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

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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.

Keywords:
low-lying electric dipole excitations, $^{48}$Ca, isospin character

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 observa-
tion of concentrated, mostly bound, $J^P = 1^-$ states in spherical medium-heavy and heavy neutron-rich nuclei. This so-called pygmy dipole resonance (PDR) \cite{4, 5}, and low-lying $1^-$ states in 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 \cite{8}, are under recent discussion. A common method for probing dipole strength in stable nuclei below the neutron threshold is real-photon scattering \cite{3, 9, 10, 11}. Additional experimental techniques applied include, e.g., Coulomb excitation using protons \cite{12} and $(\alpha, \alpha'\gamma)$ coincidence experiments dominated by the strong interaction \cite{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 \cite{14, 15, 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 \cite{17, 18, 19, 20} performed at the Darmstadt High-Intensity Photon Setup (DHP) \cite{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 \cite{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 \cite{22} reproduce the trend of the EWSR evolution of $E1$ strength along the Ca chain \cite{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 $(\gamma, \gamma')$ and $(\alpha, \alpha'\gamma)$ reactions \cite{24, 13, 25, 26, 27, 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 \cite{29, 26}.

Driven by these experiments and the previously discussed results of $(\gamma, \gamma')$ 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 \cite{3}. The $\alpha-\gamma$ coincidence method, in which inelastically scattered $\alpha$ particles are measured in coincidence with the subsequently emitted $\gamma$ rays, was used \cite{24}. The $\alpha$-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 $\alpha$ particles were detected by the EUROSUPERNOVA detection system \cite{30} of the QD-type Big-Bite Spectrometer (BBS) \cite{31} at $\theta_{lab} = 5.8^\circ$. The BBS solid-angle coverage was $\Delta\Omega_\alpha = 9.2$ msr, with a horizontal opening angle of $4^\circ$, and the excitation-energy resolution in a single $\alpha$-scattering measurement was $236(1)$ keV at 3831 keV. For $\gamma$-ray spectroscopy, an array of six high-purity germanium (HPGe) detectors, each with an opening angle of around $20^\circ$, 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 \cite{24, 13, 25, 26, 28} demonstrated the advantages of the $\alpha-\gamma$ coincidence method, which allows us to select $\gamma$-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 $\alpha$ particle in direct reactions at intermediate energies is selective to the excitation of natural parities (i.e., $J^P = 1^-, 2^+, \ldots$). The excitation cross section is measured by the singles $\alpha$-scattering cross section, $d\sigma/d\Omega_\alpha$. It is determined from the summed $\gamma$-ray spectrum of all HPGe detectors (see Fig. \ref{fig:fig1}) obtained by gating on equal $\gamma$-ray energy, $E_\gamma$, and $\gamma$-ray energy, $E_\gamma$, in the 2-dimensional spectra of excitation energy versus $\gamma$-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. \cite{24, 25, 28}.

In total seven $J^P = 1^-$ states in $^{48}$Ca were excited by the $\alpha$ particles within the sensitivity limit, which was determined by integrating the background in the $\gamma$-ray spectrum. The excitations were identified via $\gamma$ decays to the ground state. The states at 9.47 and 9.55 MeV were observed qualitatively in previous inelastic $\alpha$-scattering experiments \cite{32, 33, 34}. The fraction of the exhausted EWSR for isoscalar dipole (ISD) transitions (ISD EWSR) \cite{35} derived from the $(\alpha, \alpha'\gamma)$ experiment is shown in Fig. \ref{fig:fig2} in comparison to
are marked with stars, and transitions in
The singles
BEL \[37\] (with a global optical potential \[38\] and the
channels program CHUCK \[36\] and the program code
into fractions of the ISD EWSR by using the coupled-
deformation parameter allows calculating the transition
determined singles BBS and compared to the experimentally deter-
with CHUCK was averaged over the opening angle of
ISD (upper panel) and IV (lower panel). The grey-shaded area indicates
γ,γ − state, the di
γ,γ − experiment (lower panel). The grey-shaded area indicates
48 Ca in both, the total E1 strength and its fragment-
ation into mainly seven excitations. More remark-
able and surprising is the difference in the response to the
isovector (γ ray) and isoscalar (α particle) probes: Two excitations show a converse behavior. The $J^* = 1^-$
state at 7.3 MeV, which has the strongest E1 transition probability in the (γ, γ') experiment, was not excited by the
particles within an experimental sensitivity limit for the cross section of 0.15(4) mb/sr. On the contrary, the
state at 7.6 MeV, which provides one of the weak-
est transitions in the (γ, γ') experiment, has the largest
cross section for excitation by α particles amounting to
1.61(9) mb/sr. We analyzed this phenomenon in detail as described below.

