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Identical bands in ^{77}Sr, ^{78}Sr, and ^{78}Rb: Evidence for a very good spectator orbital

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The highest spin states in a $T_z=\frac{1}{2}$ nucleus have been observed in ^{77}Sr: $I^\pi=(\frac{49}{2}^+)$ and $(\frac{29}{2}^-)$. In addition, states up to $I^\pi=(22^+)$ have been seen in ^{78}Sr. The $\alpha=\frac{1}{2}$, $g_{9/2}$ band and both signature partners of the negative parity band in ^{77}Sr were found to be identical to the yrast band in ^{78}Sr with relative alignments of $1.22(7)\hbar$, $0.52(5)\hbar$ ($\alpha=\frac{1}{2}$), and $0.42(4)\hbar$ ($\alpha=-\frac{1}{2}$), respectively. In one of the negative parity bands, the identicality persists through the first proton band crossing. The odd spin decay sequence of the 4^- band in ^{78}Rb is identical to the ground band of ^{78}Sr [$3.02(3)\hbar$] at low spin and to the $\alpha=\frac{1}{2}$, $g_{9/2}$ band in ^{77}Rb [$1.11(3)\hbar$] at higher spins. These are the only known examples of identical bands in the neutron deficient A=80 region. The analysis indicates that the $[301]\frac{3}{2}$ Nilsson orbital is a very good spectator orbital.

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The phenomenon of identical bands and its challenge to our understanding of the basic concepts of nuclear structure at high spins, such as pairing or moments of inertia, has generated considerable recent interest [1–8]. A recent survey [1] of the normally deformed rare-earth nuclei found that a significant fraction of odd Z nuclei contained a band identical to the ground-state band in an even-even neighbor. First associated with superdeformed (SD) rotational bands [9], no single scenario can satisfactorily explain the presence of so many identical bands over such a diverse range of nuclei. A discussion of some of the ideas proposed to explain the phenomenon of band twinning can be found in [7].

The neutron deficient $A = 80$ region is unique in the chart of the nuclides. These nuclei have very elongated ground-state shapes with the Sr [10] and Zr [11] isotopes approaching deformations $\beta_2 \approx 0.4$. However, unlike SD bands, the spins, parities, and intrinsic configurations of these bands have been experimentally determined. Large deformed shell gaps in the single-particle spectrum [12] stabilize these shapes much like the subshell closures associated with the SD orbitals. The low density of single-particle levels results in rapid changes in shape as a function of particle number [12,13] and makes the occurrence of identical bands in the $A = 80$ region less likely. However, we report just such an occurrence.

The excited states in the light Sr isotopes were first established by Lister, *et al.* [14]. Although ^{77}Sr is far from stability, the ground-state spin and parity has been determined by beta decay [14] and laser spectroscopy [15] to be $I^\pi=\frac{5}{2}^+$. Quadrupole moments deduced from lifetimes measured in ^{78}Sr [14] and ^{79}Sr [10] indicate very large deformations of $\beta_2 \approx 0.4$ and are in agreement with theory [12]. The isotope shift measurements of Ref. [15] for ^{77}Sr also indicate a similarly large ground-state deformation.

High spin states in ^{77}Sr and ^{78}Sr were populated with the reaction ^{40}Ca+^{40}Ca at 128 MeV. The EUROGAM array [16] consisting of 45 Compton-suppressed Ge detectors was coupled with the Daresbury recoil separator [17]. The targets consisted of 250 μg/cm^2 of ^{40}Ca, enriched to 99.965%, evaporated onto a 10 μg/cm^2 carbon foil with a flash of gold on the calcium layer to prevent oxidation. The target was mounted with the carbon side facing the recoil separator. Recoil-γ and pure two- and higher-fold γ events were taken. It was possible to do A and Z identification of ^{77}Sr.

The deduced level schemes for ^{77}Sr and ^{78}Sr, shown in Fig. 1, confirm previous results [14,18]. For complete-

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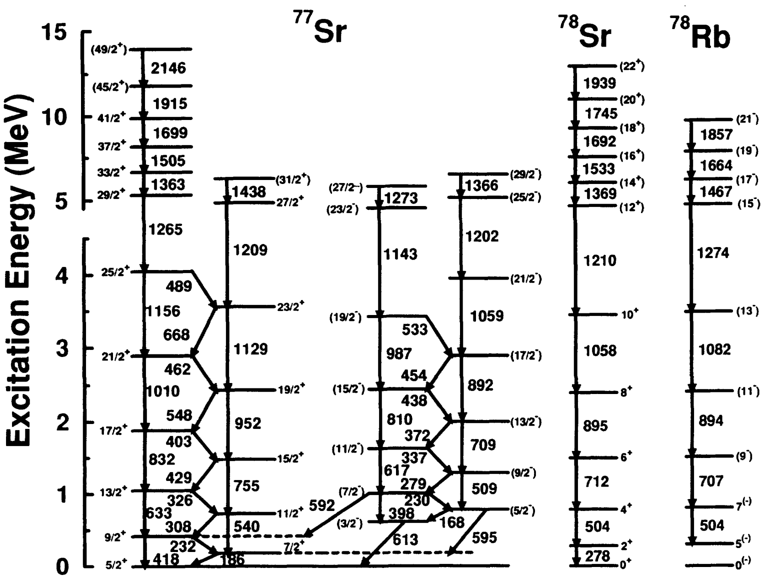

