quenching has been a matter of controversy. It is contended by some [4] that mixing with 2p–2h configurations shifts GT strength from the prominent low–lying peaks into regions of higher excitation where the strength is not identified from the background of other multipoles. Others [5] believe that, in addition to the normal nucleonic degrees of freedom, the Δ–isobar degree of freedom is also excited, thereby causing a violation of the Ikeda sum rule.

The calculations of Osterfeld *et al.* [6], of Klein *et al.* [7] and more recently, of Drożdż *et al.* [8] suggest that 2p–2h mixing is the major cause of the apparent quenching of GT strength, and that the Δ in fact plays no significant role. Osterfeld *et al.* performed a large-basis, 1p–1h RPA calculation of the ^{90}Zr(p,n) spectrum, including all multipoles up to L=4, but treating the effect of 2p–2h mixing in a phenomenological fashion only. These authors show that much of the "background" beneath the promiment peaks is GT strength, and that significant GT strength extends to high excitation energy above the low-lying peaks. They obtained impressive agreement with the experimental ^{90}Zr(p,n) spectrum below 45 MeV excitation, and concluded that the amount of GT strength satisfied the sum rule limit of $S_{\beta^-} = 3(N-Z)$. This conclusion was supported recently by a least squares fit multipole decompositon of the ^{90}Zr(p,n) data [9]. Thus, there would be no violation of the Ikeda sum rule, provided that $S_{\beta^+} = 0$. Klein *et al.* reached similar conclusions. However, all these calculations assume the ^{90}Zr ground state to be a closed shell. If there are important ground–state correlations, significant S_{β^+} strength would be opened up, and the Ikeda sum rule would be violated. Such S_{β^+} strength would be observable in the ^{90}Zr(n,p) reaction. The search for GT strength in the ^{90}Zr(n,p) reaction thus provides a crucial test for the importance of the Δ–isobar in GT states.

This experiment was performed with the TRIUMF nucleon charge exchange facility [10]. A proton beam from the TRIUMF cyclotron, of energy 200 MeV and intensity 450 nA, struck a ^{7}Li target of thickness 220 mg/cm^2. The primary proton beam was bent 20° into a beam dump. Neutrons produced by the ^{7}Li(p,n) reaction, of 198 MeV energy, struck the secondary target assembly which consisted of 5 foils of ^{90}Zr, each of thickness 250 mg/cm^2, followed by a foil of CH_2, of thickness 46 mg/cm^2.

The secondary target foils were separated by multi-wire proportional counters. Consideration of the hit pattern in these counters permitted a determination of the layer in which the (n,p) reaction occurred, and hence a correction for the energy loss of the emitted protons in subsequent target layers. This procedure allowed the recovery of an overall energy resolution of about 1.5 MeV. A full description of the segmented secondary target system can be found elsewhere [11]. The protons produced by the (n,p) reactions in the secondary target foils were momentum analyzed by the magnetic Medium Resolution Spectrometer (MRS). The main contributions to the resolution were the energy spread in the incident beam (650 keV) and the energy loss in the primary and secondary targets.

The isolated peak from the ^{1}H(n,p) scattering in the CH_2 foil provided the means of determining cross sections absolutely, as data from this target were collected simultaneously with that from the ^{90}Zr targets. The ^{1}H(n,p) cross sections were given by the program SAID, which uses the Arndt 1986 phase shifts [12]. In the laboratory frame, at 0°, a value of 54.9 mb/sr was used.

A "target empty" spectrum, taken with no Zr foils in place, was subtracted from the "target in" spectrum at each angle to obtain the spectrum from the Zr alone. All spectra presented herein have been corrected for the geometric acceptance of the MRS and the energy profile of the neutron beam, and encompass data from the full ±1.8° scattering angle bite of the MRS (±1.4° for $\theta = 1.8°$). Further details of the experimental procedure will be given in a future paper.

Figs. 1 and 2 show the spectra for average laboratory scattering angles of 1.8°, 3.5°, 6.4° and 9.2° plotted with a bin width of 0.5 MeV. All excitation energies are quoted with respect to the ^{90}Y ground state. The corresponding excitations in ^{90}Zr occur 13.1 MeV higher, due to the difference in the binding energies of the ^{90}Zr and ^{90}Y ground states (1.5 MeV) [13] and the Coulomb energy difference (11.6 MeV) [14]. Also plotted are the RPA-DWIA calculations of Klein *et al.* [7,17]. We recall that the argument of ref. [6,7] for 2p-2h admixtures as opposed to Δ–h admixtures rests on the ability of the RPA-DWIA to predict the overall strength, and in the case of ref. [6], the distribution of that strength, without the use of Δ's. Comparison of the experimental data with the RPA-DWIA predictions is therefore very interesting.

