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Isospin properties of electric dipole excitations in ^{48}Ca

V. Derya [a,*], D. Savran [b,c], J. Endres [a], M.N. Harakeh [d,e], H. Hergert [f], J.H. Kelley [g,h], P. Papakonstantinou [i], N. Pietralla [j], V.Yu. Ponomarev [j], R. Roth [j], G. Rusev [k,g,1], A.P. Tonchev [k,g,2], W. Tornow [k,g], H.J. Wörtche [d], A. Zilges [a]

[a] Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany
[b] ExtreMe Matter Institute EMMI and Research Division, GSI, 64291 Darmstadt, Germany
[c] Frankfurt Institute for Advanced Studies FIAS, 60438 Frankfurt am Main, Germany
[d] Kernfysisch Versneller Instituut, University of Groningen, 9747 AA Groningen, The Netherlands
[e] GANIL, CEA/DSM-CNRS/IN2P3, 14076 Caen, France
[f] Department of Physics, Ohio State University, Columbus, OH 43210, USA
[g] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA
[h] Department of Physics, North Carolina State University, Raleigh, NC 27695, USA
[i] Rare Isotope Science Project, Institute for Basic Science, Daejeon 305-811, Republic of Korea
[j] Institut für Kernphysik, TU Darmstadt, 64289 Darmstadt, Germany
[k] Department of Physics, Duke University, Durham, NC 27708, USA

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ABSTRACT

Two different experimental approaches were combined to study the electric dipole strength in the doubly-magic nucleus ^{48}Ca below the neutron threshold. Real-photon scattering experiments using bremsstrahlung up to 9.9 MeV and nearly mono-energetic linearly polarized photons with energies between 6.6 and 9.51 MeV provided strength distribution and parities, and an $(\alpha, \alpha'\gamma)$ experiment at $E_\alpha = 136$ MeV gave cross sections for an isoscalar probe. The unexpected difference observed in the dipole response is compared to calculations using the first-order random-phase approximation and points to an energy-dependent isospin character. A strong isoscalar state at 7.6 MeV was identified for the first time supporting a recent theoretical prediction.

Doubly-magic nuclei are exceptional cases for studying nuclear-structure properties. On one hand, such nuclei are traditionally considered as key-stones for testing theoretical approaches, such as, for example, the random-phase approximation (RPA) [1]. On the other hand, the low level density allows a detailed experimental investigation of individual excitations using different probes, therefore giving access to a variety of observables which provide a well-understood basis to confront nuclear models with. For the investigation of the isospin dependence of excitations in the many–body quantum system of an atomic nucleus consisting of few to many nucleons in two different isospin states (proton and neutron), the calcium chain offers a unique case with two stable doubly-magic nuclei, the $N = Z$ nucleus ^{40}Ca and the neutron-rich ^{48}Ca with $N/Z = 1.4$. Dominant isoscalar (IS) and isovector (IV) excitation modes at excitation energies above the particle thresholds are well known, as for example the IV giant dipole resonance (IVGDR) or the IS giant quadrupole resonance [2]. Recently, an unexpected evolution of low-lying IS electric dipole strength as a function of the neutron number was predicted in the Ca chain [3]. This transition of the structure of the excitations from proton-skin oscillation to pure IS oscillation to neutron-skin oscillation depends on the used interaction or, more generally, the theoretical approach. However, isospin-sensitive experiments can address this question.

In this Letter, we report on experimental results of electric dipole ($E1$) excitations in ^{48}Ca using different experimental techniques, which revealed different properties of single excitations. Moreover, we compare these results directly to results from RPA calculations. Interest in low-lying $E1$ strength is based on the observation of concentrated, mostly bound, $J^\pi = 1^-$ states in spherical medium-heavy and heavy neutron-rich nuclei. This so-called pygmy dipole resonance (PDR) [4,5], and low-lying 1^- states in

* Corresponding author.
E-mail address: derya@ikp.uni-koeln.de (V. Derya).
[1] Present address: Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
[2] Present address: Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

