Giant $M1$ Resonance in ^{90}Zr

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The distribution of magnetic dipole transition strength in ^{90}Zr has been measured at excitations between 8.1 and 10.5 MeV with highly polarized tagged photons. A total $M1$ strength of $\sum g\Gamma_0^2(M1)/\Gamma = 37.7^{+5.1}_{-4.0}$ eV was found to be broadly distributed throughout the region. This strength can account for the giant $M1$ resonance predicted in ^{90}Zr. A substantial amount of $E1$ transition strength was also identified. This $E1$ strength has important implications for the interpretation of forward-angle (p,p') scattering and its use in identifying $M1$ transitions in heavier nuclei.

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In recent years, several groups[1-7] have attempted to measure the distribution of magnetic dipole transitions in ^{90}Zr at excitations near 9 MeV, where simple theoretical considerations[8] would predict the giant $M1$ resonance. The results of these measurements in ^{90}Zr are not consistent, and the reported $M1$ strengths are in general much less than would be expected from the magnitude of the systematic quenching of $M1$ strengths, Gamow-Teller strengths, and magnetic moments that is observed in other heavy nuclei.[9,10] This quenching, which typically amounts to about a factor of 2 with respect to the predictions of the independent-particle model (IPM), reflects various aspects of nuclear dynamics including ground-state correlations, coupling to nucleon excitations (Δ), and coupling to more complicated nuclear states.[11,12] The latter, in particular, can result in a substantial local fragmentation of the $M1$ strength. For experimental methods of magnetic-dipole-transition identification which depend on the resolution of resonance structure above a poorly defined underlying background, such fragmentation can lead to a serious underestimation of the $M1$ strength.[12] High-resolution measurements of backward-angle inelastic electron scattering in ^{90}Zr (Ref. 1) showed a significant amount of magnetic scattering near 9 MeV. Most of the observed strength was associated with $M2$ excitations, and the reported $M1$ contribution accounts for less than about 16% of the strength that would be expected from an IPM calculation.[11] Independent lower-resolution (e,e') work at 180° (Ref. 5) saw no indication of magnetic dipole transitions within the experimental limits of sensitivity. It is known, however, that the strong response of backward-angle inelastic electron scattering to $M2$ excitations can easily mask the presence of sufficiently fragmented $M1$.[13,14] Similarly, resonance fluorescence measurements with use of polarized bremsstrahlung found no $M1$ states among the few strongest transitions that could be isolated above the very large backgrounds.[7] This negative result would be predicted for even modest $M1$ fragmentation. Forward-angle inelastic proton scattering has been used by three groups[2-4,6] to search for $M1$ transition strength in ^{90}Zr. In each case, near 9-MeV excitation, a broad bump above a large background was observed at forward angles. Of the two earlier measurements, the $M1$ cross section reported from Orsay[2,4] was almost a factor of 3 smaller than that reported from TRIUMF,[3] the latter amounting to about 60% of the IPM prediction.[15] A more recent result from the Clinton P. Anderson Meson Physics Facility (LAMPF)[6] gave a total bump cross section even smaller than that from Orsay ($\simeq$18% of IPM), and, in addition, indicated that a significant part of the strength in the bump could in fact be due to $M2$ excitations. There is a further potential problem with the use of forward (p,p') measurements to identify $M1$ strength in that the $L=0$ angular distribution corresponding to $M1$ excitations is virtually indistinguishable from the distribution associated with the Coulomb excitation of $E1$ states.[3,16,17] In the region near 9 MeV in ^{90}Zr, it is reasonable to expect that there is a very substantial amount of $E1$-transition strength associated with the low-energy tail of the giant dipole resonance (GDR).[18,19]

In an attempt to resolve the many discrepancies and questions outlined above, we have measured the distribution of magnetic-dipole-transition strength in the 9-MeV region of ^{90}Zr using highly polarized tagged photons. The use of the present technique avoids many of the difficulties that are inherent in other experimental methods.[12] The tagged-photon average elastic-scattering cross section is sensitive to the sum of the dipole transition strength in a particular tagging interval ΔE, and is independent of either the number of resonances included in the excitation interval or their respective individual magnitudes.[20,21] The tagging-coincidence requirement ensures that there is no background-subtraction problem to complicate the interpretation of the data. In addition, the present results are not confused by the proximity of $M2$ strength because the measured polarization asymmetries serve to separate $M1$ from both the dominant $E1$ and any possible $M2$ contributions.

