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Fine structure of the $E1$ response in ^{140}Ce below the particle threshold ☆

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Abstract

The $E1$ response of the semi-magic nucleus ^{140}Ce below the particle threshold was measured in a (γ,γ') experiment utilizing the new Euroball Cluster detector at the S-DALINAC. While the energy averaged data are in good agreement with tagged photon results, here they are resolved for the first time into 54 individual transitions. A quasiparticle-phonon model calculation including up to three-phonon configurations compares well to the extracted strength distribution. The interference between one- and two-phonon contributions is essential for a quantitative reproduction.

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The electric dipole response of nuclei at low excitation energies poses some unique problems to nuclear structure investigations. Theoretically, one is confronted with a delicate balance of configurations connected through large $E1$ matrix elements but extremely weak amplitudes on one hand and dominant contributions to the wave function with small $E1$ excitation probabilities on the other hand. The isoscalar dipole moment represents a spurious center-of-mass motion and does not contribute to intrinsic excitations in first order. The bulk of the isovector $E1$ strength is shifted to high excitation energies because of the strong repulsive particle-hole interaction forming the giant dipole resonance (GDR). Thus, $E1$ strength at low energies is suppressed by many orders of

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magnitude compared to the single-particle estimates. This severe reduction represents a challenge for their experimental detection via photon decay.

Here, we report on a high-resolution study of the dipole response in ^{140}Ce up to energies of about 6.7 MeV using resonant photon scattering. The semimagic nucleus ^{140}Ce is a particularly well suited candidate because of the closed $N = 82$ shell. Resonant photon scattering [or (γ,γ')] experiments are an extremely powerful tool to investigate states with spins $J = 1$ in even-even nuclei (see recent reviews [1,2] and references therein). The stable $N = 82$ isotones have been extensively studied using the (γ,γ') technique up to 4 MeV with an emphasis on the strong two-phonon $|2_1^+ \otimes 3_1^-; 1^-\rangle$ excitations [3–7]. Furthermore, the total elastic photon scattering cross section in ^{140}Ce between $E_x = 4.8$ and 8.9 MeV has been studied in a tagged photon experiment [8]. However, because of the limited energy resolution no individual states could be discerned in that experiment. Only with the advent of the new generation of gamma spectrometers and their germanium detectors with vastly improved detection characteristics it is possible to investigate in detail the fine structure of the $E1$ response with energies up to the neutron threshold.

The present results cover an energy region up to about 6.7 MeV. This includes the low-lying 1^- state at 3.643 MeV arising from the coupling of the lowest quadrupole and octupole vibrations as well as the energy region between 4 and 6 MeV where excitations from the coupling of the octupole degree of freedom to other collective surface vibrations are expected to occur. The investigation of states with small cross sections in (γ,γ') experiments in this energy region is still a challenge to present-day experimental techniques. The photopeak efficiency of the usually employed germanium detectors quickly deteriorates for γ-energies above 4 MeV. The new Euroball Cluster detector [10–12] used in the present experiment is characterized by its good energy resolution and its high photopeak efficiency at high energies (i.e. between 4 and 10 MeV) [13]. Thus the Euroball Cluster detector opens a new field of nuclear gamma-ray spectroscopy at these high energies [14].

The Cluster detector consists of seven individually encapsulated HPGe crystals placed in a common cryostat. The individual crystals have an efficiency of $\approx 60\%$ relative to a standard $3'' \times 3''$ NaI detector at ^{60}Co energies. A further advantage is the possibility to reconstruct the full energy signal for, e.g., Compton scattered gamma rays which deposit their total energy in two or more neighboring segments. This add-back procedure greatly increases the total photopeak efficiency at high energies. For a detailed discussion of the Cluster detector's operation in previous experiments see, e.g., [15].

