Measurement of the Dipole and Electric Quadrupole Strength Distributions up to 10 MeV in the Doubly Magic Nuclei ^{40}Ca and ^{48}Ca

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The doubly magic nuclei ^{40}Ca and ^{48}Ca have been studied in high resolution photon scattering experiments. We have derived absolute dipole and quadrupole excitation strengths up to 10 MeV. Evidence was found for a two-phonon quadrupole-octupole state in ^{48}Ca. At higher energies in contrast to ^{40}Ca, a concentration of dipole strength is observed in ^{48}Ca which is discussed in terms of a pygmy resonance originating from the large neutron excess.

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One major challenge of nuclear physics is to investigate and understand the influence of the ratio of the number of protons Z and neutrons N on the structure of atomic nuclei. Whereas the various models of the nucleus give very similar predictions for most fundamental properties of nuclei around the valley of stability, they disagree considerably for more exotic nuclei.

Radioactive beam facilities are designed to study the properties of nuclei with extreme N/Z ratios. However, experimental results on these nuclei are usually limited by very low beam currents and sometimes complicated reaction kinematics. Another approach to learn more about the influence of isospin on nuclear structure is to study the systematic behavior of certain fundamental excitation modes in stable nuclei with the variation of N/Z in great detail.

One prediction of several models is the existence of a low-lying electric dipole resonance in nuclei with moderate neutron excess [1–4]. In a classical picture the excess neutrons form a skin around the proton/neutron core with $N = Z$. An oscillation of the skin vs the core would lead to an electric dipole excitation mode. Because this mode bears resemblance to a "mini" giant dipole resonance it is often called pygmy dipole resonance (PDR). In very light unstable nuclei with extreme neutron excess where the neutrons form a halo at great distance to the core, a similar mode with $B(E1)$ values in the order of one Weisskopf unit has been observed at energies of a few hundred keV [5,6]. The PDR caused by the thin neutron skin in stable nuclei with moderate neutron excess is predicted to be at energies between 6 and 10 MeV with a $B(E1)$ strength in the order of 1% of the energy-weighted sum rule (EWSR), strongly depending on the N/Z ratio [1,2]. Some evidence for unbound states above the neutron threshold representing such a mode has been found in lighter nuclei; see, e.g., Ref. [7]. In addition various experiments have detected a concentration of $E1$ strength below the threshold [8–14]. However, a systematic study on the variation of the mode with the N/Z ratio is still missing. In contrast to the PDR, observables of excitation modes without a strong connection to the N/Z ratio [e.g., isoscalar $B(E2)$ strengths] are expected to vary only weakly within an isotopic chain.

The Ca isotopic chain is very well suited to study the influence of isospin on nuclear structure: One finds five stable even-even isotopes with N/Z ratios from 1.0 (^{40}Ca) to 1.4 (^{48}Ca). In ^{40}Ca the proton and neutron sd shells are completely filled. Following the isotopic chain, the neutron $f_{7/2}$ shell is successively filled up to ^{48}Ca. Because of this relatively simple microscopic structure, model calculations are supposed to be very complete and a state to state comparison with experiment should be feasible. By measuring root-mean-square radii in proton scattering experiments it has been shown that indeed a neutron skin builds up in the heavier Ca isotopes [15].

Photon scattering or nuclear resonance fluorescence is an ideal tool to investigate dipole and quadrupole strength distributions of stable nuclei in great detail [16]. Photons from a continuous bremsstrahlung source populate dipole and quadrupole modes in the target nuclei; the γ decays of these excitations are observed with high resolution semiconductor detectors. The method is strength selective; i.e., all excitations above a certain sensitivity threshold are observed. Energies can be measured with very high precision and the spins of the populated states are derived from angular correlation measurements. Because of the well known electromagnetic excitation mechanism, the natural width of the states can be determined model independently from the measured spectra. From the width, reduced absolute transition strengths or lifetimes can be calculated.

