Observation of *M*1 Strength by the Inelastic Scattering of 200-MeV Protons

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A new resonance has been observed at very forward angles in the inelastic scattering of 200-MeV protons on ^{90}Zr, ^{92}Zr, and ^{94}Zr at an excitation energy around 8.8 MeV in each target. The excitation energy, angular distribution, and strength of this state suggest that it corresponds to the previously unseen giant $M1$ transition in the zirconium isotopes.

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The location of $M1$ strength in medium and heavy nuclei has been a long-standing and major problem in nuclear structure physics.[1] While various theoretical estimates[2,3] have indicated that $M1$ states should exist below 12 MeV excitation energy in nuclei with $A > 60$, little or no significant $M1$ strength has been observed. This strength has been searched for in both hadron,[4,5] and electron[6-8] inelastic scattering but so far without success. There has been some $M1$ strength reported[9] in ^{208}Pb and a mention[10] of strength observed in (e,e') on ^{90}Zr, which has not been substantiated by later measurements.[7]

In contrast, there has been observed in recent charge-exchange[11-17] experiments on more than twenty target nuclei, a broad resonance which is generally accepted as the giant Gamow-Teller (GT) resonance. This transition, in which $\Delta J^{\pi} = 1^+$, is successfully accounted for in terms of the shell model,[18] and the same considerations would predict appreciable strength for a giant $M1$ state in the target. Hence, we have the paradoxial situation that the transition to the $T_<$ state in the daughter nucleus has been observed many times, but the parent of the $T_>$ state has never been seen. The elusiveness of the parent state casts doubt upon the interpretation of the charge-exchange experiments. The present results resolve this paradox.

The GT peak, which is greatly enhanced at forward angles, is much stronger relative to the background at 120 MeV (Ref. 14) than at 45 MeV bombarding energy.[11] Its 1^+ character has been established on the basis of excitation energy and the observed angular distributions. In addition to the broad bump observed in the reaction $^{90}Zr(p,n)^{90}Nb$, about 3.6 MeV above the isobaric analog of the target ground state, a second smaller peak is indicated about 8.3 MeV above the isobaric analog state (IAS)[13,19] which also appears to have a predominantly $l = 0$ angular distribution. It has been suggested that this peak is the $T = 5$ ($T_>$) component of the giant GT resonance. However, it is too weak and too close to the large $T = 4$ ($T_<$) bump to be clearly separated from it.

These results implied that $M1$ strength might be observable in the parent nucleus with use of the (p,p') reaction. The expected excitation energy would be given by the difference between the energies of the IAS and the $T_>$ peak, viz. 8.3 MeV in ^{90}Zr. The GT peak in (p,n) reactions is more prominent at higher bombarding energies because the ratio of the spin-flip component, $V_{\sigma\tau}$, to the non-spin-flip component, V_{τ}, of the effective interaction increases with energy.[20-24] In the (p,p') reaction above 100 MeV, the same component, $V_{\sigma\tau}$, is mainly responsible for unnatural parity transitions such as $0^+ \to 1^+$ at small momentum transfer. Since the reaction dynamics should be similar for (p,p') and (p,n) reactions at similar bombarding energies, 1^+ states in (p,p') should also be excited mainly through an $l = 0$ transfer. These states should, therefore, show the same sharp forward peaking of the angular distribution which characterized the GT peak in the (p,n) reaction.

These considerations prompted a search for $M1$ strength in medium weight nuclei with use of the 201 MeV proton beam from the Orsay synchrocyclotron and a large magnetic spectrometer. The targets used were calcium (natural Ca; 15.0 mg/cm^2), ^{90}Zr (97.65% enriched; 18.9 mg/cm^2), ^{92}Zr (95.13% enriched; 25.4 mg/cm^2), and ^{94}Zr (98.6% enriched; 16.4 mg/cm^2). The particles were detected by two multiwire proportional counters[25] backed by two plastic scintillators. The combination of large size, careful beam preparation, and the trajectory information from the counters allows such clean detection of particles that inelastic scattering data can be taken down to a laboratory angle of 3°. The energy resolution obtained was about 80 keV full width at half maximum (FWHM). Absolute values of the cross sections were determined by comparison with the known *p*-*p* scattering cross sections with use of a polyethylene target. The spectra were energy calibrated by recording the position of the elastic peak for various magnetic field settings and by using the positions of the known low lying states of ^{90}Zr, ^{40}Ca, and ^{12}C. The calibration is good to about ± 25 keV.

