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Identification of $\Delta\nu=2$ identical bands in the nuclei ^{78}Kr and ^{80}Rb

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Rotational states at high spins have been identified in the doubly odd nucleus ^{80}Rb. A striking feature of the level scheme is that the transition energies in the $\alpha=1$ signature component of the positive parity band are quite similar to those of the yrast band in ^{78}Kr. This is the only instance of identical bands at high spin, with a difference in seniority $\Delta\nu=2$, in this mass region. [S0556-2813(97)50411-0]

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The observation of rotational bands having similar moments of inertia, and in some cases even identical transition energies, in neighboring nuclei, continues to evade a theoretical understanding. This phenomenon was first reported in 1989, when it was found that the excited superdeformed bands in ^{150}Gd and ^{151}Tb closely resembled the yrast superdeformed bands in ^{151}Tb and ^{152}Dy, respectively [1]. The similarity of γ-ray energies indicated the equality of moments of inertia of these bands, which constituted a serious challenge to nuclear physicists. These, and other subsequent, fascinating findings at superdeformation were followed by the discovery of identical bands in normal deformed nuclei, ranging from the light Rb and Sr isotopes to the actinides [2–5].

The existence of identical bands cannot be reconciled with the conventional understanding of pairing correlations in nuclei. A large proportion of these identical bands have been observed in nuclei differing by an odd particle [6]. According to the BCS pairing theory, the moments of inertia associated with one quasiparticle states should exceed those of the ground state configurations of the neighboring even-even nuclei by about 10–15 % [7], while the difference is expected to be twice this number for a two quasiparticle change. An obvious implication is that bands with similar moments of inertia are not expected in nuclei differing by two or more quasiparticles. It is in this context that the observation of identical bands with a difference in seniority $\Delta\nu=2$, becomes particularly significant. Therefore, it is necessary to identify the mechanisms responsible for the rigidity of doubly even cores under the influence of polarization due to valence nucleons. For nuclei with $A\approx80$, the single particle level density is practically half that of the rare earths, where most of the identical bands have been observed, indicating a decreased probability for their occurrence in this mass region.

The particular motivation for the present study was the fact that both the valence neutrons and protons occupy the high-j $g_{9/2}$ orbital in doubly odd nuclei in this mass region. Therefore, it is possible to study the influence of these orbitals on the structure of these nuclei. Among the doubly odd Rb isotopes, ^{80}Rb is unique being the only one calculated to have an oblate ground state deformation [8]. This communication reports the observation of a band in ^{80}Rb with transition energies quite similar to those of the yrast positive parity band in ^{78}Kr [9]. It has also been possible to identify new levels in the negative parity bands, and previously unknown sidebands have been observed. These observations will be elucidated in a more detailed publication, while the discussion here is confined to the positive parity states.

The fusion-evaporation reaction ^{51}V(^{32}S,$2pn$) at 105 MeV was used to study high spin states in ^{80}Rb. A self-supporting (400 μg cm^{-2}) ^{51}V target was used, while the ^{32}S beam was delivered by the 15 UD pelletron at the Nuclear Science Centre, New Delhi. The cross section for ^{80}Rb in this reaction was a small fraction ($<10\%$) of the total yield, which indicated the need for reaction channel selection. A discrimination of residual nuclei with $A=80$ from the large number of other exit channels was aided by using eight Compton suppressed high purity Ge detectors, four each at 80° and 130° with respect to the beam direction, which were part of the Gamma Detector Array (GDA) in conjunction with the recoil mass separator HIRA (Heavy Ion Reaction Analyzer) [10]. The GDA was used to record γ-γ events in coincidence with mass-identified reaction products of $m/q=4.875$ at the focal plane of HIRA, having a solid angle acceptance of 10 msr. However, charge identification was not possible due to the relatively low velocity of the recoils ($\beta\approx0.02$). The unraveling of the low spin structure, particularly the negative parity sidebands, was facilitated by the use of the recoil mass separator. The observation of excited states in ^{80}Rb has been previously reported in [11], while levels up to an excitation energy of 9 MeV in the positive parity band had been reported in [12]. The present work has identified levels up to an excitation energy of 13 MeV and a spin $25\hbar$.

