Level structure of ^{227}Th investigated in the α decay of ^{231}U

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The level structure of ^{227}Th has been studied using the α decay of ^{231}U. The use of mass-separated ^{231}U sources and high-resolution α-particle and γ-ray spectroscopy enabled the identification of 16 excited levels of ^{227}Th. The angular distribution of α particles in the decay of low-temperature oriented ^{227}Th is consistent with a ^{227}Th ground-state spin of 1/2. The low-lying levels of ^{227}Th can be interpreted in terms of a $K=1/2^{\pm}$ parity doublet and a $K=3/2^{+}$ band coupled with the $1/2^{+}$ member of the parity doublet by the Coriolis interaction. [S0556-2813(97)05505-2]

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I. INTRODUCTION

The light actinide nuclei with $219<A<229$ are located in a region where the low-lying nuclear excitations are characterized by strong octupole correlations [1]. There is now both experimental and theoretical evidence that the nuclei in the center of this mass region (around ^{225}Ac) have a stable octupole deformation in their ground states. The most clearcut evidence for such reflection-asymmetric deformations is provided by the observation of parity doublets (rotational bands with nearly degenerate states of the same spin but opposite parity) in odd-mass nuclei [2].

An interesting phenomenon is the coexistence of reflection-symmetric and reflection-asymmetric shapes: in a deformed nucleus some Nilsson orbitals polarize the nuclear shape towards smaller octupole deformation while others polarize it towards larger octupole deformation. As a consequence one would expect to observe parity doublet bands for some orbits and singlet bands for others in the same nucleus. This phenomenon is expected at the perimeter of the region of octupole deformation (in the transition region) [3], and experimental evidence for its occurrence has been reported for ^{225}Ra, ^{227}Ra, and ^{229}Th [4–6]. From systematic calculations of the single-particle states in odd-A actinides Cwiok and Nazarewicz [7,8] predict coexistence of symmetric and reflection-asymmetric shapes for the nuclei with neutron numbers around $N=138$ and note that ^{227}Th is expected to be one of the best cases to find this phenomenon.

The nucleus ^{227}Th is also very favorable from an experimental point of view: it can be studied most easily with in-beam γ-spectroscopic techniques in the ^{226}Ra$(\alpha,3n)^{227}$Th reaction. From such an earlier investigation we identified two $E2$ rotational sequences although no linking transitions between them could be found [9]. Moreover, the two sequences could not be placed into a level scheme due to lack of experimental information on the low-lying levels of ^{227}Th. Until recently only two excited levels at 9.3 and 24.5 keV were known from the β^- decay of ^{227}Ac [10]. We therefore started a program to investigate the α decay of ^{231}U which was known to occur with a branch of $\sim$0.0055%.

To settle the question, whether the ground-state spin of ^{227}Th is $I^{\pi}=1/2^{+}$ as accepted by Nuclear Data Sheets [11] or $3/2^{+}$ as inferred from the measured anisotropy of γ rays in the decay of oriented ^{227}Th by Briancon *et al.* [12] we undertook a low-temperature nuclear orientation (NO) experiment with a ^{227}Ac*Fe* source. Detection of the α particles, emitted in the decay chain of ^{227}Ac, was chosen because this method offers low background and high sensitivity.

During the course of our investigations two publications appeared dealing with ^{231}U α decay [13] and ^{227}Pa electron-capture decay [14]. In the following we will present our study of ^{227}Th and ^{231}U α decay and one conversion-electron measurement in ^{227}Ac β^- decay. Our results will then be compared with those of the earlier work and discussed within the rotational model.

II. EXPERIMENTAL METHODS AND RESULTS

A. The ^{231}U$\rightarrow$^{227}Th decay

The ^{231}U radioactivity was produced from the ^{232}Th$(\alpha,5n)$ reaction at a bombarding energy of 53 MeV. Mass-separated sources were prepared with the Bonn isotope separator. Due to the small cross section of the $(\alpha,5n)$ reaction, the limited efficiency of the mass separation and the small α branch only very weak α activities could be obtained (<10 α decays per sec). However, the use of mass-separated sources is essential to avoid the masking of most of the α lines in the ^{231}U decay by the alphas from ^{232}U, which is produced with comparable intensity from the $(\alpha,4n)$ reaction and decays 100% by α decay.

Alpha particles were detected by an ion-implanted silicon detector of 300 μm thickness. Gamma rays and conversion electrons, measured in coincidence with α particles, were detected by a LEPS Ge detector and a cooled PIN diode, respectively.

A source for the high-resolution measurement of the singles α-particle spectrum was prepared in the following way: the uranium activity was implanted into a 20-μm-thick

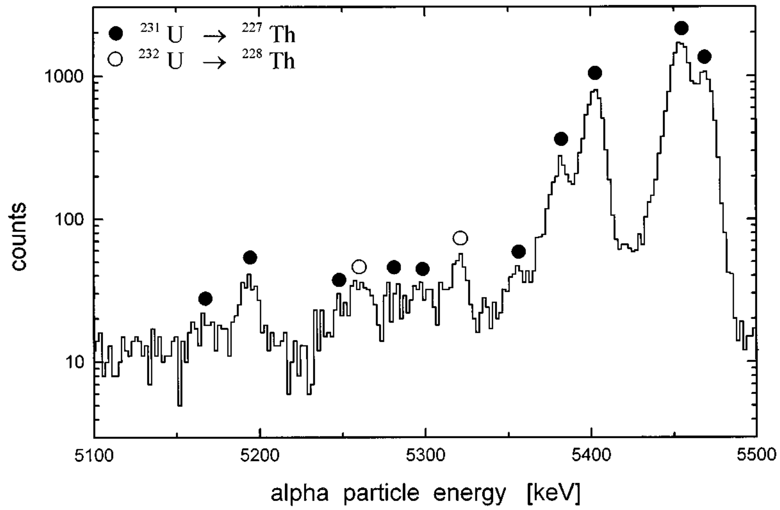

FIG. 1. Alpha-particle spectrum measured with a mass-separated source of ^{231}U. The energy resolution was FWHM=13 keV.

Al foil with the isotope separator. After the implantation the foil was cut into 2 mm broad strips from which those with the optimum ratio of ^{231}U/^{232}U activity were selected utilizing the ^{231}U→^{231}Pa decay [15]. The α-particle spectrum measured with this source is shown in Fig. 1, where the α lines assigned to the ^{231}U and ^{232}U decays are marked by dots and circles, respectively. The ^{232}U activity was reduced, compared to the unseparated activity, by approximately a factor of 1000.