We have performed photon scattering experiments on ^{40}Ca and ^{48}Ca at the new real photon setup [17] at the superconducting Darmstadt electron accelerator S-DALINAC. This setup allows one to perform very sensitive (γ, γ') experiments up to an excitation energy of 10.5 MeV without γ background induced by neutrons. The electron beam with an average current of 35 μA was stopped in a massive Cu-radiator target and converted into a continuous bremsstrahlung spectrum. The ^{48}Ca target consisted of 4.4 g CaO, enriched to 82.7% in ^{48}Ca; the ^{40}Ca target consisted of 4.7 g natural CaO with 96.9% ^{40}Ca. Both target pills were pressed to identical

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geometry to enable a simple direct comparison of the measured spectra. Scattered photons were measured with two Ge(HP) detectors with an efficiency of 100% relative to a $3'' \times 3''$ standard NaI detector. The detectors were positioned at 90° and 130° with respect to the incoming photon beam. The detector positioned at 90° was shielded with a bismuth germanate (BGO) scintillator anti-Compton device. We investigated the ^{48}Ca target at three different electron energies of 5.5, 8.0, and 9.9 MeV. This enables one to distinguish between feeding from higher-lying states and direct population from the ground state of the nucleus. The isotope ^{40}Ca was measured at an electron energy of 9.9 MeV only. For some states below 7 MeV where feeding could not be excluded, we therefore adopt the $B(E1)$ or $B(E2)$ values measured in an earlier $^{40}\mathrm{Ca}(\gamma,\gamma')$ experiment by Moreh *et al.* [18].

Figure 1 shows a (γ,γ') spectrum on ^{48}Ca between 6.4 and 9.9 MeV recorded at 90° relative to the incoming photon beam. No background has been subtracted; the very low continuous background is mainly due to nonresonant photon scattering at the target material and Compton scattering in the detector. From the peak areas the transition widths or lifetimes and the reduced transition strengths can be derived directly. This is possible due to the absolute normalization of the photon flux by measuring well known excitations in ^{11}B simultaneously. No parities could be measured. However, it is very likely that most observed $J = 1$ states in this energy region with large ground state transition width in the doubly magic nuclei ^{40,48}Ca have negative parity. This assumption is validated for all cases where parity information is available by comparison with electron scattering under backward angles where all magnetic strength would have been detected [19]. All $J = 2$ states populated in (γ,γ') from the ground state with considerable transition width have positive parity. The experimental results on the $E1$ and $E2$ strength distribution are summarized in Figs. 2 and 3, respectively. The details of the experiment and the data evaluation are discussed in Ref. [20].

A systematic study of semimagic nuclei with mass $A \simeq 50-208$ shows a characteristic bound $E1$ excitation close to the sum energy of the first 2^+ and 3^- states [16,21]. This excitation can be described as a two-phonon mode where the quadrupole vibration couples to the octupole vibration of the nuclear surface. This coupling creates a multiplet of five negative parity states with $J^\pi = 1^- - 5^-$ and a relatively large dynamic electric dipole moment. The two-phonon structure has recently been proven by experiments looking for the two-phonon to one-phonon decay pattern [22]. In ^{40}Ca, an $E1$ excitation is observed at 6950 keV with $B(E1, 0^+ \rightarrow 1^-) = (4.5 \pm 0.7) \times 10^{-3}\ e^2\,\mathrm{fm}^2$. The energy is about 9% below the sum of the energies of the 2_1^+ and 3_1^- state. This state has been observed before in a (γ,γ') experiment by Moreh *et al.* [18]. In ^{48}Ca we could for the first time identify a candidate for the two-phonon 1^- state at 7298 keV with $B(E1, 0^+ \rightarrow 1^-) = (18.6 \pm 1.8) \times 10^{-3}\ e^2\,\mathrm{fm}^2$. The energetic position is about 13% below the single phonon sum energy.

