Spectroscopy in the Second Minimum of the Potential Energy Surface of ^{239}Pu

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Conversion electrons from the decay of a spin isomer in the secondary minimum of ^{239}Pu have been measured. They are interpreted as transitions feeding and depopulating a rotational band built on the fission isomeric ground state with spin $\frac{5}{2}$. Rotational parameters of $A = 3.36 \pm 0.10$ keV and $B = 4 \pm 3$ eV have been deduced. The observed upper limit on the $M1/E2$ mixing ratio of 1.4 suggests an antiparallel coupling between orbital angular momentum and spin vectors for the wave function of the fission isomer.

Up to now single-particle models have not been crucially tested at large deformations of shape isomers ($\beta = 0.6$). Earlier attempts to identify single-particle states were based on measurements of fission-fragment angular distributions[1] and g factors[2] of the fissioning isomers in ^{237}Pu. This Letter reports on the identification of states in the second minimum of ^{239}Pu by observing conversion electrons feeding and depopulating the rotational band built on the fission isomeric state. Delayed feeding occurs from a $T_{1/2} = 2.6^{+4.0}_{-1.2}$ ns spin isomer which on the average emits 1.6 conversion electrons in its decay to the 8-μs fission isomer.[3] From the energies and the $M1/E2$ mixing ratio of the rotational transitions the spin and single-particle configuration of the fission isomer can be inferred. With the use of this information a more accurate value for the quadrupole moment is derived from previous charge-plunger measurements.[4]

Conversion electrons are measured with a solenoid spectrometer applying the recoil-shadow technique.[5] The experimental arrangement is shown in Fig. 1. The ^{239}Pu nuclei, excited to the 2.6-ns spin isomeric state via the reaction ^{238}U(α, $3n$), recoil out of the target, and the conversion electrons emitted in flight in the decay of the spin isomer are transported through the magnetic field to a Si(Li) detector with a transmission of 12%. The recoil nuclei, then in the ground state of the second minimum, are stopped on a catcher foil and their subsequent fission decay is registered in the annular detector with an efficiency of $\approx 30\%$. A converted transition in the second minimum is identified by requiring a delayed coincidence between the electron and fission detector. By placing the target 1.5 mm upstream and within the hole of the annular detector, the electron counter is shielded from δ electrons as well as shielding the ring detector from prompt fission events occurring in the target. To allow the in-beam detection of electrons with energies as low as 4 keV, an accelerating voltage of -5 kV is applied to the target region. A potential barrier of -7 kV relative to the ground potential prevents electrons with less than 2 keV energy from reaching the detector. In order to minimize the chance-coincidence background (particularly severe because of the 8 μs half-life of the fission isomer) the 33-MeV α beam provided by the Heidelberg MP-tandem Van de Graaff is reduced to 300 nA. With the use of a 100-μg/cm^2 ^{238}U target typical count rates are 6000 counts per second in the electron detector and 0.6 counts per second in the delayed-fission detector. In the total accumulation time of 150 h, 4000 true coinci-

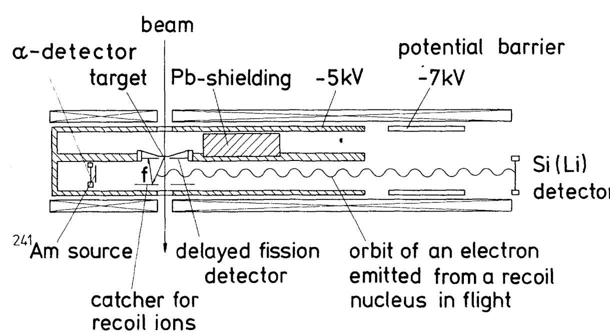

FIG. 1. Experimental setup. The drawing is not to scale. The distance between target and Si(Li) detector is 45 cm. The longitudinal baffle and the Pb shielding prevent detection of prompt electrons and γ rays from the target while delayed electrons emitted in flight can reach the detector.

dences have been recorded.

