Evidence for Deformed Ground States in Light Kr Isotopes

R. B. Piercey, J. H. Hamilton, R. Soundranayagam, A. V. Ramayya, C. F. Maguire, X.-J. Sun, and Z. Z. Zhao
Physics Department, Vanderbilt University, Nashville, Tennessee 37235

and

R. L. Robinson and H. J. Kim
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

S. Frauendorf
Physics Department, University of Tennessee, Knoxville, Tennessee 37916, and Zentralinstitut für Kernforschung Rossendorf, D-8051 Dresden, German Democratic Republic

and

J. Döring, L. Funke, and G. Winter
Zentralinstitut für Kernforschung Rossendorf, D-8051 Dresden, German Democratic Republic

and

J. Roth, L. Cleemann, J. Eberth, and W. Neumann
Institut für Kernphysik der Universitat zu Köln, D-5000 Köln 41, Federal Republic of Germany

and

J. C. Wells and J. Lin
Physics Department, Tennessee Technological University, Cookeville, Tennessee 38501

and

A. C. Rester
Physics Department, University of Florida, Gainesville, Florida 32611

and

H. K. Carter
UNISOR, Oak Ridge, Tennessee 37830
(Received 6 July 1981)

The levels in ^{74,76}Kr were studied with in-beam γ-spectroscopy techniques and the β^+ decay of ^{76}Rb. The energies of the 2_1^+ states in ^{74,76}Kr deviate from smooth behavior compared with the higher spin levels. The yrast cascade $B(E2)$'s are highly collective. The ^{74,76}Kr ground states have unusually large deformation. The origin of this deformation and of shape coexistence in this region is described in terms of the protons driving the deformation.

PACS numbers: 23.20.Ck, 23.20.Lv, 27.50.+e

The 0_2^+ energies have a deep minimum in ^{70,72}Ge and ^{72,74}Se and are near or below the 2_1^+ energies.[1] These and other data have led to various suggestions of shape coexistence in these nuclei, where the low-lying 0_2^+ states are more deformed than the ground states.[1-4] However, questions have been raised about shape coexistence and deformation in these nuclei, in part because well-developed, deformed bands built on the 0_2^+ states in ^{70,72}Ge are not seen.[1,3] In this paper we suggest that the origin of shape coexistence for $N\approx 38$ nuclei is related to the number of protons which delicately controls whether a deformed shape or near-spherical shape is lowest in nuclei in this region. Our ^{74,76}Kr data give evidence that their ground states have remarkably large deformation.

The origin of strong deformation and shape coexistence in this region can be attributed to the gaps in the single-particle spectrum seen in Fig.

1 at N (or Z) = 40, $\delta \simeq 0$, and N (Z) = 38, $\delta \simeq 0.28$, that stabilize the nuclear shape. Evidence for the spherical subshell closure around N (or Z) = 40 is found when Z (or 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 indicated by the circles in Fig. 1, and similarly for the neutrons which have almost identical single-particle levels. Away from Z (N) = 28 and 50 closed shells, maximal deformation is expected at N (Z) $\simeq 38$. However, the deformed state can coexist 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 $0_2{}^+$ states has been reported.[1-4] In ${}^{72,74}Se$, the deformed band becomes yrast at $I \simeq 2-4$ 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 deformation (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 that the $0_2{}^+$ states are spherical in ${}^{74,76}Kr$.

To investigate the nature of the $0_2{}^+$ states and the influence of the $N \simeq 40$ subshell closure farther from the proton magic numbers, levels in ${}^{74,76}Kr$ were studied with in-beam gamma-ray spectroscopy techniques via 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 accelerator. The levels in ${}^{74}Kr$ also were studied via the reaction ${}^{58}Ni({}^{19}F, p2n)$ at 68 MeV with the Köln tandem accelerator. There an additional technique[5] of measuring (n, γ) and (n, n, γ) coincidences was used to confirm the 8^+ level and to identify the 10^+ level in ${}^{74}Kr$. Finally, the ${}^{76}Rb$ decay 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. Samples were collected and then transported via a tape system to a position between two Ge(Li) detectors for γ-γ coincidence studies.