FIG. 1. Proposed level scheme deduced for ^{77}Sr and ^{78}Sr. The odd spin decay sequence from the $K^{\pi}=4^{-}$ band in ^{78}Rb [19] is also shown.

ness, the odd spin sequence of the $K^{\pi}=4^{-}$ band in ^{78}Rb [19] is also shown. The levels in ^{77}Sr can be grouped into two rotational bands built on the $K^{\pi}=\frac{5}{2}^{+}$ [15] and our proposed $K^{\pi}=\frac{3}{2}^{-}$ states. In ^{77}Sr, all negative parity levels and the positive parity states above $I=\frac{13}{2}\hbar$ have been observed for the first time. The bands are connected by two transitions of 592 and 594 keV which have directional correlation (DCO) ratios consistent with dipole radiation. The above K values were used in our analysis and are consistent with the observed strong $\Delta I=1$ transitions and almost no signature splitting at low spins. The positive parity states extend up to $I^{\pi}=(\frac{49}{2}^{+})$; they are the highest spin states observed in any $T_z=\frac{1}{2}$ nucleus.

Surprisingly, only two transitions were added to the top of the yrast band in ^{78}Sr and no side bands were observed. We conclude that any side bands probably lie very high in energy relative to the yrast states and are only weakly populated. It is observed that the γ-ray transition energies of the negative parity $\alpha=\frac{1}{2}$ band in ^{77}Sr and the yrast band in ^{78}Sr are nearly identical. Indeed, the identicality extends through the first proton band crossing [18] but is slightly disturbed at the 1203 and 1210 keV transitions.

We have adopted the definition of identical bands as outlined in Ref. [8]: rotational bands are identical when their dynamical moments of inertia are equal. This can be quantitatively expressed by the constant relative spin alignment of the bands. The slopes of straight lines fitted to the alignment versus total spin, which represent the fractional change in $J^{(2)}$, are less than 2% in the present case. The kinematical, $J^{(1)}$, and dynamical, $J^{(2)}$, moments of inertia as a function of rotational frequency for ^{77}Sr and ^{78}Sr are shown in Fig. 2 and the angular momentum alignments of the identical bands relative to the ^{78}Sr core versus γ-ray transition energy is plotted in Fig. 3. The alignments were calculated following the procedure as outlined in Ref. [8]. The proton and neutron $g_{9/2}$ band crossing frequencies are indicated in the graph of the kinematical moment of inertia:

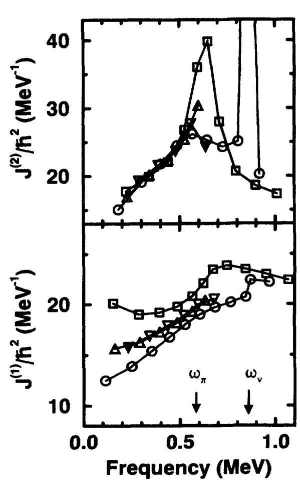

FIG. 2. Kinematical (bottom) and dynamical (top) moments of inertia as a function of rotational frequency for the yrast band in ^{78}Sr (○), positive parity $\alpha=\frac{1}{2}$ band in ^{77}Sr (□), and negative parity, $\alpha=\frac{1}{2}$ (▽) and $\alpha=-\frac{1}{2}$ (△) signature bands in ^{77}Sr. The band crossing frequencies are marked by arrows.

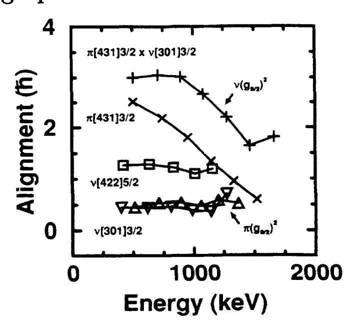

FIG. 3. Angular momentum alignment relative to the ^{78}Sr core for the identical bands in ^{77}Sr [positive parity, $\alpha=\frac{1}{2}$ (□), and negative parity, $\alpha=\frac{1}{2}$ (▽) and $\alpha=-\frac{1}{2}$ (△)] and ^{78}Rb (+). The alignment of the $\alpha=\frac{1}{2}$ $[431]\frac{3}{2}$ band in ^{77}Rb (X) is also shown. Note the constant alignment between the ^{77}Rb and ^{78}Rb bands above 800 keV.