The upper part of Fig. 4 shows the high degree of harmonicity observed for the coupling of the two phonons: The energy ratio $E(1^-)/[E(2^+) + E(3^-)]$ is always very

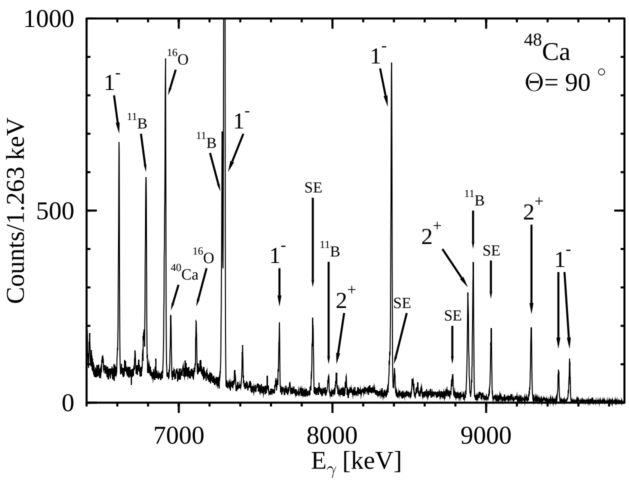

FIG. 1. Photon scattering spectrum of ^{48}Ca in the energy range from 6.4 to 10 MeV. Marked are ground state transition in ^{48}Ca, single (SE) and double (DE) escape lines, and lines from the flux standards ^{16}O and ^{11}B.

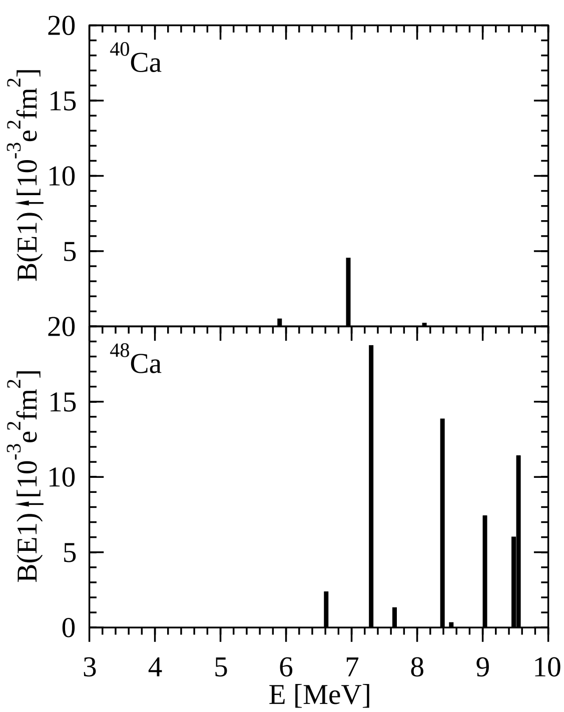

FIG. 2. Comparison of the $B(E1)\uparrow$ strength distributions in ^{40}Ca and ^{48}Ca. The $B(E1)$ excitation strengths have been derived under the assumption of negative parity for the observed dipole transitions (see text).