The linear polarization of the tagged-photon beam was substantially enhanced by means of the residual-electron–selection technique previously described.[22] An enriched (99.3%) ^{90}Zr target and a large NaI photon detector at 90° could be moved remotely between the positive (s) and negative (o) beam-polarization orientations. The detector could also be moved to 0° in either orientation in order to determine both the detector response and the photon flux incident on the target per tagging electron. Consequently, all geometric and detector efficiency factors cancel in the measured asymmetry ratios. The incident cw electron-beam energy was 15.44 MeV, and photons were tagged in the range $8.1 \le E_\gamma \le 10.5$ MeV.

The measured polarized-photon elastic-scattering asymmetry, η_0^s, is shown in Fig. 1. The asymmetries that would be expected for pure $E1$ and pure $M1$ scattering are indicated by the solid curves. These curves were determined from a detailed calculation of the photon polarizations in first Born approximation including screening, averaged over the scattering target and the residual-electron acceptance as previously described.[22] The polarization calculation was normalized by the measurement of the asymmetries of known $M1$ transitions in Mg and Si, and $E1$ transitions in Pb, and was found to be quite good. The experimentally determined multiplicative normalization factor for the calculated polarization was 1.03 ± 0.06.

In each tagging interval, the observed asymmetries give the fraction m of the total elastic photon cross section that is due to $M1$-transition strength.[22] This quantity is shown in the upper portion of Fig. 2 (filled circles). Also shown in Fig. 2 is a collateral measurement[19] of the unpolarized average elastic photon cross section for enriched zirconium which is combined with the fractions m to give the actual $M1$ cross-section distribution (open circles). All of the statistical uncertainties associated with the elastic cross-section measurement, the asymmetry measurement, and the polarization normalization are reflected in the error bars. The total magnetic-dipole-transition strength in the interval between 8 and 10.5 MeV is $\sum g\Gamma_0^2(M1)/\Gamma = 37.7^{+5.1}_{-4.0}$ eV. The contribution of electric-dipole strength is $\sum g\Gamma_0^2(E1)/\Gamma = 233.6^{+5.5}_{-4.5}$ eV.

In order to compare the measured $M1$ elastic-scattering cross section more directly with theoretical predictions, it is useful to have an estimate of the magnetic-dipole reduced transition probability $B(M1\uparrow)$. $B(M1\uparrow)$ can be derived from $\sum g\Gamma_0^2(M1)/\Gamma$ if it is assumed that the ground-state partial widths follow a Porter-Thomas distribution and if the average ratio $\langle\Gamma\rangle/\bar{D}$ can be estimated for 1^+ excitations.[18,20] $\bar{D}$ was obtained from a standard back-shifted Fermi-gas level-density formula with the parameters $a = 10.0$ MeV^{-1} and $\Delta = 1.4$ MeV taken from Dilg *et al.*[23] The average $M1$ total width was estimated from neutron-capture total-radiative-width systematics[24] and the average ratio of $E1$ to $M1$ strengths taken from the present experimental measurement. The resulting total reduced transition probability corresponding to the measured $M1$ strength is $\sum B(M1\uparrow) = 6.7\mu_0^2$. It should be noted that the derivation of $B(M1\uparrow)$ is not strongly dependent on the average parameters $\langle\Gamma\rangle$ and $\bar{D}$.[18,19] Here, a 30% change in the ratio $\langle\Gamma\rangle/\bar{D}$ would produce only a 15% change in $B(M1\uparrow)$. A similar analysis for the measured electric-dipole-transition strength gives a corresponding reduced transition probability $\sum B(E1\uparrow) = 0.47\ e^2\cdot\text{fm}^2$. This $E1$ strength amounts to 90% of what would be estimated by

