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Interplay between proton-neutron pairing and deformation in self-conjugated medium mass nuclei

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Abstract

We employ a model combining self-consistent mean-field and shell-model techniques to study the competition between particle-like and proton-neutron pairing correlations in fp-shell even-even self-conjugate nuclei. Deformation effects are realistically and microscopically described. The resulting approach can give a precise description of pairing correlations and eventually treat the coexistence of different condensate formed of pairs with different total spin/isospin. The standard BCS calculations are systematically compared with approaches including correlation effects beyond the independent quasi-particle picture. The competition between proton-neutron correlations in the isoscalar and isovector channels is also analyzed, as well as their dependence on the deformation properties.

1 Introduction

The effect of correlation between nucleons of different spin and isospin, is expected to be more pronounced in self-conjugate nuclei, i.e., nuclei with the same number of protons (Z) and neutrons (N). High intensity radioactive beams will offer new possibilities to study the interplay of the isoscalar (T = 0) and isovector (T = 1) pairing interaction between protons and neutrons in these nuclei. By analyzing the relative energies of the T=0 and T=1 states in even-even and odd-odd nuclei [1] and the T = 0 band in ^{74}Rb [2], the role of isovector proton-neutron (p-n) pairing has been recently singled out in a quite clear way. The same kind of analysis does not support the existence of the isoscalar pairing. At the same time, recent experiments seem to manifest the possibility to observe exotic structures of aligned pairs [3] that could be explained in terms of isoscalar p-n pairing correlations. For a recent review, se for example [4].

From a theoretical point of view, several frameworks have been proposed to incorporate p-n pairing correlations [5–9]. Most often, these approaches, based on a mean field-type approximation, lead to a non-coexistence of particle-like and particle unlike pairing, as a consequence of the inherent particle number and isospin symmetries violations. Alternatively, shell-model calculations can go beyond the independent quasi-particle picture and provide a particle/isospin number conserving framework able to solve the pairing problem including all spin/isospin channels.

The aim of the present work is to combine mean-field and shell model techniques to study of the role of deformation on particle-like and p-n pairing. More precisely, a microscopic mean-field is used to obtain realistic single-particle energies and two-body residual pairing interactions. Then, pairing correlations are studied in spherical and deformed nuclei through direct diagonalization of the Hamiltonian in a restricted space. This framework allows for a realistic description of nuclear deformation necessary to analyze its influence on the role of pairing correlations in both channels.

2 Methodology and results

The first step of our approach consists in solving the the self-consistent Hartree-Fock + BCS equations in a three-dimensional mesh by using the *EV8* code [10, 11]. In Fig. 1 the mean-field energy for different even-even $N = Z$ nuclei is plotted (solid-red lines), as a function of the quadrupole deformation parameter β. Starting from the mean-field results, we construct then a two-body pairing Hamiltonian written as:

$$H = H_{\mathrm{s.p.}} + H_{10} + H_{01} \quad (1)$$

where $H_{\mathrm{s.p.}}$ is the independent particle contribution. H_{10} and H_{01} correspond to a pairing two-body Hamiltonian acting respectively in the

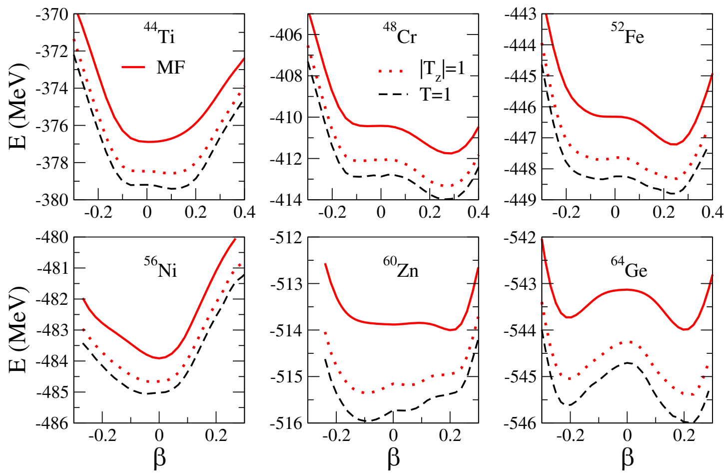

Figure 1: (Color online) Total energy as a function of the deformation parameter calculated in the mean-field (MF) approach (red-full line) is compared with different kind of SM calculations: $|T_z| = 1$ results (red-dotted line) where only particle like pairing is considered and $T = 1$ (black-dashed line) where all the components of the isovector pairing are included.

