DEFORMED GROUND STATES AND DOUBLE BACKBENDING AT HIGH SPINS IN LIGHT Kr ISOTOPES

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Abstract

The energy levels in ^{74,76}Kr have been studied with a range of in-beam, γ-spectroscopy techniques following heavy-ion reactions and in ^{76}Kr via the radioactive decay of ^{76}Rb. Breaks in the level energies and moments of inertia in ^{74,76}Kr are observed at low spins. These data can be understood in terms of the crossing of bands built on near-spherical and deformed shapes with the ground states having very large deformation. In ^{74}Kr the yrast cascade is observed to a tentative 20^+ level. Double backbending of $\mathcal{J}$ is observed at spins of 12^+ and 16^+. These changes are interpreted in terms of rotation-aligned structures.

1. Introduction

Two of the important frontiers in nuclear research are the extension of our knowledge of the structures of nuclei further from stability and to higher spins. The present paper reports on studies which extend our knowledge in both these directions in the light krypton isotopes. In both instances evidence for new structures are found, including large ground state deformation in ^{74,76}Kr and double backbending of the moment of inertia in ^{74}Kr above the 10^+ level. These latter data were obtained by using a new neutron multiplicity technique with (n,n,γ) and (n,γ,γ) coincidences.

The energies of the 0_2^+ states have a deep minimum in N ≃ 40 Ge and Se isotopes so that in ^{70,72}Ge and ^{72,74}Se they are very near or, in the case of ^{72}Ge, below the energy of the first excited 2^+ states (see review in Ref. 1). These and a variety of other data have been interpreted in terms of shape coexistence in these nuclei, where the low-lying 0_2^+ states are more deformed than the ground states[1-4]. The origin of this shape coexistence can be attributed to the gaps in the single particle spectrum seen in Fig. 1 at N = 40, δ ≃ 0 and N = 38, δ ≃ 0.25, that stabilize the nuclear shape. Evidence for the spherical subshell closure around N(Z) = 40 is found when Z(N) is close or equal to 28 or 50, because the protons (neutrons) prefer a spherical shape, as seen for example in $^{66}_{28}$Ni($^{90}_{40}$Zr$_{50}$). However, as Z moves away from 28 or 50 the level density for a spherical shape becomes very high and the minimum of the proton deformation energy moves to deformed shapes as qualitatively indicated by the circles in Fig. 1. The same holds for the neutrons since the proton and neutron single particle levels are almost identical. Away from the Z(N) = 28 and 50 closed shells, maximal deformation is expected at N(Z) ≃ 38. However, the deformed state can coexiste with a nearly spherical configuration in a delicate balance. Which one is lower depends on the proton number. For $^{70,72}_{32}$Ge$_{38,40}$ and $^{72,74}_{34}$Se$_{38,40}$ the coexistence of nearly spherical ground states with deformed

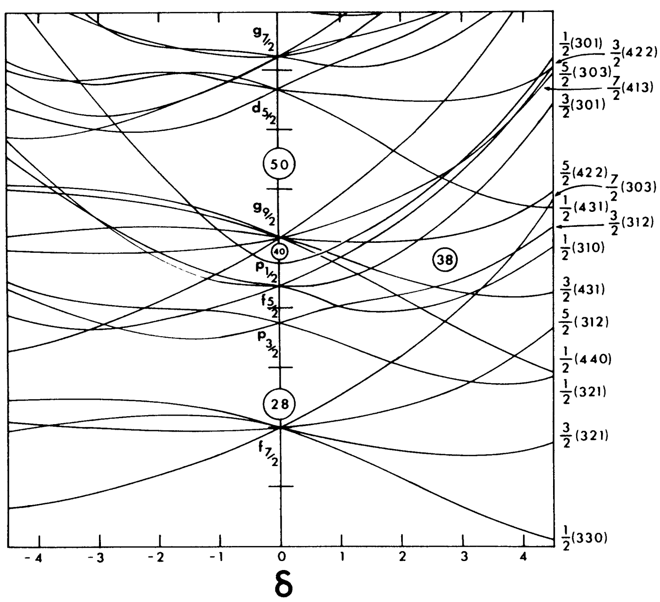

Fig. 1. Nilsson diagram for the A = 76 region for protons.

excited bands has been reported[1-4]. In ^{72,74}Se, the deformed band becomes yrast at I ≈ 2-4 because of its lower rotational energy. For the Ge isotopes, the bands built on the two different shapes are less well developed because of the smaller deformations (two protons less than Se). In the Kr-isotopes, the 36 protons favor deformation even more. Here we present evidence that the deformed minimum becomes the ground state and the lowest 0_2^+ states are the spherical ones in ^{74,76}Kr.

