Microscopic Nature of the Pygmy Dipole Resonance: The Stable Ca Isotopes

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The electric dipole strength distribution in ^{44}Ca has been measured up to 10 MeV in high resolution photon scattering experiments for the first time. The data obtained have been compared to earlier measurements on ^{40,48}Ca in order to view the evolution of the electric pygmy dipole resonance (PDR). Calculations that were performed within the framework of the microscopic extended theory of finite Fermi systems, which adds contributions of the quasiparticle-phonon coupling to random phase approximation calculations, give a qualitative agreement with the experimental data for all three isotopes. We have shown that it is necessary to include this coupling to describe the PDR.

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During the last decade much interest has been focused on the experimental investigation of electric dipole strength below the particle threshold; see, e.g., Refs. [1,2]. Frequent discussion of the possible existence of the so-called pygmy dipole resonance (PDR), a collective excitation mode generated in neutron rich nuclei, directed experimental research towards systematic investigations of nuclei with a varying N/Z ratio. In a macroscopic picture this resonance is described as an out-of-phase oscillation of a neutron skin against an inert core. Therefore, properties such as integrated strength and mean excitation energy of the PDR should strongly depend on the N/Z ratio. Such a mode becomes especially pronounced in exotic nuclei with extreme neutron excess where it is sometimes denoted as the soft dipole mode [3,4]. In addition, $E1$ excitation modes around the particle thresholds are interesting for nuclear astrophysics because they can have important implications for the synthesis of certain nuclei in explosive stellar events [5].

Until now, a comprehensive and detailed survey existed only for the lowest lying 1^- states in nuclei which are interpreted as members of a two phonon $|2_1^+ \otimes 3_1^-\rangle$ multiplet in spherical nuclei, and as the bandheads of the $K^\pi = 0^-$ and 1^- octupole vibrational bands in deformed nuclei [6]. Improvements in experimental techniques have enabled high precision studies of higher energy $E1$, $M1$, and $E2$ transitions to the ground state with nuclear resonance fluorescence (NRF). In heavy systems the $E1$ distribution up to the threshold has been studied recently in ^{116,124}Sn [7], in $N = 82$ isotones [2], and in ^{208}Pb [8]. In the medium mass region, NRF experiments on the two doubly magic nuclei ^{40,48}Ca showed a huge difference in their summed $E1$ strengths [9,10]. To investigate the systematic evolution, we performed a NRF experiment on ^{44}Ca with the same experimental conditions that were used for ^{40,48}Ca.

The importance of ^{44}Ca is, in particular, that it has a well developed pairing in contrast to ^{42}Ca and ^{46}Ca. Thus the comparison with ^{40}Ca and ^{48}Ca, where pairing is absent, will help to get a deeper insight into the role of pairing in an energy region between the lowest excitations and the giant resonances.

Although some attempts to describe the low-lying $E1$ strength in the Ca isotopes have been made, no quantitative explanations for the experimental results have been presented thus far; see, e.g., Refs. [11,12]. Macroscopic models, which, by definition, have one or more parameters for each nucleus, are not able to give an explanation of such delicate data, especially when extrapolating to unstable nuclei where data to fit the model parameters do not even exist. It is necessary to use a microscopic description with a universal interaction (to have predictive power for nuclei far off stability) and to take into account the single-particle continuum (to describe light and medium weight nuclei, where the role of the continuum is very important). Such calculations on the level of the continuum random phase approximation (CRPA) for the PDR in ^{40}Ca and ^{48}Ca have been performed in [13]. The authors used the self-consistent density functional method and obtained linear dependencies of the centroid energy and the integrated strength on the neutron excess.

While the contribution of the PDR to the Thomas-Reiche-Kuhn sum rule is roughly of the order of 1%, any noticeable redistribution of the $E1$ strength may change even the integral PDR characteristics, not to mention the structure of the separate 1^- levels. This is the case, for example, if one includes more complex configurations than those accounted for in the RPA (magic nuclei) or in the quasiparticle RPA (QRPA) (nonmagic nuclei). Some hints of the necessity of going beyond the (Q)RPA were confirmed in the large-scale QRPA calculations of the $E1$ strength by Goriely and Khan [14] where these calculations have been performed for all $8 \leq Z \leq 110$ nuclei between the proton and the neutron drip lines with the use of the SLy4 Skyrme force. The authors concluded that their calculated low-lying strength is located systematically some 3 MeV higher than observed. In their opinion an improvement of the QRPA model based on the quasiparticle-phonon coupling could shift the PDR peak energy to lower values. In [8] this coupling has been taken into account in the quasiparticle-phonon model for the heavy doubly magic nucleus ^{208}Pb.