Since a known 1^+ state at 10.32 MeV has been observed in ^{40}Ca in a backward angle (e,e') experiment,[8] this nucleus was studied to check that the same state would be selectively excited in forward-angle (p,p') measurements. Many sharp peaks were observed in the 7° spectrum in the region of excitation energy from 6.8 MeV to above 13 MeV, with the known 1^+ state[8] at 10.32 MeV being quite weak. However, at 3° the spectrum was much simpler, with a peak at 10.3 MeV excitation energy standing out quite clearly above the background. The known 2^- state at 8.43 MeV is also visible in the 3° proton spectrum. The state at 9.87 MeV is quite strong at 7° compared to the 10.32 MeV state but is much weaker at 3°. This is consistent with the previous conclusion that this peak is a close $(1^+,2^+)$ doublet with the 1^+ strength being at most $\frac{1}{3}$ that of the 10.32-MeV state.[8]

Spectra from ^{90}Zr, ^{92}Zr, and ^{94}Zr at a laboratory angle of 4° are shown in Fig. 1. These spectra show only two features, a broad peak near 9 MeV excitation and a broader peak at about 16 MeV excitation. The centroid of the 16 MeV peak moves toward the elastic peak as the scattering angle increases. This peak is probably a mixture of the $E1$ giant resonance[26] and the lower lying giant quadrupole and monopole resonances.[27-29] The dipole resonance is expected to peak near 5° or at even more forward angles due to Coulomb excitation,[30] but the quadrupole resonance should peak near an angle of 9°. The relative excitation of these three resonances at different angles accounts at least qualitatively for the shift of the centroid with angle.

The peak observed near 9 MeV in all three zirconium isotopes is believed to be the giant $M1$ resonance. The evidence for this is based on excitation energy, width, angular distribution, and cross section. To ensure that the features observed in the Zr spectra were not an instrumental effect arising from elastic scattering, a spectrum from a gold target was taken at 4°. No feature could be identified in the gold spectrum even though the elastic scattering count rate at 4° was much higher than for the zirconium target.

The excitation energy of the peak is consistent both with theoretical predictions[2,4] and with the estimate from the (p,n) data.[13] While this latter value of 8.3 ± 0.5 MeV is rather uncertain, it agrees with the position observed in ^{90}Zr of 8.9 ± 0.2 MeV. A summary of the excitation energies, widths, and cross sections for the states believed to be 1^+ are given in Table I. A recent measurement[19] with fairly good statistics gives a width of 1.8 MeV for the $T_>$ state in ^{90}Nb, a value which is consistent with the present (p,p') experiment.

The angular distributions for a number of states

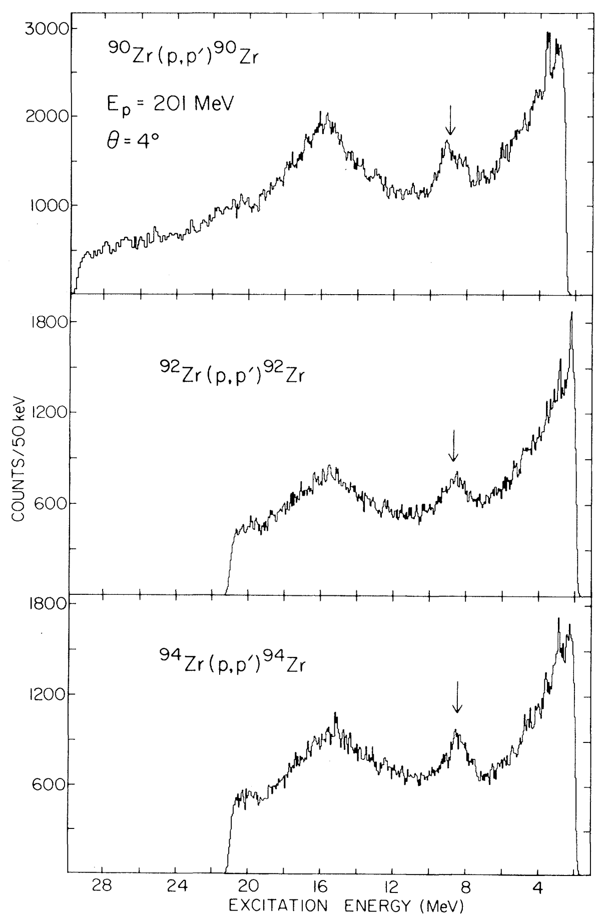

FIG. 1. Inelastic proton spectra for ^{90}Zr, ^{92}Zr, and ^{94}Zr at 4°. The arrows indicate the $M1$ state.

TABLE I. Characteristics of resonances observed with $l = 0$.

