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Nuclear Spectroscopic Properties within a Selfconsistent Multiphonon Approach

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Abstract. The equation of motion phonon method is adopted to investigate the dipole response in neutron rich nuclei. The calculation is carried out in a space spanned by one- and two-phonon basis states. It makes direct use of a nucleon-nucleon optimized chiral potential complemented with a density dependent term simulating a three-body force and is fully selfconsistent. The inclusion of the two-phonon states induces a pronounced fragmentation of both giant and pygmy resonances consistently with recent experiments.

1. Introduction

In recent years, an intense experimental and theoretical effort has been concentrated on the electric dipole response in neutron rich nuclei and, more specifically, on the low-energy levels detected around the neutron threshold and interpreted as a manifestation of a soft mode, dubbed pygmy dipole resonance (PDR), promoted by a translational oscillation of the neutron excess against a N=Z core [1].

A comprehensive and updated list of experimental investigations can be found in a recent review [2]. We mention here a radioactive beam experiment on the unstable tin isotopes around ^{132}Sn [3], the (γ, γ') [4–6] combined with the $(\alpha, \alpha'\gamma)$ experiments [7–9], which detected rich low lying spectra of weakly excited discrete levels below the neutron threshold in chains of stable nuclei over different mass regions.

^{208}Pb deserves a special mention. A recent proton scattering experiment on ^{208}Pb has extracted the electric dipole spectrum below and above the neutron threshold [10, 11] with great accuracy. The data so obtained, combined with the ones made available by previous (γ, γ') and (n, γ) [12–14] and photo-absorption experiments [15, 16], allow a detailed investigation of the properties of the dipole response and, in particular, of the low-lying soft mode. The nucleus, therefore, represents a testing ground for the theoretical models.

The mode was investigated in a considerable number of theoretical approaches. Many calculations were carried out in Hartree-Fock-Bogoliubov (HFB) plus quasi-particle RPA (QRPA) using Skyrme or Gogny forces, others were performed in relativistic RPA (RRPA) using density functionals derived from meson-nucleon Lagrangians treated in mean field approximation. An exhaustive list of references can be found in the reviews [2, 17, 18] .

Several extensions of (Q)RPA were adopted to study the fragmentation of the mode. We mention the QRPA plus phonon coupling [19], second RPA [20], the quasi-particle-phonon model (QPM) [6, 12, 21], and the relativistic quasi-particle time-blocking approximation (RTBA) [22–24].

The fragmentation was studied also within an equation of motion phonon method (EMPM) [25–27]. In such an approach, one constructs and solves iteratively a set of equations of motion to generate a multiphonon basis built of phonons obtained in Tamm-Dancoff approximation (TDA). Represented in such a basis the Hamiltonian matrix has a simple structure and can be diagonalized in large configuration and phonon spaces. The method holds for a Hamiltonian of general form, treats one-phonon and multiphonon states on the same footing and fulfills the Pauli principle.

It was first implemented numerically to study the dipole response using a modified oscillator single particle basis and a V_{lowk} potential derived from the CD-Bonn NN interaction [28]. We report here on calculations carried out for the doubly magic nuclei ^{132}Sn and ^{208}Pb in a space spanned by one-plus two-phonon basis states [29, 30].

The calculations are fully self-consistent and make use of a nucleon-nucleon (NN) chiral potential $V_\chi = NNLO_{opt}$ optimized so as to minimize the effects of the three-body forces [31]. A review of the derivation and properties of chiral potentials can be found in Ref. [32]. As we shall see, it was necessary to add to V_χ a phenomenological, density dependent, potential V_ρ, derived from a contact three-body interaction [33], in order to obtain a more realistic Hartree-Fock spectrum. This corrective term was already introduced for other realistic potentials [34, 35].

2. Outline of the EMPM method

The main goal of the EMPM method consists in generating a basis of n-phonon states $|n; \beta >$, of energies E_β, having the form

$$|n; \beta >= \sum_{\lambda\alpha} C_{\lambda\alpha}^\beta \left\{ O_\lambda^\dagger \times \mid n-1, \alpha > \right\}^\beta,$$ (1)

where

$$O_\lambda^\dagger = \sum_{ph} c_{ph}^\lambda (a_p^\dagger \times b_h)^\lambda$$ (2)

is the TDA particle-hole (p-h) phonon operator of energy E_λ acting on the $(n-1)$-phonon states $\mid n-1, \alpha >$ of energies E_α.