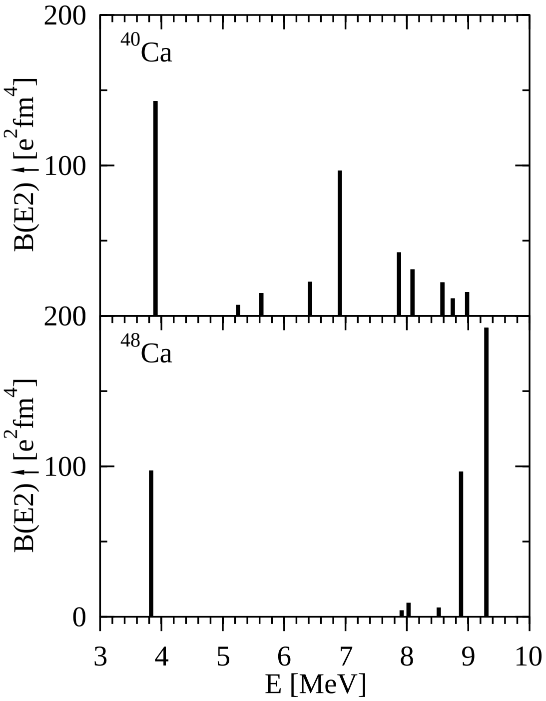

FIG. 3. Comparison of the $B(E2)\uparrow$ strength distributions in ^{40}Ca and ^{48}Ca.

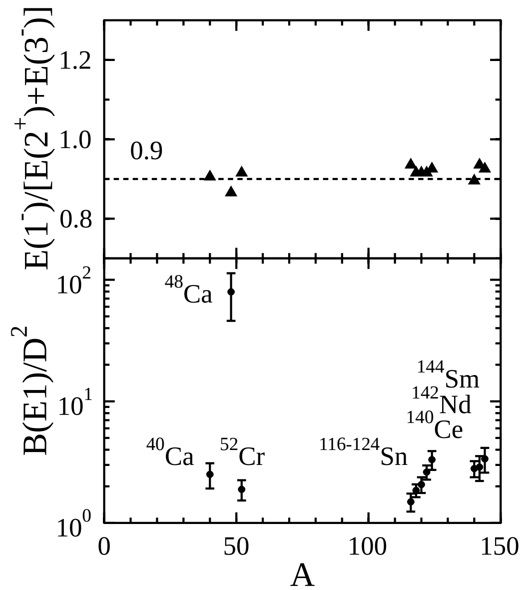

FIG. 4. Ratio of the energy of the 1^- state and the sum of the energies of the 2_1^+ and 3_1^- states for nuclei at shell closures (upper part). Ratio of the measured $B(E1)$ strengths to the two-phonon 1^- state and the square of the dynamic dipole moment D (lower part).

close to 1.0 for all identified two-phonon states in the mass range $A = 52$ to 208 [22]. The two new additional data points for ^{40,48}Ca fit nicely into the systematics. This leads to the unexpected conclusion that a highly harmonic two-phonon structure is still present in relatively light nuclei where the constituent phonons are less collective. From the simple harmonic phonon coupling picture one expects in addition that the $B(E1)$ strength (which is proportional to the square of the dynamic electric dipole moment D) should approximately scale with the square of the product of the dynamic quadrupole and octupole deformation of the nucleus, i.e., with the product of the $B(E2)$ and $B(E3)$ transition strengths to the single phonons [23]. This rule has been shown to be valid only for semimagic nuclei. The lower part of Fig. 4 gives the ratio of the $B(E1)$ strength to the state identified as the two-phonon excitation and the square of the dynamic dipole moment D. The ratio is nearly constant for most of the examined semimagic nuclei. Only the value for the two-phonon strength in ^{48}Ca sticks out dramatically, pointing to an admixture of another strong $E1$ excitation at similar energy.

Figure 2 shows that no other strong $E1$ excitation has been observed up to about 10 MeV in ^{40}Ca. The situation is completely different for ^{48}Ca: A number of $E1$ excitations with considerable $B(E1)$ strengths have been measured in our experiment. Please note that this is not due to an increased admixture of the giant dipole resonance (GDR): In ^{40}Ca as well as in ^{48}Ca the GDR lies around 19 MeV, and one would expect similar admixtures in both isotopes. In addition a realistic extrapolation of the GDR strength cannot account for the bound $E1$ strength observed in ^{48}Ca. The difference in neutron binding energies in ^{40}Ca and ^{48}Ca should not affect the (γ, γ') cross sections below the threshold.