The electron energy calibration is obtained online from electrons following the α decay of a ^{241}Am source. The overall energy resolution is 1.2 keV.

The electron spectrum in delayed coincidence with fission fragments is shown in Fig. 2. The spectral shape of the chance-coincidence background [solid curve in Fig. 2(a)] is taken from the accurately measured singles electron spectrum and its absolute magnitude has been determined from the time spectrum with an accuracy of 1.5%. The inset shows the decay curve for electrons with energies between 3.5 and 31 keV after correction for accidental coincidences. It is consistent with the known 8-μs half-life of the fission isomer and thereby proves that the observed electrons are from transitions in the second minimum of ^{239}Pu. From the energy and intensity requirements for the L, M, and N conversion we have identified two strong $E2(M1)$ transitions with energies of 24.3 and 31.9 keV, respectively. Furthermore, this assignment is supported by the existence of a crossover transition with $E_\gamma = 56.2$ keV. Although this interpretation is not unique, it gives by far the best fit to the data of all the possibilities conconsidered, within the restriction of on the average only 1.6 converted transitions per spin isomer decay.

The relative intensities of $L_{\rm I} + L_{\rm II}$ to $L_{\rm III}$ conversion lines for the 56.2-keV transition are consistent with a pure $E2$ multipolarity while a comparison of the corresponding components for the 31.9-keV transition gives an upper limit of 1.4 for the $M1/E2$ mixing ratio after correcting for internal conversion. The multipolarity of the 23.4-keV transition cannot be determined since the $L_{\rm I} + L_{\rm II}$ component is below the cutoff at 4 keV.

