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Effects of $2\mathrm{p}$-$2\mathrm{h}$ configurations on low-energy dipole states in neutron-rich N=80, 82 and 84 isotones

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Abstract. Starting from the Skyrme interaction SLy4 we study the effects of phonon-phonon coupling on the low-energy electric dipole response in $^{130-134}$Sn, $^{132-136}$Te and $^{134-138}$Xe. Our calculations are performed within the finite-rank separable approximation, which enables one to perform quasiparticle random phase approximation calculations in very large two-quasiparticle configuration spaces. A dependence of the pygmy dipole resonance strengths on the neutron skin thickness is found. The inclusion of the two-phonon configurations gives a considerable contribution to the low-lying strength.

1 Introduction

Recently, with the advent of advanced radioactive beam facilities and novel experimental techniques, unexplored regions of exotic nuclei and new phenomena became accessible for detailed spectroscopic studies. The electric dipole ($E1$) response of nuclei at energies around particle separation energy is presently attracting much attention, particularly for unstable neutron-rich nuclei produced as radioactive beams [1]. The structure and dynamics of the low-energy dipole strength, also referred to as pygmy dipole resonance (PDR), is one of the hot topics in nuclear physics. There are two major reasons in the case of the PDR. One reason is a special structure of the PDR which appears as a new collective motion in neutron-rich nuclei, but this has not been clarified [2]. The other reason is the role of the PDR in nucleosynthesis. The PDR also induces noticeable effects on (γ,n) cross section and on the r-process [3].

One of the successful tools for describing the PDR is the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field and the residual interaction derived from Skyrme energy density functionals (EDF). Such an approach describes the properties of the low-lying states less accurately than more phenomenological ones, but the results are in a reasonable agreement with experimental data (see Ref. [2] and references therein). Due to the anharmonicity of vibrations there is a coupling between one-phonon and more complex states [4, 5]. The main difficulty is that the complexity of calculations beyond standard QRPA increases rapidly with the size of the configuration space, so that one has to work within limited spaces. Using a finite-rank separable approximation (FRSA) [6–8] for the residual interaction resulting from Skyrme forces one can overcome this difficulty. The so-called FRSA was thus used to study the electric low-lying states and giant resonances within and beyond the QRPA [7, 9–12]. In particular, we applied the FRSA approach for the PDR strength distribution [13, 14].

In the present paper, we report the systematic analysis of the $E1$ response for $^{130-134}$Sn, $^{132-136}$Te and $^{134-138}$Xe in the self-consistent QRPA with some Skyrme interactions, focusing on the emergence and the properties of the PDR. The nuclei near the neutron magic number N=82 are quite suitable for studying the dependence of the PDR on neutron excess. Properties of the PDR are investigated in terms of their relation with the neutron skin thickness.

2 Brief outline of the FRSA

The FRSA approach has been discussed in detail in Refs. [6, 8] and it is presented here briefly for completeness. The calculations are performed by using the SLy4 EDF [15] in the particle-hole (p-h) channel and a density-dependent zero-range interaction in the particle-particle (p-p) channel. This parametrization was proposed for describing isotopic properties of nuclei from the stability line to the drip lines. Spherical symmetry is assumed for the Hartree-Fock (HF) ground states. The strength of the surface-peaked zero-range pairing force is taken equal to -940 MeV·fm^3 in connection with the soft cutoff at 10 MeV above the Fermi energy as introduced in Ref. [8]. This value of the pairing strength is fitted to reproduce the experimental proton and neutron pairing energies.

The residual interaction in the p-h channel $V_{\mathrm{res}}^{\mathrm{ph}}$ and in the p-p channel $V_{\mathrm{res}}^{\mathrm{pp}}$ can be obtained as the second derivative of the energy density functional with respect to the particle density ρ and the pair density $\tilde{\rho}$, respectively. Following Ref. [6] we simplify $V_{\mathrm{res}}^{\mathrm{ph}}$ by approximating it by its

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Landau-Migdal form. Moreover, we neglect the l=1 Landau parameters (Landau parameters with l>1 are equal to zero in the case of Skyrme interactions). In this work we study only normal parity states and one can neglect the spin-spin terms since they play a minor role. The two-body Coulomb and spin-orbit residual interactions are also dropped. 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_F [16]. To study the properties of the electric excitations, an effective value for k_F can be used in order to approximately reproduce the original p-h Skyrme interaction [6, 17]. For the present calculations we use the nuclear matter value for k_F. Alternative schemes to factorize the p-h interaction have also been considered in Refs. [18, 19].

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 [4, 5]

$$\Psi_\nu(JM)=\left(\sum_i R_i(J\nu)Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)\left[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}\right]_{JM}\right)|0\rangle. \quad (1)$$

where $|0\rangle$ is the phonon vacuum, $Q^+_{\lambda\mu i}$ is the phonon creation operator and ν labels the excited states. The coefficients $R_i(J\nu)$, $P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)$ 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) [4, 5], but the single-particle spectrum and the parameters of the residual interaction are obtained from the chosen Skyrme forces without any further adjustments. We take into account all two-phonon terms that are constructed from the phonons with multipolarities $\lambda \leqslant 5$ [13, 14]. All dipole excitations with energies below 35 MeV and 15 most collective phonons of the other multipolarities are included in the wave function (1). In addition, we have checked that extending the configurational space plays a minor role in our calculations.

