GAMMA DECAY OF THE POSSIBLE 1^- TWO-PHONON STATE IN ^{140}Ce EXCITED VIA INELASTIC SCATTERING OF ^{17}O*

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The γ decay from the low-lying dipole states of ^{140}Ce excited via inelastic scattering of ^{17}O at bombarding energy of 340 MeV was measured using the high resolution AGATA-Demonstrator array in coincidence with scattered ions detected in two segmented ΔE–E silicon detectors of the TRACE array. Particular attention is here given to the decay of the first 1^- state at 3643 keV which is considered to be of two-phonon character. The gamma–gamma coincidence method was applied to select desired decay branch. No direct decay from this state was observed to 2^+ and 3^-

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phonon states which would be the proof of the pure harmonic coupling. The comparison between experimentally obtained differential cross sections and analysis with distorted wave Born approximation (DWBA) allowed to conclude that the first 1^- state has a different nature than higher-lying pygmy dipole states. This was possible using the form factor obtained by folding a microscopically calculated transition density.

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1. Introduction

The lowest excited states of nuclei with near closed shells are usually a 2^+ and 3^- corresponding to quadrupole and octupole oscillations of the nuclear surface. Within the hydrodynamic nuclear model to these collective surface vibrations, one associates phonons with specific multipolarities. It was shown for several nuclei around $N = 82$ that the coupling of the two different phonons ($2^+ \otimes 3^-$) may result in observation of 1^- state. The identification of such a state is usually based on the energetic position which should be the sum energy of the single-phonon components. Systematics of the ratio between energy of the 1^- state and the sum energy of 2^+ and 3^- state *versus* the mass number have been shown to be equal to 1 within 10% uncertainty [1]. Furthermore, the existence of very harmonic quadrupole–octupole coupling was shown for the ^{142}Nd, ^{144}Nd, ^{144}Sm nuclei [1], by observing the E2 transition to the single-phonon state and demonstrating the $B(\mathrm{E2}; 1^- \to 3^-)$ to be equal to $B(\mathrm{E2}; 2^+ \to 0^+)$.

In the case of ^{140}Ce, the interpretation of the two-phonon 1^- state is not as evident as in previous examples. Figure 1 shows the part of the level scheme for ^{140}Ce including the discussed 2^+, 3^- and 1^- states, and γ transitions to the ground state marked with solid arrows. In this case, the candidate for the two-phonon 1^- state is found at the energy of 3643 keV. The sum energy of the first 2^+ and 3^- state is 4060 keV which is $\sim 10\%$ higher than the energy of the two-phonon state. This is more or less consistent with the findings for other nuclei in this mass region [1]. This shift in energy is an indication of anharmonicity which is due to the coupling among states of one-, two- and three-phonon states [2]. Experiments using the Nuclear Resonance Fluorescence (NRF) have not found in the ^{140}Ce the γ transitions to the one-phonon constituents [3, 4] which were observed in ^{142}Nd, ^{144}Nd, ^{144}Sm nuclei. However, there is another E1 γ transition, from 3^- to 2^+ state. A close correlation between the E1 transition strengths of the $1^- \to 0^+$ transition and the $3^- \to 2^+$ transition has been demonstrated for many nuclei around $N = 82$ including ^{140}Ce [5]. This was considered as an additional support for the quadrupole–octupole character of the considered 1^- state.

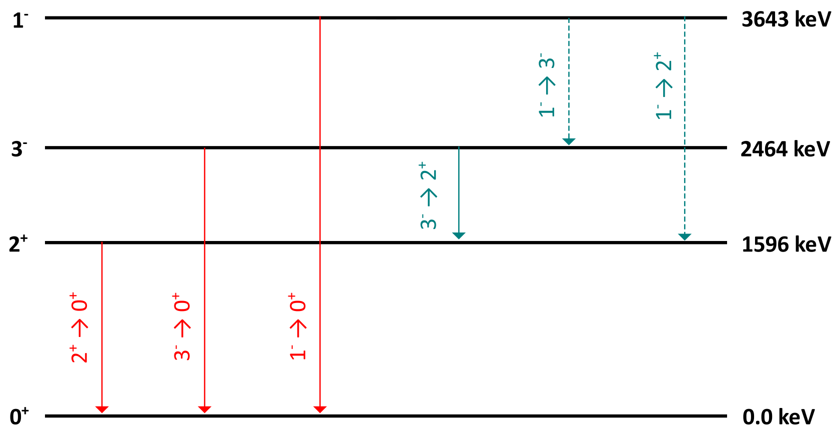

Fig. 1. Partial level scheme of ^{140}Ce showing the first quadrupole and octupole states and the candidate for the 1^- two-phonon state. γ transitions to the ground-state as well as the transition between phonon states are shown with solid arrows. Dashed arrows indicate the γ transitions from 1^- to 2^+ and 3^- constituents that were not observed yet.