The positive parity band in ^{80}Rb decays to an isomeric state at an excitation energy of 494.4 keV. This state has been assigned a spin and parity of 6^+ and a lifetime of 1.6 μs has been measured [13]. Signature inversion in the vicinity of $9\hbar$ is a feature characteristic of doubly odd nuclei in this mass region, reflecting the change in structure above the inversion point, where the rotation of a system with two fully aligned quasiparticles is involved. In ^{80}Rb, the even spin ($\alpha=0$) states are energetically favored at low spins, while the $\alpha=1$ signature component is found to be favored [14]

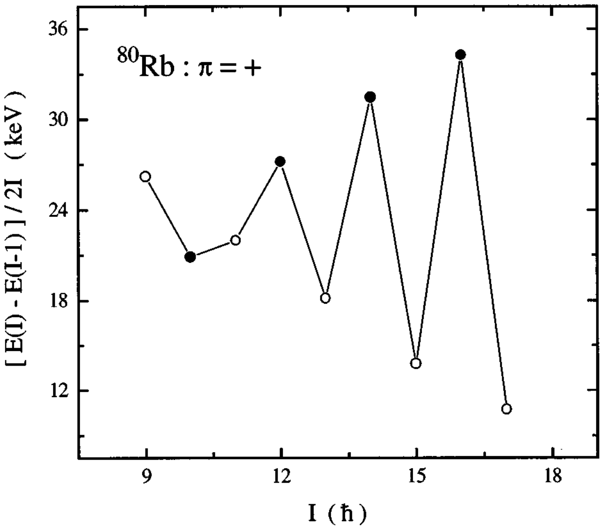

FIG. 1. Signature splitting in the positive parity band of ^{80}Rb. Signature inversion, indicated by a reversal in the phase of the odd-even staggering, is seen at $11\hbar$.

above a spin $11\hbar$, in agreement with the earlier observation [11]. The magnitude of the signature splitting is small at low spins; however a considerable increase above the inversion point is observed (Fig. 1). The positive parity states have been attributed a $(\pi g_{9/2} \otimes \nu g_{9/2})$ two quasiparticle configuration [11], which is consistent with the g factor measured for the 6^+ isomeric state [13]. This state will have $(\pi[413]\frac{7}{2}^+ \otimes \nu[422]\frac{5}{2}^+)$ as the dominating Nilsson configuration, for an oblate deformation $\epsilon_2 \approx -0.2$. The 6^+ state will result from the parallel coupling of the angular momentum components, $K=\Omega_p+\Omega_n$, while the 1^+ ground state will be due to their antiparallel coupling. The increase in the signature splitting at higher spins is attributable to mixing from low-Ω orbitals which approach the Fermi surface at high rotational frequencies.

An interesting aspect which is evident from the level scheme (Fig. 2) is that the transition energies in the $\alpha=1$ signature component of ^{80}Rb (with a ground state 1^+) above a spin $11\hbar$, are quite similar to those of the yrast band of ^{78}Kr (with a ground state 0^+) above a spin $10\hbar$. The stage at which there appears to be onset of identicality in these two bands is characterized by structural changes in both nuclei viz. a sharp band crossing in ^{78}Kr, and signature inversion in ^{80}Rb.

A variety of criteria have been utilized for deciding the identicality of two bands [6]. The equivalence of the moments of inertia (MOI), the constancy of relative alignment, and a small average fractional change in the MOI over the observed range of frequencies are among the most important requirements. Figure 3 gives a comparison of the MOI of the bands in ^{78}Kr and ^{80}Rb in the region of interest. From this figure, it is evident that except around the band crossing at $\hbar\omega=0.9$ MeV, there is a marked similarity between them. This similarity is also reflected in the plot of the distribution of spins as a function of transition energies [Fig. 4(a)]. The difference between the spins of the two bands at a constant rotational frequency is termed as the relative alignment. This quantity for the present example has been found to be $0.80(12)\hbar$ below the region of band crossing, and $0.80(27)\hbar$ for the entire band [Fig. 4(b)]. It compares well with the values of $1.28(25)\hbar$, $0.56(11)\hbar$, and $1.13(12)\hbar$ obtained for the $K^\pi=3^+$ band in ^{172}Yb, and the $K^\pi=3^-$ and 4^- bands in ^{172}Lu, respectively [Fig. 4(c)], which are identical with the ^{170}Yb yrast band [4]. It should be noted that in ^{172}Lu, the alignment at only three values of spins is considered. For the only other known examples of identical bands in the $A\approx 80$ region, i.e., the $\Delta\nu=1$, $K^\pi=5/2^+$, $5/2^-$, and $3/2^-$ bands in ^{77}Sr, values of $1.22(7)\hbar$, $0.52(5)\hbar$, and $0.42(4)\hbar$ have been obtained, relative to the ^{78}Sr core. For the $K^\pi=5/2^+$ band in ^{77}Sr, the identicality does not hold above a spin $25/2\hbar$. As expected, the deviations in the relative alignment are smaller in the case of $\Delta\nu=1$ bands.

