Observation of Rigid Nuclear Rotation

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States in ^{84}Zr with angular momenta up to $34\hbar$ and rotational frequency 1.3 MeV have been studied with the techniques of discrete-line gamma-ray spectroscopy. The measurements probe the region beyond a second upbend. In this region the results are consistent with the nucleus having undergone a transition to an axially symmetric shape with $\beta = 0.43 \pm 0.06$ and $\gamma = 3° \pm 6°$ which rotates with the rigid-body moment of inertia.

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At low angular moment nuclei have moments of inertia considerably smaller than their rigid-body values. This is largely the result of pairing correlations. Their shapes, described by parameters β and γ quantifying the degree of quadrupole deformation and triaxiality, are determined by the interplay between macroscopic potentials characterized by the liquid-drop model and microscopic potentials characterized by the various shell models.

At sufficiently high angular momentum it is expected that pairing effects will be quenched and the nucleus will then have the moment of inertia appropriate to a rigid body. However, hitherto, the onset of full rigid rotation has not been observed in a single rotational band. The angular momentum above which rigid rotation occurs depends, essentially, on the rotational frequency governing the strength of the Coriolis force and on detailed nuclear structure, such as the occupation probabilities of quasiparticle orbitals and the position of shell gaps. These factors are clearly dependent on the nuclear mass.

It is also accepted that nuclear shape will change as the angular momentum is increased. For instance, shell effects are of the order of 3 to 4 MeV and influence nuclear shape, but at sufficiently high angular momentum the macroscopic rotational energy becomes the dominant factor. Shapes having γ between 0°, corresponding to a prolate deformation rotating perpendicular to the symmetry axis, and 60°, oblate rotating parallel to the symmetry axis, will then be preferred simply because of their larger moments of inertia, and hence lower rotational energy. The angular momentum above which macroscopic effects generally determine nuclear behavior is again governed by the mass of the nucleus.

Nuclei in the region of the deformed shell gap predicted[1] at $N = Z = 38$ should be ideal for observing the onset of full rigid rotation. Many of these nuclei have been observed[2,3] to have excited bands of states characteristic of deformed rotors. At any given angular momentum, J, the nuclear rotational frequencies are 2–3 times higher in these nuclei than in rare-earth rotors as a result of their smaller moments of inertia. Consequently, Coriolis forces are correspondingly higher. In addition, the low moment of inertia implies that the macroscopic rotational energy will dominate the influence of microscopic shell structure at the relatively low angular momentum of $\sim 15\hbar$ compared to $\sim 30\hbar$ as expected in rare-earth nuclei. Finally, because protons and neutrons occupy similar quasiparticle orbitals near the Fermi surface, particle alignments and changes in pairing strengths may be expected to occur at similar frequencies.

In the present paper, results are presented on the transitional nucleus ^{84}Zr for states with angular momentum and rotational frequency almost twice as high as previously observed in this mass region. The nucleus was formed with the reactions ^{58}Ni(^{28}Si, $2p$)^{84}Zr and ^{58}Ni(^{29}Si, $2pn$)^{84}Zr at bombarding energies between 95 and 110 MeV using beams from the tandem accelerators at Daresbury Laboratory and Brookhaven National Laboratory. Gamma-ray angular distributions were measured with germanium detectors in coincidence with an array of neutron detectors filled with NE213 liquid scintillator. The lifetimes of the low-lying excited states were determined by the recoil-distance (plunger) method with the γ rays again in coincidence with the neutron detectors. Coincidence γ-ray data were also collected at Daresbury Laboratory with an array of six Compton-suppressed germanium detectors.[4] The gamma-ray multiplicity was simultaneously recorded with an array of fifty bismuth germanate scintillation crystals. Lifetimes were deduced for the higher-lying states by the Doppler-shift attenuation method, the shortest limits being determined by the γ rays exhibiting a full Doppler shift. The decay scheme, determined from the coincidence data, is shown in Fig. 1, together with the measured lifetimes.

