Lowest β-Vibrational Phonon in the Second Minima of ^{236,238}U

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(Received 1 March 1982)

Conversion electrons from electromagnetic transitions preceding the fission decay of the shape isomers ^{236,238}U have been measured. For both isomers highly converted transitions are observed which are tentatively interpreted as the decay of the lowest β-vibrational band, via $E0$ transitions, at excitation energies of 686.0 ± 0.7 and 647.8 ± 0.9 keV, respectively.

PACS numbers: 21.10.Re, 23.20.Nx, 27.90.+b

A consistent picture of fission isomers as strongly deformed shape isomers has been established by detailed measurements of excitation energies and half lives of their rotational states as well as their quadrupole moments.[1] Only indirect and, to some extent, model-dependent information is available on higher-lying vibrational excitations of fission isomers as derived from resonances in subbarrier fission probabilities.[2-4] This Letter reports on the first direct observation of the lowest β-vibrational band in the second minimum of ^{236,238}U, using conversion electron spectroscopy.

As illustrated in Fig. 1, conversion electrons from transitions preceding the fission decay of the shape isomer were measured with a solenoid spectrometer.[5] After emission of the prompt conversion electrons nuclei in the fission isomeric state recoil from the thin target. Their subsequent spontaneous fission decay is registered with two surface-barrier detectors carefully shielded against prompt fission products from the target. The prompt electrons are transported by the magnetic field to two Si(Li) detectors mounted 45 cm away from the target. With the field distribution (Fig. 1) serving as a magnetic mirror, all electrons emitted within $\pm 120°$ relative to the solenoid axis move towards the electron detectors. The target and the electron detectors are mounted parallel to the magnetic field. The distance of 8 mm between the two detectors allows for a sufficient suppression of δ electrons produced in the target; guided by the magnetic field these low-energy electrons spiral into the space between the two detectors. The total peak detection efficiency for both detectors is 17% of 4π in an energy range from 200 to 600 keV with a sharp cutoff by orders of magnitude for low-energy (≤ 100 keV) electrons.

A converted transition in the second minimum is identified by requiring a delayed coincidence between the electron and the fission detectors. With 60-μg/cm^2 targets of ^{236,238}U and a deuteron beam of about 600 nA provided by the Heidelberg MP tandem Van de Graaff accelerator, typical count rates were $(2-3)\times 10^4$ s^{-1} in the electron detectors, and 0.1–0.2 s^{-1} in the delayed fission detectors. For both isotopes, a total number of 1090 and 560 true delayed coincidence events were recorded in accumulation times of 94 and 50 h, respectively.

Figure 2 shows the electron spectra for both isotopes measured in delayed coincidence with fission. The contributions from chance coincidence events are indicated by the solid lines. Their spectral shape was taken from the accurately measured singles electron spectrum, and the absolute intensity was determined from the time spectra. In order to demonstrate that the observed electron lines result from transitions in the second minimum of ^{236,238}U, the time spectra

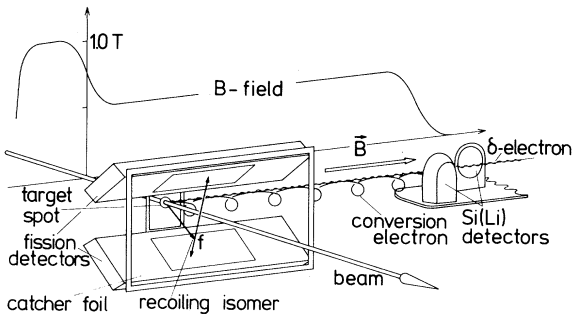

FIG. 1. Experimental setup in the solenoid spectrometer.

