Evidence for enhanced neutron-proton correlations from the level structure of the $N = Z + 1$ nucleus $^{87}_{43}$Tc$_{44}$

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The low-lying excited states in the neutron-deficient $N = Z + 1$ nucleus $^{87}_{43}\text{Tc}_{44}$ have been studied via the fusion-evaporation reaction $^{54}\text{Fe}(^{36}\text{Ar}, 2n1p)^{87}\text{Tc}$ at the Grand Accélérateur National d'Ions Lourds (GANIL), France. The AGATA spectrometer was used in conjunction with the auxiliary NEDA, Neutron Wall, and DIAMANT detector arrays to measure coincident prompt γ rays, neutrons, and charged particles emitted in the reaction. A level scheme of ^{87}Tc from the $(9/2^+_{\text{g.s.}})$ state to the $(33/2^+_1)$ state was established based on six mutually coincident γ-ray transitions. The constructed level structure exhibits a rotational behavior with a sharp backbending at $\hbar\omega \approx 0.50$ MeV. A decrease in alignment frequency and increase in alignment sharpness in the odd-mass isotonic chains around $N = 44$ is proposed as an effect of the enhanced isoscalar neutron-proton interactions in odd-mass nuclei when approaching the $N = Z$ line.

Introduction. The nuclear pairing correlation is an essential ingredient for describing the properties of finite atomic nuclei. The underlying mechanism is considered to be analogous to that formulated in the Bardeen-Cooper-Schrieffer theory [1,2]. Unique for the nuclear system is that it is a strongly correlated system of two different types of fermions (neutrons and protons). Due to isospin symmetry, the Cooper pairs can be formed in both the $T = 1$ isovector (neutron-neutron, proton-proton, and neutron-proton) channel and the $T = 0$ isoscalar (neutron-proton) channel. A wealth of experimental observations have supported the fundamental role of neutron-neutron and proton-proton pairing correlations in understanding various nuclear properties including mass, deformation, moment of inertia and rotational alignment [3,4]. The effect of $T = 1$ isovector neutron-proton (np) pairing has also been analyzed from different perspectives [5–9]. An interesting problem that is still considered open is the experimental evidence for the $T = 0$ isoscalar np pairing mode. The possible existence of such deuteron-like pairing has attracted extensive studies over the years [8–11].

It is expected that the effects of isoscalar pairing can be enhanced along the $N = Z$ line where the valence neutrons and protons occupy identical orbitals, in particular in the heaviest self-conjugate systems where many particles might contribute to form an isoscalar pairing condensate. In recent years, advances in detection and data acquisition technologies have opened up the nuclei far from stability to observation, and the newly unveiled spectroscopy data in the intermediate-mass $N \sim Z$ region has reignited the interest in investigating the possible manifestation of the $T = 0$ pairing mode. The occurrence of a significant component of isoscalar spin-aligned np pairs in the nuclear wave function is suggested in the heavy spherical $N = Z$ nuclei like ^{92}Pd [11,12]. The effect of the competition between the spin-aligned np pair interaction and the quadrupole correlation could be strong even in the lighter, modestly deformed, nucleus ^{88}Ru [13,14]. It is the response of the different pairing field components to collective rotation [11,15,16] that is of interest in such deformed systems. A possible consequence of the increase in rotational frequency is that while the $T = 1$ isovector pairs, which couple two nucleons to $J = 0$, are successively destroyed by the increasing Coriolis force, the $T = 0$ isoscalar pairs with $J > 0$ can align to build up angular momentum [10] and thus may still leave fingerprints after the quenching of $T = 1$ pairing. The ground-state rotational bands of even-even $N = Z$ nuclei from ^{72}Kr to ^{88}Ru [13,17–19] have been extended to the region

where band crossings are normally expected and increases in crossing frequency compared to their neighboring $N > Z$ nuclei were consistently observed. These "delayed" alignments have been widely suggested as arising from the $T = 0$ np pairing correlation [20], though the effect of the shape degrees of freedom can muddle the analysis in some cases.

