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Letter

Identification of the pygmy dipole resonance in a well deformed nucleus by combined isoscalar and isovector probes

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ABSTRACT

The low-energy electric dipole response in the axially deformed ^{154}Sm nucleus was investigated for the first time using complementary probes. The isoscalar (IS) response was extracted from an $(\alpha, \alpha'\gamma)$ coincidence experiment and the isovector (IV) response from polarization observables measured with the $(\vec{p}, \vec{p}')$ reaction at 0°. Both the IS and IV responses exhibit a resonance-like structure at excitation energies 5.5-6 MeV identified as the pygmy dipole resonance. Its evolution with deformation is investigated by comparison to the spherical isotope ^{144}Sm. The low-energy IV strength in ^{154}Sm departs from the K-splitting picture that characterizes the IV giant dipole resonance in this nucleus. This finding is further supported by the absence of significant IS strength above 7 MeV.

1. Introduction

The electric dipole response of nuclei is dominated by the isovector giant dipole resonance (IVGDR). However, increasing evidence has emerged supporting the existence of a low-energy, resonance-like structure of the $E1$ strength in well nuclei with neutron excess, commonly termed the pygmy dipole resonance (PDR) [1–3]. Understanding and experimentally identifying the nature of the PDR is one of the important challenges in the field of nuclear structure physics. Its strength is concentrated in the vicinity of the neutron threshold, and therefore, it is expected to impact astrophysical network calculations of reactions with photons in the entrance or exit channel [4].

The first theoretical description of the PDR was based on macroscopic models successfully describing the IVGDR as counter oscillations of proton and neutron fluids, where the excess neutrons sitting at the nuclear surface were treated as a third fluid [5]. The PDR is then interpreted as the oscillation of an inert core against a neutron skin. It is clear that in these macroscopic models, collectivity is intrinsically assumed, in the sense of a coherent bulk motion of different regions within the nucleus. If the neutron excess is directly connected with the strength of the PDR, its study could provide important information on the neutron skin thickness and properties of the symmetry energy [6–8]. However, when using more sophisticated microscopic self-consistent mean-field models, such as Hartree-Fock (HF) plus Random Phase Approximation (RPA) and Quasiparticle RPA (QRPA), more detailed insights into the PDR's main characteristics like isospin mixing are manifested via the transition densities [3]. These models show that the collectivity of the PDR, understood as coherent superimposition of many particle-hole configurations, and its relation to the neutron skin oscillation might not adhere to reality. In fact, the collectivity of the IV response of the PDR is predicted to be weak while it seems to be restored in the IS response. As a consequence, the typical picture of the neutron skin oscillating out of phase against the inert core is questioned (see Ref. [3] and Refs. therein) and an alternative interpretation as a toroidal excitation mode has been put forward [9,10].

These findings are also supported by experimental data where the total IV $E1$ strength below the neutron threshold studied in experiments with real or virtual photons is small (typically a few % of the strength concentrated in the IVGDR) [1,2], implying a lack of collectivity in this response. On the other hand, experiments using IS probes (e.g. α, ^{17}O scattering) find a much larger fraction of the total IS $E1$ strength [2]. Furthermore, the IS strength is concentrated at lower excitation energies indicating that part of the IV strength might have another origin [11–15].

By analysing the results obtained across several experiments and theoretical calculations for various nuclei, clear features characteristic of the PDR have been ideintified. The PDR consistently emerges within the E1 response of the nucleus and is marked by a strong decay to the ground state when compared to the predication for statistical decay. This feature combined with the presence of the PDR in both the IV and IS dipole response of the nucleus distinguishes this excitation mode from other low-lying E1 transitions. This dual expression provides a robust signature for identifying the PDR across different experimental probes and theoretical models.

