Photoexcitation of low-lying dipole transitions in ^{236}U

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(Received 1 December 1989)

Nuclear resonance fluorescence experiments have been performed on the deformed actinide nucleus ^{236}U. Bremsstrahlung of 3.9 MeV endpoint energy has been used as the photon source. The scattered photons were detected by three high resolution Ge-γ-spectrometers installed at scattering angles of 92°, 128°, and 150°, respectively. Precise excitation energies, decay branching ratios, and ground state decay widths of numerous previously unknown spin 1 states in the excitation energy range 1.8–3.2 MeV have been extracted. The dipole strength has been found to be concentrated in the energy range 2.1–2.5 MeV. The systematics of the so-called *scissors mode* observed as a result of the previous (γ,γ') and (e,e′) experiments on ^{232}Th and ^{238}U and, in particular, their combined analysis suggests likewise to attribute these new dipole excitations in ^{236}U to the orbital M1 scissors mode.

The discovery of a new low-lying magnetic dipole excitation in the deformed nucleus ^{156}Gd by Richter and co-workers[1] stimulated a large amount of both theoretical and experimental work (see, e.g., Refs. 2,3). The systematics of this predominantly orbital $M1$ excitation, commonly called *scissors mode*, has been established by numerous electron scattering (see, e.g., Ref. 2) and photon scattering experiments (see, e.g., Ref. 4) on rare earth nuclei. Furthermore, this collective $M1$ mode has been detected in the other island of deformed nuclei, the mass region of the actinide isotopes.[5] In spite of the increased difficulties in both photon and electron scattering experiments on these heavy nuclei, our previous (γ,γ') and (e,e′) experiments and their powerful combined analysis[5] succeeded in showing that this mode seems to be a rather general phenomenon in deformed nuclei. The two actinide isotopes investigated until now, ^{232}Th and ^{238}U, exhibit quite different strength distributions. Whereas ^{238}U shows two groups of states, whose strengths are concentrated at ≈2.2 MeV and ≈2.5 MeV, the strength of the low energy group in ^{232}Th is gathered in *one* strong excitation at 2.043 MeV and the higher lying group is centered at about 2.2 MeV. It was the aim of the present experiments to investigate a nucleus in between ^{232}Th and ^{238}U to establish a more extended systematics of the $M1$ scissors mode in the actinide mass region. The isotope ^{236}U has been chosen since it has a rather long half-life of 2.34×10^7 a and consequently can be handled even in quantities of several grams without severe safety problems.

The nuclear resonance fluorescence (NRF) experiments have been performed at the bremsstrahlung facility installed at the Stuttgart Dynamitron accelerator.[6] This accelerator provides a very intense CW electron beam with a maximum current of $\leq$4 mA at energies up to 4.3 MeV. The electron beam is bent by 120° and focused onto a water cooled gold radiator target (thickness ≈3 g/cm^2). A 98 cm long lead collimator selects a well defined bremsstrahlung beam of an intensity of some $10^9\gamma$/sec MeV at energies around 3 MeV. The target consisted of pressed discs of enriched uranium oxide sandwiched by Al foils. The target composition was ^{236}U (89.38%); ^{238}U (1.306%); ^{235}U (9.2%); ^{234}U (0.11%); ^{233}U (0.002%). Well known transitions[7] in ^{27}Al served for the absolute calibration of the photon flux. For the spectral shape of the low energy, thick target bremsstrahlung spectrum a linear shape near the endpoint energy E_0 has been assumed. This assumption has been checked by measurements of the bremsstrahlung spectra using a composite target consisting of different isotopes with known transitions [8] *and* by Monte Carlo simulations using the program GEANT 3.[9] The energy and efficiency calibration of the three Ge-γ spectrometers installed at scattering angles of 92°, 128°, and 150°, respectively, has been performed using a ^{56}Co source emitting γ quanta of various energies up to 3.5 MeV. The bremsstrahlung facility and the detector arrangements are described in detail in Ref. 6.

