Fine Structure and Spin Excitations in the Giant Resonance Region of ^{90}Zr

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Cross sections, analyzing powers, and spin-flip probabilities have been measured at small angles in the reaction ^{90}Zr$(p,p')^{90}$Zr* at 319 MeV. A rich fine structure is observed in the previously proposed $M1$ giant resonance region; angular distributions of most of these structures are consistent with $M1$ excitation. The spin-flip measurements reveal a large cross section for spin excitations distributed roughly uniformly over the excitation energy region from about 8 to 25 MeV.

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Observation of the Gamow-Teller (GT) resonance in the (p,n) reaction on medium and heavy nuclei has stimulated renewed interest in spin excitations in nuclei.[1] Excitation of this resonance proceeds by a spin transfer $\Delta S = 1$ to the nucleus; the fact that about half of the expected strength in this channel has not yet been identified has encouraged consideration of the possible spreading of this strength to much higher excitation energies.[2] Similarly, $M1$ excitations should be observable in proton or electron scattering. In ^{90}Zr, these should occur at an excitation energy of about 9 MeV, just below a region where many natural-parity resonances have been identified; these natural-parity resonances are not expected to involve spin transfer. Indeed, recent measurements[3] of cross-section angular distributions for 200-MeV proton scattering on ^{90}Zr have revealed a 2-MeV-wide bump without structure at about 9 MeV excitation which appears to exhaust a significant percentage of the expected $M1$ strength. However, a detailed high-resolution study of electron scattering at 165° has identified only a few well-separated $M1$ states amid a very large number of $M2$ states.[4] Similar differences have recently been seen for several other nuclei.[5-7]

To help resolve the apparent discrepancy between proton and electron scattering, and to determine whether significant unnatural-parity strength exists at higher excitations in ^{90}Zr, we have measured the differential cross section σ, the analyzing power A_y, and the spin-flip probability S_{nn} in the reaction ^{90}Zr$(p,p')^{90}$Zr at 319 MeV. Like back-angle electron scattering cross sections, the spin-flip cross section σS_{nn} is a measure of $\Delta S = 1$ excitations,[8] whereas σ data by themselves can seldom distinguish between $\Delta S = 0$ and $\Delta S = 1$.

The data were taken at the high-resolution spectrometer (HRS) at the Clinton P. Anderson Meson Physics Facility (LAMPF) with a beam of 319-MeV protons polarized perpendicular to the reaction plane $(\hat{n})$. Cross section and A_y measurements were carried out with the standard HRS system[9] modified to minimize the instrumental background inherent in small-angle inelastic scattering. A thin target of areal density 50 mg/cm^2 was used, and an overall resolution of 60 keV was achieved. Excitation energies were calibrated relative to known states in ^{12}C, ^{48}Ca, and ^{90}Zr. Absolute cross sections, correct to ±10%, were measured by comparison to previously measured cross sections for elastic scattering from hydrogen. The polarization of the scattered protons was measured with the HRS focal-plane polarimeter.[10] This required a thick target (250 mg/cm^2), so that the energy resolution was 180 keV and the instrumental background was decidedly worse.

A spectrum taken with the thin target at 2.75° is illustrated in Fig. 1 (top); spectra expanded in the 9-MeV region at 2.75° and 4.25° are compared in Fig. 1 (bottom). The expanded proton spectra clearly show rich fine structure not observed in the previous proton work. Cross sections were extracted in the 9-MeV region by fitting individual peaks (numbered in Fig. 1) after subtracting a background comparable to that shown by the dotted line in the figure. Many of these peaks may correspond to several unresolved states; about 40% of the cross section is not contained in the fitted peaks. The summed cross section for the entire bump at 2.0° is 5.6 ± 1.0 mb/sr, including background subtraction errors; the angular distribution lies about 15% higher than the Orsay measurement at 200 MeV.[3] Typical angular distributions are shown in Fig. 2. The curves represent distorted-wave impulse-approximation calculations with the Love-Franey interaction[11] for $M1$ (solid) and $M2$ (dashed) states assuming $(\nu g_{9/2}^{-1}, g_{7/2})_{1^+}$ and $(\pi f_{5/2}^{-1}, g_{9/2})_{2^-}$ configurations, respectively, and optical parameters extrapolated from nearby energies. The very-forward-angle data for most structures in the 9-MeV region are consistent with $M1$ excitations, in agreement with Ref. 3; the possibility of $E1$ assignments is discussed below. The values of A_y for individual states are too uncertain to be useful, but it is important to note that A_y for the whole 9-MeV peak is less than ± 0.05 out to 5°. This is consistent with distorted-wave impulse-approximation predictions for a 1^+ (or 1^-), $\Delta T = 1$ transition, but not a 1^+, $\Delta T = 0$ transition for which the predicted values lie around -0.30.