$\hbar\omega_\pi \approx$0.60 MeV [18] and $\hbar\omega_\nu \approx$0.86 MeV. The identical nature of the bands can be observed in the dynamical moments of inertia and the alignment curves. The alignments relative to the ^{78}Sr core are indeed constant but generally not quantized: 0.52(5)$\hbar$ and 0.42(4)$\hbar$ for the $I=\frac{5}{2},\frac{9}{2},\ldots$ and $I=\frac{3}{2},\frac{7}{2},\ldots$ negative parity bands in ^{77}Sr, respectively, 1.22(7)$\hbar$ for the positive parity $\alpha=\frac{1}{2}$ band in ^{77}Sr, and 3.02(3)$\hbar$ for $E_\gamma \leq$900 keV in ^{78}Rb. The additivity of alignments is illustrated by plotting the alignment of the $\pi g_{9/2}$ band in ^{77}Rb [20]; it is seen that initially $i(^{77}\text{Sr})+i(^{77}\text{Rb})=i(^{78}\text{Rb})$. However, this relationship quickly breaks down as the systems rotate. It is also worth noting that the constant relative alignment between ^{77}Rb and ^{78}Rb at higher spins is 1.11(3) $\hbar$.

Recent Nilsson-Strutinsky calculations [21] based on the Woods-Saxon average potential and the finite-range liquid drop model, predict the $[422]\frac{5}{2}$ Nilsson orbital to be the ground-state configuration for ^{77}Sr with $\beta_2 = 0.39$. The first excited single-particle state is predicted to be the $[301]\frac{3}{2}$ Nilsson orbital with a smaller deformation of $\beta_2 = 0.32$. The energy difference between the two configurations is calculated to be 650 keV and is in good agreement with the measured 613 keV. We note the different predicted deformations for the identical bands in ^{78}Sr (β_2=0.37) [12] and ^{77}Sr. If correct, then some other phenomenon must compensate for the changes in the deformation and together, produce identical bands.

While the causes of identical bands remain elusive, the suppression of pair correlations were believed [2–4] to aid in their occurrence. Although the normally deformed identical bands [1] do not provide evidence for this suggestion, we note that the Rb and Sr nuclei lie in a region of reduced pair correlations [13,20,22]. Calculations [22] indicate that the low single-particle level density at the Fermi level can cause a collapse in static pair correlations around particle number 38. Experimental evidence includes the larger moments of inertia observed at low spins in the even-even Sr isotopes as a function of decreasing neutron number [18] and the low single-particle level density as indicated by the high lying negative parity states observed in ^{77}Sr and postulated in ^{78}Sr. Our present calculations indicate that a reduction in pair correlation increases the stability of the deformed shell gaps at $N = Z$=38,40 throughout the observed frequency range ($\hbar\omega$=1 MeV).

The observed identical bands are built upon normal parity and unique parity $g_{9/2}$ orbitals and therefore, pseudospin symmetry arguments can be rejected as an explanation of this occurence. The slight shift in proton alignment in the different parity bands in ^{77}Sr may be caused by differences in shapes as predicted in our calculations. It is surprising that identical bands occur despite these differences. Pairing, although reduced, would be expected to be different depending on whether the odd neutron occupies the $[422]\frac{5}{2}$ or the $[301]\frac{3}{2}$ Nilsson orbitals. A convenient cancellation of effects caused by simultaneous changes in pairing and deformation is doubtful; the many cases of identical bands refute the randomness of such an explanation.

As can be seen in Fig. 1 the lowest three transitions in the negative parity band in ^{78}Rb are identical to the $8^+ \to 6^+ \to 4^+ \to 2^+$ cascade in ^{78}Sr. The $g_{9/2}$ proton crossing is blocked in ^{78}Rb thus revealing the proton occupation of the $g_{9/2}$ orbital. It should be noted that the identical transition energies may be accidental in the case of ^{78}Rb. This may be deduced from the rapid loss of the additivity relation of the aligned angular momenta (see discussion of Fig. 3) of the negative parity bands in ^{77}Sr and the $g_{9/2}$ band in ^{77}Rb.

A remaining question is if ^{78}Sr is such a good core, is ^{76}Sr also a good core? Our calculations predict that the single-particle gap at N = 38 is larger than at N = 40 and hence, the ground-state band of ^{76}Sr should be very rigid. Three transitions are known [23] in the ground band of this $N = Z$ nucleus yet they are not identical to the energy sequences in ^{75}Rb, ^{76}Rb, and ^{77}Sr. The data analysis of ^{75}Rb and ^{76}Rb, which were populated in the present work, is continuing.

To summarize, positive parity states in the $T_z=\frac{1}{2}$ nucleus ^{77}Sr have been extended up to $I=(\frac{49}{2}\hbar)$ and the negative parity states have been observed for the first time. These bands are identical to the yrast band in ^{78}Sr and in one of the negative parity bands, the identicality continues through the first proton band crossing. Additionally, the high spin part of the band built on the 4^- state in ^{78}Rb is also identical to the positive parity band in ^{77}Rb. In the bands of negative parity, it is believed that the $[301]\frac{3}{2}$ Nilsson orbital plays the role of spectator.

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