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Pion–nucleon correlations in finite nuclei in a relativistic framework: Effects on the shell structure

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ABSTRACT

The relativistic particle-vibration coupling (RPVC) model is extended by the inclusion of isospin-flip excitation modes into the phonon space, introducing a new mechanism of dynamical interaction between nucleons with different isospin in the nuclear medium. Protons and neutrons exchange by collective modes which are formed by isovector π and ρ-mesons, in turn, softened considerably because of coupling to nucleons of the medium. These modes are investigated within the proton–neutron relativistic random phase approximation (pn-RRPA) and relativistic proton–neutron time blocking approximation (pn-RTBA). The appearance of isospin-flip states with sizable transition probabilities at low energies points out that they are likely to couple to the single-particle degrees of freedom and, in addition to isoscalar low-lying phonons, to modify their spectroscopic characteristics. Such a coupling is quantified for the shell structure of ^{100,132}Sn and found significant for the location of the dominant single-particle states.

1. Introduction

A consistent treatment of pion degrees of freedom is still one of the challenges for nuclear structure theory, despite the fact that the meson-exchange nucleon–nucleon interaction is known since the work of Yukawa [1]. Being a mediator of the medium-range nucleon–nucleon interaction, the pion played the central role in approaches developed by the so-called 'Moscow school' [2–11] and 'Stony Brook school' [12–19]. Characteristics of the pion bound in nuclear medium were extensively discussed, in particular, in the context of possible formation of pion condensate in finite nuclei and various phases of nuclear matter [11,18,19]. Later on, chiral effective field theory (EFT) based on the approximate spontaneously broken chiral symmetry of QCD emerged from the pioneering work of Weinberg [20]. Since then, ab initio methods based on chiral EFT demonstrate an increasing success in the description of nuclear structure properties although their applicability is still limited to light nuclei only [21,22].

Many-body methods for sufficiently heavy nuclear systems ($A > 16$) include various nucleon–nucleon correlations on top of a mean field, which serves as a redefined vacuum constructed as an approximate realization of Kohn–Shahm density functional theory. The original (non-relativistic) nuclear field theory (NFT) is based on the idea of Bohr and Mottelson [23] about coupling between single-particle and vibrational degrees of freedom in atomic nuclei, often referred to as particle-vibration coupling (PVC). This idea has been developed over the years [24–27] and implemented very successfully in approaches known as a non-relativistic NFT [28–38], extensions of the Landau–Migdal theory [39–42] or quasiparticle–phonon model [43–45]. Lately, self-consistent versions of the PVC model have become available in both non-relativistic [46,47] and relativistic [48–57] formulations. In the majority of the non-relativistic self-consistent calculations the PVC effects are studied in doubly-magic nuclei, where superfluidity effects do not appear, which simplifies calculations considerably. Studies of these effects in open-shell nuclei have become possible relatively recently in a non-relativistic approach for single-quasiparticle states [35,36] and in a self-consistent relativistic approach for both single-quasiparticle spectra [50] and response [52].

The covariant (relativistic) version of the nuclear field theory [48–58] is based on the quantum hadrodynamics (QHD) Lagrangian, which, in contrast to chiral EFT, includes heavy mesons explicitly, although their masses and coupling constants are adjusted to bulk properties of medium-mass nuclei (see review [59] and references therein). Numerous calculations within these models have shown that the effects of quasiparticle-vibration coupling

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(QVC) modify nuclear shell structure and spectra of excitations considerably and bring the results in essentially better agreement to experimental data, in some cases approaching spectroscopic accuracy [50,52,54,60,61]. In particular, it turned out that the effects of QVC in open-shell nuclei are quantitatively stronger than those in closed-shell ones, which can be attributed to the existence of phonons with very low energies (∼1 MeV or even lower) in medium-mass open-shell nuclei, compared to ∼4 MeV in medium-mass doubly-magic systems. Obviously, superfluidity plays a very important role providing better conditions for the QVC, which can be seen from the structure of the QVC self-energy [50]. The pion field does not contribute on the mean-field level, if the parity conservation is imposed, however, its dynamical contribution is decisive for the description of spin–isospin transitions [56,57,62,63].

Recently, it has been realized that the spin–isospin interaction, especially the tensor interaction, is of particular and direct importance for single-particle properties of exotic nuclei [64,65]. This type of interaction is commonly associated with one-pion exchange, although other mesons can also give contributions of the tensor type, which has been obtained in the relativistic Hartree–Fock [66] and relativistic RPA (RRPA) calculations for spin–isospin-flip transitions [67]. However, the latter calculations are confined by the static approximation for the pion field, neglecting retardation effects, and include only the first-order contribution to the pion-exchange interaction. Nevertheless, RPA in the spin–isospin channel gives a sizable softening of the pion modes, where the softness is caused by medium polarization effects, as it has been recognized already in earlier calculations [11]. The appearance of such modes at low energies was interpreted as a signature for the onset of the pion condensation, although it was not clear which observables are sensitive enough to the presence of pion condensate and which of those can be detected experimentally with reasonable precision.