$(T = 1, S = 0)$ and $(T = 0, S = 1)$ channels. In our scheme, it is possible to identify pairs of time-reversed states that enters into the $T = 1$ channels as well as in the $(T = 0, S_z = 0)$ channel. Due to the specific space symmetry used in the *EV8* code, the interaction matrix elements in $T = 0$, $S_z = \pm 1$ cannot be easily restricted to $J = 0$ and $J = 1$. For this reason, only the $S_z = 0$ component is considered here. Therefore we consider the isovector pair operators:

$$P_1^\dagger(k) = \nu_k^\dagger \nu_{\bar{k}}^\dagger \quad P_{-1}^\dagger(k) = \pi_k^\dagger \pi_{\bar{k}}^\dagger, \quad P_0^\dagger(k) = (\nu_k^\dagger \pi_{\bar{k}}^\dagger + \pi_k^\dagger \nu_{\bar{k}}^\dagger)/\sqrt{2} \qquad (2)$$

and the isoscalar one:

$$D_0^\dagger(k) \quad = \quad (\nu_k^\dagger \pi_{\bar{k}}^\dagger - \pi_k^\dagger \nu_{\bar{k}}^\dagger)/\sqrt{2}. \qquad (3)$$

Different types of Shell Model (SM) calculations will be performed in order to single out specific effects:

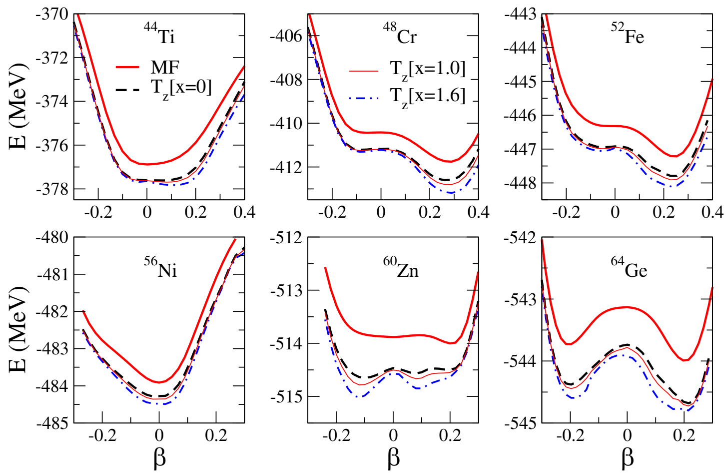

Figure 2: (Color online) Total energy as a function of the deformation obtained using only p-n pairing in the T=1 channel (black-dashed line, $T_z[x=0]$), including also the isoscalar one with equal strength ,(thin-solid red line, $T_z[x=1]$) and using the more realistic value $x = 1.6$ (blue dot-dashed line, $T_z[x=1.6]$). The results obtained in the mean-field (MF) calculations are plotted for comparison.

- particle-like pairing: only n-n and p-p pairing are treated by considering the Hamiltonian

$$H = H_{s.p.} + \sum_{i\neq j,T_z=\pm1} V_{ij}^{10} P_{T_z}^{\dagger}(i) P_{T_z}(j). \qquad (4)$$

  The corresponding SM calculations will be denoted as $|T_z| = 1$;

- full isovector-pairing: The Hamiltonian includes the full $T = 1$ component

$$H = H_{s.p.} + \sum_{i\neq j,T_z=0,\pm1} V_{ij}^{10} P_{T_z}^{\dagger}(i) P_{T_z}(j) \qquad (5)$$

  and the results will be labelled as $T = 1$;

- p-n pairing: this calculation will illustrate qualitatively the competition between isovector and isoscalar p-n pairing. The Hamiltonian:

$$H = H_{s.p.} + \sum_{i \neq j} V_{ij}^{10} P_0^\dagger(i) P_0(j) + \sum_{i \neq j} V_{ij}^{01} D_0^\dagger(i) D_0(j). \quad (6)$$

is employed and the corresponding calculations denoted as $T_z = 0$.

In Fig. 1, the total energy E is shown as a function of the deformation parameter. The results obtained in the $(S = 0, T = 1)$ channel are shown either including all channels or only particle like pairing. In all cases, the results are compared with the energy landscape obtained directly from *EV8* and we see that additional correlation energy is systematically gained compared to the original *EV8* case, due to the restoration of the particle number and isospin symmetries. In the same figure, the SM results obtained considering also the p-n pairing in the $T = 1$ channels (black-dashed lines) are plotted. Compared with the $|T_z| = 1$ results (red-dotted lines), we see that the inclusion of p-n correlations provides some extra correlation energy.

In order to study the competition of the isoscalar and isovector pairing, we consider $v_{is} = x v_{iv}$, x being a constant defining the relative weight between the isovector (v_{iv}) and isoscalar (v_{is}) pairing strengths. In Fig. 2, the potential energy curve obtained including only isovector p-n pairing (black-dashed line), i.e. x=0, is compared with the results where isoscalar correlations also are included, for different x values. It is clear from this figure that the addition of the isoscalar channel gives a gain in correlation. We also see, comparing the results with $x = 1.0$ and $x = 1.6$ that the dependence of the isoscalar correlation energy on the x value is rather weak.

3 Conclusions

In the present work, we investigate particle-like and p-n correlations and their dependence on nuclear deformation in a framework that combines self-consistent mean-field calculations and the diagonalization techniques for the treatment of the pairing Hamiltonian. This framework is here used to systematically investigate fp-shell even-even $N = Z$ nuclei, from ^{44}Ti to ^{64}Ge. We found that deformation plays also an important role, producing a strong quenching of the pairing correlations [11]. The interplay of the isoscalar and isovector correlations, and their quantitative role in the binding energies is analyzed. It is found that the isoscalar p-n pairing is generally much weaker than the isovector contribution. However, in some cases, we observed that large deformation can favor the coexistence of isoscalar and isovector p-n condensates.

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