Observation of Giant Particle-Hole Resonances in $^{90}Zr(p,n)^{90}Nb$

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Neutron spectra from $^{90}Zr(p,n)^{90}Nb$ at E_p = 120 MeV are measured in the angular range 0°–25°. Three giant resonances are seen and are interpreted as the T = 4 and T = 5 components of the Gamow-Teller strength and an $E1$ resonance. Gamow-Teller matrix elements are extracted, and a large part of the expected strength is found.

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We present here new data on $^{90}Zr(p,n)^{90}Nb$ at $E_p = 120$ MeV. One very prominant and two weaker giant resonances are observed. The most prominent peak is identified as a $T=4$ concentration of Gamow-Teller (GT) strength previously seen less strongly at $E_p = 45$ MeV.[1] The other two peaks are identified as a $T=5$ component of GT strength and a dipole resonance. We use ideas presented in another paper[2] exploiting the higher-energy and 0° spectra to identify GT transitions, and we extract GT matrix elements. A large part of the expected GT strength is observed.

Additional evidence in support of the identification of the peaks as GT transitions is their increased strengths relative to the isobaric-analog-state (IAS) transition at 120 MeV compared to 45 MeV. The increase is consistent with an increase by a factor of about 5 in $(V_{\sigma\tau}/V_\tau)^2$ as suggested in Ref. 3.

It has been known since the discovery of isobaric analog states that the distribution of strength for the Fermi operator, $|\tau|\psi_0\rangle$, is contained entirely in a single state or very narrow band.[4] It has also been conjectured that the distribution of GT strength is concentrated,[5] although the situation is much more complex than it is for Fermi strength.

In general the question of the distribution of GT strength is not amenable to study through β decay because the energetics permit access only to very low final excitation energies. Related information, the distribution of $M1$ strength, has been studied through back-angle electron scattering.[6] It has been noted,[7] however, that the (p,n) reaction is a useful tool for studying GT strength because at 0° the dominant term in the effective N-N force is the central part of the one-pion exchange potential which has the form $\sum_i V_{\sigma\tau}(\tau\cdot\tau_i)(\sigma\cdot\sigma_i)$, where $V_{\sigma\tau}$ is a strength parameter, τ and σ are the isospin and spin operators for the projectile, and τ_i and σ_i are the isospin and spin operators for the ith nucleon in the nucleus. The part of this operator acting on the nucleus is the same as the GT operator. Additional discussion on the extraction of GT matrix elements from (p,n) cross sections is given in Ref. 2.

The present experiment was performed with the beam-swinger facility[8] at the Indiana University Cyclotron Facility using a 62-m flight path and time-compensated detectors.[9] The ^{90}Zr target was 77.5 ± 3.3 mg/cm^2 thick and made from enriched material containing more than 99% ^{90}Zr.

Representative spectra are shown in Fig. 1, and the backgrounds and individual Gaussian peaks obtained from a peak-fitting program are indicated in the figure. The energy scale was calibrated with the use of a traget containing approximately equal quantities of ^{12}C and ^{13}C. This yields widely separated and easily identifiable peaks in the neutron spectrum. The energies are determined to an accuracy of ± 0.2 MeV for the well-defined peaks. For the broad resonances an additional

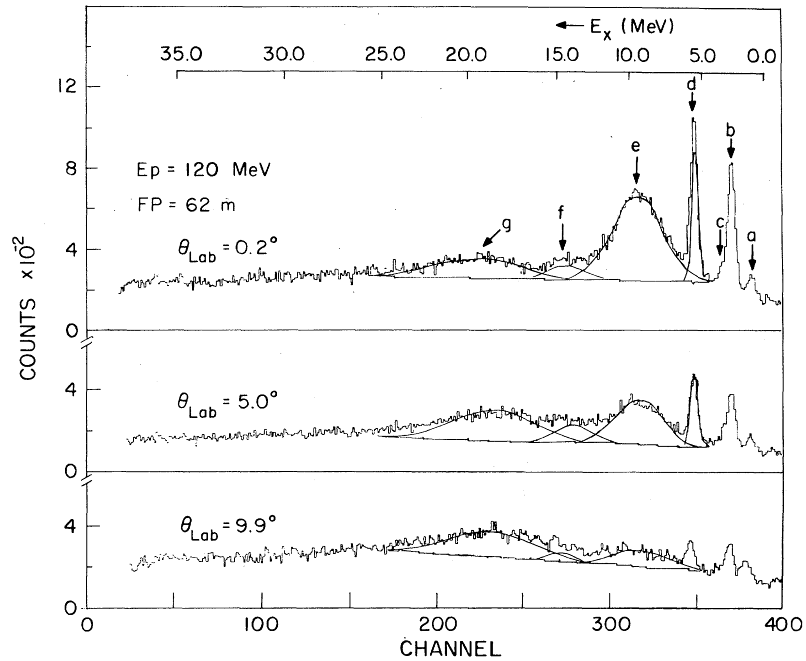

FIG. 1. Time-of-flight neutron spectra for $^{90}Zr(p,n)^{90}Nb$ at $\theta = 0°$, 5°, and 10° laboratory angles. The peak labeled "e" is assumed to be a giant GT resonance. The curves show the background and individual Gaussian peaks derived from a fitting program. The detector efficiency is essentially flat over the fitted energy region. Efficiency determination is explained in Ref. 10.

