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Relativistic mean-field models with medium-dependent meson-nucleon couplings

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Abstract. Microscopic structure models based on the relativistic mean-field approximation have been extended to include effective Lagrangians with explicit density-dependent meson-nucleon couplings. In a number of recent studies it has been shown that this class of global effective interactions provides an improved description of asymmetric nuclear matter, neutron matter and finite nuclei far from stability.

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The self-consistent mean-field framework enables a description of the nuclear many-body problem in terms of universal energy density functionals. By employing global effective interactions, adjusted to empirical properties of symmetric and asymmetric nuclear matter, and to bulk properties of few spherical nuclei, self-consistent mean-field models have achieved a high level of accuracy in the description of ground states and properties of excited states in arbitrarily heavy nuclei. A universal energy density functional theory should provide a basis for a consistent microscopic treatment of infinite nuclear and neutron matter, ground-state properties of all bound nuclei, low-energy excited states, small-amplitude vibrations, and reliable extrapolations toward the drip lines.

An important class of self-consistent mean-field models belongs to the framework of relativistic mean-field theory (RMF). The RMF framework has recently been extended to include effective Lagrangians with density-dependent meson-nucleon vertex functions. The functional form of the meson-nucleon vertices can be deduced either by mapping the nuclear matter Dirac-Brueckner nucleon self energies in the local density approximation, or a phenomenological approach can be adopted, with the density dependence for the σ-, ω- and ρ-meson–nucleon couplings adjusted to properties of nuclear matter and a set of spherical nuclei.

We have recently adjusted two new phenomenological density-dependent interactions to be used in RMF + BCS, relativistic Hartree-Bogoliubov (RHB), and quasiparticle random phase approximation (RQRPA) calculations of ground states and excitations of spherical and deformed nuclei. The eight independent parameters: seven coupling parameters and the mass of the σ-meson, have been adjusted to reproduce the properties of symmetric and asymmetric nuclear matter, binding energies, charge radii and neutron radii of spherical nuclei. In ref. [1] we introduced the density-dependent meson-exchange effective interaction (DD-ME1). It has been shown that, as compared to standard non-linear relativistic mean-field effective forces, the interaction DD-ME1 has better isovector properties and therefore provides an improved description of asymmetric nuclear matter, neutron matter and nuclei far from stability. The DD-ME1 interaction has recently been also tested in the calculation of deformed nuclei [2].

In refs. [3,4] we employed the RQRPA in a series of calculations of giant resonances in spherical nuclei. Starting from DD-ME1, and by constructing families of interactions with some given characteristic (compressibility, symmetry energy, effective mass), it has been shown how the comparison of the RQRPA results on multipole giant resonances with experimental data can be used to constrain the parameters that characterize the isoscalar and isovector channel of the density-dependent effective interactions. In particular, in ref. [4] we have shown that the comparison of the calculated excitation energies with the experimental data on the giant monopole resonances (GMR) restricts the nuclear matter compression modulus to $K_{\rm nm} \approx 250$–270 MeV. The isovector giant dipole resonance (IVGDR) in ^{208}Pb, and the available data on differences between neutron and proton radii, limit the range of the nuclear matter symmetry energy at saturation (volume asymmetry) of these effective interactions to 32 MeV $\leq a_4 \leq$ 36 MeV. The interaction DD-ME1 has

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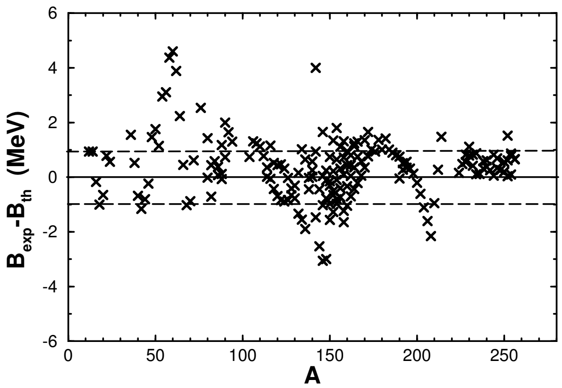

Fig. 1. Absolute deviations of the binding energies calculated with the DD-ME2 interaction from the experimental values [5].

