Evidence for non-termination of rotational bands in ^{74}Kr

J.J. Valiente-Dobón,[1,*] T. Steinhardt,[2] C.E. Svensson,[1] A.V. Afanasjev,[3,4] I. Ragnarsson,[5] C. Andreoiu,[1,6]
R.A.E. Austin,[7] M.P. Carpenter,[8] D. Dashdorj,[9] G. de Angelis,[10] F. Dönau,[11] J. Eberth,[2] E. Farnea,[12]
S.J. Freeman,[8] A. Gadea,[10] P.E. Garrett,[1,13] A. Görgen,[14] G.F. Grinyer,[1] B. Hyland,[1] D. Jenkins,[15]
F. Johnston-Theasby,[15] P. Joshi,[15] A. Jungclaus,[16] K.P. Lieb,[17] A.O. Macchiavelli,[18] F. Moore,[8] G. Mukherjee,[8]
D.R. Napoli,[10] A.A. Phillips,[1] C. Plettner,[11] W. Reviol,[19] D. Sarantites,[19] H. Schnare,[11] M.A. Schumaker,[1]
R. Schwengner,[11] D. Seweryniak,[8] M.B. Smith,[13] I. Stefanescu,[2] O. Thelen,[2] R. Wadsworth,[15] and D. Ward[18]

[1]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[2]*Institut für Kernphysik, Universität zu Köln, Zülpicher Strasse 77, D-50937 Köln, Germany*
[3]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[4]*Laboratory of Radiation Physics, Institute of Solid State Physics,*
University of Latvia, LV 2169 Salaspils, Miera str. 31, Latvia
[5]*Lund Institute of Technology, P.O. Box 118 S-221 00 Lund, Sweden*
[6]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK*
[7]*McMaster University, Hamilton, Ontario L8S 4K1, Canada*
[8]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[9]*North Carolina State University, Raleigh, North Carolina 27695*
[10]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[11]*Institut für Kern- und Hadronenphysik, FZ Rossendorf, D-01314 Dresden, Germany*
[12]*Dipartimento di Fisica, Universitá di Padova and INFN Sezione di Padova, Padova, Italy*
[13]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3, Canada*
[14]*CEA Saclay, DAPNIA/SPhN, 91191 Gif-sur-Yvette Cedex, France*
[15]*Department of Physics, University of York, Heslington, York YO10 5DD, UK*
[16]*Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[17]*II Physikalisches Institut, Universität Göttingen, D-37073 Göttingen, Germany*
[18]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[19]*Department of Chemistry, Washington University, St. Louis MO 63130*

(Dated: May 18, 2005)

Three smooth rotational bands in ^{74}Kr were studied up to (or one transition short of) the maximum spin I_{max} for the assigned configuration. Their lifetimes have been determined using the Doppler-shift attenuation method. The deduced transition quadrupole moments suggest a decrease, but not complete loss of collectivity at the maximum spin I_{max}. This feature together with the results of mean field calculations strongly suggest that the observed bands do not terminate at I=I_{max}.

PACS numbers: 27.50.+e, 21.10.Re, 21.60.Ev, 21.10.Tg

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 non-collective single-particle (terminating) state where the terminating spin coincides with the maximum spin I_{max} which can be built in the pure configuration. At present, considerable understanding of this process has been achieved both experimentally and theoretically (see Ref. [1] and references quoted therein). On the other hand, the conditions at which rotational bands do not terminate in a single-particle state even though they reach I_{max} have not been investigated experimentally so far.

Earlier studies within the harmonic oscillator [1, 2] showed that rotational bands do not terminate in a non-collective state at I_{max} if the deformation exceeds some well-defined limit at low spin. This 'non-termination' of rotational bands is due to the coupling of different N-shells leading to a mixing of different configurations. Then, even higher spins than I_{max} can be build within the mixed configuration.

Nuclear orbitals cannot be described by the harmonic oscillator but a realistic nuclear potential can be constructed as the modified oscillator potential where spin-orbit and l^2 terms are added. These terms lead to a separation into high- and low-j orbitals within the same N-shell, making it possible to specify the configuration and its maximum spin I_{max} 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]. However, 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}. Such a possibility was first studied for rotational bands in ^{81}Sr [1, 3] within the cranked Nilsson-Strutinsky (CNS) [1, 4] approach. How-