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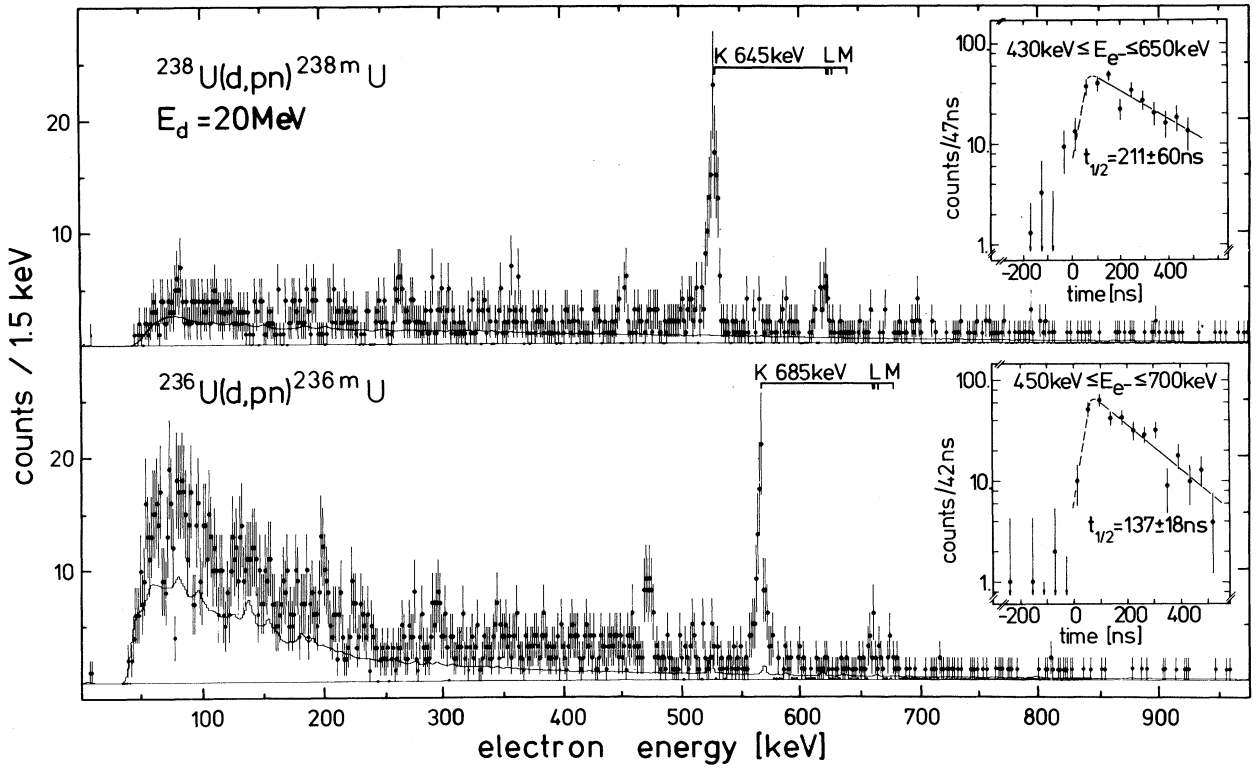

FIG. 2. Energy spectra of electrons in coincidence with the delayed fission decay of the shape isomers ^{236,238}U. Insets: time spectra of the coincidences for the specified region of electron energies.

for electrons in the energy region of the dominant conversion lines are shown as insets. The observed decay times are in agreement with the known half-lives of the ^{236,238}U fission isomers of 116 and 195 ns,[6] respectively. The time resolution is ≈ 10 ns, mainly determined by differences in flight paths of the electrons.

The statistically most significant structures in the electron spectra are lines at 569 and 664 keV for ^{236}U, and 529 and 624 keV for ^{238}U, with widths approximately twice as large as the experimental resolution of 3.4 and 4.5 keV, respectively (Table I). Because of their energy spacing and relative intensities, we interpret these lines as K and L conversion-electron lines associated with transitions of 685 and 645 keV. In both spectra, indications exist for additional transitions, but the statistics are too poor to justify any further interpretation.

The intensities of the K lines, corrected for detection efficiency, are comparable to transitions observed within the rotational bands[1] based on the fission isomer, and consequently require strongly converted transitions, most probably of $E0$ multipolarity at those transition energies. Considering the decay of any nuclear level to the ground-state rotational band, one would expect, on the basis of other known decay schemes, at least

TABLE I. Average transition energy E, width [full width at half maximum (FWHM)], energy resolution, K_e intensity, and experimental K/L ratios. For the most important multipolarities, the theoretical K/L ratios and the total number of transitions $N_{tot} = N_\gamma + N_e^-$ per delayed fission (DF) required to reproduce the observed intensities of the K lines of the two isomers are also given.

	^{236}U	^{238}U
E	684.5 ± 0.7 keV	645.2 ± 0.9 keV
FWHM	7.1 keV	8.6 keV
Resolution	3.4 keV	4.5 keV
K_e^-/DF	$(2.0 \pm 0.3) \times 10^{-2}$	$(3.5 \pm 0.4) \times 10^{-2}$
K/L^{exp}	4.7 ± 1.4	4.8 ± 1.2

Multipolarities	K/L	$10^2(N_\gamma + N_e^-)$/DF ^{236}U	^{238}U
$E0$	5.3	2.4	4.3
$E1$	5.7	370	550
$E2$	2.9	125	200
$M1$	5.2	23	35
$M2$	4.2	9.5	14

two transitions of comparable intensity, with an energy spacing equal to that of the first rotational states (20 keV). Such a doublet structure is not observed in the spectra of Fig. 2. However, in the case of an $E0$ transition, the competing $E2$ transition is relatively suppressed, because of the small $E2$ conversion coefficient of less than 2×10^{-2}. Furthermore, as summarized in Table I, multipolarities other than $E0$ require unrealistic or at least unusually large population probabilities of the decaying level to be consistent with the observed intensities. Although anomalously large conversion coefficients have been observed[7] for $E1$ transitions in the actinide region, this multipolarity can be excluded since it implies a doublet structure in the spectrum.