The intensities of the α lines assigned to the ^{231}U decay are listed in the level scheme given below. For the ground-state Q value we obtain $Q_\alpha = 5576(2)$ keV. The α-decay hindrance factors (HF's) listed in the decay scheme were calculated from the α-particle intensities—and in a few cases (38, 74, and 229 keV level) from the γ-ray intensities—according to the prescription used in the Nuclear Data Sheets with $r_0 = 1.5298$ fm and assuming an α-branching ratio in the ^{231}U decay of 0.0045% [13]. Two comments have to be made: (i) The HF given for the 77.6 keV level was calculated neglecting an α population of the 76.2 keV level. This is only justified if the latter level has negative parity, in which case it is populated with ~0.25% yielding a HF~3200. If the 76.2 keV level has positive parity and the 52 and 67 keV transitions depopulating it have $M1$ multipolarity (see the discussion of the conversion-electron spectrum below), it would be populated in the α decay by ~3% yielding a HF ~250. In this case the hindrance factor for the 77.6 keV level would increase to 42. Pure $E2$ multipolarity for the 52 and 67 keV transitions is excluded by the γ-ray intensity and conversion-electron data. But the possibility of mixed $M1/E2$ multipolarities remains and therefore the hindrance factors for the 76.2 and 77.6 keV levels are subject to unknown uncertainties. (ii) As discussed below we tentatively suggest that the 77.5 keV γ ray is an $E2$ transition depopulating a 86.8 keV level. This level would then be populated in the α decay by ~1.5% yielding a HF of ~450.

Two γ-ray spectra in coincidence with different α-particle energies are shown in Figs. 2 and 3. The low-energy spectrum of Fig. 2 shows those γ rays which depopulate levels in ^{227}Th with excitation energies below ~110 keV. It is worthwhile noting the absence of any Th K x rays: the highest level populated with this α gate, the 99 keV level, is below the K binding energy. In the γ-ray spectrum of Fig. 3 these x rays are observed (not shown in Fig. 3) and are used to discriminate between $E1$ and $M1$ multipolarities as discussed below. The energies and intensities of the γ rays assigned to ^{227}Th are listed in Table I.

The α-γ-coincidence spectra provide a powerful tool to assign γ rays to the levels they depopulate: in the α spectrum

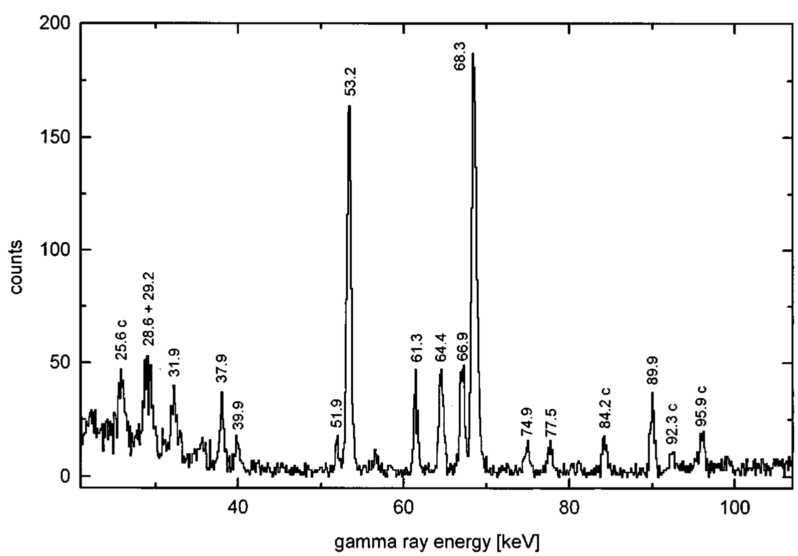

FIG. 2. Gamma-ray spectrum obtained in coincidence with alphas in the energy range from 5370 to 5425 keV. The lines marked by c result from chance coincidences from the ^{231}U→^{231}Pa EC decay.

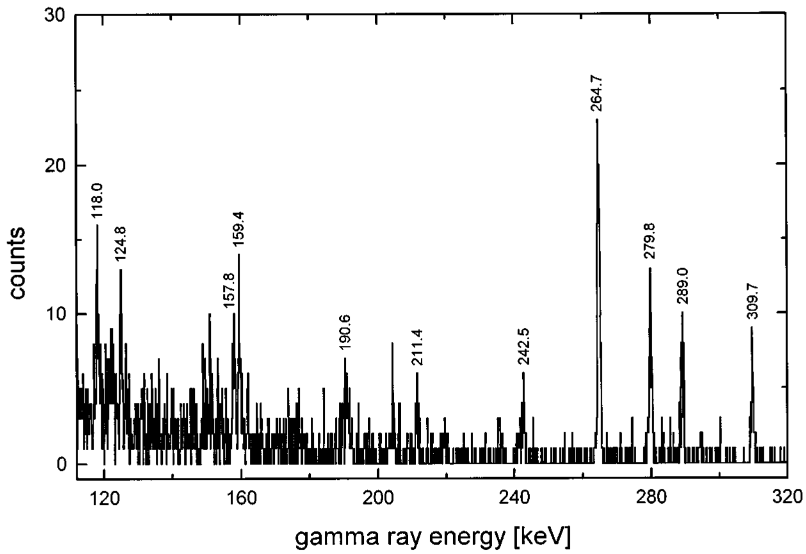

FIG. 3. Gamma-ray spectrum obtained in coincidence with alphas in the energy range from 5140 to 5370 keV.

created with a given γ ray as a gate, no α lines can be observed which populate levels below the level depopulated by the gate γ ray. The utilization of this feature for the assignment of γ rays to excited levels is illustrated for some selected low-energy γ rays in Fig. 4. These spectra allow the following conclusions: (i) The α line in coincidence with the 64.4 keV γ rays populates a level at an excitation energy of 75(3) keV. If we assume that the 9.3 and 24.3 keV levels are the lowest excited levels in ^{227}Th the 64.4 keV γ ray can only originate from a level at 64.4 keV or at 73.6 keV. The latter assignment is established by the observation of a 157.8 keV γ-ray depopulating a level at 229(3) keV. (ii) The 51.9 and 66.9 keV γ rays are in coincidence with alphas populating levels at 79(3) and 78(3) keV, respectively. As discussed below, these γ rays originate from a level at 76.2 keV. (iii) The alphas in coincidence with the 77.52(6) keV γ rays populate a level at 85(3) keV. We tentatively conclude that this γ ray depopulates a level at 86.8 keV.

