Energy Separation of the Doublet of Intrinsic States at the Ground State of ^{229}Th

C. W. Reich and R. G. Helmer
Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, Idaho 83415
(Received 23 October 1989)

It has been known for some time that the intrinsic state labeled by the asymptotic quantum numbers $\frac{3}{2}^+$[631] lies quite close (<0.1 keV) to the $\frac{5}{2}^+$[633] ground state of ^{229}Th. Using the energies of selected γ rays emitted following the α decay of ^{233}U, we have obtained a value of 1 ± 4 eV for the energy separation of these two intrinsic states.

PACS numbers: 23.20.Lv, 27.90.+b

In a study[1] of the rotational-band structure of ^{229}Th, populated in the α decay of ^{233}U, states interpreted as the spin $\frac{5}{2}$ through $\frac{11}{2}$ members of a $\frac{3}{2}^+$[631] band were reported. The bandhead ($I^\pi=\frac{3}{2}^+$) of this band, however, was not directly observed. From indirect, but convincing, evidence it was concluded[1] that this $\frac{3}{2}^+$ state must be quite close to (within 0.1 keV of) the ^{229}Th ground state ($\frac{5}{2}^+$[633]) and that the reason for its nonobservation was that the energy separation of these two states was too small to be determined from the existing data. This inference was supported, essentially concurrently, by data from a study[2] of the ^{230}Th(d,t) reaction, in which various members of the $\frac{3}{2}^+$[631] band, and, in particular, the bandhead itself, were observably populated. Although the ground state was not observed in this reaction, the location of the peak assigned as $\frac{3}{2}$, $\frac{3}{2}^+$[631] relative to the other band members indicated that it should lie close to the ground state.

In a subsequent study[3] of the ^{233}U decay for the purpose of obtaining accurate values of the emission probabilities of a number of the more intense γ rays, the energies of many of the γ rays were determined with precisions of a few eV. This has made it possible, in turn, to obtain a more precise estimate of the energy separation of these two states. In this paper, we present the results of our redetermination of this energy separation.

The portion of the low-energy level scheme of ^{229}Th which is pertinent to the present discussion is shown in Fig. 1. From this scheme the following three energy combinations can be used to determine the energy Δ of the $\frac{3}{2}^+$ bandhead:

$$\Delta_1 = E(97) - E(71) - E(25)\,,$$

$$\Delta_2 = E(97) - E(67) - E(29)\,,$$

$$\Delta_3 = [E(148) - E(118)] - [E(146) - E(117)]$$
$$= [E(148) - E(146)] - [E(118) - E(117)]\,.$$

