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Relativistic RPA plus phonon-coupling analysis of pygmy dipole resonances

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Abstract

The relativistic random-phase approximation (RRPA) plus phonon-coupling (PC) model is applied in the analysis of E1 strength distributions in ^{208}Pb and ^{132}Sn, for which data on pygmy dipole resonances (PDR) have recently been reported. The covariant response theory is fully consistent: the effective nuclear interaction NL3 is used both to calculate the spectrum of single-nucleon Dirac states, and as the residual interaction which determines the collective phonon states in the relativistic RPA. It is shown that the picture of the PDR as a resonant oscillation of the neutron skin against the isospin saturated proton–neutron core, and with the corresponding RRPA state characterized by a coherent superposition of many neutron particle–hole configurations, remains essentially unchanged when particle–vibration coupling is included. The effect of two-phonon admixtures is a weak fragmentation and a small shift of PDR states to lower excitation energy. Even though the PDR calculated in the extended model space of $ph \otimes$ phonon configurations contains sizeable two-phonon admixtures, it basically retains a one-phonon character and its dynamics is not modified by the coupling to low-lying surface vibrations.

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The multipole response of nuclei far from the β-stability line and the possible occurrence of exotic modes of excitation has been the subject of a number of recent theoretical and experimental studies. For neutron-rich nuclei in particular, the pygmy dipole resonance (PDR), i.e. the resonant oscillation of the weakly-bound neutron skin against the isospin saturated proton–neutron core has been investigated. The onset of low-lying E1 strength has been observed not only in exotic nuclei with a large neutron excess, e.g. for neutron-rich oxygen isotopes [1], but also in stable nuclei with moderate proton–neutron asymmetry, like ^{44,48}Ca and ^{208}Pb [2–4]. Very recently the dipole strength distribution above the one-neutron separation energy was also measured in the unstable ^{130}Sn and the doubly-magic ^{132}Sn [5]. In addition to the giant dipole resonance (GDR), evidence was reported for a PDR structure at excitation energy around 10 MeV both in ^{130}Sn and ^{132}Sn, exhausting a few percent of the E1 energy-weighted sum rule.

The interpretation of the dynamics of observed low-lying E1 strength in nuclei with a pronounced neutron excess is very much under discussion. Virtually all theoretical analyses, including shell-model studies and a number of models based on the random-phase approximation (RPA), have shown that in light nuclei, e.g. in neutron-rich oxygen isotopes, the low-lying dipole strength is not collective and originates from non-resonant single-neutron excitations. The situation is different in medium-heavy and heavy nuclei, where the occurrence of collective PDR states has been predicted by several RPA-based calculations, whereas other studies, including also RPA-based models, did not find collective pygmy states in the energy region below the GDR, but only dipole states characterized by single-neutron particle–hole configurations. In particular, studies based on the relativistic RPA [6–9] have shown that in neutron-rich nuclei the electric dipole response is characterized by the fragmentation of the strength distribution and its spreading into the low-energy region. In contrast to light nu-

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clei where the onset of dipole strength in the low-energy region is due to non-resonant single-particle excitations of the loosely bound neutrons, in relativistic RPA calculations of heavier nuclei low-lying dipole states appear which display a more distributed structure of the RPA amplitudes. For these nuclei a single collective dipole state is identified in the low-energy region, and the characteristic dynamics of the pygmy resonance becomes apparent from the analysis of the corresponding transition densities and velocity distributions. The relativistic RPA analysis of Ref. [6] predicted the PDR in ^{208}Pb at an excitation energy close to the neutron emission threshold, and subsequently such a resonant structure was identified in a high-resolution (γ, γ') study [2], with a centroid energy precisely at the neutron threshold ($E_{th} = 7.37$ MeV). In Refs. [7–9] the relativistic RPA and quasiparticle (Q)RPA were employed in the analysis of the E1 response in Sn isotopes, and the occurrence of the PDR was predicted in neutron-rich Sn nuclei. This prediction was confirmed in the recent Coulomb dissociation experiment reported in Ref. [5], in which the PDR structure was observed in ^{130}Sn and ^{132}Sn.

