# First Observation of Backbending in an Actinide Nucleus

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(Received 18 August 1983)

The yrast bands in $^{242}$Pu and $^{244}$Pu have been studied up to spin $26^+$ by Coulomb excitation using $^{208}$Pb beams of 5.1 and 5.3 MeV/u. In the case of $^{244}$Pu a pronounced backbending has been observed for the first time in an actinide nucleus. Microscopic calculations are presented which indicate that the observed anomalies in the yrast sequences of both nuclei are due to alignment effects in the $i_{13/2}$ proton shell.

PACS numbers: 21.10.Re, 25.70.Cd, 27.90.+b

Our understanding of the structure of heavy nuclei has been influenced decisively by the discovery of the backbending effect[1] and its subsequent experimental and theoretical investigations.[2] These irregularities occur in the yrast sequences of many deformed nuclei in particular in the lanthanide region. It was therefore rather surprising that in our investigation of the high-spin states of the equally strongly deformed actinide nuclei $^{232}$Th, $^{234,236,238}$U, and $^{248}$Cm by Coulomb excitation with $^{208}$Pb projectiles, no pronounced backbending effect could be observed.[3-6] In these nuclei the ground-state band was investigated up to spin $30^+$ corresponding to a rotational frequency of 270 keV. Thus the spin as well as the frequency at which the backbending occurs in the lanthanides had been exceeded considerably in these experiments without observing any strong irregularity.

It is generally accepted that the backbending effect is caused by the rotational alignment of high angular momentum orbitals due to the Coriolis interaction.[7] In the actinide region the $i_{13/2}$ proton and the $j_{15/2}$ neutron shells are both in the vicinity of the Fermi surface and can thus easily align. Indeed, the measured increase of the $g$ factor of the yrast state in $^{232}$Th and $^{238}$U with increasing spin can be attributed to an increasing contribution of the magnetic moment of an aligned $i_{13/2}$ proton pair to the magnetic moment produced by the rotating core.[8] From the study of the energy spectra of the odd nuclei $^{235}$U and $^{237}$Np it can also be deduced that the $i_{13/2}$ proton alignment plays an important role in the structure of high-spin states of the actinide nuclei.[9] However, a backbending effect is only expected in case the interaction between the ground-state band ($g$ band) and the two-quasiparticle aligned band ($s$ band) is sufficiently weak. As the calculated strength of the interaction shows a periodicity in proton (neutron) number with two subsequent minima being about 6 (10) units apart,[10-12] the nonoccurrence of a strong backbending in the actinide isotropes studied so far might thus result from the fortuitous circumstance that all nuclei investigated so far exhibit a strong interaction between the $g$ band and the $s$ band. Actually the series of the $_{90}$Th, $_{92}$U and $_{96}$Cm isotopes spans a range of $\Delta Z = 6$, i.e., at least one oscillation in the interaction strength; consequently, the intermediate $_{94}$Pu isotopes not yet investigated are favorable candidates for an observation of backbending.

We investigated the high-spin states of $^{242}$Pu and $^{244}$Pu by bombarding enriched $^{242}$Pu and $^{244}$Pu targets[13] of 0.31 mg/cm$^2$ and 0.25 mg/cm$^2$ with $^{208}$Pb beams of 5.1 MeV/u and 5.3 MeV/u. The deexcitation $\gamma$ rays were observed in three Ge detectors located at angles of 30° and ±150° relative to the beam (and an additional two NaI detectors) in coincidence with the recoiling Pu nuclei and the scattered Pb projectiles, which were detected in two position-sensitive avalanche detectors, covering an angular range of $17° \leq \vartheta \leq 58°$ and $-52° \geq \vartheta \geq -88°$, respectively. For center-of-mass scattering angles of 95° to 146° it was possible to distinguish the Pb from the Pu ions by their kinematical angular correlation. Our particle-$\gamma$-coincidence apparatus allows the correction of the large Doppler shift caused by the high recoil velocities and the determination of cross sections over a wide range of impact parameters. For an absolute calibration of the transition energies for both nuclei (in the Pu rest system) the energies in the ground band of $^{242}$Pu, previously known with a sufficient accuracy up to $I^\pi = 8^+$, were used.[14] A detailed description of the experimental method is given in Ref. 3.