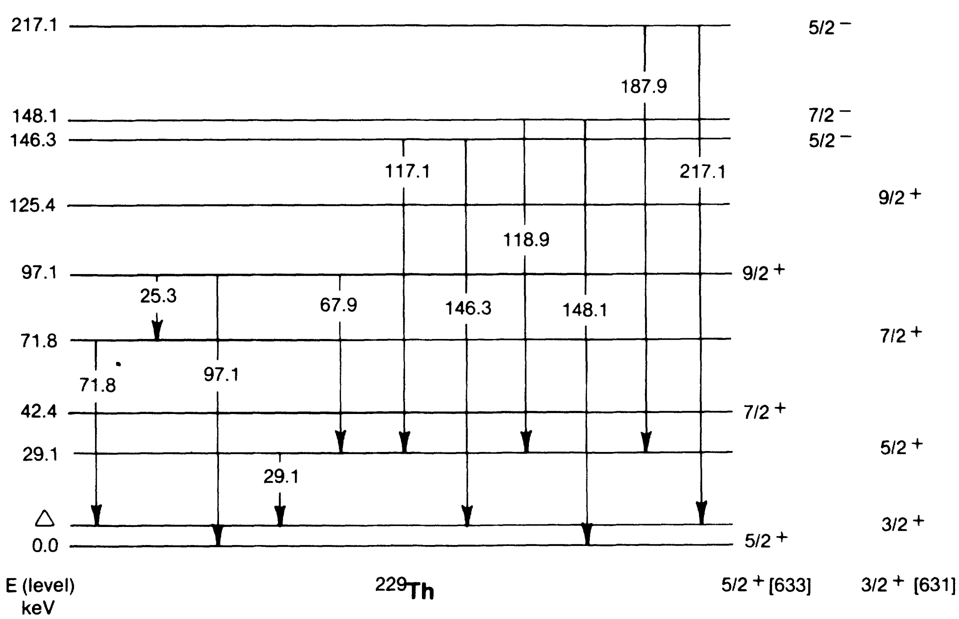

FIG. 1. Partial level scheme of ^{229}Th, showing those γ-ray transitions whose energy values were used in determining the energy separation Δ of the $\frac{5}{2}^+$[633] and $\frac{3}{2}^+$[631] bandheads.

In addition, the following energy combination should be identically zero, and thereby provides a check on the quality of the energy values:

$$0.0 = E(217) - E(187) - E(29) . \qquad (1)$$

The validity of the determination of the energy difference Δ depends on the assumption that the observed γ-ray peaks are not multiplets and that these peaks actually correspond to the transitions shown in Fig. 1. In particular, it is important that the levels considered do not depopulate to both the $\frac{5}{2}^+$[633] and $\frac{3}{2}^+$[631] bandheads. From spin-parity considerations alone, it is clear that the 97- and 148-keV levels do not populate the $\frac{3}{2}^+$ level, since those transitions would be $M3$ and $M2$, respectively, and hence should be very weak compared to the $E2$ and $E1$ transitions from these levels to the $\frac{5}{2}^+$ bandhead. The 29- and 71-keV γ rays are $M1+E2$ and $E2$ transitions within the $\frac{3}{2}^+$[631] band. It is observed[1] that, higher up in the $\frac{3}{2}^+$ band, the within-band transitions are considerably more intense than the possible interband transitions (to $\frac{5}{2}^+$[633]). It is assumed that this behavior applies also to the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ members of the band and, thus, that the contribution to the 29- and 71-keV peaks from possible γ-ray transitions to the $\frac{5}{2}$, $\frac{5}{2}^+$[633] state is negligible. On the basis of spin-parity considerations alone, the γ rays from the two $\frac{5}{2}^-$ levels could go to both the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ bandheads. However, as pointed out in Ref. 1, the $E1$ decay of the observed negative-parity states below 0.24 MeV in ^{229}Th takes place entirely to members of the $\frac{3}{2}^+$ band, with no detectable feeding of the $\frac{5}{2}^+$ band. (This phenomenon is directly observed only for the excited states of these bands, and it is assumed to be true for the bandheads as well. A theoretical basis for this observation has been proposed,[4] and an empirical justification for terminating these $E1$'s on the $\frac{3}{2}^+$ bandhead is noted below.)

The γ-ray energies of interest here were measured with an intrinsic Ge detector system having resolutions (FWHM) of 0.45 and 0.61 keV at 29 and 146 keV, respectively. Portions of a typical γ-ray spectrum of the ^{233}U sample are shown in Fig. 2. Details of these measurements have been presented elsewhere[3] and are thus only briefly indicated here. From the measured γ-ray spectra, the difference in energy between closely spaced lines, both within the ^{233}U spectrum itself or from a calibration source and the ^{233}U, was determined. Anywhere from three to seven separate spectra were used to determine a particular energy difference.

The measured energy differences, together with the derived energies for the relevant ^{233}U-decay γ rays, are given in Table I. The sum in Eq. (1), which should be zero, is found to have the value -0.002 ± 0.003 keV; and the following values are obtained for the energy Δ of the $\frac{3}{2}^+$ bandhead:

$$\Delta_1 = -0.003 \pm 0.005 \text{ keV} ,$$

$$\Delta_2 = -0.001 \pm 0.006 \text{ keV} ,$$

$$\Delta_3 = +0.002 \pm 0.008 \text{ keV} .$$

A weighted average of these three Δ_i values gives the fol-

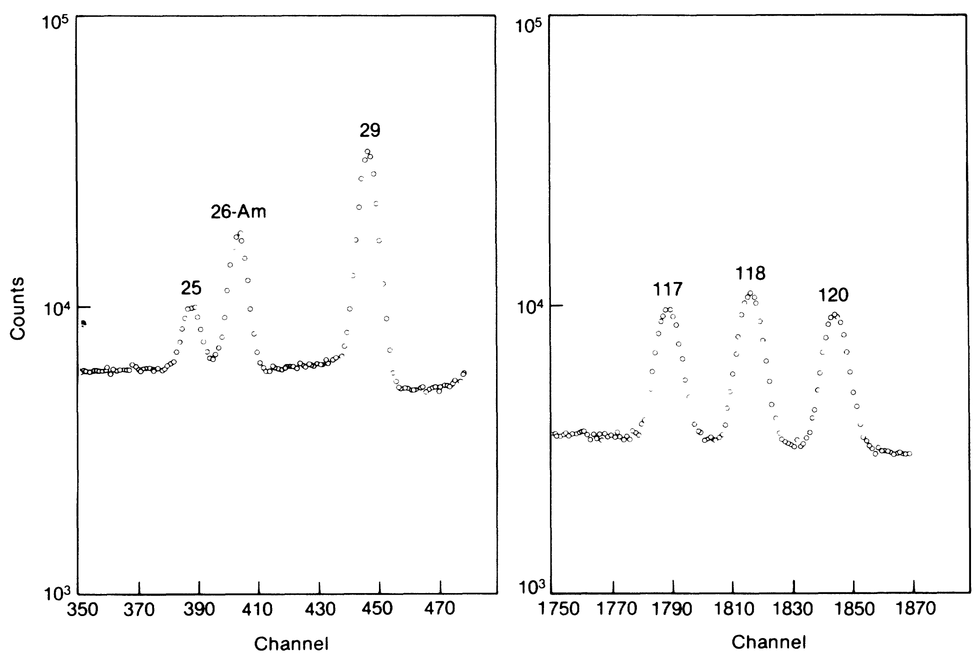

FIG. 2. Portions of γ-ray spectrum of ^{233}U. Peak energies are labeled in keV and the ^{241}Am peak is identified.

TABLE I. Measured γ-ray energy differences and deduced γ-ray energies. The γ rays are from the ^{233}U decay unless otherwise noted. The data are from Ref. 3.

Transitions	Energy difference (keV)	γ-ray energy (keV)
25-26(^{241}Am)	1.027 ± 0.004	25.318 ± 0.004
29-26(^{241}Am)	2.847 ± 0.001	29.192 ± 0.001
67-66	1.821 ± 0.004	
66-70	4.158 ± 0.003	67.943 ± 0.006
70-71	1.539 ± 0.003	
71-69(^{153}Gd)	2.141 ± 0.003	
71-67(^{182}Ta)	4.072 ± 0.003	71.819 ± 0.002
71-84(^{182}Ta)	12.859 ± 0.003	
97-100(^{182}Ta)	2.973 ± 0.001	97.134 ± 0.001
117-118	1.809 ± 0.001	
146-148	1.811 ± 0.008	
187-179(^{182}Ta)	8.576 ± 0.002	187.969 ± 0.002
187-198(^{182}Ta)	10.385 ± 0.003	
217-222(^{182}Ta)	4.951 ± 0.002	217.159 ± 0.002

lowing estimate for the energy of the $\frac{3}{2}^{+}$ bandhead:

$$\Delta = -0.001 \pm 0.004 \text{ keV}.$$

Although the Δ_i are correlated through the use of a common set of energy standards, and Δ_1 and Δ_2 are correlated through their common use of $E(97)$, the uncertainties in the individual Δ_i are dominated by the contributions from the other γ-ray peaks. Thus, the simple average shown here should be valid.