After tentatively arranging these two levels in

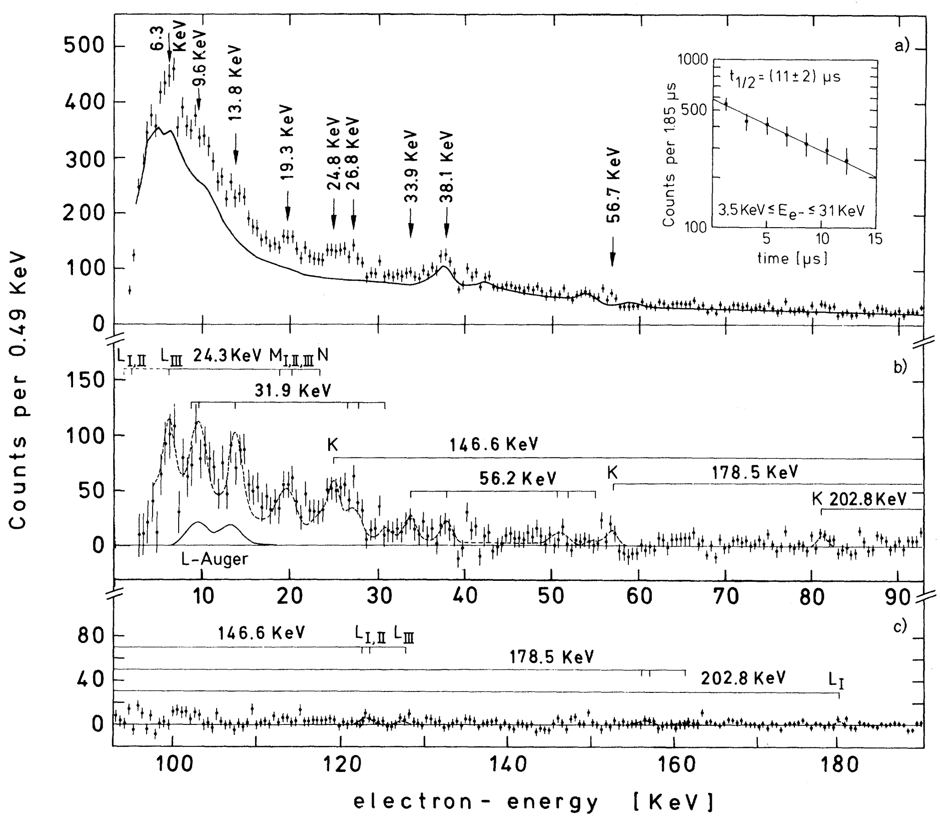

FIG. 2. Spectrum of electrons measured in delayed coincidence with fission. (a) Raw data in the range from 3 to 90 keV. Peaks in the background arise from the ^{241}Am source. (b),(c) The electron spectrum corrected for random coincidences in the range from 3 to 190 keV. The dashed curve represents the fit to the data as discussed in the text. The position of the K, L, M, and N components of the different transitions are indicated. The curve denoted L-Auger is our estimate for the intensity and spectral distribution of Auger electrons which is included in the fit.

a decay scheme (Fig. 3) where the sequence is suggested by the relative intensities of the respective transitions, the spectrum has been searched for possible feeding transitions. Considering again the average of only 1.6 converted transitions per decay of the spin isomer, the feeding transitions can only be partially converted, thus ruling out $M1$ or $E2$ transitions unless the energies are larger than 250 keV or their observed intensities are weak. The strong, remaining intensity at $E_e = 24.8$ keV may therefore be explained as the K conversion line of a 146-keV feeding transition of $E1$ character which is converted to only 22%. There are weak indications of additional feeding transitions at 179 and 203 keV. All three lines would fit energetically into a decay scheme in which the spin iosmer is located at an excitation energy of 203 keV.

The level scheme in Fig. 3 suggests interpreting the three low-energy transitions as cascade and crossover transitions within a rotational band. The rotational energy expansion

$$E_I - E_K = AI(I+1) + BI^2(I+1)^2$$

involves three unknown parameters: the spin $I_0 = K$ of the fission isomer, the rotational constant $A = \hbar^2/2\theta$ related to the moment of inertia θ, and the coefficient B of the second-order term describing the perturbation of the band. If one assumes spins of $\frac{3}{2}$ to $\frac{11}{3}$ for the fission isomer, a fit of the observed transition energies yields the values of A and B listed in Table I. Previous measurements of the rotational band structure in the second minimum give rotational constants $A = 3.343 \pm 0.003$ keV for ^{240}Pu (Ref. 6) and

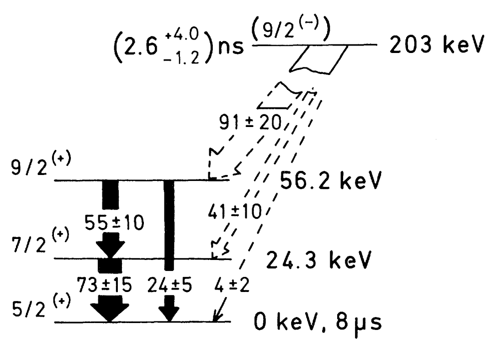

FIG. 3. Proposed decay shceme of the 2.6-ns isomer. The intensities of the feeding transitions are corrected for internal conversion assuming multipolarities of $E1$ (147, 179 keV) and $M2$ (203 keV). The positive parity of the $\frac{5}{2}$ state is suggested by comparison with theory. No $\frac{5}{2}^-$ state is predicted close to the Fermi surface.

$A = 3.36 \pm 0.01$ keV for ^{236}U (Ref. 7). The small value of $B = -0.28 \pm 0.04$ eV reported[6] for ^{240}Pu is in accordance with predictions of a very adiabatic rotation for strongly deformed nuclei. For states in the first minimum an increase in the moment of inertia of the order of up to 20% is generally observed between even and odd nuclei apart from a few exceptional cases due to specific single-particle states. Taking this odd-even variation and the experimental results for even-even nuclei into account, $I_0 = \frac{5}{2}$ giving $A = 3.36 \pm 0.10$ keV and the smallest distortion parameter $B = 4 \pm 3$ eV seems to be the only possible spin of the fission isomer. Theoretically, the relative odd-even difference in the moment of inertia is actually expected to be much smaller for the second minimum (by approximately a factor 6) since the spacing of the relevant single-particle states is about three times larger[6,7] than at the first minimum. This estimate is confirmed by calculations of Hamamoto[8] who finds, using a Woods-Saxon potential, moments of inertia for odd-mass nuclei at the deformation of the second minimum which exceed the even-even values by less than 3% in agreement with our experimental result.

