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Band structure in ^{79}Y and the question of $T=0$ pairing

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Gamma rays in the $N=Z+1$ nucleus ^{79}Y were identified using the reaction ^{28}Si(^{54}Fe, $p2n$)^{79}Y at a 200 MeV beam energy and an experimental setup consisting of an array of Ge detectors and the Recoil Mass Spectrometer at Oak Ridge National Laboratory. With the help of additional γ-γ coincidence data obtained with Gammasphere, these γ rays were found to form a strongly coupled rotational band with rigid-rotor-like behavior. Results of conventional Nilsson-Strutinsky cranked shell model calculations, which predict a deformation of $\beta_2\sim0.4$, are in excellent agreement with the properties of this band. Similar calculations for the neighboring $N=Z$ and $N=Z+1$ nuclei are also in good agreement with experimental data. This suggests that the presence of the putative $T=0$ neutron-proton pairing does not significantly affect such simple observables as the moments of inertia of these bands at low spins.

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Heavy $N\sim Z$ nuclei have recently become the subject of very intense experimental and theoretical studies. This is partly because they are amenable to a variety of theoretical approaches, including the Monte Carlo shell model [1], symmetry-conserving models [2], as well as mean-field or algebraic methods [3,4]. Therefore, they provide excellent laboratories to study both effective nuclear forces and methods, approximations, and coupling schemes. However, what makes them truly attractive is the richness of physical phenomena appearing in these nuclei. For example, shape coexistence, prolate-oblate mixing or shape transitions are commonly encountered in the medium-mass nuclei. Due to low level density, these shape effects vary strongly with mass, spin, isospin, and excitation energy.

Closer to the $N=Z$ line, one expects an enhancement of neutron-proton (np) pairing, including the exciting possibility of observing np superconductivity. However, despite vigorous investigation of this problem, we still face many questions and conceptual difficulties regarding the existence of a np-pairing phase, its fundamental building blocks, and its experimental signatures. For example, the shell model adapts rigorous definition of the Cooper pairs in terms of isospin-spin (T,J) quantum numbers, but lacks a natural definition of the order parameter. In contrast, the mean-field approach offers a natural definition of the order parameter Δ, but is less rigorous concerning parametrization of the pairing interaction. One of the possible manifestations of the np pairing is the extra binding energy in $N=Z$ nuclei, known as the Wigner energy (see, e.g., [5,6] and references therein). Indeed, conventional mean-field models, which only allow for $T=1,|T_z|=1$ pairing irrespective of its form, systematically underbind $N=Z$ nuclei [7]. But a generalized mean-field approach, which also allows for the $T=0$ np pairing, can naturally account for this extra binding energy which is characterized by an $\sim|N-Z|$ behavior [8]. Similarly, detailed microscopic shell-model calculations that correctly reproduce the Wigner energy show that the Wigner energy is indeed due to $T=0$ interaction [5,6]. However, its structure is very complex when expressed in terms of isoscalar nucleonic pairs of various angular momenta [6].

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Heavy $N=Z$ nuclei perhaps offer the most favorable conditions for the manifestation of np-pairing phase in nuclear matter mainly because of the large number of valence protons and neutrons. A recent study of ^{74}Rb [9] has already provided some evidence for the presence of (collective) $T=1, T_z=0$ pairing in the even-spin band based on its similarity to the ground-state band in ^{74}Kr, its isobaric analog. It seems, however, that the odd-spin $T=0$ band in this nucleus reflects mostly the (noncollective) coupling of a pair of [431]3/2 neutron and proton orbitals. Although shell model Monte Carlo calculations [1] seem to support this interpretation, it is not entirely clear whether the structure of ^{74}Rb reflects collective or noncollective components of np pairing. Therefore, systematic experimental studies of heavy $N \approx Z$ nuclei are needed to provide more clear clues concerning the question of isoscalar np pairing. The present study of ^{79}Y is part of our systematic studies of $T_z=1/2$ nuclei [10–12]. Earlier reports of this work has been presented in Refs. [13,14].

The results presented in this work have been obtained in two separate experiments. In the first experiment, γ rays associated with ^{79}Y were identified at the Holifield Radioactive Ion Beam Facility (HRIBF) using the reaction ^{28}Si(^{54}Fe, $p2n$)^{79}Y at 200 MeV and a beam intensity of $\sim$10 particles nA. The target consisted of a layer of 0.5 mg/cm^2 ^{28}Si evaporated onto a 1 mg/cm^2 Ta foil that faced the beam. The emitted γ rays were detected by an array of six segmented-Clover and four Compton-suppressed HPGe detectors. All events were tagged by information regarding the mass and atomic numbers of the recoiling nuclei. This information was provided by the Recoil Mass Spectrometer (RMS) [15] at HRIBF and its associated focal-plane detectors. Recoils with a mass of $A=79$ constituted $\approx$70% of all the recoils detected at the focal plane of the RMS. A total of 1.5×10^8 coincidences between one- and two-fold γ rays and the recoils were acquired.

