Evidence for Nontermination of Rotational Bands in ^{74}Kr

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Three rotational bands in ^{74}Kr were studied up to (in one case one transition short of) the maximum spin I_{max} of their respective single-particle configurations. Their lifetimes have been determined using the Doppler-shift attenuation method. The deduced transition quadrupole moments reveal a modest decrease, but far from a complete loss of collectivity at the maximum spin I_{max}. This feature, together with the results of mean field calculations, indicates that the observed bands do not terminate at $I = I_{max}$.

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The atomic nucleus reveals a number of features of a finite many-fermion quantum mechanical system which either do not exist or cannot be experimentally measured in other systems. One of these unique features is smooth band termination, namely, a continuous transition within the same configuration from collective rotation at low spin to a noncollective single-particle (terminating) state at I_{max} corresponding to the maximum spin which can be built in the pure configuration. At present, detailed understanding of this process has been achieved both experimentally and theoretically (see Ref. [1] and references therein). It is important to note that theoretical calculations [1–3] indicate that not all bands have to terminate in a noncollective state at I_{max}. However, the phenomenon of nontermination of rotational bands at I_{max} has not been studied experimentally until now.

Earlier studies with an harmonic oscillator potential [1,2] showed that rotational bands do not terminate in a noncollective state at I_{max} if the deformation exceeds a critical value at low spin (see Fig. 2 in Ref. [1]). This is a basic feature of the harmonic oscillator potential, which is due to the coupling of different N shells leading to a mixing of different configurations. In this situation, even higher spins than I_{max} can be build within the mixed configuration. However, the harmonic oscillator potential is too simplistic for real nuclei.

In realistic nuclear potentials, it is possible to make a separation into high- and low-j orbitals within the same N shell. Thus, the configurations and their corresponding I_{max} values are defined in terms of the distribution of particles and holes over low- and high-j subshells. Known terminating bands are well classified within such a scheme [1]. Therefore, it is appropriate to start from these I_{max} values when searching for possible nonterminations of rotational bands in nuclei. Indeed, it is reasonable to expect similar features as in the harmonic oscillator, i.e., with increasing deformation the mixing between low- and high-j subshells will become large leading to mixed rotational bands which do not terminate at I_{max}.

Optimal conditions for the study of possible collectivity at the $I_{\max}$ state (and thus of the phenomenon of nontermination of rotational bands) are present in the neutron-deficient $A \sim 75$ region. With the distinction between high-j $f_{7/2}$ and low-j $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals in the $N = 3$ shell, the maximum spin that can be generated in the valence-space subshells between the $Z, N = 28$ and 50 gaps is around $I = 35\hbar$. Such spin values are within reach of modern facilities. Furthermore, the appreciable deformation of the rotational bands in the middle of the region suggests strong mixing of low- and high-j orbitals. In this Letter we report the observation of rotational bands up to the $I_{\max}$ value in the nucleus ^{74}Kr, where measured transition quadrupole moments indicate that they do not terminate in a noncollective state at $I_{\max}$. This represents the first observation of "nontermination" of rotational bands at $I_{\max}$.

High-spin states in ^{74}Kr were studied using the ^{40}Ca(^{40}Ca$, 2p\alpha$)^{74}Kr fusion-evaporation reaction with two different setups. The first experiment was performed at Laboratori Nazionali di Legnaro (LNL), using a 185 MeV beam delivered by the XTU Tandem accelerator. The experiment was performed using a ^{40}Ca target with a thickness of 900 μg/cm^2. The γ rays produced in the reaction were measured with the Euroball III array [4], which was equipped with 26 clover and 15 cluster composite Compton-suppressed Ge detectors. Euroball III was coupled to the 4π charged particle detector ISIS [5], consisting of 40 silicon $\Delta E/E$ telescopes, and to a neutron wall [6], which comprised 50 liquid scintillator neutron detectors covering the forward 1π section of Euroball III. A total number of 1×10^9 γ-γ-γ events were recorded with an event trigger requiring coincidences between three or more HPGe detectors. The second experiment was carried out at Argonne National Laboratory (ANL), using a 165 MeV beam delivered by the Tandem Linac Accelerator System (ATLAS). A thin 350 μg/cm^2 ^{40}Ca target was used. The γ rays of the reaction were detected with 99 Compton-suppressed HPGe detectors of the Gammasphere array [7], with the heavimet collimators removed in order to obtain summed γ-ray energy per event. The evaporated charged particles were detected in coincidence with the γ rays and identified with the 95-element CsI(Tl) Microball detector [8]. A total of 1.5×10^9 particle-γ coincidence events were recorded with an event trigger requiring coincidences between four or more HPGe detectors. The $2p\alpha$ channel was enhanced, in this experiment, by applying the total energy plane channel-selection method [9].

