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HIGH SPIN STATES AND THE COMPETITION OF SPHERICAL AND STRONGLY DEFORMED SHAPES IN THE A = 70 - 80 REGION

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Abstract A wide variety of collective band structures are seen in Ge to Sr nuclei to make this an important new testing ground for nuclear models. These include bands built on coexisting and competing near-spherical and deformed shapes, γ vibrational bands and multiple positive and negative parity bands. Ground state bands in Ge and Kr but not ^{78,80}Sr are crossed at the 8^+ to 12^+ levels. Gaps in the Nilsson levels for both N and Z = 38 at large deformation lead to large ground state deformation in Kr and Sr around N = 38. The crossing of rotation aligned bands based on $(g_{9/2})^2$ configuration are correlated with the ground state deformations. A second high spin crossing is seen in ^{74}Kr. Measured g factors in ^{68}Ge yield a two-quasineutron structure for the 8_2^+ state.

INTRODUCTION

The A = 60 to 84 region has become an important, new testing ground for many types of nuclear structure models because of the richness of different collective motions and structures which are found in this region and the rapid changes seen in some structures with the addition of only two protons or two neutrons. The rapidity of change is related to two facts: the nuclei cross four orbitals, $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, for

both N and Z, and the strong competition between near spherical and strongly deformed shapes which are correlated with gaps in the Nilsson levels at around N = Z = 40 for spherical shapes and N = Z = 38 for well deformed shapes. Some of the variety of different structures and the rapidity of their changes can be seen in plots of the moments of inertia as a function of the rotational frequency $(\hbar\omega)^2$ for the Ge, Se yrast states.[1] The first nucleus studied to high spin was ^{72}Se (Ref. 2) and its strong forward bend of $\mathcal{I}$ above 4^+ was interpreted in terms of shape coexistence.[2-4] The $\mathcal{I}$'s for ^{70}Se, ^{70}Ge and ^{68}Ge show very different behavior (backbending above 4^+ to triple forking at 8^+ with backbending, respectively). Recent studies[5] of ^{74,76}Kr have illuminated the origin of the shape coexistence in this region and have confirmed the recent calculations of Möller and Nix[6] that predicted that nuclei around N = Z = 38 should have the strongest ground state deformations of any nuclei with $\beta \gtrsim$ .35-0.4. The presence of deformed shapes for ground or excited states makes possible two quasiparticle (qp) rotation aligned bands based on high j, low Ω orbitals, which are here the $g_{9/2}$ orbitals for both protons and neutrons. Rotation aligned structures and the competition between the near spherical and deformed shapes provide explanations of the rapidly varying and different behaviors of the yrast cascades, including the first report in this region of two high spin discontinuities of $\mathcal{I}$ in ^{74}Kr. This competition is considered first because it is necessary to understand the high spin states.

SHAPE COEXISTENCE AND STRONG DEFORMATION AROUND N = Z = 38

The first clear evidence[2] for shape coexistence in this region was $^{72}_{34}Se_{38}$. Studies of the light Kr isotopes[5] provided the clues to understanding the competition of spherical and deformed shapes in this region. While the B(E2;2-0)'s for $^{78-86}$Kr rapidly increase with decrease in N to suggest the onset of deformation, the 2-0 energies (455-617 keV) do not suggest large deformation. The levels in ^{76}Kr from in-beam spectroscopy[5,7] are shown in Fig. 1. Note the