In the off-line analysis of these data, fusion-evaporation events were cleanly separated from those associated with beam scattering and pileup, by requiring that the recoils conform to the appropriate gates in a two-dimensional matrix of kinetic energy vs mass-to-charge ratio (A/q) of the recoils. We also required that the two energy-loss (ΔE) signals obtained from the ionization chamber have the expected ratio for the recoils. Finally, after removing the energy dependence of the energy-loss signals, a two-dimensional matrix of ΔE vs γ-ray energy was formed. Since ΔE signals provide information about the Z of the recoils, this matrix was used to identify the characteristic gamma rays associated with each of the reaction products.

The (A/q)-gated spectrum corresponding to mass $A=79$ contains four nuclei, namely ^{79}Rb ($3p$), ^{79}Sr ($2pn$), ^{79}Y ($p2n$), and ^{76}Kr ($\alpha 2p$). (The last nucleus appears in this gate due to the mass-to-charge ratio ambiguity.) With the help of a two-dimensional gate on the total energy vs (A/q) matrix, a large fraction of the ^{76}Kr events was removed. The relative intensities of ^{79}Rb, ^{79}Sr, and ^{76}Kr in the mass-79 spectrum were 67%, 26%, and 6%, respectively. To identify the characteristic γ rays associated with the weakly populated nucleus ^{79}Y, we followed the following iterative procedure. First, using the known γ rays in the strongly populated ^{79}Rb and ^{79}Sr nuclei, we projected out their

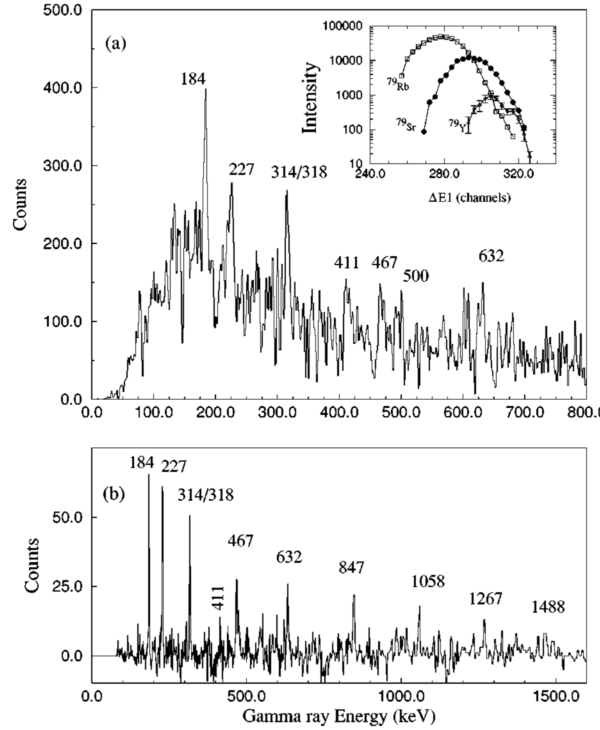

FIG. 1. (a) A spectrum of characteristic γ rays in ^{79}Y ($N=Z+1$) gated with the RMS and ionization chamber at HRIBF. Gamma rays assigned to ^{79}Y have been marked by their energies in keV. Note that the 500 keV γ ray is not placed in the level scheme. The inset shows the γ-ray intensity as a function of the energy-loss signal (ΔE) for ^{79}Rb, ^{79}Sr, and ^{79}Y. (b) A spectrum obtained by summing several gates on transitions belonging to the favored signature of the ground-state band in ^{79}Y.