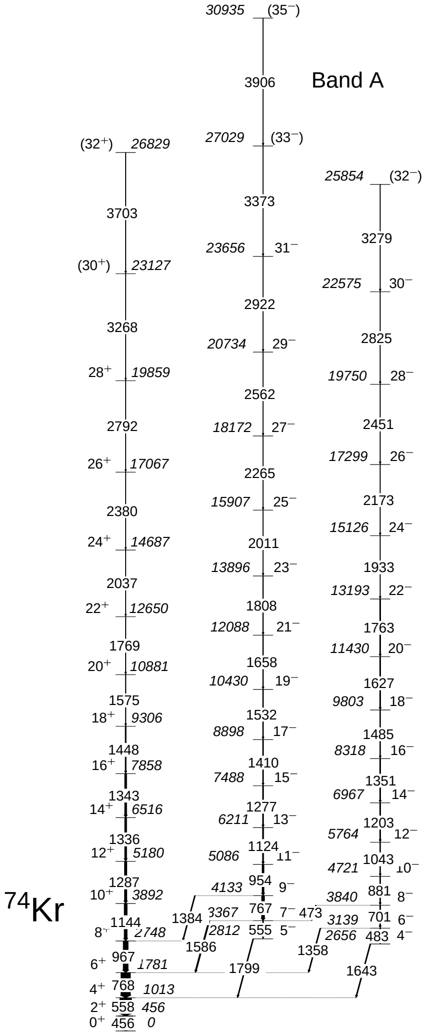

FIG. 1: Partial level scheme deduced from the current work for ^{74}Kr. The energy of the γ-ray transitions are given in keV and arrow widths are proportional to relative γ-ray intensities.

ever, the experimental data in this nucleus are limited, and do not extend to the maximum spin, I_{max}.

Optimal conditions for the study of possible collectivity at the I_{max} state seem to be present in the neutron-deficient $A\backsim75$ region. 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 non-collective state at I_{max}. This represents the first observation of 'non-termination' of rotational bands at I_{max}.

High-spin states in ^{74}Kr were studied using the

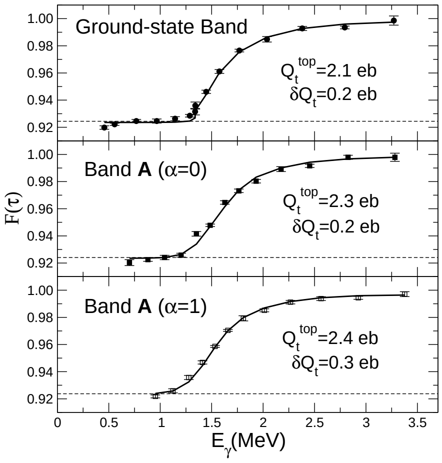

FIG. 2: Experimental $F(\tau)$ values for the ground-state band and Band **A** as a function of γ-ray energy in ^{74}Kr. The solid line shows the calculated $F(\tau)$ values. The dashed line represents the saturation $F(\tau)$ value, when the recoils leave the target.

^{40}Ca(^{40}Ca,2$p\alpha$)^{74}Kr fusion-evaporation reaction with two different setups. The first experiment was performed at Laboratori Nazionale di Legnaro (Lnl), using a 185-MeV beam delivered by the Xtu Tandem accelerator. The experiment was performed using an ^{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 [5], 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 [6], consisting of 40 silicon ΔE/E telescopes, and to a Neutron Wall [7], which comprised 50 liquid scintilator 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, 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 target was sandwiched between two 150 μg/cm^2 Au layers. The γ rays of the reaction were detected with 99 Compton-suppressed HPGe detectors of the Gammasphere array [8], with the heavimet collimators removed 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 [9]. 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 2$p\alpha$ channel was enhanced, in this experiment, by applying the total energy plane channel-selection method [10].

A partial decay scheme for ^{74}Kr showing the ground-state band and the favoured negative-parity band (Band

A) is presented in Fig. 1. The relative spin values for the highest spin states were deduced from an analysis of γ–γ directional correlations of oriented states. These bands were previously observed up to a tentative I^{π}=(28^{+}), (29^{-}) and (28^{-}) [11] for the ground-state band , Band **A** (α=1) and Band **A** (α=0), respectively. The deformation of the ground-state band and Band **A** (α=1) were previously measured up to I$^{\pi}$=18^{+} and 17^{-} [12], respectively, using the Doppler-shift attenuation method. 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 and the favoured negative-parity band (Band **A**) in ^{74}Kr using the centroid-shift Doppler attenuation method [13]. The measured fraction F of the full Doppler shift is plotted for the three bands as a function of γ-ray energy in Fig. 2. The F values were measured by gating on the top three transitions of the band of interest. Due to the collectivity and high transition energies at high spins, all the top transitions decay within the target while the nucleus is slowing down. The transitions from states with I$\lesssim$11 decay outside the target, showing a constant F, see Fig. 2. The experimental F values were fit taking into account the slowing down process of the recoil in the target, that was modelled using the stopping powers obtained by the SRIM-2003 code [14]. The fitting program takes into account the momentum distribution of the recoils, due to particle emission. It has been shown previously [15, 16] that in the channels where α particles are present the angular dependence in the particle detection efficiency of MICROBALL is not isotropic and must be included in the lifetime analysis. The decay of the nucleus was modelled using the empirical equation $Q_t(I) = Q_t^{top} + \delta Q_t\sqrt{I^{top} - I}$ [17], to fit the experimental data. The *top* superscript 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^{top}=30^{+}, 32^{-} and 33^{-} for the ground-state band, Band **A** (α=0) and Band **A** (α=1), respectively. The δQ_t represents the variation of the Q_t value within the band. The side feeding is only considered into the top three states and was modelled assuming a rotational band sequence, with four transitions with the same Q_t as the band that is fed. It should be noticed that if a lower Q_t^{top} is consider in any of the studied bands, then the fit curve will lie all along the band below the experimental points.