The (γ,γ') experiment was performed at the superconducting electron accelerator S-DALINAC in Darmstadt. A continuous wave electron beam with an energy of 6.7 MeV and an average current of 27 μA impinged on a rotating 3 mm thick Ta disk where it was converted to bremsstrahlung. The photons were collimated through a 60 cm long conical opening to the target position about 80 cm downstream. The target consisted of 4.96 g CeO_2 of natural composition (88.48% ^{140}Ce, 11.08% ^{142}Ce) as well as of two metallic discs of chemically pure boron (20.0% ^{10}B, 80.0% ^{11}B) for the photon flux calibration with a total mass of 0.52 g. The radiation scattered from the target was observed with two detectors. The Cluster detector was located at 130° with respect to the incoming photon beam. Additionally, a single hexagonal encapsulated detector identical to the individual segments of the Cluster detector was placed at 90°. To suppress the very large radiation background from the Ta bremstarget the detectors were shielded by a lead housing with an average thickness of approximately 30 cm. The data acquisition system used two different approaches for events from the Cluster detector. The one-fold events were recorded online in individual 16 K spectra while the multi-fold events used in the add-back mode were recorded as listmode data onto 8 mm video tapes. Through this procedure the listmode counting rate could be kept below 6 kHz which could easily be handled by the FERA-bus analyzer [16].

Fig. 1 shows the measured spectra from the Cluster detector (top part) and the single detector (bottom part) between 3 and 7 MeV. The difference in the photopeak efficiency of the Cluster vs. the single detector is striking, particularly above 5 MeV. Note the almost constant background from nonresonant scattering above 4 MeV. This remarkably low background is in contrast to the observations in (γ,γ') experiments on deformed nuclei in the same mass region where a much steeper rise towards lower energies is observed.

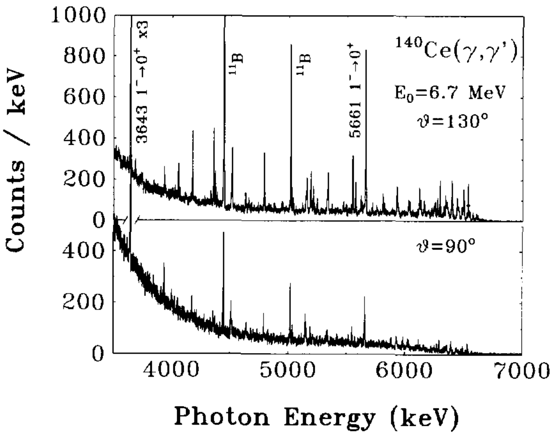

Fig. 1. Comparison of the ^{140}Ce(γ,γ') spectra taken with the Euroball Cluster detector at 130° (top part) and the single detector at 90° (bottom part). The lines marked with ^{11}B stem from the photon flux calibration. Only the two strongest transitions of ^{140}Ce are labeled. Note the uniformly low background above 4 MeV. In the special geometry used in this experiment the Cluster detector has approximately six times the efficiency of the single detector in the energy range between 5 and 6 MeV.

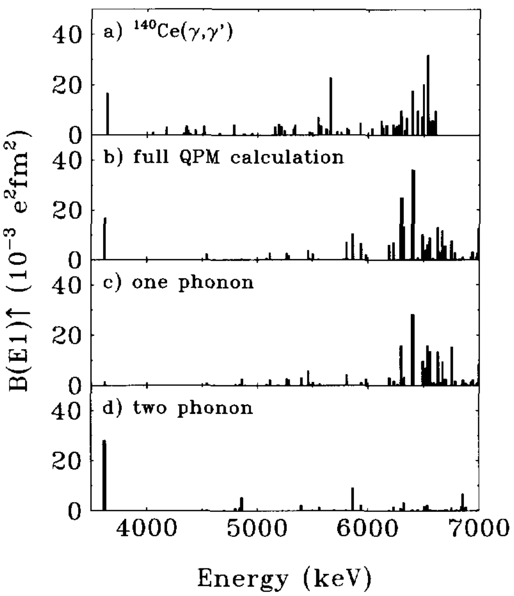

Fig. 2. (a) Experimental $B(E1)$ strength distribution up to the endpoint energy of 6.7 MeV. (b) Results of the QPM calculation including one-, two- and three-phonon configurations. (c) One-phonon part of the $E1$ excitations. (d) Two-phonon part of the $E1$ excitations. Note the interference effects in b) that are essential to reproduce the experimental strength distribution. Three-phonon configurations in this calculation are mainly responsible for the fragmentation.

