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Enhancement of high-spin collectivity in $N = Z$ nuclei by the isoscalar neutron–proton pairing

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Abstract

Pairing from different fermions, neutrons and protons, is unique in nuclear physics. The fingerprint for the isoscalar $T = 0$ neutron–proton (np) pairing has however remained a question. We study this exotic pairing mode in excited states of rotating $N \approx Z$ nuclei by applying the state-of-the-art shell-model calculations for ^{88}Ru and the neighboring ^{90,92}Ru isotopes. We show that the $T = 0$ np pairing is responsible for the distinct rotational behavior between the $N = Z$ and $N > Z$ nuclei. Our calculation suggests a gradual crossover from states with mixed $T = 1$ and $T = 0$ pairing near the ground state to those dominated by the $T = 0$ np pairing at high spins. It is found that the $T = 0$ np pairing plays an important role in enhancing the high-spin collectivity, thereby reducing shape variations along the $N = Z$ line.

Keywords: Neutron–proton pairing; Isospin invariance; $N = Z$ nuclei; High-spin states; Large-scale shell model

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1. Introduction

The introduction of pairing to nuclear systems [1] was inspired by the success of the BCS theory [2] in understanding superconductivity in electron systems. However, the pairing concept is more plentiful in nuclei than in electron systems because two kinds of nucleons, neutrons and protons, can form neutron–neutron, proton–proton, and neutron–proton (np) pairs [3]. The nuclei having equal proton and neutron numbers ($N = Z$), where the valence protons and neutrons occupy the same single-particle orbits and thus have the largest spatial overlaps, are the places to study the np pairing mode. Following Wigner [4] to use isospin $t = 1/2$ to label protons and neutrons as its two components $t_z = -1/2$ and $1/2$, respectively, the two types of nucleons can couple together to give rise to isovector $T = 1$ triplet pairs (with antiparallel spins) and isoscalar $T = 0$ singlet pair (with parallel spins). The experimental evidence for the $T = 1$ np pairing has been well established (see Ref. [5] for the most recent review). For example, the existence of $T = 1$ np pairs has been confirmed from the examination of CEDs (Coulomb energy differences) [6].

On the other hand, evidence for the isoscalar np pairing seems to be more difficult to establish. Over the years, many theoretical and experimental works, through analyzing different physical quantities, have been devoted to finding evidence for the $T = 0$ np pairing [5]. After summarizing the study of binding energy differences, Ref. [7] eventually questioned the existence of an isoscalar pair condensate in $N = Z$ nuclei. It was concluded [5] that although the nuclear force is stronger in the $T = 0$ than in the $T = 1$ channel it seems not give rise to a “deuteron-like condensate”.

Is the isoscalar np pairing really important for nuclei, and if it is, where one can see fingerprints? It has been pointed out that the effect of np pairing must be confined to a narrow region along the $N = Z$ line [8,9], and if it is not present in the ground state it may be generated at large rotational frequencies [5,8]. In the normal $T = 1$ pairing mode, two like-nucleon spins are antiparallel at lower spins due to the $T = 1$, $J = 0$ pairing. When the nucleus rotates, the increasing Coriolis force tends to break the pairs and forces them to align their spins to the direction of collective rotation, causing a sudden increase in moment of inertia (MoI) at critical frequencies. The suggestion by Stephens and Simon [10] successfully explained experimental observations of irregular behavior of this type, such as backbending in MoI, in many rotating $N > Z$ nuclei. However, the $T = 0$ np-pairs can be easily decoupled from the deformed core by the Coriolis force with much smoother alignment processes [8]. Thus, high-spin states of rotating $N = Z$ nuclei seem to be appropriate places to see clues for the $T = 0$ np pairing. The recent experimental observation of excited states in the $N = Z = 46$ nucleus ^{92}Pd has suggested a possible existence of a new $T = 0$ coupling mode [11], the so-called spin-aligned mode, which also can cause a smooth alignment. Here the $T = 0$ interaction favors coupling of np-pairs to the maximum angular momentum $J = 9$. Since such pairs align with increasing angular momentum as far as allowed by the Pauli principle, the more such pairs can be formed the smoother the alignment becomes. At variance with the isoscalar np-pairing condensate, spin-aligned np pairs do not need to be correlated. Shell-model calculations showed that the low-lying yrast states of ^{92}Pd are mainly built upon $T = 0$ np pairs, each carrying the maximum spin $I = 9$ allowed by the $0g_{9/2}$ shell [12]. These works have generated new discussions about the $T = 0$ np pairing [13], but more experimental and theoretical works are clearly needed to understand its real nature.