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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(80)90725-X

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
1980

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Janssens, RVF., Jansen, JFW., Emery, GT., Hageman, DCJM., & Lukasiak, J. (1980). High-spin states in 232U investigated with the 232Th(α, 4nγ) reaction. Physics Letters B, 90(3), 209-213. https://doi.org/10.1016/0370-2693(80)90725-X

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HIGH-SPIN STATES IN ^{232}U INVESTIGATED WITH THE ^{232}Th(α, 4nγ) REACTION

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Received 10 December 1979

The ground-state rotational band of ^{232}U is established up to $I^{\pi} = 16^+$ (tentatively 18^+) through a study of the ^{232}Th(α, 4nγ) reaction. Conversion electron spectroscopy is found to be especially useful in circumventing the difficulties caused by strong fission competition.

During the last decade nuclear states of high angular momentum, particularly the yrast states, have been the subject of numerous investigations. For well-deformed nuclei in the rare-earth region many cases of irregular ground-state band rotational-level spacings have been reported (including many cases of "backbending"), and the role of rotation-particle coupling in their interpretation has been recognized [1]. The behaviour of yrast or ground-band levels in strongly-deformed actinide nuclei is much less well established. The usual technique of in-beam γ-ray spectroscopy with (α,xn) or (HI,xn) reactions becomes much more difficult, if not prohibitive, for actinide nuclei due to strong competition from fission. The only information currently available on high-spin yrast levels in such nuclei comes from multiple Coulomb excitation experiments and concerns nuclei as ^{238}U and ^{232}Th. For ^{238}U the excitation energies and decay properties of the levels of the ground-state band were studied up to the 22^+ (and perhaps 24^+) level through Coulomb excitation by Kr and Xe ions [2], and these measurements have recently been extended by the use of ^{208}Pb beams [3]. In ^{232}Th the ground-state band is known up to 18^+, also through Kr and Xe Coulomb excitation [4].

For other nuclei in the actinide region only relatively low-spin states are known from studies of radioactive decay, neutron capture, and direct reactions. For ^{232}U, for example, the ground-state band is known up to 6^+ from work on ^{236}Pu α-decay and ^{232}Np electron capture [5]. The peak value of the ^{232}Th(α, 4n) reaction cross section at about 40 MeV is $\approx$55 mb, while the fission cross section at that energy is about 1.3 b [6]. A few years ago, additional transitions have been tentatively assigned to the ^{232}U ground-state band on the basis of an (α, 4nγ) experiment with a fission anticoincidence detector [7], though no information was obtained about the multipolarity and coincidence relationships of the transitions.

In the present work we show that contrary to the widely held belief, it is possible to investigate high-spin states in ^{232}U by in-beam gamma- and conversion-electron spectroscopy. Our results were obtained without a fission anticoincidence requirement, but include γ–γ coincidence spectra. We found that conversion electron spectra showed much more favourable peak-to-background ratios than the corresponding γ-ray spectra. This feature may be useful in further studies of nuclear structure with compound nucleus reactions in cases where there is a strong competition with fission channels.

Self-supporting metallic thorium targets of 0.9 and 2.0 mg/cm^2 were bombarded with external α-particle beams from the KVI cyclotron at energies of 40 and 44 MeV. Gamma-rays were detected with two 17% efficient Ge(Li) detectors, and conversion

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electrons with a Si(Li) detector (FWHM: 1.8 keV at 600 keV) coupled to the magnetic filter of a mini-orange spectrometer [8]. Gamma- and electron spectra were registered in coincidence with the beam bursts as well as in singles mode. Gamma–gamma and gamma–conversion electron coincidences were recorded as four-parameter events ($E_1, E_2, \Delta t_{12}, \Delta t_{1,\text{beam burst}}$).