Since the calculations of Klein *et al.* assume a closed proton subshell at Z=40, no GT$^+$ strength is possible in their model. The dominant features in the calculated spectrum are the spin dipole peaks at 3.5 and 12 MeV excitation in ^{90}Y, which we tentatively identify with the experimental peaks at 5 and 10 MeV. This identification is supported by the angular distributions at these excitation regions, which are dominated by an L=1 dipole shape. Also predicted is a peak at 23 MeV excitation, which is a combination of spin-isovector monopole and spin-isovector quadrupole [15], and which might be associated with the weak peak in the experimental data at 22 MeV. The RPA-DWIA predicts features that are too sharp, but this was also true of the (p,n) calculations presented in ref. [7], and the disagreement may be attributed to the presence of more 2p-2h spreading than accounted for by the folding Gaussians used in ref. [7]. However, there also appears to be more overall strength in the experimental spectrum than theory predicts, especially at high excitations. The excess strength may be due to two–step processes, which were predicted by Smith *et al.* [18] for the ^{90}Zr(p,n) reaction to contribute 0.75 mb/sr/MeV at 30 MeV excitation, which is about the size of the observed excess. Esbensen *et al.* [19] have calculated a much smaller value, however. Two–step processes are not expected to contribute at low

excitation in any case. The excess strength could also be due to GT$^+$ strength opened up by ground state correlations in the parent nucleus [16]. This has been variously estimated to be from 12% [20] to 20% [4] or even more [21] of 3 (N-Z) in the (p,n) channel, and by conservation of $S_{\beta^-} - S_{\beta^+}$, in the (n,p) channel also. Another possible cause of the excess strength is deficiencies in the optical potentials used; for L=1 states, the cross section is zero at 0° in the plane-wave approximation, so the amount of dipole strength predicted near 0° must be sensitive to the distorted waves used.

Fig. 1b also shows an RPA calculation by Wambach *et al.* [22], which includes 1p-1h and 2p-2h configurations. It is seen that the locations of the dipole peaks are well predicted , but the features are still too sharp, despite the inclusion of spreading due to 2p-2h mixing. The reason for this is not known.

Also shown in fig. 1a is the spectrum predicted by the shell-model calculation of Bloom *et al.* [23]. By adjusting the single-particle energies, either to fit the known ground state correlations in ^{90}Zr (model A), or to fit the positive parity spectra in the vicinity of A=90 (model B), they were able to substantially change the magnitude, but not the distribution, of the GT strength in ^{90}Y. All of their predicted GT strength lies below 10 MeV excitation, with the bulk of it lying at 2 ± 2 MeV.

If there were strong, concentrated GT strength, it would show as a positive signal in the 1.8° – 3.5° difference spectrum, but in fact the 3.5° spectrum is everywhere larger in cross section than the 1.8° spectrum. The main reason for this is the occurrence of the strong spin-dipole resonance, which grows from 1.8° to 3.5°. We must therefore ultimately look to a multipole decomposition of the angular distributions of various excitation regions for evidence of L=0 admixtures [9].

Even in the absence of a full multipole analysis, we can put meaningful upper limits on the amount of GT^+ strength. A very conservative limit can be obtained by assuming that all of the strength below 10 MeV is GT strength. The integrated cross section at 1.8° up to 10 MeV is 13.4 mb/sr. We use $\sigma(1.8°)/S_{\beta^+} = 3.75$, obtained by scaling $\sigma(0°)/S_\beta = 4.2$ [16] using the 1 g 9/2 $\rightarrow$ 1 g 7/2 DWIA angular distribution of Ref. [24]. We therefore derive an upper limit for S_{β^+} of 3.6 units, up to an excitation of 10 MeV, which corresponds to 12% of 3 $(N - Z)$. Perhaps more realistically, if we assume as an upper limit that all the strength at 1.8° below 10 MeV in excess of the calculation of Klein *et al.* is GT strength, we obtain $S_{\beta^+} \leq 1.6$ units. Finally, if we assume that the calculation of Bloom *et al.* accurately predicts the distribution of GT strength (and this is somewhat questionable given the severe truncation of their model space), the experimental cross section of 1.10 mb/sr/MeV at 2 MeV excitation imposes an upper limit of $S_{\beta^+} \leq 0.5$ units.

