$M1$ and $E1$ transition strength near threshold in ^{140}Ce†

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The ^{140}Ce(γ,n) ^{139}Ce reaction has been studied near threshold with high energy resolution. The angular distribution of photoneutrons was measured at 90° and 135°, and the $M1$ and $E1$ strength functions at an excitation of approximately 9.1 MeV were determined. The measured integrated $M1$ strength was found to be consistent with the existence of a giant $M1$ resonance centered at 8.7 MeV as suggested both by calculation and previous electron scattering data. The integrated $E1$ strength was also found to be consistent with what is known of the $E1$ strength function in the threshold region.

[NUCLEAR REACTIONS ^{140}Ce(γ,n), $E=9.1$ MeV, measured $\sigma(E_n,\theta)$, deduced $\sum\Gamma_{\gamma 0}(M1)$ and $\sum\Gamma_{\gamma 0}(E1)$.]

I. INTRODUCTION

There is considerable current interest in the distribution of magnetic dipole transition strength in nuclei, and more particularly in the question of $M1$ giant resonances attributed to a collective spin-flip mode of excitation. Such $M1$ resonances are expected to be most prominent near closed shells where one member of an orbital split into subshells by the spin-orbit interaction lies above the nuclear Fermi surface. Some experimental evidence for unusual concentrations of $M1$ strength has been obtained for nuclei with the closed neutron shell $N=82$.[1,2] In the particular case of ^{140}Ce, inelastic electron scattering results have shown a broad resonance, centered at 8.7 MeV, that exhibits the transverse angular dependence characteristic of magnetic transitions.[3] The exact multipolarity assignment of this resonance has been somewhat problematical,[1,3] but it is thought to be $M1$.

In the present work we have attempted a further investigation of the magnetic dipole transition strength in ^{140}Ce using the threshold photoneutron technique. The energy spectrum of neutrons from the ^{140}Ce$(\gamma,n)^{139}$Ce reaction was measured near threshold for laboratory angles of 90° and 135°. From these data it was possible to extract the individual ground-state strengths for $M1$ and $E1$ transitions in a 40-keV interval of excitation at 9.08 MeV.

II. EXPERIMENTAL PROCEDURE

Since the Argonne threshold photoneutron facility has been previously described in some detail,[4] only its main features will be outlined here. The Argonne high current linac provides a pulsed beam of 9.7-MeV electrons with a repetition rate of 800 Hz. Each beam burst is 4 ns wide, and has a peak current of 10 A. The electrons are focused onto a 1.5-mm-thick Ag bremsstrahlung converter, and are then stopped in 7.5 cm of aluminum. Current detected in the aluminum stopping block provides both a starting signal for the neutron time-of-flight measurement and a means of monitoring the intensity of the beam. Bremsstrahlung photons strike a 1-cm-thick target of enriched (99.7%) ^{140}Ce in the form of CeO_2.

Photoneutrons from the target travel along two 10-m flight paths located at 90° and 135° with respect to the direction of the incident beam, and are observed by banks of ^{6}Li-loaded-glass detectors. Neutron energies are determined from the time interval between the starting signal, and a stop signal from one of the ^{6}Li-glass detectors. Time-of-flight data for the reaction ^{140}Ce(γ,n)-^{139}Ce are shown in Fig. 1.

The relative neutron yields observed at 90° and 135° were normalized to the measured neutron distribution for the 254-keV line in ^{208}Pb which was taken to be isotropic.[5] Transition strengths in ^{140}Ce were also determined relative to the known width[6] of 16.8 eV for this 254-keV resonance.

III. DATA ANALYSIS

The diagram in Fig. 2 illustrates the process of photoexcitation in ^{140}Ce. The end point energy of the bremsstrahlung beam used in this experiment was such that neutron emission could occur