The α-γ coincidences can also be used to identify or confirm the transitions from higher-lying levels to a given level. For example, in the α spectrum in coincidence with the 64 keV γ rays, α peaks are observed corresponding to the population of the 184, 200, and 231 keV levels, and conversely in the γ-ray spectra in coincidence with these α lines the 64 keV line is strongly present. This establishes transitions from these levels to the 74 keV level, from which the $231 \rightarrow 74$ keV γ transition is directly observed. The transitions from the 184 and 200 keV levels to the 74 keV level, shown as dashed lines in the decay scheme given below, have energies of 110.0 and 126.4 keV and γ-ray intensities of less than ~ 3 in the normalization used in Table I. However, for $M1$ multipolarity they would have total conversion coefficients of 15.4 and 10.3, respectively, which accounts for the observed α-γ coincidences.

The α-particle and γ-ray intensities and the α-γ coincidences allow one to draw some conclusions about the multipolarities of selected γ transitions. The α-γ intensity balances establish $E1$ multipolarity for the 56.4 and 72.8 keV transitions, provided their placement in the level scheme given below is correct. The intensities of the K x rays observed in the γ-ray spectra in coincidence with the alphas populating the 289 and 319 keV levels establish that the strongest transitions depopulating these levels (the 265 and 310 keV transitions) have predominantly $M1$ multipolarity, and thus establish positive parity for the 289 and 319 keV levels. The same reasoning gives somewhat weaker evidence for $M1$ multipolarity of the 158 keV γ transition yielding tentatively negative parity for the 231 keV level. Finally, both the α-γ intensity balance and the K x-ray intensities confirm $M1$ multipolarity of the 103 and 118 keV transitions depopulating the 127 keV level [14].

Some further information on multipolarities can be obtained from the conversion-electron spectrum measured in the present work. A section of this spectrum in coincidence with α-particles populating the levels around 75 keV is shown in Fig. 5. The strong lines which dominate the spectrum shown in Fig. 5 result predominantly from the L and M conversion electrons of the 53.2 and 68.3 keV transitions, which are known to have $M1$ multipolarity [14]. However, the data do not exclude contributions from the L and M lines of the 51.9 and 66.9 keV transitions and therefore the multipolarities of these transitions remain uncertain. $E1$ multipolarity is established for the 61.3 keV transition (and confirmed for the 64.4 keV transition) from the intensity limit of the L conversion electrons, which are located between the strong $53L$ and $53M/68L$ groups.

B. The ^{227}Ac$\rightarrow$^{227}Th$\rightarrow$^{223}Ra decay

For NO measurements a weak source of ^{227}Ac*Fe* was prepared by implantation of the radioactive precursors of ^{227}Ac (^{227}Fr and ^{227}Ra) into an iron foil with the ISOLDE facility at CERN at an implantation energy of 60 keV. About half a year after implantation, when short-lived isotopes had decayed, the sample was mounted in the NO apparatus FOLBIS [16] and oriented at low temperatures by an external magnetic field of 0.54 T. In order to reach high sensitivity for small anisotropies and avoid background problems we observed the anisotropy of α particles in the decay of ^{227}Th populated by β^- decay of ^{227}Ac. The α particles were detected by PIN diodes mounted on the 4 K cold shield of the refrigerator at 20° and 90° with respect to the orientation axis.

TABLE I. Gamma-ray energies and intensities of transitions in coincidence with α particles in the ^{231}U→^{227}Th decay.

E_γ (keV)	I_γ [a]	Multipolarity	Levels Initial→Final
24.33 *5*	20 *4*	$M1/E2$	24.3→0
28.57 *5*	25 *5*	$E1$ [b]	37.9→9.3
37.90 *3*	26 *5*	$E1$ [b]	37.9→0
39.88 *6*	8 *2*	$E1$	77.5→37.9
42.09 *6*	4.4 *10*		
51.85 *4*	7.9 *15*		76.2→24.3
53.23 *2*	83 *8*	$M1$(≤10% $E2$)	77.6→24.3
56.41 *2*	30 *3*	$E1$ [b]	183.7→127.3
58.1 *2*	3 *1*		
60.6 *2*	1.3 *4*		289.0→228.6
61.33 *3*	20 *2*	$E1$	99.2→37.9
64.38 *2*	39 *3*	$E1$ [b]	73.6→9.3
66.94 *3*	31 *3*		76.2→9.3
68.33 *2*	100 *5*	$M1$(≤20% $E2$)	77.6→9.3
72.14 *7*	13 *3*		
72.78 *7*	10 *2*	($E1$)	200.0→127.2
74.85 *5*	12 *2*		99.2→24.3
77.52 *6*	7.8 *15*		86.8→9.3
89.88 *5*	25 *6*		99.2→9.3
99.09 *8*	6.4 *15*		99.2→0
102.93 *4*	21 *2*	$M1$ [b]	127.3→24.3
111.1 *2*	≈4		400.1→289.0
117.98 *7*	9.2 *18*	$M1$ [b]	127.3→9.3
124.80 *8*	7.5 *15*		
150.7 *2*	4 *2*	$E1$ [b]	228.6→77.6
157.79 *8*	7.7 *15*	($M1$)	231.4→73.6
159.39 *8*	7.7 *15*		183.7→24.3
189.9 *3*	2.2 *7*		289.0→99.2
190.62 *10*	6.1 *14*		200.0→9.3
204.2 *2*	4.1 *10*	$E1$ [b]	228.6→24.3
211.4 *2*	4.9 *10*		289.0→77.6
219.6 *4*	2.7 *10*	$E1$ [b]	228.6→9.3
241.2 *3*	0.7 *3*		318.9→77.6
242.7 *2*	1.7 *6*		318.9→76.2
264.66 *3*	36 *3*	$M1$	289.0→24.3
279.76 *5*	19 *2*		289.0→9.3
289.01 *6*	16 *2*		289.0→0
294.5 *2*	3 *1*		318.9→24.3
309.68 *7*	12 *2*	$M1$	318.9→9.3

[a] For absolute intensities per 100 α decays divide by 210±40.
[b] Multipolarities from Liang *et al.* [14]. Our data confirm these multipolarities for the 56.4, 64.4, 102.9, and 118.0 keV transitions.

The α spectra measured with the 90° detector at ''warm'' and cold ($T\approx 7$ mK) temperatures are shown in the upper part of Fig. 6. The lines relevant in the present context are marked by their parent isotopes. In addition to the α lines in the decay chain of ^{227}Th, we observe the 5305 keV α line from the decay of ^{210}Po, which is present in the source as contamination. This line should show no anisotropy because $I=0$ for ^{210}Po and can therefore serve as a measure for the quality of the data and their normalization.

