

# Splitting of the Pygmy Dipole Resonance

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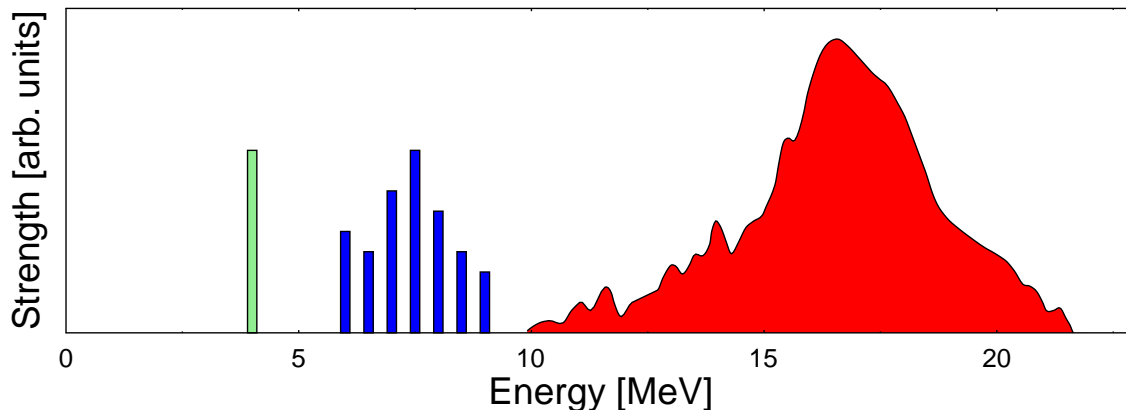
## Abstract.

We report on experiments using the  $(\alpha, \alpha'\gamma)$  method to investigate the structure of the Pygmy Dipole Resonance (PDR) in the nuclei  $^{94}\text{Mo}$ ,  $^{124}\text{Sn}$ ,  $^{138}\text{Ba}$  and  $^{140}\text{Ce}$ . The experiments were performed with the Big-Bite Spectrometer (BBS) at the KVI at an incident energy of  $E_\alpha = 136$  MeV. The method allows a clean separation of the PDR from other excitations in the same energy region by selecting the ground-state  $\gamma$ -decay channel. In addition, the high resolution of the  $\gamma$ -ray spectroscopy using high-purity Germanium detectors allows a state-to-state analysis even in the case of the rather high level density of the investigated nuclei. The comparison to  $(\gamma, \gamma')$  experiments on the same nuclei reveals a splitting of the PDR into two groups of states with different underlying structure.

## 1. Introduction

The electric dipole ( $E1$ ) response is one of the basic properties of atomic nuclei. For medium to heavy spherical nuclei it can roughly be divided into three major contributions as shown schematically in Fig. 1. The major part (red) is exhausted by the well-known Isovector Electric Giant Dipole Resonance (IVGDR) located at energies well above the particle separation thresholds, which has been investigated extensively in the past, see e.g. [1] for an overview. The second contribution is the so-called two-phonon states (green), which arise from the coupling of the lowest quadrupole and octupole phonons and represent typically the lowest lying  $E1$  excitation in heavy spherical nuclei [2, 3]. In the energy region in between, in the vicinity of the particle thresholds, another contribution to the  $E1$  response has been found in most studied nuclei (blue). This fragmented resonance-like structure is usually denoted as Pygmy Dipole Resonance (PDR) and exhausts depending on the nucleus around 1% of the energy-weighted sum rule (EWSR). Whereas the basic structure of the IVGDR and the two-phonon states are known, the nature of the PDR is still a matter of on-going discussions.

Up to now the PDR has been nearly exclusively studied in real photon scattering experiments. This method is well suited, since it is very selective to  $J = 1$  states and by using high-purity Germanium (HPGe) detectors it provides the necessary energy resolution in order to resolve the states of the fragmented  $E1$  strength in the PDR region. A systematic survey has been



**Figure 1.** Schematic picture of the  $E1$  strength in heavy nuclei. For details see text.

performed in the last decade in order to investigate the PDR using the  $(\gamma, \gamma')$  method in nuclei in different mass regions, see e.g. [4, 5, 6, 7, 8, 9, 10, 11]. In recent years, the investigations have also been extended to exotic nuclei using the method of Coulomb excitation in inverse kinematics [12, 13, 14, 15].