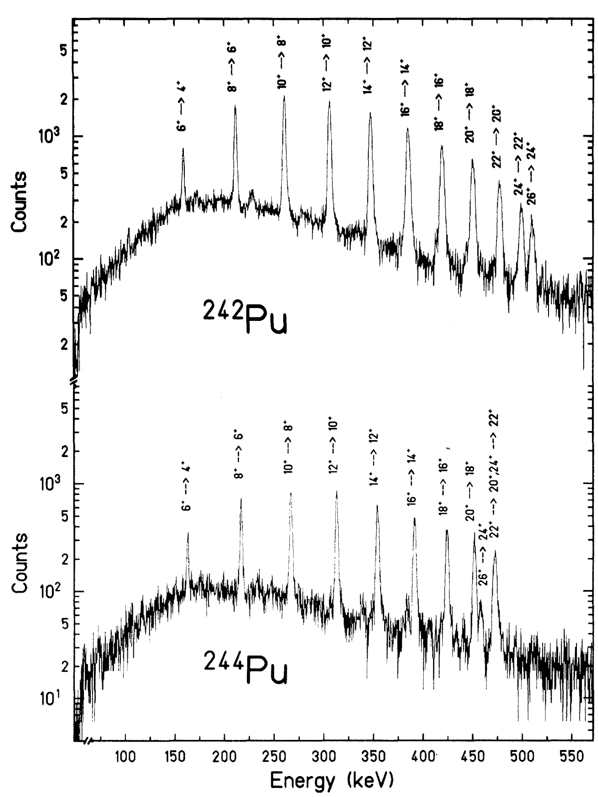


FIG. 1. The Doppler-shift–corrected $\gamma$ spectra following the Coulomb excitation of $^{242}$Pu and $^{244}$Pb ions. The spectra were obtained for c.m. scattering angles $100° \leq \theta \leq 146°$, adding the runs performed at the two beam energies of 5.1 and 5.3 MeV/u.

The Doppler-corrected $\gamma$-ray spectra resulting from the excitation of the two isotopes are shown in Fig. 1. The spin assignments have been obtained from the systematic impact-parameter dependence of the $\gamma$-ray yields, from the particle-$\gamma$ directional correlation, and from $\gamma$-multiplicity measurements. For $^{242}$Pu the yrast transitions could be assigned up to spin $I^\pi = 26^+$. For $^{244}$Pu the yrast sequence seems to terminate at spin $22^+$; however, the intensity of this peak is 30% higher than the intensity of the $20^+$ (and still 4% higher than the intensity of the $18^+$) and its width is larger by a factor of 1.5. Both facts indicate an unresolved doublet, which was assigned to the $22^+ \to 20^+$ and $24^+ \to 22^+$ transitions. The sum of the two intensities as inferred from a smooth extrapolation from the low-spin states accounts well, within the errors, for the measured peak intensity. The peak just above the $20^+ \to 18^+$ transition is identified as a transition between high-spin states because of its characteristic impact-parameter dependence, and it is tentatively assigned to the $26^+ \to 24^+$ transition. The resulting transition energies for $^{242}$Pu and $^{244}$Pu are given in Table I and are shown in Fig. 2 in an $I$ versus $\omega$ plot. At low spins the data show the familiar

TABLE I. Transition energies $E_\gamma = E_I - E_{I-2}$ between the yrast states for $^{242}$Pu and $^{244}$Pu.

| | $^{242}$Pu | | | $^{244}$Pu | | |
|---|---|---|---|---|---|---|
| $I$ | $E_\gamma$ (keV) | a | b | $E_\gamma$ (keV) | a | b |
| 2 | 44.5 | ± 0.1[c] | | 46.0 | ± 2.0[d] | |
| 4 | 102.8 | ± 0.1[c] | | 110.0 | ± 2.0[d] | |
| 6 | 158.7 | ± 0.4 | ± 0.2 | 162.4 | ± 0.4 | ± 0.3 |
| 8 | 211.7 | ± 0.4 | ± 0.2 | 216.4 | ± 0.4 | ± 0.3 |
| 10 | 260.5 | ± 0.6 | ± 0.3 | 266.5 | ± 0.6 | ± 0.3 |
| 12 | 305.8 | ± 0.8 | ± 0.3 | 312.4 | ± 0.8 | ± 0.3 |
| 14 | 347.3 | ± 1.0 | ± 0.3 | 353.7 | ± 1.0 | ± 0.4 |
| 16 | 385.0 | ± 1.1 | ± 0.4 | 391.0 | ± 1.1 | ± 0.4 |
| 18 | 419.3 | ± 1.2 | ± 0.4 | 423.8 | ± 1.2 | ± 0.4 |
| 20 | 450.2 | ± 1.3 | ± 0.5 | 451.5 | ± 1.4 | ± 0.5 |
| 22 | 477.2 | ± 1.4 | ± 0.5 | 472.0 | ± 2.5 | ± 1.5 |
| 24 | 499.2 | ± 1.5 | ± 0.5 | 472.0 | ± 2.5 | ± 1.5 |
| 26 | 510.0 | ± 1.5 | ± 0.6 | 457.7 | ± 1.4 | ± 0.5 |

[a]Absolute errors (keV). [c]From Ref. 14.
[b]Relative errors (keV). [d]From Ref. 15.

