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Giant $M1$ resonance in ^{140}Ce

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Highly polarized tagged photons were used to measure the distribution of $M1$ transition strength in ^{140}Ce at excitations between 6.7 and 8.7 MeV. A strength of $\sum g\Gamma_0^2(M1)/\Gamma = 11.2^{+4.5}_{-3.1}$ eV corresponding to a $B(M1\uparrow)$ of about $7.5\mu_0^2$ was observed centered at an excitation of 7.95 MeV. This distribution of $M1$ strength can account for the giant magnetic dipole resonance predicted in ^{140}Ce.

Simple theoretical arguments suggest that the best examples of the spin-flip giant magnetic dipole resonance should be found in heavier nuclei near closed shells.[1] Aside from the Pb nuclei, for which the extensive theoretical and experimental work has been recently reviewed,[2] the closed neutron shell $N=82$ nuclei are perhaps the most interesting candidates for investigation. Early inelastic electron scattering at backward angles showed broad resonances near 9 MeV in Ce, La, and Pr which exhibited an angular dependence typical of magnetic transitions.[3] A further analysis of the Ce data favored an $M1$ assignment for the 8.7 MeV resonance in this nucleus.[4] Threshold (γ,n) measurements also indicated that the $M1$ radiative strength functions $k(M1)$ were anomously large in ^{138}Ba and ^{140}Ce at excitations just above the respective neutron binding energies.[5,6] These threshold results could be understood in terms of quasiparticle-phonon model calculations,[7] and were not inconsistent with an $M1$ interpretation of the (e,e′) data.[5,6] Subsequently, more precise backward (e,e′) measurements with improved resolution were able to show that the broad 8.7 MeV resonance observed in ^{140}Ce was in fact due to $M2$ transition strength.[8,9] It became clear, however, that the strong sensitivity of the backward (e,e′) technique to $M2$ strength was capable of masking the possible presence of $M1$ transition strength, particularly if the $M1$ was in some degree fragmented.[9,10] More recently, forward inelastic proton scattering has been used to look for $M1$ strength in ^{140}Ce (Ref. 11). As in the (e,e′) work, a very broad bump was observed centered at about 8.6 MeV. The measured (p,p′) angular distribution was found to be consistent with the presence of both $M1$ and $M2$ transitions in the resonance region.[11] Quantitative estimates of the $M1$ strength are problematical not only because of the possible $M2$ admixture, but also because of a large inelastic scattering background that is not well determined.

In the present paper, we report the results of a measurement of the distribution of magnetic dipole transition strength in ^{140}Ce using highly polarized elastically scattered tagged photons. The tagged photon average elastic scattering cross section is sensitive to all 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.[12,13] The tagging coincidence requirement insures 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 in Refs. 14 and 15. A natural cerium 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 to give a direct measure of both the photon flux incident on the target per tagging electron, and the detector response. As a result, all geometric and detector efficiency factors cancel in the measured asymmetry ratios. The incident cw electron-beam energy was 12.9 MeV and photons were tagged in the range $6.7 \leq E_\gamma \leq 8.7$ MeV. The residual electron azimuthal acceptance was $3.0° \leq \Delta \leq 4.5°$.[14] Although a natural cerium target was employed, at excitations above 7.2 MeV essentially all of the elastic photon scattering comes from the ^{140}Ce isotope.

The measured polarized photon elastic scattering asymmetry $\eta\delta$ is shown in Fig. 1. The solid curves are an indication of the asymmetries that would be expected for pure $E1$ and pure $M1$ scattering. These curves were obtained

