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MICROSCOPIC DESCRIPTION OF THE PYGMY DIPOLE RESONANCE IN NEUTRON-RICH NUCLEI

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Abstract

We study the effects of the phonon-phonon coupling on the low-energy electric dipole response in a microscopic model based on an effective Skyrme interaction. The finite rank separable approach for the quasiparticle random phase approximation is used. Choosing as an example the calcium isotopic chain, we demonstrate the ability of the method to describe the properties of the low-energy $E1$ strength distribution. Using the same set of parameters we describe available experimental data for ^{40,44,48}Ca and we give predictions for $^{50-58}$Ca.

keywords: QRPA, Energy density functional, Pygmy resonance

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1 Introduction

The structure of exotic neutron-rich nuclei is one of the main scientific drivers in contemporary nuclear physics research. In addition, much attention has been devoted to the effects of varying the ratio N/Z of neutron-to-proton numbers on different nuclear structure characteristics. One of the phenomena associated with the change in N/Z ratios is the evolution of the pygmy dipole resonance (PDR). The PDR leads to the enhancement of dipole strength below the region of the usual giant dipole resonance (GDR). The structure and dynamics of the PDR is one of the actively studied topics in nuclear physics [1, 2].

The study of new exotic nuclei (or/and modes of excitation) stimulates the development of nuclear models to describe properties of nuclei away from the stability lines. The quasiparticle random phase approximation (QRPA) with a self-consistent mean-field derived from Skyrme energy density functionals (EDF) is one of the most successful methods for studying the low-energy dipole strength, see e.g. Ref. [2]. A description of the properties of the low-energy $E1$ strength distribution requires the including of the coupling between one-phonon and more complex states [3, 4]. The complexity of calculations taking into account the phonon-phonon coupling (PPC) increases rapidly with the size of the configuration space. Using a finite-rank separable approximation (FRSA) [5, 6, 7, 8] for residual interactions of the Skyrme type one can overcome this difficulty. The so-called FRSA was thus used to study the electric low-energy excitations and giant resonances within and beyond the QRPA [7, 8, 9]. In particular, we applied the FRSA approach to the PDR strength distribution [10, 11, 12]. The nuclei near the neutron magic number N=28 are quite suitable for studying the dependence of the PDR on neutron excess. In the present report we analyze the PPC effects on the $E1$ response for $^{40-58}$Ca, focusing on the emergence and the properties of the PDR. There are reliable experimental data for the properties of the PDR in ^{40,44,48}Ca isotopes [13]. Thus, the isotopes in the Ca chain are ideal candidates for such a study of the PDR evolution.

2 Brief outline of the method

The FRSA approach has been discussed in detail in Refs. [5, 8, 12] and it is presented here briefly for completeness. The SLy5 [14] and SLy5+T [15] EDF are used for the Hartree–Fock-BCS (HF-BCS) calculations as well as for the particle-hole (p-h) channel. The parameters of the force SLy5 have been adjusted to reproduce nuclear matter properties, as well as nuclear charge radii, binding energies of doubly magic nuclei. The force SLy5+T involves tensor terms added without refitting the parameters of the central interaction (the tensor interaction parameters are $\alpha_T = -170$ MeVfm^5 and $\beta_T = 100$ MeVfm^5). These parametrizations describe correctly the binding energies of even-even Ca isotopes. This is illustrated in Fig. 1, where the calculated binding energies for $^{40-60}$Ca and the experimental and extrap-

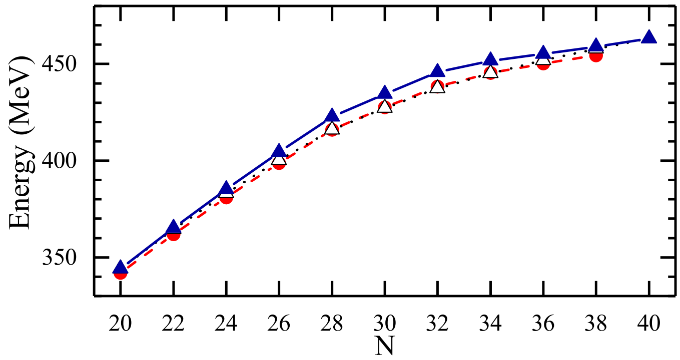

Figure 1: Binding energies of the even-even Ca isotopes as a function of neutron number, compared with experiment and extrapolated energies (filled circles) from the AME2016 atomic mass evaluation [16]. Results of the calculations within the HF-BCS with the SLy5 EDF (open triangles) and with SLy5+T (filled triangles).

olated data [16] are shown. The agreement between the HF-BCS results and data is reasonable, the deviations being less than 2%.

For the interaction in the p-p channel, we use a zero-range volume force. The pairing strength is taken equal to -270 MeVfm^3. This value of the pairing strength is fitted to reproduce the experimental neutron pairing energies of ^{50,52,54}Ca obtained from binding energies of neighboring isotopes. This choice of the pairing interaction has also been used for a satisfactory description of the experimental data of ^{70,72,74,76}Ni [17], ^{90,92}Zr and ^{92,94}Mo [9]. Thus, hereafter we use the Skyrme interaction SLy5 with and without tensor components in the particle-hole channel together with the volume zero-range force acting in the particle-particle channel.