The effect of $T = 0$ np pairing correlations may be strong also for $N = Z + 1$ nuclei even though the impact is expected to diminish rapidly as one goes away from the $N = Z$ line [13]. In the rotational odd-mass nuclei, the first rotational alignment can be explicitly assigned to either aligned neutrons or aligned protons due to the odd-particle blocking in the isovector pairing field. After the crossing to the 3-quasiparticle band, due to the simultaneous presence of unpaired neutrons and protons at high spin will be favored by the $T = 0$ np pairing field. In the $T_z = \pm 1/2$ nuclei, such a competition may lead to a transition between the two pairing phases. In Ref. [21], it is argued that the negative parity bands in ^{73}Kr can be accounted for by means of $T = 0$ pair correlations. The deformed region around ^{88}Ru is an ideal laboratory to verify the condensation of isoscalar pairs due to the fact that most valence particles are confined in the high angular momentum $g_{9/2}$ orbital below the magic number $N = Z = 50$. The intermediate-mass $T_z = 1/2$ nuclei have been mapped up to ^{95}Ag [22] with relatively rich spectroscopic information. The exception is ^{87}Tc, for which only two excited states were previously known [23]. In this study, we report on the observation of excited states in the yrast band of ^{87}Tc from the $(9/2^+_{\text{g.s.}})$ state to the $(33/2^+_1)$ state. The results are discussed based on the systematical studies and compared with large-scale and single-j shell model calculations including the possible effects from the $T = 0$ np pairing correlation.

Experiment. The experiment was performed at the Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France. The reaction $^{54}\text{Fe}(^{36}\text{Ar}, 2n1p)^{87}\text{Tc}$ was induced by a 5- to 10-pnA ^{36}Ar beam at 115 MeV which was led to bombard the 6-mg/cm^2-thick ^{54}Fe target foils. Prompt γ rays from the deexcitation of the rare ^{87}Tc nuclei produced in the reaction were measured with the Advanced Gamma Tracking Array (AGATA) [24] spectrometer consisting of 11 triple-cluster segmented HPGe detectors [25]. The indispensable channel selection was achieved by operating AGATA in conjunction with auxiliary detector systems for light particles. Evaporated charged particles were recorded in the DIAMANT [26,27] detector array consisting of 60 CsI(Tl) scintillators placed inside the target chamber. In the forward hemisphere, with
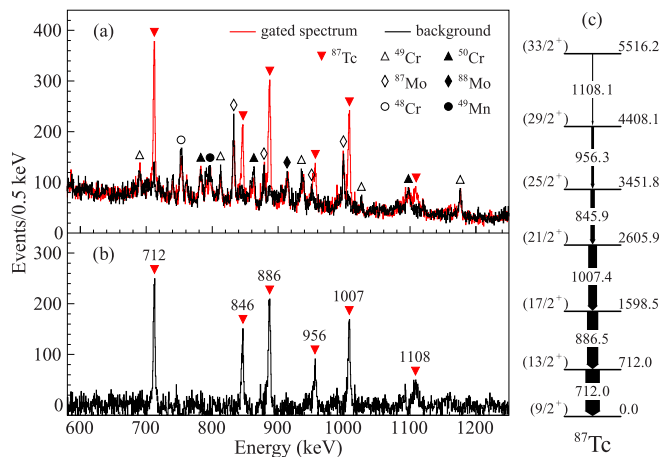
FIG. 1. (a) Sum of the spectra gated on the 712.0-, 886.5-, 1007.4-, 845.9-, and 956.3-keV lines (red), and the summed background spectrum (black) gated 4 keV above these lines. The background spectrum was normalized to the gated spectrum according to the statistics below 2 MeV. γ-ray peaks due to contaminant reactions are indicated. The coincidence spectrum in (b) is the difference between the two spectra shown in (a). (c) Level scheme of ^{87}Tc deduced from the present work. The tentative spin-parity assignments were made based on the systematics as well as shell-model calculations, and the width of the arrows are proportional to the relative intensities of the γ rays. The relative intensities: 100(4), 80(3), 65(5), 37(4), 26(3), and 13(3).

approximately 1.6π solid angle coverage, the NEDA [28,29] and Neutron Wall [30] detector arrays, consisting of 54 and 42 organic liquid scintillator detectors, respectively, were placed to detect the emitted neutrons. AGATA was calibrated with a standard ^{152}Eu radioactive source giving a 0.095% σ/E resolution for the 1408.1 keV γ-ray transition. The trigger condition in the experiment required at least 1 (NEDA or Neutron Wall) neutron and 2 (AGATA) γ-ray detectors to fire in coincidence.