2. Evidence for deformed ground states

To investigate the nature of the 0_2^+ states and the influence of the N ≈ 40 subshell closure farther from the proton magic numbers, levels in ^{74,76}Kr were studied with in-beam gamma-ray spectroscopy techniques via, a) the reactions ^{60}Ni(^{16}O, 2n) and ^{66}Zn(^{12}C, 2n) with 45 MeV ^{16}O and 39 MeV ^{12}C ions from the Oak Ridge EN tandem, including angular distribution and γ-γ coincidence measurements with Ge(Li) detectors, and b) the reaction ^{58}Ni(^{19}F, p2n) with 68 MeV ions from the University of Köln tandem (in that work an additional technique[5] of measuring (n,γ,γ) and (n,n,γ) coincidences was used), and the radioactive decay of ^{76}Rb to ^{76}Kr was studied with mass-separated samples at the UNISOR facility. The ^{76}Rb was produced in the reaction ^{nat}Ni(^{20}Ne, xn) at 112 MeV. Mass separated samples were collected and then transported via a tape transport system to a position between two Ge(Li) detectors for γ-γ coincidence studies. As one sample was being counted, the next was being collected.

From the ^{76}Kr in-beam and the ^{76}Rb decay studies, a 0_2^+ state at 770 keV and a 2^+ state at 1688 keV that feeds only the 0_2^+ level were established in ^{76}Kr (see Fig. 2). Thus, the energies of the 0_2^+ levels continue to drop sharply as one goes from ^{80}Kr to ^{76}Kr. The even-parity yrast cascades in ^{74}Kr and ^{76}Kr were established to 10^+ and 12^+, respectively, in the first studies. The moments of inertia for the low-spin members of the even-parity yrast bands in ^{74,76}Kr (present work) and ^{78,80}Kr [6-8], Fig. 3, become larger when going from N = 44 to N = 38, except for ^{74}Kr, where the point corresponding to the 2 → 0 energy in ^{74}Kr strongly deviates. This tendency can already be seen in

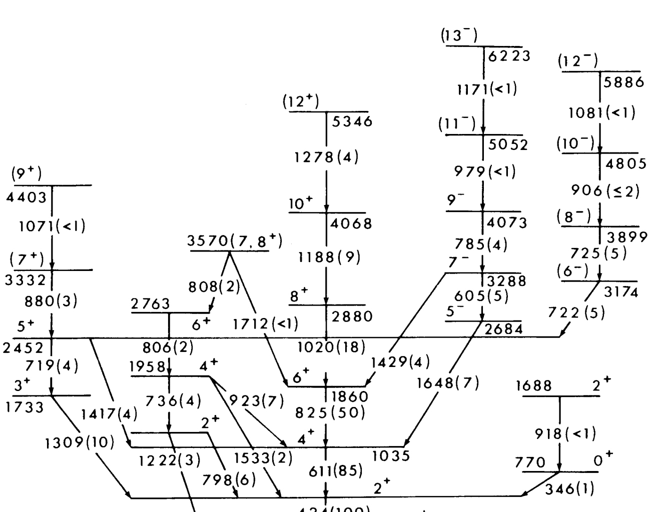

Fig. 2. Energy levels in ^{76}Kr observed via in-beam spectroscopy.

