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BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Rotational bands with identical transition energies in actinide nuclei

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We point out the existence of ground-state rotational bands with identical transition energies (up to spin $8\hbar$) in ^{240}Pu, ^{244}Cm, ^{246}Cm, and ^{250}Cf. The corresponding transitions in the ground-state bands of ^{236}U and ^{238}U have identical energies (within ~ 2 keV) up to spin $24\hbar$. These features are very similar to those recently observed for superdeformed bands in the mass-150 and mass-190 regions and suggest that the phenomenon of identical bands is not restricted to superdeformed bands.

Since the discovery [1] of a superdeformed rotational band in ^{152}Dy, more than 30 such rotational bands have been observed in the mass-150 and mass-190 regions [2,3]. One striking and unexpected feature [2] of these bands is that, in several instances, transitions in the superdeformed bands of nearby nuclei have almost identical energies within ~ 2 keV [4–6]. The occurrence of identical bands in neighboring even-even nuclei requires that the moments of inertia in the two bands be identical. The identical bands in the neighboring even-even and odd-A nuclei require identical moments of inertia and some additional property to compensate for different spins (integers and half-integers) in the rotational formula. Explanations of these observations have been discussed in terms of the strong-coupling limit of the particle-rotor model [7,8]. In the case of the $A \sim 150$ region, the pseudo-spin-coupling scheme [8] has been invoked. Bands with identical energies in neighboring nuclei are not expected to occur on the basis of general arguments. For example, γ-ray energies should scale with the moment of inertia $\mathcal{J}$, which is proportional to $A^{5/3}$ for a rigid body, so that adjacent mass nuclei would have energies different by 14 keV in the $A \sim 150$ and 5 keV in the $A \sim 190$ region. The $A^{5/3}$ rigid-rotor dependence of the moment of inertia is a zeroth-order estimate. Changes in deformation with mass, orbital alignment effects, and/or changes in pairing produce changes in moment of inertia which depart from this simple estimate.

In this Brief Report, we point out that the observation of identical moments of inertia, while surprising, is perhaps not as unique as previously thought. We have found identical transitions in the ground-state bands of neighboring nuclei with normal deformation. These identical bands are ground-state bands of even-even actinide nuclei, where the spins and relevant orbitals are well established. The data are taken from the literature, but to our knowledge, the identical transition energies presented here have not been pointed out before.

The two known large regions of well-deformed nuclei are the rare earths and actinides. In both regions, as one moves away from closed neutron and proton shells, deformation (as deduced from the quadrupole moments) and moments of inertia (as deduced from the energies of the first 2^+ state) increase. For nuclei with a half-filled shell, it has been well established that the deformation reaches a maximum and remains practically constant for a range of nuclei before decreasing. The region of nuclides where the deformation saturates will be larger when the magic numbers are farther apart. Here the shells are large, there are many close-lying orbitals in the middle of the shell occupied by the nucleons, and addition or removal of a few particles does not change the shape of the system appreciably. Thus one would expect to see more nuclei with constant deformation in the actinide region than in the rare earths.

The energy of the rotational first $I^\pi = 2^+$ level provides a good indication of the nuclear deformation and the moment of inertia, as shown by the systematics of Grodzins [9]. In the actinide region, the deformation for known nuclei heavier than ^{234}U remains practically constant [10–12]. The lowest energy (42.1 keV) for a 2^+ state occurs in the ^{242}Cm nucleus [13]. Thus ^{242}Cm has the largest moment of inertia, and nuclei around it should have similar deformation and moments of inertia. Indeed, in several of these nuclei, the rotational energies are found [13,14] to be identical in the respective ground-state bands; these are shown in Fig. 1. The identical energies of corresponding levels show that ^{240}Pu, ^{244}Cm, ^{246}Cm, and ^{250}Cf have identical moments of inertia, and at least up to $I = 8$, there is no variation at all, in

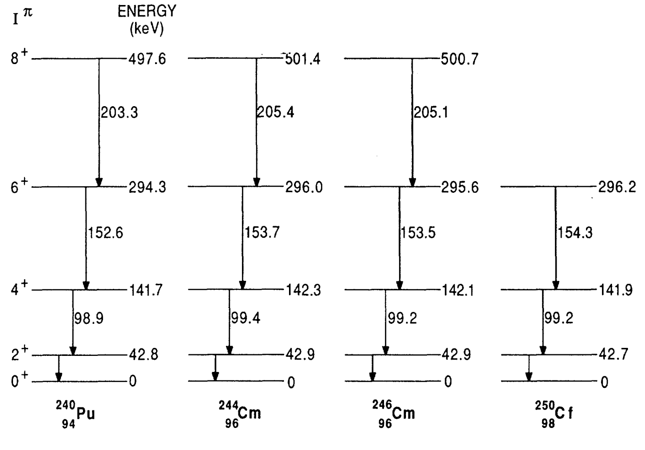

FIG. 1. Known levels [13,14] in ground-state bands of ^{240}Pu, ^{244}Cm, ^{246}Cm, and ^{250}Cf. The β_2 deformations of ^{240}Pu, ^{244}Cm, and ^{246}Cm are 0.248(8), 0.284(11), and 0.286(11), respectively [12].

contrast to general expectations.

