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Self-consistent relativistic QRPA studies of soft modes and spin-isospin resonances in unstable nuclei

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Abstract. The excitation phenomena in unstable nuclei are investigated in the framework of the relativistic quasiparticle random-phase approximation (RQRPA) in the relativistic Hartree-Bogoliubov model (RHB) which is extended to include effective interactions with explicit density-dependent meson-nucleon couplings. The properties of the pygmy dipole resonance (PDR) are examined in ^{132}Sn and within isotopic chains, showing that already at moderate proton-neutron asymmetry the PDR peak energy is located above the neutron emission threshold. A method is suggested for determining the size of the neutron skin within an isotopic chain, based on the measurement of the excitation energies of the Gamow-Teller resonance relative to the isobaric analog state. In addition, for the first time the relativistic RHB + RQRPA model, with tensor ω meson-nucleon couplings, is employed in calculations of β-decay half-lives of nuclei of the relevance for the r-process.

PACS. 21.60.Jz Hartree-Fock and random-phase approximations – 21.30.Fe Forces in hadronic systems and effective interactions – 24.10.Jv Relativistic models

1 Introduction

Studies of excitation phenomena and β-decay rates in nuclei away from the valley of β-stability provide a sensitive test for theoretical models of nuclear structure, and relevant input for nuclear astrophysical applications. Of particular importance is a quantitative description of nuclear masses, (n,γ) and (γ,n) rates, α- and β-decay half-lives, fission probabilities, electron and neutrino capture rates, and excitations. A well known example of an exotic excitation mode is the low-lying 1^- excited state in neutron-rich nuclei. As one moves away from the valley of β-stability towards the neutron-rich side, modification of the effective nuclear potential results with the appearance of the neutron skin and halo structures. Excitations in these nuclei may give rise to the existence of pygmy dipole resonance (PDR), when loosely bound neutrons coherently oscillate against the isospin saturated proton-neutron core [1,2,3]. The evidence of the low-energy $E1$ strength has been provided in electromagnetic excitations in heavy-ion collisions in oxygen isotopes [4], and via (γ,γ') scattering in lead isotopes [5,6,7], and $N = 82$ [8,9,10] isotone chain. The properties of PDR are closely related to the size of the neutron skin [11,12], and are of a particular importance in the calculations of cross-sections for radiative neutron capture in the r-process [13,14]. There is still some discussion on the issue whether the PDR corresponds to a collective, or non-collective excitation phenomena [15,16,17, 18,19]. The β-decay process in neutron-rich nuclei is of a particular importance, because it generates elements with higher Z-values, and sets the time scale for the r-process. Due to the lack of experimental data, β-decay rates of most r-process nuclei have to be determined from various theoretical models. A consistent microscopic treatment of the β-decay in exotic nuclei is therefore necessary. Two microscopic approaches have been successfully applied in large-scale modeling of weak interaction rates: the shell-model [20,21,22] and the proton-neutron quasiparticle random-phase approximation (PN-QRPA) [23,24]. In comparison to the shell model, there are important advantages of a QRPA approach based on the microscopic self-consistent mean-field framework: it includes the use of global effective nuclear interactions and enables the treatment of arbitrarily heavy systems. In this work we present an analysis of the low-lying excitation modes, spin-isospin resonances, and β-decay process in the framework of the relativistic quasiparticle random-phase approximation.

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2 The relativistic quasiparticle random-phase approximation

A consistent and unified treatment of mean-field and pairing correlations is crucial for a quantitative analysis of ground state properties and multipole response of nuclei away from the line of β-stability. In ref. [19], we have formulated the relativistic quasiparticle random-phase approximation (RQRPA) in the canonical single-nucleon basis of the relativistic Hartree-Bogoliubov (RHB) model. The RHB model presents the relativistic extension of the Hartree-Fock-Bogoliubov framework, and provides a unified description of particle-hole (ph) and particle-particle (pp) correlations. In this framework the ground state of a nucleus can be written either in the quasiparticle basis as a product of independent quasiparticle states, or in the canonical basis as a highly correlated BCS-state. By definition, the canonical basis diagonalizes the density matrix and it is always localized. It describes both the bound states and the positive-energy single-particle continuum. The formulation of the RQRPA in the canonical basis is particularly convenient because, in order to describe transitions to the low-lying excited states in weakly bound nuclei, the two-quasiparticle configuration space must include states with both nucleons in the discrete bound levels, states with one nucleon in a bound level and one nucleon in the continuum, and also states with both nucleons in the continuum. The pairing correlations in the RHB model are described by the finite range Gogny interaction D1S [25].