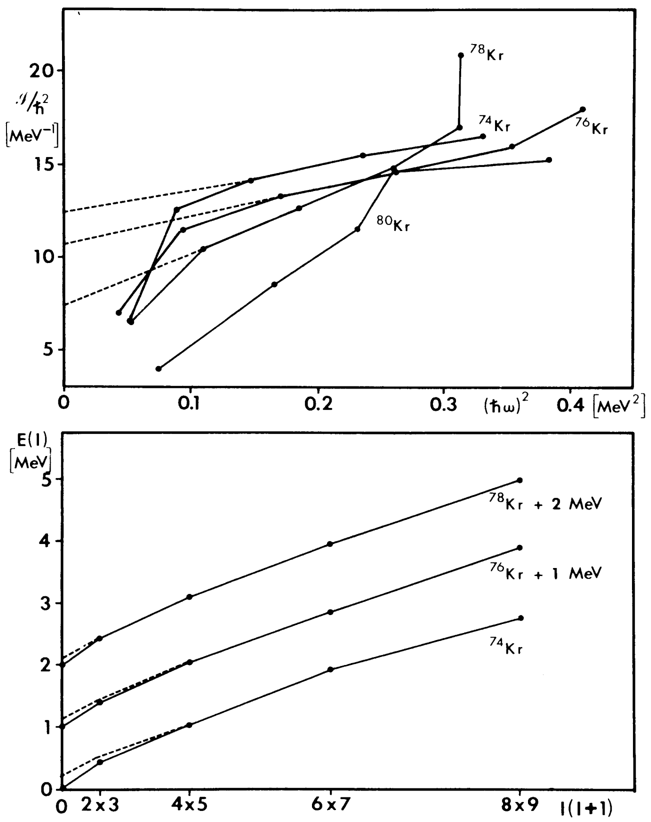

Fig. 3. Analysis of the energies of the yrast levels in the even-mass Kr isotopes. The dashed lines show the Harris extrapolation of high spin levels. The frequency and the moment of inertia are defined in Ref. 10 as $\hbar\omega = E_\gamma/2$ and $\mathcal{J}/\hbar = (I+1)/\omega$. The Harris extrapolation is given by $\mathcal{J} = \mathcal{J}_0 + \omega^2\mathcal{J}_1$, where $\mathcal{J}_0/\hbar^2$ = 12.5, 10.8, 7.3 MeV^{-1} and $\mathcal{J}_1/\hbar^2$ = 12.3, 15.0, 29.0 MeV^{-3} for ^{74}Kr, ^{76}Kr and ^{78}Kr, respectively. The dashed lines in the lower figure for the yrast levels are obtained by using the parameters $\mathcal{J}_0$ and $\mathcal{J}_1$, and fitting the energies of the 6^+ level in ^{74,76}Kr and the 4^+ level in ^{78}Kr, as in Ref. 10.

^{76}Kr to a lesser degree. In $^{72,74}Se_{38,40}$ [1,4] as in $^{184-188}$Hg [9] strong forward bends in the moments of inertia above the 2_1^+ states were interpreted in a shape coexistence picture, with bands built on the ground and excited 0^+ states with quite different deformations. The forward bend of $\mathcal{J}$ occurs[1,4,9] when the deformed band crosses the sequence of states built on the nearly spherical minimum. Because of the larger proton number in the Kr isotopes, deformed shapes may have a slightly lower energy than the spherical ones. The observation that in ^{76}Kr the 0_2^+ level is low but the 2_2^+ level, which feeds it, is 918 keV above it while the 2_1^+ state is only 425 keV above the ground state supports this. Thus we suggest that it is the ground state which is more deformed and the 0_2^+ level which is associated with a near-spherical shape in ^{76}Kr, in contrast to the reverse situations in ^{72,74}Se and $^{184-188}$Hg. A similar situation should be occurring in ^{74}Kr.

The relative large 2 → 0 energies in ^{74,76}Kr (which make these look less deformed than they really are) would arise from an interaction between the 0_1^+ deformed and 0_2^+ near-spherical states to push down the 0_1^+ energy. Since the 2^+ spherical state is quite high in energy, there will be little mixing of the 2^+ and higher spin states, since the energies for the near-spherical structure grow much faster with I than in the deformed band. In $^{72,74}Se$ there also is considerable mixing of the deformed and spherical configurations near the band crossing at I ≃ 2-4 observed[1].

Calculations described below indicate that for N = 38, the deformed structure is generated from the spherical one by promoting two pairs of neutrons from the $f_{5/2}$ into the $g_{9/2}$ shell. Correlations of the pairing type contain the multiple scattering of pairs from the $f_{5/2}$ to the $g_{9/2}$ shell (and vice-versa) and may be an important source for the coupling of the two structures.