3 Results and discussion

The simple hydrodynamical picture of the PDR [20] is a collective oscillation of neutron skin against the core part, from which the correlation between skin thickness and PDR is expected. Therefore, we pay special attention to the neutron skin thickness.

The neutron skin thickness ΔR_{np} is defined by the difference of root-mean-square radii of neutrons and protons, as

$$\Delta R_{np}=\sqrt{\langle r^2\rangle_n}-\sqrt{\langle r^2\rangle_p}. \quad (2)$$

In Fig. 1, we show the neutron skin thickness of Sn isotopes as a function of neutron number. The proton-neutron root-mean-square differences become larger when the number of the neutrons is increased. As seen in Fig. 1 from ^{120}Sn to ^{132}Sn the neutron skin thickness is accompanied by a 7% increase since there is the occupation of the $1h_{11/2}$ intruder orbit in the neutron subsystem. A 13% increase of ΔR_{np} is found at ^{132}Sn→^{134}Sn. For ^{132}Sn, an extremely thick neutron skin is building up leading to a sudden jump in the neutron root-mean-square radii (the neutron $2f_{7/2}$ subshells become populated). Thus, the increase is directly related to the shell structure in the heavy tin isotopes. The same evolution is obtained in the Hartree-Fock-Bogoliubov (HFB) model with SLy4 interaction [21]. The neutron shell effect on the neutron skin thickness is qualitatively in agreement with the theoretical predictions in the time-dependent Hartree-Fock-Bogoliubov (TDHFB) with the SkM* interaction [22]. The available experimental data [23, 24] are reasonably well reproduced.

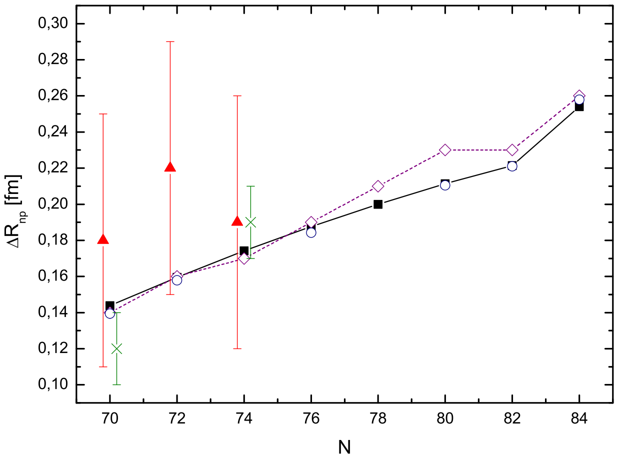

Figure 1. (Color online) The neutron skin thickness ΔR_{np} of the tin isotopes calculated with the SLy4 EDF: our results (■) and the predictions of HFB model calculations [21] are also drawn (○). Open diamond symbols (◊) show the results of the TDHFB with SkM* interaction [22]. Experimental data of the neutron skin thickness are derived from charge-exchange reactions [23] (▲) and from the antiprotonic x-ray data [24] (×).

Next, let us examine the correlation between the PDR and the neutron skin thickness ΔR_{np} in $^{130-134}$Sn, $^{132-136}$Te and $^{134-138}$Xe. Obviously, the crucial point of such an investigation is the determination of the energy region of the giant dipole resonance (GDR). To quantify the low-lying $E1$ strength in a systematic analysis, we use the summed energy-weighted $E1$ strengths in the low-energy region below 11 MeV. The ratio of this to the classical Thomas-Reiche-Kuhn (TRK) sum rule

$$f_{\mathrm{PDR}}=\frac{\sum\limits_k^{E_x\leqslant 11\ \mathrm{MeV}} E_k\cdot B(E1;0^+_{g.st.}\to 1^-_k)}{14.8\cdot NZ/A}, \quad (3)$$

is referred to as “PDR fraction”, hereafter.

Figure 2 shows the PDR fraction as a function of the neutron skin thickness ΔR_{np}. The left and right panels of Fig. 2 correspond to the calculations within the QRPA, or QRPA plus inclusion of 2p-2h configurations, respectively. The QRPA results indicate that the PDR strength is related with the neutron skin thickness. This is confirmed in the