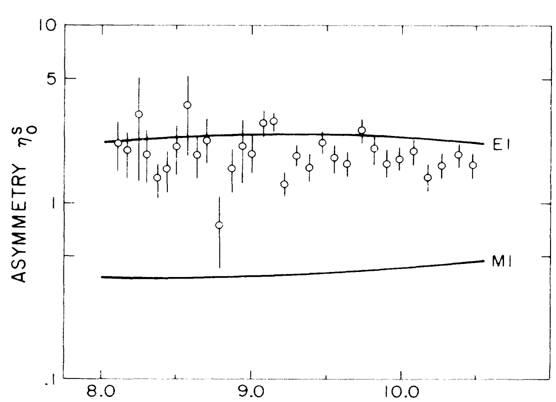

FIG. 1. The observed polarized photon elastic-scattering asymmetry at 90° in ^{90}Zr. The curves correspond to the expected asymmetries for pure $E1$ and pure $M1$ scattering.

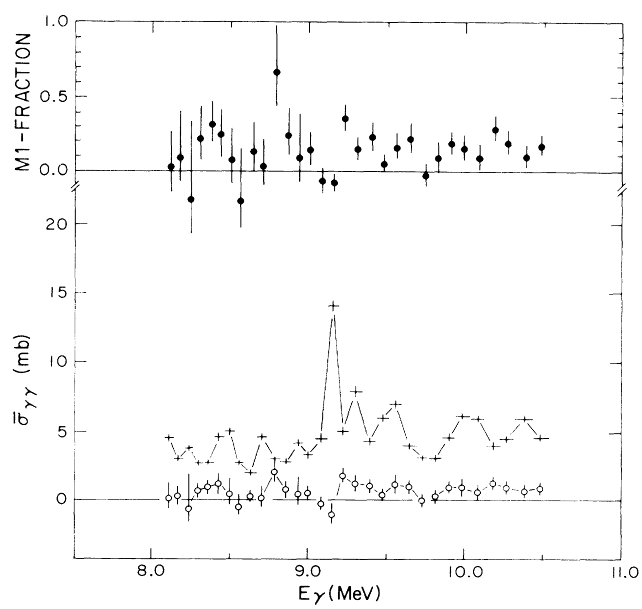

FIG. 2. Top: Fraction of the elastic-scattering cross section which is due to $M1$-transition strength. This fraction is combined with average elastic-cross-section data from Ref. 19 (crosses) to give the actual $M1$ cross-section distribution (open circles).

a simple extrapolation into the 9-MeV region of the tail of the Lorentz-line fit to the GDR.[19,25]

The magnetic-dipole strength in ^{90}Zr that is observed in the present work (Fig. 2) is more fragmented and less localized than that found previously in the heavier nuclei ^{140}Ce and ^{206}Pb (Ref. 22). There are perhaps slight concentrations of strength near 8.4 and 8.8 MeV, and more broadly above 9 MeV, but in general, the $M1$ strength appears to be distributed over many individually weak transitions. This observation is consistent with the relatively small amount of $M1$ strength that could be resolved in the (e,e') work.[1,5] The present measurement of $B(M1\uparrow)\simeq 6.7\mu_0^2$, however, corresponds to about 43% of the $15.7\mu_0^2$ that is predicted by the IPM for the giant $M1$ resonance in ^{90}Zr.[11] Although it is not known if there is additional $M1$ strength to be found outside the range of excitations examined here, the present result is quite consistent with the generally observed degree of systematic quenching of magnetic strengths in heavier nuclei.[9] More sophisticated calculations of the $M1$ giant resonance in ^{90}Zr predict $B(M1\uparrow)\simeq 5.4\mu_0^2$ with use of the Migdal effective-operator approach,[26] and $B(M1\uparrow)\simeq 5.8\mu_0^2$ in the case of a more microscopic theory.[11] Both of these results are in very good agreement with the present measurement.