The procedure leading to such a basis starts with constructing the equations of motion

$$< n, \beta \parallel [H, O_\lambda^\dagger] \parallel n-1, \alpha >= \left(E_\beta - E_\alpha \right) < n, \beta \parallel O_\lambda^\dagger \parallel n-1, \alpha > .$$ (3)

After expanding the commutator and expressing the p-h operators, present in the expanded commutator, in terms of the phonon operators $O_\lambda^\dagger$ upon inversion of Eq. (2), one obtains [27] the generalized eigenvalue equation

$$\sum_{\lambda'\alpha'\lambda_1\alpha_1} \left[\mathcal{A}^\beta(\lambda\alpha, \lambda_1\alpha_1) - E_\beta \delta_{\lambda_1\lambda} \delta_{\alpha_1\alpha} \right] \mathcal{D}^\beta(\lambda_1\alpha_1, \lambda'\alpha') C_{\lambda'\alpha'}^\beta = 0.$$ (4)

Here

$$\mathcal{D}^\beta(\lambda_1\alpha_1; \lambda'\alpha') = \left[< n-1, \alpha_1 \mid \times O_{\lambda_1} \right]_\beta \left[O_{\lambda'}^\dagger \times \mid n-1, \alpha' > \right]_\beta$$ (5)

is the metric matrix and $\mathcal{A}^\beta$ is a matrix of the simple structure

$$\mathcal{A}^\beta(\lambda\alpha, \lambda'\gamma) = (E_\lambda + E_\alpha)\delta_{\lambda\lambda'}\delta_{\alpha\gamma} + \sum_\sigma W(\beta\lambda'\alpha\sigma; \gamma\lambda)\mathcal{V}^\sigma_{\lambda\alpha,\lambda'\gamma}, \tag{6}$$

where W is a Racah coefficient and $\mathcal{V}^\sigma$ a phonon-phonon potential given by

$$\mathcal{V}^\sigma_{\lambda\alpha,\lambda'\gamma} = \sum_{rstq} \rho_{\lambda\lambda'}([q \times t]^\sigma)F^\sigma_{qtrs}\rho^{(n)}_{\alpha\gamma}([r \times s]^\sigma). \tag{7}$$

We have denoted by $\rho_{\lambda\lambda'}$ and $\rho^{(n)}_{\alpha\alpha'}$, respectively, the $n = 1$ (TDA) and the n-phonon ($n > 1$) density matrices

$$\rho_{\lambda\lambda'}([r \times s]^\sigma) = \langle\lambda' \parallel \left[a_r^\dagger \times b_s\right]^\sigma \parallel \lambda\rangle, \tag{8}$$

$$\rho^{(n)}_{\alpha\alpha'}([r \times s]^\sigma) = \langle n; \alpha' \parallel \left[a_r^\dagger \times b_s\right]^\sigma \parallel n; \alpha\rangle. \tag{9}$$

The formal analogy between the structure of the phonon matrix $\mathcal{A}^\beta(\lambda\alpha, \lambda'\alpha')$ and the form of the TDA matrix $A^\lambda(ph; p'h')$ was pointed out in Ref. [27]. The first is deduced from the second by replacing the TDA p-h energies with the sum of phonon energies $(E_\lambda + E_\alpha)$ and the TDA p-h interaction with the phonon-phonon interaction $\mathcal{V}^\sigma$.

Eq. (4) represents the eigenvalue equation in the overcomplete basis $\left\{O_\lambda^\dagger \times \mid n-1, \alpha >\right\}^\beta$. The redundant states are eliminated by the procedure outlined in [25, 26], based on the Cholesky decomposition method.

Since recursive formulas hold for all quantities entering $\mathcal{A}$ and $\mathcal{D}$, the eigenvalue equations are solved iteratively starting from the TDA phonons and, thereby, yield a set of orthonormal multiphonon states $\{\mid 0 >, \mid 1, \lambda >, \dots \mid n, \alpha > \dots\}$.