The mini-orange spectrometer is characterized by high transmission over a limited energy window, with a typical width $\Delta E/E = 0.4$. The position and width of the transmission window depends on the type and number of magnets used, as well as on the distance between the magnetic filter and the detector. Wedge-shaped $SmCo_5$ magnets of the B-type [8] were mounted in three different configurations. The magnet–detector distance was varied from 20 to 82 mm to shift the transmission window to the various regions of interest. The transmission curves needed for the analysis of the electron spectra were deduced from two separate measurements. During the on-line experiments the Th target was interchanged with a ^{160}Gd target, and well-known [9] transitions in ^{160}Dy, following the ^{160}Gd(α, 4nγ) reaction, were used for relative transmission calibration. This procedure was repeated for all mini-orange configurations used. The response was further checked off-line with the β-ray continuum of a thin ^{137}Cs source. The two sets of results for the transmissions were in good agreement. The mini-orange spectrometer was placed at an angle of 135° with respect to the beam.

A singles γ-ray spectrum taken at $E_\alpha = 40$ MeV, is shown in fig. 1a. Discrete lines assigned to the ground-state band of ^{232}U are hardly visible in the presence of a high background and numerous discrete lines attributed mainly to prompt fission events. Nevertheless, gates were placed on the γ-ray lines at 109 and 166 keV, known [5] to be the $4^+ \to 2^+$ and $6^+ \to 4^+$ transitions in ^{232}U, and on the adjacent background. The net γ–γ coincidence spectra showed the presence of higher lines in the ground-state band. Similar spectra were then generated for gates placed on the new lines observed in the primary coincidence data. The sum of all net γ–γ coincidence spectra obtained for transitions in ^{232}U is shown in fig. 1b. Coincident transitions of 218.4, 264.8, 305.7, 342.3 and 374.5 keV are clearly visible.

Information about the multipolarity of the observed transitions was provided by electron spectra in coincidence with the beam bursts. A sum of such spectra taken with different mini-orange transmissions is shown in fig. 1c. It is notable that peak-to-background ratios are much higher than in the similar γ-ray data of fig. 1a, for example, 1 : 1.4 for the 218.4 L_{I+II} line versus 1 : 6 for the 218.4 γ-line. The transitions in ^{232}U are by far the strongest ones observed and K, L_{I+II}, L_{III}, M and N + ... lines are apparent. The enhancement of the high-Z conversion lines over the fission-fragment background, relative to the γ-ray spectra, is easily understood from the Z-dependence of internal conversion; e.g. the ratio of the theoretical L-conversion coefficients [10] for $Z = 92$ to those for $Z = 46$ of a 320 keV transition, is 8.7 for E1, 23 for E2 and 78 for M1.

From the various electron spectra, similar to that of fig. 1c, L_{I+II}/L_{III} ratios could be determined for all transitions of interest between 150 and 400 keV. No reliable information could be obtained for lower-energy transitions because of the strength of the δ-ray background. Further information about multipolarity was provided for some cases by K/L and L_{I+II}/M ratios. Experimental values for the conversion ratios are compared in table 1 with theoretical predictions for E1, E2 and M1 (higher multipolarities are precluded by the prompt character of the γ–γ coincidence relations). All L_{I+II}/L_{III} ratios are found to be in good agreement with a pure E2 assignment. Within somewhat larger uncertainties the K/L and L_{I+II}/M ratios are also consistent with pure E2 for the transitions measured (the latter ratios are not presented). The total relative intensities deduced from the electron and coincident γ-ray spectra determine the ordering of the observed transitions. We are thus able to establish the ground-state band of ^{232}U up to the 16^+ level.

We also identify in our spectra a transition of 403.2 keV, which we tentatively assign as the $18^+ \to 16^+$ transition on the basis of the following evidence: (i) the electron–gamma coincidence data reveal the presence of a weak γ-line at 403.2 keV (not shown here); (ii) a weak conversion line is present at the position expected for 403.2 L_{I+II}; (iii) the presence of the 403.2 K line is suggested in singles electron spectra, where it is unresolved from the 305.7 L_{III} line which is slightly more intense than expected from the 305.7 L_{I+II} and M intensities.