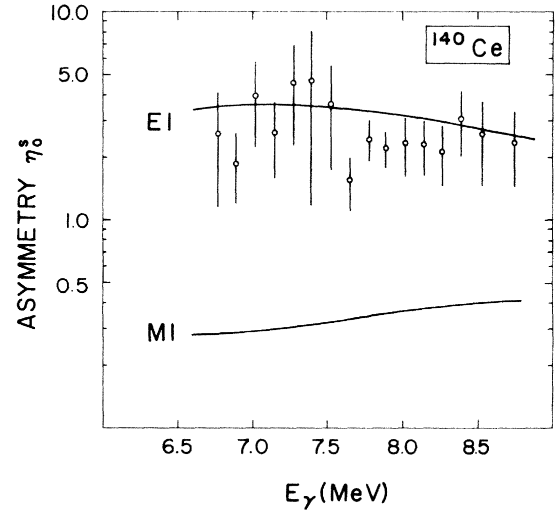

FIG. 1. The observed polarized photon elastic scattering asymmetry at 90° in cerium. The curves correspond to the expected asymmetries for pure $E1$ and pure $M1$ scattering.

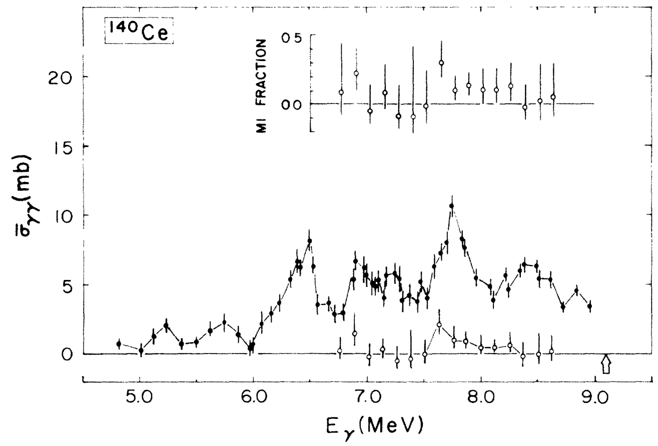

FIG. 2. The fraction of the elastic scattering cross section which is due to $M1$ transition strength is shown in the inset. This fraction is combined with average elastic cross section data from Ref. 16 (filled circles) to give the actual $M1$ cross section distribution (open circles).

from a detailed calculation of the photon polarization in first Born approximation, with screening, averaged over the photon target and the residual electron acceptance as described in Ref. 14. The polarization distribution was normalized to the nine largest asymmetries in the ^{140}Ce data. These points could be assumed to reflect predominantly $E1$ scattering. In the two target orientations, the respective photon polarizations changed slowly with energy, having mean values $\bar{P}^s = +0.47$ and $\bar{P}^0 = -0.53$, consistent with previous measurements.[14,15]

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,[14,15]

$$m = \tfrac{1}{2}[1-(1-\eta_0^s)/(P^s - P^0\eta_0^s)] .$$

A plot of this quantity is shown in the inset to Fig. 2. Also shown in Fig. 2 are previously measured natural cerium average elastic cross section data from Ref. 16 which are 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. There is a concentration of $M1$ cross section at excitations between about 7.6 and 8.3 MeV. The total magnetic dipole transition strength in the interval is $\sum g\Gamma_0^2(M1)/\Gamma = 11.2^{+4.5}_{-3.1}$ eV.

This $M1$ strength, centered near 7.9 MeV, is much more localized than the broad magnetic scattering bump found in the (p,p′) data of Ref. 11, which extends from 7 to 11 MeV. Part of the width of this latter may derive from uncertainties due to target contaminants and large backgrounds.[11] It is possible, however, that much of the width of the (p,p′) bump may reflect the broad concentration of $M2$ strength observed by inelastic electron scattering in the range between about 7.5 and 10 MeV;[8] and that both the $M1$ strength, observed in the present experiment to be spread over 0.8 MeV centered at 7.9 MeV, and the $M2$ strength of Ref. 8, which is distributed over 2.2 MeV centered at 8.7 MeV, can together provide a consistent explanation for the observed (p,p′) angular distribution of Ref. 11.