A partial decay scheme for ^{74}Kr showing the ground-state band and the favored negative-parity bands (band A and band B) is presented in Fig. 1. The level scheme has been confirmed in both experiments. The highest spins in the ground-state band $I^\pi = (32^+)$ and in band A $I^\pi = (35^-)$ were observed only in the Euroball experiment and

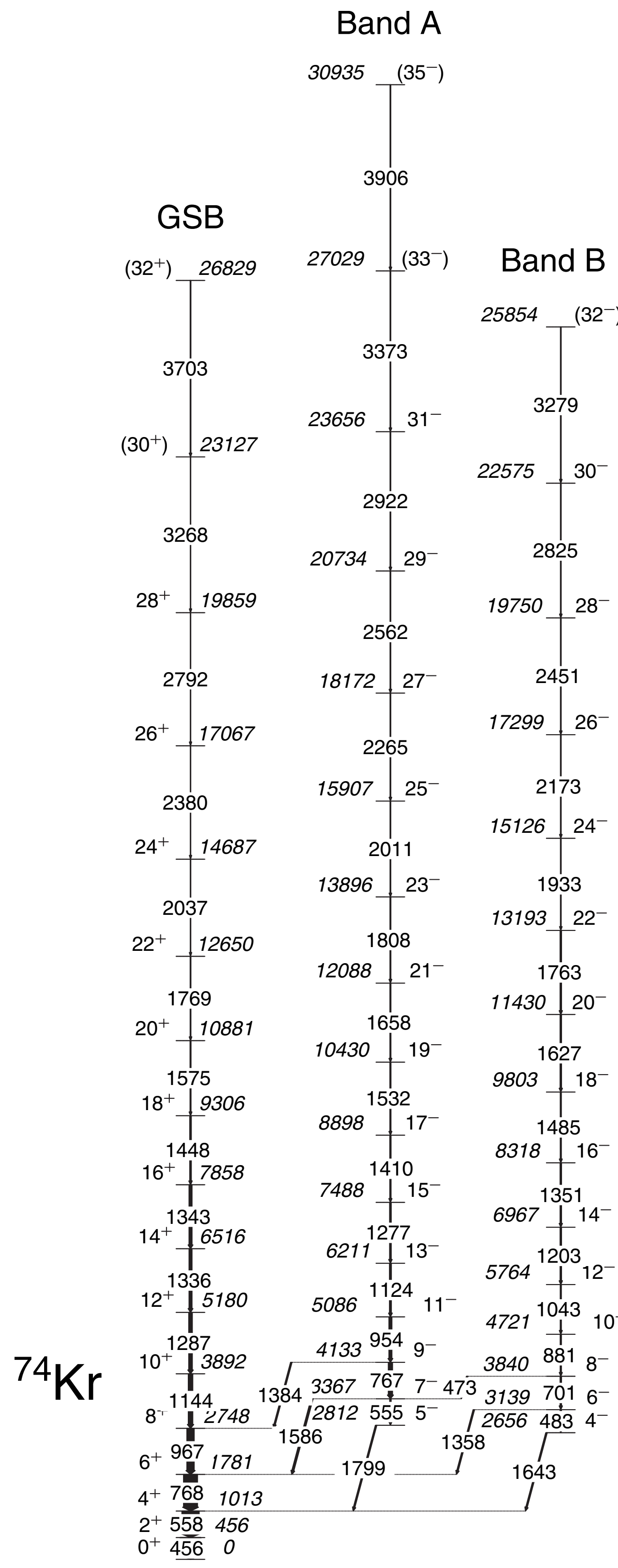

FIG. 1. Partial level scheme deduced from the current work for ^{74}Kr. The energy of the γ-ray transitions are given in keV and arrow widths are proportional to relative γ-ray intensities.

resulted from using a higher beam energy. The relative spin values for the highest-spin states were deduced from an analysis of γ-γ directional correlations of oriented states, using the Gammasphere data. These bands were previously observed up to a tentative $I^\pi = (28^+)$, (29^-), and (28^-) [10] for the ground-state band, band A, and band B, respectively.