The residual interaction in the p-h channel $V_{\rm res}^{\rm p-h}$ and in the p-p channel $V_{\rm res}^{\rm p-p}$ can be obtained as the second derivative of the energy density functional with respect to the particle density and the pair density, accordingly. Following Ref. [5] we simplify $V_{\rm res}^{\rm p-h}$ by approximating it by its Landau-Migdal form. Moreover, we neglect the l=1 Landau parameters (in the case of the Skyrme EDFs, the Landau parameters with l>1 are equal to zero). The Landau parameters F_0, G_0, F_0', G_0' expressed in terms of the Skyrme force parameters depend on the Fermi momentum $k_{\rm F}$ of nuclear matter [18]. In this work we study only normal parity states and one can neglect the spin-spin terms since they play a minor role [6]. The two-body Coulomb and spin-orbit residual interactions are also dropped.

We take into account the coupling between the one- and two-phonon components in the wave functions of excited states. Thus, in the simplest case one can write the wave functions of excited states as

$$\Psi_\nu(\lambda\mu)=\left(\sum_i R_i(\lambda\nu)Q^+_{\lambda\mu i}+\sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(\lambda\nu)\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{\lambda\mu}\right)|0\rangle\,, \qquad (2.1)$$

where $|0\rangle$ is the phonon vacuum, $Q^+_{\lambda\mu i}$ is the phonon creation operator and ν labels the excited states. The coefficients $R_i(\lambda\nu)$, $P^{\lambda_1 i_1}_{\lambda_2 i_2}(\lambda\nu)$ and energies of the excited states E_ν are determined from the variational principle which leads to a set of linear equations [7]. The equations have the same form as in the quasiparticle-phonon model (QPM) [3, 4, 19], but the single-particle spectrum and the parameters of the residual interaction are obtained from the chosen Skyrme EDFs without any further adjustments. We take into account all two-phonon terms that are constructed from the phonons with multipolarities $\lambda\leq 5$ [10, 11, 12]. All dipole excitations with energies below 35 MeV and the 15 most collective phonons of the other multipolarities are included in the wave function (2.1). In addition, we have checked that extending the configuration space plays a minor role in our results.

3 Results and discussion

As a first step in the present analysis, we examine the PPC effects on the $E1$ strength distributions for doubly magic ^{48}Ca isotopes. The dipole strength distribution is well studied experimentally, see e.g., Refs. [20, 21]. The dipole strength function up to 27 MeV is displayed in Fig. 2. The calculated $E1$ strength distribution is computed by using a Lorentzian smearing with an averaging parameter Δ=1.0 MeV. The PPC effects yield a noticeable redistribution of the GDR strength in comparison with the RPA results. It is worth mentioning that the coupling increases the GDR width from 6.9 to 7.3 MeV in the energy region 10$\div$26 MeV. We find that the total energy-weighted $E1$ strength calculated in the RPA with the SLy5 EDF exhausts 114% of the Thomas-Reiche-Kuhn (TRK) sum rule value in the present energy range. The inclusion of the two-phonon terms results in an decrease of the integrated energy-weighted $E1$ strength by 5%. Also, the PPC induces a 300-keV downward shift of the GDR energy (19.3 MeV for the RPA). The experimental GDR width and energy are 6.98 MeV and 19.5 MeV, respectively [20]. The calculated characteristics of the GDR are in agreement with the observed values. The general shapes of the GDR obtained in the PPC are somewhat close to those observed in experiment. We conclude that the main mechanisms of the GDR formation in ^{48}Ca can be taken into account correctly and consistently in the PPC approach. Calculations with the SLy5+T EDF do not change the above conclusions.

Let us now discuss the low-energy $E1$ strength. To quantify the low-lying strength in a systematic analysis, we use the summed energy-weighted strengths in the low-energy region below 10 MeV [12]. The ratio of this quantity to the

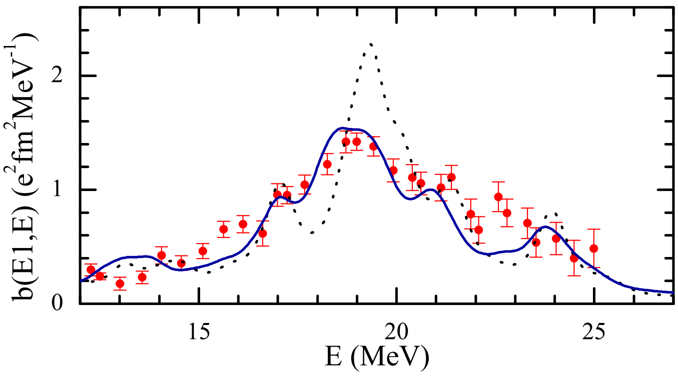

Figure 2: The experimental dipole strength distribution for ^{48}Ca (filled circles) are taken from Ref. [20]. The dotted and solid curves correspond to the calculations within the RPA and taking into account the PPC, respectively.