The relativistic QRPA of ref. [19] is fully self-consistent. For the interaction in the particle-hole channel effective Lagrangians with nonlinear meson self-interactions have been used, and pairing correlations have been described by the pairing part of the finite range Gogny interaction. Both in the ph and pp channels, the same interactions are used in the RHB equations that determine the canonical quasiparticle states, and in the matrix equations of the RQRPA. This is an essential feature of our calculations, and it ensures that RQRPA amplitudes do not contain spurious components associated with the mixing of the nucleon number in the RHB ground state (for 0^+ excitations), or with center-of-mass translational motion (for 1^- excitations). The RQRPA configuration space includes also the Dirac sea of negative energy states.

Relativistic mean-field and RPA calculations based on effective Lagrangians with nonlinear meson self-interactions present not only a number of technical problems, but also the description of finite nuclei obtained with these effective interactions is not satisfactory, especially for isovector properties. Several recent analyses have shown that relativistic effective interactions with explicit density dependence of the meson-nucleon couplings provide an improved description of asymmetric nuclear matter, neutron matter, and nuclei far from stability. In ref. [26] we have extended the RHB model to include density dependent meson-nucleon couplings. The effective Lagrangian is characterized by a phenomenological density dependence of the σ, ω, and ρ meson-nucleon vertex functions, adjusted to properties of nuclear matter and finite nuclei. It has been shown that, in comparison with standard RMF effective interactions with nonlinear meson-exchange terms, the new density-dependent meson-nucleon force DD-ME1 significantly improves the description of asymmetric nuclear matter and of ground-state properties of $N \neq Z$ nuclei. This is, of course, very important for the extension of RMF-based models to exotic nuclei far from β-stability, and for applications in the field of nuclear astrophysics.

3 Soft dipole mode in neutron rich nuclei

The dipole response of very neutron-rich isotopes is characterized by the fragmentation of the strength distribution, its spreading into the low-energy region, and by mixing of isoscalar and isovector modes. The structure of the low-lying dipole strength changes with mass. While in relatively light nuclei the onset of dipole strength in the low-energy region is due to non-resonant independent single particle excitations of the loosely bound neutrons, in heavier nuclei low-lying dipole states appear that are characterized by a more distributed structure of the RRPA amplitude [18]. Among several peaks characterized by single particle transitions, a single collective dipole state, known as the pygmy dipole resonance (PDR) is identified below 10 MeV. Its amplitude represents a coherent superposition of many neutron particle-hole configurations. A typical example of PDR is obtained in ^{132}Sn. The corresponding strength distribution for DD-ME1 interaction results with a characteristic peak of the isovector giant dipole resonance (IVGDR) at 15.2 MeV. In addition, among several dipole states in the low-energy region between 7 MeV and 10 MeV that are characterized by single particle transitions, at 7.8 MeV a single pronounced peak is found with a more distributed structure of the RQRPA amplitude, exhausting 1.6% of the energy weighted sum rule (EWSR), where EWSR $= (1+\kappa)$TRK. Here TRK corresponds to the classical Thomas-Reiche-Kuhn sum rule [27], and the enhancement factor from calculation equals $\kappa = 0.35$. The peak at 7.8 MeV is composed mainly of 11 neutron ph transitions from loosely bound orbits, each contributing more than 0.1% to the total RRPA amplitude $\sum_{\tilde{p}h} |X^{\nu}_{\tilde{p}h}|^2 - |Y^{\nu}_{\tilde{p}h}|^2 = 1$, where X^{ν} and Y^{ν} are RRPA eigenvectors. The low-lying pygmy state does not belong to statistical $E1$ excitations sitting on the tail of the GDR, but represents a fundamental structure effect: the neutron skin oscillates against the core.