Figure 2 shows the kinematic $\mathfrak{J}^{(1)}$ and dynamic $\mathfrak{J}^{(2)}$ moments of inertia for the ground-state band, band A, and band B in ^{74}Kr. Above the paired band crossing at $\hbar\omega \sim 0.6$ MeV these bands show all features typical for rotation in the unpaired regime such as $\mathfrak{J}^{(2)} \leq \mathfrak{J}^{(1)}$ and a smooth decrease of both quantities with increasing rotational frequency [1]. The smooth character of $\mathfrak{J}^{(1)}$ and $\mathfrak{J}^{(2)}$ indicates that no configuration change takes place above $\hbar\omega \sim 0.7$ MeV. The cranked relativistic Hartree-Bogoliubov calculations of Ref. [11] clearly show that pairing has little effect on the moments of inertia above the band crossing. Indeed, in this regime, the energies of the bands are well described [11] by the cranked Nilsson-Strutinsky (CNS) [1] and the cranked relativistic mean field (CRMF) [12] calculations without pairing. According to these calculations the $[2,4](\alpha = 0)$ and $[3,4](\alpha = 1,0)$ configurations are assigned to the ground-state band and to the bands A and B, respectively. Here the shorthand notation $[p,n](\alpha_{\rm tot})$ indicates the number $p(n)$ of occupied $g_{9/2}$ proton (neutron) orbitals in the configuration having a total signature $\alpha_{\rm tot}$. The number of low-j $N = 3$ protons and neutrons is then fixed from the total number of particles, $Z = 36$ and $N = 38$.

The maximum spins $I_{\rm max}$ of the $[2,4](\alpha = 0)$, $[3,4](\alpha = 0)$, and $[3,4](\alpha = 1)$ configurations are 32^+, 34^-, and 35^-, respectively. For example, the detailed structure of the $[2,4](\alpha = 0)$ configuration with respect to the ^{56}Ni spherical core is $\pi[g_{9/2}]_8^2[p_{1/2}p_{3/2}f_{5/2}]_6^6 \otimes \nu[g_{9/2}]_{12}^4[p_{1/2}p_{3/2}f_{5/2}]_6^6$, where the subscripts indicate the maximum spin built within the group of orbitals, i.e., $I_{\rm max} = 8 + 6 + 12 + 6 = 32$. Thus the ground-state band and band A ($\alpha = 1$) were observed up to their maximum spins, while band B ($\alpha = 0$) was one transition short of $I_{\rm max}$. However, the minima of the calculated potential energy surfaces for these configurations at $I_{\rm max}$ are associated with some collectivity ($\varepsilon_2 \sim 0.2$, $\gamma \sim 20°$) and do not correspond to the noncollective $\gamma = 60°$ value, as illustrated for the ground band configuration in Fig. 3.

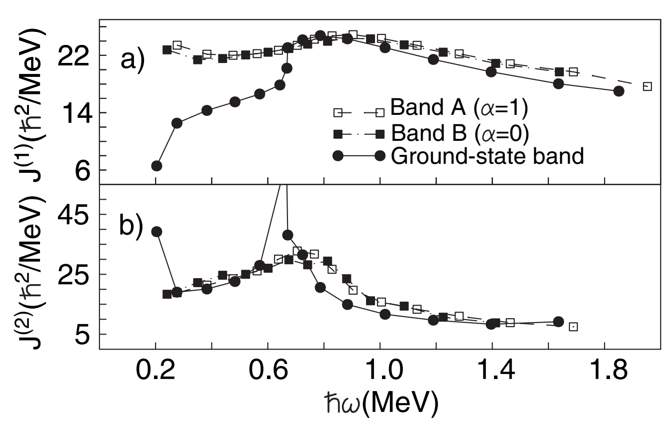

FIG. 2. (a) Kinematic and (b) dynamic moments of inertia for the ground-state band, band A, and band B in ^{74}Kr plotted versus rotational frequency.