The following quantities can be extracted from our NRF experiments[10]: The measured energy spectra of the scattered photons deliver precise excitation energies. The observed intensities directly yield the ratios Γ_0^2/Γ (Γ_0 and Γ are the ground state and total widths, respectively) and hence the reduced transition probabilities $B(\lambda L)\uparrow$. The angular distributions allow unambiguous spin assignments. In the favorable case of an even-even nucleus it is only necessary to measure at two scattering angles. The intensity ratios $W(92°)/W(128°)$ amount to 0.73 and 2.0 for pure dipole and quadrupole cascades, respectively. These values are slightly reduced for realistic geometries used in the experiments. From the measured branching ratio for the decay of the excited levels to the first excited 2^+ rotational state and to the ground state the K quantum number of the excited state can be extracted within the validity of the Alaga Rules.[11] Furthermore, due to the well known excitation energy of the first 2^+ state (45.2 keV) an ***unambiguous*** assignment of the observed transitions to the isotope ^{236}U is possible.

Figure 1 shows a typical pulse height spectrum as measured in the ^{236}U(γ,γ') experiments at the facility in Stuttgart (bremsstrahlung endpoint energy E_0= 3.9 MeV). The spectrum is dominated by the 2.614 MeV line (^{208}Pb) and its single escape peak at 2.103 MeV resulting from a ^{232}U impurity ($\leq 10^{-5}$; $T_{1/2}$ =70 a) in the target and its daughter decays within the corresponding decay chain, finally feeding the first excited state in ^{208}Pb (E=2614 keV; $J^\pi = 3^-$). The shoulder in the pulse height spectrum near 2.35 MeV stems from the Compton continuum produced by the 2.614 MeV ^{208}Pb transition. Besides the ^{27}Al calibration lines numerous peaks are evident in the excitation energy range 1.8–3.2 MeV, which all can be attributed to the isotope ^{236}U.

The results of the angular distribution measurements for all ground state transitions [intensity ratios $W(92°)/W(128°)$] are summarized in Fig. 2. All observed ground state transitions belonging to ^{236}U are of dipole character, except for a weak $E2$ transition at 2924 keV.

In Table I the results for the excitation energies, the

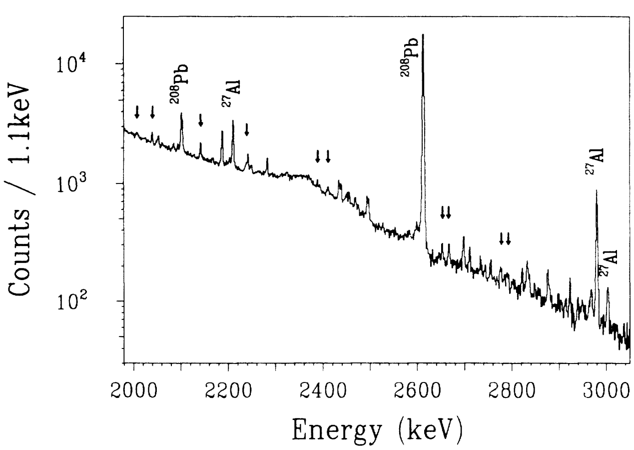

FIG. 1. ^{236}U(γ,γ') spectrum measured at the Stuttgart bremsstrahlung facility (E_0 = 3.9 MeV). The lines marked by ^{208}Pb originate from the feeding of the 3^- state in ^{208}Pb within the decay chain of the target impurity ^{232}U (see text). The lines marked by ^{27}Al are used as internal standards. All other visible lines can be attributed to ^{236}U (see text). Arrows mark transitions corresponding to inelastic photon scattering off ^{236}U (transitions to the first 2^+ state).

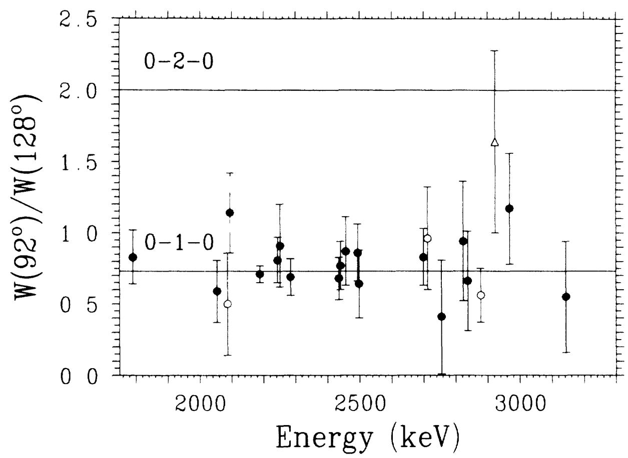

FIG. 2. Intensity ratios $W(\theta = 92°)/W(\theta = 128°)$ for all transitions given in Table I together with the expected values for pure dipole and quadrupole cascades, respectively (spin sequences 0-1-0 and 0-2-0). •: ΔK=1 dipole transitions; o: ΔK=0 dipole transitions; △: quadrupole transition (tentative $E2$ assignment).