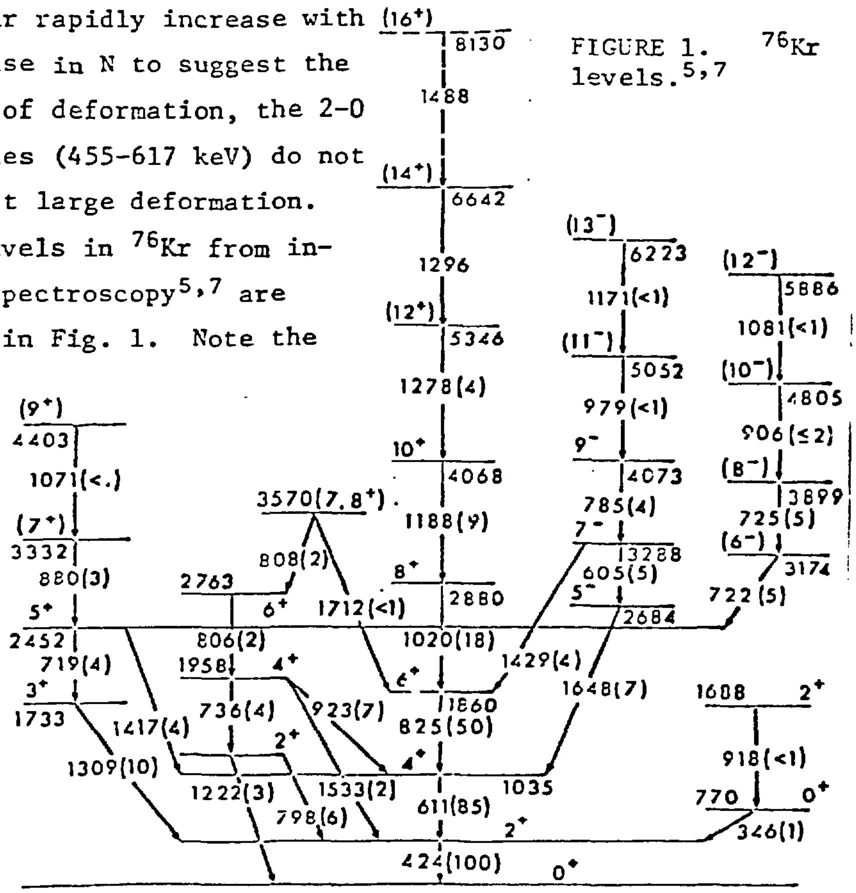

FIGURE 1. ^{76}Kr levels.[5,7]

dominance of rotational-like structures. The ^{76}Kr lifetime measurements[5,8] yield surprisingly large collective B(E2) strengths of 80 to 120 single particle units in going from 2^+ to 10^+, respectively. For comparison the $B(E2)_{exp}/B(E2)_{sp}$ for the 2-0 and 4-2 transitions in $^{68-72}$Ge are the order of 10-20 spu. The Kr data[5,8] provide strong evidence for large collective effects associated with nuclear deformation. Without repeating details, the data indicate that the ground states of ^{74,76}Kr are well deformed. The extracted unperturbed 2-0 energy of 200 keV in ^{74}Kr corresponds to an unusually large ground-state deformation,[5] comparable to the "super deformation" reported[9] for ^{100}Sr. The relatively large 2-0 energies, which make ^{74,76}Kr look less deformed than they really are, arise from interactions between the 0_1^+ deformed ground states and low-lying, near-spherical 0_2^+ states that push down the 0_1^+ energies.

The origin of strong deformation and shape coexistence in this region can be understood from the gaps in the single-particle spectrum seen in Fig. 2 at N(Z) = 40, $\delta \simeq 0$, and N(Z)=38, $\delta \simeq 0.3$, that stabilize the nuclear shape. Spherical subshell closure is found around N = 40 when Z is 28 or 50, and around Z = 40 when N is 28 or 50 because then the protons and neutrons prefer a spherical shape; for examples, $^{68}_{28}$Ni$_{40}$ and $^{90}_{40}$Zr$_{50}$ which look like double closed shell nuclei. These double closed shell-like nuclei demonstrate the winning out of spherical shapes in the competition between spherical and deformed shapes for N,Z $\gtrsim$ 38-40. However, away from 28 or 50 the level density for a spherical shape becomes very high