corresponding ΔE spectra. From both the shapes and centroids of these so-called Z spectra, we could determine the optimal ΔE gates for ^{79}Rb, ^{79}Sr, and ^{79}Y. In the second step, using these Z gates, we obtained total γ-ray spectra for each of these three channels. The resulting spectrum for ^{79}Rb was free of contaminants, and was used to subtract out any contributions from this channel to the ^{79}Sr spectrum. Finally, a fraction of each of these two ''purified'' spectra were subtracted from the ^{79}Y spectrum to identify the characteristic γ rays associated with this nucleus. The resulting γ-ray spectrum is shown in Fig. 1(a). In all, six γ rays—184 keV, 227 keV, 318 keV, 411 keV, 467 keV, and 632 keV—were assigned to ^{79}Y. Gamma-ray intensities as a function of the energy-loss signal in the ionization chamber confirmed that all of these γ rays belong to ^{79}Y. One such spectrum for the 184-keV transition is compared with those associated with γ rays in ^{79}Rb and ^{79}Sr in the inset of Fig. 1(a). We may define the quality factor for Z resolution as $(P1-P2)$/FWHM, where $P1$ and $P2$ are the centroids of the ΔE spectra for two isobaric nuclei with $\Delta Z=1$ and FWHM is the full width at half maximum of these spectra. We obtained a quality factor of 0.7 for the present experiment. The partial cross section for ^{79}Y was estimated to be less than 200 μb.

In order to establish the coincidence relationship between the identified γ rays in ^{79}Y, a γ-γ matrix and a γ-γ-γ cube were created from the data obtained in a second experiment using the reaction ^{58}Ni(^{28}Si, $\alpha p2n$)^{79}Y. The 130-MeV ^{28}Si beam was provided by the 88-Inch Cyclotron at the

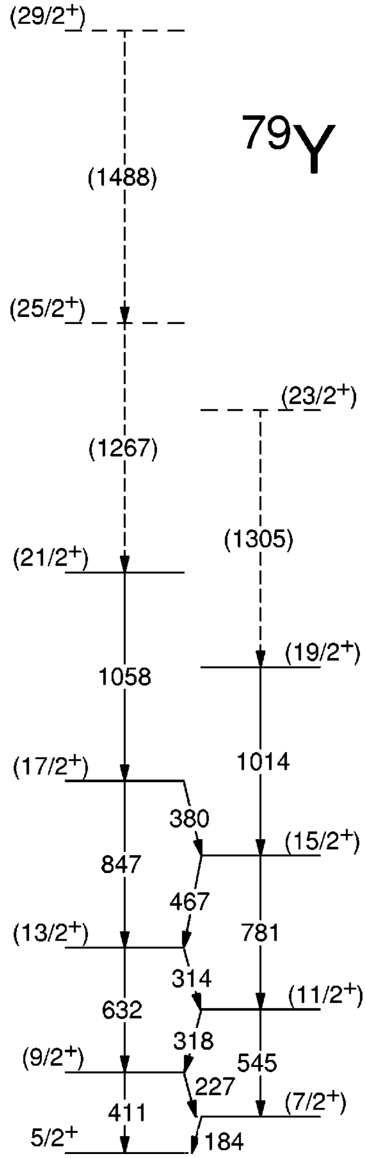

FIG. 2. A partial level scheme for ^{79}Y obtained in the present work.

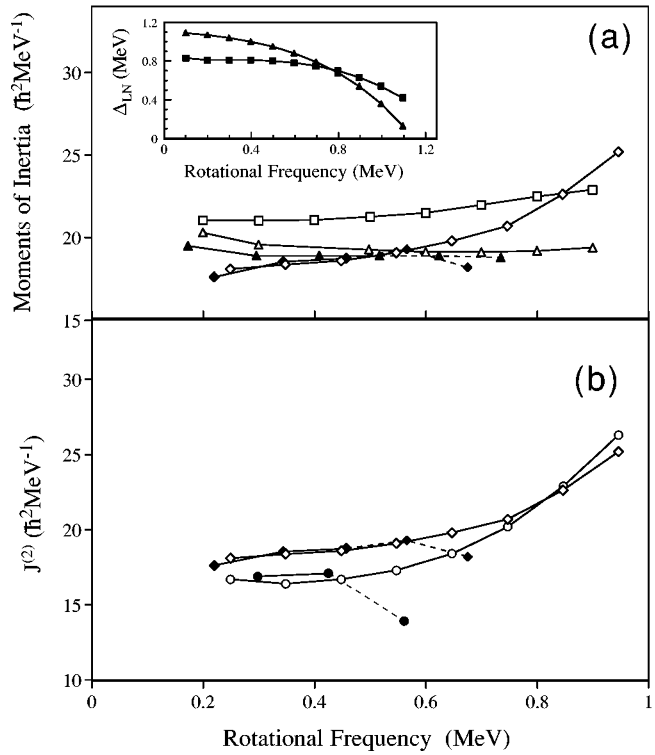

FIG. 3. (a) Comparison of experimental (full symbols) and theoretical (open symbols) moments of inertia for the favored signature band in ^{79}Y as a function of $\hbar\omega$. The $J^{(1)}$ and $J^{(2)}$ moments of inertia are marked by triangles and diamonds, respectively. The open squares show the $J^{(1)}$ values from calculations with no pairing. The inset shows the pairing order parameters Δ_{LN} for protons (squares) and neutrons (triangles), respectively. (b) Comparison between the experimental (full symbols) and theoretical (open symbols) $J^{(2)}$ values for both signatures.

