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Study of the isospin character of 1- states using hadronic probes at intermediate energies

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Abstract. The complementary (γ,γ') and $(\alpha,\alpha'\gamma)$ reactions were used to study the isospin properties of low-lying $E1$ excitations in the doubly-magic nucleus ^{48}Ca. In contrast to heavier nuclei, a state-to-state change in isospin character was revealed in ^{48}Ca and a dominant isoscalar excitation was found which is interpreted as an isoscalar oscillation. Recently, protons at 80 MeV were used as an additional hadronic probe in a p-γ coincidence experiment on ^{140}Ce for the first time. Results of the experiments on ^{48}Ca and first results of the ^{140}Ce will be presented in this contribution.

1 Introduction

Low-lying electric dipole excitations, in particular the electric Pygmy Dipole Resonance (PDR), were investigated in neutron-rich nuclei using various experimental methods [1]. Aiming at isospin characters of these 1^- states, it has been demonstrated that the complementary studies of real-photon scattering and high-resolution $(\alpha,\alpha'\gamma)$ coincidence experiments at 136 MeV allow separating isovector and isoscalar dipole response which is important for a deeper understanding of the underlying mechanisms generating the dipole strength [2]. Systematic studies using these complementary probes revealed a splitting into low-lying isospin-mixed $E1$ excitations and higher-lying dominantly isovector $E1$ excitations in neutron-magic, proton-magic, and non-magic nuclei (namely ^{140}Ce, ^{138}Ba, ^{124}Sn, and ^{94}Mo) [2–5]. This experimentally observed common feature of the low-lying $E1$ response is reproduced by several theoretical calculations (see, e.g., Refs. [6–9]) which suggest a distinction between a low-lying neutron-skin oscillation mode and a transitional mode towards the well-known isovector Giant Dipole Resonance (IVGDR) [10]. Recently, the crossover between the neutron-skin mode and the higher-lying proton-neutron oscillation mode was investigated in detail by means of random-phase approximation (RPA) calculations [11] and a decomposition method was introduced which might be important for a robust comparison with experimental data. In addition to the aforementioned α-particles, the hadronic probe of ^{17}O at 20 MeV/u was recently used in a high-resolution experiment on ^{208}Pb at Legnaro National Laboratory [12].

In the following, we present results of two experiments using the hadronic probes of α particles at 136 MeV and protons at 80 MeV which we performed to achieve a better understanding of the nature of low-lying $E1$ excitations in ^{48}Ca and ^{140}Ce. The $^{48}\mathrm{Ca}(\alpha,\alpha'\gamma)$ and $^{140}\mathrm{Ce}(p,p'\gamma)$ experiments go beyond the systematic study of low-lying dipole excitations in $(\alpha,\alpha'\gamma)$ and (γ,γ') experiments in two ways: On the one hand, by studying a much lighter neutron-rich nucleus and, on the other hand, by using a complementary hadronic probe with a higher energy per nucleon, namely protons at 80 MeV which penetrate more deeply into the nucleus.

2 Experimental setup and results

Both experiments were performed at the KVI Groningen, The Netherlands, exploiting the Big-Bite Spectrometer in combination with an array of HPGe detectors for γ spectroscopy. The scattered particles and the de-exciting γ-rays were acquired in hardware coincidence. In the data-analysis process, particle-γ coincidence matrices are constructed which are then used to generate energy spectra with specific energy conditions on the excitation energy (E_x) and the γ-ray energy (E_γ). Gates on ground-state transitions ($E_x = E_\gamma$) highly increase the sensitivity to dipole transitions which dominantly decay via this channel. Details on the experimental setup and data analysis tools can be found in Ref. [13]. Results of the two experiments on ^{48}Ca and ^{140}Ce are presented in the following subsections. Main experimental parameters are given in Table 2.

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Table 1. Experimental parameters for the ^{48}Ca($\alpha,\alpha'\gamma$) and ^{140}Ce($p,p'\gamma$) experiments.

	^{48}Ca($\alpha,\alpha'\gamma$)	^{140}Ce($p,p'\gamma$)
target thickness	1.7 mg/cm^2	20 mg/cm^2
isotopic enrichment	99%	99.72%
beam energy	136 MeV	80 MeV
average beam current	0.9 pnA	0.6 pnA
BBS central angle	5.8°	5.6°
collected charge	794 μC	408 μC

2.1 Results of the ^{48}Ca($\alpha,\alpha'\gamma$) experiment

Low-lying $E1$ excitations and their $B(E1)$ strength distributions in stable Ca isotopes, including the doubly-magic ^{48}Ca, have been studied in several (γ,γ') experiments [14, 15]. Hence, the results of the ^{48}Ca($\alpha,\alpha'\gamma$) experiment of this work, allow a comparison of singles α-scattering cross sections and reduced $B(E1)\uparrow$ transition strengths [14] (presented in Fig. 1) which gives access to the isospin character of low-lying 1^- states in ^{48}Ca. It reveals a state-to-state dependent isospin character of the 1^- states where isoscalar, isospin-mixed, and isovector dipole excitations are in close vicinity. An isospin splitting as observed in the heavier nuclei is not present in ^{48}Ca. Remarkable is also a strong dominantly isoscalar state at 7.6 MeV close to a strong isovector state at 7.3 MeV. The strong isoscalar state is interpreted as a pure isoscalar oscillation on basis of RPA calculations [16] under consideration of the corresponding velocity fields and transition densities. Furthermore, the well-separated dominant isovector and isoscalar states at 7.3 MeV and 7.6 MeV, respectively, are an optimal test case for the investigation of isospin mixing in a two-state mixing approach. A value of 0.061(6) was determined for the squared mixing amplitude. This results in an isospin-mixing matrix element of 85(3) keV. Further results of this experiment were presented in more detail in Ref. [17].