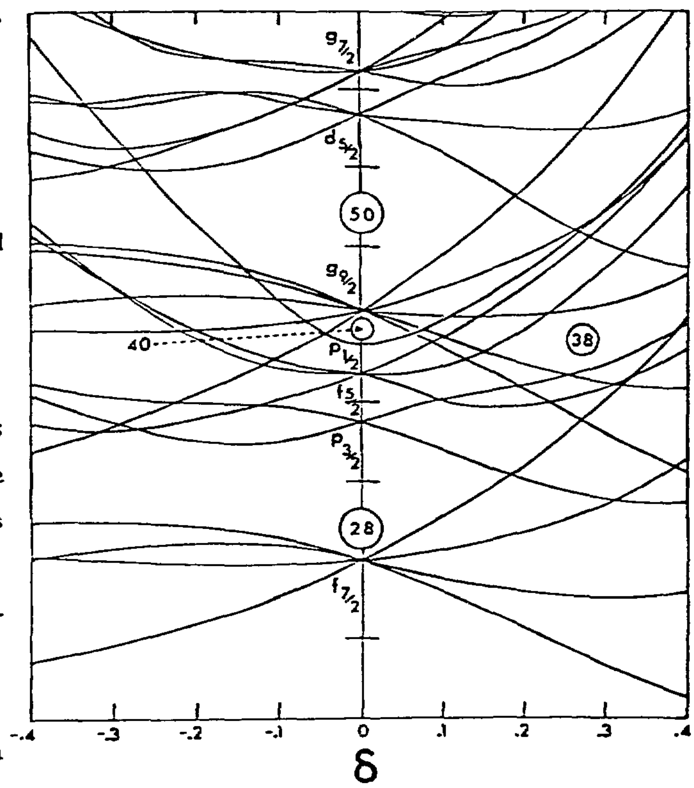

FIGURE 2. Nilsson levels.

and the minima of the proton and neutron energies move to deformed shapes. From Fig. 2 maximal deformation is expected around N = Z = 38. The deformed state can coexist with a near-spherical configuration in a delicate balance for N=38. Which one is lower depends on the proton number.

Recently Möller and Nix[6] calculated nucleon masses and ground-state shapes for 4023 nuclei from ^{16}O to $^{279}112$ with a Yukawa-plus-exponential macroscopic model and a folded Yukawa single-particle potential. Their calculations[6] predict that nuclei with both N and Z at or near 38 should be among the most strongly deformed ones in nature with $\beta \approx 0.35$-0.4. The Kr data[5] provided the first confirmation of these results. The competition between spherical and deformed shapes here is also seen in the calculations of Siewert et al.[10] Further support for the importance of Z=38 in driving deformation when gaps in the Nilsson levels for N also favor deformation come from $^{78,80}Sr$ (Refs. 4,11-13) and ^{100}Sr (Ref. 9) (see Refs. 4, 14 for details).

STRUCTURE OF HIGH-SPIN STATES

Other evidence for the importance of deformation in this region are the γ-type vibrational bands with very rotational energies up to spin 11^+. Here we will concentrate on the high-spin states in the yrast cascades and the negative parity bands which are seen systematically in this region beginning at either 3^- or 5^- and 6^- up to 13^- and 12^-.

Two discontinuities of the moments of inertia, $\mathscr{I}$, of the yrast cascades in ^{158}Er and ^{160}Yb (Refs. 15,16), and very recently a third and apparently higher discontinuity of $\mathscr{I}$ in ^{158}Er (Refs. 17,18) have provided evidence for the persistence of collective rotations and the alignment of individual pairs of quasiparticles to much higher spins than thought possible for deformed rare earth nuclei. Rotation aligned bands crossing the ground state band were first reported[19] in this region in ^{68}Ge (Fig. 3) and next[20] in ^{80}Kr. The two backbends at 8^+ were first interpreted[19] as the crossing of rotation aligned bands built on both proton and neutron $(g_{9/2})^2$ configurations in ^{68}Ge and a proton one[20,21] in ^{80}Kr. With a newly employed neutron multiplicity technique, the yrast cascade in ^{74}Kr was observed to the highest spin reported for a medium-light nucleus, tentatively to 20^+ (Fig. 4) with two high spin discontinuities in $\mathscr{I}$.[22]

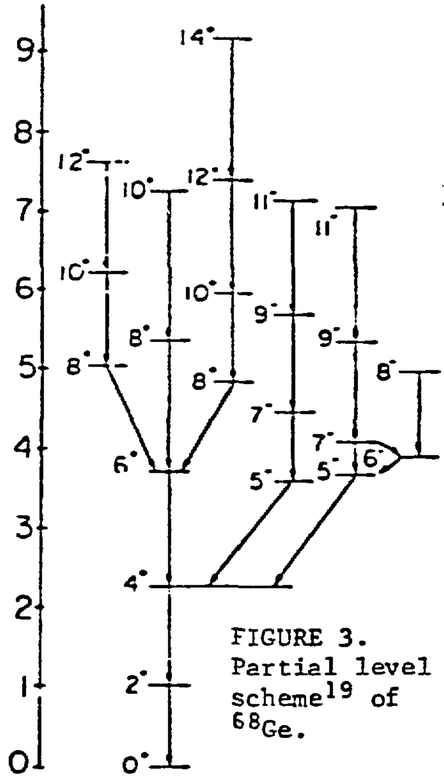

FIGURE 3. Partial level scheme[19] of ^{68}Ge.

