Systematic calculation of $T = 1$ triplets with proton–neutron mixed energy density functionals

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We performed a systematic calculation for $T = 1$ isobaric analog states (IASs) based on energy density functionals (EDFs) including proton-neutron (p-n) mixing. Recently, we developed a new model to calculate IASs on the basis of the Skyrme EDFs that include arbitrary mixing between protons and neutrons[1]. In this framework, single-particle states are generalized as superpositions of proton and neutron components. In connection with this extension of single particles, density functionals are also extened to those with mixing between protons and neutrons[2]. In this work, we consider an extension of EDFs including p-n mixing only in the particle-hole (p-h) channel, with both the rotational and isospin symmetries conserved. Our ultimate goal, however, is to develop a consistent symmetry-unrestricted EDF approach including p-n mixing both in the p-h and pairing channels.

We developed a code for the p-n mixing calculation by extending the code "HFODD,"[3] which solves the nuclear Skyrme–Hartree–Fock(–Bogolyubov) problem by using the Cartesian deformed harmonic-oscillator basis. In this p-n mixing calculation, we perform isocranking calculation by adding the isocranking term to the Hamiltonian: $\hat{h}' = \hat{h} - \vec{\lambda}\cdot\hat{\vec{t}}$. Here, $\hat{\vec{t}}$ is the isospin operator. The isocranking term is analogous to that used in the standard tilted-axis-cranking calculations for high-spin states. By adjusting the isocranking frequency $\vec{\lambda}$, we can control the size and direction of the isospin of the system.

In Ref. 1), we developed an efficient method for determining the isocranking frequency and successfully applied the isocranking model to the IASs in even-even $A = 40 - 56$ and odd-odd $A = 14$ isobars. Thus, we demonstrated that the p-n mixed single-reference EDF approach is capable of quantitatively describing the isobaric analog excited states. Among the results in Ref. 1), that of odd-odd $T = 1$ IASs is of particular interest (See Fig. 4 in Ref. 1)). We calculated the energies of the $I = 0^+, T = 1$ triplet of states in the $A = 14$ isobars, ^{14}C, ^{14}N, and ^{14}O by using the SkM* EDF. We found that there is asymmetry between the energy differences $|E(T_z = 0) - E(T_z = -1)|$ and $|E(T_z = 0) - E(T_z = 1)|$, which may be related to charge asymmetry and independence of the NN interaction. To investigate this point, in this study, we performed a systematic calculation of the $T = 1$ triplets in $A = 4n + 2$ nuclei. We calculated the triple energy difference (TED)[4] $2E(T_z = 0) - E(T_z = 1) - E(T_z = -1)$ with several Skyrme parameter sets. In this model, while the $T_z = \pm 1$ IASs are obtained with the standard Hartree-Fock calculation without p-n mixing, the $T_z = 0$ IAS is calculated using the isocranking model and is described by a single time-even Slater determinant consisting of p-n mixed single particles.

Figure 1 shows examples of the results of the calculation. We plot the deviation of the calculated TEDs from the experimental data in the $A = 14 - 58$ region. The TEDs in the $T = 1$ triplets calculated with the SLy4, SIII, and SkM* parameter sets are shown. One can see a systematic underestimation of the TEDs in Fig. 1. In this calculation, we used isoscalar EDFs, which are invariant under rotation in isospin space, plus the Coulomb energy functional. This systematic deviation may imply that we need to extend functionals further to include isospin breaking terms. We already started performing a calculation including the isospin breaking interaction, which will be reported elsewhere.

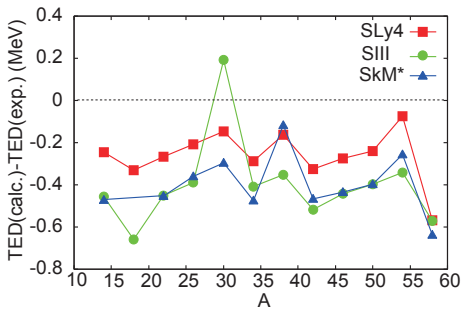

Fig. 1. Deviation of the calculated triple energy difference from the experimental data[5], TED(calc.)-TED(exp.), for the $T = 1$ triplets in $A = 14 - 58$ nuclei. The TEDs calculated with SLy4, SIII, and SkM* are plotted.

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