So far, many detailed experimental investigations of the PDR have focused on spherical and weakly deformed nuclei [1–3]. Studies in well-deformed systems remain comparatively scarce, although low-lying dipole strength has been reported in deformed nuclei, for example in the Fe region [16] where the low-lying E1 strength is observed to increase with neutron number toward the more neutron-rich, pointing to a dominant role of neutron excess in the observed enhancement. However, a systematic investigation of the PDR in nuclei with a pronounced deformation, including possible deformation-induced effects such as K splitting, is still limited. Extending such studies to nuclei with a quadrupole-deformed ground state would be highly interesting, since in the picture of a neutron skin oscillation, one would expect a splitting of the mode with respect to the projection of the total angular momentum on the elongated axis (the K quantum number). In analogy to the IVGDR [17], this could be used to support or refute the oscillatory picture of this low-lying dipole strength. Recent investigations using γ probes at the HIγS facility explored the PDR in deformed nuclei such as ^{76}Se [18], isotopic chains of Xe and Mo [19], ^{156}Gd [20], and ^{164}Dy [21]. However, no clear evidence of a splitting effect for the PDR was found. In this work the low-lying electric dipole strength was investigated, for the first time, in the axially deformed nucleus ^{154}Sm using the $(\alpha, \alpha'\gamma)$ and $(\vec{p}, \vec{p}')$ reactions to simultaneously explore its IS and IV response, which is crucial to elucidate the collectivity question.

2. Experiments

The IS and IV responses of ^{154}Sm were investigated in two independent experiments using the $(\alpha, \alpha'\gamma)$ reaction at the Separated Sector Cyclotron facility at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), South Africa, and the $(\vec{p}, \vec{p}')$ reaction at the RING cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University, Japan, respectively.

2.1. Experiment at iThemba LABS

In the experiment conducted at iThemba LABS, a dispersion-matched beam was tuned to an energy of 120 MeV, and a self-supporting ^{154}Sm target with an areal density of 4.98 mg/cm^2 and 98% enrichment was used. The scattered α particles were momentum analyzed by the K600 magnetic spectrometer placed in the zero-degree configuration [22]. The focal-plane detector system consisted of a vertical drift chamber (VDC) and a plastic scintillator detector covering an excitation-energy range of 4–16 MeV. The measurement of the subsequent γ decay was performed using the Ball of Germanium and LaBr detectors (BaGeL), where 8 high-purity Germanium (HPGe) Clover-type detectors and 2 large-volume $LaBr_3$:Ce detectors were arranged at angles between 90° and 135° to allow a determination of the multipolarity of the emitted radiation from the angular distribution.

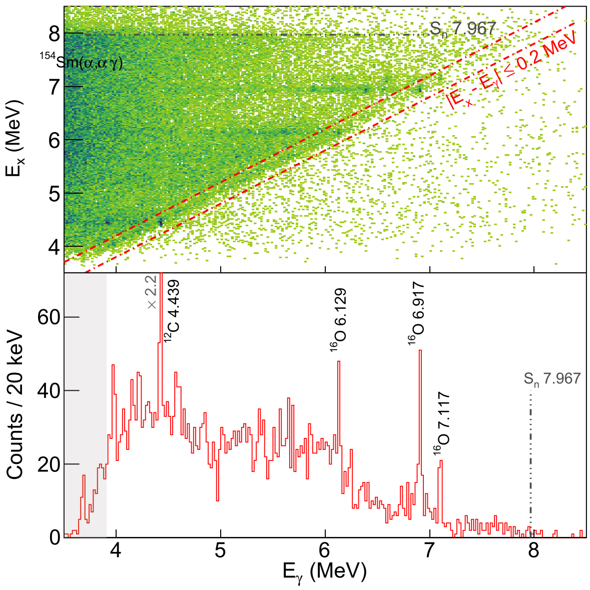

Fig. 1. Top panel: Particle-γ coincidence matrix of the ^{154}Sm$(\alpha,\alpha'\gamma)$ reaction measured with the K600 spectrometer coupled to γ-ray array BaGeL.The γ-ray spectra were obtained using the HPGe detectors of the array. Bottom panel: Projection of the summed ground state and first excited state γ-ray decays for the diagonal gate selection highlighted in red in the top panel. The shaded grey area indicates the region of the spectrum lacking full spectrometer acceptance.