Represented in such a basis, the Hamiltonian matrix is composed of a sequence of diagonal blocks, one for each n, mutually coupled by off-diagonal terms $\langle n' \mid H \mid n \rangle$ which are non vanishing only for $n' = n \pm 1, n \pm 2$ and are computed by means of recursive formulas. A matrix of such a simple structure can be easily diagonalized yielding eigenfunctions of the form

$$\mid \Psi_\nu \rangle = \sum_{n\alpha} C_\alpha^{(\nu)} \mid n; \alpha\rangle. \tag{10}$$

3. Calculations and results

The Hamiltonian we used is composed of an intrinsic kinetic operator T_{int} plus the two-body potential

$$V = V_\chi + V_\rho. \tag{11}$$

As pointed out in the introduction, $V_\chi = NNLO_{opt}$ is the NN optimized chiral potential [31] and V_ρ is a corrective repulsive, density dependent, two-body potential simulating a three-body contact force [33] which improves the description of bulk properties in closed shell nuclei [36].

We generate a HF basis in a configuration space including up to the $N_{max} = 12$ harmonic oscillator major shells, sufficient for reaching a good convergence. The benefits coming from adding the density dependent potential can be noticed already within the HF context. In fact, the inclusion of V_ρ enhances the diffuseness of the charge density, which thereby approaches the empirical charge distribution, and yields a neutron skin radius compatible with the one deduced from the experimental data.

Moreover, as illustrated in Figure 1, it induces a compression of the single particle spectrum [29] thereby filling partially the gap with the empirical levels [37]. Such a compression improves also the (Q)TDA and (Q)RPA descriptions of the dipole response [29].
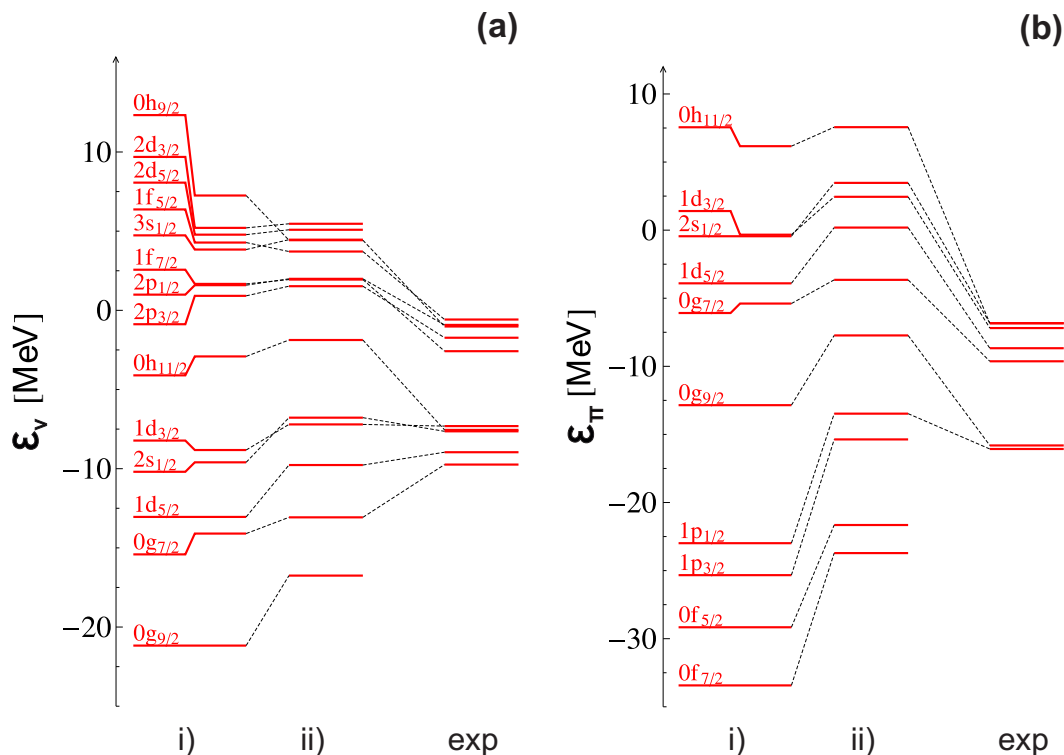
Figure 1. Neutron and proton single particle spectra in ^{132}Sn with i) $V = V_\chi$ and ii) $V = V_\chi + V_\rho$ (from [29]). The empirical (exp) single particle levels are taken from [37]