The large amount of $E1$ strength that is identified in the 9-MeV region of ^{90}Zr by the tagged–polarized-photon technique has important consequences for the interpretation of forward (p,p') measurements. The coupled-channel code ECIS79[27] was used to calculate the Coulomb-excitation contribution of our measured $B(E1\uparrow)$ to the ^{90}Zr inelastic proton cross section for kinematic conditions appropriate for comparison with the results of Refs. 2–4 and 6. The comparison is summarized in Table I. In the worst case,[6] The $E1$ Coulomb-excitation correction amounts to one-half of the reported (p,p') cross section. Taken at face value this would give a corrected $M1$ strength of only about 10% of the IPM. The real implication of Table I, however, is that unless the Coulomb excitation of all of the $E1$ strength in the region is taken into account, there is insufficient guidance for establishing where the (p,p') background line should lie. We note that nuclear resonance-fluorescence measurements can be expected to underestimate substantially the amount of this $E1$ strength, particularly in heavier nuclei.[12,20,21,28] In the report of the TRIUMF work,[3] an attempt was made to fit the Coulomb excitation of the peak of the GDR taken from (γ,n) measurements[25] to the (p,p') cross section, and although the tail of the GDR was not extended into the 9-MeV region, the presence of the GDR above neutron threshold apparently constrained the background line to lie well below the place where it would otherwise be naively interpolated. This is likely to be the reason why the (p,p') $M1$ cross section of Ref. 3 is so much larger than the one reported in the other (p,p') work.[2,4,6] When our present calculation of the contribution of the $B(E1\uparrow)$ near 9 MeV is subtracted from the TRIUMF 9-MeV $M1$ cross section, the corrected result corresponds to about 55% of the IPM and comes into reasonable agreement with the tagged–polarized-photon measurement of the $M1$ strength. The fact that this (p,p') cross section remains somewhat large may reflect additional contributions from $M2$ excitations as observed in Ref. 6. There is evidence that the distribution of low-energy $E1$ strength in heavier nuclei, away from the Pb region, is dominated by the tail of the GDR.[18,19,28] This implies that, in general, there is likely to be a much greater contribution of Coulomb-excited $E1$ to forward (p,p') measurements than has previously been appreciated.

In summary, the distribution of magnetic-dipole-transition strength in ^{90}Zr has been measured at excitations between 8.1 and 10.5 MeV with highly polarized tagged photons. A total $M1$ strength of $\sum g\Gamma_0^2(M1)/\Gamma = 37.7^{+5.1}_{-4.0}$ eV corresponding to $B(M1\uparrow)\simeq 6.7\mu_0^2$ was found to be broadly distributed throughout the region. This strength can account for the giant magnetic dipole resonance expected in ^{90}Zr. A substantial amount of $E1$-transition strength corresponding to a $B(E1\uparrow)\simeq 0.47\ e^2\cdot \mathrm{fm}^2$ was also identified. This large amount of $E1$ strength has serious implications for the interpretation of forward-angle (p,p') scattering and its use as a

TABLE I. Comparison of ^{90}Zr(p,p') results.

Experiment	E_p (MeV)	θ (deg)	$d\sigma/d\Omega$(expt) (mb/sr)	$d\sigma/d\Omega(E1)$[a] (mb/sr)	Percent $E1$	$d\sigma/d\Omega$("$M1$")[b] (mb/sr)	Percent of IPM
Orsay[c]	201	4	2.8 ± 0.3	1.0	36	1.8	16
TRIUMF[d]	200	4	7.2 ± 2	1.0	14	6.2	55
LAMPF[e]	319	2	5.6 ± 1	2.8	50	2.8	10

[a]Contribution of $E1$ Coulomb excitation to the cross section, calculated from the present determination of $B(E1\uparrow)\simeq 0.47\ e^2\cdot \mathrm{fm}^2$ with the coupled-channel code ECIS79 (Ref. 27).

[b]Inferred $M1$ cross sections obtained by the subtraction of the calculated $d\sigma/d\Omega(E1)$ from the respective reported $d\sigma/d\Omega$(expt).

[c]References 2 and 4.

[d]Reference 3.

[e]Reference 6.

means of identifying $M1$ transitions in heavier nuclei.

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