In Fig. 2 are plotted, as a function of rotational frequency, $\hbar\omega$, the kinematic moment of inertia $\mathscr{I}^{(1)} = I_x/\omega$, the angular momentum aligned along the rotation axis $I_x = [(I+\frac{1}{2})^2 - K^2]^{1/2}$, and the transition quadrupole moment Q_t $[B(E2) = (5/16\pi) \times Q_t^{\,2}(I200/I\text{–}20)^2]$, determined from the data. In the low-frequency regime, up to $\hbar\omega = 0.6$ MeV, the behavior of $\mathscr{I}^{(1)}$ and I_x is characteristic of a soft rotor. In particular $\mathscr{I}^{(1)}$ changes quite rapidly with frequency. This is compatible with the transitional nature of ^{84}Zr, insofar as potential-energy-surface calculations[3,5] predict it to be almost spherical in the ground state, but soft to changes in the deformation parameters. The transition quadrupole moments for the yrast band vary from 2.1 ± 0.1 $e\cdot$b for the 2^+ state to 1.5 ± 0.1 $e\cdot$b for the 14^+ state. These would correspond to changes in β from 0.24 to 0.17 for an axially symmetric nucleus. However, the presence of the low-lying second 2^+ state indicates that the nucleus is triaxial. Indeed, in the Davydov[6] model, the energy of the second 2^+ state implies a γ of 28°. These values are comparable[7,8] to the deformation parameters of other transitional nuclei in this mass region.

It is apparent from Fig. 2 that there are two upbends in the $\mathscr{I}^{(1)}$ vs ω and I_x vs ω plots of the yrast band at frequencies of 0.48 and 0.60 MeV. Since the crossing of the ground-state band with an aligned $g_{9/2}$ two-quasiproton band in the isotones ^{80}Kr and ^{82}Sr has been described[8] successfully in terms of the cranked shell model, such calculations were carried out by us for ^{84}Zr using similar parameters.

The calculations predicted a first crossing of the ground-state band with an aligned two-$g_{9/2}$-

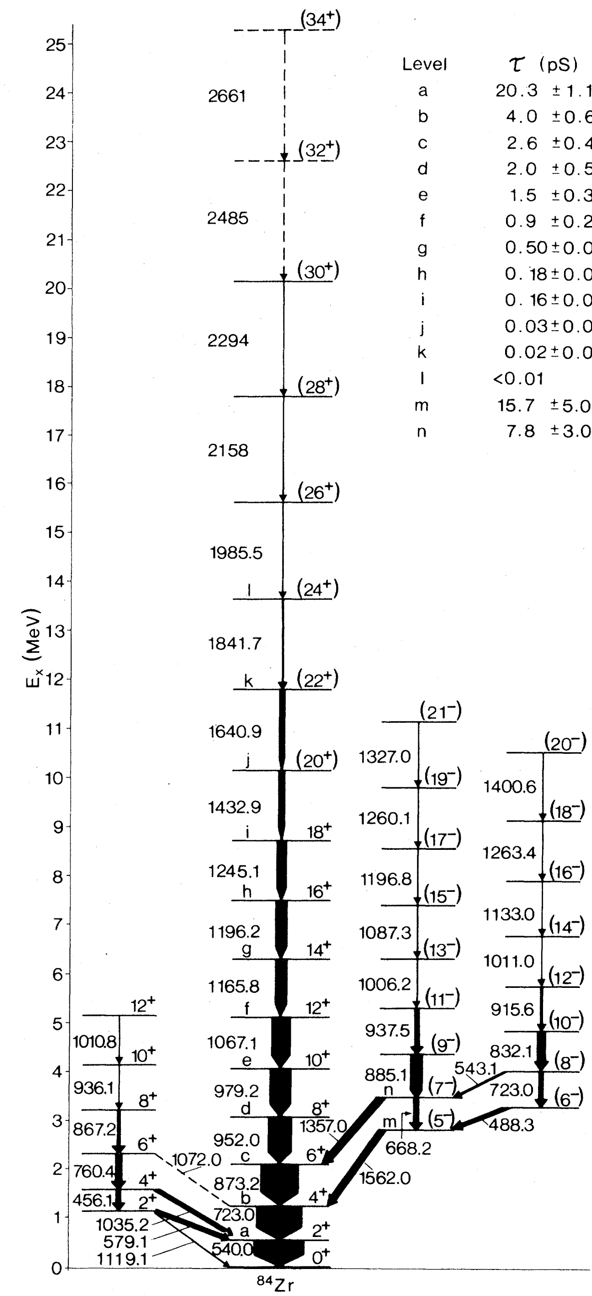

FIG. 1. The decay scheme for ^{84}Zr.

quasiproton band at $\hbar\omega = 0.50$ MeV and a subsequent crossing when two $g_{9/2}$ quasineutrons align at $\hbar\omega = 0.60$ MeV. The predicted gains in alignment following these crossings were $6.1\hbar$ and $5.7\hbar$, respectively. The crossing frequencies for the upbends agree well with those observed experimentally, while the experimental increases in alignment are both approximately $4\hbar$. A similar discrepancy between the observed and cal-