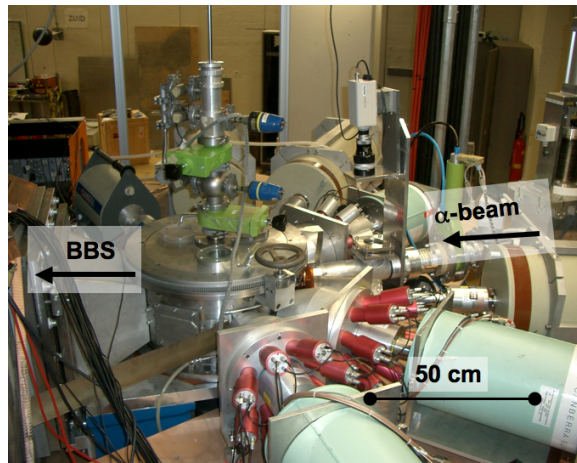
The experimental studies are accompanied by many theoretical investigations; see [16] for a recent review. The models include different microscopic approaches [17, 18, 19, 20, 21, 22, 23, 24]. In most models, the nature of the PDR is predicted as an oscillation of a neutron skin against a proton/neutron core. The experimental data seem to support such a description, since the systematic investigations report an enhancement in more neutron-rich nuclei, which might be due to a more developed neutron skin. However, the experimental data based on real and virtual photon scattering are not sufficient in order to verify this picture of the PDR. Complementary experiments using different probes are thus of high importance in order to learn more on the structure of this low-energy dipole strength.

An experimental approach has to provide two major conditions in order to allow an investigation of the PDR on a state-to-state basis: an excellent selectivity to  $E1$  excitations and a high energy resolution. The first one is fulfilled in the  $(\alpha, \alpha'\gamma)$  reaction by measuring in coincidence the excitation and decay energy to select the ground-state decay channel [25]. By using HPGe detectors for the  $\gamma$ -ray spectroscopy also the second condition can be fulfilled [26]. This new method has been used to investigate the PDR in the  $(\alpha, \alpha'\gamma)$  reaction in the  $N=82$  isotones [27, 28] and in  $^{124}\text{Sn}$  [29]. The results show a structural splitting of the PDR in these nuclei. Here, we report on further experiments in order to establish first systematics of the PDR using this method.

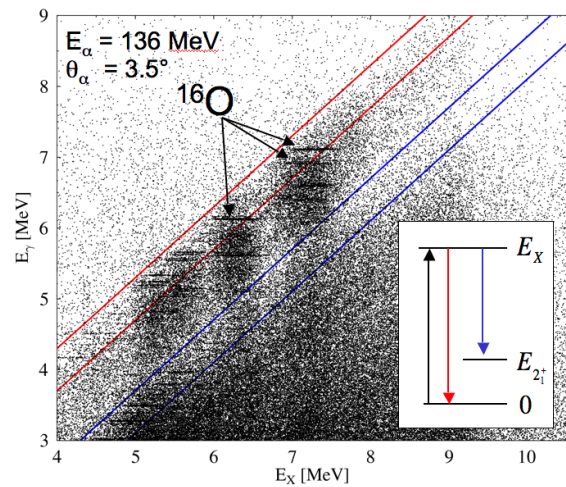
## 2. Experiments and Results

The experiments were performed at the Big-Bite spectrometer (BBS) at the AGOR cyclotron facility of KVI. For light-ion detection the BBS is equipped with the EUROSUPERNOVA (ESN) detection system [30]. The large solid angle of the BBS of up to 13 msr [31] allows the efficient performance of coincidence experiments with additional detector systems. An array of HPGe detectors is positioned for the  $\gamma$ -ray detection as close as possible to the target. A picture of the setup for one of the experiments is shown in Fig. 2. The absolute photo-peak efficiency at 1.33 MeV photon energy is about 0.5%. A detailed description of the setup can be found in [26].

The excitation energy is determined by measuring the energy loss of the scattered  $\alpha$  particle and the deexcitation energy is determined by the measured  $\gamma$ -ray energy. The combination of



**Figure 2.** Experimental setup at the BBS at KVI. Large volume HPGe detectors surround the target chamber in order to measure the  $\gamma$  decay in coincidence with the scattered  $\alpha$  particles.