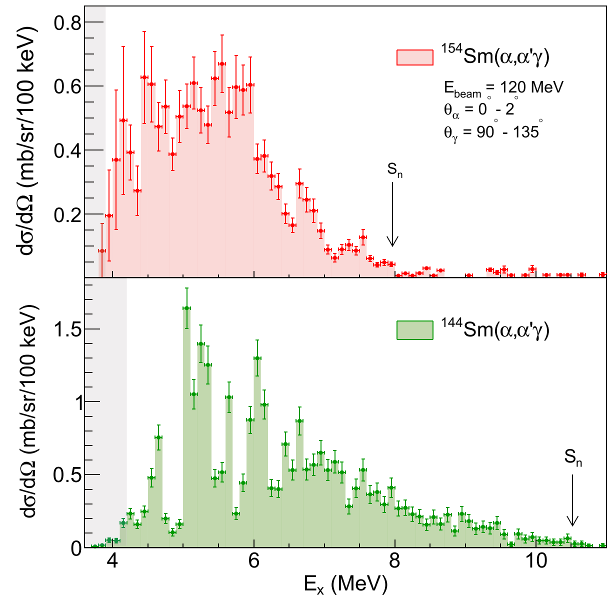

Fig. 2. ^{144,154}Sm differential cross sections obtained from the $(\alpha,\alpha'\gamma)$ experiment as described in the text. The shaded grey area indicates the region of the spectrum lacking full spectrometer acceptance. Note the difference in scales of the ordinates.

The particle-γ coincidence matrix obtained from the ^{154}Sm$(\alpha,\alpha'\gamma)$ experiment is shown in the top panel of Fig. 1. The diagonal gate, indicated by the two red dashed lines, identifies the direct decays to the ground and first excited states. Due to the magnetic spectrometer energy resolution limited by the target thickness, and given that the energy of the first excited state in ^{154}Sm is very low (82 keV), it was not possible to exclusively isolate the γ decays into the ground state from the ones into the first excited state. The bottom panel of Fig. 1 shows the projection of the direct ground state and first excited state γ-ray decays for the applied gate selection. Peaks that correspond to ^{12}C and ^{16}O contaminants are indicated and they were subsequently subtracted using a Mylar-target spectrum [23]. Background subtraction was then performed by using the particle-γ matrix gated on the random-coincidence time peak.

The differential cross sections for the prolate-deformed ^{154}Sm obtained from the $(\alpha,\alpha'\gamma)$ experiment are shown in the top panel of Fig. 2. These results were extracted with the assumption that the de-excitation of the PDR is dominated by direct γ-ray decays to the ground and first excited state. Studies on spherical nuclei support the validity of this assumption in the energy region below 7 MeV, where it was quantified that direct decay almost exclusively populates the ground state [24–29]. Furthermore, a recent ^{154}Sm$(\vec{\gamma},\gamma')$ experiment conducted at the High Intensity γ-ray Source (HIγS), USA [30] observes strong ground state decays from this energy region.

For comparison, the cross sections for the spherical nucleus ^{144}Sm, obtained in a subsequent experiment using the same experimental setup with additional HPGe and LaBr$_3$ detectors, are shown in the bottom panel of Fig. 2.

In both cases, the region below the neutron separation energy (S_n) was excited and the dipole character of the γ radiation was verified using particle-γ angular correlations.

For the ^{154}Sm case, a concentration of strength in the region 4.5-7 MeV is evident and the response appears to decrease significantly in the higher energy region between 7 MeV and the neutron threshold ($S_n = 7.967$ MeV). This behaviour has already been observed in the IS response of several neutron-rich nuclei, and it has been associated with the isospin-mixed nature of the states forming the PDR [11,26–29,31]. It should also be noticed that the absence of strength above 7 MeV cannot be attributed to the limitation in the efficiency of the detectors because transitions from contaminant nuclei and calibration targets were observed.

While for the spherical samarium isotope the cross-section distribution is concentrated in a few strongly excited peaks, the deformation of the ^{154}Sm ground state seems to spread the associated dipole strength over an energy region. The integrated differential cross section extracted between 4.5 MeV and the corresponding neutron thresholds for the isotopes ^{154}Sm (7.967 MeV) and ^{144}Sm (10.520 MeV) are 11.6(1.7) mb/sr and 25.3(3.6) mb/sr, respectively. When comparing the integrated cross sections in the same energy region 4.5-8 MeV (limited by the lower S_n in ^{154}Sm), the corresponding value for ^{144}Sm is 21.9(2.6) mb/sr, approximately twice as large. This indicates that, although the PDR strength is generally expected to grow with neutron excess, deformation suppresses the total strength, yielding only about half of that observed in the spherical nucleus within the same energy window. However, these values should be regarded as lower limits, as they were deduced under the assumption of pure ground-state decay.