For our purposes the anisotropy of α particles at angle θ relative to the orientation axis can be written as [17]

$$R(\theta,T)=f\cdot\sum B_k(\mu\cdot B_{\mathrm{eff}},T)A_kQ_kP_k[\cos(\theta)],$$

where $P_k[\cos(\theta)]$ are Legendre polynomials and the Q_k correct for the finite solid angle of the detector. The A_k are the angular correlation coefficients of the observed α radiation and the B_k describe the orientation of the nuclear state with magnetic moment μ in the effective magnetic field B_{eff} at temperature T. Finally, the factor f represents the fraction of nuclei experiencing the orienting magnetic hyperfine field assuming a simple two-site model, in which the fraction $(1\text{-}f)$ of the nuclei is not oriented and therefore does not contribute to the experimental anisotropy [18]. The index k is even and $\leqslant 2\cdot I$, where I is the spin of the oriented nuclei.

Experimentally, R is derived as

$$R(\theta)=[N_c(\theta)-N_w(\theta)]/N_w(\theta),$$

where $N_c(\theta)$ and $N_w(\theta)$ are the counting rates at a temperature with orientation (cold) and with no orientation (warm), respectively. The experimental R values observed with the 90° detector are shown in the lower part of Fig. 6. As is apparent from this figure the three α lines in the decay of ^{227}Th are isotropic within the experimental accuracy. Averaging the anisotropies over these lines we obtain $R(90°)=-0.004(8)$, 0.003(7), and 0.010(9) for the 5752, 5977, and 6038 keV lines, respectively. The data for $\theta=20°$ are in accord with these results, although the energy resolution of this detector was somewhat worse. The most natural explanation for this finding is that the ground-state spin of ^{227}Th is 1/2, which in α and γ detection automatically results in zero anisotropy. If the spin were $\neq 1/2$, as suggested by the NO data of Briancon *et al.* [12], our data would imply that the hyperfine interaction is too weak to lead to a measurable orientation of the ^{227}Th ground state. In the following we will discuss this possibility and compare our results to those of Ref. [12].

The fraction of nuclei experiencing the hyperfine interaction can be derived from the anisotropy of the 6623 keV $9/2^-(L=5)1/2^+$ α line in the decay of ^{211}Bi which is in equilibrium with the ^{227}Th activity in our sample. This line shows an anisotropy of $R(90°)=0.794(7)$. With $\mu(^{211}\mathrm{Bi})=4.11\mu_N$ and $B_{\mathrm{hf}}(\mathrm{Bi}Fe)=119$ T [19,20] we calculate a theoretical anisotropy $R_{\mathrm{th}}(90°)=1.45$ yielding $f=0.55(1)$ in line with systematics [18]. The hyperfine interaction strength can now be estimated from the observed anisotropy of the 5752 keV α line which populates a $1/2^+$ level in ^{223}Ra and therefore has pure multipolarity for any ^{227}Th ground-state spin. This latter spin is restricted to $\leqslant 7/2$ from the log ft value observed in the ^{227}Ac decay [14]. For spins of 3/2, 5/2, and 7/2 we derive for our sample from the observed $R(90°)\leqslant 0.004$ an upper limit of $|\mu(^{227}\mathrm{Th})\cdot B_{\mathrm{eff}}(\mathrm{Th}Fe)|\leqslant 6\mu_N\cdot\mathrm{T}$. The magnetic hyperfine field can be estimated from the systematics [20] as $B_{\mathrm{eff}}(\mathrm{Th}Fe)\approx -60$ T yielding $|\mu(^{227}\mathrm{Th})|\leqslant 0.1\mu_N$. This result is smaller than calculated magnetic moments in this mass region (see, e.g., Table X of [6]), although it cannot be excluded completely on theoretical grounds.

Briancon *et al.* [12] have performed a NO experiment with a sample of ^{227}Ac in host gadolinium. They observed anisotropies of the order of a few percent for the γ rays

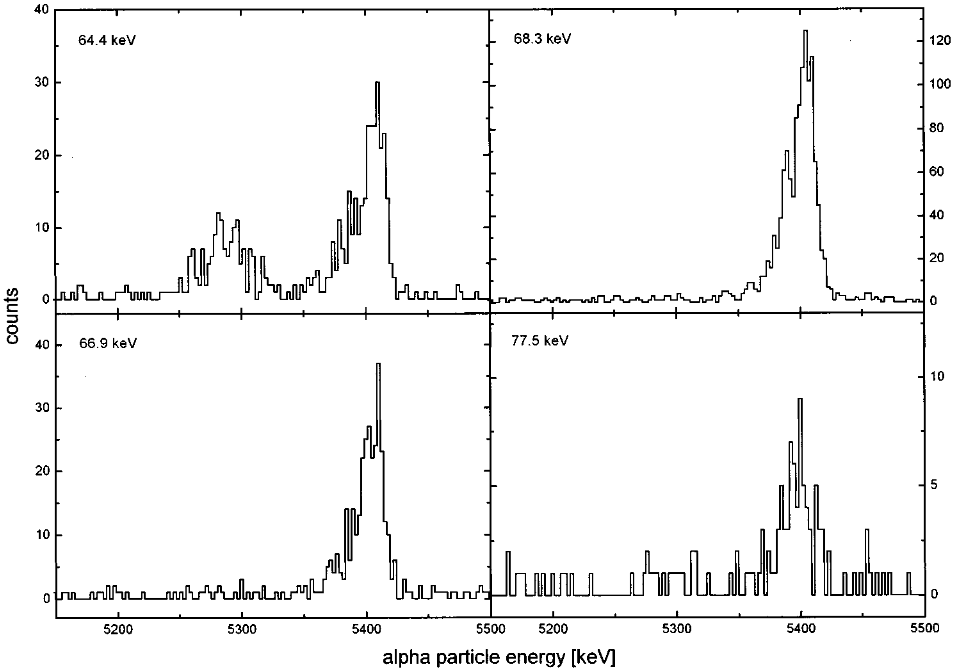

FIG. 4. Alpha spectra in coincidence with low-energy γ rays.

following the α decay of ^{227}Th in accord with their assumed $I^{\pi}(^{227}\mathrm{Th}_{\mathrm{g.s.}})=3/2^{+}$. Adopting $f=1$ they obtain from their data $|\mu(^{227}\mathrm{Th})\cdot B_{\mathrm{eff}}(\mathrm{Th}Gd)|=158(8)\mu_N\cdot T$. To derive the corresponding value for host iron one has to multiply by the ratio of the hyperfine fields. From [21] we obtain for the ratio of the hyperfine fields for cerium in iron and gadolinium a value of 0.76 which should be a good estimate for its chemical analogue thorium. Using this ratio we expect $|\mu(^{227}\mathrm{Th})\cdot B_{\mathrm{eff}}(\mathrm{Th}Fe)|=120\mu_N\cdot T$ as compared to the experimental result of $\leqslant 6\mu_N\cdot T$. Correspondingly, if the ground-state spin parity of ^{227}Th is taken as $3/2^{+}$, the 5752 keV α line should have an anisotropy of $R(90°)=0.264$ at our experimental temperature using the parameters derived above, at least a factor 50 larger than the measured result which is zero within errors.