As noted above, the validity of this result depends on the fact that all the γ-ray peaks represent single γ rays with the assigned placements. (For this reason, we have not used any combinations involving the 42-keV γ ray, since it may be a doublet.[1]) From the nuclear-structure considerations presented above, we believe that these peaks are in fact singlets. One empirical argument can be added. We believe that it is extremely unlikely that, within each of the three Δ_i sums, there would be one or more doublet peaks whose deduced energy value would be shifted by amounts that would in all cases "accidentally" produce a sum near zero.

We conclude that the energy separation of these two intrinsic states is smaller than the precision of our measurements and in any event is almost certainly less than 10 eV. This represents the closest approach to complete degeneracy thus far known for a pair of states where one is the ground state.

It has been tacitly assumed here, and elsewhere in the literature, that the ^{229}Th ground state is $\frac{5}{2}^{+}[633]$. A little reflection, however, reveals that all that the previously available data[5,6] really establish in this regard is that the $\frac{5}{2}^{+}[633]$ state is the 7340-yr activity in ^{229}Th. (This is also true for the results of a recently published[7] Coulomb-excitation study of ^{229}Th, in which the $\frac{5}{2}^{+}[633]$ band was strongly excited, but no evidence was found for population of the $\frac{3}{2}^{+}[631]$ band.) If the half-life of a γ transition connecting these two bandheads is significantly shorter than this 7340-yr half-life, the $\frac{3}{2}^{+}[631]$ bandhead would be definitely established as being an excited state in ^{229}Th. The Moszkowski estimate[8] of the transition rate of a putative 1-eV $M1$ transition connecting these two states gives a value (neglecting possible effects from the influence of atomic electrons) of ~ 7 h for the level half-life. No evidence for a half-life of this order of magnitude in ^{229}Th presently exists, but, to the best of our knowledge, no careful search for such an isomeric state has been carried out. Certainly, its experimental observation would be difficult. However, should it turn out for some reason that the half-life of a γ transition between these two ^{229}Th states is significantly greater than 7340 yr, then the possibility that $\frac{3}{2}^{+}[631]$ is the ground state of ^{229}Th cannot be definitely excluded.

The authors wish to thank J. W. Rogers for making available the Ge detector used for making most of the energy determinations reported here. This work was carried out under the auspices of the U.S. Department of Energy under Contract No. DE-AC07-76ID01570.

[1] L. A. Kroger and C. W. Reich, Nucl. Phys. **A259**, 29 (1976); L. A. Kroger, Ph.D. thesis, University of Wyoming, 1971 (unpublished).

[2] J. R. Erskine (private communication), also quoted in K. S. Toth, Nucl. Data Sheets **24**, 263 (1978).

[3] C. W. Reich, R. G. Helmer, J. D. Baker, and R. J. Gehrke, Int. J. Appl. Radiat. Isot. **35**, 185 (1984).

[4] In Ref. 1, it was suggested that this preferential feeding of the $\frac{3}{2}^{+}[631]$ band was due to the presence, in these negative-parity states, of a significant component of the $K^{\pi}=0^{-}$ octupole vibrational built on $\frac{3}{2}^{+}[631]$. The apparent absence in these states of corresponding 0^{-} octupole strength associated with the $\frac{5}{2}^{+}[633]$ band was commented on, but not accounted for. With the subsequent recognition that intrinsic reflection-asymmetric (static octupole-deformed) nuclear shapes are a feature of many of the nuclides in this mass region, interest in this question has arisen once again. In particular, in their discussion of intrinsic reflection asymmetry, Leander and Sheline [G. A. Leander and R. K. Sheline, Nucl. Phys. **A43**, 375 (1984)] treat the specific case of the negative-parity states of ^{229}Th in considerable detail and present an explanation of the different properties observed for the $K^{\pi}=\frac{3}{2}^{-}$ and $\frac{5}{2}^{-}$ octupole excitations in this nuclide.

[5] Toth, Ref. 2.

[6] Y. A. Ellis, Nucl. Data Sheets **24**, 289 (1978).

[7] C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, P. H. Stelson, G. A. Leander, and C. W. Reich, Phys. Scr. **38**, 657 (1988).

[8] S. A. Moszkowski, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, p. 863.