The spin of the observed $J = 1$ states was determined in a (γ, γ') experiment \[18\] by means of the angular dis-
btribution of the scattered γ rays. For the states at 8.9 and
9.3 MeV observed in the (γ, γ') experiment, $J = 1$ was assigned as a result of a new reanalysis of the data. This
corrects the total $B(E1)$ strength to $80(8) \times 10^{-3}$e2fm2 compared to the results published in \[18\].

Since the α particle in inelastic scattering is selective to the excitation of natural parities, a possible explana-
tion for the non-excitation of the state at 7.3 MeV could be a positive parity (i.e., $J^* = 1^+$). In order to clarify the
parities, an additional (γ, γ') measurement with linearly polarized photons was performed at the High Intensity
Gamma-ray Source (HIγS) facility \[40\] at the Triangle Universities Nuclear Laboratory in Durham, USA. A
nearly mono-energetic beam bombarded a CaCO3 tar-
get of 1015 mg weight enriched in $^{48}$Ca to 90.04%. The
scattered γ rays were detected by five HPGe detectors. Four detectors were placed perpendicular to the beam
direction, thereof two parallel and two perpendicular to the polarization axis. This setup allows an unam-
biguous, model-independent parity determination \[41\]. Beam energies between 6.6 and 9.51 MeV were used for the investigation of nine dipole excitations in $^{48}$Ca. The experimental asymmetries $\epsilon = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ of the measured photon intensities in the horizontal ($I_\parallel$) and vertical ($I_\perp$) detectors are shown in Fig. 3. Electric character can be certainly assigned to all excited

Two known isoscalar dipole excitations in $^{40}$Ca were studied in a previous ($α, α'γ$) experiment at 120 MeV
by Poelhekken et al. \[39\]. In contrast to the experiment on $^{48}$Ca, the covered range of $α$-scattering angles was between $−3^\circ \leq θ_{lab} \leq 3^\circ$. The total $B(E1)$ strength in $^{40}$Ca is mainly carried by one excitation, which be-
ongs to the state with the largest exhaustion of the ISD EWSR. For $^{40}$Ca the α-scattering cross sections are roughly proportional to the E1 strengths deduced from the (γ, γ') experiment. The situation in $^{48}$Ca differs from
that in $^{40}$Ca in both, the total E1 strength and its fragment-
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$J = 1$ states. We conclude that the absence of the state at 7.3 MeV in the $(\alpha, \alpha'\gamma)$ experiment cannot be explained by its parity.

Close to the $1^-$ state at 7.6 MeV, a $3^-$ state, which can be populated in $\alpha$-scattering experiments, has previously been observed with an estimated strength of $B(3^+) \approx 1.5$ W.u. Therefore, one needs to exclude a contribution of this $3^-$ state to the peak corresponding to the ground-state transition of the $1^-$ state in the $(\alpha, \alpha'\gamma)$ experiment. Ground-state transitions of this $3^-$ state are about 1000 times weaker than ground-state transitions of the $1^-$ state. Double-differential cross sections were determined from the $(\alpha, \alpha'\gamma)$ data and compared to $\alpha-\gamma$ angular distributions calculated from m-state amplitudes that were obtained from DWBA calculations [42] to clarify the origin of the observed ground-state transitions (see Fig. 4). Results for the $2^+$ state at 3.8 MeV and the first $3^-$ state in $^{48}\text{Ca}$ at 4.5 MeV are in clear agreement with the calculated angular correlations for quadrupole and octupole transitions, respectively (see Fig. 4). For the transition at 7.6 MeV, a pure dipole character is favored in a fit using a linear combination of $E1$ and $E3$ transitions (see Fig. 4). Therefore, a strong contribution from the ground-state transition of the $3^-$ state that might affect the observed cross section of the $1^-$ state at 7.6 MeV can be excluded. Hence, the reason for the different excitation behavior of the states at 7.3 and 7.6 MeV must lie in essentially different structures of these states. This is exposed by the different properties of the experimental probes. In addition to the isospin character, the localization and kind of interaction and the (un)selectivity to natural parities, distinguish $\gamma$ rays and $\alpha$ particles. For a complete interpretation, input from theory is needed.