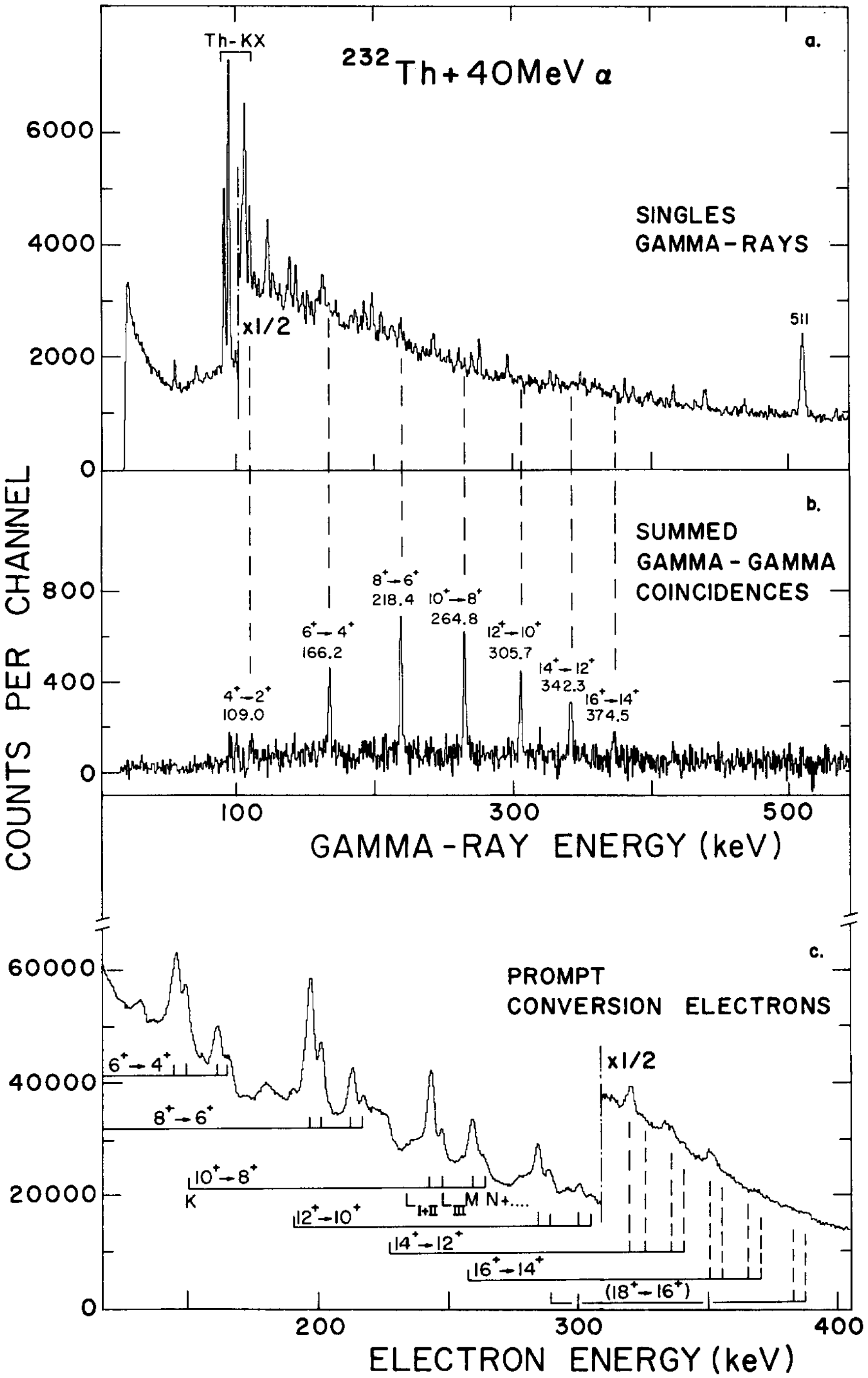

Fig. 1. Gamma-ray and conversion-electron spectra (different energy scales) measured in the ^{232}Th + 40 MeV α reaction under various experimental conditions. Transitions in ^{232}U are indicated. The electron spectrum is a sum of spectra obtained with different mini-orange transmissions (see text).

Table 1
Energy, total intensity and experimental and theoretical conversion coefficients for the transitions observed in ^{232}U.