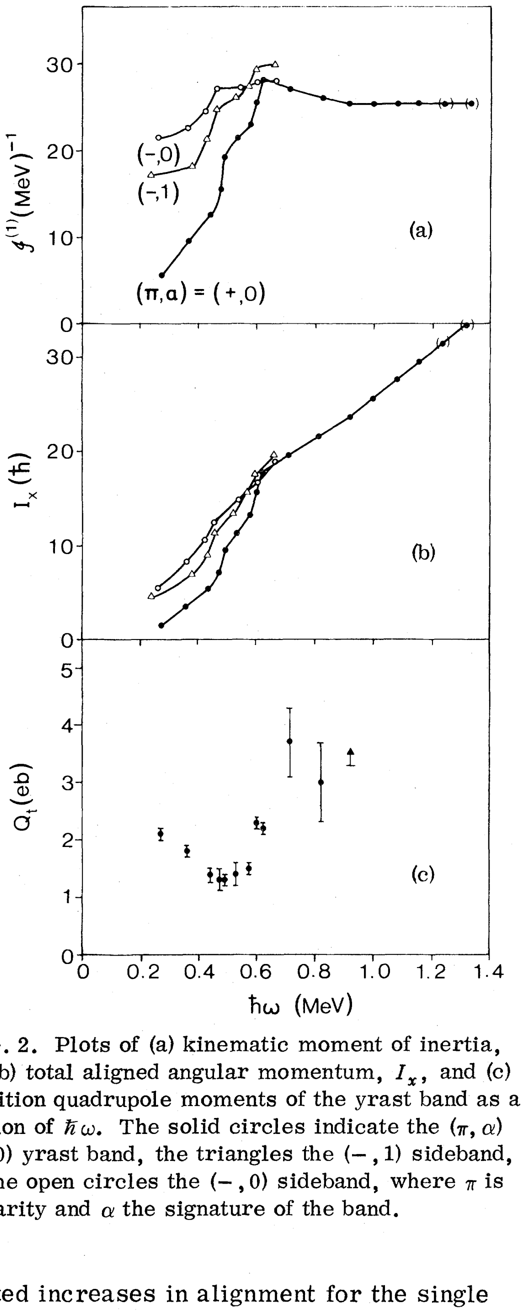

FIG. 2. Plots of (a) kinematic moment of inertia, $\mathcal{J}^{(1)}$, (b) total aligned angular momentum, I_x, and (c) transition quadrupole moments of the yrast band as a function of $\hbar\omega$. The solid circles indicate the $(\pi, \alpha) = (+, 0)$ yrast band, the triangles the $(-, 1)$ sideband, and the open circles the $(-, 0)$ sideband, where π is the parity and α the signature of the band.

culated increases in alignment for the single crossing in ^{80}Kr and ^{82}Sr was attributed to the neglect of the γ degree of freedom.[8] The calculations suggest, then, that the experimentally observed upbends in the ^{84}Zr yrast sequence are caused by the alignments of two $g_{9/2}$ quasiprotons followed by two $g_{9/2}$ quasineutrons.

The extent of the present results beyond the second crossing in the yrast band is unique. In this high-frequency regime, beyond $\hbar\omega = 0.9$ MeV, a striking change in the behavior of the nucleus occurs. The previously rapid variation of $\mathcal{J}^{(1)}$ with frequency decreases and it stabilizes to a value of 25.5 MeV^{-1}. This then remains constant to better than 1% over a frequency range of almost 0.5 MeV, an angular momentum range of $10\hbar$. The aligned angular momentum I_x varies linearly with frequency and extrapolates back to $I_x \approx 0.5\hbar$ at $\hbar\omega = 0$. The dynamic moment of inertia $\mathcal{J}^{(2)} = \Delta I_x/\Delta\omega$ is also constant in this frequency range and almost equal to the kinematic moment of inertia $\mathcal{J}^{(1)}$. Such an effect has recently been observed[9] in the nucleus ^{168}Hf although in that case the moment of inertia is less than the rigid value. At frequencies greater than 0.9 MeV, then, ^{84}Zr behaves not only as a good rotor but the properties are those of rigid rotation. Certainly the combination of high rotational frequency, the fact that both protons and neutrons have undergone a band crossing, and the proximity of the deformed shell gap at $N = Z = 38$ would favor the elimination of the pairing gaps for both the protons and the neutrons.