In the off-line analysis, γ-ray events belonging to the $2n1p$ channel were identified by using the information on the detected light particles. The γ-γ coincidence matrix for ^{87}Tc was sorted with the condition of "$2n01p$", which means that two neutrons together with either none or one proton had to be detected in prompt coincidence. The acceptance of "$0p$" events is mainly due to the low single-proton detection efficiency of only about 39(1)%. In order to suppress the contamination from $1n$ channels, a purification of the "$2n$" events was performed by rejecting the neutron-scattering events using the time-of-flight of the detected neutrons and the positions of the detectors that fired. The requirement of "$01p$" events was either a complete silence of the whole DIAMANT array or the only signal must be assigned to a proton. In the γ-γ coincidence matrix, a mutually coincident cascade of six transitions was observed (see Fig. 1). In addition to the first two transitions at 712.0(1) and 886.5(1) keV which have been reported previously [23], four new lines at 1007.4(1), 845.9(1), 956.3(2), and 1108.1(4) keV were identified. The background-subtracted spectrum is shown in Fig. 1(b) in which all six peaks are clearly visible. A level scheme of
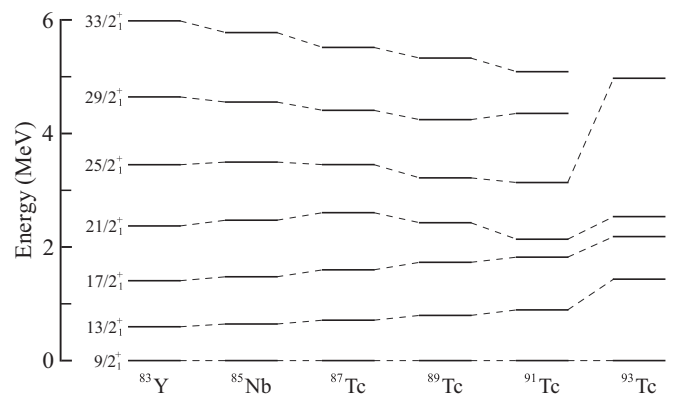

FIG. 2. Systematics of positive-parity yrast states below 6 MeV in ^{87}Tc together with the odd-A $N = 44$ isotones [31,32] in comparison with neighboring technetium isotopes ^{89,91,93}Tc [33–35]. The results for ^{87}Tc are from the present work.

^{87}Tc, established based on the coincidence relationships and the relative intensities of the γ rays, is displayed in Fig. 1(c).

Discussion. The systematics of positive-parity yrast states below 6 MeV in the odd-A $N = 44$ isotones and those in the neighboring technetium isotopes ^{89,91,93}Tc are shown in Fig. 2. The $N = 44$ isotones show a characteristic rotational behavior while a strong transition to spherical coupling is observed along the Tc isotopic chain as one approaches $N = 50$. In the semimagic nucleus ^{93}Tc, the level pattern up to $21/2_1^+$ is of a typical spherical $\pi(g_{9/2})^3$ multiplet character. Here a sudden and significant increase in the excitation energy is seen for the $25/2_1^+$ state which involves the excitation and breaking of a proton pair and has the configuration $\pi(g_{9/2})_{25/2}^5$. As expected, the energy gaps between the $25/2_1^+$ and $21/2_1^+$ states are reduced in ^{89,91}Tc in the presence of both valence protons and neutrons. In the middle of the $\nu(g_{9/2})$ subshell, the level pattern of ^{87}Tc is characterized by a fully developed rotational band similar to the other $N = 44$ isotones.

