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2-D lattice HFB calculations for neutron-rich zirconium isotopes

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Abstract. Using the Hartree-Fock-Bogoliubov (HFB) mean-field theory in coordinate space, we investigate ground-state properties of the zirconium isotopes from the line of stability up to the two-neutron dripline ($^{102-122}$Zr). In particular, we calculate two-neutron separation energies, quadrupole moments, and r.m.s. radii for protons and neutrons. We find large prolate ground-state deformations for the isotopes ^{102}Zr through ^{112}Zr, and the spherical shapes starting from ^{114}Zr up to the dripline nucleus ^{122}Zr.

PACS. 21.60.-n Nuclear structure models and methods – 21.60.Jz Hartree-Fock and random-phase approximations

1 Introduction

The neutron-rich $A \sim 100$ region is known for its competition between various coexisting nuclear shapes. The isotopes in this region are produced in the fission of transuranic elements and have been studied via γ-ray spectroscopy techniques. Among these are the zirconium isotopes which possess rapidly changing nuclear shapes when the neutron number changes from 56 to 60 [1].

In this paper we study the ground-state properties of neutron-rich zirconium nuclei. For this purpose, we solve the Hartree-Fock-Bogoliubov (HFB) equations for deformed, axially symmetric nuclei in coordinate space on a 2-D lattice [2,3]. Recently, triple-gamma coincidence experiments have been carried out with Gammasphere at LBNL [4] which have determined half-lives and quadrupole deformations of several neutron-rich zirconium, cerium, and samarium isotopes. Furthermore, laser spectroscopy measurements [5] for zirconium isotopes have yielded precise r.m.s. radii in this region. These medium-mass nuclei are among the most neutron-rich isotopes ($N/Z \approx 1.6$) for which spectroscopic data are available. It is therefore of great interest to compare these data with the predictions of the self-consistent HFB mean-field theory. In our calculations we find large ground-state prolate deformations and the spherical shapes as well. The same results were also obtained by calculations, which utilize the Transformed Harmonic Oscillator basis (THO) approach [6].

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2 Results

We have solved, for the first time, the computationally challenging Hartree-Fock-Bogoliubov (HFB) continuum problem for deformed, axially symmetric even-even nuclei in coordinate space on a 2-D lattice, without any further approximations. Our computational technique (Basis-Spline collocation and Galerkin method) [7,8,9,10,11,12] is particularly well suited to study ground-state properties of nuclei near the driplines. The unique feature of our HFB code is that it treats the continuum wave functions consistently on the lattice and takes into account the strong coupling to high-energy continuum states, up to an equivalent single-particle energy of 60 MeV or higher.

For the p-h channel, the Skyrme (SLy4) effective N-N interaction is utilized, and for the p-p and h-h channel we use a delta interaction. For axially symmetric nuclei, we diagonalize the HFB Hamiltonian separately for fixed isospin projection q and angular-momentum quantum number Ω (typically up to 21/2). For fixed values of q and Ω, we obtain $4 \cdot N_r \cdot N_z$ eigenstates, typically up to 1000 MeV. In particular, we recently calculated the properties of the zirconium ($^{102-122}$Zr) isotope chain up to the two-neutron dripline.

Figure 1 shows the calculated two-neutron separation energies for the zirconium isotope chain. The dripline is located where the separation energy becomes zero. As one can see our HFB calculations predict the dripline nucleus to be at mass number 122. We also give a comparison with the latest available experimental data up to the isotope ^{110}Zr [13].

In fig. 2 we show the intrinsic proton and neutron quadrupole moments. We find very strong prolate deformations for the $^{102-112}$Zr isotopes and the spherical shapes for the remaining isotopes in the chain including

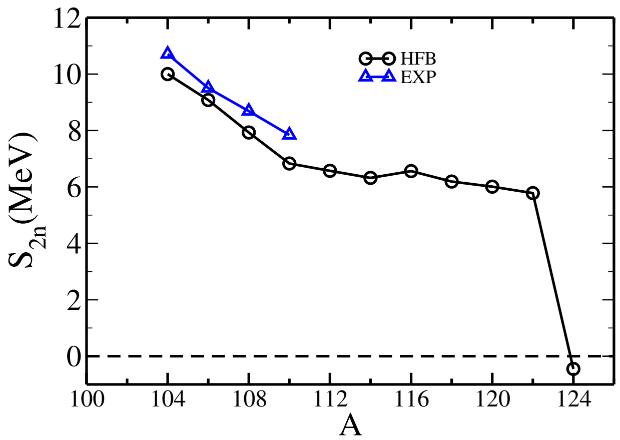

Fig. 1. Two-neutron separation energy.

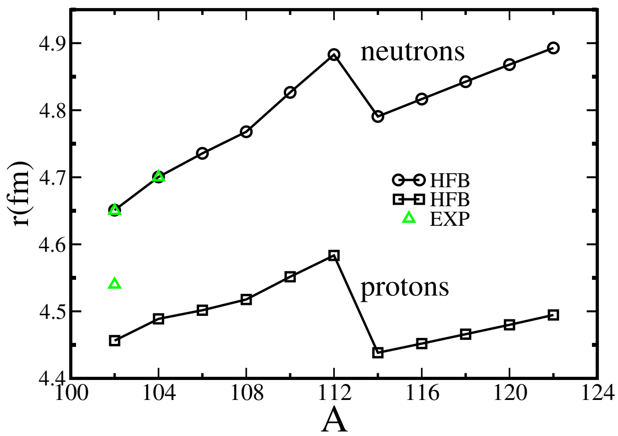

Fig. 3. The root-mean-square radii for the chain of zirconium isotopes.

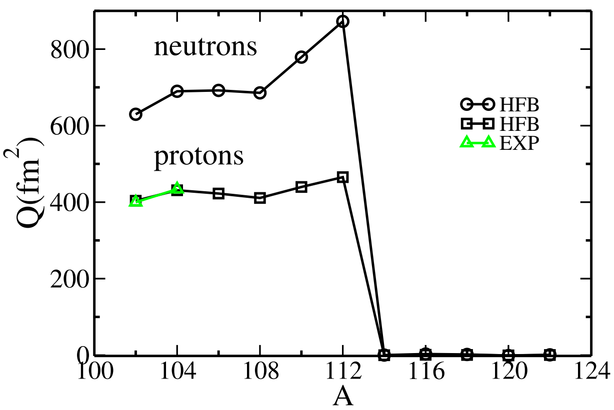

Fig. 2. Intrinsic quadrupole moment for protons and neutrons.

the dripline nucleus ^{122}Zr. Our HFB lattice code predicts the ^{112}Zr isotope to have the largest intrinsic ground-state quadrupole moment; for the corresponding quadrupole deformation parameter β_2 of the neutron density distribution we find the value 0.47. The experimental deformations for protons are available for two isotopes, ^{102}Zr and ^{104}Zr [4]. Our theoretical results for these two nuclei ($\beta_2 = 0.42, 0.43$) agree very well with the experimental data of $\beta_2^{102} = 0.42$, and $\beta_2^{104} = 0.45$.

In fig. 3 we plot the root-mean-square radii of protons and neutrons. We can clearly observe the presence of the neutron-skin manifested by the large differences between the neutron and proton r.m.s. radii for all of the isotopes in the chain. As expected the neutron-skin becomes "thicker" as we approach the dripline. Starting at the mass number $A = 114$ up to the dripline the nuclei prefer a spherical ground-state shape (fig. 2) which results in the sudden shrinking of the r.m.s. radius at $A = 114$.

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