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 ${}^{76}Kr$. Thus, the energies of the $0_2{}^+$ levels con-

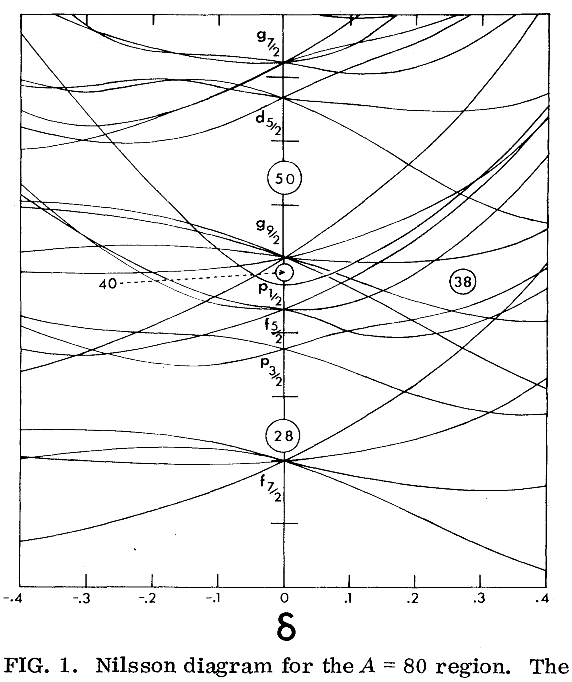

FIG. 1. Nilsson diagram for the A = 80 region. The circles with the particle numbers are placed where gaps occur between the levels.

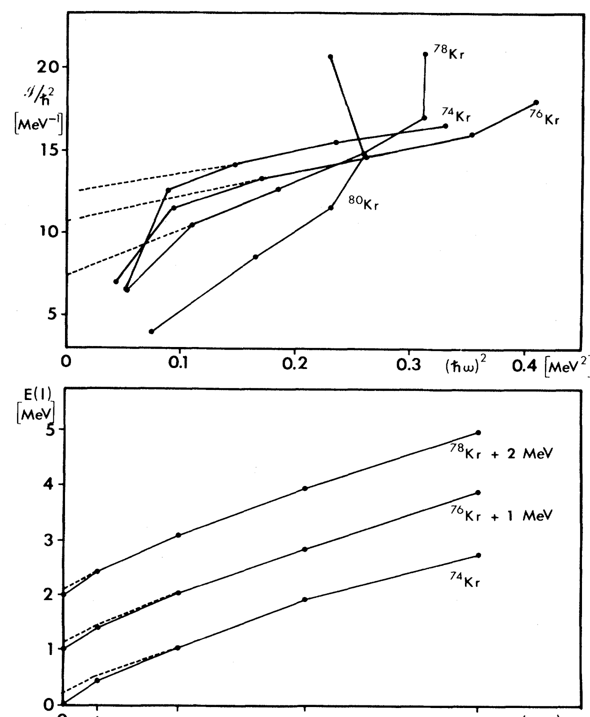

FIG. 2. The moments of inertia (upper) and energies (lower) of the yrast levels in ${}^{74-80}Kr$ (present work and Refs. 6–8). The dashed lines show the Harris extrapolation of high spin levels.

TABLE I. Mean lives of levels and $B(E2)$ values in ^{76}Kr.

$E_{\rm level}$ (keV)	I_i^π	$\tau_{\rm mean}$ (ps)	$B(E2)/B(E2)_{\rm sp}$	$B(E2)/B(E2)_{\rm rot}$
424	2^+	53(7)[a]	59(7)[a]	0.75(9)
1035	4^+	5.0(20)	$77(^{23}_{14})$[b]	$0.70(^{21}_{14})$
1860	6^+	1.25(12)	89(8)	0.72(6)
2880	8^+	0.30(3)	129(13)	1.0(10)
4068	10^+	0.14(2)	129(19)	0.98(15)
5346	(12^+)	0.24(5)[c]	52(11)[c]	0.38(9)[c]

[a]Nolte *et al.* (Ref. 9).
[b]Based on an average ($\tau = 6.6 \pm 1.5$) of the present data and that of Nolte *et al.* ($\tau = 8.2 \pm 2.3$) (Ref. 9).
[c]Composite lifetime and composite $B(E2)$ compared to single-particle value.

TABLE II. Properties of the 0^+ states in Kr-isotopes. The quantities are explained in the text.

