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Microscopic analysis of $T = 1$ and $T = 0$ proton–neutron correlations in $N = Z$ nuclei

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Abstract

The competition between the isovector ($T = 1$) and isoscalar ($T = 0$) proton–neutron (p–n) correlations in $N = Z$ nuclei is investigated by calculating their correlation energies with a realistic effective interaction which reproduces observed nuclear properties very well, in a strict shell model treatment. It is shown in the realistic shell model that the double-differences of binding energies $(B(A + pn : T) + B(A) - B(A + p) - B(A + n))$ ($B(A)$ being the binding energy) are good indicators of the $T = 1$ and $T = 0$ p–n correlations. Each of them, however, originates in plural kinds of correlations with $T = 1$ or $T = 0$.

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1. Introduction

The competition between isovector ($T = 1$) and isoscalar ($T = 0$) pairing correlations has been a matter of renewed concern in nuclear structure studies of $N \approx Z$ nuclei [1–3]. The competition appears in the near degeneracy of the lowest $T = 1$ and $T = 0$ states in odd–odd $N = Z$ nuclei. The $T = 0$ proton–neutron (p–n) pairing correlations in $N \approx Z$

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nuclei have been studied by the two approaches [2,3] with different treatments of the symmetry energy. The two conclusions about the importance of the $T = 0$ p–n pairing correlations are in opposition to one another. The $T = 1$ and $T = 0$ pairing correlations, which are considered to be induced by $T = 1$ and $T = 0$ nuclear interactions, should be treated consistently on the same footing [3]. The structure of $N = Z$ nuclei has been well described by the shell model which does treat $T = 1$ and $T = 0$ pairing consistently. Large-scale shell model calculations were applied to the investigation of the isovector and isoscalar pairing correlations in Refs. [4–6], where the contributions of $T = 1$, $J = 0$ and $T = 0$, $J = 1$ interactions are compared [4] and the contributions of the quadrupole–quadrupole (QQ) force are also considered [5]. The authors have recently shown that the competition between the $T = 1$ and $T = 0$ pairing correlations are approximately explained with the $T = 1$, $J = 0$ pairing force (P_0) and a $T = 0$ p–n force ($V^{T=0}_{\mathrm{mp}}$ below) [7]. In order to understand the competition in detail, it is important to evaluate the two types of correlations induced by realistic effective interactions.

In this paper, we investigate the competition between $T = 1$ and $T = 0$ p–n correlations in the lowest states of $N = Z$ nuclei using a realistic effective interaction in a strict shell model treatment. The spherical shell model, which gives an excellent description of various properties of $N \approx Z$ nuclei (not only the binding energies but also other properties), has the advantage that the correlation energies of respective interactions are properly calculated. A shell model Hamiltonian is composed of the $T = 0$ and $T = 1$ interactions,

$$H = H_{\mathrm{sp}} + V^{T=0} + V^{T=1}, \tag{1}$$

$$V^T = \sum_{a\leqslant b} \sum_{c\leqslant d} \sum_{JM} \sum_{TK} G_{JT}(ab:cd) A^{\dagger}_{JMTK}(ab) A_{JMTK}(cd) \quad (T = 0, 1), \tag{2}$$

where H_{sp} stands for the single-particle energies, $A^{\dagger}_{JMTK}(ab)$ is the creation operator of a nucleon pair with the spin JM and the isospin TK in the single-particle orbits (a, b), and $G_{JT}(ab:cd)$ denotes the interaction matrix elements. The so-called realistic effective interactions contain multipole ($J \geqslant 0$) pairing forces of $T = 0$ and $T = 1$ in the expression (2). In this sense, the shell model with a realistic effective interaction is to deal with all the *multipole pairing correlations*. We investigate the competition between the $T = 0$ and $T = 1$ correlations induced by the $T = 0$ and $T = 1$ interactions.

The realistic effective interactions have the property that the centroid of $T = 0$ diagonal interaction matrix elements $\overline{G_{T=0}(ab)} = \sum_J (2J + 1) G_{J0}(ab:ab) / \sum_J (2J + 1)$ has a roughly constant value, being independent on the orbits (ab) [8]. By setting $-k^0 = \sum_{ab} \overline{G_{T=0}(ab)} / \sum_{ab}$, we obtain the average $T = 0$ p–n force

$$V^{T=0}_{\mathrm{mp}} = -k^0 \sum_{a\leqslant b} \sum_{JM} A^{\dagger}_{JM00}(ab) A_{JM00}(ab). \tag{3}$$

Let us write residual $T = 0$ interactions as $V^{T=0}_{\mathrm{res}} = V^{T=0} - V^{T=0}_{\mathrm{mp}}$ and rewrite the Hamiltonian as

$$H = H_{\mathrm{sp}} + V^{T=0}_{\mathrm{mp}} + V^{T=0}_{\mathrm{res}} + V^{T=1}. \tag{4}$$

The separation of $V^{T=0}_{\mathrm{mp}}$ in Eq. (4) follows the procedure of Dufour and Zuker in Ref. [9], where the Hamiltonian is divided into the monopole and multipole parts as $H = H_{\mathrm{m}} + H_{\mathrm{M}}$.