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 corresponding 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.[12,17] $\bar{D}$ was obtained from a standard back shifted Fermi-gas level density formula[18,19] with the parameters $a = 15.1\ \text{MeV}^{-1}$ and $\Delta = 1.35$ MeV taken from Ref. 19. The average $M1$ total width was estimated from neutron capture total radiative width systematics[20,21] and the approximation

$$\frac{\langle\Gamma_T(M1)\rangle}{\langle\Gamma_T(E1)\rangle} \approx \frac{\langle\Gamma_0(M1)\rangle}{\langle\Gamma_0(E1)\rangle} = \left(\frac{\bar{m}}{1-\bar{m}}\right),$$

where $\bar{m} = 0.14$ is taken from the present experimental measurement. The resulting total reduced transition probability corresponding to the measured $M1$ strength is $B(M1\uparrow) = 7.5^{+3.0}_{-2.1}\mu_0^2$. It should be noted that the derivation of $B(M1\uparrow)$ is not strongly dependent on the average parameters $\langle\Gamma\rangle$ and $\bar{D}$.[17] In the present case, a 30% change in the ratio $\langle\Gamma\rangle/\bar{D}$ would produce only a 12% change in $B(M1\uparrow)$.

It is expected that a number of effects including ground state correlations, 2p-2h and isobar couplings, and meson exchange currents will serve overall to reduce the strength of the giant $M1$ resonance in ^{140}Ce relative to the value that might be predicted by the naive independent particle model.[2] In the case of Pb, both a Landau-Migdal effective operator calculation with explicit one-meson exchange,[22] and a more microscopic theory which attempts to include some of the effects listed above explicitly[23] were able to accurately predict the observed distribution of $M1$ strength

TABLE I. Comparison of predicted and observed $M1$ strength in ^{140}Ce.

	Configuration	E_- (MeV)	$B(M1\uparrow)_-$	E_+ (MeV)	$B(M1\uparrow)_+$
Theory (Ref. 24)	(ν)	7.89	$8.25\mu_0^2$	$\cdots$	$\cdots$
	$(\nu+\pi)$	7.99	$9.85\mu_0^2$	6.13	$0.78\mu_0^2$
Present work	$\cdots$	7.95	$7.5^{+3.0}_{-2.1}\mu_0^2$	$\cdots$	$\cdots$

in ^{206}Pb (Ref. 15). A corresponding effective operator calculation of the giant $M1$ resonance in ^{140}Ce using the renormalization of Ref. 22 has been done by Wambach.[24] The results of this calculation are compared with the present experimental work in Table I. Because the contribution of the $\pi(g_{7/2},g_{9/2}^{-1})$ configuration is expected to be at least partially blocked by protons filling the $g_{7/2}$ orbital, the calculation is given for the $\nu(h_{9/2},h_{11/2}^{-1})$ configuration alone, as well as for both $\nu(h_{9/2},h_{11/2}^{-1})$ and $\pi(g_{7/2},g_{9/2}^{-1})$. In the latter case, as in Pb, both isoscalar (+) and isovector ($-$) states are predicted, with the bulk of the strength going to the isovector state. Table I shows that the agreement in both excitation energy and strength between the theoretical prediction and the present experiment is very good. Microscopic calculations in ^{208}Pb and ^{90}Zr predict giant $M1$ resonance widths on the order of 1 MeV, with a fraction of the strength tailing upward to much higher excitations.[23] These predictions are consistent with the observed $M1$ strength in ^{140}Ce which is seen to be concentrated within a range of about 0.8 MeV. A similar high energy $M1$ tail in ^{140}Ce might also be reflected in the enhanced $k(M1)$ found above threshold at 9.1 MeV.[6]

In summary, the distribution of magnetic dipole strength in ^{140}Ce has been measured at excitations between 6.7 and 8.7 MeV using highly polarized tagged photons. A total $M1$ strength of $\sum g\Gamma_0^2(M1)/\Gamma = 11.2^{+4.5}_{-3.1}$ eV corresponding to $B(M1\uparrow) \sim 7.5\mu_0^2$ was found at an excitation of 7.95 MeV. This distribution of $M1$ strength can account for the giant magnetic dipole resonance predicted in cerium.

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