It allows the measurement even of weakly excited states with high precision in the present experiment. However, for a realistic comparison of both spectra one should note that the nonresonant background is somewhat higher under 90° than under 130°, and the angular correlation of dipole transitions shows a pronounced minimum at 90°.

Spin assignments were based on the ratio of the γ-ray intensities observed at 90° and 130°. In (γ,γ') experiments on even-even nuclei only states with spin $J = 1$ or 2 are excited from the ground state. Therefore, the ratio W(90°)/W(130°) suffices to distinguish between dipole and quadrupole cascades for a $J^\pi = 0^+$ target. It takes the values 0.71 (2.14) for the $0 \rightarrow 1 \rightarrow 0$ ($0 \rightarrow 2 \rightarrow 0$) cascades, respectively. No parity information is available from the present experiment.

The integrated cross sections for resonant scattering of photons by the excited states were determined relative to the well known cross sections of transitions in ^{11}B [17] in a well established procedure described, e.g., in [18]. Above 6 MeV the shape of the bremsstrahlung spectrum changes considerably. Since no information from reference transitions was available in this energy range, a linear drop was assumed between 6 and 6.7 MeV. This behavior is in accordance with the shape of the photon spectrum computed using a Schiff formula [19,20] and Monte Carlo simulations of thick target bremsstrahlung [21,22]. Nonetheless, the uncertainties in the photon flux increase above 6 MeV, but a comparison of our data with previously measured tagged photon data discussed below shows good correspondence giving additional confidence to the described procedure.

A total of 54 transitions were observed in ^{140}Ce. Most of these were hitherto unknown. Assuming that all observed levels have 1^- character the resulting strength distribution is displayed in Fig. 2(a). Laszewski et al. [8,9] performed scattering experiments on ^{140}Ce with tagged polarized photons sensitive between 4.8 and 8.7 MeV to investigate the gross properties of $E1$ and $M1$ strength distributions. In the energy region above 6.7 MeV a fraction of the observed intensity was attributed to have $M1$ character. No parity information was deduced below 6.7 MeV. The high-resolution data obtained with the Cluster detector can be compared to the tagged photon data

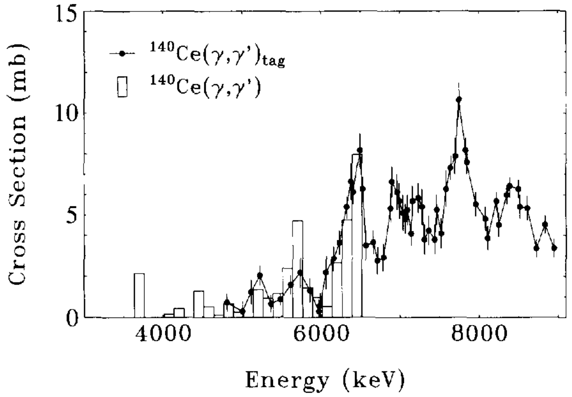

Fig. 3. Gross features of the $E1$ response in ^{140}Ce from the tagged photon experiments [8] (filled circles) and from the present data binned accordingly (bars). The agreement is very good up to 6.5 MeV. Above, the systematical uncertainties in the photon flux calibration are too large for a meaningful comparison.

by summing the observed cross sections over appropriate energy intervals. Fig. 3 shows the resulting cross sections as bars and the results from [8] as filled circles. The agreement over the entire energy range up to 6.5 MeV is very good.

In the following, two states excited by fast $E1$ transitions are discussed in more detail.