Since we have only estimated upper limits to the GT strength up to 10 MeV excitation, and the sum rule S_{β^+} and S_{β^-} are for the entire GT^+ and GT^- strength over *all* excitations, we cannot say definitively whether the sum rule is violated or not. As pointed out by Auerbach *et al.* [16], because σ/S_β decreases as the excitation energy increases, large amounts of S_{β^+} strength could be hidden at high excitations without being readily visible in the cross section. It is not yet known whether any of the strength above 10 MeV excitation is GT strength, although the concentration of GT^- strength in the $^{90}Zr(p,n)$ reaction would suggest that most of the GT^+ strength should be located at low excitations. A least-squares fit multipole decomposition, which fits the angular distribution of each excitation bin with a sum of angular distributions of different multipoles [9], will hopefully shed light on the multipole character of the higher excitation region. An explicit calculation of the contribution

of two-step processes will also be important in understanding the high excitation region.

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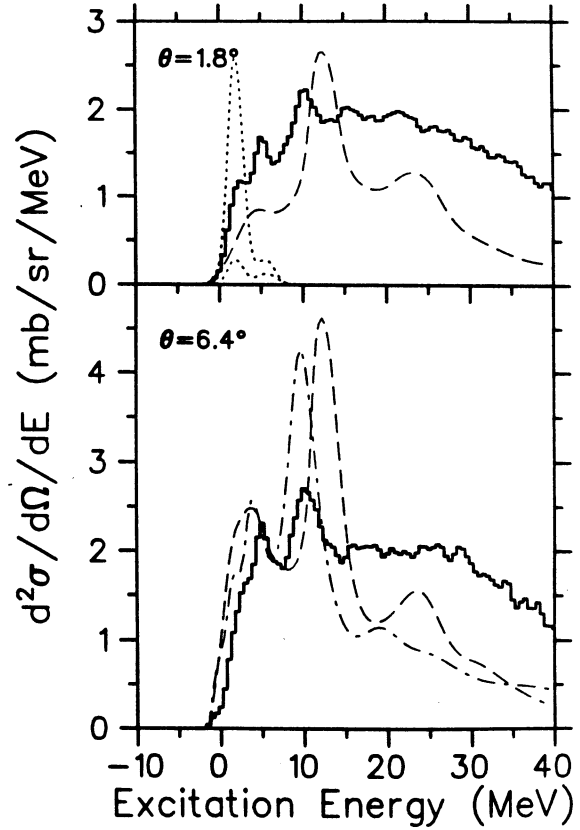
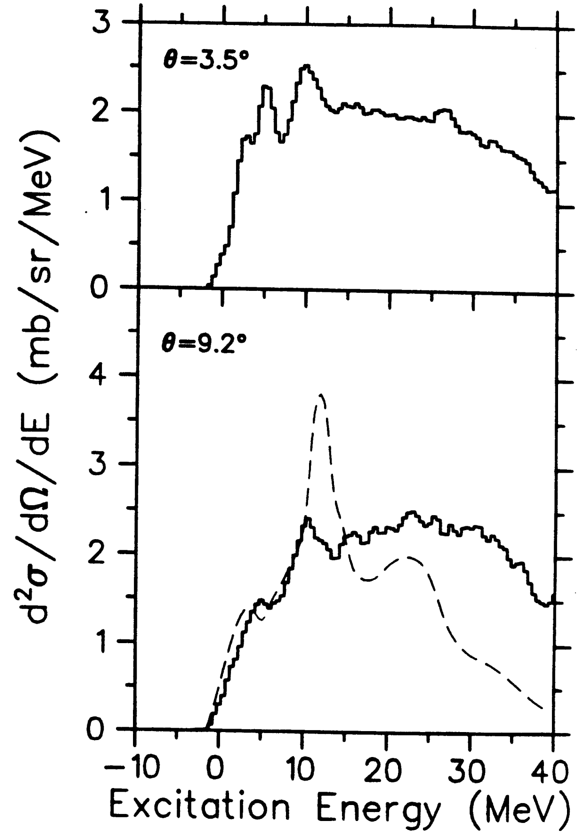
Figure Captions

1. Cross sections for the $^{90}\mathrm{Zr}(n,p)$ reaction at 198 MeV for 1.8° and 6.4°. The top and bottom dashed curves represent, respectively, the 0° and 5° calculations of Klein *et al.* The tall and short dotted curves represent the 0° calculations of models A and B of Bloom *et al.*, respectively, plotted with a resolution of 2.1 MeV FWHM; the peaks would be taller by a factor 1.4 if plotted with the experimental resolution of 1.5 MeV FWHM. The dot–dash curve represents the 6° calculation of Wambach *et al.*

2. Same as fig. 1, but for 3.5° and 9.2°. The dashed curve represents the 8° calculation of Klein *et al.*


θ=1.8°
θ=6.4°
d²σ/dΩ/dE (mb/sr/MeV)
Excitation Energy (MeV)
Fig. 1


θ=3.5°
θ=9.2°
d²σ/dΩ/dE (mb/sr/MeV)
Excitation Energy (MeV)
Fig. 2