In order to quantify the band mixing suggestion, we analyzed the Kr-yrast bands in terms of a two-level model. For I $\gtrsim$ 6 ħ one expects that the yrast levels are purely deformed. In Fig. 3 this region corresponds to the nearly linear part of $\mathcal{J}$. The up bends are related to the alignment of a $g_{9/2}$- proton pair[7,8]. The position of the unperturbed deformed levels were determined by extrapolating the linear part of $\mathcal{J}(\omega^2)$ down to ω = 0. As discussed in Ref. 10 this corresponds to a Harris or VMI-parameterization of the deformed g-bands. The relation between the level energy E(I) and the Harris parameters $\mathcal{J}_0$, $\mathcal{J}_1$ given in Fig. 3 may be found in Ref. 10. Figure 3 compares the extrapolated with the measured levels. The deviation is much larger in ^{76}Kr than in ^{78}Kr in accordance with the higher position of the known 0_2^+ level in the latter.

The shifts $\delta E = E^o_{0_1^+} - E_{0_1^+}$ can be found in Table 1. The difference between the unperturbed levels $\Delta E_0 = E^o_{0_2^+} - E^o_{0_1^+}$ is equal $E_{0_2^+} - E_{0_1^+} - 2\delta E$. The interaction V is equal to $(1/2)\sqrt{\Delta E^2 - \Delta E_0^2}$, where $\Delta E = E_{0_2^+} - E_{0_1^+}$. These quantities are also included in Table 1. The close values of V for ^{76}Kr and ^{78}Kr indicate that the smaller energy perturbations in ^{78}Kr are related to the higher position of the (unperturbed) spherical state. One may suggest that the interaction V in ^{74}Kr has a value similar to that of ^{76}Kr. Adopting this value of 0.33 MeV, one may use δE to predict the $E_{0_2^+}$-level at 0.68 MeV. The extracted, unperturbed 2 → 0 energies in the deformed ground bands are 200 and 237 keV in $^{74,76}Kr$, respectively. By scaling the unperturbed 2 → 0 energy by $A^{5/3}$, one may compare the deformation of ^{74}Kr to that of ^{238}U. The 200 keV transition in ^{74}Kr would correspond to 29 keV in ^{238}U compared to the actual value of 45 keV. This is an unusually large ground state deformation, slightly larger than the "super deformation" recently reported[11] for ^{100}Sr.

Table 1. Properties of the 0^+ states in Kr-isotopes.

Nuclide	δE	$E_{0_2^+}$	ΔE_0	V	$\frac{BE2(2\to0)}{BE2(2\to0)_{ROT}}$
^{74}Kr	0.256	0.681*	0.169*	0.330*	0.62
^{76}Kr	0.187	0.770	0.396	0.330	0.74
^{78}Kr	0.102	1.017	0.813	0.305	0.88

*The value V is assumed and $E_{0_2^+}$ and ΔE_0 calculated by using this value. The energies are in MeV.

As further support for the importance of deformation effects, the lifetimes of several levels were measured by Doppler shift line shape analysis. The B(E2) strengths for the transitions between the yrast states in ^{76}Kr are given in Table 2.

Table 2. Measured mean lives and extracted B(E2) values for transitions in ^{76}Kr.

E_{level} (keV)	E_γ (keV)	$I_i \to I_f$	τ_{mean} (ps)	$\frac{B(E2)}{B(E2)_{sp}}$
424	424	$2^+ \to 0^+$	53(7) †	59(7)†
1035	611	$4^+ \to 2^+$	5.0(20)	$76(^{23}_{14})$††
1860	825	$6^+ \to 4^+$	1.25(12)	89(8)
2880	1020	$8^+ \to 6^+$	0.30(3)	129(13)
4068	1188	$10^+ \to 8^+$	0.14(2)	129(19)
5346	1278	$(12^+) \to 10^+$	0.24(5)*	52(11)*

*Composite lifetime and composite B(E2) compared to single particle values.
†Nolte, et al. (Ref. 12).
††Based on an average (τ = 6.6 ± 1.5) of the present data and that of Nolte et al. (τ = 8.2 ± 2.3) (Ref. 12).

