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Observation of the ground-state band of ^{234}Th using the ^{232}Th(^{18}O,^{16}O) reaction

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The ground-state rotational band of ^{234}Th is established up to $I^{\pi}=10^{+}$ (12^{+}) by in-beam γ-ray spectroscopy. Heavy-ion transfer reactions are shown to be useful to investigate otherwise unaccessible neutron-rich actinide nuclides.

During the last years, numerous γ-spectroscopic investigations of nuclei, particularly in the rare-earth region, revealed many new phenomena and contributed essentially to our understanding of the nuclear structure. However, the behavior of the actinide nuclei is still not sufficiently investigated, since standard methods of in-beam γ-ray spectroscopy are of rather limited use in this region. The, so far, mostly applied technique for studying heavy actinides—multiple Coulomb excitation—is restricted to a few long-living isotopes. Heavy-ion fusion reactions, on the other hand, become prohibitive due to strong competition from fission, except for very neutron-deficient nuclei ($A \leq 224$).[1,2] In more recent investigations[3] the (α,xn) reaction could be applied to study heavier, but still neutron deficient, actinides.

In the present work we demonstrate that heavy-ion transfer reactions provide a new possibility of performing in-beam γ-ray spectroscopy, especially on otherwise unaccessible neutron-rich actinide nuclei. The experiment focused on the isotope ^{234}Th, where only the 2^{+} and 4^{+} ground-state band levels were previously known from studies of the ^{232}Th (t,p) reaction[4] and the α decay of ^{238}U.[5] A self-supporting metallic ^{232}Th target of 0.7 mg/cm^2 was bombarded with ^{18}O projectiles—providing a favorable Q_{gg} value of -0.7 MeV—supplied by the accelerator facility at the Max-Planck-Institute. The energy ($E_{\text{lab}}=90$ MeV) was chosen close to the Coulomb barrier ($E_{\text{lab}}/V_c \approx 1.08$) to optimize the production cross section for the neutron transfer channels. Backscattered projectilelike particles were detected with a Si ring detector ($155° \leq \theta_p \leq 167°$), which was covered by a 1.6 mg/cm^2 Ni foil to stop most of the fission products. Five Compton-shielded Ge counters ($\theta_\gamma=55°$, 57°, 63°, 115°, and 116°) served to detect coincident γ rays. The obtained γ spectra were corrected for the Doppler shift caused by the recoiling targetlike ejectiles ($v/c \approx 0.016$).

To suppress background from inelastic reactions and fission, an energy $E_p \geq 57$ MeV was demanded for the backscattered particles in the analysis. The corresponding, remarkably clean γ spectrum shown in Fig. 1(a) (sum of all Ge-detector spectra) is dominated by ^{232}Th yrast transitions. Although the known 114.5 keV $4^{+}\rightarrow 2^{+}$ transition of ^{234}Th is attenuated by internal conversion and almost degenerate with the dominant 112.8 keV $4^{+}\rightarrow 2^{+}$ transition of ^{232}Th, a gate was placed on this γ-ray line and on the adjacent background. The net p-γ-γ coincidence spectrum indicated the presence of lines not belonging to ^{232}Th. Similar spectra then were generated for gates placed on the new lines in the primary coincidence data. The net sum of these secondary p-γ-γ spectra is shown in Fig. 1(b). The new transitions with energies of 173.5 keV, 228.3 keV, 278.2 keV, and 317.2 keV are attributed together with the 114.5 keV line to the ground-state band decay of ^{234}Th as the energy of the lowest γ transition at 114.5 keV is in perfect agreement with the known $4^{+}\rightarrow 2^{+}$ transition in this nucleus.

Further support for the γ cascade to belong to a Th isotope is obtained from the energies of the coincident K-x-ray lines, which are clearly distinct from x-ray energies of neighboring elements. Support for the mass number of the isotope is obtained by comparing the energy distribution of the particles coincident with the proposed