Referring to the γ anisotropies reported by Briancon *et al.* [12] it should be noted that these are difficult measurements with many closely spaced low-energy γ lines. All anisotropies listed in Table 3 of [12] are rather small up to $\sim 5\%$. For the 236.0, 256.3, 286.1, and 350.5 keV lines anisotropies of 0.0048(5), $-0.0062(25)$, $-0.0130(31)$, and 0.0040(32), respectively, are listed. These results indicate the experimental difficulties of [12], because it is assumed there that the corresponding γ transitions depopulate an $I=1/2$ level and therefore should have zero anisotropy.

We conclude that the NO experiments reported by Briancon *et al.* [12] must be in error, and thus the only experimental evidence for a ^{227}Th ground-state spin $\neq 1/2$ is eliminated. Although our NO data do not strictly exclude $I\neq 1/2$, systematics of magnetic moments and hyperfine fields in this mass region leave spins other than 1/2 quite unlikely.

Finally, a source of ^{227}Ac evaporated on a gold backing and covered by a very thin plastic layer (for safety reasons) was used for the measurement of conversion electrons. The electrons were measured in an iron-free orange spectrometer in coincidence with α particles detected by a silicon detector. The singles and α-coincident electron spectra around the M-subshell conversion electrons of the 24.3 keV transition in ^{227}Th are shown in Fig. 7. From the singles spectrum we obtain intensity ratios of $M_2/M_1=0.39(4)$ and $M_3/M_1=0.24(3)$ yielding an $E2/M1$ mixing parameter of $\delta^2=0.010(1)$.

III. THE LEVEL SCHEME OF ^{227}Th

The level scheme of ^{227}Th derived from the present work is shown in Fig. 8. The spin-parity assignments are based on the assumption of $I^{\pi}=1/2^{+}$ and $5/2^{+}$ for the ground and 9.3 keV levels, respectively. These assignments were first proposed by Leander and Chen [6] and are also assumed in the most recent Nuclear Data Sheets [11] and the work of Liang *et al.* [13,14]. The $1/2^{+}$ assignment to the ground state of ^{227}Th, which represents the basis for all other spin-parity assignments made in the present work, is now firmly established (see Sec. II B). It is interesting to note that the $3/2^{+}$ assignment to the 24 keV level follows strictly from the fact that the 24 keV transition has mixed $M1/E2$ multipolarity.

The low-energy part of the level scheme shown in Fig. 8

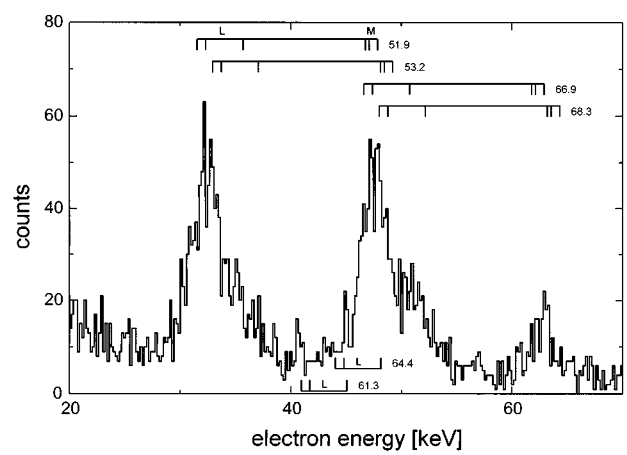

FIG. 5. Conversion-electron spectrum in coincidence with alphas in the energy range from 5365 to 5430 keV.

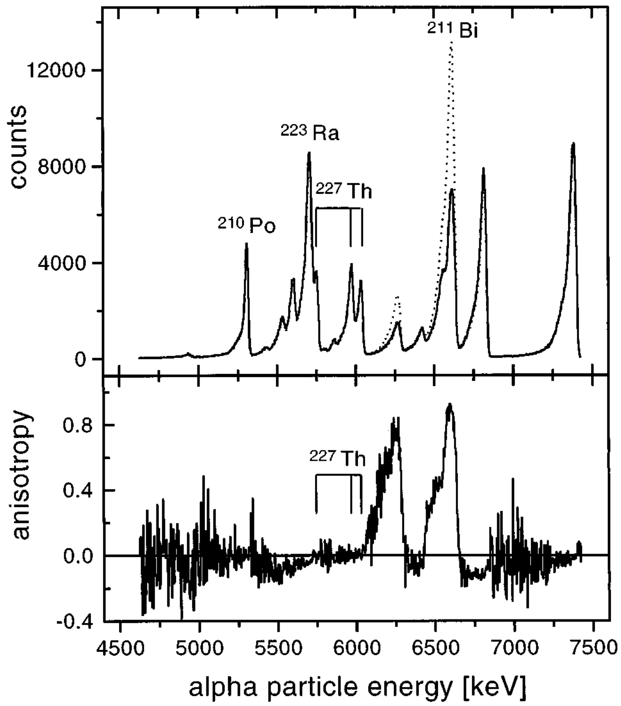

FIG. 6. Upper part: normalized intensity of α particles in the ^{227}Ac decay chain as a function of sample temperature for $\theta = 90°$. Solid line, warm sample; dashed line, sample at $T \approx 7$ mK. The α lines of interest for the discussion are labeled by the parent isotope. A contaminating ^{210}Po line is also shown. Lower part: anisotropy as a function of energy calculated from the data shown in the upper part.

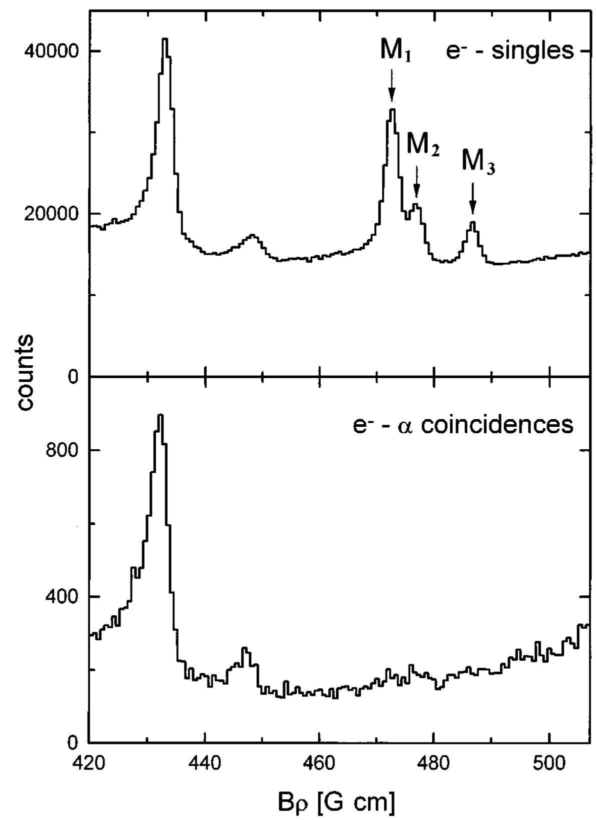

FIG. 7. Electron spectrum from 15 to 22 keV in the decay of ^{227}Ac, measured with the Bonn iron-free orange spectrometer. The spectrum shown in the upper part of the figure is the singles electron spectrum, that in the lower part the spectrum in coincidence with α particles.