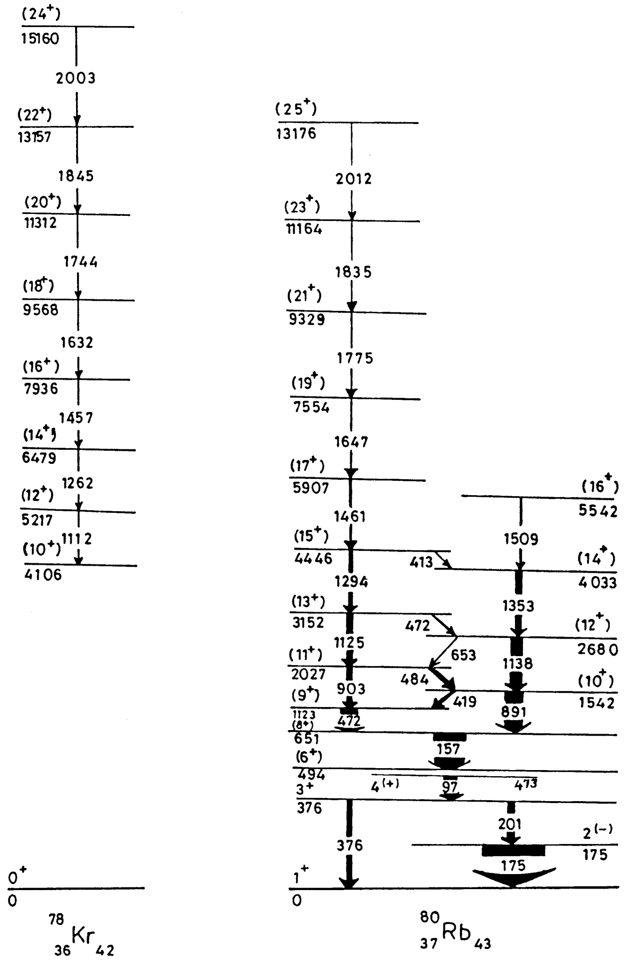

FIG. 2. Partial level scheme of ^{80}Rb obtained from the present work. Only the positive parity states are shown. The thickness of the arrows is approximately proportional to the intensities of the transitions. The energy scale has been expanded by a factor of five below a spin of $8\hbar$, for the sake of clarity. It should be noted that the 6^+ state in ^{80}Rb is a μs isomer, and therefore the transitions above this state do not have a prompt coincidence with those below it. The yrast band of ^{78}Kr is shown alongside, for a comparison of the bands under consideration.

Another procedure to test the identicality, which is closely related to the above considerations, takes into account the global fluctuations in the MOI. It involves a least square fitting of the relative alignment as a function of spin, and the requirement [6] for the identicality of two bands is that the

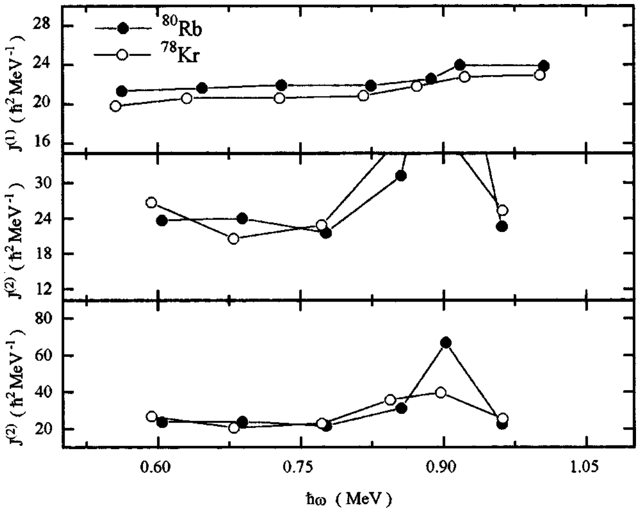

FIG. 3. Comparison of the kinematic $\mathbf{J}^{(1)}$ and dynamic $\mathbf{J}^{(2)}$ moments of inertia for the yrast positive parity bands of ^{78}Kr and ^{80}Rb, illustrating their identical nature. A band crossing, evidenced by the abrupt increase in the $\mathbf{J}^{(2)}$ values around $\hbar\omega\approx0.9$ MeV, is visible in both cases, although it is more pronounced for ^{80}Rb. An expanded scale has been employed for $\mathbf{J}^{(2)}$ in the second panel, to illustrate the minor variations in the dynamic moments of inertia.