Nuclide	δE	$E(0_2^+)$	ΔE_0	V
^{74}Kr	0.256	0.681[a]	0.169[a]	0.330[a]
^{76}Kr	0.187	0.770	0.396	0.330
^{78}Kr	0.102	1.017	0.813	0.305

[a]The value V is assumed and $E(0_2^+)$ and ΔE_0 are calculated by using this value. The energies are in megaelectronvolts.

tinue 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 Fig. 2 are shown the moments of inertia, $\mathcal{J}$, of the even-parity yrast bands in ^{74,76}Kr (present work) and ^{78,80}Kr (Refs. 6–8). One can see from Fig. 2 that at low spin $\mathcal{J}$ of each band becomes larger when going from $N=44$ to $N=38$, except for ^{74}Kr, where the point corresponding to the $2\to0$ energy in ^{74}Kr strongly deviates. This tendency also is seen in ^{76}Kr to a lesser degree. In $^{72,74}Se_{38,40}$ strong forward bends in $\mathcal{J}$ above the 2_1^+ states were interpreted[1,4] in a shape-coexistence picture with bands built on the ground and 0_2^+ states of quite different deformations. The forward bend occurs[1,4] when the deformed band crosses the sequence of states built on the nearly spherical minimum.

The lifetimes of the yrast levels were measured by Doppler-shift line-shape analysis (Table I) and give strong evidence for large deformation effects. The $B(E2)$'s are highly collective, the most collective known for any nucleus in the $A=70$ region. For comparison $B(E2)_{\rm exp}/B(E2)_{\rm sp}$ are 10(4) and $12(^4_3)$ for the $2\to0$ and $4\to2$ transitions, respectively, in ^{68}Ge and 20(2) and 45(6) for ^{72}Se where mixing with deformed states is reported, however. From the 2^+ to the 10^+ state, the $B(E2)$ values generally follow the gradual increase expected in a rotational model, in sharp contrast to the rapid increase in $B(E2)$ values in a vibrational model.

How can we understand large deformation but relatively small $\mathcal{J}$'s extracted from the relatively large $2\to0$ energies in ^{74,76}Kr? As we noted above in Fig. 1, as the proton number approaches $Z=38$ in the Kr isotopes, deformed shapes could have a lower energy than the spherical ones. The relatively large $2\to0$ energies and correspondingly small $\mathcal{J}$ in ^{74,76}Kr, which makes these nuclei look less deformed than they really are, can arise from an interaction between the 0_1^+ deformed ground states and higher states such as the 0_2^+ states to push down the 0_1^+ energies.

From Fig. 1 one can see that for $N=38$, the deformed structure is generated from the spherical one by transferring 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 different structures.

To quantify our interpretation, we analyzed the Kr yrast bands in a two-band mixing model. For $I \gtrsim 6\hbar$, where $\mathcal{J}$ is nearly linear, we considered the yrast levels to be purely deformed. 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 $\omega=0$. This corresponds to a Harris or variable moment of inertia (VMI) parametrization of the deformed g bands $[\hbar\omega = E_\gamma/2;\ \mathcal{J}/\hbar = (I+\frac{1}{2})/\omega;\ \mathcal{J} = \mathcal{J}_0 + \omega^2\mathcal{J}_1]$ (see Bengtsson and Frauendorf[10]). The deviation between the extrapolated and measured levels (Fig. 2) is much larger in ^{76}Kr than in ^{78}Kr in accordance with the higher 0_2^+ energy in ^{78}Kr.

The shifts $\delta E = E(0_1^+)^0 - E(0_1^+)$ can be found in Table II, where $E(0_1^+)^0$ is the extrapolated and $E(0_1^+)$ the measured ground-state energy. The measured energies $E(0_2^+)$ of the 0_2^+ states are also given in Table II. The difference between the unperturbed levels $\Delta E_0 = E(0_2^+)^0 - E(0_1^+)^0$ is equal to $E(0_2^+) - E(0_1^+) - 2\delta E$. The interaction,[10] V, is equal to $\frac{1}{2}(\Delta E^2 - \Delta E_0^2)^{1/2}$, where $\Delta E = E(0_2^+) - E(0_1^+)$. 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 energy of the (unperturbed) 0_2^+ state. Assuming that the interaction V in ^{74}Kr has a value similar to that of ^{76}Kr, 0.33 MeV, we predict the 0_2^+ energy at 0.68 MeV. The extracted unperturbed $2 \rightarrow 0$ energies in the deformed ground bands are 200 and 237 keV in ^{74,76}Kr, respectively. By scaling the unperturbed $2 \rightarrow 0$ energy by $A^{5/3}$, one may compare the deformation of ^{74}Kr to that of ^{240}Pu. The 200-keV transition in ^{74}Kr would correspond to 28 keV in ^{240}Pu compared with the actual value of 43 keV. This is an unusually large ground-state deformation, slightly larger than the "super deformation" recently reported[11] for ^{100}Sr with its scaled 30-keV 2_1^+ energy. Such interaction of two 0^+ levels and their splitting may have masked strong ground-state deformation in other regions.