Lawrence Berkeley National Laboratory. Reaction γ rays were detected by 57 Ge detectors of the Gammasphere Phase-I array [16], while charged particles were detected by 95 CsI detectors of Microball [17]. The target consisted of an enriched ^{58}Ni foil with a thickness of $\sim$0.4 mg/cm^2. A total of 1.5×10^9 events with a γ-ray coincidence fold of three or higher were collected. The level structure obtained from the analysis of these data is shown in Fig. 2. Lenz *et al.* [18] have previously reported a level structure for ^{79}Y. But, except for the pair of 184 and 227 keV transitions, our analysis did not find these γ rays to be in coincidence with each other. In accordance with the β-decay results given in Ref. [19], we have adopted $5/2^+$ for the ground-state spin and parity. This is consistent with the theoretical assignment of $g_{9/2}$ for the configuration of the ground-state band, as will be discussed below. Although lack of adequate statistics prevented us from confirming the tentative spin and parity assignments shown in Fig. 2, the presence of several interband transitions that connect the two signature partners of the band support our assignments for levels up to $I^\pi=(17/2^+)$. The 1488 keV ($29/2\rightarrow25/2$) and 1267 keV ($25/2\rightarrow21/2$) transitions in the favored signature of the band are shown as dotted because their placement could not be confirmed with respect to the 1058 keV ($21/2\rightarrow17/2$) transition. However, our data indicate that they are in coincidence with other transitions in this band. Similar arguments hold for the 1305 keV ($23/2\rightarrow19/2$) transition. Figure 1(b) shows sum of spectra gated by 184, 227, 314, 318, 467, 632, and 847 keV transitions.

The experimental kinematic, $J^{(1)}[\equiv I/\omega]$, and dynamic, $J^{(2)}[\equiv dI/d\omega]$, moments of inertia (MoI) for the positive parity, positive signature $[(\pi,\alpha)=(+,+1/2)]$ band in ^{79}Y are shown in Fig. 3(a). Remarkably, $J^{(1)}$ and $J^{(2)}$ are almost constant and equal ($J^{(1)}\sim J^{(2)}\sim19\hbar^2$ MeV^{-1}) over the entire frequency range. Their values are only slightly less than the $J_{\rm rig}\sim22\hbar^2$ MeV^{-1} which corresponds to the MoI of a rigid spheroidal nucleus of mass $A=79$ and deformation of $\beta_2=0.4$. Equality of kinematic and dynamic moments of inertia is a signature of rigid body like rotation. Furthermore, Peker *et al.* [20] have previously noted that $J^{(2)}\sim J_{\rm rig}$ in ^{98}Y and have argued that this relationship signifies quenching of pairing correlations in ^{98}Y. As we shall see below, our detailed theoretical calculations show the importance of pairing correlations in ^{79}Y despite the fact that $J^{(2)}\sim J_{\rm rig}$.

Indeed, the near constancy of MoI in ^{79}Y is not unexpected and may be anticipated. The structure of the nucleus

^{79}Y ($Z=39, N=40$) is governed by the large shell gaps that appear at particle numbers $N=38$ and 40 at a deformation of $\beta_2\sim0.4$. (Please see Refs. [4,21] for a Nilsson diagram of the single-particle energies in this mass region.) These two gaps are separated by the Nilsson orbital [422]5/2 which is occupied by the unpaired proton in ^{79}Y. The proton pairing correlation in ^{79}Y is, therefore, expected to be particularly weak because of both blocking and formation of an effective *super*-gap at $Z=38$–40 after the [422]5/2 orbital is occupied. However, a quantitative assessment of the pairing strength requires detailed theoretical calculations which will be presented below.