It has been demonstrated [6] that the inelastic scattering of ^{17}O at the energy of 20 MeV/u successfully populates the dipole states below the particle emission threshold, the so-called pygmy dipole resonance (PDR), for a few nuclei: ^{90}Zr [7], ^{124}Sn [8], ^{140}Ce [9], ^{208}Pb [10]. As discussed above, the lowest lying dipole state in ^{140}Ce is considered to have a two-phonon character. The aim of this work is to study the gamma decay of the 1^- state at 3643 keV and eventually observe the decays to the single-phonon components. Another aim is to get more insight into the nature of these states. The issue will be addressed by comparing the experimental cross sections for the excitation of this state with distorted wave Born approximation (DWBA) calculations. Different excitation mechanisms will be studied using various form factors including the one microscopically calculated by double folding the transition densities obtained for the pygmy dipole state. The comparison of the results for the two-phonon and pygmy dipole states is intended to show the possible different characters of these states.

2. Experiment

The ^{17}O beam at the energy of 20 MeV/u was delivered by the PIAVE-ALPI accelerator system of the Legnaro National Laboratories to excite the ^{140}Ce target of 2.5 mg/cm^2 thickness. The choice of ^{17}O was to avoid the γ rays background due to projectile excitation. As it is lightly bound nucleus (4.1 MeV), for the energies higher than 4 MeV, the projectile transforms into

^{16}O which can be easily separated. In order to detect the scattered ^{17}O ions, two ΔE–E silicon telescopes of the TRACE array [11] were mounted inside the scattering chamber at an angle of 9° with respect to the beam axis on the left- and right-hand sides. Each telescope consisted of 2 segmented Si-pad detectors, each made of 60 pixels (with a pixel size of 4×4 mm^2). The resulting solid angle covered by the Si telescopes was 100 msr. The γ rays emitted from excited nuclei were registered by 5 triple clusters of AGATA-Demonstrator (AD) which consists of high purity germanium (HPGe) detectors [12, 13]. AD capabilities to identify a point of interaction of γ rays in Ge crystal using PSA (Pulse Shape Analysis) and further reconstruction of the γ rays path (tracking) were exploited during data analysis.

3. Results

The first part of the analysis concentrated on identification of the ^{17}O scattering channel. This aim was achieved by plotting for each pixel of the Si detectors the two dimensional histogram of the energy deposited in the first layer (ΔE) *versus* total kinetic energy (TKE) deposited in both layers. Clear separation between different reaction products allowed to select the ^{17}O.

The velocity of the recoiling target nucleus was at the level of 0.5% speed of light, thus the Doppler shift was not negligible and correction for the γ rays emitted from ^{140}Ce was performed in event-by-event mode. The angle for the velocity vector of the target nucleus was deduced from the measurement of ^{17}O detected in Si detectors and using the two-body reaction kinematics.

In order to observe only ground state γ transitions, the γ-ray energy must be equal to the excitation energy. It was possible to reach such a condition by constructing the coincidence matrix between energy of the emitted γ rays measured with AGATA *versus* excitation energy deduced from Si detectors as a total kinetic energy deposited by ^{17}O. Then, a diagonal gate ($E_\gamma = E_x$) with a width of ± 1.2 MeV was applied and the obtained spectrum is shown in Fig. 2. Many different ground state transitions can be observed, especially the single-phonon 2^+ and 3^- states at the energy of 1596 and 2464 keV, respectively, as well as the 1^- state at 3643 keV. The inset of Fig. 2 shows the PDR energy region, in which the same state at 3643 keV is indicated with an arrow as well as the most intense pygmy dipole state at 5660 keV.