Using the HF basis, we first create the TDA one phonon states $\mid \lambda \rangle$ and, then, adopt the EMPM procedure outlined in Sect. 2 to produce an orthonormal correlated two-phonon basis $\mid \alpha \rangle$. The one- + two-phonon basis is used to diagonalized the residual Hamiltonian and yield the final eigenvalues and eigenvectors.

The inclusion of the two-phonon states has a strong damping effect on the response. As shown in Figure 2, the cross section is severely quenched and reshaped by the one- to two-phonon coupling in both ^{132}Sn and ^{208}Pb. It has a smoother behavior and follows more closely the experimental points.

In ^{132}Sn, the calculation yields a small peak in the cross section around ~ 10 MeV, fairly close in position and height to the one at ~ 9.8 MeV observed experimentally [3]. The EMPM strength collected by the low-lying states up to ~ 11 MeV exhausts $\sim 5.8\%$ of the TRK sum rule. This value is within the error of the measured fraction 4(3)% [3]. A similar peak is produce around ~ 7 MeV also in the cross section of ^{208}Pb and overlaps with the measured peak.

The phonon coupling enhances greatly the fragmentation of the strength [29]. As compared with TDA, the EMPM spectrum is much more dense and is composed of peaks of considerably shorter height in both GDR and PDR regions.

Figure 3 shows that also in the low energy sector the level density is greatly enhanced by the phonon coupling. It is even higher than the density of the observed levels. The calculation [30], in fact, yields about 20 1^- peaks between ~ 4.5 MeV and ~ 7 MeV, twice as much as the ones detected experimentally [10, 11].

On the other hand, the experimental strength distribution is reproduced only qualitatively. Figure 4 shows that significant discrepancies exist. Some EMPM transitions result to be too strong compared to the measured ones, while the large majority of them are considerably weaker.
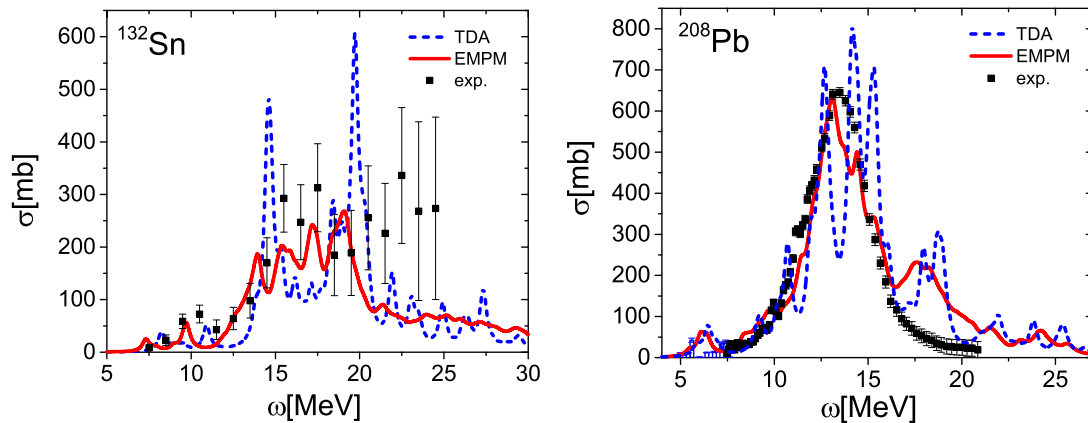
Figure 2. EMPM and TDA versus experimental cross sections in ^{132}Sn [29] and ^{208}Pb [30]. A Lorentzian width $\Delta = 0.5$ MeV was used to compute the cross sections. The experimental data are taken from [3] for ^{132}Sn and from [10, 11] for ^{208}Pb.
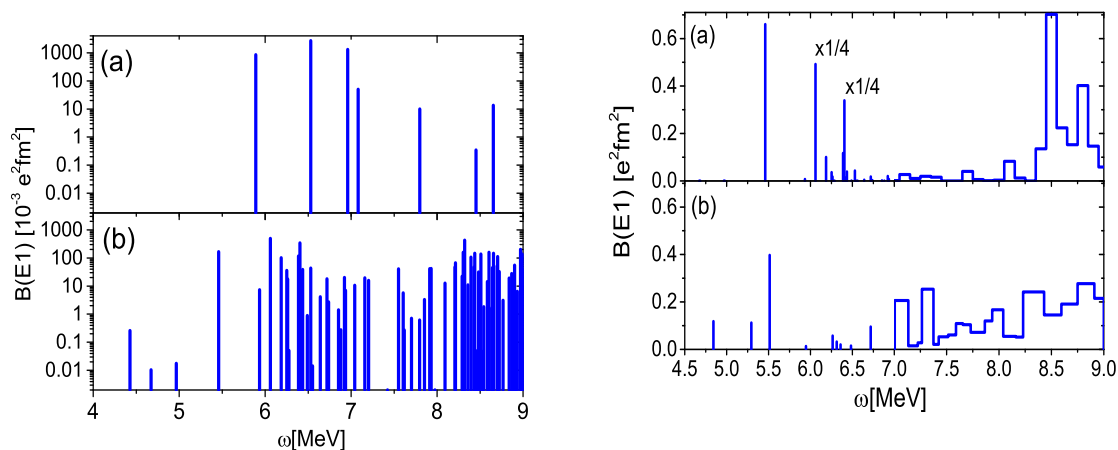
Figure 3. TDA (a) versus EMPM (b) $E1$ low-lying spectra in ^{208}Pb [30].