Thus, contrary to the terminating bands in the $A = 110$ region [1], the CNS calculations suggest that these smooth bands remain collective at $I_{\rm max}$ and that it may be possible to follow them to even higher spins. These higher spin states are formed mainly because of the coupling to the $f_{7/2}$ orbitals, which are outside the valence space, in a similar way as higher spin states might be formed in strongly deformed harmonic oscillator configurations due to the coupling to other N shells [1,2].

In order to study the evolution of the deformation at high spins, we measured the lifetimes of the high-spin states of the ground-state band, band A, and band B in ^{74}Kr using the centroid-shift Doppler attenuation method [13] with the Gammasphere data. The deformation of the ground-state band and band A were previously measured up to $I^\pi = 18^+$ and 17^- [14], respectively, using the Doppler-shift attenuation method. The measured fraction F of the full Doppler shift is plotted for the three bands as a function of γ-ray energy in Fig. 4. The F values were measured by gating on the top three transitions of the band of interest. Because of the collectivity and high transition energies at high spins, all the top transitions decay within the target while the nucleus is slowing down. On the contrary, the transitions from states with $I \lesssim 11$ decay outside the target, showing a constant F; see Fig. 4. The experimental F values were fit taking into account the slowing down process of the recoil in the target, which was modeled using the stopping powers obtained from the SRIM-2003 code [15]. The fitting program takes into account the momentum distribution of the recoils, due to particle emission. It has been shown previously [16,17] that in the channels where α particles are present the angular depen-

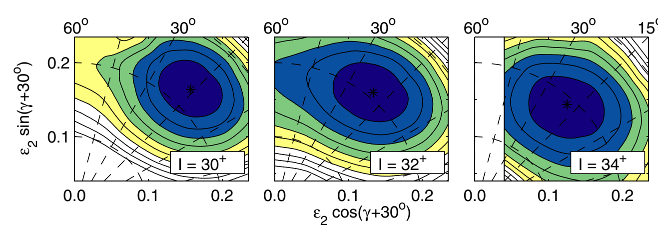

FIG. 3 (color online). Potential energy surfaces at $I = 30, 32, 34\hbar$ calculated in the CNS formalism for the $[2,4]$ configuration. The contour line separation is 0.2 MeV. Note that the minimum remains at $\varepsilon_2 \sim 0.2$, $\gamma \sim 20°$ for all these spin values corresponding to $I_{\rm max} - 2$, $I_{\rm max}$, and $I_{\rm max} + 2$. No noncollective state can be defined for $I > I_{\rm max}$, and a region around the $\gamma = 60°$ axis is therefore excluded from the $I = 34$ surface.

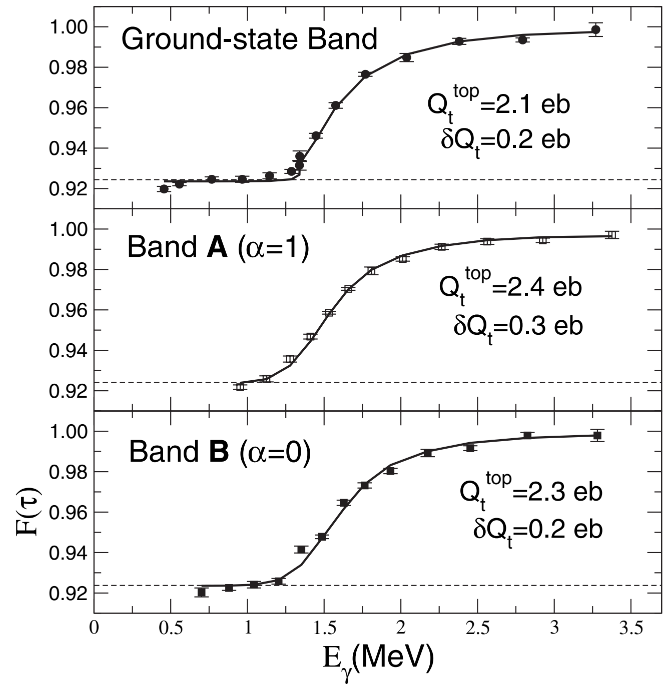

FIG. 4. Experimental $F(\tau)$ values for the ground-state band, band A, and band B as a function of γ-ray energy in ^{74}Kr. The solid line shows the calculated $F(\tau)$ values. The dashed line represents the saturation $F(\tau)$ value when the recoils leave the target.