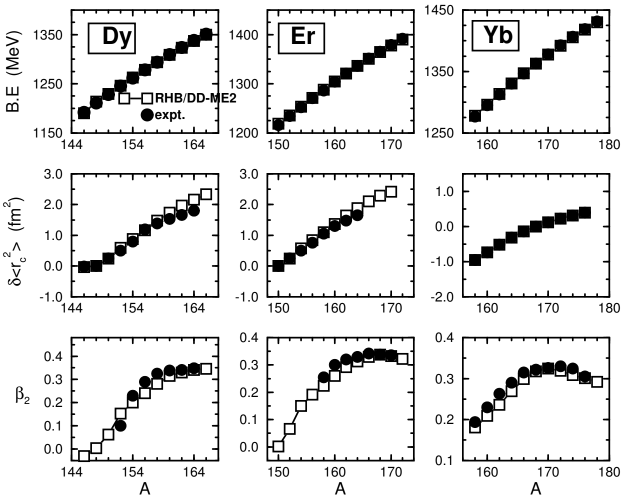

Fig. 2. The binding energies [5], charge isotope shifts [6], and quadrupole deformation parameters [7] of the Dy, Er and Yb isotopes, compared with predictions of the RHB model with the DD-ME2 plus Gogny D1S interactions.

also been employed in the proton-neutron RQRPA analysis of charge-exchange modes: isobaric analog resonances and Gamow-Teller resonances in spherical nuclei [8].

Taking into account these results, a new global effective interaction DD-ME2 has been tested in ref. [9]. Similar to the case of DD-ME1, the parameters have been adjusted to a set of twelve spherical nuclei. For DD-ME2, in addition, data on excitation energies of isoscalar GMR and IVGDR have been used. The interaction has been adjusted to the excitation energies of the ISGMR and IVGDR in ^{208}Pb, which practically do not display any fragmentation. The calculated centroid energy of 12.1 MeV for the isoscalar giant quadrupole resonance in ^{208}Pb, compared to the empirical excitation energy 10.9 ± 0.3 MeV [10], reflects the rather low effective nucleon mass. DD-ME1 and DD-ME2 display very similar equations of state for symmetric nuclear matter, the symmetry energies as function of the nucleon density, and the neutron matter equations of state. In general, when compared with the results obtained with DD-ME1 [1,2,3], DD-ME2 improves the agreement with experimental data on ground-state

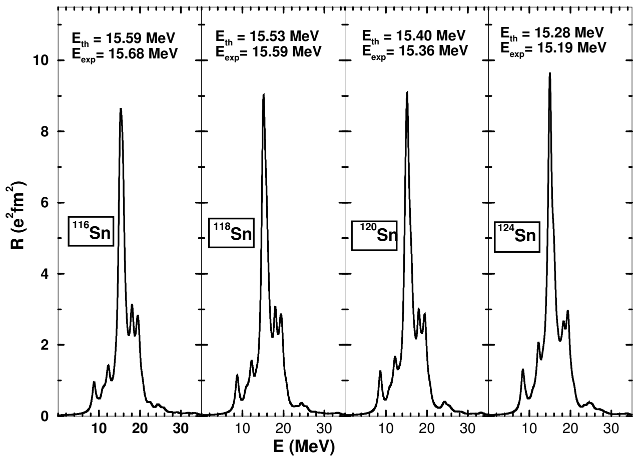

Fig. 3. The isovector dipole strength distributions in ^{116,118,120,124}Sn. The experimental excitation energies for the Sn isotopes are compared with the RHB + RQRPA results calculated with the DD-ME2 effective interaction.

properties of spherical and deformed nuclei, and excitation energies of giant resonances in spherical nuclei. In the following figures we present several illustrative results obtained with the DD-ME2 effective interaction. The theoretical binding energies of approximately 200 nuclei calculated in the RHB model with the DD-ME2 plus Gogny D1S interactions, are compared with experimental values in fig. 1. The rms error including all the masses shown in the figure is less than 900 keV. The predictions for the total binding energies, charge isotope shifts, and ground-state quadrupole deformation parameters of three rare-earth isotopic chains Dy, Er and Yb, are shown in comparison with experimental results in fig. 2. Finally, in fig. 3 we compare the RQRPA results for the isovector dipole response of Sn isotopes with experimental data on IVGDR excitation energies [11].

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