In ^{76}Kr the observed 0_2^+ level is low in energy, but the 2_2^+ level which feeds it is 928 keV above it, while the 2_1^+ state is only 425 keV above the ground state. Thus in addition to large ground-state deformation, we suggest that the 0_2^+ level is associated with a near-spherical shape, in contrast to the reverse situation in ^{72,74}Se. A similar situation should be occurring in ^{74}Kr. Since the 2^+ spherical state is high in energy and the near-spherical energies grow much faster with spin than in the deformed band, there will be little mixing of the 2^+ and higher spin states. By contrast, in ^{72,74}Se considerable mixing of the deformed and spherical configurations near the band crossing at $I \simeq 2$–4 is observed.[1]

In summary, the present data give evidence for large ground-state deformation in these light Kr isotopes. This interpretation for the $N = 38$ and 40 Kr nuclei supports the expectation that at these neutron numbers as the proton number approaches the middle between the $Z = 28$ 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 importance of the triaxial deformation in these nuclei is reflected by the observation of the γ band at low energy. These data also 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 well deformed and the excited 0_2^+ states associated with the near-spherical minima.

This research is supported in part by U. S. Department of Energy Contracts No. DE-AS05-76ER05034, No. DE-AC05-760R00033 with Oak Ridge Associated Universities, and No. W-7405-ENG-26 with Union Carbide Corporation; by the Bundesministerium für Forschung und Technologie; and by the Akademie der Wissenschaften of the German Democratic Republic. This work was performed while two of us (X.-J.S. and Z.Z.Z.) were on leave from the Institute of Modern Physics, Lanzhou, People's Republic of China. J. H. H. acknowledges a Senior Alexander von Humboldt Award and L. C. an Alexander von Humboldt Fellowship during parts of this work.

[1] J. H. Hamilton, A. V. Ramayya, and R. L. Robinson, *Nuclear Interactions*, edited by B. A. Robson (Springer-Verlag, Berlin, 1979), p. 253, and references noted in this paper.

[2] K. Kumar, J. Phys. G 4, 849 (1978).

[3] M. Vergnes, *Structure of Medium-Heavy Nuclei*, edited by G. S. Anagnostatos *et al.*, Institute of Physics Conference Series No. 49 (Institute of Physics, London, 1980), p. 25.

[4] J. H. Hamilton, A. V. Ramayya, W. T. Pinkston, R. M. Ronningen, G. Garzia-Bermudez, H. K. Carter, R. L. Robinson, H. J. Kim, and R. O. Sayer, Phys. Rev. Lett. 32, 239 (1974).

[5] J. Roth, L. Cleemann, J. Eberth, W. Neumann, R. B. Piercey, A. V. Ramayya, and J. H. Hamilton, in *Proceedings of the International Conference on Nuclear Behavior at High Angular Momentum, Strassbourg, France, 1980* (Société Française de Physique, Paris, 1980), p. 25.

[6] R. L. Robinson, H. J. Kim, R. O. Sayer, W. T. Milner, R. B. Piercey, J. H. Hamilton, A. V. Ramayya, J. C. Wells, and A. J. Caffrey, Phys. Rev. 21, 603 (1980).

[7] D. L. Sastry, A. Ahmed, A. V. Ramayya, R. B. Piercey, H. Kawakami, R. Soundranayagam, J. H. Hamilton, C. F. Maguire, A. P. de Lima, S. Ramavataram, R. L. Robinson, H. J. Kim, and J. C. Wells, Phys. Rev. C 23, 2086 (1981).

[8] L. Funke, J. Döring, F. Dubbers, P. Kemnitz, E. Will, G. Winter, V. G. Kiptilij, M. F. Kudojarov, I. Kh. Lemberg, A. A. Pasternak, A. S. Mishin, L. Hildingsson, A. Johnson, and Th. Lindblad, Nucl. Phys. A355, 228 (1981).

[9] E. Nolte, Y. Shida, W. Kutschera, R. Prestele, and H. Morinaga, Z. Phys. A 268, 267 (1974).

[10] R. Bengtsson and S. Frauendorf, Nucl. Phys. A314, 27 (1970), and A327, 139 (1979).

[11] R. E. Azuma, G. L. Borchert, L. C. Carraz, P. G. Hansen, B. Jonson, S. Mattsson, O. B. Nielson, G. Nyman, I. Ragnarsson, and H. L. Ravn, Phys. Lett. 86B, 5 (1979).