Focusing on the rotational patterns of the $N = 44$ isotones with $T_z = 5/2$ (^{83}Y), $3/2$ (^{85}Nb), and $1/2$ (^{87}Tc), a gradual decrease in the collectivity of the 1-quasiparticle (1-qp) bands from ^{83}Y to ^{87}Tc may be expected as can be inferred from the increasing gap between the $9/2_1^+$ and $13/2_1^+$ states. On the other hand, the higher-spin states starting from $J = 21/2$ clearly show an opposite trend. In order to clarify this striking feature we have extracted the kinematic moments of inertia, $J^{(1)}$ [36], as a function of rotational frequency for the $N = 44$ isotones from ^{83}Y to ^{88}Ru, as illustrated in Figs. 3(a) and 3(b). The even-even $N = 44$ isotones ^{84}Zr [42] and ^{86}Mo [37] show a $g_{9/2}$ proton alignment at $\hbar\omega \approx 0.48$ MeV followed by a neutron crossing around 0.6 and 0.5 MeV, respectively. All odd-A isotones in the figure show $\nu g_{9/2}$ quasiparticle alignments [31,32] around $\hbar\omega = 0.5$ MeV with a clear and unexpected increases in the crossing sharpness with the decrease of T_z. The first alignment in the even-even nuclei shows an upward trend in frequency from $Z = 42$ to 44. The considerably "delayed" alignment in self-conjugate $^{88}_{44}$Ru$_{44}$ was suggested to be associated with isoscalar pairing correlations [13,14]. Considering now also the $N = 43$ isotones with $T_z = 5/2$
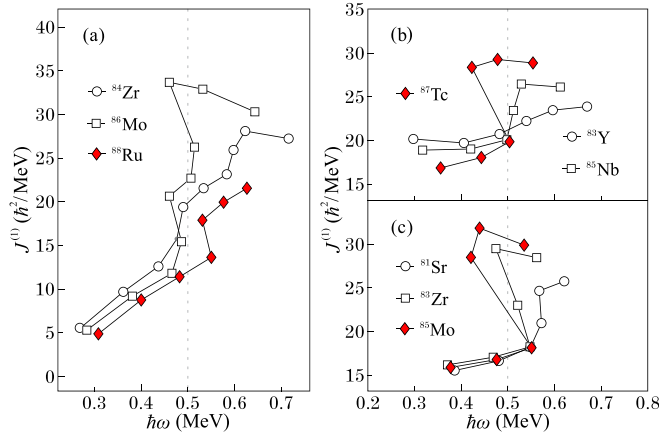
FIG. 3. Kinematic moments of inertia [$J^{(1)}$] as a function of rotational frequency for the positive parity and positive signature bands in the $N = 44$ even-even [13,37,38] isotones (a), $N = 44$ odd-mass isotones (b), and $N = 43$ odd-mass [39–41] isotones (c).

(^{81}Sr), 3/2 (^{83}Zr), and 1/2 (^{85}Mo) [see Fig. 3(c)], all the odd-mass isotones reveal the same trend: The band crossings become earlier and sharper when approaching the $N = Z$ line regardless of the nature of these alignments.

In Fig. 4 (left), we compare the observed level scheme of ^{87}Tc with those from shell-model calculations in the pg model space based on the effective interaction slgmt0 [43]. A calculation in the large-scale fpg space with the interaction jun45 [44] was also performed and no significant difference between calculations in the two model spaces is expected since the wave functions for those states are dominated by the occupation of the $g_{9/2}$ orbitals. A slight modification of the lowest-lying states may be expected by the inclusion of
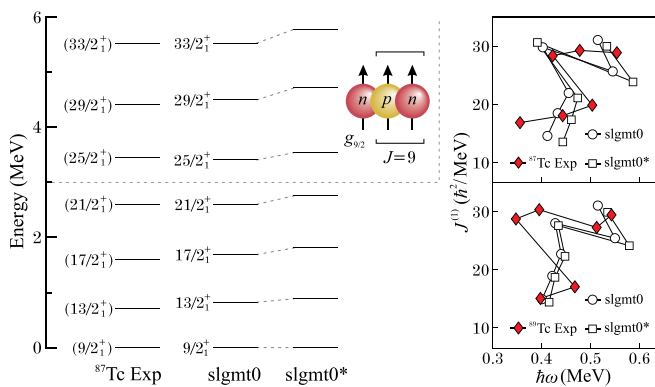