These values are highly collective; the most collective known for any nucleus in the A = 70 region. For comparison $B(E2)_{exp}/B(E2)_{sp}$ are 10(4) and $12(^4_3)$ for the 2 → 0 and 4 → 2 transitions, respectively, in ^{68}Ge and 20(2) and 45(6) for ^{72}Se where mixing presumably occurs, however. From the 2^+ to the 10^+ state, the B(E2) values generally follow the gradual increase expected for a rotational nucleus in sharp contrast to the rapid increase in B(E2) values in a vibrational model.

In the two-level model, one also may calculate the square of the amplitude, C_1^2, of the deformed state in the perturbed ground state which is equal to $(1 + \delta E^2/V^2)^{-1}$. Assuming that the E2 matrix elements between the bands is much smaller than the matrix element within the deformed band, the B(E2: 2 → 0) value will be reduced by $C_1^2(I = 0) \times C_1^2(I = 2)$. This reduction factor is also included in Table 1. It represents an upper limit of the reduction, since one expects a finite matrix element between the bands. The data in Table 2 are consistent with the predicted reduction of B(E2: 2 → 0).

In summary, these data extend our understanding of the coexistence of different nuclear shapes first proposed in ^{72}Se. However, apparently in $^{74,76}Kr$ the role of the near-spherical and deformed minima are reversed with the ground states strongly deformed and the excited 0_2^+ states associated with a near-spherical minima. This interpretation for the N = 38, 40 Kr nuclei supports the expectation that at these neutron numbers as the proton number approaches the middle between the N = 28 and 50 closed shells, the protons can drive a nucleus with a pair of $g_{9/2}$ neutrons toward deformation. It is not certain whether these deformed states are prolate or perhaps triaxial. The low level density on the oblate side (δ = -0.25) of Fig. 1 for N $\approx$ 38 indicates that the deformation energy could weakly depend on the γ-degree of freedom. The importance of the triaxial deformations in these nuclei is reflected by the observation of the γ-band at low energy.

The odd spin negative parity band seen to 13^- in ^{78}Kr has been interpreted in the interacting Boson approximation as arising from the coupling of octupole and quadrupole Bosons[13]. To further test our interpretation of this band in ^{78}Kr and in ^{76}Kr as arising from two quasiparticles with one in the $g_{9/2}$ orbital, we carried out 2-quasiparticle-plus-rotor calculations for $^{76,78,80}Kr$ in the Flaum-Cline approach[14]. For the negative parity states, 8 basic states close to the Fermi level were included. The assignment of even spin and odd parity to the experimental levels in ^{76}Kr, as shown in Fig. 4, is based essentially on the close agreement of their energies with those from the calculations. All of the calculations are strongly supportive of the importance of the 2-quasiparticle structures in both the negative parity bands beginning at 5^- and the positive parity bands beginning at 8^+.

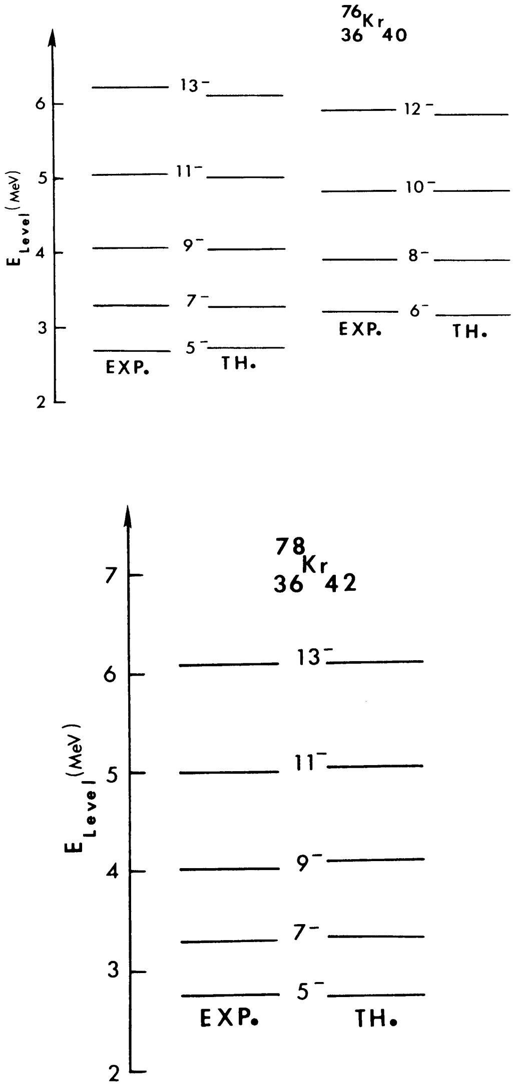

Fig. 4. Two-quasiproton levels in ^{76,78}Kr. The experimental levels associated with the theoretical 6^-, 8^-, levels in ^{76}Kr have been assigned tentatively.

