Systematic Study of the Pygmy Dipole Resonance

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Abstract. In recent years, a systematic comparative study of the pygmy dipole resonance (PDR) using the (γ,γ') and the (α,α'γ) reactions on the nuclei ¹⁴⁰Ce, ¹³⁸Ba, ¹²⁴Sn, ⁹⁴Mo, and ⁴⁸Ca was performed. The aim of this systematic study is to explore the structure of the PDR by the usage of two complementary probes and several different nuclei. The real-photon scattering experiments were performed at the S-DALINAC in Darmstadt, Germany, while the (α,α'γ) coincidence experiments were performed at the Big-Bite Spectrometer (BBS) at KVI in Groningen, The Netherlands. The comparison of the results from both kinds of experiments showed an energetic splitting of the PDR into two parts that might be due to the different isospin character of these states.

First experimental results of the (α,α'γ) experiments on the nuclei ⁹⁴Mo and ⁴⁸Ca will be presented.

1. Introduction

The main component of the electric dipole strength in atomic nuclei is the isovector giant dipole resonance (IVGDR) which exhausts almost the total energy-weighted sum rule [1]. Moreover, in neutron-rich nuclei electric dipole strength to low-lying Jπ = 1− states around the neutron separation threshold, the electric pygmy dipole resonance (PDR), has been observed [2].

The most direct way to induce dipole transitions from the ground state, i.e. excite 1− states in even-even stable nuclei, is the (γ,γ') reaction, because real photons are highly selective to low multipolarities [3, 4, 5, 6]. Experiments using the (γ,γ') reaction are thus a commonly used method to study electric dipole excitations. Most of the available data on the PDR in many nuclei were established in this kind of experiments. Observables like excitation energy, spin, parity, and B(E1) strength of excited states can be determined using the (γ,γ') reaction in a model-independent way. In the experiments, the emitted γ rays were detected by HPGe detectors which provide an excellent energy resolution that is essential because of the high density of excited levels.

Additional information about the structure of the PDR can be deduced by a combination with a complementary excitation mechanism. The interaction of an α particle with an atomic nucleus, at intermediate energies, includes strong interaction mainly with the surface besides electromagnetic interaction with the whole nucleus. Furthermore, the strongly interacting α-particle is a scalar-isoscalar probe which therefore excites states of natural parity and isoscalar nature. The experimental method which was applied to allow for using α particles as a probe
of electric dipole strength is the $\alpha$-$\gamma$ coincidence method. The $(\alpha, \alpha'\gamma)$ coincidence experiments at $E_\alpha=136$ MeV and forward scattering angles were performed at KVI in Groningen, The Netherlands. The beam was provided by the AGOR cyclotron and the scattered $\alpha$ particles were detected by the QQQ-type magnetic Big-Bite Spectrometer which was positioned at 3.5° or 5° (depending on the nucleus) with respect to the beam axis. Around the target chamber an array of HPGe detectors was placed for $\gamma$ spectroscopy with an excellent energy resolution. A hardware coincidence between HPGe detectors and the BBS was used as a main trigger to reduce the count rates and the dead time of the system. This setup enables the determination of the singles $\alpha$-scattering cross sections by integrating over the full solid angle of $\gamma$ detection. More details about the experimental setup are given in Ref. [7].

One result of the performed systematic study of the PDR in $(\alpha, \alpha'\gamma)$ and $(\gamma, \gamma')$ experiments is the observation of an energetic splitting in a low-energy part, which is observed in both types of experiments, and a high-energy part, which is observed only in the $(\gamma, \gamma')$ experiments. It was first discovered in $^{140}$Ce [8] and it has been shown, by the study of $^{138}$Ba and $^{124}$Sn [9, 10], that this is not an exceptional case but a general behaviour of the low-lying electric dipole strength (see Fig. 1).

In the following sections, results for the nuclei $^{94}$Mo and $^{48}$Ca experiments will be presented.

Figure 1. Experimental results of the systematic study of the PDR in $^{140}$Ce, $^{138}$Ba, and $^{124}$Sn [3, 8, 9, 10, 11]. The singles $\alpha$-scattering cross sections were determined in the $(\alpha, \alpha'\gamma)$ experiment and the $B(E1)$ transition strengths were determined in the $(\gamma, \gamma')$ experiment. The dashed lines correspond to the sensitivity limit in the $(\alpha, \alpha'\gamma)$ experiments.

2. The non-magic nucleus $^{94}$Mo

In order to extend the systematic study, the nucleus $^{94}$Mo was measured with the $\alpha$-$\gamma$ coincidence method. The BBS was placed at 3.5° with respect to the beam axis and the HPGe detector array consisted of seven HPGe detectors.