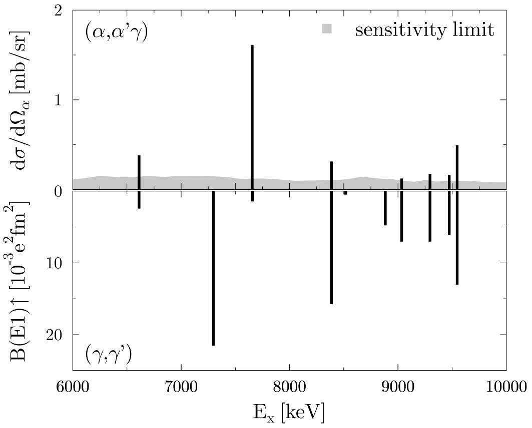

Figure 1. Cross sections obtained in the ^{48}Ca($\alpha,\alpha'\gamma$) experiment (upper panel) in comparison with results of a real-photon scattering experiment [14] (lower panel).

2.2 Results of the ^{140}Ce($p,p'\gamma$) experiment

The neutron-magic ^{140}Ce was the first nucleus for which an isospin splitting of low-lying $E1$ excitations was observed and it is the first nucleus for which the studies were extended by a $(p,p'\gamma)$ experiment at intermediate energy. The summed γ-ray spectrum of all HPGe detectors with a gate on ground-state transitions obtained in the ^{140}Ce($p,p'\gamma$) experiment is shown in Fig. 2.

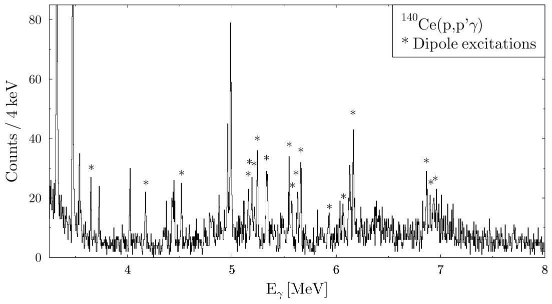

Figure 2. Summed γ-ray spectrum of all HPGe detectors with gate on $E_x = E_\gamma$ measured in the ^{140}Ce($p,p'\gamma$) experiment. Dipole transitions are marked with stars.

Dipole transitions were identified via their ground-state transition energy in comparison with (γ,γ') data [18, 19]. Singles proton-scattering cross sections were determined on basis of this spectrum. Compared to the results from the inelastic α-scattering experiment, the proton-scattering cross sections are almost one order of magnitude smaller. The ratio of the cross sections is shown in Fig. 2. It is nearly constant with an average value of $(d\sigma/d\Omega_\alpha)/(d\sigma/d\Omega_p) = 6.2(7)$. The central part of the nucleon-nucleon interaction is strongly energy-dependent [20] and decreases with increasing energy from 34 MeV/u to 80 MeV/u. This also leads to a higher degree of transparency for the proton probe and additional cancellation effects for dipole transitions. The experimentally determined ratio for the cross sections is reproduced by Distorted-Wave Born Approximation (DWBA) calculations.

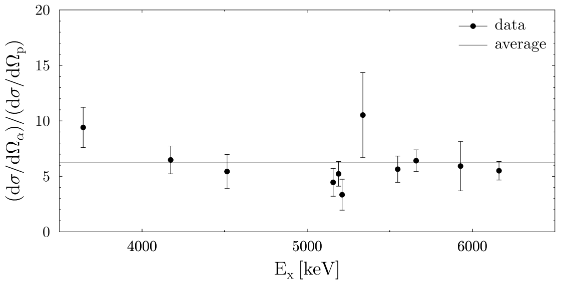

Figure 3. Ratios of singles α-scattering cross sections [2] and proton-scattering cross sections (this work) for the dipole excitations observed in both experiments. The horizontal line indicates the average ratio.

3 Summary and outlook

Inelastic scattering experiments using hadronic probes at intermediate energies, namely an $(\alpha,\alpha'\gamma)$ experiment at $E_\alpha = 136\,\mathrm{MeV}$ on the doubly-magic ^{48}Ca and a $(p,p'\gamma)$ experiment at $E_p = 80\,\mathrm{MeV}$ on the neutron-magic ^{140}Ce were performed at KVI Groningen to further study the nature of low-lying $E1$ strength. These experiments complement previous real-photon scattering experiments on both nuclei [14, 18] and an additional $^{140}\mathrm{Ce}(\alpha,\alpha'\gamma)$ experiment [2]. In contrast to the observations in heavier nuclei, low-lying $E1$ excitations in the lighter nucleus ^{48}Ca show a state-to-state dependent isospin character. Furthermore, a strong isoscalar dipole state was revealed which supports theoretical predictions of a strong isoscalar oscillation [16].

For the dipole excitations in ^{140}Ce, the singles proton-scattering cross sections are considerably smaller compared to the α-scattering cross sections. Nevertheless, the general excitation pattern seems to be very similar which is supported by a nearly constant ratio of these cross sections.

In the future, different experimental techniques will be combined to achieve a deeper understanding of coexisting electric dipole modes throughout the nuclear landscape. Essential observables testing the underlying structures more thoroughly include γ-decay branchings, isospin characters, as well as single-particle contents. In particular, the isospin character of 1^- states will be addressed in particle-γ coincidence experiments with hadronic probes at intermediate energies at iThemba LABS in Somerset West, South Africa, and within an experimental PDR campaign with the CAGRA Clover-detector array at RCNP in Osaka, Japan.

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