Different theoretical approaches are available that, in conjunction with the experimental results, may help to clarify the nature of the $E1$ excitations in the Ca isotopes [44, 19, 23, 45, 46, 47]. In an early study, Chambers et al. [44] applied density functional theory and predicted a linear dependence of the low-lying $E1$ strength on the excess neutrons in the Ca chain. This behavior was not found experimentally, since the $E1$ strength up to 10 MeV in $^{44}\text{Ca}$ is similar to that in $^{48}\text{Ca}$. Further calculations [23] pointed out that phonon coupling (as well as coupling to the single-particle continuum, pairing, and complex configurations) is required to reproduce the $(\gamma, \gamma')$ data. Recently, the $E1$ response in even Ca isotopes was investigated along with the ISD response on basis of first-order quasiparticle RPA using the Gogny D1S interaction [3]. Over the whole range of neutron numbers ($N = 14 - 40$) different scenarios explain the origin and nature of ISD strength which is present in all Ca isotopes. Proton-skin oscillation, pure IS oscillation, as well as neutron-skin oscillation are the generating mechanisms, where the latter one is predicted for $N \geq 30$. The RPA results in terms of strength distributions are shown in Fig. 5 for both doubly-magic Ca isotopes [3]. Such an energetic discrepancy with data is consistent with other
RPA studies of various nuclei (see, e.g., Ref. [48]) and is expected to be caused by coupling to complex configurations and low-lying phonons, effects which RPA does not take into account. For lighter isotopes up to \(^{40}\)Ca one excitation with a dominantly IS character and almost constant ISD strength is predicted. This state is visible for \(^{40,48}\)Ca in Fig. 5 and can be assigned to the strongly excited state in the \((\alpha,\alpha'\gamma)\) experiments on \(^{40}\)Ca and \(^{48}\)Ca at 6.9 and 7.6 MeV, respectively. The corresponding IS velocity fields (see Fig. 5) show similar flows for both nuclei, while the transition densities and form factors are similar as well [3], with an oscillation of a surface layer against a core and a toroidal surface oscillation. From this comparison of our data with the-
comparison of the results reveals a state-to-state difference in the underlying structure of the $1^-$ states with a dominantly isoscalar excitation at 7.3 MeV, a strong dominantly isovector excitation at 7.6 MeV and excitations with isospin-mixed character showing similar patterns in the $(\gamma, \gamma')$ and $(\alpha, \alpha')$ experiments. This behavior is qualitatively reproduced by RPA calculations which are presented in a direct comparison. In particular, our data show the presence of a strong IS dipole state in $^{48}$Ca contributing very little $E1$ strength and reminiscent of the IS state of $^{40}$Ca. We conclude from these experimental and theoretical results in the heaviest stable isotope, $^{48}$Ca, that diverse underlying structures contribute to the total $E1$ strength with neighboring states showing different structures with abrupt changes in their isospin character. Thus, the dipole response of $^{48}$Ca does not show an isospin splitting as observed in heavier neutron-rich nuclei $^{19}F$, $^{27}$Al, $^{39}$K, $^{43}$Ca, $^{46}$Ti, $^{48}$Ca in the energy range of the PDR could be determined for the first time.

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