RAPID COMMUNICATIONS

PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 43, NUMBER 3 MARCH 1991

RAPID COMMUNICATIONS

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication in **Physical Review C** *may be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

Observation of simultaneous $g_{9/2}$ proton and neutron alignment in ^{74}Kr

J. Heese,* D.J. Blumenthal, A.A. Chishti,† P. Chowdhury, B. Crowell, P.J. Ennis, C.J. Lister, and Ch. Winter
A.W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511
(Received 5 November 1990)

High spin states in ^{74}Kr were investigated in the reaction ^{40}Ca(^{40}Ca,$\alpha 2p$)^{74}Kr at 125 and 140 MeV. A new decay scheme was established up to probable spin I=20. The rotational structure was found to be similar to ^{76}Kr, showing a double alignment in the ground-state band and sidebands with constant moments of inertia. Measured lifetimes using the Doppler-shift attenuation method indicate very collective $E2$ transitions in the ground-state band.

Light krypton isotopes were among the first medium-mass nuclei to indicate very large prolate deformation ($\beta_2 \approx 0.35$) stabilized by shell structure. However, the ground-state bands of the even-even isotopes $^{72-82}$Kr (Refs. 1–5) show pronounced deviations from simple rotational behavior, because of shape coexistence effects and because of particle alignments. The interplay of these effects is a result of competition between proton and neutron occupancy of levels near subshell gaps at Z,N=34,36 for oblate shapes and Z,N=38,40 for prolate shapes. Understanding this interplay and its development with rotational frequency is the object of this work.

Levels in ^{74}Kr have been reported up to a tentative spin of 20$^+$ by Roth *et al.*[6] and up to 14$^+$ by Tabor *et al.*[7] Both authors used the reaction ^{58}Ni(^{19}F,$2pn$)^{74}Kr at 56–62 and 62 MeV, respectively. The level schemes deduced from these works disagree in essential points. The ground-state band of Ref. 6 shows two irregularities: a backbending at a rotational frequency $\hbar\omega$=0.57 MeV, followed by an additional upbending at $\hbar\omega$=0.66 MeV. In the work of Tabor *et al.*, the yrast states above 10$^+$ and the sidebands of Ref. 6 were not confirmed. In recent studies of ^{76,78}Kr,[4,5] the known level schemes were extended to $I \geq 20$ and the upbendings in the ground-state bands were interpreted as $g_{9/2}$ proton and neutron alignments. Evidence for particle alignment in ^{74}Kr was reported in Ref. 7 at $\hbar\omega$=0.66 MeV in good agreement with Hartree-Fock-Bogolyubov cranking (HFBC) calculations[5,7] which suggested ^{74}Kr should have an alignment scheme similar to that of ^{76}Kr, i.e., simultaneous $g_{9/2}$ proton and neutron alignment. Lifetimes of the 2$^+$ and 4$^+$ state in ^{74}Kr have been measured using the recoil distance Doppler shift (RDDS) technique[6] and of the 6$^+$–14$^+$ states with the Doppler-shift attenuation (DSA) method.[7] The lifetimes of the 2$^+$ and 4$^+$ states indicate quadrupole deformation of β_2=0.31 and 0.24, respectively, while the higher-lying states show larger $E2$ transition strengths indicating a quadrupole deformation β_2=0.41.

In the present work, interest was focused on the extension of the ground state band. As the sidebands observed in ^{76,78}Kr were crucial in the interpretation of the level schemes, considerable attention was paid to those in ^{74}Kr. In order to populate ^{74}Kr at high spins, the reaction ^{40}Ca(^{40}Ca,$\alpha 2p$) ^{74}Kr was used at beam energies of 125 and 140 MeV. The beam was supplied by the new Yale ESTU tandem accelerator. Two experiments, using backed and unbacked target were performed. In both experiments, γ rays were detected in the Yale γ array consisting of five HP Ge detectors of 23–25% efficiency in Compton suppression shields mounted at 143° to the beam. In the first run, the 125 MeV ^{40}Ca beam was focused on a 800 μg/cm^2 Ca layer of natural composition evaporated onto a 30 mg/cm^2 gold foil. Only γ-γ coincidences were recorded in this experiment. In the second experiment, a ^{40}Ca beam of 140 MeV was used with a 470 μg/cm^2 natural calcium target, the beam entering the calcium layer through a 1 mg/cm^2 gold support foil on which the target layer was evaporated. The Ca layer was covered with an additional 48 μg/cm^2 layer of gold to prevent oxidation. The thin target and gold layers allowed the recoils to escape and decay in flight. The recoils were stopped after a flight distance of 1.65 mm in a 27 mg/cm^2 gold foil which also served as a beam stopper. With an average recoil velocity β=3.51(12)%, this geometry corresponds to a mean flight time of 157 ps. The beam stopper was thin enough to allow the detection of evaporated alpha particles and protons in four 10 mm×10 mm square Si surface barrier ΔE-E telescopes of 90 μm and 1000 μm mounted at forward angles behind the beam stopper. In this experiment, γ-γ and (charged particle)-γ-γ coincidences were recorded.