From the upper limit of the $M1$ admixture of 60% one finds that $|g_K - g_R|/Q_0 < 8 \times 10^{-3}\ \mathrm{b}^{-1}$. A reanalysis of the charge-plunger data[4] on this fission isomer using $K = \frac{5}{2}$ and the observed mixing ratio yields a value for the quadrupole moment of $Q_0 = (36 \pm 4)$ b and therefore $|g_K - g_R| \leq 0.30$. This implies that the coupling between spin and orbital angular momentum vectors of the fission isomeric state has to be antiparallel. A parallel coupling should result in a value for $|g_K - g_R| \approx 0.90$. The only single-particle orbit with $I = \frac{5}{2}$ and orbital angular momentum projection $\Lambda = 3$ which has been predicted to lie close to the Fermi surface for $N = 145$ at a deformation $\beta \simeq 0.6$ is the state $[633]\frac{5}{2}^+$ only found in the single-particle spectrum of Hamamoto and Ogle[9]

TABLE I. Rotational parameters deduced from fitting the observed transition energies assuming different values for the spin of the fission isomeric state.

I	A (keV)	B (eV)
3/2	5.17±0.11	−25±6
5/2	3.36±0.10	4±3
7/2	2.30±0.10	10±2
9/2	1.61±0.11	10±2
11/2	1.09±0.09	9±1

who have used a spin-orbit force increased by 20% compared to other calculations. They note, however, that this state is strongly mixed with the [862]$\frac{5}{2}^+$ orbit. Since the latter is an orbit with low Ω and large j, it is particularly sensitive to Coriolis mixing and may explain the observed distortion of the band. The measured limit on $|g_K - g_R|$, however, allows only an admixture of up to 40% of any component of the wave function with spin and orbital angular momentum vectors parallel.

Since the feeding transition to the $\frac{9}{2}^+$ rotational member is most likely of $E1$ character, the spin of the excited state must be $\frac{7}{2}^-$ or $\frac{9}{2}^-$. The observed reduced branching ratios are in disagreement with intensities calculated for three K-allowed $E1$ transitions.[10] The decay of the spin isomer is thus either intrinsically forbidden or its spin and parity is $\frac{9}{2}^-$. A likely candidate would then be the [734]$\frac{9}{2}^-$ orbit.[9] This makes the main decay from the isomer a once K-forbidden $E1$ transition with a hindrance factor of 10^5 and the decay to the ground state would then be an $M2$ transition of single-particle strength.

Applying improved detection techniques, the rotational band built upon the fission isomeric state in an odd-even nucleus has been observed for the first time. The spin of the 8-μs fission isomer in ^{239}Pu is found to be $\frac{5}{2}$. Comparison with theory suggests the assignment of the [633]$\frac{5}{2}^+$ orbit which is found close to the Fermi surface only in one of numerous calculations, indicating that the spin-orbit force may have to be increased with deformation. Measurements of this kind thus provide really sensitive tests of the single-particle potentials underlying Strutinsky-type calculations of fission barriers.

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Second Irregularity in the Yrast Line of ^{160}Yb

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Yrast states of ^{160}Yb with spins up to $30\hbar$ were identified in the reaction ^{148}Sm(^{16}O,$4n\gamma$). In addition to an initial backbend at $I=12\hbar$, a second backbend occurs at $I=28\hbar$. This result is discussed in terms of recently proposed explanations of the backbending effect.

A large amount of new information allowing one to follow the rotational bands of many deformed nuclei up to levels with spin reaching $I\approx 20\hbar$ has been provided during the last few years. Recently,[1] it was even possible to observe higher-lying discrete yrast transitions in the ^{158}Er nucleus and to see, in addition to the first backbending previously established, a second discontinuity at $I=28\hbar$.

Several mechanisms have been proposed to ex-