A change also occurs in the transition quadrupole moments which, beyond the second crossing, increase to 3.5 ± 0.5 $e\cdot$b on average. Clearly a change in the nuclear shape has occurred at these high rotational frequencies. For a rigidly rotating nucleus the transition quadrupole moment can be represented by the expression

$$Q_t = [3/(5\pi)^{1/2}]\, ZeR_0^2\beta \cos(30+\gamma)/\cos 30,$$

and the moment of inertia[10] by

$$\mathcal{J}^{(1)} = \tfrac{2}{5}AR_0^2[1 - (5/4\pi)^{1/2}\beta\cos(120+\gamma)]$$

with $R_0 = 1.2A^{1/3}$ fm, to first order in β. With the above expressions, values of β and γ allowed by the experimental measurements, $Q_t = 3.5 \pm 0.5$ $e\cdot$b and $\mathcal{J}^{(1)} = 25.5 \pm 0.3$ MeV^{-1}, are shown in Fig. 3. As can be seen, consistency occurs for shape parameters of $\beta = 0.43 \pm 0.06$ and $\gamma = 3° \pm 6°$. Thus the results are consistent with the rotation of an axially symmetric body in the absence of pairing. Corrections to the lifetimes of the high-spin states due to unobserved feeding would result in an increase in their transition rates and hence the deformation parameters.

We must consider, however, the situation if the moment of inertia has not as yet reached the rigid-body value. Experimentally, if $\mathcal{J}^{(1)} < \mathcal{J}_{\rm rigid}$, the nucleus must have a much more deformed shape in order to explain the transition-rate data. For example, for $\mathcal{J}^{(1)}/\mathcal{J}_{\rm rigid} = 0.8$ shape parameters of $\beta = 0.79$ and $\gamma = 33°$ are implied. Such a large deformation is certainly not expected to constitute a stable nuclear configuration.

In summary, two upbends in the yrast sequence

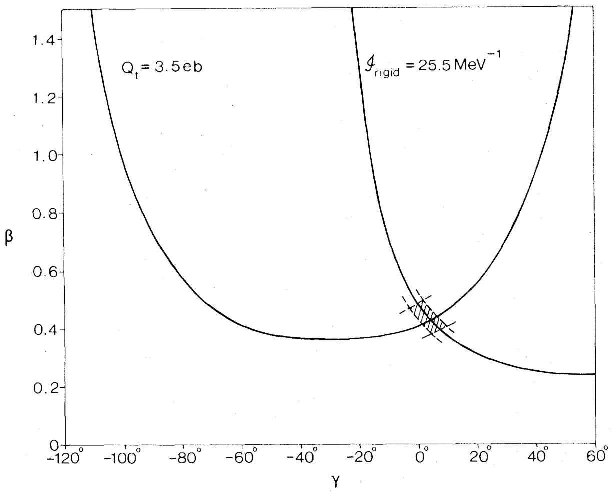

FIG. 3. A plot of β vs γ giving a transition quadrupole moment of 3.5 ± 0.5 $e \cdot$b and moment of inertia of 25.5 ± 0.3 MeV^{-1} for a rigid body. The range of values for β and γ due to the errors on Q_t and $\mathcal{J}_{rigid}$ are shown as the cross-hatched area.

of ^{84}Zr have been observed and attributed to the alignment of two $g_{9/2}$ quasiprotons followed by the alignment of two $g_{9/2}$ quasineutrons. After the second alignment a transition to classical rotational behavior is observed, experimentally compatible with the rotation of an axially symmetric nucleus having $\beta = 0.43 \pm 0.06$, $\gamma = 3° \pm 6°$, and the rigid-body moment of inertia. This is the first observation of such behavior.

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[1]P. Möller and J. R. Nix, At. Data Nucl. Data Tables 26, 165 (1981).
[2]C. J. Lister, B. J. Varley, H. G. Price, and J. W. Olness, Phys. Rev. Lett. 49, 308 (1982).
[3]R. B. Piercey *et al.*, Phys. Rev. Lett. 47, 1514 (1981)
[4]P. J. Twin *et al.*, Verh. Dtsch. Phys. Ges. 16, 747 (1981), and to be published.
[5]S. Åberg, Phys. Scr. 25, 23 (1982).
[6]A. S. Davydov and G. F. Filippov, Nucl. Phys. 8, 237 (1958).
[7]J. Panqueva *et al.*, Nucl. Phys. A389, 424 (1982).
[8]L. Funke *et al.*, Nucl. Phys. A355, 228 (1981); L. Funke *et al.*, Phys. Lett. 108B, 243 (1982); L. Funke *et al.*, Phys. Lett. 120B, 301 (1983).
[9]J. C. Lisle *et al.*, private communication.
[10]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II.