The new ^{74}Kr level scheme is presented in Fig. 1. It is in full agreement with the work of Tabor *et al.* The sidebands are labeled NE and NO for negative parity and even and odd spin, respectively. Figure 2 shows a gate on the 558 keV line from γ-γ coincidence data. The intensities of the coincident lines clearly give the order of the ground-state band transitions. The line at 1338 keV is a doublet with components at 1334 and 1342 keV as visible from Fig. 3 which shows a gate on the 1342 keV line. The gate was chosen only two channels wide in order to suppress contaminant ^{77}Rb lines.[8] Angular correlations were not measured in this work, so the proposed sequence of spins is based on the measurements of Refs. 6 and 7 combined with the γ-γ coincidences and transition probabilities of this study. The assignments show close similarities to bands recently found in ^{76,78}Kr. By comparing the data from backed and unbacked targets the intraband transitions were all limited to have lifetimes between 4 and 50 ps, which are consistent with those expected for $E1$ transition strengths in this region.

Figure 4 shows the aligned single-particle momentum in the ground-state bands of ^{74,76,78}Kr as a function of the rotational frequency. Due to similar deformations, the reference angular momentum was parametrized as $I_{\rm ref}=21\omega-3.5$ in all nuclei. In ^{78}Kr, the gains in alignment at $\hbar\omega$=0.55 MeV and $\hbar\omega$=0.90 MeV have been interpreted as alignments of $g_{9/2}$ protons and neutrons, respectively.[4,5] In ^{76}Kr the alignment at $\hbar\omega$=0.65 MeV shows an increase which is as large as both alignments in ^{78}Kr. Therefore, it was concluded that $g_{9/2}$ protons and neutrons align simultaneously in ^{76}Kr.[5] The comparison of the alignment plots of the ^{74}Kr and ^{76}Kr ground-state bands now suggests that the same effect occurs in ^{74}Kr. The constant alignments in the ^{74}Kr sidebands also visible in Fig. 4 suggest that the NE and NO bands show no pronounced irregularities of the moments of inertia and contain aligned particles (most likely $g_{9/2}$ protons) as was suggested for the sidebands in ^{76,78}Kr.

Two different theoretical approaches predict the simultaneous alignment of $g_{9/2}$ protons and neutrons, which is in other words a transition from the ground-state configuration to a four-quasiparticle (qp) structure. Sheikh *et al.*[9] suggested that the population of 4qp structures containing rotational aligned proton and neutron pairs at lower frequencies than 2qp bands may be a consequence of the np interaction taking place in $N \approx Z$ nuclei. The role of the np interaction as the driving force for the development of collectivity in this mass region is well known.[10] Despite this fact, one of the most successful descriptions of the features of collective nuclei is the HFBC model which does not take the np interaction into account explicitly. If N and Z approach each other, the active Nilsson orbits for protons and neutrons are very close. Therefore, the HFBC model predicts protons and neutrons to align at similar frequencies due to the Coriolis interaction. The occurrence of a double alignment in ^{74}Kr and its measured frequency is in excellent agreement with predictions of the HFBC model.

Doppler broadened line shapes observed at 143° were analyzed using the code GNOMON. To fit the line shapes, we used the parametrization of Ziegler, Biersack, and Littmark[11] for the electronic component of the stopping power; for the nuclear part the formula of Kalbitzer and Oetzmann[12] was applied and the angular straggling of the ions was treated according to Blaugrund.[13] The kinematic effects of the α evaporation were taken into account with a Gaussian recoil energy distribution. The inset of Fig. 2 shows the Doppler-broadened line shape of the 967 keV transition. States with very short lifetimes ($\tau \leq 0.14$ ps) decay almost exclusively in the calcium layer. The line shapes for these transitions have poor sensitivity to lifetime, due to the slow deceleration of recoils in cal-

TABLE I. Lifetimes, $B(E2)$ values, transitional quadrupole moments, and deformations in ^{74}Kr.