As one goes away from stability in the A = 70 region the neutron evaporation channels quickly become too weak to be studied in any detail, if only γ-rays are recorded. A neutron multiplicity technique has been developed and used at Köln and at the Holifield Heavy Ion Research Facility. A full range of experiments including n-n-γ, n-γ-γ, n-γ(θ), n-e, and n-γ (plunger τ) experiments have been done[22] for ^{74}Kr. More recently a charged particle-neutron-γ technique has been shown to add even greater capability to go farther from stability.[11]

In Fig. 5 is shown a plot of the angular momentum I(ω) as a function of $\hbar\omega$ where $\hbar\omega = E_\gamma[(I + 1) \rightarrow (I - 1)]/2$ for ^{74,76,78}Kr (Refs. 22,5,23). There are three discontinuities seen in I(ω) for ^{74}Kr. The break at 2_1^+ was discussed

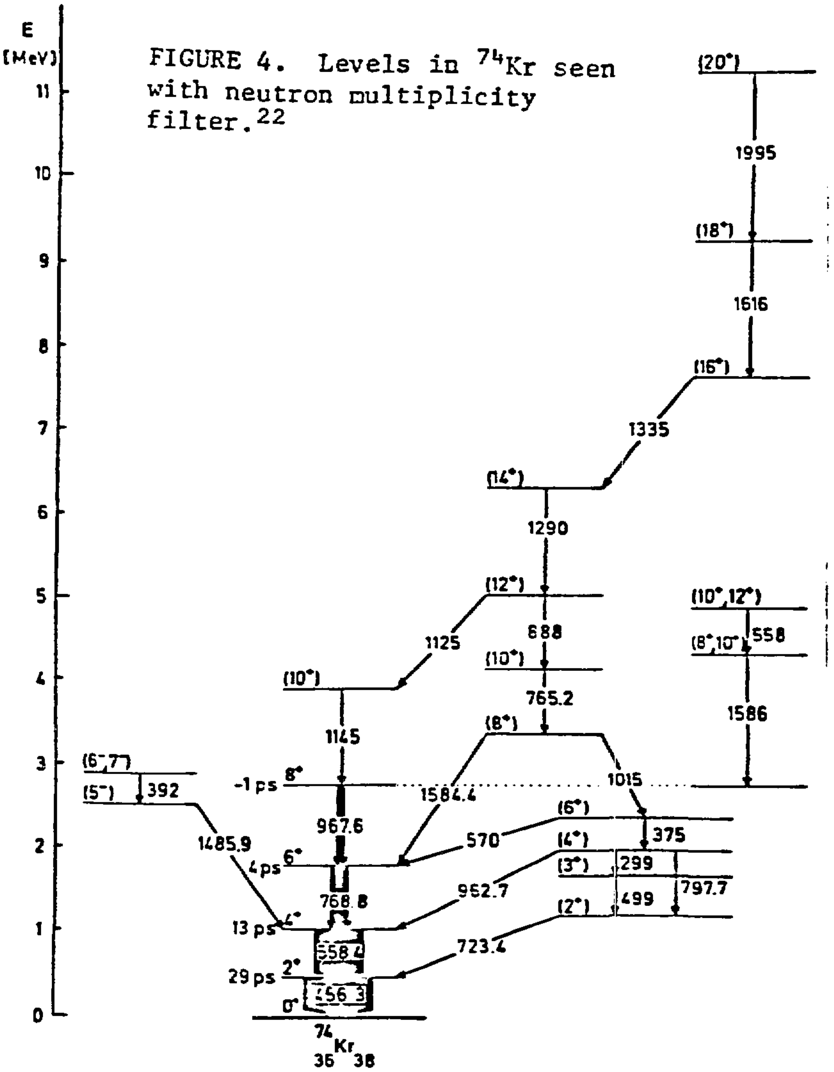

FIGURE 4. Levels in ^{74}Kr seen with neutron multiplicity filter.[22]