The fully self-consistent RHB + RQRPA model with DD-ME1 + D1S combination of effective interactions is also employed in a microscopic description of low-lying dipole excitations for Pb isotopic chain. The PDR strength in Pb isotopes is always concentrated in one peak. The corresponding peak energies are displayed in fig. 1, together with the neutron separation energies. The RQRPA calculations predicts a very weak mass dependence of the PDR excitation energies. The interesting result here is that for Pb isotopes $A < 208$ the PDR excitation energies are lower than the corresponding one-neutron separation energies, whereas for $A > 208$ the pygmy resonance is located above

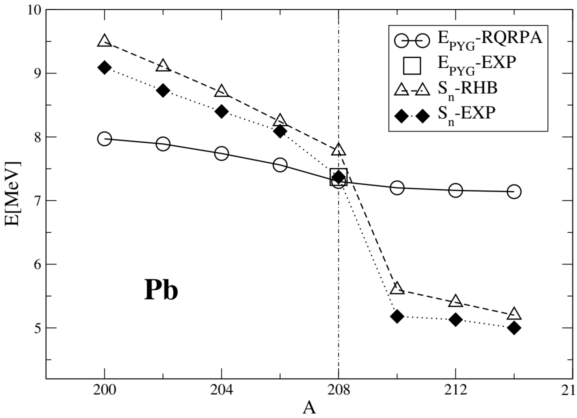

Fig. 1. The calculated PDR peak energies and the one-neutron separation energies for Pb isotopes, as functions of the mass number. The open square denotes the experimental position of the PDR in ^{208}Pb [5]. The RHB results for the neutron separation energies are compared with the experimental values [28].

the neutron emission threshold. These results imply that in isotopes heavier than ^{208}Pb the observation of the PDR in (γ, γ') experiments will be strongly hindered. The crossing point between the PDR and the one-neutron separation energy, which is calculated at $A = 208$, is in excellent agreement with the recent experimental data on the PDR in ^{208}Pb [5]. Future (γ, γ') experiments on Pb nuclei could confirm the other predictions of the RHB + RQRPA analysis [29].

4 Spin-isospin resonances and the neutron skin in nuclei

The determination of neutron density distribution in nuclei provides not only basic nuclear structure information, but it also places important additional constraints on effective interactions used in nuclear models. Recently, we have suggested a new method for determining the difference between the radii of the neutron and proton density distributions along an isotopic chain, based on measurement of the excitation energies of the Gamow-Teller resonances (GTR) relative to the isobaric analog resonances (IAR) [30]. In this analysis we employ the self-consistent RHB plus proton-neutron (PN) RQRPA [31] to calculate the GTR and IAR in the Sn isotopic chain. The RMF effective interaction is DD-ME1. The π- and ρ-meson exchange generate the spin-isospin dependent terms in the *ph* residual interaction ($m_\pi = 138\,\mathrm{MeV}, f_\pi^2/4\pi = 0.08$). The Landau-Migdal zero-range force in the spin-isospin channel is also included in the residual interaction with the strength parameter $g' = 0.55$. In the $T = 1$ *pp* channel of the PN-RQRPA we use the D1S Gogny interaction. For the $T = 0$ proton-neutron pairing we employ a similar interaction which consists of a short-range repulsive Gaussian with a weaker longer-range attractive Gaussian. The only free parameter, the overall strength, is set to $V_0 = 250\,\mathrm{MeV}$. In fig. 2 we display the calculated differences between the centroids of the direct spin-flip GT strength and the respective isobaric analog resonances for the sequence of even-even Sn target nuclei in comparison with experimental data [32]. The energy difference between the GTR and the IAR reflects the magnitude of the effective spin-orbit potential, and therefore it is closely related to the proton and neutron density distributions in nuclei. A uniform dependence of the energy spacings between the GTR and IAR on the size of the neutron skin can be observed. In principle, therefore, the value of $r_n - r_p$ can be determined from the theoretical curve for a given value of $E_{\mathrm{GTR}} - E_{\mathrm{IAR}}$. Of course, this necessitates implementation of a model which reproduces the experimental values of the $r_n - r_p$, as it is displayed for Sn isotopes in the lower panel of fig. 2.

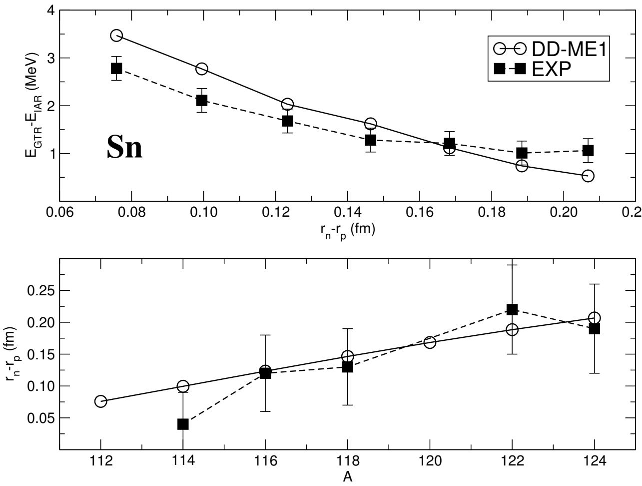

Fig. 2. The PN-RQRPA and experimental [32] differences between the excitation energies of the GTR and IAR, as a function of the calculated differences between the r.m.s. radii of the neutron and proton density distributions of even-even Sn isotopes (upper panel). In the lower panel the calculated differences $r_n - r_p$ are compared with experimental data [33].