I^π	τ (ps)	$B(E2)$ (e^2fm^4)	(W.u.)	$\lvert Q_t \rvert$ (b)	β_2 [a]
2^+	28.8(58)[b]	$1440(^{350}_{240})$	78	$2.69(^{31}_{23})$	0.31(3)
4^+	13.2(7)[b]	$1140(^{70}_{50})$	62	$2.00(^{6}_{4})$	0.24(1)
6^+	0.91(10)	$3360(^{410}_{330})$	182	$3.28(^{19}_{17})$	0.37(2)
8^+	0.24(4)	$4030(^{800}_{580})$	218	$3.51(^{33}_{27})$	0.40(3)
10^+	0.10(3)[c]	$\geq$3190	$\geq$172	$\geq$3.08	$\geq$0.35
12^+	$\leq$0.11	$\geq$2100	$\geq$114	$\geq$2.48	$\geq$0.28

[a] Woods-Saxon deformation parameter assuming axial symmetry.

[b] Taken from Roth *et al.*[6]

[c] Effective lifetime not corrected for feeding.

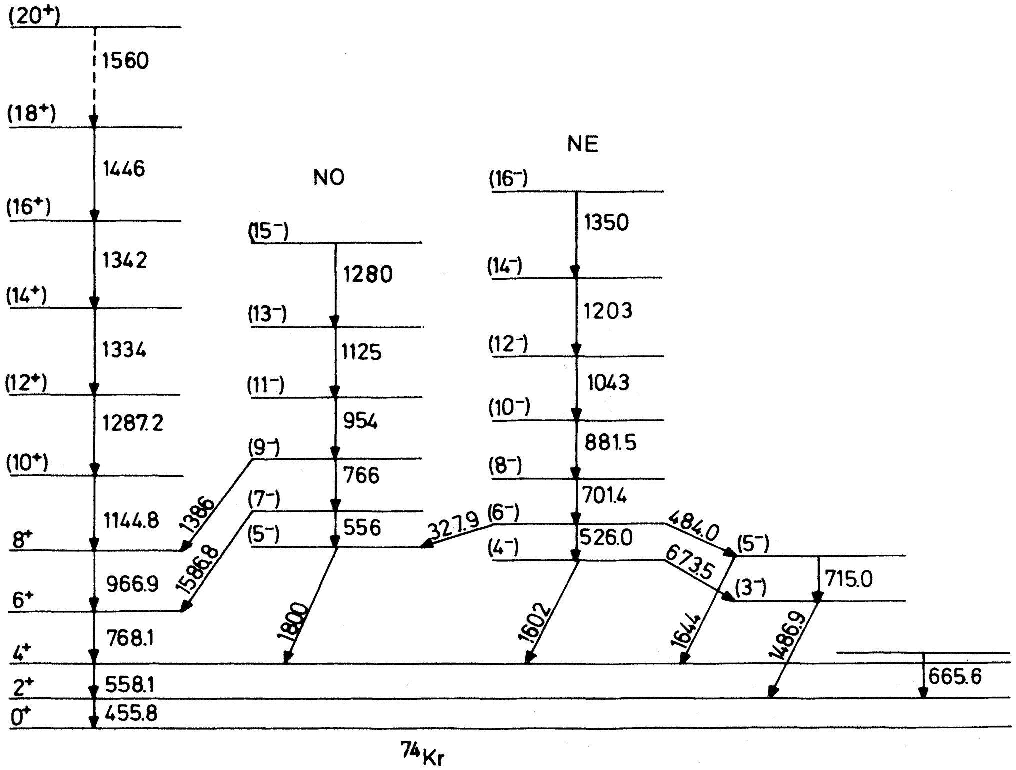

FIG. 1. The proposed ^{74}Kr level scheme. γ-ray energies given accurate to 0.1 keV were taken from the backed target run. For the other γ energies precision is reduced due to the large Doppler broadening in the in-flight spectra.