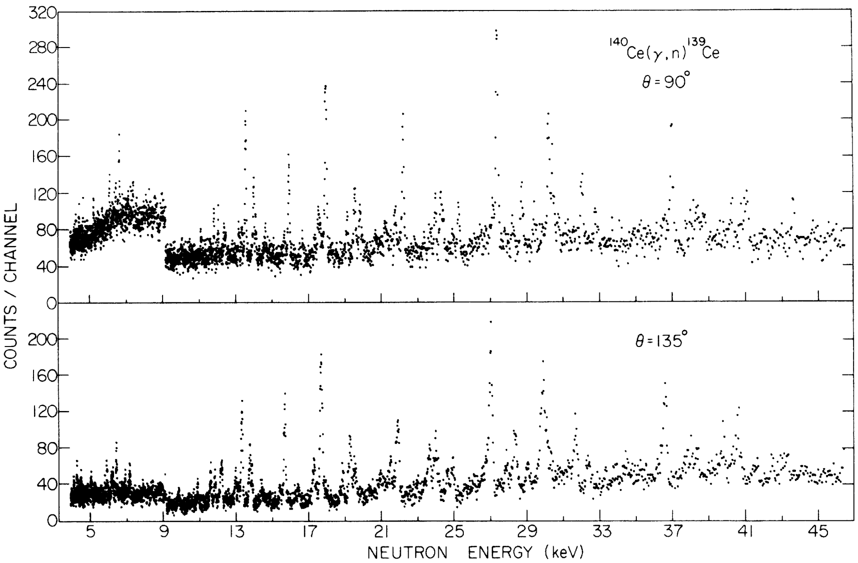

FIG. 1. Photoneutron time-of-flight data for angles of 90° and 135° from the $^{140}Ce(\gamma,n)^{139}Ce$ reaction, plotted as a function of neutron energy. The step in the data at low energies is caused by a change in the channel widths from 2 to 4 ns.

to both the ground state of the ^{139}Ce residual nucleus and to its first excited state at 250 keV. No attempt was made to separate the two decay modes in the time-of-flight spectra. Rather, the fraction of the total observed strength going to the ground state was estimated in a statistical manner, the details of which are outlined in what follows.

Parities of individual nuclear levels were determined from the neutron angular distributions at 90° and 135° by comparing the ratio $R \equiv \sigma(90°)/\sigma(135°)$, with values calculated for the various possible transitions.[7] These calculated values

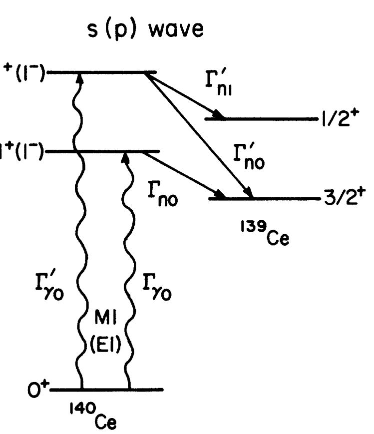

FIG. 2. Dipole photoexcitation of ^{140}Ce. Neutron decay can occur to both the ground state and first excited state of ^{139}Ce.

are listed in Table I. If, in the case of $M1$ transitions, only s-wave neutrons to the final state are important, then R will be equal to 1.0 for both ground-state and first excited state decays. In the case of $E1$ transitions on the other hand, if emitted neutrons are primarily p wave in character then R can range between 0.67 and 1.0 for decays to the ground state, and between 0.67 and 2.0 for decays to the first excited state. The most probable $E1$ values were determined to be $R = 0.8$ in the first case, and $R = 1.2$ in the second. This determination was made by assuming that the two possible neutron channel spins in the final state would occur with equal probability. Contributions from f-wave neutron decay in the case of $E1$ excitations and from d wave in the case of $M1$ excitations could be neglected here because only neutron energies less than about 45 keV were considered in the analysis. Even at 100 keV, the d-wave penetration is only about 1% of the s wave, and the f wave is less than a few tenths of a percent of the p wave. The analysis was not extended above 45 keV because, much above this energy, the density of levels becomes too great for individual lines to be identified unambiguously.

Between the neutron energies of 4 and 44 keV, 56 levels were resolved in ^{140}Ce. Figure 3 shows the distribution of the total transition strengths of these levels as a function of the ratio R. There is a clear clustering of strengths about the values $R \sim 1.0$ and $R \sim 0.8$ indicating $M1$ and ground-state $E1$ transitions, respectively. It is noticeable that there is not a particularly large concentration

TABLE I. Expected ratios of 90° and 135° cross sections for the reaction $^{140}Ce(\gamma, n)^{139}Ce$.