Figure 4. EMPM versus experimental $E1$ low-lying spectra in ^{208}Pb [30]. The experimental data are taken from [11].

In any case, one can infer from a comparison with Figure 6 of Ref. [11] that our computed spectrum is comparable with the ones computed in QPM and RTBA and, especially, with the spectrum obtained in shell model by using empirical single particle energies and a phenomenological potential in a restricted configuration space [14].

The analysis of the structure of the wavefunctions shows that the low-lying excitations are mainly promoted by the valence neutrons hinting at their pygmy nature, a suggestion supported by the transition densities and the excitation mechanism [29].

In fact, the theoretical low-lying levels are excited by both isoscalar and isovector probes [29, 30], in analogy with the experimental spectrum produced by (γ, γ') and $(\alpha, \alpha'\gamma)$ experiments in the open shell ^{124}Sn [8, 9, 38]. On the other hand, our ^{132}Sn and ^{208}Pb do not exhibit any splitting between isoscalar and isovector dipole modes at low-energy, at variance with the conclusions drawn from the analysis of the observed spectra in ^{124}Sn [7].

4. Conclusions

According to our EMPM study, the two-phonon states exert a strong damping and fragmentation of the TDA peaks in the GDR region thereby yielding a smooth cross section consistently with experiments. The same two-phonon states greatly enhance the density of low-lying levels more in qualitative agreement with recent experiments.

Serious discrepancies between theoretical and experimental spectra remain. They may be cured by trying to improve the HF description of the single particle spectra, which amounts to improving the nucleon-nucleon potential. The optimized chiral potential $V_\chi = NNLO_{opt}$[31] we used, though representing a promising starting point, is not sufficient. In fact, we had to add a phenomenological density dependent potential which simulates a repulsive three-body contact force. Such a potential however, is phenomenological and contains an unconstrained coupling constant. Moreover, it fills only partially the gap between HF and empirical single particle energies.

It is also desirable to try to enlarge the space by including the three-phonon states which are known to couple strongly to the one-phonon subspace [27]. Such a coupling is supposed to induce a further redistribution of the dipole strength. In this perspective, we are trying to improve the efficiency of the codes and to achieve reliable truncations of the phonon space.

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