uncertainty occurs in the peak fitting. Table I lists the peaks with their excitation energies in ^{90}Nb. Figure 2 shows the differential cross sections. The peaks labeled b, c, d, e, and f appear to have $L = 0$ angular distributions. Peak a, although not completely monopole, seems to have a small monopole component not energetically resolved from a higher multipole. Peak g appears to have an $L = 1$ angular distribution.

The solid curves in Fig. 2 correspond to results of macroscopic distorted-wave (DW) calculations with use of the code DWUCK.[11] Optical-model parameters from Nadasen *et al.*[12] were used. Normalizing the DW calculation to the measured IAS cross section, a value $V_1 = 8.2$ MeV was obtained for the isovector strength. These calculations

TABLE I. Information extracted from peaks identified in Fig. 1.

Peak	E_x	FWHM (MeV)	0° cross section[d] $(\mathrm{mb/sr})_{\mathrm{c.m.}}$	Deduced squares of GT matrix elements
a	1.0 ± 0.2	0.66^{c}	$0.8 \pm 35\%$	0.3
b	2.3 ± 0.2	0.66^{c}	$5.0 \pm 10\%$	1.8
c	3.0 ± 0.3	0.66^{c}	$0.9 \pm 33\%$	
d^{a}	5.1 ± 0.2	0.66^{c}	$6.0 \pm 11\%$	10^{e}
e^{b}	8.7 ± 0.3	4.4 ± 0.2	$23 \pm 12\%$	8.3
f	13.4 ± 0.4	3.1 ± 0.3	$3 \pm 21\%$	1.0
g	17.9 ± 0.6	7.8 ± 0.7	$7.9 \pm 20\%$	

[a] IAS.
[b] Giant GT resonance.
[c] Instrumental resolution.
[d] The quoted errors are the relative uncertainties in the peak fitting. An additional 10% should be added in quadrature to obtain uncertainties in the absolute cross sections.
[e] Fermi matrix element.

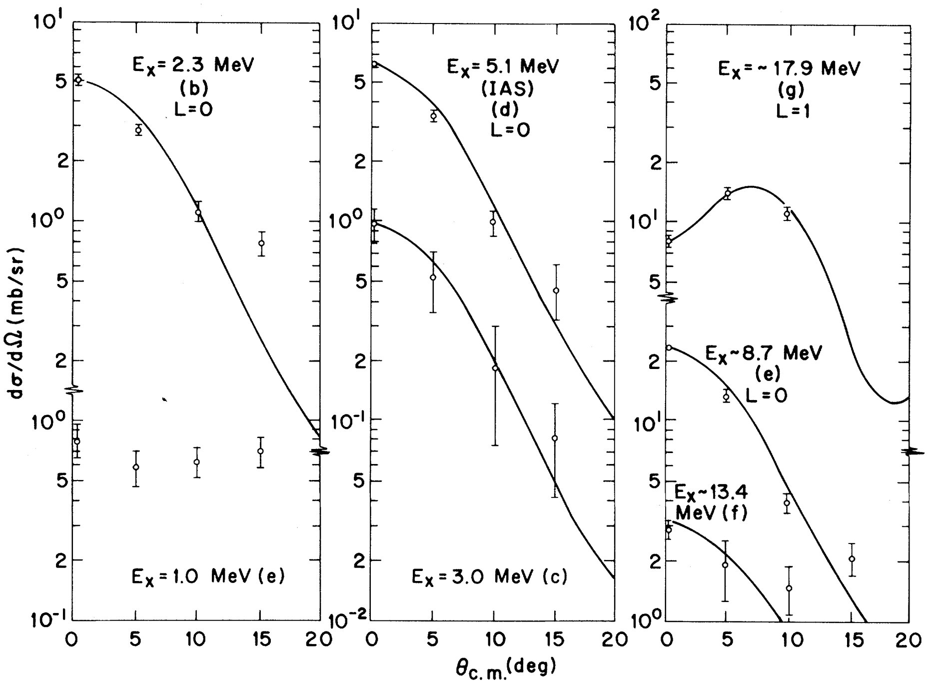

FIG. 2. Differential cross sections for the peaks identified in Fig. 1. The solid curves are macroscopic DWBA calculations used to assign angular-momentum-transfer values.

are used only to differentiate between $L=0$ and $L=1$ shapes. Complete microscopic distorted-wave Born-approximation (DWBA) calculations have also been carried out and will be reported in a future paper.[13]

In the present experiment both a very simple reaction model and a very simple structure model seem applicable. At 0° we expect the dominant interaction term to be $V_{\sigma\tau}(\sigma\cdot\sigma_i)(\tau\cdot\tau_i)$. Thus we expect to see the excitation of states in ^{90}Nb which are connected to ^{90}Zr by the GT operator.