earlier. In both ^{74}Kr and ^{78}Kr a discontinuity in I(ω) occurs above 10^+, but in ^{76}Kr it occurs above 12^+. In ^{80}Kr two 8^+ and 10^+ states are seen and are interpreted as the crossing of a two $(g_{9/2})^2$ quasiproton rotational aligned band. Two quasiparticle-plus-rotor calculations[21] and recent data[24] on ^{81}Kr support the proton nature. This first band to cross the ground band at 12^+ in ^{74}Kr and ^{78}Kr is interpreted as a two qp $(g_{9/2})^2$ configuration, presumably also two quasiprotons. The second high-spin discontinuity occurs above 14^+ with the (16^+), (18^+), and tentative (20^+) states showing similar alignment. The band that crosses at 16^+ is interpreted as a 4-quasiparticle $g_{9/2}$ configuration. The extra alignment is about the same as the extra alignment in the first band, i.e. 2-3 units. No such break in I is seen in the tentatively assigned 16^+ level in ^{78}Kr (Ref. 23) which has 4 more neutrons. These data suggest a blocking effect of the extra neutrons and indicate at least two of the four quasiparticles in the highest band in ^{74}Kr are neutrons. Recent results[7] for ^{76}Kr show the 16^+ level has similar alignment as ^{78}Kr, but the first high spin break occurs one state higher than in ^{74,78}Kr. This difference for ^{76}Kr is not understood. The ^{74}Kr data show that in light nuclei too, rotation aligned two quasiparticle structures persist to quite high energies, over 11 MeV.

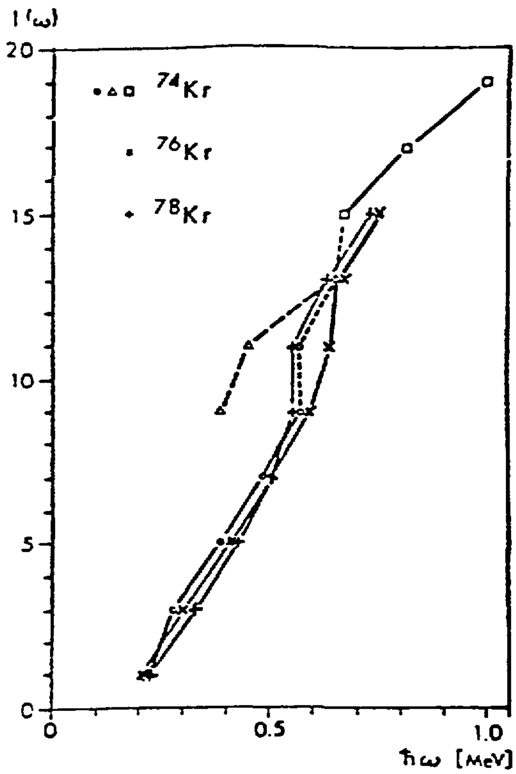

FIGURE 5.

Plots of I(ω) for $^{78-84}$Sr (Refs. 11-13) are shown in Fig. 6. In contrast to $^{74-78}$Kr no sudden change in I is seen for ^{78,80}Sr even though cranked shell model calculations indicate the interaction strength of the ground and S band should be lowest at Z=38 and thus the backbending strongest for Sr.

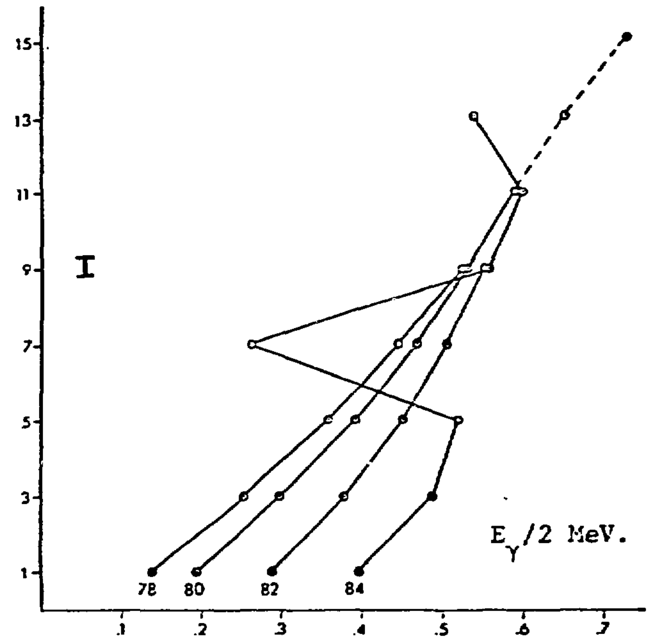

FIGURE 6. $I(\omega)$ plots for $^{78-84}Sr$.