Target	E_x (MeV)	FWHM (MeV)	$(d\sigma/d\Omega)_{c.m.}(4^\circ)$ (mb/sr)
^{40}Ca	10.32 ± 0.02	< 0.1	0.24 ± 0.02
^{90}Zr	8.90 ± 0.15	1.7 ± 0.2	2.8 ± 0.3
^{92}Zr	8.8 ± 0.2	1.7 ± 0.2	2.8 ± 0.3
^{94}Zr	8.63 ± 0.15	1.5 ± 0.2	3.1 ± 0.3

in ^{40}Ca, ^{90}Zr, and ^{94}Zr are shown in Fig. 2. The known 1^+ state at 10.3 MeV in ^{40}Ca, the state at 12.0 MeV in ^{40}Ca, and the peaks at 8.9 MeV in ^{90}Zr and 8.6 MeV in ^{94}Zr all show the very strong forward peaking which is characteristic of an $l = 0$ angular momentum transfer. This is consistent with the angular distributions observed for the GT resonances in the (p,n) reaction. If a state observed at 12.0 MeV in ^{40}Ca is assumed to have natural parity [since it was not excited in the backward angle (e,e') experiment] its spin and parity assignment is probably 0^+. The known 2^- state at 8.4 MeV in ^{40}Ca is expected to be excited predominantly by an $l = 1$ transfer and indeed it does not show a rapid decrease with angle. The broader bump in ^{90}Zr which probably contains electric dipole, quadrupole, and monopole strengths, also has an angular distribution which is less sharply forward peaked than that expected for the case of a pure $l = 0$ transfer. The fact that the peaks near 9 MeV in ^{90}Zr and ^{94}Zr have angular distributions similar to that for the known 1^+ state in ^{40}Ca is strong evidence that these states have spin and parity assignment 0^+ or 1^+. However, the fact that no resonance was seen at this excitation energy in ^{90}Zr (α,α')[28,29] implies that the J^π of the resonance is indeed 1^+.

Distorted-wave Born approximation (DWBA) calculations have also been carried out with use of the code DWUCK[31] with macroscopic form factors. The optical-potential parameters have been taken from the systematic studies of Nadasen *et al.*[32] While this model of form factors is known to be unrealistic for $l = 0$ and 1 transfers and cannot be used for absolute comparison with experiment, these calculations are also known to give angular distribution shapes which are very close to those obtained from more realistic microscopic calculations. For example, the $l = 0$ shape matches very well the experimental angular distribution for the GT resonance observed in (p,n). As is clear from Fig. 2, these calculations show

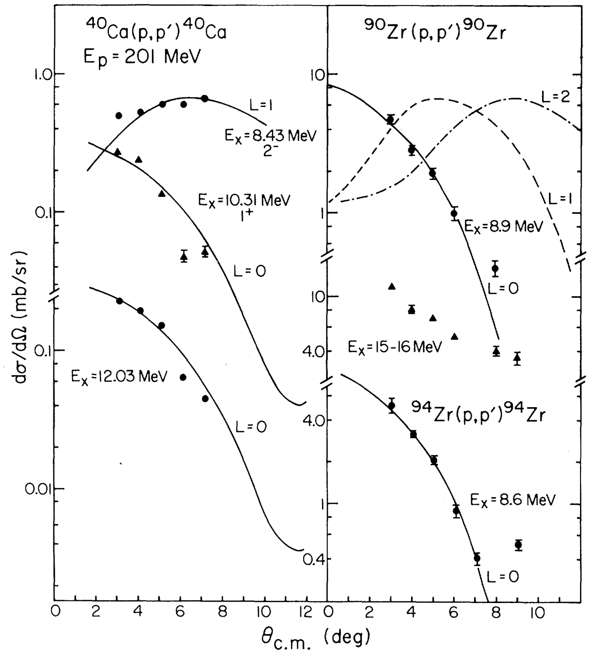

FIG. 2. Angular distributions for the indicated states in ^{40}Ca, ^{90}Zr, and ^{94}Zr. The curves are the results of DWBA calculations discussed in the text and are labeled by the l transfer of the transitions.

that the peaks near 9 MeV in ^{90}Zr and ^{94}Zr are populated by transitions with an $l = 0$ transfer and are therefore consistent with their identification as predominantly $M1$ transitions.

A further piece of evidence for the $M1$ nature of the transitions is provided by the strength observed. We assume, as seems consistent with the known values of $V_{\sigma\tau}$ and V_σ,[23,24] that the transition is mediated mainly by $V_{\sigma\tau}$. Following the method given by Goodman *et al.*,[14] the cross section for the giant $M1$ transition at 0° for ^{90}Zr(p,p') is estimated to be ~6 mb/sr, including a reasonable quenching factor of about 2 compared to the pure shell model.[33] If we now use the DWBA calculations to extrapolate from 0° to 4°, the predicted cross section for ^{90}Zr at 4° is ~3 mb/sr, which is in good agreement with the 2.8 mb/sr observed.

In summary, resonances about 1.5–1.7 MeV wide at excitation energies between 8.6 and 8.9 MeV are observed in the (p,p') reaction on ^{90}Zr, ^{92}Zr, and ^{94}Zr. A comparison with the angular distribution for a known 1^+ state in ^{40}Ca and with DWBA calculations indicates that these states are populated by transitions with an angular momentum transfer of zero. The position and cross section of these features suggest that they correspond to $M1$ transitions observed for the first time in these nuclei.

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