FIG. 4. Left: The experimental level scheme of ^{87}Tc in comparison with the shell-model calculations in the pg model space based on the slgmt0 [43] interaction (slgmt0* denotes the calculation with the spin-aligned neutron-proton interaction reduced by 200 keV). The cartoon illustrates the coupling between the unpaired neutron with the spin-aligned np pair which is the dominant component of the wave function for the higher-spin states. Right: Kinematic moments of inertia as a function of rotational frequency for the positive parity and positive signature bands in ^{87}Tc and ^{89}Tc from the experimental data and theoretical calculations (slgmt0 and slgmt0*).

the $d_{5/2}$ orbital as was shown in the case of the even-even ^{88}Ru [14]. For the higher-lying states from spin $J = 25/2$, our calculations indicate that the coupling $\pi g_{9/2} \otimes (\pi \nu g_{9/2})_9$ is strongly favored in energy in relation to the fact that the spin-aligned np pairs are more strongly attractive than other pairs, as discussed in Refs. [12,13,45]. It leads to a fully aligned 3-qp-like structure at the $25/2_1^+$ state as a result of the coupling between one unpaired neutron and a spin-aligned np pair formed by the last odd proton and the other unpaired neutron. Higher-lying states can be built on top of that by the coupling to additional valence np pairs. To illustrate this picture, as in Ref. [45], we have redone our shell-model calculations in the pg and fpg model spaces by reducing the strength of the spin-aligned np pair interaction. As an example, in the right part of Fig. 4 we have plotted calculations in the pg space with the $(g_{9/2})^2_{J=9}$ spin-aligned np pair interaction matrix element reduced slightly by 200 keV (denoted as slgmt0*). The reduced np pair matrix element leads to an increase in the excitation energy for the higher-spin states much more significant than that of the low-lying states due to the enhanced np pair coupling in their wave function. The increment is as much as 133 keV for the $25/2_1^+$ state and nearly 200 keV for the states with higher spin. Our calculations furthermore show that the effect is much less pronounced when one goes away from $N = Z$. For example, in ^{89}Tc, calculation with the same reduced np pair matrix element leads only to a change of only 70 keV in the excitation energy of its $25/2_1^+$ state. That is because the spin-aligned np pair plays even larger role in ^{87}Tc than in ^{89}Tc. The experimental kinematic moments of inertia as a function of rotational frequency for ^{87}Tc and ^{89}Tc are compared with the shell-model calculations in Fig. 4 (right). The results of the calculations illustrate the importance of the spin-aligned neutron-proton coupling for the $T_z = 1/2$ nucleus ^{87}Tc as compared with ^{89}Tc ($T_z = 3/2$). In the latter case a reduction of the spin-aligned neutron-proton interaction energy by 200 keV has little influence on its structure.

Based on the results above, we suggest that the enhancement of the isoscalar np correlations approaching the $N = Z$ line will make such spin-aligned states more energetically favored, leading to an increasing collectivity after the band crossing. Hence, in the presence of strong isoscalar np correlation the aligned np pair can result in a significant structural change between the 3-qp band and the 1-qp band within the conventional pairing scheme, which will additionally reduce the interaction strength between them and consequently induce a sharper alignment in line with the experimental observations.

Conclusions. In summary, we have studied the low-lying yrast states in ^{87}Tc via the ^{54}Fe(^{36}Ar, $2n1p$)^{87}Tc fusion-evaporation reaction at the GANIL accelerator complex. The prompt $\gamma\gamma$-neutron and charged-particle coincidences were measured by using the AGATA γ-ray spectrometer with the auxiliary NEDA, Neutron Wall, and DIAMANT arrays, resulting in an extension of the known ^{87}Tc level scheme by 8 units of angular momentum to the tentative $33/2_1^+$ state with the first band crossing included. The observed level structure is compared with the neighboring odd-mass $N = 44$ and 43 isotonic chains as well as shell-model calculations. A striking

feature of decreasing excitation energy in the higher spin states starting from $25/2^+$ is observed when approaching the $N = Z$ line. This observation may be a result of the strong spin-aligned np pairing interaction which favors a three-quasi-particle-like configuration as the coupling between an aligned np pair and an odd particle. Such effects of strong isoscalar pairing correlations are unique to odd-A $N \sim Z$ nuclei like ^{87}Tc.

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