Strong backbending is seen in ^{84}Sr. These differences can be understood because of the differences in deformations and differences in the energies of the ground state bands (gsb). The 8^+ $(g_{9/2})^2$ configuration energies are rather constant in this region. Thus, when the gsb energies are low (the lowest observed in this region are in deformed $^{78,80}Sr$), the S band is too high to cross below 14^+-16^+, while in the more spherical ^{84}Sr with much higher gsb energies the crossing occurs at 8^+. In strongly deformed $^{74,76}Kr$, the interaction of the two 0^+ states keeps the ground band energies higher than in $^{78,80}Sr$ and thus the S band can cross at 12^+ to 14^+.

Throughout this region negative parity bands that begin at 3^- or 5^- and 6^- are seen. Those which begin at 5^- and 6^- are believed to be built on rotation aligned structures with one $(g_{9/2})$ particle. It is not definite if there are really octupole bands in this region as first reported[25] in ^{74}Se or if rotation aligned bands accidentally have occurred near the 3^- octupole states. The ^{76}Kr bands which begin at 5^- and 6^- are shown in Fig. 7 along with results of 2 quasiproton-plus-rotor calculations.[21] The most surprising feature is the remarkably large B(E2) strengths[8] in these bands, 600-

900 spu! There has been no theoretical effort to understand these exceptionally large values.

Space does not permit a discussion of all the various collective bands seen in odd A and odd-odd nuclei in this region. The latter were reviewed by Funke.[26] Two examples will illustrate the interesting results being obtained. In ^{73}Se (Fig. 8) one sees a regular spaced band built on the $g_{9/2}$ ground state and a more deformed band built on a $(p_{3/2})^{-1}$ $(g_{9/2})^2$ configuration with $\beta \approx 0.31$ from lifetime measurements in this band.[27] These bands likewise illustrate the strong deformation effects in this region.

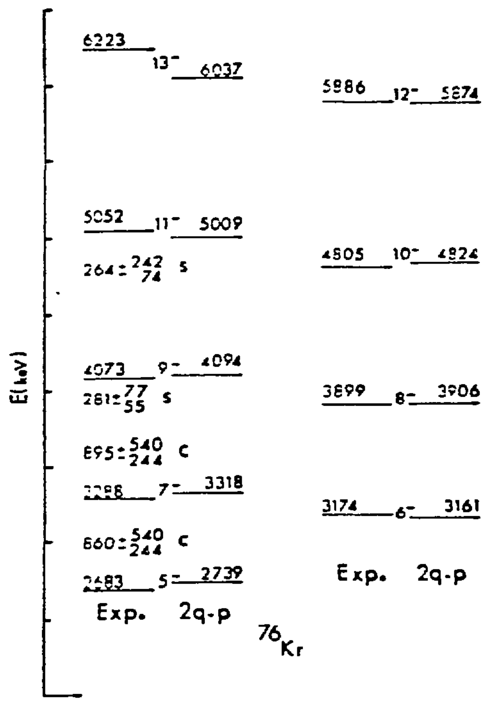

FIGURE 7. 5^- and 6^- bands in ^{76}Kr. Coincidence and singles data $B(E2)_{spu}$ are shown between levels.

The $\nu g_{9/2}+$ band in ^{81}Kr (Fig. 9) is crossed at $21/2^+$, presumably by a $\nu g_{9/2}$ $\pi(g_{9/2})^2$ configuration.[24] The lowest spin for these

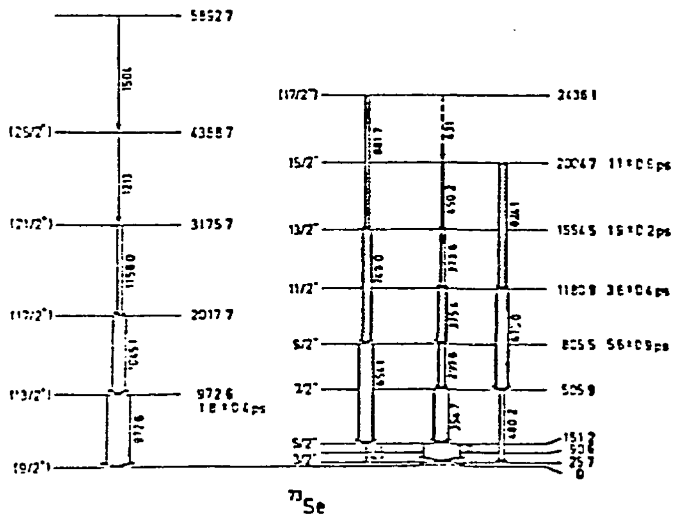

FIGURE 8. ^{73}Se levels.