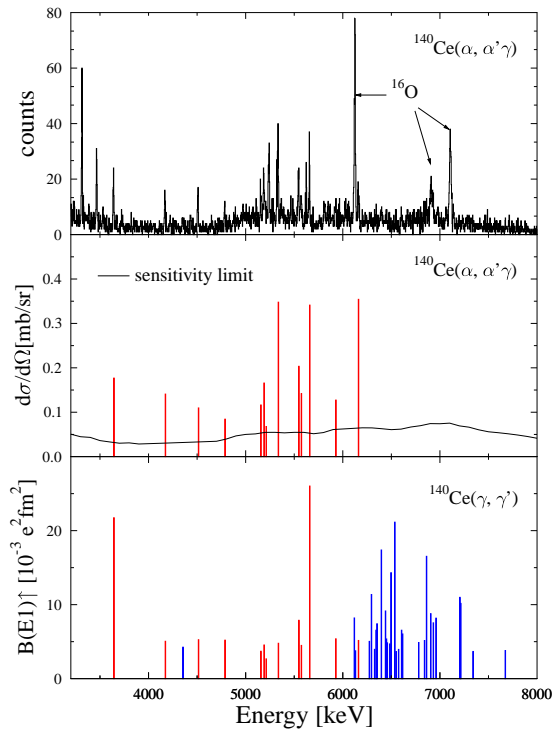
**Figure 3.** Two-dimensional scatter plot with the excitation energy on the x-axis and the decay energy on the y-axis. Transitions to different final states can be selected by narrow cuts as indicated for the ground state and first-excited state.

both allows to produce a scatter plot, which is shown in Fig. 3 for the case of  $^{140}\text{Ce}$ . In this representation, transitions between (excited) levels appear as thin horizontal lines, because of the much better energy resolution in the  $\gamma$ -ray spectroscopy (about 10 keV at 10 MeV photon energy). Beside the three strong transitions belonging to the  $^{16}\text{O}$  contamination in the target, all transitions stem from the deexcitation of excited states in  $^{140}\text{Ce}$ .

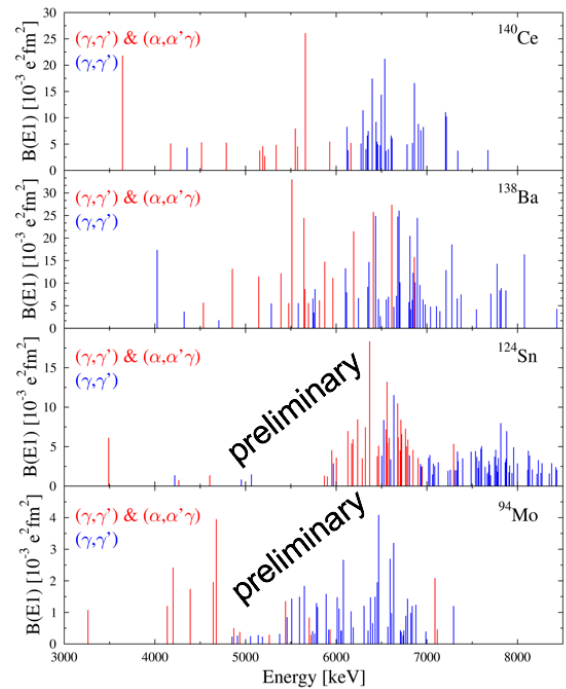
As indicated by the red and blue lines the transitions are ordered in diagonal bands, each belonging to a certain decay channel. The upper most band represents the decays into the ground state (red lines), i.e. excitation and deexcitation energy are the same. Beside the decays into the ground state also other decay channels are visible, as for example into the first-excited state (blue lines). The lines appearing in between are single- and double-escape lines and thus are due to the detector response of the HPGe detectors.