In this Letter, we present the first NRF results for the $B(E1)$ strength in ^{44}Ca and results of microscopic calculations for the isotopes ^{40,44,48}Ca performed with an approach that includes all known sources of resonance widths in a finite nucleus: decay via $1p1h$ configurations of a discrete spectrum (Landau damping), decay via $1p1h$ configurations with a particle in the continuum (escape width), and a decay via more complex configurations of the two quasiparticle-phonon type (spreading width). We show that the correlation between the features of the PDR and the neutron excess of a nucleus is nontrivial and that it is necessary to go beyond (Q)RPA to explain the properties of the PDR. This fact will become especially important for the predictions for exotic nuclei.

The ^{44}Ca(γ, γ') experiment was performed at the NRF setup at the Darmstadt superconducting electron linear accelerator S-DALINAC. Details of the experimental setup and the data analysis are described in [1,10,15], respectively. Because of both its spin selectivity and the well known reaction mechanism, this method is very well suited to extract half lives, spins, and $B(E1)$ strengths of excitations below the particle threshold in stable nuclei independent of any model assumptions. Using high purity germanium detectors ensures a very good energy resolution. A (γ, γ') spectrum of the measurement with 9.9 MeV end point energy is shown in Fig. 1. One can see a concentration of lines corresponding to ground state transitions in the energy region between 6 and 8 MeV. From angular correlation measurements the radiation of all of the transitions could be identified as having $\Delta J = 1$ character, leading to $J = 1$ assignments for the depopulated states. Electron scattering experiments did not detect any magnetic strength with $B(M1) > 0.15\mu_N^2$ [which corresponds to $B(E1) > 1.7 \times 10^{-3} e^2 fm^2$] between 8 and 12 MeV [16]. The expected energy for the isovector $M1$ resonance is 13.7 MeV (based on the isobaric analog state in ^{44}K), i.e., far above the energy region of the PDR. Orbital $M1$ strength at lower energies is not expected due to the absence of deformation. We assume therefore that all observed $J = 1$ levels have negative parity. The energies and $B(E1)$ strengths of these states have been extracted. The exhaustion of the isovector $E1$-EWSR (energy-weight sum rule) is calculated to 0.39(7)%, which is about 20% higher than for the nucleus ^{48}Ca with 0.33(4)%. The $B(E1)$-strength distribution in ^{44}Ca and the results from the previously measured nuclei ^{40}Ca and ^{48}Ca are shown in the upper part of Fig. 2. The nuclear structure calculations of the properties of low-lying 1^- states in all three Ca isotopes have been performed with the microscopic extended theory of finite Fermi systems (ETFFS). For nuclei without pairing, this approach has been applied successfully for the last ten years to describe characteristics of giant resonances, including their widths and gross structures. The details and some results of the ETFFS are given in [17,18]. As far as nonmagic nuclei are concerned, the ETTFS with pairing has only recently been developed [19,20], so we are presenting an application of the ETFFS for nuclei with pairing (i.e., for ^{44}Ca) for the first time. Our ETFFS approach takes into account all three mechanisms that are necessary for a quantitative description of the giant resonance damping, namely, the RPA or QRPA configurations, more complex $1p1h \otimes$ phonon or $2qp \otimes$ phonon configurations, and the single-particle continuum. This approach is based on a consistent use of the Green function technique and is a generalization of the standard theory of finite fermi systems by Migdal [21], which has been modified to take into account complex configurations with phonons in addition to the above-mentioned (Q)RPA configurations. For technical reasons (see [20]) we are at present unable to account for the ground state correlations beyond the (Q)RPA [17,19].