2.2. Experiment at RCNP

The IV response of ^{154}Sm was studied at RCNP where a polarized proton beam accelerated to 295 MeV was provided. The scattered protons were detected by the Grand Raiden spectrometer [32] placed at 0° [33] covering an angular and excitation-energy range of 0° – 2.5° and 5–22 MeV, respectively. An isotopically enriched (98.7%) self-supporting ^{154}Sm foil with an areal density of 4.0 mg/cm^2 served as target. The beam intensity was about 2 nA with the degree of polarization varying between 65 and 70%. To extract the electric dipole strength, a decomposition of spinflip and non-spinflip cross sections at 0° can be achieved [34] by the combined information of the polarization transfer observables D_{LL} and D_{SS} or D_{NN} [35] determined in a secondary scattering experiment. Application of the technique at RCNP is described in Ref. [36] and details of the data analysis for ^{154}Sm are provided in Ref. [37].

Due to the different reaction mechanisms, the non-spinflip and spinflip transitions can be identified with E1 or M1 excitations due to Coulomb excitation or the spin-isospinflip part of the proton-nucleus

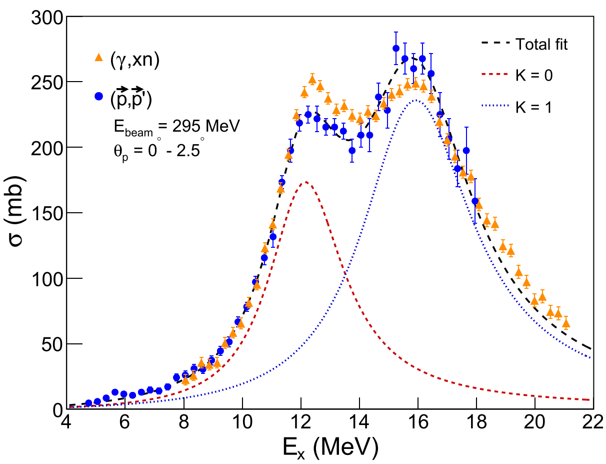

Fig. 3. Comparison between the ^{154}Sm equivalent photoabsorption cross sections deduced from the $(\vec{p},\vec{p}')$ reaction described in this paper (blue circles) and the (γ,xn) reaction studied at Saclay [45] (orange triangles). A fit of the IVGDR in the $(\vec{p},\vec{p}')$ data (using the sum of two Lorentzians, of the form given in Eq. (1), with the associated parameters given in Table 1) is shown as a black dashed line.

interaction, respectively. The background from other nuclear processes has been found to be small in studies of heavy nuclei, and it was subtracted using the empirical parametrization described in Refs. [38,39]. Furthermore, the contributions of the IS giant monopole and quadrupole resonances in ^{154}Sm [40] to the 0° spectrum were estimated as described in Refs. [41,42] and subtracted. The remaining non-spinflip cross sections were converted to the equivalent photoabsorption cross sections using the virtual photon method within an eikonal approach [36,43]. Possible effects of ground-state deformation on the virtual photon flux [44] were investigated by averaging over a set of calculations with different projections of the elongated axis on the photon direction and comparison to a spherical nucleus of the same radius. Differences were found to be less than 3%.

The equivalent photoabsorption cross sections, displayed in Fig. 3 as blue circles, exhibit a double-hump structure in the energy region of the IVGDR due to the K-splitting characteristic for nuclei with a quadrupole-deformed ground state. Above the neutron threshold, the data can be compared to previous results from the (γ,xn) reaction studied at Saclay [45] (orange triangles). While the Saclay data show comparable heights of the two-hump structure, the $(\vec{p},\vec{p}')$ data presented in this work result in an imbalance between the maximum values of the $K=0$ and $K=1$ components corresponding to the first and second resonance peak, respectively. A similar reduction in the $K=0/K=1$ ratio compared to Saclay data [45,46] has recently been reported for deformed Nd isotopes and ^{152}Sm [41].

The IVGDR energy region was fitted by the sum of two Lorentzians

$$\sigma(E_x) = \sum_{i=1,2} \frac{\sigma_i (E_x \Gamma_i)^2}{(E_x^2 - E_i^2)^2 + (E_x \Gamma_i)^2}, \quad (1)$$

where σ_i and E_i denote the maximum cross section and energy, respectively, and Γ_i the width of the ith component. The fit was restricted to the excitation-energy region 10–18 MeV to exclude any possible influence from low-energy resonances. The resulting parameters are given in Table 1 together with the corresponding results for the Saclay data [45]. The fit function obtained (black dashed line in Fig. 3) was then extended to the low-energy region to search for a possible excess of strength above the IVGDR tail that could be associated with the PDR. Two resonance-like structures are suggested with peak energies of about 5.7 and 7.9 MeV. Their parameters are also given in Table 1. In order to obtain a meaningful fit for the 7.9 MeV peak it was necessary to additionally constrain the width to $\Gamma_2 = 0.6$ MeV. However, it was tested that a variation of the width did not affect the integrated cross sections.