For odd-mass nuclei in this region, the moment of inertia for an orbital not appreciably affected by Coriolis mixing is ~15% larger than the value for the neighboring even-even nuclei. This difference is understood in terms of the reduction in pair correlations due to the unpaired nucleon. This feature is quite different from the situation in superdeformed nuclei, where the neighboring odd and even nuclei have identical moments of inertia in a number of cases. In addition, in the superdeformed nuclei, the ground band in one nucleus and the excited band in the neighboring nucleus have identical moments of inertia, whereas in the present case only ground bands display this feature.

Calculations of moments of inertia have been performed for actinide nuclei by Brack *et al.* [15] using the quasiparticle formalism. These calculations reproduce the observed moments of inertia within 10% only. For example, the ratios of theoretical moments of inertia to experimental values of 1.11 (^{236}U), 1.00 (^{238}U), 0.96 (^{240}Pu), 1.00 (^{244}Cm), 1.10 (^{246}Cm), and 0.89 (^{250}Cf) have been reported. In these calculations the moments of inertia were shown to be very sensitive to the pairing interaction, which was not adjusted to reproduce the moments of inertia. The calculations indicate that it is difficult to reproduce the moments of inertia to the experimental accuracy for the ground-state bands, let alone for the superdeformed bands.

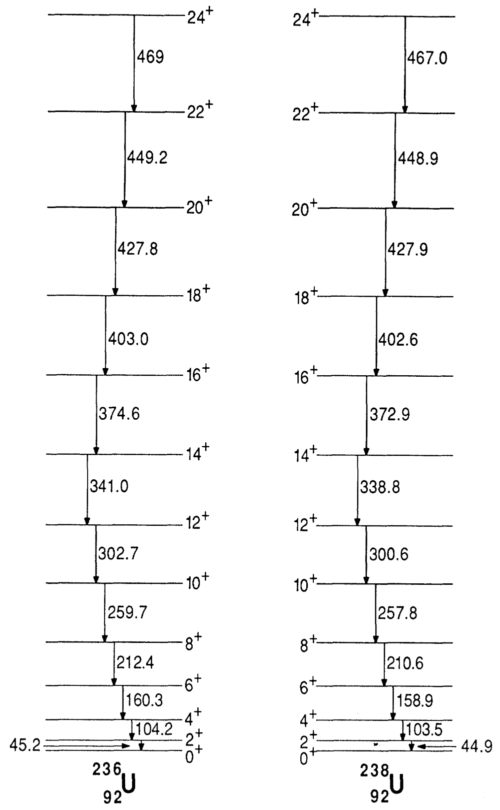

FIG. 2. Known levels [17,18] in the ground-state bands of ^{236}U and ^{238}U. The measured β_2 deformations of ^{236}U and ^{238}U are 0.232(7) and 0.253(7), respectively [12].

States with spin higher than $8\hbar$ have not been observed in the nuclei shown in Fig. 1. These nuclei are difficult to produce by (charged particle, *xn*) fusion reactions and the available structure information comes from radioactive decay studies. However, high-spin states in ^{232}Th [16,17], ^{234,236,238}U [17,18], ^{242,244}Pu [19], and ^{248}Cm [20] have been identified in Coulomb excitation studies. A look at the levels in these nuclei shows that corresponding transitions in ^{236}U and ^{238}U have identical energies over a wide range of spin. The levels in these two nuclei are displayed in Fig. 2, and the difference between the transition energies is shown in Fig. 3. The energy differences ΔE_γ are identical within ~2 keV for all transitions up to spin $24\hbar$, i.e., over 12 transitions, quite similar to those observed in the superdeformed bands. Above spin $24\hbar$, the transition energies in these two nuclei do not agree, and we have not shown them in this figure. The deviation at higher spins is caused by the alignment under rotation of $j_{15/2}$ neutrons and $i_{13/2}$ protons [21]. It is interesting to note that these two orbitals play an essential role in stabilizing the superdeformed shape in the

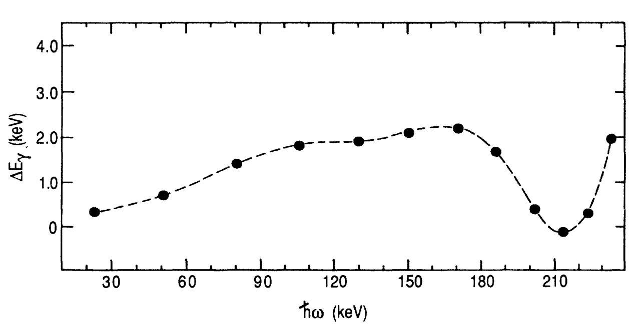

FIG. 3. Plot of energy difference ΔE between the corresponding transitions of ^{236}U and ^{238}U against the rotational frequency ($\hbar\omega = E\gamma/2$), as deduced from the data in Fig. 2.