The main goal of the present work is to reveal dynamical contributions of the pion-exchange interaction to nuclear structure properties. The most important dynamical contributions are identified as terms in the nucleonic self-energy, which represent exchange by collective modes. Technically, besides the isoscalar modes, which are exchanged between nucleons of the same isospin and commonly considered in NFT, the isovector modes exchanged between nucleons with different isospin are added. First of all, the approach of Refs. [56,62], namely the proton–neutron relativistic random phase approximation (pn-RRPA) and proton–neutron relativistic time blocking approximation (pn-RTBA) is applied to calculations of the isospin-flip and spin–isospin-flip excitations. The obtained spectra are evaluated to identify the low-lying isovector modes of excitation, which give the most important contribution to the nucleonic self-energy, according to their degree of collectivity. Then, the selected most collective modes are coupled to the single-particle degrees of freedom by means of introducing corresponding terms into the single-nucleon self-energy. Thus, on one hand, the relativistic NFT is extended by isospin vibrations and, on the other hand, dynamical effects of the pion exchange are introduced into the theory beyond the Hartree–Fock approximation. The effects of these new terms on the single-particle characteristics, such as their energies and spectroscopic factors, are discussed. In the context of the discussion of pion condensate, it is shown that nuclear single-particle characteristics can represent observables which are sensitive to the presence of soft pion modes.

2. Theoretical framework

2.1. Nucleonic self-energy and Dyson's equation

The motion of protons and neutrons in nuclei is quantified by one-nucleon self-energy, or mass operator. In contrast to free nucleons, protons and neutrons in the nuclear medium are exposed to strong polarization effects and, hence, their motion is modified considerably. In the simplest mean field (Hartree or Hartree–Fock) approximation, this effect can be described by introducing an energy-independent effective mass m^* instead of the bare nucleon mass, which helps to reproduce bulk nuclear properties reasonably well, but gives a very poor description of the single-particle spectra. The latter problem can only be solved by going beyond the mean-field approximation and by introducing an energy-dependent effective mass. The most important origin of the energy dependence is given by the coupling of the single particle motion to low-lying collective vibrations [24–27], see also the discussion in Ref. [48], where a relativistic particle-vibration coupling (RPVC) model was originally proposed. In both the RPVC model and relativistic quasiparticle-vibration coupling (RQVC) model for systems with pairing correlations [50], the energy-independent part of the nucleonic self-energy is given by the relativistic mean field (relativistic Hartree (RH) or Hartree–Bogoliubov (RHB)) approximation. The RH/RHB eigenstates $\{k,\eta\}$ are used as a basis for calculating the dynamical part of the self-energy, matrix elements of which in this basis read:

$$\Sigma^{(e)\eta_1\eta_2}_{k_1k_2}(\varepsilon) = \sum_{\eta_\mu=\pm1}\sum_{\eta=\pm1}\sum_{k,\mu}\frac{\delta_{\eta\eta_\mu}\gamma^{\eta_\mu;\eta_1\eta}_{\mu;k_1k}\gamma^{\eta_\mu;\eta_2\eta*}_{\mu;k_2k}}{\varepsilon-\eta E_k-\eta_\mu(\Omega_\mu-i\delta)}, \qquad (1)$$

$\delta\to+0$,

where the indices k, k_1, k_2 represent the complete set of the single-particle quantum numbers, and the indices η, η_1, η_2 indicate the upper and lower components of the matrix elements in the Nambu space. In the limit of no superfluidity $\eta_1 = 1$, if the state k_1 is above the Fermi energy, and $\eta_1 = -1$, if the state k_1 is below the Fermi energy. The index μ in Eq. (1) runs over the set of phonons taken into account. Their vertices γ_μ and frequencies Ω_μ can be calculated in the self-consistent relativistic quasiparticle random phase approximation, as described in Ref. [52], and E_k are the energies of the Bogoliubov's quasiparticles obtained in the RHB approach, so that the product ηE_k takes the correct limit of the mean-field energy in the case of no superfluidity. The index η_μ labels forward and backward going diagrams in the self-energy (1), see Eq. (6) below. Using the same representation, the Dyson's equation for the single-quasiparticle Green's function can be formulated as follows:

$$\sum_{\eta=\pm1;k}\Big((\varepsilon-\eta_1E_{k_1})\delta_{\eta_1\eta}\delta_{k_1k}-\Sigma^{(e)\eta_1\eta}_{k_1k}(\varepsilon)\Big)G^{\eta\eta_2}_{kk_2}(\varepsilon)=\delta_{\eta_1\eta_2}\delta_{k_1k_2}. \qquad (2)$$

By solving this equation, as described in detail in Ref. [48], one can obtain the energies of the fragmented states $E^{(\nu)}_k$ and the corresponding spectroscopic factors $S^{(\nu)}_k$, which characterize the probability of occupying the levels $E^{(\nu)}_k$ by quasiparticles.

In the following we will focus on the isospin structure of the self-energy of Eq. (1). It represents the lowest-order phonon polarization correction to the single-particle propagator and contains already an infinite sum of the diagrams dressing the fermionic line. If the summation is performed for the ring type of diagrams, the vertices γ_μ and frequencies Ω_μ are approximated by an R(Q)RPA phonon solution. Formally, the sum in Eq. (1) runs over all possible intermediate nucleonic states k. The common practice is to include only the states k of the same isospin as the one of the external states k_1, k_2. In the relativistic framework, this practice leads to a very good description of the single-quasiparticle spectra in open-shell nuclei, compared to data, and to a considerable improvement of the results in the closed shell nuclei, although in the latter case