Table 1
Comparison of the IVGDR parameters obtained from a two-Lorentzian fit, Eq. (1), in this work (top) and from the Saclay data [45] (middle), and parameters of low-energy resonances extracted as described in the text (bottom).

E_1 (MeV)	σ_1 (mb)	Γ_1 (MeV)	E_2 (MeV)	σ_2 (mb)	Γ_2 (MeV)
12.16(6)	174(8)	3.12(19)	15.93(8)	236(6)	4.60(39)
12.35(10)	192(10)	3.35(15)	16.10(10)	204(10)	5.25(20)
5.69(11)	6(2)	0.55(22)	7.90(20)	4(2)	0.60(5)

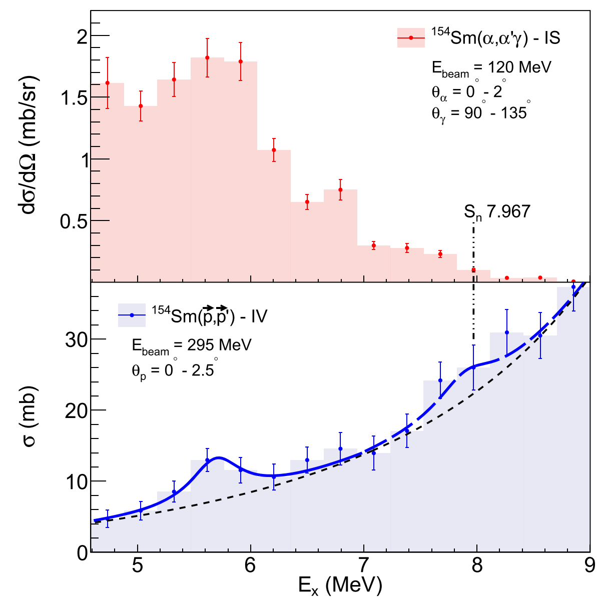

Fig. 4. Comparison between the IS and IV dipole responses in the quadrupole-deformed ^{154}Sm nucleus. Top panel: Differential cross sections obtained using $(\alpha,\alpha'\gamma)$ at 120 MeV. Bottom panel: Photoabsorption cross sections from the $(\vec{p},\vec{p}')$ reaction at 295 MeV. The black dashed line corresponds to the tail of the IVGDR obtained from the fit of Eq. (1) to the present data.

3. Isoscalar and isovector response of the PDR

The resulting $E1$ response at low energies is summarized in Fig. 4. The top panel presents the differential cross sections associated with the IS response of ^{154}Sm, while the bottom panel shows the photoabsorption cross sections corresponding to the IV dipole response. In the 5-6.5 MeV excitation-energy interval, both reactions populate dipole strength, in line with observations from other spherical nuclei and indicative of the isospin-mixed nature characteristic of PDR transitions. An additional observation from the isoscalar response is that the α-scattering data on ^{154}Sm exhibit only very small dipole strength between 6.5 MeV and S_n, providing no evidence for a possible second-hump structure in this region.

The photoabsorption cross sections derived from the proton scattering experiment indicate a possible excess of strength above the extrapolated IVGDR tail around 8 MeV. Its detailed shape depends sensitively on the assumed low-energy extrapolation of the IVGDR and is therefore subject to considerable model dependence and limited statistics. In the present analysis this excess is treated as a single resonance-like component; however, within the present experimental uncertainties a fragmented or double-peak structure cannot be excluded and should be clarified by future measurements.

The integrated $E1$ strength up to the neutron threshold amounts to 2.24(12)% of the classical Thomas-Reiche-Kuhn (TRK) sum rule. The PDR (i.e., the resonance peaking at 5.7 MeV) and the possible structure observed above the IVGDR low-energy tail at 8 MeV exhaust much smaller fractions of 0.23(11)% and 0.17(10)%, respectively. If one uses the IVGDR parameters from the Saclay experiment instead, these values reduce to 0.19(11)% and 0.13(9)%. The small IV strength of the low-energy peak is consistent with a recent study of the stable Sn isotope chain [15,47]. The order-of-magnitude suppression of the strength around 8 MeV, relative to the Sn case, may originate from the enhanced contribution of the low-energy tail of the IVGDR in deformed nuclei, combined with the increased level density associated with deformation, which leads to substantially stronger fragmentation.