average fractional change in the MOI ($\overline{FC}$) obtained using this procedure should not exceed the scaling of the rigid rotor MOI with mass. This scaling factor for the case of ^{78}Kr and ^{80}Rb is 0.04. The value obtained by the fitting procedure, $\overline{FC}=0.01(\pm0.03)$, lies within this threshold. A similar analysis for the $\Delta\nu=2$, $K^{\pi}=6^{+}$ band in ^{172}Hf, which is identical with the ^{170}Yb yrast band [6], yields a value of $\overline{FC}=0.005(\pm0.008)$. The corresponding values for the $\Delta\nu=1$, $K^{\pi}=5/2^{+}$, $5/2^{-}$, and $3/2^{-}$ bands in ^{77}Sr are $\overline{FC}=0.013(\pm0.010)$, $0.009(\pm0.006)$, and $0.017(\pm0.014)$, respectively. The errors in $\overline{FC}$ are quite large, since they are a result of local fluctuations in the MOI. The magnitude of the errors is greater in the case of $\Delta\nu=2$ bands, since the variations in the MOI are expected to be more than the $\Delta\nu=1$ cases.

It seems reasonable to us, to conclude therefore, on the basis of the above discussion, that the bands in ^{78}Kr and ^{80}Rb are indeed identical.

Although there have been a number of cases of identical bands in normal deformed nuclei reported in the literature [6], we feel that this example presents some unique features which we would like to emphasize. This is the only known case of identical bands with a difference in seniority $\Delta\nu=2$, in the $A\approx80$ region. The other examples of such bands in nuclei differing by a single proton and a neutron, have been reported in the $A\approx170$ region, e.g., the identicality of the $K^{\pi}=3^{-}$ and 4^{-} bands in ^{172}Lu with the ^{170}Yb core [4]. However, these cases are essentially different from the present example, since for these bands there are actually no observed $E2$ transitions between the levels. For the two quasiproton and two quasineutron configurations in ^{172}Hf and ^{172}Yb, the signature splitting is small, and the identical nature is evident only when both the signature components are

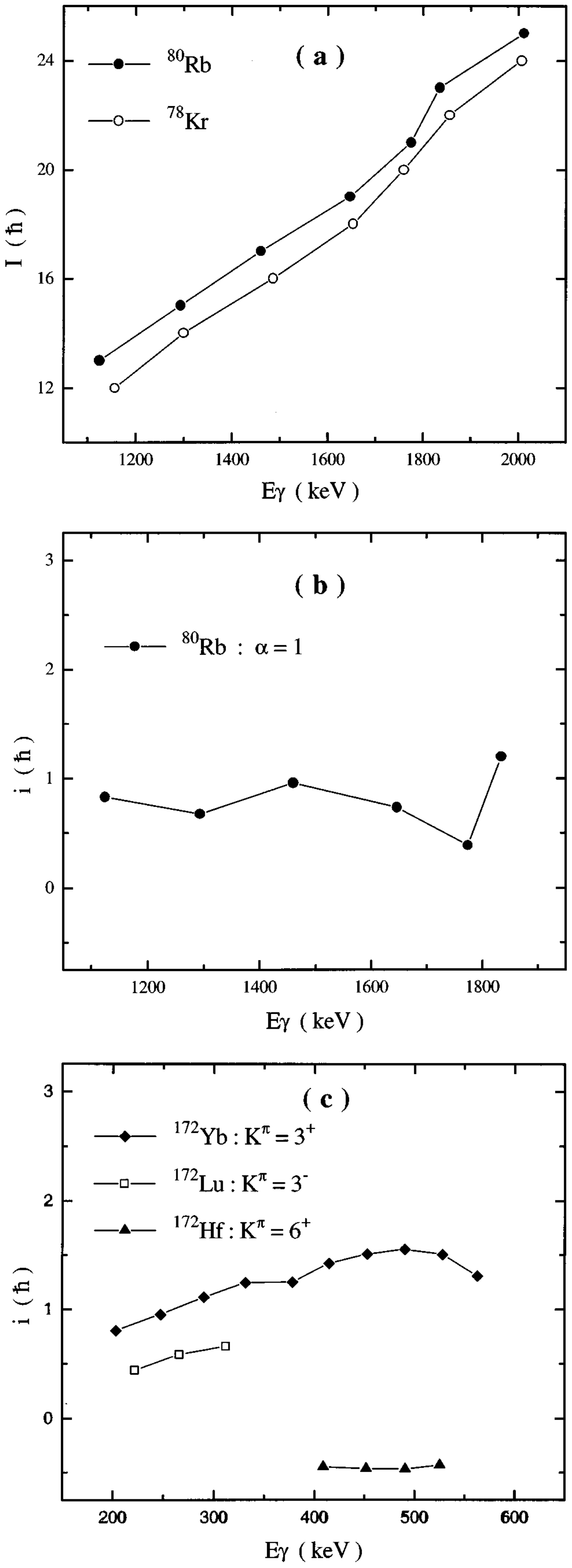

FIG. 4. (a) Distribution of spins as a function of transition energies in ^{78}Kr and ^{80}Rb. Relative alignment as a function of spin for the $\Delta\nu=2$ identical bands in: (b) ^{80}Rb with respect to ^{78}Kr (c) ^{172}Yb, ^{172}Hf, and ^{172}Lu with respect to ^{170}Yb.

