Ground-state properties of rare-earth nuclei in the relativistic Hartree-Bogoliubov model with density-dependent meson-nucleon couplings

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The relativistic mean-field effective interaction with density-dependent meson-nucleon couplings DD-ME1 is tested in the calculation of deformed nuclei. Ground-state properties of six isotopic chains $(60 \leqslant Z \leqslant 70)$ in the region of rare-earth nuclei are calculated by using the relativistic Hartree-Bogoliubov (RHB) model with the DD-ME1 mean-field interaction, and with the Gogny D1S force for the pairing interaction. Results of fully self-consistent RHB calculations for the total binding energies, charge isotope shifts, and quadrupole deformation parameters are compared with the available empirical data.

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Relativistic mean-field (RMF) models have been very successfully employed in analyses of a variety of nuclear structure phenomena, not only in nuclei along the valley of β stability, but also in exotic nuclei with extreme isospin values and close to the particle drip lines. The relativistic Hartree-Bogoliubov (RHB) model [1], based on the relativistic mean-field theory and on the Hartree-Fock-Bogoliubov framework, provides a unified description of mean-field and pairing correlations, which is particularly important for the structure of very weakly bound nuclei close to the particle drip lines. An interesting alternative to the highly successful RMF models with nonlinear meson self-interaction terms is an effective hadron field theory with medium dependent meson-nucleon vertices. Such an approach retains the basic structure of the relativistic mean-field framework, but can be more directly related to the underlying microscopic description of nuclear interactions. In particular, the density-dependent relativistic hadron field model [2] has been successfully applied in the calculation of nuclear matter and ground-state properties of spherical nuclei [3], and extended to hypernuclei [4], neutron star matter [5], and asymmetric nuclear matter and exotic nuclei [6]. In Ref. [7] we have extended the relativistic Hartree-Bogoliubov 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. The DD-ME1 effective interaction has been introduced and tested in the analysis of the equations of state for symmetric and asymmetric nuclear matter, and of ground-state properties of the Sn and Pb isotopic chains. It has been shown that, when compared to results obtained with standard nonlinear relativistic mean-field effective forces, the DD-ME1 interaction provides an improved description of asymmetric nuclear matter and of ground-state properties of $N \neq Z$ nuclei. In Ref. [8] we have also shown that the relativistic random phase approximation with the DD-ME1 effective interaction reproduces the experimental excitation energies of multipole giant resonances in spherical nuclei.

Relativistic density-dependent effective mean-field interactions have never before been used in the calculation of deformed nuclei. Of course, the structure of deformed nuclei presents an important test for every effective interaction. Ground-state properties, in particular, are sensitive to the isovector channel of effective interaction, to the spin-orbit term of the effective single-nucleon potentials, and to the effective mass. For example, in Ref. [9] the standard NL3 nonlinear meson-exchange interaction [10] has been employed in a detailed RMF analysis of ground-state properties of 1315 even-even nuclei $(10 \leqslant Z \leqslant 98)$, and it has been shown that this interaction produces very good results for deformed nuclei.

In this Brief Report we test the DD-ME1 effective interaction in the region of rare-earth nuclei. We compare predictions of the RHB model for the total binding energies, charge isotope shifts, and ground-state quadrupole deformations of six even-Z isotopic chains $(60 \leqslant Z \leqslant 70)$, with available empirical data. The DD-ME1 effective interaction is used in the particle-hole (p-h) channel, and pairing correlations are described by the pairing part of the finite range Gogny D1S interaction [11]. The RHB equations are solved self-consistently, with potentials determined in the mean-field approximation from solutions of Klein-Gordon equations for the meson fields. The Dirac-Hartree-Bogoliubov equations and the Klein-Gordon equations are solved by expanding the nucleon spinors and the meson fields in terms of eigenfunctions of a deformed axially symmetric oscillator potential [12]. The number of oscillator shells in the expansion is 12 for nucleon fields and 20 for meson fields [13].

The predictions of the RHB model for the total binding energies of the Nd, Sm, Gd, Dy, Er, and Yb isotopes are

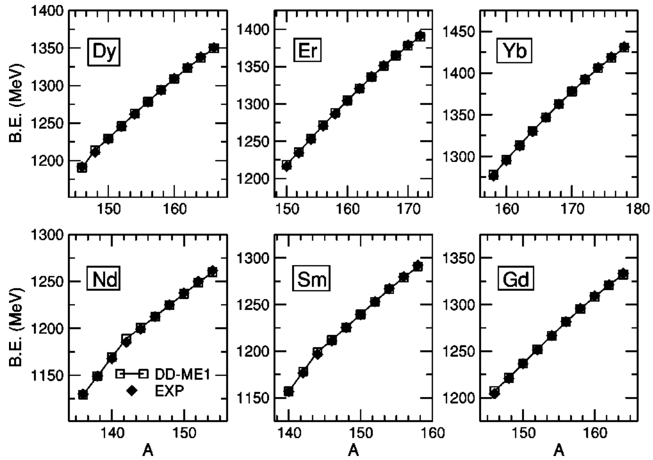

FIG. 1. The binding energies of Nd, Sm, Gd, Dy, Er, and Yb isotopes, calculated in the RHB model with the DD-ME1 interaction, are compared with experimental data [14].

shown in Fig. 1, in comparison with the experimental data [14]. We notice a very good agreement over the entire region of rare-earth nuclei. The maximum deviation of the calculated binding energies is below 0.1% for all isotopes, except ^{142}Nd, ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er. For these nuclei the deviation from experimental binding energies is 0.2%.