Usually, the multipolarity of a converted transition can be determined by the K/L ratio. Our limited statistics, however, does not allow an assignment by this method. Only pure $E2$ transitions seem to be inconsistent with the experimental K/L ratios.

The detection efficiency for electrons depends strongly on the position of their emission, which in turn is related to the half-life of the transition by the velocity of the recoiling isomer (0.2–0.4 mm/ns). Consequently, further restrictions on the multipolarity of the transitions can be obtained from the upper limit on the half-lives of the observed transitions of roughly 10 to 20 ns. This eliminates possible $E3$ or $M3$ and—with less confidence—$M2$ transitions.

In view of all these arguments, the most likely multipolarity of the observed transitions is $E0$. Their interpretation as the decay of the lowest β-vibrational band in the second well, illustrated in Fig. 3, is based on the comparison with the electron spectra of the first well which were recorded simultaneously and will be published elsewhere.[9] At ground-state deformation, the decay of the β band to the ground-state rotational band occurs via five resolved $E0$ transitions assigned to $0_\beta^+ \rightarrow 0_g^+$ up to $8_\beta^+ \rightarrow 8_g^+$.[9,10] If the moments of inertia in the two bands of the second minimum were nearly the same, one could understand the measured K-L patterns as the superposition of several transitions nearly degenerate in energy. If we assume the same intensity distribution in the second and first well, a comparison of the widths of the observed K lines with the experimental resolution and the supposed decay pattern yields a difference $\Delta A = |A_g - A_\beta|$ of 0.2–0.4 keV between the two rotational constants. If $A_g > A_\beta$ as is usually the case, the deduced moments of inertia

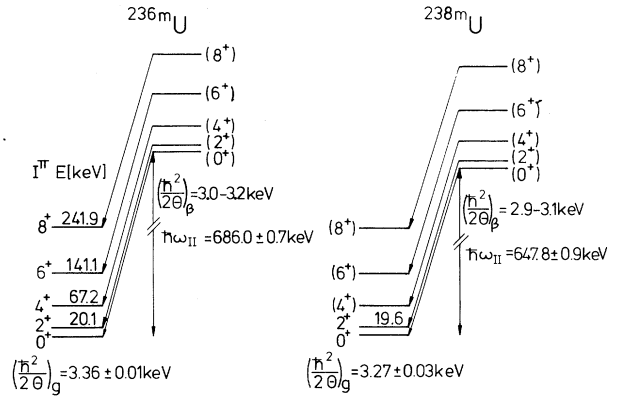

FIG. 3. The proposed decay of the β band in the second minimum via unresolved $E0$ transitions in analogy to the decay scheme of states in the first minimum. The competing $E2$ transitions are suppressed by the conversion coefficient and are therefore not drawn in the figure. (The excitation energies of the rotational states are taken from Refs. 1 and 8.)

of the β bands correspond to roughly 85% of the value for rigid rotation at the deformation of the second minimum. The phonon energies $\hbar\omega_{II}$ themselves are determined to be 686.0 ± 0.7 and 647.8 ± 0.9 keV for ^{236,238}U, respectively.

An interpretation of the $K=0^+$ bands in the actinides in terms of a simple vibrational model is difficult in view of the ambiguous character of these bands.[11] In such a model, only the ratio of the stiffness C of the potential and the mass parameter B is determined via $\hbar\omega_{II}=\hbar(C/B)^{1/2}$ and no values for the parameters C and B can be extracted separately. The mass parameter B is expected to decrease with deformation and to approach the reduced mass for two separated fission fragments.[12] Strutinski-type calculations[13] show a strong modulation of this dependence as a result of shell effects. The mass parameter calculated for ^{240}Pu decreases by a factor of about 1.7 from the first to the second minimum. With this theoretical prediction and our values for $\hbar\omega_{II}$, a stiffness C that is 3–4 times smaller in the second minimum than in the first is derived. The calculation[13] indeed roughly shows such a behavior of the potential energy with respect to the β-deformation degree of freedom.

The parameters B and C also determine the $B(E2)$ values of the vibrational transitions via $B(E2)\sim(C*B)^{-1/2}$. The above estimates for C and B give $B(E2,0_g^+\rightarrow2_\beta^+)$ values which are about 2–3 times larger in the second minimum than in the first (roughly 3 single-particle units compared to about 1.2 single-particle units[14]). Thus,

the vibrational transitions of the shape isomers seem to be slightly more collective.

In summary, we have identified the lowest β bands of the shape isomers in ^{236,238}U by direct observation of their decays via converted transitions. Other vibrational excitations such as, e.g., the octupole band have not been observed, since they decay via weakly converted transitions ($E1$) to which the present experiment is not sensitive. In the future it may be feasible to study the γ decay of these vibrations with an efficient 4π detector system such as a NaI crystal-ball spectrometer.

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