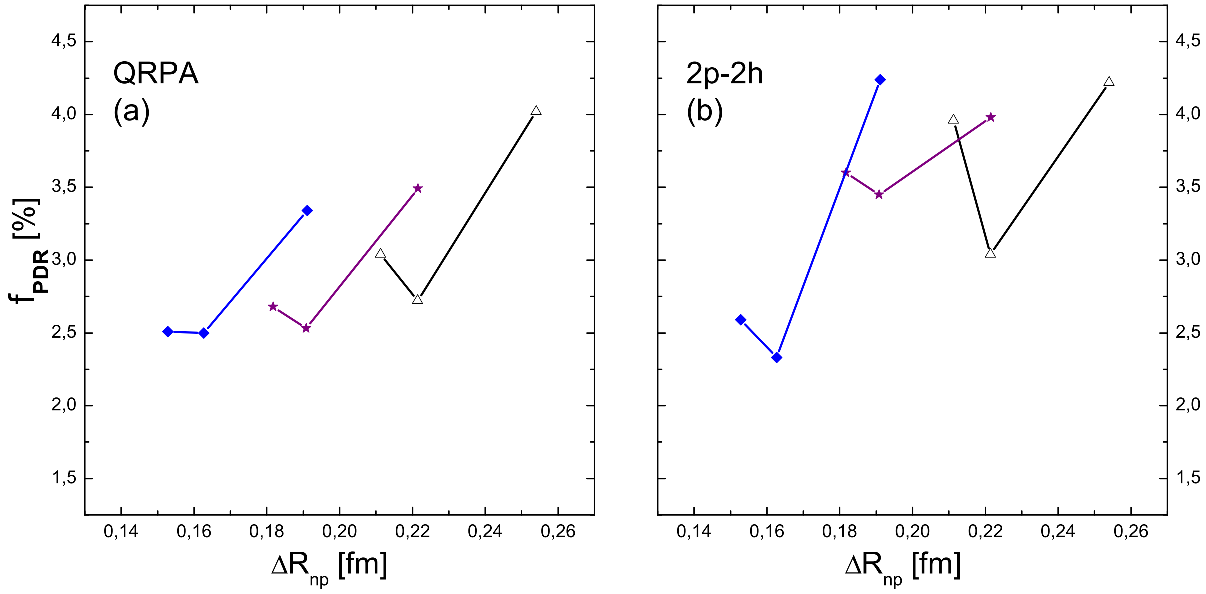

Figure 2. (Color online) The PDR fraction of $^{130-134}$Sn, $^{132-136}$Te and $^{134-138}$Xe isotopes as a function of the neutron skin thickness: (a) QRPA results; (b) QRPA plus phonon-phonon coupling results. Results for the Xe isotopes – filled diamond symbols (♦); results for the Te isotopes – filled star symbols (★); results for the Sn isotopes – open triangle symbols (△).

left panel of Fig. 2. The closure of the neutron subshell $1h_{11/2}$ leads to a reduction of the strength of the PDR. In addition, the GDR becomes more collective with increasing neutron number, the fraction of the energy-weighted sum rule (EWSR) contained in the PDR actually goes down as the neutron skin continues to increase. In contrast, there is an abrupt jump of the PDR fraction between N=82 and 84. This seems to be caused by the occupation of the neutron $2f_{7/2}$ subshell. The PDR fraction $f_{\rm PDR}$ is strongest for the Sn isotopic chain, and somewhat weaker for Te and Xe, see Fig. 2(a). This is, of course, to be expected because the PDR strength must be proportional to the neutron excess [2, 22]. In all the three chains the local minima in the PDR fraction are obtained at N=82 due to the neutron-shell closure. Thus, the QRPA results indicate the shell-closure impact on the PDR strength. A similar behavior for Sn isotopes was observed in other self-consistent calculations with the Skyrme EDF [22].

Let us now discuss the extension of the space to one and two-phonon configurations in the FRSA model. In the right panel of Fig. 2, we can see that the two-phonon contribution is noticeable for the PDR fraction and its quantitative value is clearly increased. The principal effect of the coupling with phonons in the low-energy region is the redistribution of the $E1$ strength and a shift toward lower energies. In particular, for ^{130}Sn, the QRPA and the calculations with the inclusion of the two-phonon terms give a PDR fraction of about 3.0% and 4.0%, respectively. The experimental data suggest the value of 4±3% [25]. For ^{132}Sn, the experimental data give an integrated strength of the PDR of about 4±3% of the TRK sum rule [25], while the calculations with and without the two-phonon configurations lead to 3.0% and 2.7%, respectively. Our calculations [14] show that the inclusion of the two-phonon terms results in an increase of the pygmy $E1$-resonance width from 1.2 to 2.0 MeV. An upper limit of experimental PDR width is 2.5 MeV [25]. Thus, we find that the impact of the phonon-phonon coupling on the correlation between the neutron skin thickness and the PDR strength gives results very similar to the QRPA.

4 Summary

Starting from the Skyrme mean-field calculations, the properties of the electric dipole strength in neutron-rich N=80, 82, and 84 isotones are studied by taking into account the coupling between one- and two-phonons terms in the wave functions of excited states. The finite-rank separable approach for the QRPA calculations enables one to reduce remarkably the dimensions of the matrices that must be inverted to perform nuclear structure calculations in very large configuration spaces.

Neutron excess effects on the PDR excitation energies and transition strengths have been investigated for the even-even nuclei $^{130-134}$Sn, $^{132-136}$Te and $^{134-138}$Xe. The strong enhancement of the PDR strengths are studied by taking into account the 2p-2h configurations. Correlations between the PDR strength and the neutron skin thickness are found.

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