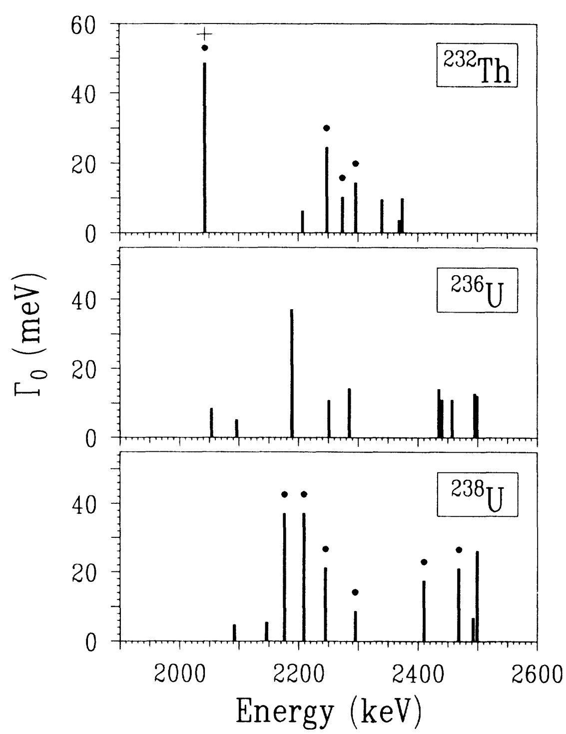

FIG. 3. Dipole strength distribution (ΔK = 1 transitions) in ^{236}U in comparison with the results recently obtained for ^{232}Th and ^{238}U.[5] For transitions marked by (•) and (+) the parities have been determined experimentally in recent (e,e′) experiments[5] and linear polarization measurements,[12] respectively.

TABLE I. Experimental results on low-lying excitations in ^{236}U obtained in the present photon scattering work. The quoted excitation energies have a systematic uncertainty of ≈1 keV. Details are given in the text.

Energy (keV)	Γ_0^2/Γ (meV)	$\frac{W(92°)}{W(128°)}$	R	K	J	Γ_0 [a] (meV)	$B(M1)\uparrow$ (μ_N^2)	$B(E1)\uparrow$ ($10^{-3}\,e^2\mathrm{fm}^2$)
1791.3	5.7±0.7	0.83±0.19	0.41±0.09	1	1	8.3±1.1	0.38±0.05	
2054.2	4.6±0.6	0.59±0.22	0.81±0.15	1	1	8.5±1.3	0.25±0.04	
2087.0	3.1±0.7	0.50±0.36	1.78±0.37	0	1	8.4±2.1		2.64±0.66
2095.7	3.3±0.7	1.14±0.28	0.51±0.16	1	1	5.2±1.2	0.15±0.03	
2188.8	23.6±2.0	0.71±0.06	0.53±0.03	1	1	37.0±3.2	0.92±0.09	
2243.9	8.7±0.9	0.81±0.16	0		1	9.1±1.0		
2251.1	5.0±0.7	0.91±0.29	1.12±0.15	(1)	1	10.9±1.7	0.25±0.04	
2284.7	9.0±1.0	0.69±0.13	0.54±0.07	1	1	14.3±1.7	0.31±0.04	
2435.6	10.0±1.1	0.68±0.15	0.36±0.07	1	1	14.1±1.7	0.25±0.03	
2440.2	8.3±1.0	0.77±0.17	0.28±0.08	1	1	11.0±1.4	0.19±0.03	
2457.3	7.0±0.9	0.87±0.24	0.53±0.09	1	1	11.0±1.6	0.21±0.03	
2494.5	9.4±1.2	0.86±0.20	0.31±0.08	1	1	12.8±1.8	0.21±0.03	
2498.5	7.0±1.0	0.64±0.24	0.69±0.13	1	1	12.2±2.0	0.20±0.03	
2699.0	8.9±1.3	0.83±0.20	0.55±0.11	1	1	14.3±2.3	0.19±0.03	
2712.1	3.2±0.6	0.96±0.36	2.18±0.41	0	1	9.7±2.1		1.40±0.30
2756.2	3.9±0.9	0.41±0.40	0.58±0.17	1	1	6.3±1.6	0.08±0.02	
2823.3	4.8±1.1	0.94±0.42	1.02±0.27	1	1	9.8±2.6	0.11±0.03	
2838.3	3.5±0.8	0.66±0.35	1.14±0.34	(1)	1	7.6±2.2	0.09±0.03	
2877.8	4.4±0.8	0.56±0.19	2.10±0.41	0	1	13.1±3.0		1.58±0.36
2924.0	2.4±0.6	1.64±0.64	1.54±0.44 [b]		(2)	5.8±1.8		
2969.0	7.8±1.7	1.17±0.39	0.52±0.12	1	1	12.3±2.8	0.12±0.03	
3143.8	11.3±1.9	0.55±0.39	0.58±0.14	1	1	18.4±3.5	0.15±0.03	