The upper part of Table I lists the summed experimental $B(E1)$ values between 5 and 10 MeV in e^2 fm^2 and in Weisskopf units (W.u.), the energy-weighted experimental sum $\sum E_x B(E1)\uparrow$ (where E_x denotes the excitation energy), and the percentage of this value of the energy-weighted sum rule EWSR.

In our photon scattering experiment we measured in addition the complete quadrupole strength distributions in ^{40,48}Ca. The results are shown in Fig. 3 and the summed strengths are given in the lower part of Table I. We note that our results for ^{40}Ca are in excellent agreement with an earlier work by Moreh *et al.* [18]. Although the difference in the summed $B(E2)$ strengths for ^{40}Ca and ^{48}Ca are rather small as expected, it may be a challenge for model calculations to reproduce the different strength distributions, e.g., the shift of the $E2$ strength to higher energies in ^{48}Ca.

The following main conclusions can be drawn from Table I: (i) The summed $B(E1)$ strength between 5 and 10 MeV in ^{48}Ca is about 10 times larger than in ^{40}Ca. (ii) The $E1$ strength in ^{48}Ca exhausts about 0.3% of the energy-weighted sum rule. (iii) The summed $B(E2)$ strengths are very similar in both isotopes. These observations are in full agreement with the assumption that in ^{48}Ca an $E1$ pygmy dipole resonance caused by the neutron excess can be observed. This résumé is in sharp contrast to a recent work by Ottini-Hustache *et al.* [24] who did not observe any difference in the dipole response

TABLE I. Summed electric dipole and quadrupole strengths in ^{40}Ca and ^{48}Ca between 5 and 10 MeV.

	^{48}Ca	^{40}Ca
$\sum B(E1)\uparrow [10^{-3}\ e^2\,\text{fm}^2]$	61.5 ± 7.8	5.3 ± 0.9
$\sum B(E1)\uparrow [\text{mW.u.}]$	78.4 ± 9.9	7.6 ± 1.2
$\sum E\,B(E1)\uparrow [\text{keV}\ e^2\,\text{fm}^2]$	512 ± 67	36 ± 6
$\sum E\,B(E1)\uparrow [\%\text{EWSR}]$	0.29 ± 0.04	0.025 ± 0.004
$\sum B(E2)\uparrow [e^2\,\text{fm}^4]$	302 ± 42	263 ± 46
$\sum B(E2)\uparrow [\text{W.u.}]$	29.1 ± 4.1	32.4 ± 5.6

of ^{40}Ca and ^{48}Ca in a heavy ion scattering experiment. In addition, their energy weighted $E1$ sum strength between 6 and 10 MeV exhausts more than 6% of the EWSR which is a factor of 20 higher than our value measured for ^{48}Ca.

A simple hydrodynamic model [1,2] predicts for the PDR a strength of about 2.7% of the EWSR at 3.4 MeV for a system with two excess neutrons relative to a ^{46}Ca core. A more realistic microscopic approach by Chambers *et al.* with the density functional theory predicts a collective electric dipole mode in Ca isotopes caused by the oscillation of the neutron excess against a ^{40}Ca core [3]. The strength increases linearly with neutron excess whereas the mean energy decreases. For ^{48}Ca the PDR is predicted around 7.6 MeV and should exhaust about 1.6% of the EWSR. Both models predict no PDR strength for the $N = Z$ core ^{40}Ca. We hope that our new detailed data will help to improve the model calculations and predictions.

In conclusion, we have identified a two-phonon $2^+ \otimes 3^-$ coupling leading to a 1^- state in the medium mass nuclei ^{40}Ca and ^{48}Ca. At energies around 6–10 MeV possible evidence for a bound $E1$ excitation caused by a neutron excess has been found from the comparison of ^{40}Ca and ^{48}Ca. Our detailed data will enable refined theoretical calculations. A systematic study on the remaining isotopes of the Ca chain is planned to investigate further the influence of a neutron excess on the structure of atomic nuclei.

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