Figure 3 shows the kinematic $\Im^{(1)}$ and dynamic $\Im^{(2)}$ moments of inertia for the ground-state band and Band **A** in ^{74}Kr. Above the paired band crossing at ω∼0.6 MeV these bands show all features typical for the rotation in the unpaired regime such as $\Im^{(2)}\leq\Im^{(1)}$ and a smooth decrease of both quantities with increasing rotational frequency [1]. The cranked relativistic Hartree-Bogoliubov calculations of Ref. [18] 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 [18] by the CNS and the cranked relativistic mean field (CRMF [19]) calculations without pairing. According to these calculations the [2,4](α=0) and [3,4](α=0,1) configurations are assigned to the ground state and two branches of Band **A**. Here the shorthand notation $[p, n](\alpha_{tot})$ indicates the number p(n) of occupied $g_{9/2}$ proton (neutron) orbitals in the configuration having a total signature α_{tot}. The number of low-j $N = 3$ protons and neutrons is then fixed from the total number of particles, $Z = 36$ and $N = 38$.

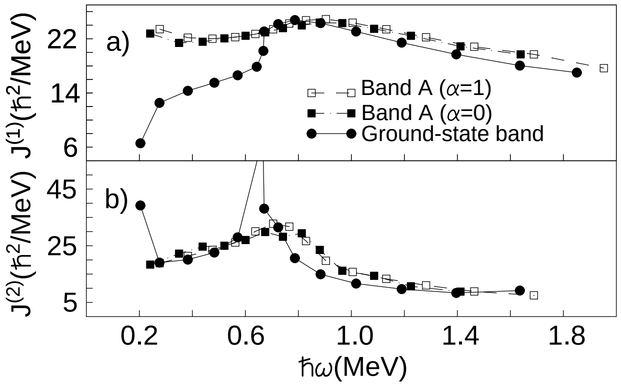

FIG. 3: (a) Kinematic and (b) dynamic moments of inertia for the ground-state band and Band **A** in ^{74}Kr plotted versus rotational frequency.

The maximum spins I_{max} of the [2,4](α=0), [3,4](α=0) and [3,4](α=1) configurations are 32^{+}, 34^{-} and 35^{-}, respectively. For example, the detailed structure of the [2,4](α=0) configuration with respect of the ^{56}Ni spherical core is $\pi[g_{9/2}]^2_8[p_{1/2}p_{3/2}f_{5/2}]^6_6 \otimes \nu[g_{9/2}]^4_{12}[p_{1/2}p_{3/2}f_{5/2}]^6_6$, where the subscripts indicate the maximum spin built within the group of orbitals, i.e. I_{max}=8+6+12+6=32. Thus the ground-state band and Band **A** (α=1) are observed up to their maximum spins, and Band **A** (α=0) is one transition short of I_{max}. However, the minima of calculated potential energy surfaces of these configurations at I_{max} are associated with some collectivity (ε_2∼0.2, γ∼20°) and do not correspond to non-collective γ=60° value, as illustrated for the ground band configuration in Fig. 4. Thus, contrary to for example the terminating bands in the $A = 110$ region [1], the CNS calculations suggest that these smooth bands remain collective at I_{max} and that it might be possible to follow them to even higher spins. These higher spin states are formed mainly because of the coupling to the f7/2 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 [2].

The experimental and theoretical Q_t values as a function of spin for the ground-state band and the two signature-partners of Band **A** are shown in Fig. 5a,c,d. The calculations were performed within the CNS and

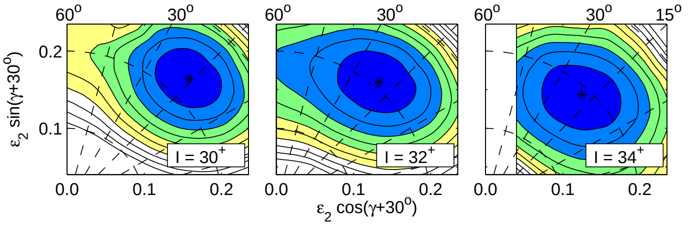

FIG. 4: Potential energy surfaces at I=30,32,34 calculated in the CNS formalism for the [2,4] configuration. The contour line separation is 0.2 MeV. Note that the minimum remains at ε_2~0.2, γ~20° for all these spin values corresponding to I_{max}-2, I_{max} and I_{max}+2. No non-collective state can be defined for I>I_{max} explaining why a region around the γ=60° axis is excluded from the I=34 surface.