In Fig. 2 we compare the theoretical values for the charge isotope shifts with the data from Ref. [15]. The charge density is obtained by folding the calculated point-proton density distribution with the Gaussian proton-charge distribution. For the latter a rms radius of 0.8 fm is used, and the resulting ground-state charge radius reads

$$r_c = \sqrt{r_p^2 + 0.64} \quad \text{fm}, \tag{1}$$

where r_p is the radius of the point-proton density distribution. The isotope shifts are calculated with respect to a reference nucleus in each isotopic chain

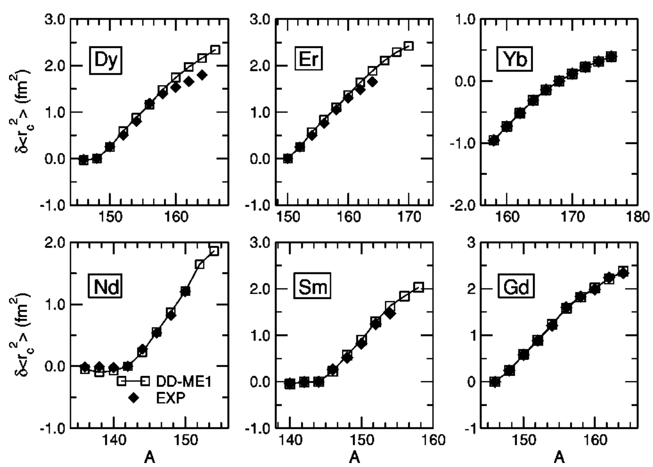

FIG. 2. Charge isotope shifts of Nd, Sm, Gd, Dy, Er, and Yb isotopes. The results of the RHB calculation with the DD-ME1 effective interaction, and with the Gogny D1S interaction in the pairing channel, are compared with empirical data [15].

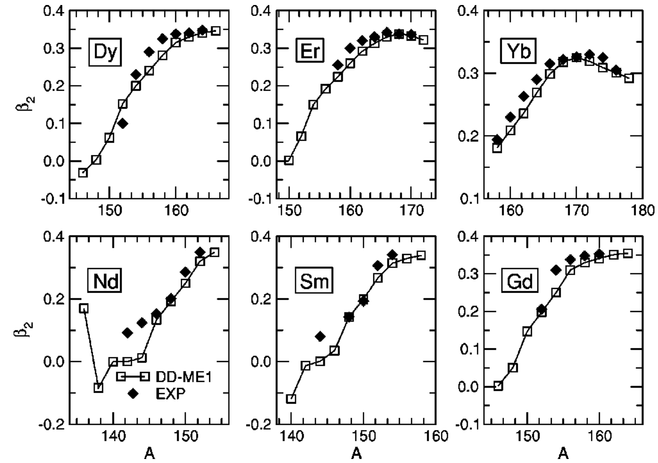

FIG. 3. Comparison between the DD-ME1 predictions for the ground-state quadrupole deformation parameters of the Nd, Sm, Gd, Dy, Er, and Yb isotopes, and empirical data [16].

$$\delta r_{ch}^2 = r_{ch}^2 - r_{ch}^2(\text{ref}). \tag{2}$$

The reference nucleus is the $N=82$ isotope, except for the chains Dy and Yb, for which the reference nuclei are ^{156}Dy and ^{168}Yb, respectively. The calculated charge radii reproduce in detail the empirical isotope shifts. A slight deviation from the empirical trend is observed only for heavier Dy nuclei. However, even for ^{164}Dy the deviation of the theoretical charge radius from the empirical value is only 0.3%.

The ground-state quadrupole and hexadecupole deformation parameters β_2 and β_4 are calculated according to the prescription of Ref. [17]. The theoretical values of the quadrupole deformation parameters are displayed in Fig. 3, in comparison with the empirical data from Ref. [16]. We notice that the RHB results reproduce not only the global trend of the data, but also the saturation of quadrupole deformation for heavier isotopes.

In conclusion, we have applied the RHB model with the density-dependent meson-nucleon couplings to the analysis of ground-state properties of six isotopic chains $(60 \leqslant Z \leqslant 70)$ in the region of rare-earth nuclei. The DD-ME1 effective interaction has been used in the p-h channel, and pairing correlations have been described by the pairing part of the finite range Gogny D1S interaction. An excellent agreement has been obtained in comparison with empirical data on total binding energies, charge isotope shifts, and quadrupole deformation parameters. These results show that relativistic mean-field interactions with explicit density dependence of the meson-nucleon couplings, and in particular the DD-ME1 effective interaction, provide an accurate description of the structure of deformed nuclei.

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