The K splitting of the IVGDR can be characterized by the energy splitting $S = (E_2 - E_1)/(E_2 + E_1)$ and the ratio of oscillator strengths $R = \sigma_2\Gamma_2/\sigma_1\Gamma_1$. The present work finds $S_{\rm GDR} = 0.13(1)$ and a $K=1/K=0$ oscillator strength ratio $R_{\rm GDR} = 2.01(24)$ compatible with the expectation $R = 2$ for a prolate-deformed ground state. While the value $S_{\rm PDR} = 0.16(2)$ for the two low-energy structures could be seen as rough agreement, the integrated strength ratio of $R_{\rm PDR} = 0.74(55)$ – despite the large systematic uncertainty due to the parametrization of the low-energy tail of the IVGDR – is clearly much smaller than expected within the geometrical model. It is evident from the present results that an interpretation of the two low-energy bumps as K splitting, in analogy to the IVGDR, is not supported. This is consistent with the lack of strength above 7 MeV in the $(\alpha, \alpha'\gamma)$ results.

The absence of K splitting for the low-energy dipole strength exceeding the GDR tail is also supported by theoretical calculations performed using QRPA based on Hartree-Fock-Bogoliubov (HFB) ground states with Skyrme energy density functionals [48,49], where a mixed contribution of $K = 0$ and $K = 1$ dipole states is found below the particle threshold. A theoretical study of extremely neutron-rich Sn isotopes [50] predicts a reduction of $K = 1$ with respect to $K = 0$ contributions to the low-energy IV strength for deformed nuclei, but not at a level that would support an interpretation of the resonance structures to result from K splitting. Only QRPA-level calculations are currently available for describing the electric dipole response of well deformed nuclei. However, experience from spherical nuclei demonstrates that QRPA alone cannot account for the observed PDR strength distribution, which requires the inclusion of higher-order configurations [3,15]. Such advanced models have not yet been developed for deformed nuclei due to the considerable computational and theoretical complexity involved.

4. Conclusions

The low-energy IS and IV electric dipole strength distributions were investigated for the first time in a well-deformed nucleus (^{154}Sm) up to the neutron threshold using inelastic α scattering and polarized inelastic proton scattering at 0°. In the IS response, the strength is concentrated in the energy region 4.5-7 MeV with a large degree of fragmentation when compared to the spherical isotope ^{144}Sm. The IV response shows a clear resonance at 5–6.5 MeV consistent with spherical nuclei of similar mass number [51]. This structure present in both IS and IV response is identified as the PDR. A second resonance-like structure might be present in the IV response at about 8 MeV, but its magnitude is subject to considerable uncertainty depending on the parametrization of the low-energy tail of the IVGDR. No evidence of a corresponding structure is found in the IS response. While the double-hump structure of the IVGDR observed in the present work is consistent with the expectations for K splitting in a prolate-deformed nucleus, such a description fails for the low-energy resonances. Similar conclusions on the absence of K splitting in the low-lying dipole response have been drawn independently from the average branching ratios of decay to the ground and first excited state in the deformed nucleus ^{150}Nd measured with the $(\vec{\gamma}, \gamma')$ reaction [52].

The absence of a pronounced K splitting disfavours an interpretation of the low-energy dipole strength in terms of a simple collective neutron-skin oscillation against an isospin-saturated core. However, the present data do not exclude more complex excitation patterns, such as mixed-mode contributions or toroidal-type dynamics, which are not necessarily expected to produce a strong K splitting.

Investigations of the PDR in additional deformed nuclei would be highly beneficial for establishing a better picture of the general properties of this low-lying dipole mode. Moreover, the separation of direct γ decay of the PDR to the 0_1^+ ground state and the 2_1^+ state as recently demonstrated for the IVGDR [17] could provide further insight into the distribution of $K = 0$ and $K = 1$ dipole strength at low energies.

There are only limited theoretical studies of electric dipole strength in well deformed nuclei and they are presently on the QRPA level only. However, a realistic description of the low-energy strength distributions requires at least the inclusion of leading-order two-particle two-hole configurations (so-called quasiparticle vibration coupling) [3,15]. Such calculations may become available in the near future [53].

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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