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Odd–even staggering in neutron drip line nuclei

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Abstract

We have done systematic Hartree–Fock–Bogoliubov calculations in coordinate space on the one-quasiparticle energies and binding energy odd–even staggering (OES) in semi-magic nuclei with the zero-range volume, mixed and surface pairing forces in order to explore the influence of their density dependence. The odd-N isotopes are calculated within the blocking scheme. The strengths for the pairing forces are determined in two schemes by fitting locally to reproduce pairing gap in ^{120}Sn and globally to all available data on the OES of semi-magic nuclei with $Z \geq 8$. In the former calculations, there is a noticeable difference between the neutron mean gaps in neutron-rich O, Ca, Ni and Sn isotopes calculated with the surface pairing and those with the mixed and volume pairing. The difference gets much smaller if the globally optimized pairing strengths are employed. The heavier Pb isotopes show the opposite trend. Moreover, large differences between the mean gap and the OES may be expected in both calculations when one goes towards the neutron drip line.

Keywords: Nuclear pairing; Odd–even staggering; Hartree–Fock–Bogoliubov approach; Density dependence

1. Introduction

The study of highly unstable nuclei around the neutron drip line has been one of the most active research fields in nuclear physics in the past few decades (see Refs. [1–3] and references therein). The properties of those isotopes heavier than oxygen are mostly unknown and rely on the theoretical extrapolation based on models optimized for known nuclei. The predictions are

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also important inputs for the study of the astrophysical r-process. A challenging problem that one realizes is the strong deviation between theory and experiment and between different models that may occur when one goes toward those extreme cases with large N/Z ratio. The deviation is mostly related to our limited understanding of the theoretical uncertainty and the underlying effective nuclear force [4–8]. Significant efforts have been devoted to optimize the single-particle spectroscopy and binding energy prediction of various mean-field models [5,9–11]. For example, in recent studies, the uncertainties in predicting the location of neutron drip line as induced by the single-particle energy, pairing and the macroscopic symmetry energy at sub-saturation density are highlighted [12–14]. Extensive work has also been done in studying the pairing features of drip line nuclei in relation to the coupling involving loosely bound orbitals as well as the continuum. However, it is still difficult to constrain the property of the effective nuclear pairing interaction for which no universal form has been achieved.

The so-called density-dependent zero-range (or contact) pairing interaction has been widely used in nuclear mean field and density functional calculations due to its intrinsic simplicity. In its simplest form, the zero-range δ interaction is given by (see, e.g., Ref. [15] and references therein)

$$V_{pair}(\mathbf{r},\mathbf{r}') = V_0\left(1-\eta\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}-\mathbf{r}') \tag{1}$$

where V_0 is the pairing strength, $\rho(\mathbf{r})$ is the isoscalar nucleonic density and $\rho_0 = 0.16$ fm^{-3}. $\eta = 0$, 0.5 and 1 correspond to the so-called volume, mixed and surface pairing interactions, respectively. As it is defined, the surface pairing generates a pairing field peaked around the nuclear surface whereas the volume pairing is mainly active inside the nucleus. One question is how the density dependence of the zero range pairing interaction affects the pairing correlation. To address this issue, extensive calculations have been done within the Hartree–Fock (HF) plus BCS and Hartree–Fock–Bogoliubov (HFB) approaches. A systematic calculation of the odd–even staggering (OES) in binding energies has been done in Ref. [16] by using the HF+BCS approach with three different density dependent pairing forces as well as by using the HFB approach with the mixed pairing. No significant difference between different calculations was seen. A mixed pairing force is used in the systematic studies of Refs. [13,3] and Monte Carlo calculations in the configuration space (seniority-zero) in Refs. [17,18]. A surface pairing was used in recent calculations on the electric dipole strength of the nucleus ^{120}Sn [19] and the soft dipole excitations in neutron-rich O, Ca and isotopes [20]. Calculations with the volume pairing were also done in Ref. [20]. No noticeable difference between calculations with the two types of pairing forces of surface and volume was seen. HFB calculations for the isotopic chain $^{100-132}$Sn was given in Ref. [21] where it was found that the pairing density was insensitive to the density dependence of the pairing force. As commented in Ref. [15], one may not be able to extract reliable information on the density dependence of the effective pairing interaction from available data on the OES in nuclear binding energy.

One may expect that the different density dependence of the pairing force may lead to drastic differences of pairing fields at the nuclear surface in very neutron rich nuclei where weakly bound orbitals are coupled to the continuum, e.g., when one goes towards neutron-rich Sn isotopes beyond $N = 82$ [22–25]. In Ref. [26] the pairing vibrations in ^{124,36}Sn were analyzed with the HFB+QRPA approach where it was shown that neutron transition density and pairing vibration in the neutron-rich nucleus ^{136}Sn are more sensitive to the density dependence of the pairing than that in ^{124}Sn. A slight preference for the surface-peaked pairing was suggested in [16] based on binding energy systematics. Calculations on the α clustering on the nuclear surface of heavy nuclei also favors surface-enhanced pairing interaction [27,28]. The density dependence