Starting with a 0^+ target, the GT operator connects only to 1^+ final states. Within the g-shell space, there are only three 1^+ wave functions based on the neutron configuration $(g^{9/2})^{-1}$. These are $(g^{9/2})^{10}$, $T=4$, and $(g^{9/2})^9(g^{7/2})^1$, $T=4$ and $T=5$. Because of the spin-orbit splitting, we expect the states with the $g^{7/2}$ component to be at a higher excitation than the simple $g^{9/2}$ configuration state. Since, in detail, the $p^{1/2}$ shell is not full for protons, we can also expect to excite 1^+ states containing p-shell particle-hole components.

The spectrum in Fig. 1 looks qualitatively like what one would expect from such a simple model. Peaks labeled "a," "b," "c," are plausibly the states with the p-shell 1^+ components and $(g^{9/2})^{10}$, $T=4$, 1^+ component. The peak labeled "d" is the isobaric analog state and it represents the strength distribution of the Fermi operator $|\tau|\psi_0\rangle$. The broad peak labeled "e" plausibly contains the 1^+ strength from the $(g^{9/2})^9(g^{7/2})^1$, $T=4$ configuration. The fact that this peak is clearly identifiable indicates that a vestige of the simple structure of the g-shell space persists and the 1^+ strength of the simple configuration is not completely dissolved among the 1^+ states of the much larger real space.

Because of the simplicity of the target state we can also make simple strength estimates. In the approximation that the g shell is empty for protons the GT operator can operate with its full force and the sum of the squares of the GT matrix elements for all states should be 30. The 0° cross sections are tabulated in Table I. These should be approximately proportional to the β-decay matrix elements that connect the same states. The Fermi matrix element for the IAS transition, $\langle\psi_{\rm IAS}|F|\psi_{^{90}{\rm Zr}}\rangle^2=10$, is used to normalize the cross sections. For the GT to F force ratio we use $(V_{\sigma\tau}/V_\tau)^2=4.6$.[5] The results are also shown in Table I. More than one-third of the expected strength is observed.

Included in our assignment of GT strength is the broad peak at $E_x\sim 13.4$ MeV. The angular distribution suggest an $L=0$ transfer. The cross-section ratio, 1:8.3, of this peak to the 8.7-MeV peak is in agreement with the expected ratio of 1:9 for the $T=5$ to $T=4$ components of the $(g^{7/2})^1$-$(g^{9/2})^9$, 1^+ configuration. Thus, we tentatively identify the $E_x \sim 13.4$-MeV peak as a $J^\pi = 1^+$, $T=5$ resonance. One would expect to see the $T_Z = 5$ component of this as an $M1$ resonance in ^{90}Zr at about $E_x = 8.2$ MeV. Possible evidence for an $M1$ resonance at about 9 MeV in ^{90}Zr is seen in 180° electron scattering.[6] Galonsky *et al.*[14] speculated that a peak at $E_x \sim 18.5$ MeV is the $T=5$, 1^+ component. That reported peak may correspond to our observation of a peak at $E_x \sim 17.9$ MeV, which we tentatively assign at a 1^- peak.

The $E1$ resonance in ^{90}Zr has been identified at an excitation energy of 16.8 MeV (Berman and Fultz[15]). Thus its analog in ^{90}Nb should correspond to a broad peak at around 21.9 MeV. Assuming the same isospin splitting observed in the $M1$ states, $\Delta E \sim 4.7$ MeV, then the $T=4$, $J^\pi = 1^-$ resonance in ^{90}Nb should be around 17.2 MeV in very good agreement with the excitation energy of the observed resonance (g). The $T=5$, $J=1^-$ resonance in ^{90}Nb should be more weakly excited, which might be the reason it was not observed in the present experiment.

Further discussion on observation of GT strength in low-energy experiments is contained in Galonsky.[16]

In summary, we have observed several pronounced peaks in the 0° spectrum from ^{90}Zr(p, n)^{90}Nb and interpreted them as GT transitions. A broad peak with apparent $L=1$ angular distribution is assigned as a possible $E1$ resonance component.

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