Transition	Multipolarity	Neutron decay	R	Most probable R
$0^+ \to 1^+ \to \frac{3}{2}^+$	$M1$	s wave	1.0	1.0
$0^+ \to 1^- \to \frac{3}{2}^+$	$E1$	p wave	$0.67 \le R \le 1.0$	0.8
$0^+ \to 1^+ \to \frac{1}{2}^+$	$M1$	s wave	1.0	1.0
$0^+ \to 1^- \to \frac{1}{2}^+$	$E1$	p wave	$0.67 \le R \le 2.0$	1.2

of strength with $R \sim 1.2$ corresponding to $E1$ transitions to the first excited state. The estimated errors in the determination of R range between about 2% and 6% of R, depending on the width of the individual transition. It is clear from this diagram that most of the strength can reasonably be identified as to whether it is $E1$ or $M1$ in character, and that non-ground-state transitions contribute a relatively small fraction to the total. Levels having $0.9 < R < 1.1$ were taken to be $M1$ except for an $E1$ background which was estimated to be about 0.2 eV from the amount of strength located above and below this range in R. The $M1$ and $E1$ total transition strengths were thus found to be $\sum \Gamma_{\text{exp}}(M1) = 1.0$ eV and $\sum \Gamma_{\text{exp}}(E1) = 2.2$ eV, respectively.

The total neutron yield Y in the energy range $4 \le E_n \le 44$ keV consists of contributions from transitions to both the ground state and to the first excited state. The average ground-state yield of neutrons from a group of levels with average total width Γ is

$$\overline{Y}_0 = \frac{2\pi^2}{k^2}\, g\left\langle \frac{\Gamma_{\gamma 0}\Gamma_{n0}}{\Gamma}\right\rangle, \tag{1}$$

where k is the wave number of the incident photon and g is the statistical factor $\frac{1}{2}(2J+1)/(2I+1)$, J and I being the spins of the excited and ground states of the target nucleus, respectively. Similarly, the yield to the first excited state for neutrons of a corresponding energy is

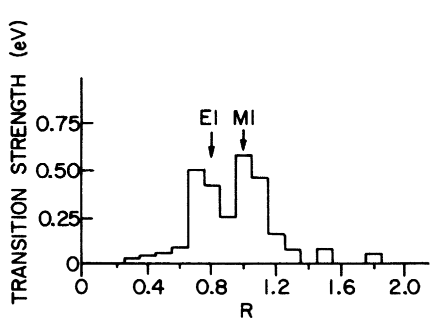

FIG. 3. Distribution of transition strength with respect to the angular distribution ratio R.

$$\overline{Y}_1 = \frac{2\pi^2}{k^2}\, g\left\langle \frac{\Gamma'_{\gamma 0}\Gamma'_{n1}}{\Gamma'}\right\rangle$$

in which the primes indicate that the parameters are for intermediate states of an appropriately higher excitation (see Fig. 2). The total yield is then

$$\begin{aligned}\overline{Y} &= \overline{Y}_0 + \overline{Y}_1 \\ &= (1+r)\overline{Y}_0 .\end{aligned} \tag{2}$$

The ratio, r, is just

$$r = \frac{\overline{Y}_1}{\overline{Y}_0} = \left\langle \frac{\Gamma'_{\gamma 0}\Gamma'_{n1}}{\Gamma'_\gamma + \Gamma'_{n0} + \Gamma'_{n1}}\right\rangle \left\langle \frac{\Gamma_\gamma + \Gamma_{n0}}{\Gamma_{\gamma 0}\Gamma_{n0}}\right\rangle, \tag{3}$$

where the widths Γ and Γ' have been written out explicitly, and Γ_γ and Γ'_γ are the respective total widths for photon decay. The value of this ratio was estimated by means of a Monte Carlo program which selected 800 sets of the reduced widths implicit in Eq. (3) from Porter-Thomas distributions about appropriate average values. The energy dependence of the neutron widths was taken into account explicitly in multiplying the reduced widths by the penetration factors. It was assumed that

$$\langle \Gamma_\gamma \rangle \sim \langle \Gamma'_\gamma \rangle \sim 0.1 \text{ eV} \quad \text{(Ref. 8)}$$

and that

$$\langle \gamma_n^2 \rangle \sim 8 \text{ eV} \quad \text{(Ref. 9)}.$$

The values obtained in this manner for r had to further be divided by a factor of 1.8 in order to take into account a reduction in the number of incident photons at the higher excitation due to the shape of the bremsstrahlung spectrum. The resulting numbers were $r = 0.22$ in the case of s-wave neutron emission and $r = 0.26$ for p wave. These results imply that almost 80% of the yield observed in this experiment can be attributed to ground-state transitions.