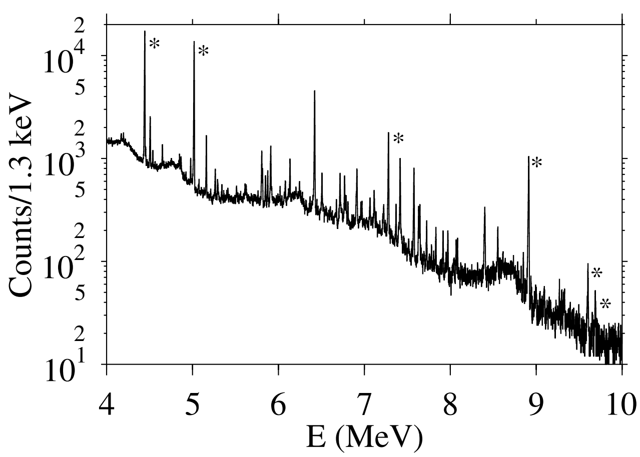

FIG. 1. NRF spectrum of ^{44}Ca taken at an end point energy of 9.9 MeV at a scattering angle of 130°. Lines marked with an asterisk stem from the calibration standard ^{11}B and from background lines.

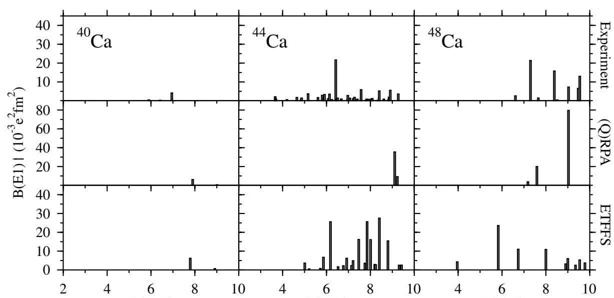

FIG. 2. Comparison of the experimental $B(E1)$-strength distribution in ^{40}Ca, ^{44}Ca, and ^{48}Ca (upper panel) with calculations in the (Q)RPA (middle panel) and ETFFS (lower panel). The neutron (proton) separation energies for ^{40}Ca, ^{44}Ca, and ^{48}Ca are 15.6 (8.3), 11.1 (12.2), and 9.9 (15.8) MeV, respectively.

The general scheme of our calculations for magic and nonmagic nuclei is the same as in the previous ETFFS calculations for ^{40}Ca to ^{208}Pb [17,18,22]. We have solved the basic integral equation for the change of the density matrix in an external field in the coordinate space. Using this representation allows us to take the single-particle continuum into account within the Green function formalism. The same set of values for the parameters of the nonseparable universal Landau-Migdal forces has been used [18]. The same numbers of low-lying collective phonons in ^{40}Ca (3_1^- and 5_1^-) and in ^{48}Ca (2_1^+, 3_1^+, and 5_1^-) were used in the complex configurations considered. In order to have the same calculational scheme, we used the same phonon modes for ^{44}Ca that we used for ^{48}Ca (calculated for ^{44}Ca, of course).

However, in order to check the sensitivity of the results to the numbers of phonons, we repeated the calculations for ^{44}Ca with nine low-lying phonons. No essential difference between these two variants was obtained. Even the structure does not change noticeably; only the strong peak at about 6.2 MeV is shifted to a higher energy. With the present calculations we have also obtained a reasonable description of the giant dipole resonance in all the nuclei considered, including their mean energies, exhaustion of the EWSR, and their widths.

In order to understand the microscopic nature of the PDR, it is necessary to perform calculations with a simpler model without a complex configuration, like the continuum (Q)RPA [C(Q)RPA] that is contained in our ETFFS. It is especially important, of course, to compare the results with and without complex configurations in the same calculational scheme. The calculations in both approaches for the three nuclei ^{40,44,48}Ca are compared to the experimental results in Table I and Figs. 2 and 3. For ^{48}Ca we obtained an improvement of the description of the summed strength when we included complex configurations, while for ^{44}Ca we did not obtain a better agreement within the approximation used; see Ref. [20]. However, the ETFFS yields the same trend as the experimental findings: the summed strength in ^{44}Ca is larger than in ^{48}Ca; in other words, there is no linear dependence of the summed $B(E1)$ strength on the neutron excess. Such a linear prediction for the dependence that corresponds to the results of Chambers *et al.* [13] is achieved with our C(Q)RPA approach. For ^{48}Ca and ^{44}Ca, we obtained a structure caused only by complex configurations. The rich structure seen in ^{44}Ca is not reproduced in the QRPA calculations (see Fig. 2). Thus, we can conclude that this approach is not capable of describing even the summed strength in the calcium isotopes, not to mention the structure. The mean energies of the PDR, given by $\overline{E} = \Sigma E_i B_i(E1)\uparrow / \Sigma B_i(E1)\uparrow$, decrease when the quasiparticle-phonon coupling is included. For ^{44}Ca, it is especially important to take the quasiparticle-phonon coupling into account, and it improves the description of the experiment considerably. Because we are limited to a maximum energy of 10 MeV with our setup, no information about $E1$ strength in the region between 10 and 13 MeV is available.