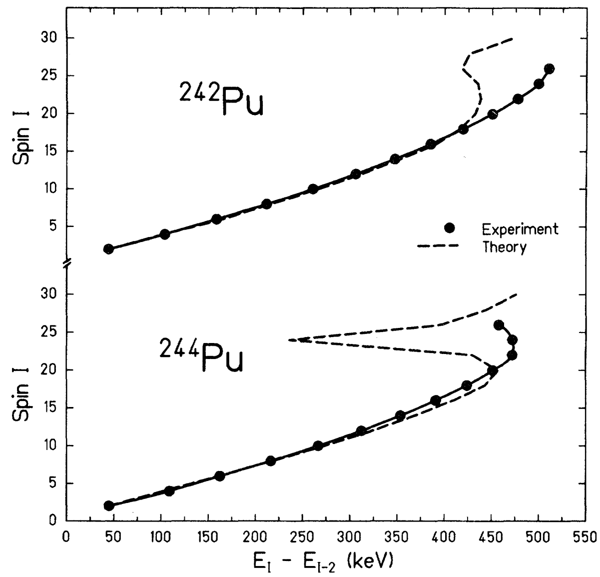


FIG. 2. Plot of the spin vs the experimental transition energies (solid line). The dashed line represents the result of the model calculation discussed in the text.

smooth increase of the spin with the rotational frequency $2\hbar\omega = E_I - E_{I-2}$. However, while $^{242}$Pu shows an upbending at $\hbar\omega \simeq 250$ keV, a pronounced backbending is observed for $^{244}$Pu at $\hbar\omega \simeq 230$ keV.

To get a quantitative understanding for the observed anomalous behavior of the yrast lines in $^{242,244}$Pu we performed a microscopic calculation as described in detail in Egido and Ring.[16] For these calculations the spherical single-particle energies are taken from Gustafson *et al.*[17] and the deformation and gap parameters $(\beta_i, \Delta_\tau)$ were deduced from experiment[18] and from the odd-even mass differences: We used $\beta_2 = 0.292$, $\beta_4 = 0.041$, $\Delta_p = 0.805$ MeV, $\Delta_n = 0.580$ MeV for $^{242}$Pu; $\beta_2 = 0.307$, $\beta_4 = -0.016$, $\Delta_p = 0.882$ MeV, $\Delta_n = 0.570$ MeV for $^{244}$Pu. The constant moments of inertia $J_c$ for the core were adjusted to the experimental $2^{\pm}$ levels. The comparison of the experimental and theoretical transition energies is shown in Fig. 2. The calculations predict backbending in $^{242}$Pu and $^{244}$Pu at spins $24^+$ and $22^+$, respectively, the calculated effect being somewhat more pronounced than actually observed. For the other actinide nuclei studied so far the calculations predict[16] only a washed out irregularity at these frequencies in agreement with the experimental findings.[3-6]

To discuss the relative importance of proton and neutron alignment we also calculated the aligned angular momenta for protons and neutrons separately. From this calculation it is obvious that the backbending in both Pu isotopes is caused by proton alignment whereas in the critical region between $I^\pi = 22^+$ and $I^\pi = 28^+$ the neutron alignment is very small. This interpretation is in agreement with Ref. 11 where it is shown that the interaction strength between the ground-state band and the band of an aligned pair of $i_{13/2}$ protons has a minimum close to $Z = 94$.

In summary, a strong backbending effect—the first observed in the actinide nuclei—has been found in $^{244}$Pu; in the neighboring $^{242}$Pu isotope the irregularity is less pronounced but still clearly seen. The effect can be assigned to the sudden alignment of protons out of the $i_{13/2}$ shell under the influence of the Coriolis force.

We would like to thank H. Folger for his assistance in the preparation and handling of the Pu targets. We also acknowledge the effort of the UNILAC crew to produce the $^{208}$Pb beam which made these experiments possible. The authors are indebted to the Office of Basic Energy Science, U. S. Department of Energy, and the transplutonium-element production facility at Oak Ridge National Laboratory for the use of the plutonium isotopes.

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