The average yield of a transition to the ground state, given in equation (1), can be written

$$\overline{Y}_0 = \frac{2\pi^2}{k^2}\, g\, \frac{\langle \Gamma_{\gamma 0}\rangle \langle \Gamma_{n0}\rangle}{\langle \Gamma \rangle}\, \gamma . \tag{4}$$

The factor γ takes into account the difference between the average of an expression involving

Porter-Thomas distributed widths, and the expression in terms of the average widths themselves.[10] If it is assumed that $\Gamma = \Gamma_{\gamma 0} + \Gamma_{n0}$, it can be shown that γ can be expressed in the closed form

$$\gamma = \frac{q^2+1}{q^2+2q+1}, \quad q^2 \equiv \frac{\langle \Gamma_{n0}\rangle}{\langle \Gamma_{\gamma 0}\rangle}.$$

Combining Eqs. (2) and (4) produces an expression for the average total yield

$$\bar{Y} = \frac{2\pi^2}{k^2}\, g\, \frac{\langle \Gamma_{\gamma 0}\rangle \langle \Gamma_{n0}\rangle}{\langle \Gamma \rangle}\, \gamma(1+r) \tag{5}$$

which, in terms of experimentally measured quantities can also be written

$$\bar{Y}_{\mathrm{exp}} = \frac{2\pi^2}{k^2}\, g\, \frac{1}{N} \sum \Gamma_{\mathrm{exp}}. \tag{6}$$

The sum is over all the N resonances included in the measurement. Combining relations (5) and (6) provides an estimate of the ground-state transition strength $\sum \Gamma_{\gamma 0}$ in terms of the total measured strength $\sum \Gamma_{\mathrm{exp}}$:

$$\sum \Gamma_{\gamma 0} = N \langle \Gamma_{\gamma 0}\rangle \approx \frac{\sum \Gamma_{\mathrm{exp}}}{\gamma(1+r)} \tag{7}$$

in which the approximation arises from the assumption that $\langle \Gamma_{\gamma 0}\rangle \ll \langle \Gamma \rangle$. This expression holds only for isotropic neutron emission (i.e., for states for which $R=1$). It is easily extended, however, into a more general form

$$\sum \Gamma_{\gamma 0} \approx \frac{\sum \Gamma_{\mathrm{exp}}(\theta)}{\gamma(1+r)^2} \left(\frac{1}{W(\theta)_0} + \frac{r}{W(\theta)_1} \right), \tag{8}$$

where the subscripts 0 and 1 refer to ground-state and first excited state transitions, respectively, and

$$W(\theta) = \left.\frac{d\sigma}{d\Omega}\right|_{\theta} \Big/ \left(\frac{1}{4\pi} \int \frac{d\sigma}{d\Omega}\, d\Omega \right).$$

IV. RESULTS AND DISCUSSION

The integrated $M1$ and $E1$ ground-state transition strengths in the 40-keV interval of excitation examined in this experiment were determined from Eqs. (7) and (8), respectively. The final results are listed in Table II both in terms of the widths $\sum \Gamma_{\gamma 0}(M(E)1)$ and in terms of the corresponding reduced transition probabilities[11] $B(\uparrow, M(E)1)$. Also listed in Table II are the reduced widths $\bar{k}_{M1}$ and $\bar{k}_{E1}$ which were determined from[12]

$$\bar{k}_{M1} = \sum \Gamma_{\gamma 0}(M1)/(E_\gamma{}^3 \Delta E)$$

and

$$\bar{k}_{E1} = \sum \Gamma_{\gamma 0}(E1)/(E_\gamma{}^3 A^{2/3} \Delta E).$$

TABLE II. $M1$ and $E1$ ground-state transition strengths integrated over the 40-keV interval centered at 9.08 MeV. Statistical uncertainties are estimated to be of the order 1%. Possible systematic uncertainties of the order 10% are estimated as discussed in the text.

Transitions	$\sum \Gamma_{\gamma 0}(M(E)1)$	$B(\uparrow, M(E)1)$	$\bar{k}_{M(E)1}$
$M1$	1.1 eV	$0.39\left(\frac{e\hbar}{2mc}\right)^2$	37×10^{-3}
$E1$	1.7 eV	$6.6\times10^{-3}\ e^2\,\mathrm{fm}^2$	2.2×10^{-3}

In these expressions, $\Gamma_{\gamma 0}$ is in eV, and both the excitation energy E_γ and the interval of excitation ΔE are in MeV. The statistical error in the numbers given in Table II is on the order of 1%. However, there is also a systematic error due to the uncertainty with which the width of the 254-keV calibration line is known which can be estimated to be perhaps 10% based upon the most recently reported measurements.[5,6,13]