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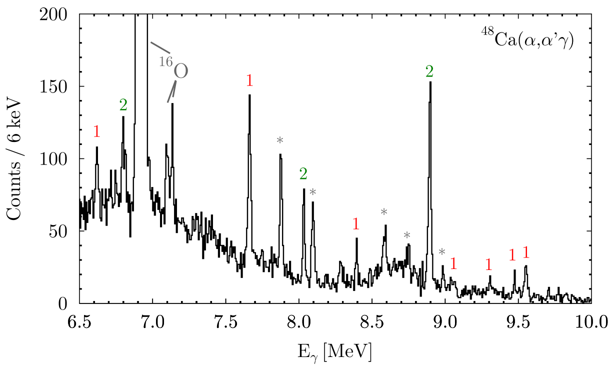

Fig. 1. Summed γ-ray spectrum of the HPGe detectors obtained by gating on de-exciting transitions to the ground state ($E_X \approx E_\gamma$), measured in the ^{48}Ca$(\alpha,\alpha'\gamma)$ experiment. Observed electric transitions in ^{48}Ca are labeled according to their multipolarity. Transitions in ^{40}Ca are marked with stars, and transitions in ^{16}O are labeled.

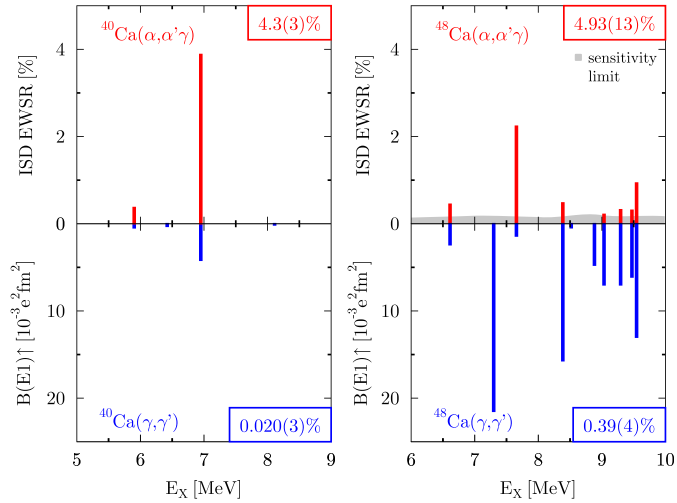

Fig. 2. Low-lying $E1$ strength in ^{40}Ca [39,17] and ^{48}Ca ([17,18] and present work), obtained in an $(\alpha,\alpha'\gamma)$ experiment (upper panel) and a (γ,γ') experiment (lower panel). The grey-shaded area indicates the experimental sensitivity limit for the $(\alpha,\alpha'\gamma)$ experiment on ^{48}Ca. The framed percentages give the summed exhaustion of the respective ISD (upper panel) and IV (lower panel) EWSR.

general, have been investigated in experimental and theoretical studies (see Refs. [6,1,7] and references therein). In addition, the diversity and interplay of different low-lying $E1$ modes, including a significant IS toroidal mode [8], are under recent discussion. A common method for probing dipole strength in stable nuclei below the neutron threshold is real-photon scattering [5,9–11]. Additional experimental techniques applied include, e.g., Coulomb excitation using protons [12] and $(\alpha,\alpha'\gamma)$ coincidence experiments dominated by the strong interaction [13]. Inelastic-scattering experiments in inverse kinematics using radioactive beams, as well as Coulomb dissociation and Coulomb excitation experiments using radioactive beams, can provide insight into dipole strength distributions of very neutron–proton asymmetric nuclei [14–16]. One of the remaining open questions is the systematic evolution and nature of $E1$ excitations for nuclei with different masses and neutron-to-proton ratios. In this regard, Ca isotopes are of particular interest because of their light-to-medium mass and their wide range of N/Z ratios.