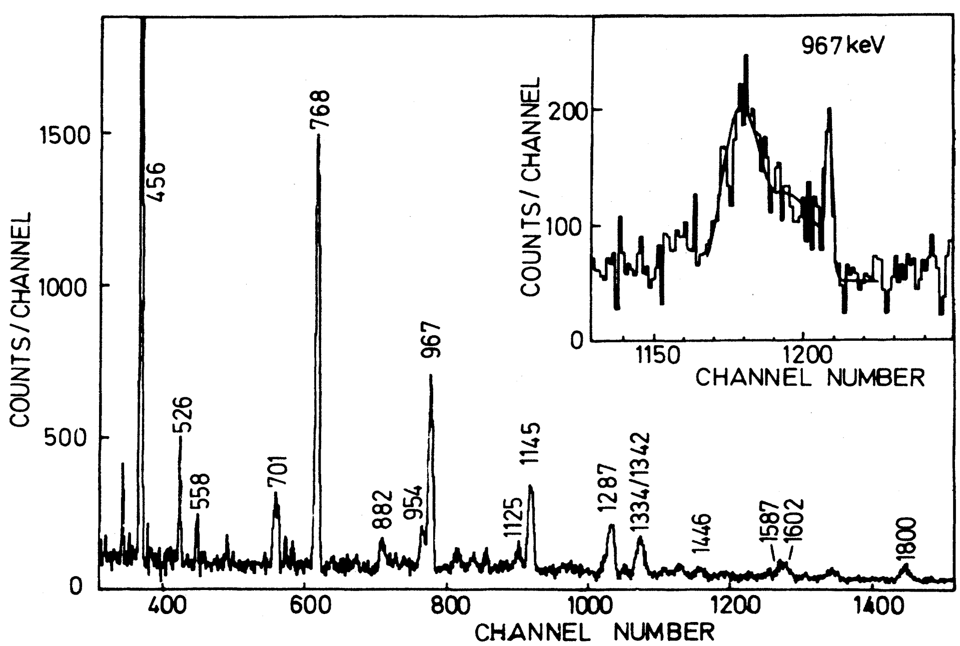

FIG. 2. γ-ray spectrum in coincidence with the 558 keV transition in ^{74}Kr taken from the unbacked target experiment. The insert shows the line-shape of the 968 keV transition from the backed target run.

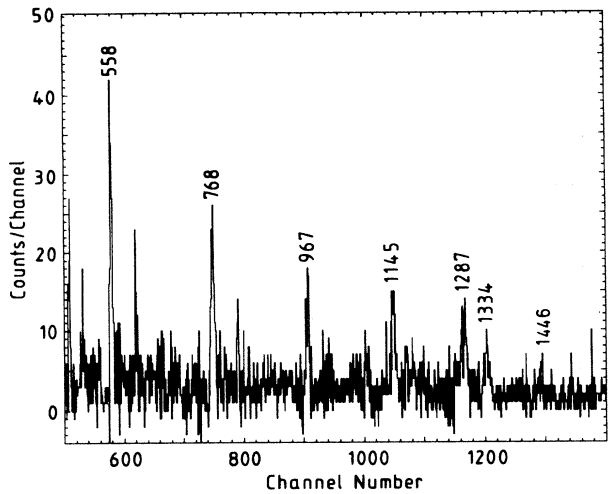

FIG. 3. γ spectrum in coincidence with the 1342 keV line from γ-γ data of the unbacked target run.

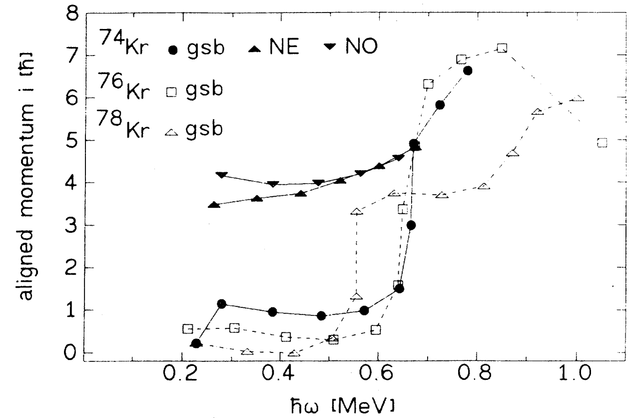

FIG. 4. Aligned single-particle momentum for the ^{74}Kr ground-state band, sidebands and for the ground-state bands in ^{76,78}Kr.