classical TRK sum rule

$$f_{\mathrm{PDR}}=\frac{\sum\limits_{k}^{E_k\leq 10\ \mathrm{MeV}} E_k\cdot B(E1;0^+_{g.\,st.}\rightarrow 1^-_k)}{14.8\cdot NZ/A\ \mathrm{e^2fm^2MeV}}, \tag{3.1}$$

is referred to as the "PDR fraction", hereafter. As shown in Fig. 3, the behavior of the PDR fraction can be divided into two categories: light and heavy Ca isotopes. In particular, we find that there is a sharp increase after the doubly magic isotope ^{48}Ca in the QRPA with the SLy5 EDF. In light Ca isotopes, a completely different behavior is observed in Ref. [13]: the measured energy-weighted sum rule in ^{44}Ca is 19.5 times larger than in ^{40}Ca and 1.2 times in the case of ^{48}Ca. From Fig. 3, one can see that the QRPA calculations fail to reproduce the experimental data. Thus, the correlation between the PDR integrated strength and the neutron excess of Ca isotopes is nontrivial and it is necessary to go beyond QRPA to explain the properties of the PDR.

Moving from ^{48}Ca to ^{50}Ca, the QRPA calculations predict a jump of the f_{PDR} value. The neutron number N=30 corresponds to the occupation of the $\nu 2p\frac{3}{2}$ subshell, resulting in two rather pronounced states below 10 MeV which are pure neutron two-quasiparticle excitations: 99%$\{3s\frac{1}{2}2p\frac{3}{2}\}_\nu$ and 98%$\{2d\frac{5}{2}2p\frac{3}{2}\}_\nu$. The integrated energy-weighted $E1$ strength of these states is 4.69 e^{2}fm^{2}MeV (about 2.6% of the TRK sum rule value). As one can see from Fig. 3, two states determine the value of f_{PDR} calculated below 10 MeV. The PDR fractions continue to increase until N=34 where the $\nu 2p\frac{1}{2}$ subshell is filled. Beyond N=34, the neutrons start filling the $\nu 1f\frac{5}{2}$ subshell, thus reducing the slope of f_{PDR}. It is shown that the PPC does not affect the description of the PDR fraction in the case of the heavy Ca isotopes. For the light Ca isotopes, the two-phonon contribution is noticeable for the PDR fraction

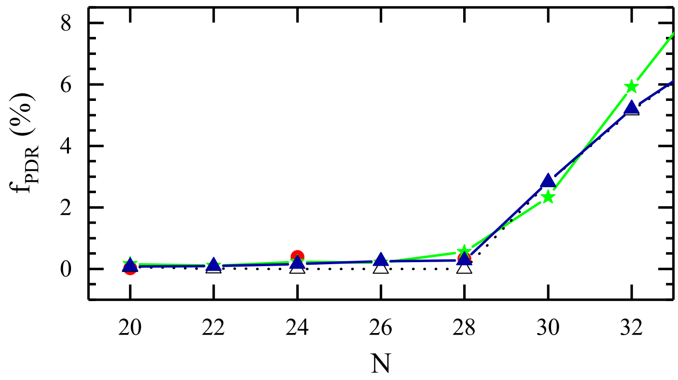

Figure 3: Ratio of the PDR energy-weighted strength below 10 MeV to the TRK sum rule for various Ca isotopes, as a function of the neutron number. The open triangles indicate discrete QRPA results, while the filled triangles are PPC results. The filled stars correspond to the ratio calculated in the RQTBA. Experimental data (filled circles) are taken from Ref. [13].

and its quantitative value is clearly increased. There is a redistribution of the $E1$ strength and a shift toward lower energies. For example, the dominant contribution in the wave function of the dipole states of ^{48}Ca comes from the two-phonon configurations (>60%) [12]. These states originate from the fragmentation of the RPA states above 10 MeV. It should be noted that including the tensor components changes the contributions of the main configurations only slightly. Finally, the same evolution of the PDR fraction in the Ca isotopes is obtained with the relativistic quasiparticle time blocking approximation (RQTBA) [22].

4 Conclusions

In summary, by starting from the Skyrme mean-field calculations, the properties of the electric dipole strength in Ca isotopes are studied by taking into account the coupling between one- and two-phonon terms in the wave functions of the excited states. The finite-rank separable approach for the QRPA calculations enables one to reduce considerably the dimensions of the matrices that must be inverted to perform nuclear structure calculations in very large configuration spaces. As an illustration, we study the properties of the low-lying dipole states in the even-even nuclei $^{40-58}$Ca. Using the same set of the EDF parameters we describe available experimental data for ^{40,44,48}Ca and give predictions for $^{50-58}$Ca. In particular, there is an impact of the coupling between one- and two-phonon states on low-energy $E1$ strength in ^{40,44,48}Ca. We predict a strong increase of the integrated energy-weighted $E1$ strength below 10 MeV, with increasing neutron number above ^{48}Ca.

Acknowledgments

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