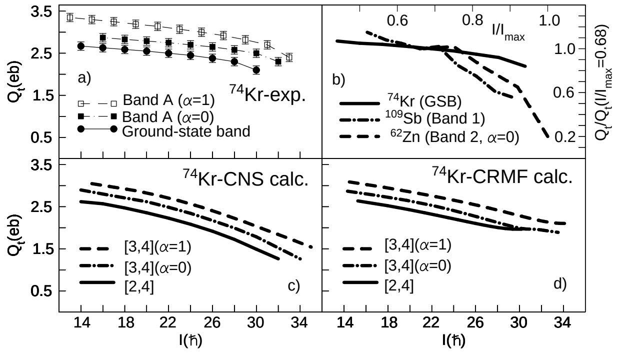

FIG. 5: (a) The measured transition quadrupole moments Q_t for the ground-state band and Band **A**. (c,d) The calculated Q_t values for the [2,4] and [3,4] configurations assigned to the ground-state band and Band **A**, respectively. (b) Transition quadrupole moments of the bands in ^{62}Zn, ^{74}Kr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

CRMF approaches which describe the Q_t values in the smooth terminating bands of ^{62}Zn [20] and ^{109}Sb [21, 22] with a good accuracy. The experimental values 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}Sn (Fig. 5b). Although, the transition quadrupole moments have not been measured for the (I_{max}→I_{max}-2) transition, this result strongly suggests that the experimental bands do not terminate at I_{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 highest spins are explained by the difficulties to follow the configurations close to I_{max}.

In summary, three smooth rotational bands have been observed in ^{74}Kr up to (or one transition short of) the maximum spin I_{max}. Contrary to the previously known cases of rotational bands, which terminate in a non-collective state at I_{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 ‘non-termination’ of rotational bands at I=I_{max}.

This work has been partially supported by the NSERC of Canada, the BMBF of Germany under contract number 06K167, the U.K. Engineering and Physical Sciences Research Council, the Swedish Science Research Council, and the U.S. Department of Energy under Contract Nos. DE-AC03-76SF00098, DE-FG02-88ER-40406 and DE-F05-96ER-40983.

---

[*] Electronic address: valiente@physics.uoguelph.ca

[1] A. V. Afanasjev, D. B. Fossan, G. J. Lane, and I. Ragnarsson, Phys. Rep. **322**, 1 (1999).
[2] T. Troudet and R. Arvieu, Annals of Physics **134**, 1 (1981).
[3] I. Ragnarsson and A. V. Afanasjev, Proc. Conf. on Nuclear Structure at the Limits, Argonne, USA **ANL/PHY-97/1**, 184 (1997).
[4] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).
[5] J. Gerl and R. M. Lieder, *Euroball iii, a european γ-ray facility* (1992).
[6] E. Farnea et al., Nucl. Instrum. Methods Phys. Res. A **400**, 87 (1997).
[7] Ö. Skeppstedt et al., Nucl. Instrum. Methods Phys. Res. A **421**, 531 (1999).
[8] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[9] D. G. Sarantites et al., Nucl. Instrum. Methods Phys. Res. A **381**, 418 (1996).
[10] C. E. Svensson et al., Nucl. Instrum. Methods Phys. Res. A **396**, 228 (1997).
[11] D. Rudolph et al., Phys. Rev. C **56**, 98 (1997).
[12] A. Algora et al., Phys. Rev. C **61**, 031303R (2000).
[13] B. Cederwall, Nucl. Instrum. Methods Phys. Res. A **354**, 591 (1995).
[14] J. F. Ziegler, http://www.srim.org.
[15] C. E. Svensson et al., Acta Phys. Pol. **B9**, 2413 (2001).
[16] C. J. Chiara et al., Nucl. Instrum. Methods Phys. Res. A **523**, 374 (2004).
[17] J. J. Valiente-Dobón et al., Phys. Rev. C **71**, 034311 (2005).
[18] A. V. Afanasjev and S. Frauendorf, PRC **in press** (2005).
[19] A. V. Afanasjev, J. König, and P. Ring, Nucl. Phys. **608** (1996).
[20] C. E. Svensson et al., Phys. Rev. Lett. **80**, 2558 (1998).
[21] R. Wadsworth et al., Phys. Rev. Lett. **80**, 1174 (1998).
[22] D. Vretenar, A. V. Afanasjev, G. A. Lalazissis, and P. Ring, Phys. Rep. **409**, 101 (2005).