[a] For 1^+ levels an additional decay branching to higher lying excited states of 5% , not to be detected in the present experiments, has been assumed in the extraction of the ground state decay width Γ_0, following the arguments given in Ref. 6.
[b] The branching ratio for this tentatively assigned 2^+ state is calculated as $R = (\Gamma_{2^+}/\Gamma_{0^+})(E_{\gamma_{0^+}}/E_{\gamma_{2^+}})^5$.

ratio Γ_0^2/Γ, the angular distributions, and the branching ratios $R = (\Gamma_{2^+}/\Gamma_{0^+})(E_{\gamma_{0^+}}/E_{\gamma_{2^+}})^3$ are summarized and the spin and K assignments are given together with the deduced ground state widths and the reduced transition probabilities. Most of the observed dipole transitions have been unknown until now. A negative parity ($E1$ multipolarity) has been assigned to $\Delta K = 0$ transitions, a positive parity ($M1$ multipolarity) has been *assumed* for $\Delta K = 1$ transitions in the energy range of the orbital $M1$ excitations as observed in the previous work[5] on the neighbor isotopes ^{232}Th and ^{238}U.

In Fig. 3 the strengths of these excitations are compared with those observed in ^{232}Th and ^{238}U. Not only does the dipole strength distribution in ^{236}U fit nicely into the systematics, but also its splitting into two groups of states is evident, with nearly the same separation in energy of ≈250 keV as in ^{232}Th and ^{238}U. Furthermore, the summed total $B(M1)\uparrow$ strength in ^{236}U, assuming a positive parity for all observed $\Delta K = 1$ dipole transitions in this energy range (see Table I), amounts to $(2.94\pm0.23)\mu_N^2$ and is comparable to the results for ^{232}Th $[(2.58 \pm 0.25)\mu_N^2]$ and ^{238}U $[(3.19 \pm 0.24)\mu_N^2]$.[5] For the transitions in ^{232}Th and ^{238}U marked by full dots in Fig. 3 the positive parity and the orbital character of the $M1$ excitations have been established by electron scattering form factor measurements.[5] The reliability of these assignments furthermore has been confirmed for the strong 2.043 MeV transition in ^{232}Th by measurements of the linear polarization of the scattered photons using Compton polarimeters.[12] However, until now no parities have been determined for the dipole excitations in ^{236}U. The tentative positive parity assignments are entirely based on the systematics of the $M1$ "scissors mode" as shown in Fig. 3. Therefore, it should be emphasized that polarization measurements and electron scattering data are highly desirable for definite parity assignments and a deeper insight into the nuclear structure of the observed strong low-lying dipole excitations.

The authors thank Prof. K.-W. Hoffmann and his collaborators for the warm hospitality at the Institut für Strahlenphysik at Stuttgart University and their kind support during the experiments. The financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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