5 β-decay rates of r-process nuclei

The low-lying GT strength distribution, crucial in the description of the β-decay lifetimes, is very sensitive to the single-quasiparticle levels that enter the calculations. In order to reproduce the data on β-decay lifetimes, the relativistic description of single-particle energies around the Fermi surface has to be improved. The inclusion of the ω-meson tensor coupling to nucleon enables the enhancement of the nucleon effective mass, while still retaining a good description of the spin-orbit splitting. We have constructed a new density-dependent effective interaction DD-ME1*, with the value of the nucleon effective mass $m^* = 0.76m$. In addition, the low-lying Gamow-Teller strength strongly depends on the proton-neutron pairing in the residual *pp* QRPA interaction [23]. In the $T = 0$ and $T = 1$ *pp* channel of the residual interaction we use the force described in sect. 4. The overall strength parameter $V_0 = 225\,\mathrm{MeV}$ is adjusted to reproduce the half-life of ^{130}Cd.

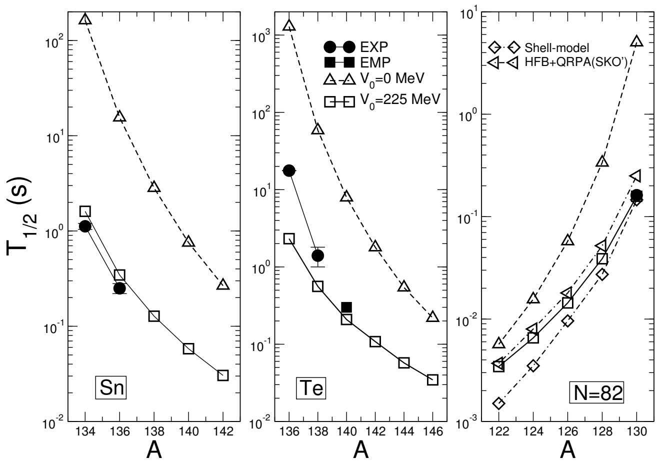

Fig. 3. Calculated half-lives of Sn and Te isotopes with ($V_0 = 225\,\mathrm{MeV}$), and without ($V_0 = 0\,\mathrm{MeV}$) $T = 0$ pairing, in comparison with experimental data [34,35]. In the right panel the results for the $N = 82$ isotones are compared with the shell-model [36], and non-relativistic HFB + QRPA results [23].

In fig. 3 we display β-decay half-lives in Sn and Te isotopes, and $N = 82$ isotones, in comparison to the available empirical data and the results of similar nonrelativistic mean-field [23] and shell-model [36]. The particular choice of the $T = 0$ pairing strength $V_0 = 225\,\mathrm{MeV}$ results in β-decay half-lives which overestimate the empirical data for Sn isotopes, while the ones for Te isotopes are slightly underestimated. For $N = 82$ isotones, our results are in good agreement with the results obtained in similar non-relativistic QRPA study [23], whereas the shell-model predicts somewhat shorter half-lives [36].

6 Conclusions

The RHB + (PN-)RQRPA model with density dependent effective meson-nucleon couplings has been employed in an analysis of the low-lying excitation modes, spin-isospin resonances, and β-decay process. We have demonstrated that the one-neutron separation energies along Pb isotope chain decrease much faster than the PDR excitation energies. As a result, the PDR energy is located above the neutron emission threshold for $A > 208$. This implies that the experimental observation of the PDR will be strongly hindered in these isotopes. In addition, it has been shown that the energy spacings between the GTR and IAR provide direct information on the evolution of neutron skin-thickness along the Sn isotopic chain. In principle, the value of $r_n - r_p$ could be determined from the theoretical curve for a given value $E_{\mathrm{GTR}} - E_{\mathrm{IAR}}$. Finally, we have applied the PN-RQRPA in the description of the weak interaction rates. The resulting β-decay half lives are in good agreement with both the available empirical data and the results obtained in previous studies of the β-decay process.

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