It was also possible to construct the matrix of γ rays detected in coincidence. This allows to select different decay branches. In this case, it was chosen to examine the γ-ray spectrum in coincidence with the 1596 keV transition from the 2^+ state because this transition is much more intense than that at 2464 keV from the 3^- state. Such coincidence spectrum after background reduction is shown for different energy ranges in Fig. 3. Several transitions to the 2^+ state can be seen. The possible decay at 2047 keV from

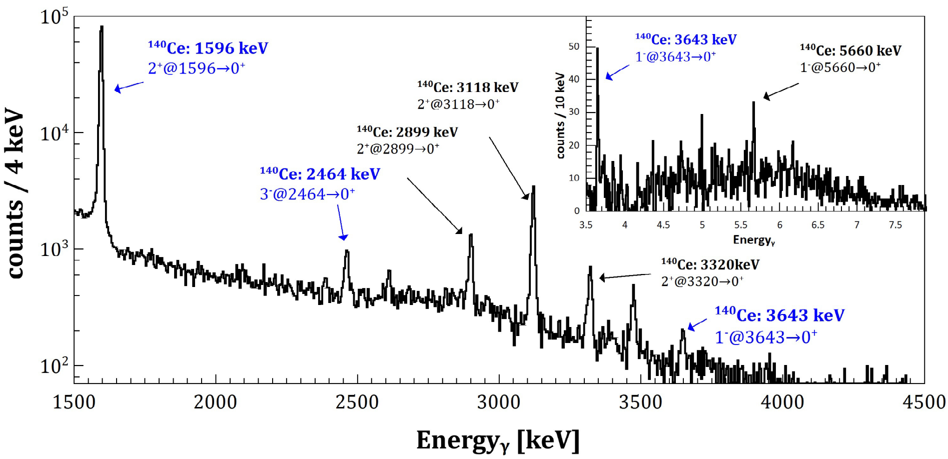

Fig. 2. A γ-ray energy spectrum measured with AGATA in coincidence with the ^{17}O inelastic scattering and corresponding to the selection of the ground state transitions. The transition at 3643 keV is the candidate for a de-exciation of the two-phonon state. Single-phonon 2^+ and 3^- transitions are also marked. The spectrum in PDR energy region is shown in the inset.

1^- state to 2^+ phonon state is marked. One can see that for this energy, there is a peak-like structure, but it is not statistically significant. Theory predicts that the branching ratio for this γ transition should be 0.45% [14]. In our case, the measurement of such branching is below the sensitivity limit so we cannot exclude the existence of the pure harmonic coupling of the two-phonons. One can also see the γ transition at 867 keV: $3^- \to 2^+$ which was considered in Ref. [5] as a support for the two-phonon coupling. Our analysis revealed also another transition at 1522 keV (marked with dashed arrow) which corresponds to the energy difference between 2^+ state at 3118 keV and 2^+ state at 1596 keV, which was not observed before.

The next step was to find evidence of whether the expected two-phonon state has different features than other dipole states which were found to have a pygmy-type nature. For this purpose, the experimental differential cross sections as a function of the scattering angle were compared with predictions based on the DWBA model. All the DWBA calculations were done using the FRESCO code [15].

The comparison of the experimental differential cross sections with DWBA calculations for the elastic scattering channel allowed to obtain the normalization factor taking into account the beam current and target thickness. This normalization was used for the further analysis of inelastic excitations. Afterwards, it was possible to perform the analysis of the excited dipole states using the deformed Woods–Saxon potential and known B(E1)

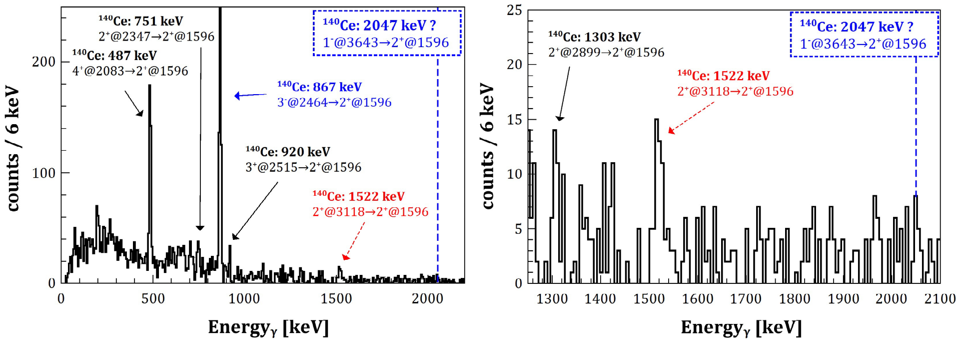

Fig. 3. Left panel: γ-ray energy spectrum measured in coincidence with the 1596 keV transition from the 2^+ state. Right panel: The same spectrum in the energy range from 1200 to 2100 keV. The expected energy of γ rays at 2047 keV is marked.