To better understand the structure of the observed bands, we have performed deformation and pairing self-consistent total Routhian surface (TRS) calculations using a Woods-Saxon potential. The pairing channel includes seniority and doubly stretched quadrupole pairing interactions to avoid spurious shape dependence. To avoid a superfluid-to-normal phase transition due to the mean field approximation, we employed an approximate particle-number projection known as the Lipkin-Nogami method [22,23]. These calculations reveal that correct treatment of pairing is crucial for a quantitative understanding of the MoI despite the presence of large shell gaps that weaken pairing correlations. The role of pairing is illustrated in Fig. 3(a) where we have compared the calculated $J^{(1)}$ values for the paired (open triangles) and unpaired (open squares) systems. The calculated unpaired $J^{(1)}$ overestimates the experimental MoI by $2-3\hbar^2$ MeV^{-1}, i.e., by more than 10%. The Lipkin-Nogami order parameters $\Delta_{\rm LN}$ (i.e., the seniority-type correlations) are shown in the inset of Fig. 3(a). They are weakly dependent on the rotational frequency below the point where $\nu g_{9/2}$ aligns and are $\Delta_{\rm LN}^{(\pi)}\approx0.8$ MeV and $\Delta_{\rm LN}^{(\nu)}\approx1.1$ MeV for protons and neutrons, respectively. These values may be compared with an estimate of the static pairing gap for this mass region, namely, $\Delta\approx12/\sqrt{A}\approx1.3$ MeV. Since Lipkin-Nogami order parameters take into account also the pairing fluctuations, indeed the calculated values of $\Delta_{\rm LN}$ indicate weakened pairing correlations.

Results of the paired calculations for MoI are in excellent agreement with the data for both signatures as seen in Fig. 3(b). The detailed TRS calculations fully confirm all the anticipated trends. The $\sim$10% difference between the unpaired value of the MoI and the data may be attributed to the presence of (weak) pairing correlations. The calculated deformation ($\beta_2\sim0.4$) of the strongly coupled yrast band built on the $g_{9/2}$ proton orbital remains almost constant up to $\hbar\omega\approx0.7$ MeV. At this frequency, this band is predicted to be crossed by a less-collective, triaxial band of $\beta_2\approx0.30$ and $\gamma=-30°$.

The agreement between theory and experiment in ^{79}Y is remarkable. Our earlier studies in this mass region [10,11,21] have shown that the agreement is not accidental: Very good agreement between theory and experiment has been obtained also in the lighter $T_z=1/2$ nuclei ^{75}Rb [10] and ^{77}Sr [11]. It is noteworthy that the ground-state band in ^{77}Sr ($Z=38, N=39$) shares many similarities with that in ^{79}Y: Occupation of the [422]5/2 orbital by the unpaired neutron creates a supergap at $N=38$–40 and deformation of $\beta_2\sim0.40$. Furthermore, the gap at $Z=38$ in ^{77}Sr closely resembles that at $N=40$ in ^{79}Y. Indeed, these two bands were found to be nearly identical both experimentally and theoretically. Figure 4 shows the differences in the values of $J^{(1)}$ for the ground-state bands in these two nuclei calculated from data and the theory. The agreement is again excellent.

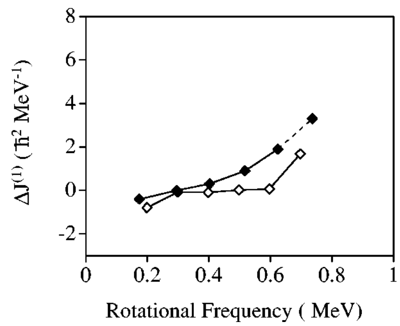

FIG. 4. Comparison of the experimental (solid diamonds) and theoretical (open diamonds) differences of the moments of inertia, $\Delta J^{(1)}=J^{(1)}(^{77}\mathrm{Sr})-J^{(1)}(^{79}\mathrm{Y})$, as a function of rotational frequency for the positive-signature bands.

It is rather unexpected that our conventional TRS calculations, which do not explicitly include the $T=0$ np interactions, can explain the experimental data in the $N\sim Z$ nuclei so well. Two reasons may be suggested. First, such simple observables as the moments of inertia may not be sensitive to the presence of $T=0$ np interactions. Alternatively, effects due to the $T=0$ np interaction may manifest themselves more clearly at very high spins where Coriolis antipairing nearly quenches the $T=1$ interaction. Therefore, high-spin states in the $N=Z$ nuclei may provide the best data set to look for $T=0$ pairing correlation.

To summarize, by combining data from two separate experiments we have identified a strongly coupled band in the $T_z=1/2$ nucleus ^{79}Y which shows a rigid-rotor-like behavior. The favored and unfavored members of this band extend up to spins of $(29/2)\hbar$ and $(23/2)\hbar$, respectively. Conventional TRS calculations, which do not invoke any explicit $T=0$ proton-neutron correlations, are in excellent agreement with the experimental data for this nucleus, as well as its neighboring $T_z=1/2$ nuclei ^{75}Rb and ^{77}Sr. This suggests that the presence of the putative $T=0$ neutron-proton pairing does not significantly affect such simple observables as the moments of inertia of these bands. However, high-spin states in $N=Z$ nuclei may provide some sensitivity to the effects of $T=0$ np interaction.

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