3. Double backbending of the moment of inertia

The structure of nuclei and how a nucleus most efficiently carries angular momentum at higher and higher rotational frequencies is of current major interest. In the course of developing the neutron multiplicity-γ coincidence technique (n,n,γ), (n,γ,γ) to study weak reaction channels, new surprises were found in ^{74}Kr. This technique is described in more detail elsewhere in these proceedings, Roth et al.[5] These ^{74}Kr studies show the power and promise of this technique. In a second experiment that included (n,γ,γ) and (n,γ-plunger) studies, the yrast levels in ^{74}Kr were extended from 10^+ to a proposed 20^+ level and other side bands observed as shown in Fig. 5. This is the highest spin state

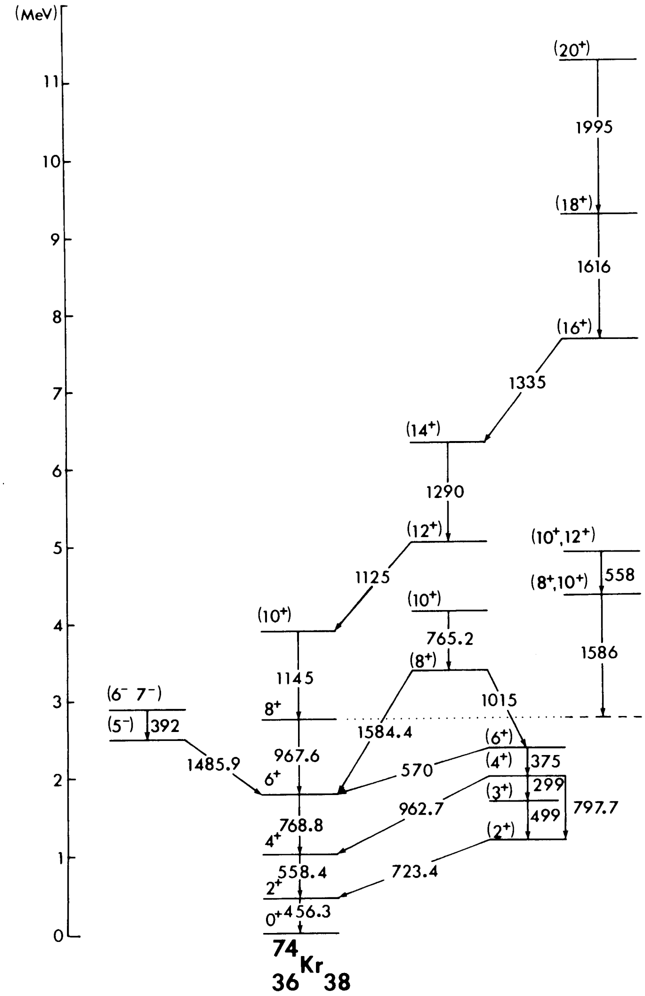

Fig. 5. Energy levels in ^{74}Kr observed in (n,γ,γ) studies (see Ref. 5).

reported in this region and is remarkably high for such a light nucleus. Spin assignments were made by (n,γ) and (n,n,γ) coincidence yield functions between 58 and 68 MeV and γ-angular distribution measurements.

As shown in Fig. 6, the plot of the angular momentum I(ω) as a function of ω, where $\hbar\omega = E_\gamma[(I + 1) \rightarrow (I - 1)]/2$, clearly shows two distinct breaks -- double backbending in the moment of inertia! Coupled with the interaction of the deformed and near-spherical 0^+ states, one has a record three crossings of the ground band! Only in ^{158}Er and ^{160}Yb [15,16] have double backbends been observed in yrast cascades. The break above the 10^+ state is undoubtedly from a crossing of a $(g_{9/2})^2$ configuration. The observed 8^+_2 and 10^+_2 states are assigned as the low spin members of this band which carries about 3 units of angular momentum. Calculations in the approach of Bengtsson and Frauendorf[10] indicate that the proton and neutron $(g_{9/2})^2$ configurations are close in energy so the character of these levels is not established yet. The next (8^+_3) and (10^+_3) states may be the aligned states of the other configuration. Magnetic moment measurements could help identify the character of these levels. Note I(ω) for the 8^+_2 and 10^+_2 levels are in line with those of the 12^+ and 14^+ levels.