values [3]. This analysis was performed both for the state at 3643 keV and that at 5660 keV, the latter supposed to have a pygmy nature and having a large B(E1) value (see the inset of Fig. 2). The comparison of the results

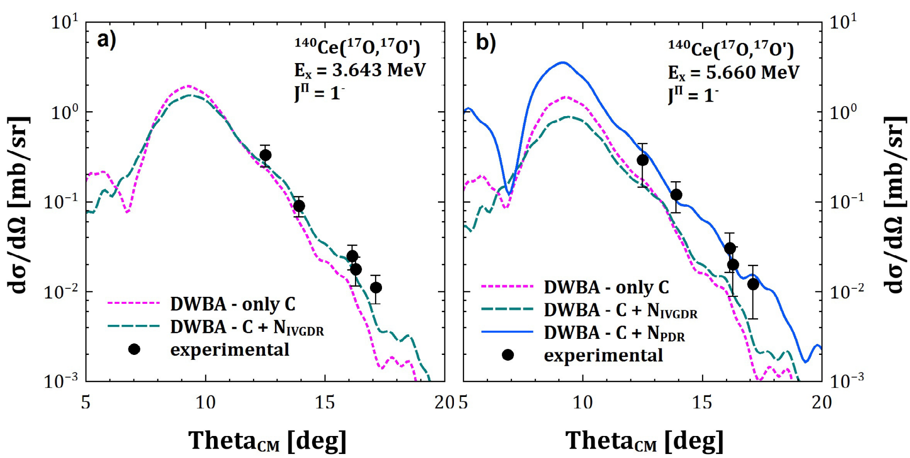

Fig. 4. Experimental cross sections for the state at 3643 keV ((a) panel) and for the state at 5660 keV ((b) panel) in ^{140}Ce measured in the present (^{17}O, ^{17}O'γ) experiment. The calculations shown in these panels are made using the DWBA approach. The dotted lines give the calculated Coulomb cross section (C), while the dashed lines give the total cross section (Coulomb plus nuclear contributions) and used the standard IVGDR form factor (C+N_{IVGDR}). The solid line represents the total cross section obtained using the microscopic form factor for pygmy states (C+N_{PDR}).

for these two states is shown in Fig. 4. It suggests a different nature of these states. Indeed, the cross section for the excitation of the two-phonon state is rather satisfactorily described by the Coulomb interaction with a small nuclear contribution evaluated using the isovector giant dipole resonance (IVGDR) form factor in FRESCO as a standard for dipole states. In contrast, in the case of the pygmy dipole state at 5660 keV, the nuclear contribution plays a significant role. Only using the form factor of pygmy dipole type, it is possible to reproduce the measured cross sections. Such a form factor was obtained by double folding [16] the transition densities obtained using the relativistic quasiparticle random phase approximation (RQRPA) model [17].

4. Summary

This paper presents the results of a study of the gamma decay from dipole states below particle emission threshold in ^{140}Ce. These dipole states were excited using inelastic scattering of ^{17}O at 20 MeV/u. We focus here on the 1^- state with the lowest excitation energy, that at 3643 keV, which is assumed to have a two-phonon nature. It was possible to observe in this experiment the known decays to ground state from the single phonon states (2^+ and 3^-) which should be the constituents of the two-phonon state. The gamma–gamma coincidence analysis allowed to select the decays to the 2^+ state but no clear indication of the direct decay from 1^- to 2^+ was observed. Such observation would be the proof of the pure harmonic coupling of the phonons. However, this is below sensitivity limit of this experiment so that the possibility of pure harmonic coupling cannot be excluded.

The analysis of the experimental differential cross section as a function of scattering angle using the DWBA approach allowed to shade light into the nature of the possible two-phonon state. Indeed, the obtained results were compared with those for the higher-lying pygmy dipole state at 5660 keV and this comparison allowed us to conclude that these two states have different nature. The excitation mechanism of the two-phonon state at 3643 keV is mainly due to the Coulomb interaction with a rather small nuclear contribution well-described by the standard IVGDR form factor. In contrast, the cross section for the pygmy dipole state at 5660 keV was found to have a strong nuclear contribution and it was reproduced using the form factor calculated by double-folding transitions densities obtained with the RQRPA model for the pygmy dipole state.

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