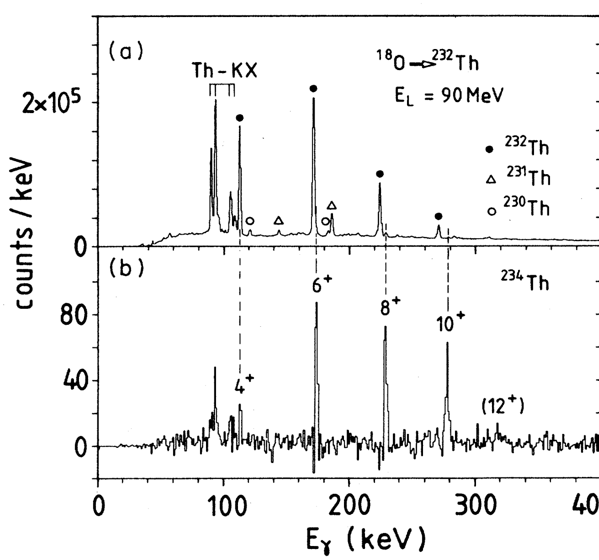

FIG. 1. (a) γ spectrum in coincidence with backscattered projectilelike particles. The most prominent lines belong to ground-state band transitions in ^{232}Th. In addition, transitions corresponding to few-neutron transfer channels are seen. (b) Summed p-γ-γ coincidence spectrum with gates on the 173.5 keV, 228.3 keV, and 278.2 keV transitions. $I\rightarrow(I\text{-}2)$ transitions assigned to ^{234}Th are indicated.

TABLE I. Energy, total intensity, and angular correlation coefficients of the transitions assigned to ^{234}Th.

Transition	E_γ (keV)	I_{tot}	a_2/a_0	a_4/a_0
$6^+ \to 4^+$	173.5 ± 0.3	$\equiv 100$	0.23 ± 0.10	
$8^+ \to 6^+$	228.3 ± 0.2	44 ± 4	0.17 ± 0.06	-0.11 ± 0.08
$10^+ \to 8^+$	278.2 ± 0.2	10 ± 1	0.39 ± 0.23	
$(12^+ \to 10^+)$	317.2 ± 0.4	2 ± 1		

^{234}Th transitions to the corresponding distributions of the identified isotopes ^{230}Th and ^{231}Th (no γ-ray lines corresponding to ^{233}Th could be identified). The centroid energy of ^{19}O was about 2 MeV and the energy of ^{20}O about 1 MeV lower than the centroid energy of the expected ^{16}O. This is in good agreement with what is expected from the different Q_{gg} values, taking into account that the excitation energies are rather similar for all neutron transfer channels in this reaction.[6]

The spin and parity assignments of the new transitions are based on the observed energies and line intensities, and on the particle-γ angular correlation. Taking into account the expected[7] vacuum deorientation, the anisotropies shown in Table I are typical for quadrupole transitions, although a clear distinction between stretched and unstretched transitions is not possible due to statistical and systematical uncertainties.

In the observed spin region the ground-state band of ^{234}Th does not show any irregularities, though, as expected from the other actinide nuclei, the moment of inertia increases moderately with increasing spin. The generally observed increase of the moment of inertia with the mass of the Th isotopes, caused by an ever stronger deformation, is reversed in ^{234}Th. Compared with ^{232}Th, its moment of inertia is reduced by about 1.6%. This is predicted by shell model calculations as a consequence of a substantially decreasing hexadecapole deformation over compensating the increasing quadrupole deformation.[8]

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[1] W. Bonin, H. Backe, M. Dahlinger, S. Glienke, D. Habs, E. Hanelt, E. Kankeleit, and B. Schwartz, Z. Phys. A **322**, 59 (1985).

[2] B. Schwartz, Ch. Ender, D. Habs, D. Schwalm, M. Dahlinger, E. Kankeleit, H. Folger, R. S. Simon, and H. Backe, Z. Phys. A **323**, 489 (1986).

[3] P. Schüler, Ch. Lauterbach, Y. K. Agarwal, J. de Boer, K. P. Blume, P. A. Butler, K. Euler, Ch. Fleischmann, C. Günther, E. Hauber, H. J. Maier, M. Marten-Tölle, Ch. Schandera, R. Tölle, and P. Zeyen, Phys. Lett. B **174**, 241 (1986).

[4] B. B. Back, E. R. Flynn, O. Hansen, R. F. Casten, and J. D. Garrett, Nucl. Phys. **A217**, 116 (1973).

[5] R. E. Bell, S. Bjornholm, J. C. Severiens, K. Dan. Vidensk. Selsk. Mat. Fiz. Medd. **32**, 12 (1960).

[6] J. Gerl *et al.*, Z. Phys. A (to be published).

[7] D. Pelte and D. Schwalm, in *Heavy Ion Collisions*, edited by R. Bock (North-Holland, Amsterdam, 1982).

[8] M. Brack, T. Ledergerber, H. C. Pauli, and A. S. Jensen, Nucl. Phys. **A234**, 185 (1974).