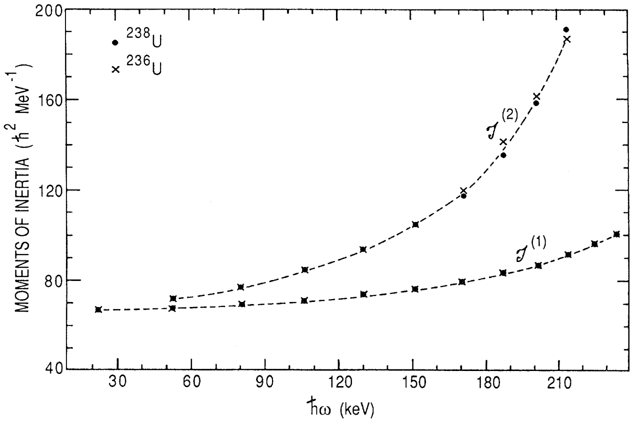

FIG. 4. Plot of static moment of inertia $\mathcal{J}^{(1)}$ and dynamic moment of inertia $\mathcal{J}^{(2)}$ against the rotational frequency, deduced from the data in Fig. 2. $\mathcal{J}^{(1)}=(2I-1)\hbar^2/E\gamma, \mathcal{J}^{(2)}=4\hbar^2/\Delta E$.

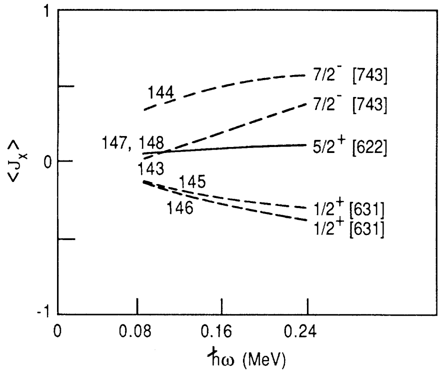

FIG. 5. Calculated alignments for neutron orbitals near Fermi surface in ^{236}U and ^{238}U. The asymptotic quantum numbers of the orbitals at $\omega=0$ are also indicated. The number on the left side of the curve indicates the neutron number filling that orbit.

$A \sim 190$ nuclei [3,7]. The static and dynamic moments of inertia $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$, derived from the level energies of Fig. 2, are plotted against the rotational frequency in Fig. 4. The similarities are striking, although the frequency range covered in the two uranium nuclei is smaller than that observed in the superdeformed nuclei. (The moments of inertia for known uranium isotopes were also plotted against the rotational frequency by Dudek, Nazarewicz, and Szymanski [22] and were discussed in terms of the Mottelson-Valatin effect.)

The occurrence of identical bands and the moments of inertia of ground-state bands in the rare-earth region have recently been discussed [23–25]. In Ref. [25] it was found that the kinematic moments of inertia of many nuclei, as derived from the respective 22^+-20^+ transition energies, actually agree within 5%. This agreement is much better than that expected on the basis of an $A^{5/3}$ mass dependence, which varies by ~40% for the range of masses considered in the evaluation of Ref. [25]. This observation has been tentatively explained [6,25] in terms of cancellation of the effects of deformation changes and orbital alignments. Similar effects could produce constant moments of inertia in the ground-state bands of the actinide nuclei.

We note certain similarities between the neutron orbitals associated with the identical bands in the superdeformed Hg region and with the actinides at the normal deformation. In both cases there is a large gap in the single-particle spectrum just before the region of identical bands starts. In the Hg nuclei, there is a large gap [26] at $N=112$, and in the actinides [10] there is a gap at $N=142$. Just above the gap in the Hg region [3], there are several orbitals with small values [3,27] of $\langle J_x \rangle$. Using a potential parametrization given previously [28], we have calculated the alignments associated with neutron orbitals near the Fermi surface in ^{236}U and ^{238}U, and these are shown in Fig. 5. As the figure shows, the alignment for the $\frac{5}{2}^+[622]$ orbital is quite small. The alignments for the $\frac{7}{2}^-[743]$ and $\frac{1}{2}^+[631]$ orbitals are not so small individually, but the two sets of orbitals should be filling together almost equally and the net change for $\langle J_x \rangle$ is indeed small.

Variations in the moment of inertia between neighboring nuclei are caused [6] by changes in deformation, pairing, orbital alignment, and mass ($A^{5/3}$ dependence). As shown above, the changes in alignment are likely to be small. Thus the changes in deformation and pairing between ^{236}U and ^{238}U are most likely small and counteract the mass-dependent term (which is 1.4%) to produce identical moments of inertia.

In conclusion, we emphasize the occurrence of identical ground-state bands in the actinide region. The importance of these identical bands is that the single-particle states are well characterized at normal deformation (much more so than in the superdeformed bands), and hence there is a better chance of understanding the underlying physics in these identical bands. They provide an ideal first test for calculations which attempt to explain identical bands.

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