taken into consideration. On the contrary, the splitting between the two signature components of the positive parity band in ^{80}Rb is substantially large after the inversion point, and an actual comparison of the observed $E2$ transition energies between the $\alpha=1$ component in ^{80}Rb and the yrast band in ^{78}Kr, is possible. Besides, the identicality in ^{80}Rb persists over a considerably large range of frequency (≈ 0.5 MeV), compared to the other cases (≈ 0.1–0.2 MeV) mentioned above.

Several attempts have been made to explain the phenomenon of identical bands, but have thus far met with limited success. It is generally believed that the suppression of pair correlations aids the occurrence of identical bands [15,16]. Besides, any such bands should have similar deformations and underlying configurations, along with a comparable evolution in shape. In the light of these facts, we have attempted to understand the occurrence of identical bands in ^{78}Kr and ^{80}Rb. As mentioned earlier, in ^{78}Kr, the identicality is evident after the first band crossing, signifying a reduction in pairing, whereas the corresponding point in ^{80}Rb is associated with signature inversion, indicative of rotational bands built upon two fully aligned noninteracting quasiparticles. Therefore, in both the cases, the magnitude of the pairing correlations is small near the region of onset of identicality. The second aspect which deserves consideration involves the shapes of the bands in the two nuclei. The ground state deformations for the two nuclei have been calculated by Moller and Nix [8], and a similar value of $\epsilon_2=-0.225$ has been predicted for ^{78}Kr and ^{80}Rb. This might be taken to indicate similar deformations for the yrast bands in the two cases. To substantiate such a conclusion, it is necessary to know, for example, the magnetic moments of the observed rotational states. Experimental evidence for the case of ^{78}Kr exists in the form of the g factors deduced for states up to a spin $8\hbar$ [17]. It has been found that there is a significant decrease in the g factor in the region of the first band crossing (around $8\hbar$), in contrast to the collective value ($\approx +0.5$) determined by Ward *et al.* [18]. This is strongly suggestive of a neutron alignment, implying an oblate shape for the ground state band. In the case of ^{80}Rb, the g factor for the 6^+ state has been measured [13], and a value of $g=+0.563(4)$, quite close to the collective value has been found. Although, in the absence of any measurements for the higher spin states, it is not possible to reach any definite conclusions regarding the evolution of shape in the ground state band of ^{80}Rb, it appears to us that since both the proton and neutron crossings are blocked, their opposite shape driving effects result in the well-deformed oblate minimum at the ground state to persist up to higher spins. This, we feel, is a plausible mechanism which would account for the similar shapes of the bands in ^{78}Kr and ^{80}Rb, leading to their identicality.

A surprising observation was the presence of a relatively pronounced band crossing at $\hbar\omega\approx 0.9$ MeV in ^{80}Rb. Both the proton and neutron crossings in the positive parity band of ^{80}Rb are blocked, and the observation of such a crossing was not expected. The understanding of the nature of band crossings at high frequencies is a challenging problem both experimentally and theoretically, which is further complicated by the fact that ^{80}Rb is a doubly odd nucleus. At this juncture, one guess that we can hazard is that this band crossing might be the result of the alignment of a pair of nucleons from two different components of the $g_{9/2}$ orbital. This appears to us a possible reason for this band crossing, in view of the magnitude of the frequency being considered. However, this aspect is being explored further.

In conclusion, we have reported the observation of identical bands in the positive parity yrast states of ^{78}Kr and ^{80}Rb, which is particularly interesting due to the difference of two quasiparticles between these nuclei. The virtual absence of core polarization due to these two quasiparticles is a challenging problem for existing theories. The observation of $\Delta\nu=2$ identical bands in relatively low mass nuclei has extended the range that any theoretical explanation of this phenomenon will need to span. A better understanding of the evolution of the structure of both the nuclei will require more experimental inputs, for example, the measurement of the magnetic moments of the states in both nuclei, up to the highest possible spins.

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