In contrast to the other nuclei studied, this nucleus is non-magic but still spherical and close to a sub-shell closure. The low-lying $1^-$ states, which were excited by the $\alpha$ particles, could be identified by a comparison to results from a $(\gamma, \gamma')$ experiment. In Fig. 2, the singles cross sections are shown. They were determined in this experiment from the summed $\gamma$ spectrum with a gate on the excitation energy $E_x = E_\gamma$, which is the condition for a de-excitation to
the ground state. A branching to an excited state with a level energy $E_{\text{level}}$ becomes visible in the $\gamma$ spectrum by gating on $E_x = E_\gamma - E_{\text{level}}$. First results indicate a branching of low-lying $1^-$ states to the first $2^+$ state, which is included in the calculation of the cross section. If no branching was observed, a branching ratio of $\Gamma_0/\Gamma = 1$ was assumed.

![Figure 2.](image)

Figure 2. Singles $\alpha$-scattering cross sections of dipole excitations in $^{94}$Mo. Branching ratios are included. If no branching was observed, a branching ratio of $\Gamma_0/\Gamma = 1$ was assumed. The dashed line corresponds to the experimental sensitivity limit.

### 3. The doubly-magic nucleus $^{48}$Ca

Whereas in heavy neutron-rich nuclei the occurrence of the PDR has been shown, the existence of the PDR mode in lighter nuclei is still an open question. Light nuclei which have a neutron halo are known (for example $^{11}$Li [12]), but in these cases only single weakly-bound nucleons contribute to the excitation, so it is a different phenomenon than the PDR in heavy nuclei. Further investigations are necessary to clarify in which mass region and at which neutron-proton asymmetries the development of a neutron skin and the PDR starts. Dipole transitions in the Calcium chain have been studied systematically in $(\gamma,\gamma')$ experiments at the Darmstadt High-Intensity Photon Setup [13] at the S-DALINAC (see Refs. [14, 15, 16]). Furthermore, the summed $B(E1)$ strength can be reproduced by theoretical calculations [16]. Knowledge of the development of electric dipole-strength in the Calcium chain, with increasing neutron number and therefore increasing $N/Z$ ratio, may provide access to some unanswered questions concerning the low-lying dipole strength.

The doubly-magic isotope $^{48}$Ca, which is known to have a neutron skin (Refs. [17, 18]), was studied by real photon scattering at the S-DALINAC [14] and by the $\alpha-\gamma$ coincidence method at the BBS at KVI. The setup for the $(\alpha,\alpha'\gamma)$ experiment was the same as for $^{94}$Mo except that the BBS was positioned at $5^\circ$ and in total six HPGe detectors were arranged around the target chamber. Again, the $\alpha$-beam energy in the experiment was $E_\alpha = 136$ MeV. First results of this experiment show that almost all dipole excitations which were observed in the $(\gamma,\gamma')$ experiment are also visible in the summed $\gamma$ spectrum with a gate on ground-state transitions (see Fig. 3), which was obtained in the $\alpha-\gamma$ coincidence experiment. Surprisingly, the state at
7.3 MeV which has the highest $B(E1) \uparrow$ value of $16.5(19) \cdot 10^{-3} e^2 \text{fm}^2$ (see Fig. 4) of in total $55.7(41) \cdot 10^{-3} e^2 \text{fm}^2$ was not excited by the $\alpha$ particles. In contrast, the state at 7.6 MeV, which was strongly excited by $\alpha$ particles, has a small $B(E1) \uparrow$ transition strength and therefore seems to have a different structure compared to the other observed transitions. The analysis is still in progress.

Recently, in addition a direct parity measurement in $^{48}$Ca has been performed by means of the $(\vec{\gamma},\gamma')$ reaction. The polarized and nearly mono-energetic photons were produced at the High Intensity Gamma-Ray Source (HI$\gamma$S) facility at the Duke University in Durham, USA. First results assign negative parity to all observed dipole excitations.

**Figure 3.** Summed $\gamma$ spectrum with a gate on $E_x = E_\gamma$ measured in the $\alpha-\gamma$ coincidence experiment on $^{48}$Ca. Dipole transitions are marked with stars. Besides the transitions of excited states in $^{48}$Ca, also transitions in $^{40}$Ca and $^{16}$O are visible.

**Figure 4.** The $B(E1)$ strength distribution was determined in a $(\gamma, \gamma')$ experiment at the S-DALINAC [14, 15].

### 4. Summary and outlook
The $\alpha-\gamma$ coincidence method, which was performed to study the low-lying electric dipole strength, was introduced and first results for two nuclei, $^{94}$Mo and $^{48}$Ca, which were obtained by using
this method were presented. Singles $\alpha$-scattering cross sections were determined for $^{94}$Mo from
the summed $\gamma$ spectrum with a gate on ground-state transitions. There are clear indications for
decay of two states into the first $2^+_1$ state in addition to decay to the ground state.

Dipole excitations in the doubly-magic $^{48}$Ca are visible in the summed $\gamma$ spectrum with a gate
on ground-state transitions and will allow the determination of absolute singles cross sections.
The comparison to results from a ($\gamma,\gamma'$) experiment once again emphasizes the importance
of using different excitation mechanisms to get a deeper insight into the structure of low-lying $1^-$
states, especially their isospin character.

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