It is now possible to begin to compare (e, e') and (p, p') results, although it is clear that better statistics and resolution are necessary for a definitive comparison. The centroids of peaks identified in (p, p') as consistent with mostly 1^+ excitation are listed in Table I. Most of these peaks can be followed through the eight angle bins, but several fragment or disappear as the scattering angle increases. Peaks fitted at 7.53, 7.94, and 8.26 MeV appear to have $\Delta L = 1$ angular distributions. A number of the structures in Table I have angular distributions like that of the 8.26-MeV state shown in Fig. 2 which indicate significant $\Delta L = 1$ strength as well; their $\Delta L = 1$ contribution at the most forward angles, however, is very small. Also listed in Table I are the definite and possible $M1$ assignments from electron scattering. While Table I reveals better agreement between the (p, p') and (e, e') results than previously apparent,[3-5] it is clear that substantial prob-

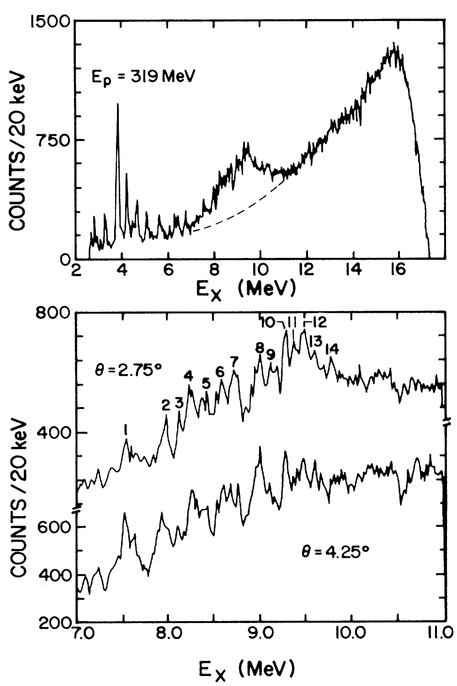

FIG. 1. Top: spectrum of the reaction $^{90}Zr(p,p')^{90}Zr^*$ at 2.75° (lab). Bottom: spectra for the same reaction at 2.75° and 4.25° expanded in the 9-MeV region.

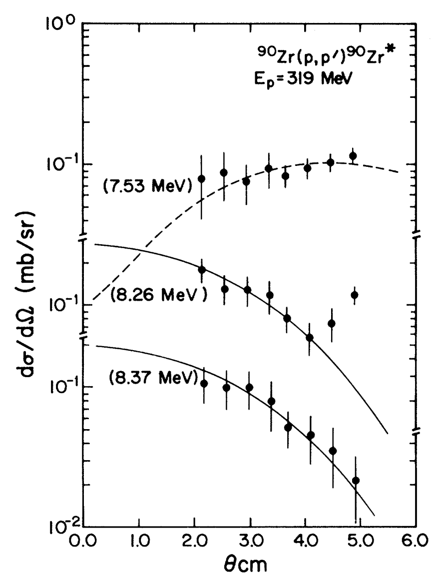

FIG. 2. Cross-section angular distributions for typical structures. The solid and dashed curves are distorted-wave impulse-approximation predictions (normalized to the data) for pure one-particle, one-hole configurations for $M1$ and $M2$ states, respectively.

lems remain. For example, the strongest peak in the (p,p') spectrum, at 9.28 MeV, is not seen as a 1^+ in (e,e').

A number of possible reasons for the differences between the two reactions can be adduced, but none appears able to explain all the differences at this time. Preliminary results of recent fluorescence experiments[12] indicate many $E1$ states in this region, but their radiative widths appear mostly too small to account for the cross sections of structures listed in Table I. The (p, p') data extend to smaller q values (0.16 fm^{-1}) than the (e,e') data (0.31 fm^{-1}), so that the relative sensitivity to $M1$ states is considerably enhanced. Possible current contributions to electron scattering are unlikely to be important for the mostly neutron $M1$ transitions, but they may enhance the $M2$ states. While $\Delta T=0$ contributes relatively more to proton scattering, these amplitudes are weak in the Love-Franey interaction; large $\Delta T=0$ contributions seem ruled out by our A_y data.