The 1^- *state at 3.643 MeV:* It is the 1^- member of the two-phonon $(2_1^+ \otimes 3_1^-)$ multiplet. The g.s. transition has one of the largest widths of an $E1$ decay in this nuclear mass region below the particle threshold. The value obtained in the present experiment $B(E1; 0^+ \rightarrow 1^-) = (18.2 \pm 2.2) \times 10^{-3}\,e^2\mathrm{fm}^2$ agrees with a recent precision study [7] performed at an endpoint energy $E_0 = 4$ MeV where $B(E1; 0^+ \rightarrow 1^-) = (16.7 \pm 1.2) \times 10^{-3}\,e^2\mathrm{fm}^2$ was found.

The 1^- *state at 5.66 MeV:* This level is known from scattering experiments using a discrete energy photon source [23,24]. With the branching ratio $\Gamma_0/\Gamma = 0.95(5)$ from [23] we find a remarkable strength $B(E1; 0^+ \rightarrow 1^-) = (24.8 \pm 4.9) \times 10^{-3}\,e^2\mathrm{fm}^2$. This is one order of magnitude larger than reported in [23,24]. However, since a discrete ^{60}Co line was used for the excitation, their results are extremely sensitive to the precise determination of the excitation energy difference determining the overlap integral.

The lowest 1^- state in ^{142}Ce at $E_x = 2.187$ MeV was also excited. While the existence of this level is known from β-decay, no information on its lifetime was available [25]. Utilizing the branching ratio given in [25], we obtain $B(E1; 0^+ \rightarrow 1^-)) = (11.7 \pm 3.6) \times 10^{-3}$ $e^2\mathrm{fm}^2$. This state should also exhibit a dominant two-phonon $2^+ \otimes 3^-$ structure similar to other $N = 84$ nuclei as, e.g., observed in ^{144}Nd [26,27].

For a more detailed insight into the experimental results a microscopic calculation in the framework of the quasiparticle-phonon model (QPM) was carried out. In the QPM nuclear excitations are treated as RPA phonons with an underlying fermionic structure. For an in-depth treatise of the model see [28]. A first approach to the problem of low-energy $E1$ transitions in spherical nuclei was made with the QPM a decade ago where these 1^- states were treated as pure two-phonon $2^+ \otimes 3^-$ configurations [29]. Recently, it was demonstrated that the mixing with the GDR is essential to explain their g.s. transition strengths quantitatively [30].

A diagonalization of the model Hamiltonian was performed in a space including one-, two-, and three-phonon configurations. Wavefunctions and excitation probabilities $B(E1; 0^+ \rightarrow 1^-)$ and $B(M1; 0^+ \rightarrow 1^+)$ were computed for states in ^{140}Ce. One-phonon 1^- configurations were taken into account up to 20 MeV. Thus, the whole GDR was covered and the introduction of renormalized effective charges in the $E1$ operator due to core polarization effects could be avoided. In our calculation we included two- and three-phonon configurations consisting of natural parity phonons with $J^\pi = 1^-$ to 6^+ up to 9 MeV.

Since the density of multi-phonon configurations increases strongly with the excitation energy we carefully excluded those which did not play an essential role in the $E1$ strength distribution in the energy region up to 7 MeV. The mixing of one-, two-, and three-phonon configurations in the wave functions of excited states depends on the matrix elements of the interaction between these configurations. In the QPM, these are calculated microscopically and are rather sensitive to the collectivity of the basic phonon configurations. Therefore, the parameters of the residual interaction were adjusted to reproduce the $B(E\lambda)$ values of the lowest 2^+, 3^-, and 4^+ states. This procedure yields a good description of the properties of such states [31].

The theoretical results are summarized in Fig. 2(b). The agreement with the experimental $B(E1)$ strength distribution shown in part (a) is very good. In spherical nuclei no collective one-phonon 1^- configurations appear in the low energy region and there are three main mechanisms to explain the $E1$ strength observed in the experiment. The first is an influence of the GDR. In phenomenological approaches it is treated as an extrapolation of its low-energy tail. In microscopic theories it appears in a natural way due to the coupling of one- and two-phonon configurations. Since the GDR is located about 10 MeV above the energies of our interest, this coupling yields only a very small portion of the observed strength. The second mechanism is the excitation of non- and weakly-collective one-phonon 1^- configurations which have relatively small $B(E1)$ values but are located in this energy region. The last mechanism is the direct excitation of two-phonon configurations from the ground state. In the QPM such transitions take place due to the fermionic structure of phonons. Although the direct excitation of two-phonon configurations from the ground state is a second order effect, excitation of some collective two-phonon configurations, especially $(2_1^+ \otimes 3_1^-)_{1^-}$, play an essential role since the other two mechanisms yield much weaker $E1$ strengths.