Transition	E_γ (keV)	I_{tot} [a]	K/L exp.	K/L theory [b]			L_{I+II}/L_{III} exp.	L_{I+II}/L_{III} theory [b]		
				E2	E1	M1		E2	E1	M1
$6^+ \to 4^+$	166.2 ± 0.2	≡100		0.20	4.6	5.2	2.2 ± 0.4	2.0	4.6	215
$8^+ \to 6^+$	218.4 ± 0.1	85 ± 7		0.45	5.0	5.2	2.5 ± 0.4	2.5	5.7	222
$10^+ \to 8^+$	264.8 ± 0.1	66 ± 6		0.68	5.1	5.3	3.2 ± 0.5	3.0	6.7	228
$12^+ \to 10^+$	305.7 ± 0.1	52 ± 6	0.9 ± 0.2	0.91	5.2	5.3	3.1 ± 0.6	3.4	7.4	233
$14^+ \to 12^+$	342.3 ± 0.2	25 ± 5	1.6 ± 0.4	1.17	5.3	5.3	4.2 ± 1.2	3.9	8.0	238
$16^+ \to 14^+$	374.5 ± 0.5	20 ± 5	2.3 ± 0.9	1.36	5.4	5.3	4.1 ± 2.8	4.2	8.6	241
$(18^+ \to 16^+)$	403.2 ± 0.5	<15		1.51	5.4	5.3		4.7	9.2	242

[a] Total intensities deduced from the experimental γ- and conversion-electron data and normalized to 100 for the $6^+ \to 4^+$ transition.

[b] Ref. [10].

In fig. 2 the information deduced from this work about the ground-state rotational band of ^{232}U is presented in a level scheme and in a plot of the moment of inertia versus the square of the rotational frequency. The ground-state band of ^{232}U does not show a pronounced irregularity up to spin-18, though the moment of inertia increases approximately linearly by about 20% between $I = 2$ and $I = 12$, and increases even more steeply at higher spin. As a result of lower rotational frequencies, "backbending" in actinide nuclei is expected to occur at higher spins ($I \gtrsim 24$) if a behaviour analogous to that observed in the rare-earth region at $I \approx 16$ is assumed. The approximately linear increase at low spin is common to both regions.

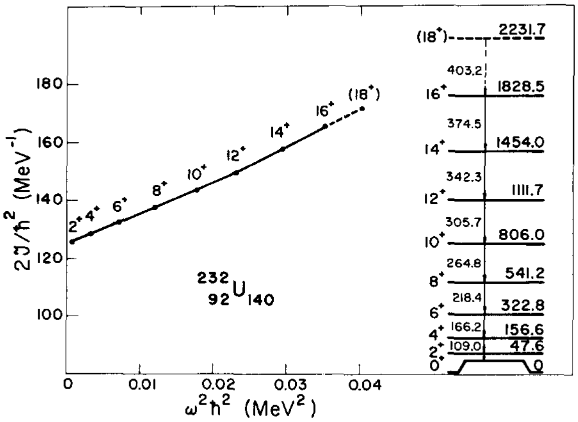

Fig. 2. Level scheme and a plot of the moment of inertia versus the square of the rotational frequency for ^{232}U as deduced from the present experiments.

In summary, it has been found possible to investigate the yrast band of ^{232}U up to 16^+ with the ^{232}Th(α, 4nγ) reaction in spite of a small cross section and the presence of a strong fission background. While transitions in the ground-state band could be identified in γ–γ coincidence data, confirmation, multipolarity determination, and information about the ordering came from surprisingly clean conversion electron spectra, which are much less affected by the fission background than the corresponding γ-ray spectra. The techniques applied in this investigation promise to be powerful in the study of other actinide nuclei produced in heavy-ion induced reactions.

It is a great pleasure to thank Dr. J. van Klinken for advice about the use of the mini-orange spectrometer and for stimulating discussions, Mr. H. Hofker for help in part of the experiments, and Professor Dr. R.H. Siemssen for enthousiastic support. This work has been performed as part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM) with financial support from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek" (ZWO).

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