The value of $\bar{k}_{M1} = 37\times10^{-3}$ observed in ^{140}Ce is appreciably larger than the average value of about 18×10^{-3} which is found in most heavy nuclei.[14] This may be an indication that a part of the giant magnetic dipole resonance extends into the threshold region where the present measurement was made. In ^{140}Ce, the $1h_{11/2}$ neutron and $1g_{9/2}$ proton shell are filled, and spin-flip transitions can proceed by $1h_{11/2} \to 1h_{9/2}$ and $1g_{9/2} \to 1g_{7/2}$, respectively. Bohr and Mottelson[15] have calculated both the excitation energy and integrated $M1$ strength that might be expected for this collective spin-flip mode. They obtain $E_R = 8.7$ MeV, which coincides with the energy of the transverse excitation seen in electron scattering,[3] and

$$\sum \Gamma_{\gamma 0}(M1) = 74 \text{ eV} \quad \left[B(\uparrow, M1) = 29 \left(\frac{e\hbar}{2mc} \right)^2 \right].$$

The theory implies nothing about the way in which this strength might spread into the threshold region, but by assuming that the envelope of the $M1$ strength is a Lorentz shaped line centered at 8.7 MeV, an estimate of the total $M1$ strength can be made from the amount of strength that was observed within the 40-keV interval at 9.08 MeV. Figure 4 shows that for a wide range in widths of the Lorentzian, $0.3 \lesssim \Gamma_R \lesssim 2.0$ MeV, the implied total strength is $60 \lesssim \sum \Gamma_{\gamma 0}(M1) \lesssim 90$ eV. The correspondence between these numbers and the Bohr and Mottelson calculation suggests that the unusually large amount of threshold $M1$ strength in ^{140}Ce does indeed indicate the proximity of a giant $M1$ resonance. These results also support

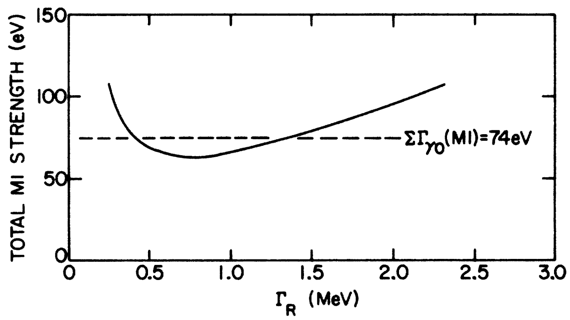

FIG. 4. Amount of total $M1$ strength in a Lorentz shaped resonance centered at 8.7 MeV implied by the 1.1 eV of strength, observed over 40 keV at 9.08 MeV, as a function of the Lorentzian width Γ_R. The dotted line indicates the total $M1$ strength predicted by Bohr and Mottelson.

the $M1$ assignment given the 8.7-MeV electron scattering resonance with its reported width of 2.2 MeV and total strength of 90 eV.[3]

The value of $\bar{k}_{E1} = 2.2\times10^{-3}$ seems to be consistent with what is known of $E1$ strength in the threshold region. The reduced width correspond ing to an estimate of the $E1$ strength function from an extrapolation of the tail of the giant dipole resonance[16] is $\bar{k}_{E1} \sim 9.8\times10^{-3}$. This is somewhat more than four times greater than the observed value. It has been shown,[14] however, that such estimates are consistently high, and that in fact experimental measurements of $\bar{k}_{E1}$ commonly fall between 2 and 4×10^{-3} for nuclei with $A \gtrsim 100$.

It should be noted that $E2$ and higher multipolarity transitions were assumed to make a negligible contribution to the total observed integrated strength. In a case such as this, where d-wave contributions can be ignored, $E2$ transitions are expected to have an angular distribution ratio $R = 1.0$, and consequently if there is any significant $E2$ strength in the threshold region of ^{140}Ce it will serve to decrease the observed $M1$ strength. An estimate of the $\sum\Gamma(E2)$ to $\sum\Gamma(E1)$ ratio at 9 MeV based on single-particle transition rates[17] implies that in the excitation region examined in this experiment one might expect 2.7 meV of $E2$ strength, which is only 0.25% of the total $M1$. However, it should be kept in mind that the actual $E2$ strength found in nuclei can be enhanced well above the single-particle estimate by collective effects. The collective isoscalar $E2$ giant resonance is thought to be located at 12.0 MeV in ^{140}Ce.[3] By assuming that this resonance has a Lorentz shape in much the same manner as was done above for the $M1$ resonance, the amount of $E2$ strength that can be extrapolated into the threshold region is about 0.17 eV. Even this much $E2$ strength could only serve to reduce the observed $M1$ strength by about 15%.

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