By applying narrow cuts on this two-dimensional matrix, very clean spectra for the ground-state decay channel can be produced. Figure 4 shows a part of the resulting spectrum (after selecting the ground-state decay channel, i.e. the region between the two red lines in Fig. 3) for one detector at backward angles for  $^{140}\text{Ce}$ . Since states with  $J > 1$  predominantly decay to excited states in contrast to states with  $J = 1$ , which decay predominantly into the ground state, this cut provides a very high selectivity to the  $E1$  excitations of interest. Beside the peaks stemming from the  $^{16}\text{O}$  contamination in the target, exclusively peaks corresponding to the decay of  $J^\pi = 1^-$  states are present at  $E_x > 4\text{MeV}$ . This demonstrates the selectivity of the method. At the same time, the achieved excellent energy resolution allows the separate analysis of single excitations. For a detailed discussion of the analysis see [28].

The middle part of Fig. 4 shows the results of the  $(\alpha, \alpha'\gamma)$  experiment together with its sensitivity limit. The lower part of Fig. 4 shows the results of the  $(\gamma, \gamma')$  experiment [7]. The comparison between the two experiments shows a clear difference in the distribution of the observed  $E1$  strength. Up to an excitation energy of about 6 MeV all states were observed in both experiments (except for one weak state), while all higher-lying states, especially the group of strong  $E1$  excitations around 6.5 MeV are completely missing. The spectrum does not even show a sign of peaks in the region around 6.5 MeV. Since the sensitivity of the experiment is



**Figure 4.** Spectrum after selecting the ground-state decay channel (upper part) together with the determined  $\alpha$ -scattering cross sections (middle part) [28]. The lower part shows the results of a  $(\gamma, \gamma')$  experiment [7]. States observed in both kind of experiments are marked in red, states observed only in  $(\gamma, \gamma')$  in blue.



**Figure 5.**  $B(E1)\uparrow$  strength distributions measured in  $(\gamma, \gamma')$  experiments [4, 7]. States observed in both kinds of experiments are marked in red, states observed only in  $(\gamma, \gamma')$  are marked in blue. In all studied nuclei, the same splitting between the lower- and higher-lying states is present.

nearly constant in the region 4-8 MeV, the absence of peaks at  $E_x > 6$  MeV means, that these states are not excited in  $\alpha$  scattering (from the NRF experiment it is known, that they decay strongly into the ground state). This must be related to a difference in the underlying structure of the  $J^\pi = 1^-$  states and thus a different response to excitation by photons and  $\alpha$  particles.

Figure 5 shows the  $B(E1)\uparrow$  strength distributions of the four nuclei we have investigated with the  $(\alpha, \alpha'\gamma)$  reaction so far. The color coding is the same as for the lower part of Fig. 4, i.e. the red indicated states were observed in both reactions, while the blue states were observed in  $(\gamma, \gamma')$  only. For all cases the results indicate the same splitting as discussed for  $^{140}\text{Ce}$  above. This splitting thus seems to be a generic feature of the PDR.

### 3. Conclusions and Outlook

We have reported on a new experimental approach to study the structure of the PDR, a concentration of low-lying  $E1$  strength below the IVGDR. The results of the performed  $(\alpha, \alpha'\gamma)$  experiments point to a splitting of the PDR into two groups of states with different underlying structure: A lower-lying group, which is excited by photons as well as  $\alpha$  particles, and a higher-lying group, which is exclusively excited in the  $(\gamma, \gamma')$  reaction.

Further investigations, theoretical and experimental, will be necessary in order to fully understand and pin down the nature of the low-lying part of the  $E1$  strength. On the

experimental side different experiments are on the way in order to provide additional observables and systematics on the PDR. On stable nuclei,  $(p, p'\gamma)$  experiments will allow to further investigate the structure of the PDR. Using tagged photons at the NEPTUN facility [32, 33] will allow to close the gap between the IVGDR and the low-energy strength. At this new experimental site, photon-induced experiments can be studied independently of limitations due to the particle thresholds, which will also play an important role in extending systematics on photon-induced reactions for nuclear astrophysics [34, 35, 36, 37]. On exotic nuclei, further systematics will be collected in order to confirm the dependence of the PDR on the neutron excess and also to connect to the experiments on the stable isotopes. Using hadronic interaction in inverse kinematics will allow to perform similar experiments as the presented  $(\alpha, \alpha'\gamma)$  also in exotic nuclei in the PDR region and hence will bring further light into the structure of the low-lying  $E1$  strength of atomic nuclei.

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