Low-lying $E1$ excitations in the calcium chain have been systematically investigated by real-photon scattering experiments [17–20] performed at the Darmstadt High-Intensity Photon Setup [21] at the S-DALINAC. The experiments showed that the exhaustion of the Thomas–Reiche–Kuhn (TRK) energy-weighted sum rule (EWSR) for IV $E1$ transitions [2] up to 10 MeV increases from 0.020(3)% for ^{40}Ca to 0.39(4)% for ^{48}Ca. To complete the N/Z systematics, a measurement was conducted on the nucleus in between, ^{44}Ca, which exhausts 0.39(7)% of the EWSR. Microscopic calculations using the extended theory of finite Fermi systems [22] reproduce the trend of the EWSR evolution of $E1$ strength along the Ca chain [23]. However, during the last years, it became evident that one needs additional experimental probes to understand the structure of the $E1$ strength. In neutron-rich spherical nuclei in the medium-mass region the low-lying $E1$ strength was investigated in systematic studies by means of the (γ,γ') and $(\alpha,\alpha'\gamma)$ reactions [24,13,25–28]. These systematic studies revealed an isospin splitting into lower-energy isospin-mixed $E1$ excitations, usually referred to as the “real” PDR, and higher-energy isovector-dominated $E1$ excitations, which belong to the tail of the IVGDR [29,26].

Driven by these experiments and the previously discussed results of (γ,γ') experiments on the calcium isotopes, the present work employed the $(\alpha,\alpha'\gamma)$ reaction on ^{48}Ca to learn about the nature of its $E1$ excitations, which was also discussed in a recent theoretical work [3]. The α–γ coincidence method, in which inelastically scattered α particles are measured in coincidence with the subsequently emitted γ rays, was used [24]. The α-particle beam at an energy of 136 MeV and an average beam current of 1.0 particle nA was provided by the AGOR cyclotron at the Kernfysisch Versneller Instituut in Groningen, The Netherlands. The scattered α particles were detected by the EUROSUPERNOVA detection system [30] of the QQD-type Big-Bite Spectrometer (BBS) [31] at $\theta_{lab} = 5.8°$. The BBS solid-angle coverage was $\Delta\Omega_\alpha = 9.2$ msr, with a horizontal opening angle of 4°, and the excitation-energy resolution in a singles α-scattering measurement was 236(1) keV at 3831 keV. For γ-ray spectroscopy, an array of six high-purity germanium (HPGe) detectors, each with an opening angle of around 20°, was mounted around the target chamber and achieved an absolute photopeak-efficiency of 0.504(1)% at 1238 keV. The self-supporting Ca target had a thickness of 1.7 mg/cm^2 and was enriched to 99% with ^{48}Ca.

Previous experiments [24,13,25,26,28] demonstrated the advantages of the α–γ coincidence method, which allows us to select γ-ray transitions to the ground state or excited states. In this way an excellent selectivity to $E1$ excitations is achieved, providing a very good peak-to-background ratio in the projected spectra. The α particle in direct reactions at intermediate energies is selective to the excitation of natural parities (i.e., $J^\pi = 1^-, 2^+, \ldots$). The excitation cross section is measured by the singles α-scattering cross section, $d\sigma/d\Omega_\alpha$. It is determined from the summed γ-ray spectrum of all HPGe detectors (see Fig. 1) obtained by gating on equal excitation energy, E_X, and γ-ray energy, E_γ, in the 2-dimensional spectra of excitation energy versus γ-ray energy (not shown). Furthermore, the HPGe-detector array allows us to measure double-differential cross sections, $d^2\sigma/(d\Omega_\alpha\, d\Omega_\gamma)$, which are sensitive to the multipolarity of transitions. Details about the setup and the data analysis can be found in Refs. [24,25,28].

In total seven $J^\pi = 1^-$ states in ^{48}Ca were excited by the α particles within the sensitivity limit, which was determined by integrating the background in the γ-ray spectrum. The excitations were identified via γ decays to the ground state. The states at 9.47 and 9.55 MeV were observed qualitatively in previous inelastic α-scattering experiments [32–34]. The fraction of the exhausted EWSR for isoscalar dipole (ISD) transitions (ISD EWSR) [35] derived from the $(\alpha,\alpha'\gamma)$ experiment is shown in Fig. 2 in comparison to $B(E1)\!\uparrow$ values from a (γ,γ') experiment on ^{48}Ca [17]. The singles α-scattering cross sections were converted into fractions of the ISD EWSR by using the coupled-channels program CHUCK [36] and the