In conclusion, the dipole strength distribution below 10 MeV has been measured for the nucleus ^{44}Ca for the first time. Compared with the results for ^{48}Ca, the value of the measured exhaustion of the EWSR is about 20% larger, which contradicts a linear dependence between neutron excess and the strength of the pygmy dipole resonance. Microscopic calculations with quasiparticle-phonon coupling for the summed $E1$ strengths reproduce the observed trend, although the theoretical value of the summed strength in ^{44}Ca exceeds the experimental one by a factor of 2 (which may be connected with the approximations used). Because of the quasiparticle-phonon coupling and pairing, the summed $E1$ strength in ^{44}Ca below 10 MeV exceeds that of ^{40}Ca and ^{48}Ca, and is much more fragmented than in the (Q)RPA. In order to

TABLE I. Comparison of the experimental data with C(Q)RPA and ETFFS calculations for the three isotopes ^{40,44,48}Ca below 10 MeV. Summed strengths, energy weighted strengths, and mean energies are given.

		^{40}Ca	^{44}Ca	^{48}Ca
	Exp.	5.1(8)	92.2(156)	68.7(75)
$\sum B(E1)\uparrow/10^{-3}e^2\ \mathrm{fm}^2$	ETFFS	7	170	71
	C(Q)RPA	7	45	103
	Exp.	35(5)	629(107)	570(62)
$\sum E\cdot B(E1)\uparrow/\ \mathrm{keV}\cdot e^2\ \mathrm{fm}^2$	ETFFS	55	1284	509
	C(Q)RPA	55	409	898
	Exp.	0.020(3)	0.39(7)	0.33(4)
$\sum E\cdot B(E1)\uparrow/\%$EWSR	ETFFS	0.032	0.744	0.295
	C(Q)RPA	0.032	0.237	0.520
	Exp.	6.8	7.1	8.4
$\overline{E}$/MeV	ETFFS	7.9	7.6	7.2
	C(Q)RPA	8.0	9.1	8.7

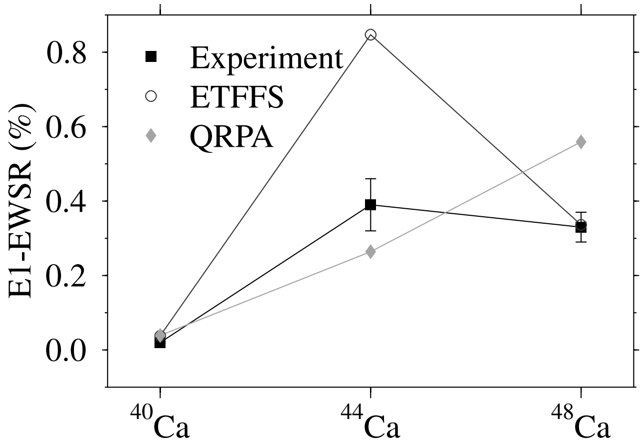

FIG. 3. Exhaustion of the isovector $E1$-EWSR. Experimental data points (squares) are compared to calculations in the C(Q)RPA (circles) and ETFFS (diamonds). The experimental errors are based on a linear addition of errors from each state, because the strength calculation uses the same photon flux calibration; i.e., the errors are not independent. The lines are drawn to guide the eye. One can see that the C(Q)RPA calculations give an approximately linear dependence on the neutron number, while those in the ETFFS scheme lead to an enhancement of the summed strength for ^{44}Ca in comparison to ^{48}Ca.

explain the properties of the PDR, one must consider the phonon coupling in addition to the (Q)RPA approach. This is the first quantitative confirmation of this fundamental fact noted by Goriely and Khan [14]. For exotic nuclei this approach will be useful also because it takes into account simultaneously the single-particle continuum, pairing, complex configurations, and more or less universal interaction parameters.

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