agrees with that proposed by Liang *et al.* [14] from the investigation of the electron capture decay of ^{227}Pa for the 9, 24, 38, 78, 99, 127, and 184 keV levels apart from two minor though important exceptions in connection with the 99 keV level, which is strongly populated in the ^{231}U α decay, but only very weakly in the ^{227}Pa EC decay: (i) Liang *et al.* assign a 74.7(2) keV γ ray as a transition from a 142 keV level to a 67 keV level, whereas a 74.85(5) keV γ ray observed in the ^{231}U α decay is established by the $\alpha-\gamma$ coincidences as a transition from the 99 keV level to the 24 keV level. (ii) The $E1$ multipolarity of the 61.3 keV transition from the 99 kev level to the 38 keV $3/2^-$ level establishes positive parity for the 99 keV level, in contrast to the $I^\pi = 7/2^-$ assignment proposed by Liang *et al.*

A few important differences remain in the low-energy level schemes derived from the ^{231}U and ^{227}Pa decays: (i) Liang *et al.* observe 67.2 and 72.7 keV γ rays which they assign as transitions from 67.2 and 82.0 keV levels to the ground state and 9.3 keV level, respectively. We observe γ rays corresponding to these lines within the experimental errors, which we assign as depopulating new levels at 76.2 and 200.0 keV. The assignment of the 67 keV line as a $76 \rightarrow 9$ keV transition is suggested by the observation of a 52 keV γ ray, assigned as a $76 \rightarrow 24$ keV transition yielding $\Delta E_\gamma = 15.09(5)$ keV compared to the adopted energy difference of the 24 and 9 keV levels of 15.08(3) keV. The 76 keV level is further supported by the α-γ coincidences as discussed above and the observation of a 243 keV γ ray depopulating the 319 keV level (see Fig. 8). The assignment of the 73 keV γ ray as a $200 \rightarrow 127$ keV transition is established by the α-γ coincidences. The 200 keV level is also depopulated by a 190.62 keV γ ray and we note that a 190.8 keV γ ray is observed in the ^{227}Pa decay and assigned as a $229 \rightarrow 38$ keV transition. The γ-ray intensities are consistent with a double assignment of this 190.8 keV γ ray in the ^{227}Pa decay. (ii) Liang *et al.* assign a 64.40(5) keV γ ray as a $142 \rightarrow 78$ keV transition, whereas we observe a 64.38(2) keV γ ray which depopulates a level at 73.6 keV as discussed above.

The levels at 200, 231, 289, 319, and 400 keV were not observed in the EC decay of ^{227}Pa studied by Liang *et al.* [14]. We note, however, that these authors list an unassigned 157.7(3) keV γ ray which corresponds to the $231 \rightarrow 74$ keV transition in our level scheme. If this transition has $M1$ multipolarity as indicated above it would account for approximately half the intensity of the 64.40 keV γ ray depopulating a 74 keV level in the ^{227}Pa decay.

On the other hand, Liang *et al.* propose 4 levels between 200 and 400 keV at 207, 225, 229, and 252 keV. These levels require reconsideration in the light of our results: (i) The 207 keV level is based solely on the assignment of a 129.5 keV transition from this level to the 78 keV level. Liang *et al.* give no arguments for this assignment, but presumably they rejected the natural placement of the 129.5 keV γ ray as a transition from the 229 keV level to the 99 keV level because this transition has $E1$ multipolarity, whereas with their parity assignments the $229 \rightarrow 99$ keV tran-