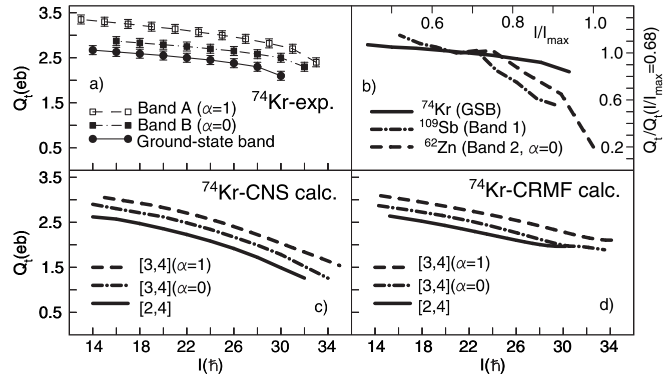

FIG. 5. (a) The measured transition quadrupole moments Qt for the ground-state band (GSB), band A, and band B. (c),(d) The calculated Qt values for the $[2,4]$, $[3,4](\alpha = 1)$, and $[3,4] \times (\alpha = 0)$ configurations assigned to the ground-state band, band A, and band B, respectively. (b) Transition quadrupole moments of the bands in ^{62}Zn, ^{74}Kr, and ^{109}Sb, normalized at $I/I_{\rm max} = 0.68$, as a function of $I/I_{\rm max}$.

dence in the particle detection efficiency of Microball is not isotropic and must be included in the lifetime analysis. The decay of the nucleus was modeled using the empirical equation $Q_t(I) = Q_t^{\rm top} + \delta Q_t \sqrt{I^{\rm top} - I}$ [18], to fit the experimental data. The superscript "top" indicates the highest-spin state observed experimentally in a given band for the current work, for which a centroid shift could be measured. In the current data, this corresponds to $I^{\rm top} = 30^+, 33^-$, and 32^- for the ground-state band, band A, and band B, respectively. The δQ_t represents the variation of the Q_t value within the band. The side feeding was considered into the top three states, which were used for gating, and was modeled assuming a rotational band sequence, with four transitions with the same Q_t as the band that is fed. It should be noted that if a lower $Q_t^{\rm top}$ is considered in any of the studied bands, then the fit curve will lie below the experimental points all along the band [19].

The experimental and theoretical Q_t values as a function of spin for the ground-state band and the two signature partners band A and band B are shown in Fig. 5(a), 5(c), and 5(d). The calculations were performed within the CNS and CRMF approaches which describe the Q_t values in the smooth terminating bands of ^{62}Zn [20] and ^{109}Sb [21,22] with good accuracy. The experimental values in ^{74}Kr are well described and they show a smooth decrease of Q_t as the spin increases. However, this decrease is very marginal compared with that of the smooth terminating bands in ^{62}Zn and ^{109}Sb [Fig. 5(b)]. Although, the transition quadrupole moments have not been measured for the ($I_{\rm max} \rightarrow I_{\rm max} - 2$) transition, this result strongly suggests that the experimental bands do not terminate at $I_{\rm max}$. This conclusion is supported by the comparison with Q_t values obtained in the CNS and CRMF calculations which reproduce the transition quadrupole moments, including their modest decrease. The decrease is somewhat better reproduced in the CRMF approach where the discontinuities observed at the highest spins are explained by the difficulties in following the configurations close to $I_{\rm max}$ in the calculations.

In summary, three smooth rotational bands have been observed in ^{74}Kr up to (or one transition short of) the maximum spin $I_{\rm max}$. Contrary to the previously known cases of rotational bands, which terminate in a noncollective state at $I_{\rm max}$, the measured transition quadrupole moments strongly suggest that these bands do not terminate. This feature, which is supported by mean field calculations, represents the first observed case of nontermination of rotational bands at $I = I_{\rm max}$, thus opening a new field for the study of nuclei at the extremes of angular momentum.

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