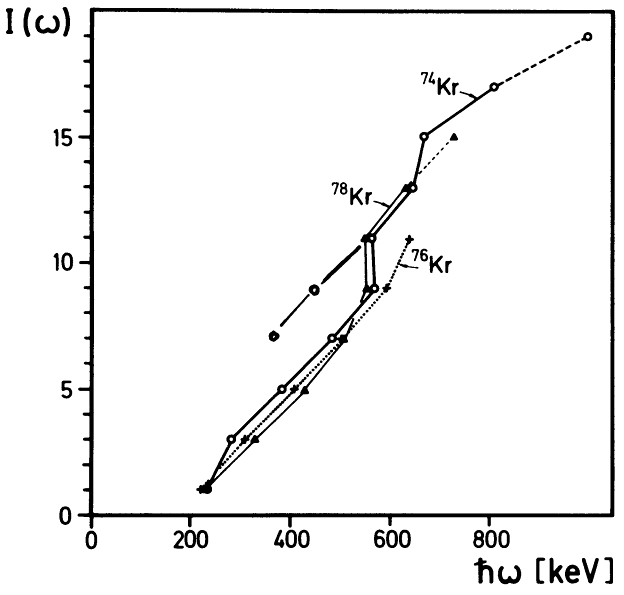

Fig. 6. A plot of the angular momentum I as a function of $\omega = E_\gamma[(I + 1) \to (I - 1)]/2\hbar$ for ^{74}Kr.

The second break above the 14^+ state has an aligned angular momentum compared to the ground state about double that of the first band to cross the ground state. Note in ^{68}Ge where both proton and neutron $(g_{9/2})^2$ 2 quasiparticle bands are reported to cross the ground band, each band has about the same 6 units of aligned angular momentum[17]. This larger alignment compared to the ground state suggests that this new band which crosses at 16^+ is a four-particle, aligned configuration which is most probably composed of two $(g_{9/2})^2$ quasiprotons and two $(g_{9/2})^2$ quasineutrons. Such an interpretation is in line with the double backbends in ^{158}Er and ^{160}Yb where first two $i_{13/2}$ neutrons align and then two $h_{11/2}$ protons. Here both particles are in the same orbital. Note the high spin data for ^{78}Kr do not show a second break in I at the tentatively proposed 16^+ level. If the first crossing is for two quasiprotons and the second for the addition of two quasineutrons to the 2qp configuration in ^{74}Kr, then this second crossing could be blocked by the presence of the four extra neutrons in ^{78}Kr.

4. Acknowledgements

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DISCUSSION

W. Andrejtscheff: I would like to mention here some preliminary thoughts on some delayed ground-state cascades in Se and Kr isotopes which we got as a by-product from lifetime measurements. The experiments were performed on the Rutgers tandem with the generalized centroid shift method (delayed coincidences). The first slide demonstrates a typical centroid diagram. Average delays are presented on the second figure. Delayed feeding of several hundreds of picoseconds in ^{74,76}Se and maybe ^{74}Kr indicate possible isomeric levels at high excitations.

J.H. Hamilton: We also observed long feeding time in ^{70}Se and ^{80}Kr. In ^{80}Kr produced by α particle long feeding times were not observed. Then there seem to be more high spin isomers in this region.

H. Morinaga: 1) Sometimes odd nuclei like ^{77}K show simpler rotational structure, free from complication due to co-existence. 2) As for anomaly in rotational structure, one should look at it comparing not only with the situation in heavy nuclei but also with light nuclei like ^{20}Ne.

A. Gelberg: How do the B(E2)'s in ^{76}Kr compare with the leading-order theoretical values from the rotational model?

J.H. Hamilton: One expects a reduction in B(E2, $2^+ \rightarrow 0^+$) because of mixing of the two 0^+ states. However, the high-spin data follow rotor predictions.