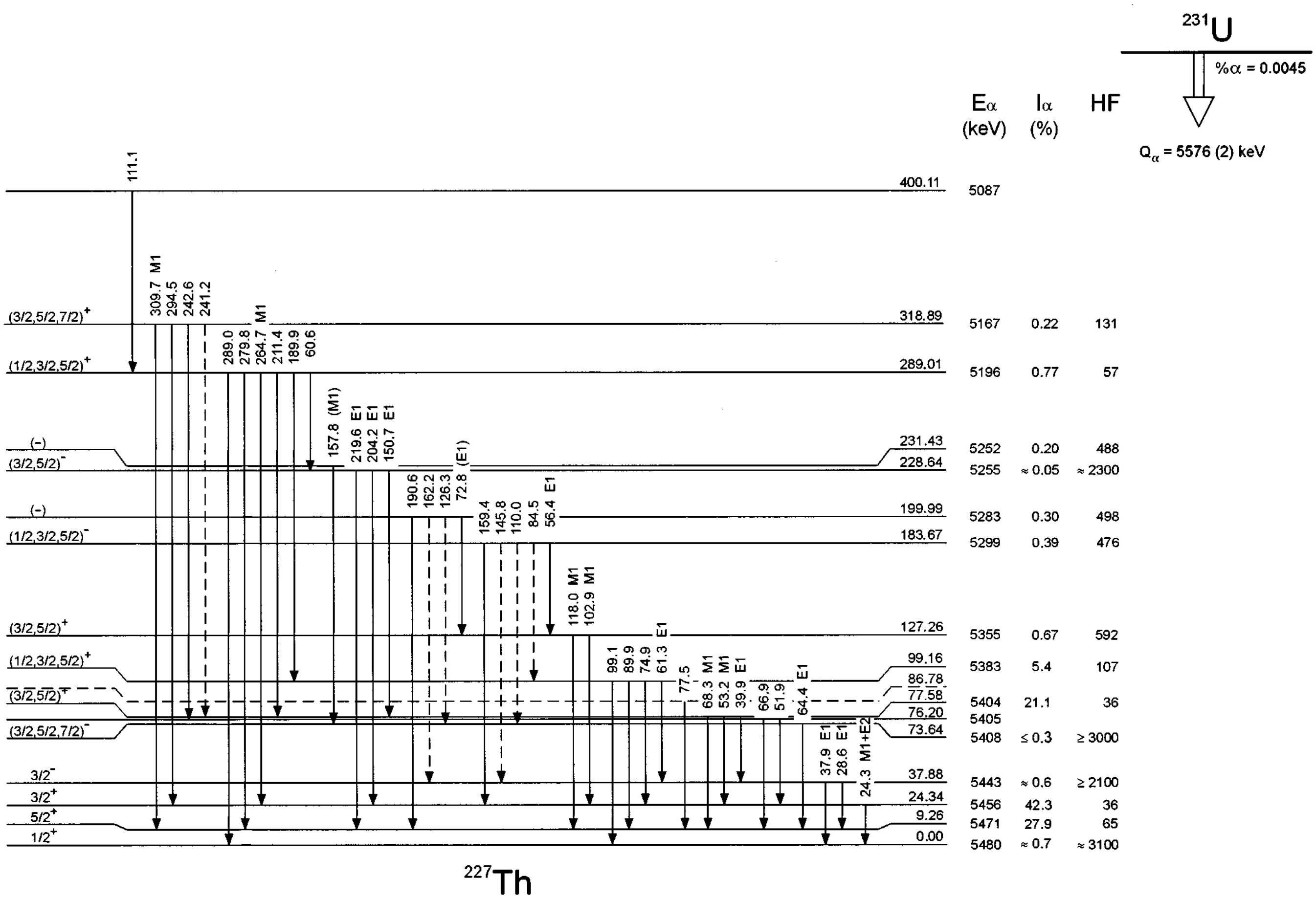

FIG. 8. Level scheme of ^{227}Th as determined from the α decay of ^{231}U. Spin parities are indicated for those levels for which the populating and depopulating γ rays restrict I^{π} to at most three values.

sition would have $M1/E2$ multipolarity. However, as discussed above, the 99 keV level has positive parity and we see no argument against the placement of the 129.5 keV γ ray as a 229→99 keV $E1$ transition only. (ii) A 225 keV level is tentatively proposed by Liang *et al.* on the basis of its decay by 143 and 216 keV transitions to the levels at 82 and 9 keV, respectively. As discussed above our experimental data make the existence of the 82 keV level highly questionable and therefore eliminate the basis for the assignment of a 225 keV level. (iii) We observe weak 151, 204, and 220 keV γ rays which are assigned in the level scheme as depopulating the 229 keV level proposed by Liang *et al.* These assignments are confirmed by the observed α-γ coincidences. We note, however, that the double assignment proposed by Liang *et al.* for the 204 keV γ-ray (689→448 keV transition) is wrong. (iv) The 252 keV level is based on its population by a 295 keV transition from a 547 keV level, and its depopulation by a 124.8 keV transition to the 127 keV level. The latter transition is not listed in Table I of Liang *et al.* but shown in their decay scheme (we note that in the figure caption to the decay scheme it is stated that a dot indicates alpha-gamma coincidences, which cannot be correct; the meaning of the dots is thus unclear). We observe a 124.8 keV γ ray in coincidence with alphas corresponding to the population of a level at 193(3) keV (not shown in the decay scheme), and thus our data do not support the 252 keV level.

In summary there is strong evidence that the assignments of the γ rays defining the 67, 82, 142, 207, and 225 keV levels in the level scheme proposed by Liang *et al.* [14] are incorrect. We suggest that these levels do not exist. All levels shown in Fig. 8 are safely established by the α-γ coincidences, except for the 87 and 400 keV level. The latter level is only assigned on the basis of the observation of a very weak α peak in coincidence with 111 keV γ rays, which are masked by the γ rays from the $2^+ \rightarrow 0^+$ transition in ^{222}Ra produced in the ^{230}U→^{226}Th→^{222}Ra α chain.

IV. DISCUSSION

The levels in ^{227}Th shown in Fig. 8 can only be interpreted on the basis of model considerations due to the lack of detailed experimental spin assignments. We therefore start our discussion by presenting in Fig. 9 the intrinsic Nilsson levels for ^{227}Th and its neighboring isotone ^{225}Ra as calculated by Cwiok and Nazarewicz [8]. This calculation predicts three intrinsic levels below 500 keV with reflection asymmetric shapes, resulting in parity doublets with $K^{\pi}=1/2^{\pm}$, $5/2^{\pm}$, $7/2^{\pm}$, and three levels with reflection symmetric shapes and $K^{\pi}=3/2^{+}$, $3/2^{-}$, and $5/2^{+}$. According to this prediction the lowest levels in ^{227}Th are expected to be rotational members of the $1/2^{\pm}$ parity doublet and the $3/2^{+}$ level.

The basis for the interpretation of the levels in ^{227}Th was suggested by Leander and Chen [6] who have interpreted the

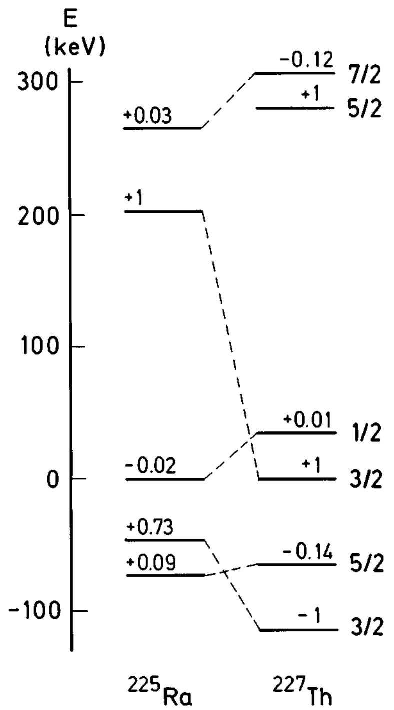

FIG. 9. Intrinsic levels predicted in ^{225}Ra and ^{227}Th [8]. The numbers on the level bars are the parity content $\langle\pi\rangle$, those besides the bars the spins. Levels with $\langle\pi\rangle \sim 0$ are predicted to be parity doublets.

three lowest levels known from the β decay of ^{227}Ac as $1/2^+$ and $5/2^+$ members of a $K^\pi = 1/2^+$ band and bandhead of a $K^\pi = 3/2^+$ band (ground state, 9.3 keV and 24 keV levels, respectively). One comment on this interpretation seems appropriate: it is based, in addition to the $1/2^+$ assignment for the ground state, on the assumption of $E2$ multipolarity for the 9.3→0 keV transition derived from the conversion-electron data of Novikova *et al.* [10]. From this work an M-subshell ratio of $M_3/M_2 = 1.1$ is obtained which is inconsistent with pure $M1$ multipolarity but consistent with pure $E2$ multipolarity ($M_3/M_2 = 0.068$ and 1.19 for $M1$ and $E2$ multipolarity, respectively). However, due to the fact that the relevant conversion coefficients for $E2$ multipolarity are more than 1000 times larger than those for $M1$ multipolarity the experimental M-subshell ratio is consistent with an $E2/M1$ mixing ratio of $\delta^2 > 2\times10^{-3}$, e.g., with up to 99.8% $M1$ multipolarity. Even this small $E2$ content is unlikely for such a low-energy transition [the Weisskopf estimate is $\delta^2(9.3\ \text{keV}) = 2.7\times10^{-7}$] which makes the assumption of pure $E2$ multipolarity plausible. We will therefore adopt the interpretation of the lowest levels given by Leander and Chen although it must be clearly noted that it is not yet strictly established by experiment. The $3/2^+$ and $5/2^+$ states are populated in the α decay with comparatively low hindrance factors whereas the $1/2^+$ ground state is only weakly populated. Liang *et al.* [13] suggest that this might be explained by a coupling of the rotational members of the $1/2^+$ and $3/2^+$ bands with the same configuration as the ^{231}U ground state, which is expected to have $I^\pi = 3/2^+$ or $5/2^+$. The $1/2^+$ ground state would then be unable to Coriolis couple with any state related to the ^{231}U ground state which would explain its low population in α decay.