cium. The short effective lifetimes of the 10^+ and 12^+ levels suggest fast continuum feeding times which were assumed to be less than or equal to the cascade feeding times in the analysis. The time constants of the discrete feeding from the negative-parity sidebands are unknown, but this feeding contributes only 5% of the total intensity. Since the lines at 1386 and 1587 keV show no visible Doppler broadening in the backed target spectra, a time constant of 3(1) ps was used. Table I summarizes the measured lifetimes and the resulting $B(E2)$ values, quadrupole moments, and deformations. The values are in good agreement with those of Ref. 7 except for the 12^+ lifetime. The deexciting 1287 keV transition only shows a fully shifted peak, yielding a lifetime $\tau \leq 0.14$ ps. Therefore, a reduction of the $E2$ strength above spin 12^+ is not visible in our data. Especially noteworthy is the jump in the collectivity between the 4^+ and 6^+ state. The lower transition rates in the 2^+ and 4^+ states reflect coexistence of shapes which has been suggested for some time at low spins in ^{74}Kr.[1] This type of reduction of transition strength due to the interference of coexisting prolate and oblate minima in the potential energy surfaces has been observed before in ^{70}Se and ^{72}Se.[14,15] However, in the selenium isotopes the proton alignment and decline of shape coexistence occur at the same rotational frequencies. Therefore, for selenium, it is not clear whether the stabilization of the prolate shape is driven by polarizing effects of the aligned protons, driven by rotational frequency, or a mixture of both. In ^{74}Kr, the situation appears clearer. The rapid increase in transition strength occurs first, as the more deformed prolate shape is energetically favored by rotation, and so is rapidly separated from the competing oblate shape and mixing decreases. This occurs at $\hbar\omega$=0.4 MeV, and is then followed by proton (and neutron) alignment at $\hbar\omega$=0.67 MeV.

In summary, a new ^{74}Kr level scheme was established which shows close similarities to the known level schemes of the even-even neighbors ^{76,78}Kr and fully agrees with that of Ref. 7. The low-spin shape coexistence in ^{74}Kr disappears at spin 6^+ as a consequence of rotation. This is followed by a simultaneous alignment of $g_{9/2}$ protons and neutrons which is found to be in very good agreement with predictions of the HFBC model. The measured transition strengths of the $6^+ \to 4^+$, $8^+ \to 6^+$, and $10^+ \to 8^+$ transitions suggest an average deformation of β_2=0.39 for an axially symmetric shape, making ^{74}Kr one of the most deformed nuclei known.

*On leave from II. Physikalisches Institut der Universität Göttingen, Bunsenstr. 7-9,D-3400 Göttingen, FRG; present address: Hahn-Meitner-Institut Berlin GmbH, Glienicker Str. 100, D-1000 Berlin 39, FRG.

†On leave from Schuster Laboratory, University of Manchester, Manchester M13 9PL, U.K.

[1]R.B. Piercey et al., Phys. Rev. Lett. **47**, 1514 (1981); Phys. Rev. C **25**, 1941 (1982).

[2]H.P. Hellmeister, J. Keinonen, K.P. Lieb, U. Kaup, R. Rascher, R. Ballini, J. Delaunay, and H. Dumont, Nucl. Phys. **A332**, 241 (1979); Phys. Lett. **85B**, 34 (1979).

[3]B.J. Varley, M. Campbell, A.A. Chishti, W. Gelletly, L. Goettig, C.J. Lister, A.N. James, and O. Skeppstedt, Phys. Lett. B **194**, 463 (1987).

[4]M.S. Kaplan, J.X. Saladin, L. Faro, D.F. Winchell, H. Takai, and C.N. Knott, Phys. Lett. B **215**, 251 (1989).

[5]C.J. Gross et al., Z. Phys. A **331**, 361 (1988); Nucl. Phys. **A501**, 367 (1989).

[6]J. Roth, L. Cleemann, J. Eberth, T. Heck, W. Neumann, M. Nolte, R.B. Piercey, A.V. Ramayya, and J.H. Hamilton, J. Phys. G **10**, L25 (1984).

[7]S.L. Tabor, P.D. Cottle, J.W. Holcomb, S.G. Buccino, and F.E. Durham, Phys. Rev. C **41**, 2658 (1990).

[8]L. Lühmann, K.P. Lieb, C.J. Lister, B.J. Varley, H.G. Price, and J.W. Olness, Europhys. Lett. **1**, 623 (1986).

[9]J.A. Sheikh, N. Rowley, M.A. Nagaranjan, and H.G. Price,

Phys. Rev. Lett. **64**, 376 (1990).
[10]S.L. Tabor, Phys. Rev. C **34**, 311 (1986).
[11]J.F. Ziegler, J.P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon Press, New York 1985), Vol. 1.
[12]S. Kalbitzer and H. Oetzmann, presented at the International Conference on Ion Beam Modifications of Materials, Budapest, 1978 (unpublished).
[13]A.E. Blaugrund, Nucl. Phys. **88**, 501 (1966).
[14]J. Heese, K.P. Lieb, L. Lühmann, F. Raether, B. Wörmann, D. Alber, H. Grawe, J. Eberth, and T. Mylaeus, Z. Phys. A **325**, 45 (1986).
[15]J. Eberth *et al., Proceedings of the XXIV Zakopane School on Physics* (World Scientific, Singapore, 1990), Vol. 1, p. 154.