The spin-flip data yield their own surprises. Shown in Fig. 3 are the spectra of S_{nn} and σS_{nn} at 3.5° without background subtraction; data at 5° are similar, but they extend only to 16 MeV. As expected, spin-flip cross sections are small at low excitation energy in the region of isolated states; they rise to significant values around 8 MeV. Compared to the higher excitation energy region, however, the region around 9 MeV is in no way remarkable. Rather, spin excitations are observed up to at least 25 MeV where only natural-parity states have previously been seen.

If a simple background is drawn in the 9-MeV region, then a value of 0.62 ± 0.20 is obtained for S_{nn}; because of the uncertainty in the background, the systematic error in this value is large. To calibrate the value expected for a pure $M1$ transition, S_{nn} was measured for the reaction $^{48}Ca(p,p')^{48}Ca^*$ to the 10.23-MeV 1^+ state; the value obtained, 0.44 ± 0.08 at 3.5°, is consistent with an $M1$ assignment for the 9-MeV bump in ^{90}Zr. The poor resolution of the present S_{nn} data does not permit isolation of individual $E1$ states.

We have closely examined many possible sources of error in obtaining the spectra of Fig. 3, but because of the uniform spreading of the spin-flip strength, it is difficult to be certain that all sources of error have been eliminated. Nevertheless, our results strongly suggest that the spin-flip cross section at 3.5° is approximately 0.8 mb/sr MeV throughout the region from 8 to 25 MeV excitation.

While no spin excitations have previously been observed above 10 MeV, it is important to note that no experiments really sensitive to such strength have been performed. The uniform spreading of the σS_{nn} strength is suggestive of the apparent quasifree background observed in

TABLE I. Comparison of (p,p') and (e,e') results. The peak numbers for (p,p') correspond to the labels in Fig. 1; only structures with angular distributions consistent with 1^+ are listed. Errors on (p,p') excitation energies are ±20 keV; errors on (e,e') excitation energies are ±10 keV. Definite assignments from (e,e') are underlined.

(p,p') No.	(p,p') E_x (MeV)	(e,e')[a] E_x (MeV)	(e,e')[a] J^π
		7.77	$(1^+,2^-)$
		7.87	$(1^+,2^-)$
3	8.13	8.14	$1^+,(2^-)$
4	8.26	<u>8.23</u>	<u>1^+</u>
5	8.37	<u>8.37</u>	(1^+)
		8.60	(1^+)
7	8.73		
8	8.98	<u>9.00</u>	<u>1^+</u>
9	9.14		
10	9.28		
11	9.38	<u>9.37</u>	<u>1^+</u>
		<u>9.44</u>	$1^+,(2^-)$
12	9.48		
		9.52	$(1^+,2^-)$
13	9.60		
14	9.77		

[a]Ref. 4.

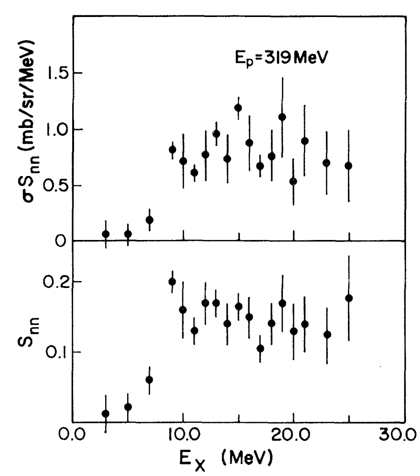

FIG. 3. Spectra of S_{nn} and σS_{nn} for the reaction $^{90}Zr(p,p')^{90}Zr^*$ at 3.5°.

the (p, n) reaction; Osterfeld[13] is able to explain this as $\Delta S = 1$ excitations up to spin 3^+ even at 0°. It is interesting to observe that the S_{nn} predicted by Arndt's phase-shift solutions[14] at 3.5° is 0.37 and 0.20 for free *pp* and *pn* scattering, respectively. Comparison with the S_{nn} values in Fig. 3 shows that the nuclear response is not dramatically different from that of a Fermi gas, even though this is a region of high natural-parity collectivity. This disagrees with the conclusions of Moss *et al.*[15] for ^{208}Pb at 400 MeV.

In summary, proton and electron scattering now agree that the 9.0-MeV excitation-energy region shows considerable fine structure in apparent *M*1 strength, but they continue to disagree on spin assignments and relative strengths for some structures. Our spin-flip data are consistent with unnatural-parity assignments here, but they are not definitive; high-resolution spin-flip experiments with high statistics are necessary. On the other hand, the spin-flip measurements reveal for the first time considerable spin-excitation cross section over the entire region from 8 to 25 MeV.

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