All these effects were included in the calculation presented in Fig. 2(b). The $E1$ transition operator consists of two terms corresponding to one- and two-phonon exchange, respectively. To give an idea of the role of each mechanism and their interference in different parts of the energy spectrum, we also present in Fig. 2(c) the one-phonon contribution and in 2(d) the two-phonon contribution of the $E1$ operator to the total $E1$ strength distribution over the same set of states as shown in part (b).

The energy and g.s. transition strength of the $|2_1^+ \otimes 3_1^-; 1_1^-\rangle$ state are almost perfectly reproduced by the present model results. As was the case for the nuclei ^{116,124}Sn [30], we observe a destructive interference between one- and two-phonon components. The calculation yields an amplitude of 85% of the $2_1^+ \otimes 3_1^-$ structure in the wavefunction.

For the experimentally observed excitations around 4.5 MeV the total $E1$ strength is underestimated by the present calculation. In the QPM the collective two-phonon $|4_1^+ \otimes 3_1^-; 1^-\rangle$ configuration located roughly at this energy has a much smaller matrix element for a g.s. transition than the $|2_1^+ \otimes 3_1^-; 1^-\rangle$ configuration. In order to increase the theoretical strength at these energies one would need a stronger coupling between the one-phonon and two-phonon parts which would destroy the good description at higher excitation energies.

It is interesting to note that the energy of the most strongly excited 5.66 MeV level agrees within 5 keV with the sum energy of the octupole 3_1^- phonon and twice the quadrupole 2_1^+ phonon. In a naive harmonic picture a three-phonon structure $2_1^+ \otimes 2_1^+ \otimes 3_1^-$ would be suggested, but the QPM predicts very small g.s. excitation probabilities for three-phonon states.

For $E_x \approx 5.5$–6.5 MeV a strong constructive interference between one- and two-phonon parts is visible which roughly doubles the $B(E1)$ strength around 6 MeV relative to the pure one-phonon strength in this energy region and is essential for a description of the experimental findings. This coherence effect seems to be a general phenomenon in heavy nuclei near closed shells and might explain the observation of very strong $E1$ transitions in similar (γ,γ') experiments on $Z = 50$ nuclei [30].

We have also calculated the $B(M1)$ strength distribution below 7.5 MeV. The main part stems from the direct excitation of two-phonon configurations. The total strength is $\sum B(M1; 0_1^+ \rightarrow 1^+) = 0.87\,\mu_N^2$. If converted to a photon scattering cross section, this $B(M1)$ value corresponds to less than 5% of the total cross section observed. This gives an estimate for possible erroneously assigned $B(E1)$ strength.

Summarizing, we have performed a high resolution (γ,γ') experiment on ^{140}Ce for energies up to 6.7 MeV. The excellent properties of the Euroball Cluster detector allowed the extraction of the fine structure of the $E1$ response up to these high energies. The experimental strength distribution is well reproduced by QPM calculations taking into account the coupling of up to three phonons. Interference between the one- and two-phonon components is found to be essential for a quantitative agreement with the data. The effects are particularly pronounced for the excitation the $|2_1^+ \otimes 3_1^-, 1^-\rangle$ two-phonon state and in the energy region around 6 MeV, where a considerable enhancement is observed. Inclusion of three-phonon configurations does not contribute to the g.s. excitation strength, but is necessary to achieve a realistic picture of the strength fragmentation. Clearly, a test of these features in other $N = 82$ nuclei and at other shell closures is of considerable interest. Work along these lines is under way.

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