orbitals is $21/2^+$. The observed energy is consistent with the $\pi(g_{9/2})^2$ band in ^{80}Kr that crosses the ground band. Such a 3 particle band crossing was first reported[28] in ^{65}Ga. The interesting feature of ^{81}Kr is the obvious change in the level spacings in the band from strong signature splitting to no splitting to indicate a definite shape change in going from one configuration to the other.[24,26] Funke et al.[24] interpret the 1qp band to have $\gamma \approx 30^\circ$ and the 3qp band $\gamma \approx 0$. Thus, in the odd A nuclei as well one can see the effects of the competition of near spherical and deformed shapes and the interaction of rotation aligned band crossings.

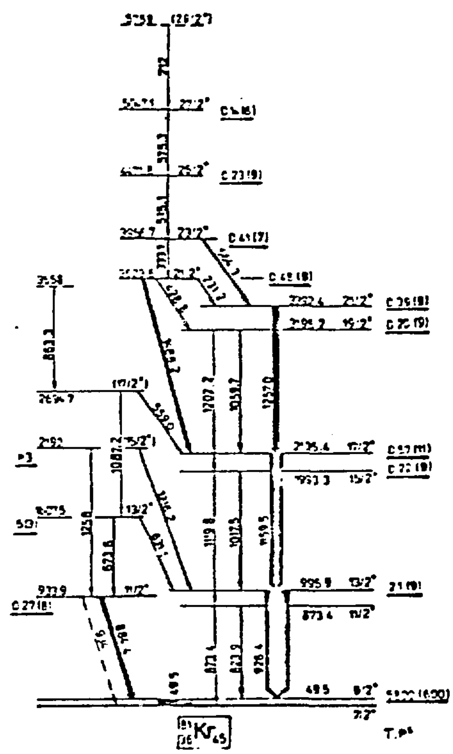

FIGURE 9. ^{81}Kr levels.

g FACTOR MEASUREMENTS

In ^{68}Ge (Fig. 3) the two lowest 8^+ states were interpreted[19] as rotation aligned structures built on $(g_{9/2})^2$ for both protons and neutrons. Very recently Petrovici and Faessler[29] have calculated the levels of ^{68}Ge in an asymmetric-rotor model with two quasiparticle admixtures. They suggest that the lowest 8^+ state is a member of the ground state band and the 8_2^+, 8_3^+ states are 2 quasineutron levels with full and partial alignment. Their calculations put the 2 quasiproton band an MeV higher. They calculate the g factors of the lowest $8^+_{1,2,3}$ levels as 0.466, -0.546 and -0.275, respectively.

To distinguish between these interpretations we have carried out g factor measurements.[30] The transient field technique was employed. The reaction $^{40}Ca(^{32}S, 4p)^{68}Ge$ at 100 MeV on a 230 μg/cm² ^{Nat}Ca target backed by 896 μg/cm² ^{Nat}Fe was used with a 340 Gauss external magnetic field switched every 2 min. Because of beam difficulties that kept the energies below 100 MeV most of the time and the cross section low, the statistics were sufficient to extract information only for the $8^+_{1,2}$ states. A preliminary analysis yields g factors of 0.81 ± 0.49(8^+_1) and -0.64 ± 0.43(8^+_2). These results agree in sign and magnitude with the recent theoretical calculations.[29] However, the definite proof of the calculations rests in g(8^+_3). A second experiment is planned with good statistics to make a definitive test. These data do indicate that at least the 8^+_2 state does involve a 2 quasineutron configuration in ^{68}Ge. In the Kr isotopes these 2 qp states are presumably 2 quasiproton.

In summary, the A = 60-80 region has now revealed a rich variety of collective motions at low and high spin. The variety of structures and rapidity of their change with N and Z make this region an important new testing ground for nuclear models.

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