The relativistic RPA and QRPA analyses of the dynamics of low-lying E1 strength distributions described above were performed on the mean-field level, i.e. without taking into account the spreading effects which arise from the coupling of single-nucleon states to the collective low-lying excitations (phonons). The principal effect of the particle–vibration coupling is an increase of the nucleon effective mass at the Fermi surface, and this is reflected in an increase of the density of single-nucleon states close to the Fermi energy. It has been argued that the inclusion of particle–vibration coupling in (Q)RPA calculations, i.e. extending the (Q)RPA model space to include selected two-quasiparticle ⊗ phonon states, would not only improve the agreement between the calculated and empirical widths of the GDR structures, but it could also have a pronounced effect on the low-lying E1 strength. For instance, the coupling to low-lying phonons could fragment the PDR structure over a wide region of excitation energies. As a result of this fragmentation only an enhancement of the E1 strength would be observed in the low-energy region, rather than a prominent PDR peak. The importance of particle–vibration coupling effects for the multipole response of neutron-rich nuclei has particularly been emphasized in studies that have used the QRPA plus phonon coupling model based on the Hartree–Fock (Q)RPA with Skyrme effective forces [10,11]. For the neutron-rich oxygen isotopes it was shown that the experimentally observed dipole strength below 15 MeV [1] could not be reproduced with a simple QRPA calculation, but only with the inclusion of the coupling with phonons [10]. In Ref. [11] the QRPA plus phonon coupling model was applied in the analysis of dipole excitations in ^{208}Pb, ^{120}Sn and ^{132}Sn. In contrast to the results obtained in the relativistic (Q)RPA framework, the QRPA plus phonon coupling model predicts low-lying E1 strength of non-collective nature in all three nuclei. In particular, from the analysis of the structure of RPA amplitudes, it was concluded that none of the four peaks lying below 10 MeV in ^{132}Sn contains contributions of more than two or three different neutron particle–hole (ph) configurations. Predominantly these peaks correspond to just a single-neutron transition, and each of them exhausts less than 0.5% of the energy-weighted sum rule. Low-lying E1 excitations in neutron-rich Sn isotopes have also been studied in the quasiparticle phonon model (QPM) [12], in a model space that included up to three-phonon configurations built from a basis of QRPA states, and with separable multipole–multipole residual interactions. The single-nucleon spectra were calculated for a Woods–Saxon potential with adjustable parameters. Empirical couplings were used for the QPM residual interactions. In the QPM spectra for $^{120-132}$Sn the low-energy dipole strength was found concentrated in a narrow energy interval such that the PDR could be identified. A dependence of the PDR strength and centroid energies on the neutron-skin thickness was analyzed. It was shown that, despite significant multi-phonon contributions to the mean-energy and transition strength, the PDR states basically retain their one-phonon character.

In this work we report the first application of the relativistic RPA plus phonon-coupling model in the calculation of the E1 strength distribution in ^{208}Pb and ^{132}Sn. The relativistic mean-field framework has recently been extended to include the coupling of single-nucleon states to low-lying vibrational states (phonons), and its effect on the single-nucleon spectra has been analyzed [13]. In the present study we employ a fully consistent covariant response theory, which uses the particle–vibration coupling model in the time-blocking approximation (TBA) [14–17] to describe the spreading widths of multipole giant resonances in even–even spherical nuclei. In the TBA a special time-projection technique is used to block the propagation of ph configurations through states which have a more complex structure than ph ⊗ phonon. The nuclear response can then be explicitly calculated on the ph ⊗ phonon level by summation of infinite series of Feynman's diagrams.

The linear response function is the solution of the Bethe–Salpeter equation (BSE) in the particle–hole (ph) channel

$$R(14,23) = \tilde{G}(1,3)\tilde{G}(4,2) + \frac{1}{i}\sum_{5678} \tilde{G}(1,5)\tilde{G}(6,2)W(58,67)R(74,83), \quad (1)$$

where the notation for the single-particle quantum numbers includes the set of Dirac quantum numbers $\{k_1\}$ and the time variable t_1: $1 = \{k_1, t_1\}$, and the summation implies also integration over the respective time variables. In addition to the usual particle–hole pairs, the configuration space must also include pair-configurations built from positive-energy states occupied in the ground-state solution, and empty negative-energy states in the Dirac sea [18]. Thus the set $\{k_i\}$ includes both positive- and negative-energy states. The dimension of the configuration space is truncated in such a way that the unperturbed particle–hole (antiparticle–hole) energies are smaller than 100 MeV (larger than -1800 MeV) with respect to the positive-energy continuum. The model equations are solved by expanding the nucleon spinors in a spherical harmonic oscillator basis [19]. In the present calculation we have used a basis of 20 oscillator shells.