The $K^\pi = 1/2^+$ and $3/2^+$ bands are expected to be strongly coupled by Coriolis interaction and the above explanation of the hindrance factors suggests that the levels in ^{227}Th populated with low hindrance factors—the 77.6 and 99.2 keV levels—belong to these coupled bands. The spin parity of the 77.6 keV level is restricted from its $M1$ decays to $3/2^+$ or $5/2^+$, and thus it could be the $3/2^+$ member of the $1/2^+$ band or the $5/2^+$ member of the $3/2^+$ band. To distinguish these two possibilities we have performed two-band mixing calculations. The level energies of the unperturbed $K = 1/2$ and 3/2 bands and the matrix element of the Coriolis interaction H_c are given by

$$E_I(K=1/2) = A_1[I(I+1) + a(-1)^{I+1/2}(I+1/2)] + E_0(K=1/2),$$

$$E_I(K=3/2) = A_2 I(I+1) + E_0(K=3/2),$$

$$\langle K=3/2|H_c|K=1/2\rangle = \langle 3/2|h_{+1}|1/2\rangle \sqrt{(I-1/2)(I+3/2)}.$$

Assuming $A_1 = A_2 = A$ the four band constants A, a, $E_0(K=1/2)$, and $E_0(K=3/2)$ can be calculated for a given reduced interaction matrix element $\langle 3/2|h_{+1}|1/2\rangle$ (which we will denote $\langle h_{+1}\rangle$) from the $1/2^+$, $5/2^+$, $3/2^+$, and $3/2^+$ (left side of Fig. 10) or $5/2^+$ (right side of Fig. 10) states at 0, 9.3, 24.3, and 77.6 keV. The level energies of the remaining band members can then be calculated and are shown up to the $9/2^+$ states as a function of $\langle h_{+1}\rangle$ in Fig. 10 (for the case that the 77.6 keV level is the $3/2^+$ member of the $K = 1/2$ band the energy of the $9/2^+$ member of this band at $\langle h_{+1}\rangle = 0$ is 67.4 keV, and not 24.6 keV as given by Liang *et al.* [14]; the band constants quoted by these authors for the $1/2^+$ band are in error).

The calculation suggests that the 86.8 keV level tentatively observed in the present work is the $9/2^+$ member of the $1/2^+$ band and the 99.2 keV level is the missing $3/2^+$ or $5/2^+$ state. Assuming these assignments to be correct we have calculated optimal band constants for the two spin assignments of the 77.6 keV level as given in Table II. With both assumptions the experimental energies can be reproduced satisfactorily, in particular if the A coefficients are allowed to be different. We believe, however, that the band constants for the $5/2^+$ assignment of the 77.6 keV level are more reasonable than those for the $3/2^+$ assignment. We therefore prefer to assign the 77.6 keV level as the $5/2^+$ member of the $K^\pi = 3/2^+$ band, and consequently the 86.8 and 99.2 keV levels as $9/2^+$ and $3/2^+$ members of the $K^\pi = 1/2^+$ band, respectively. It is interesting to note that with this interpretation the $7/2^+$ member of the $K^\pi = 3/2^+$ band is predicted to lie close to the 127.3 keV level. It is in fact possible, with a slight change of the band constants, to reproduce all levels including the 127.3 keV level to better then 0.1 keV. However, if the $M1$ multipolarity of the 103 keV 127.3→24.3 keV transition is correct such an interpretation is excluded. Finally, we have included in Table II the amplitudes $c(K)$ of the wave functions for the calculation denoted calc(B). These values show that the various levels can still be associated with the two different bands: all levels listed in Table II retain their unperturbed K values to more than 90%. Note, however, the alternating sign of the ad-

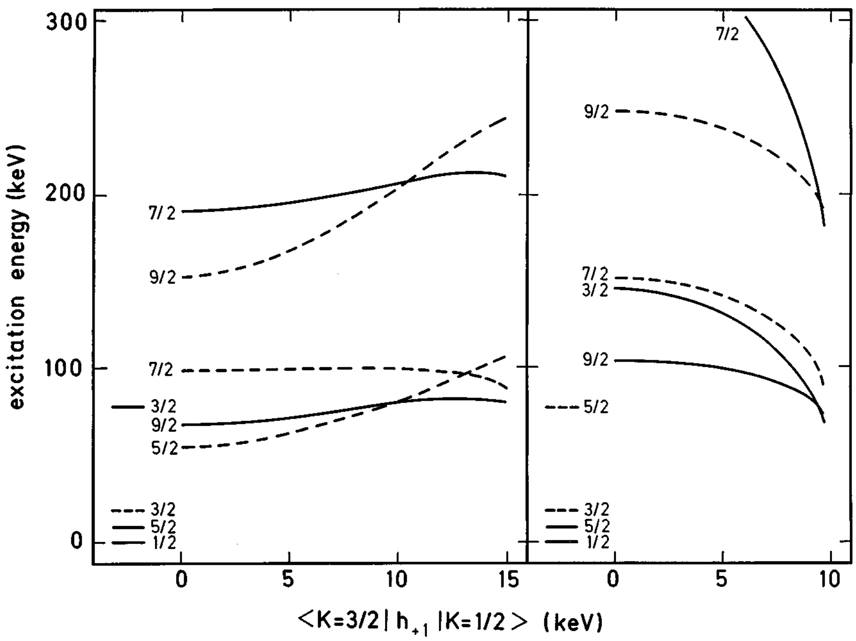

FIG. 10. Energies of the Coriolis-coupled $K^{\pi}=1/2^{+}$ and $3/2^{+}$ bands vs the reduced Coriolis interaction matrix element $\langle 3/2|h_{+1}|1/2\rangle$ [left part for $I(78\,\text{keV})=3/2$, right part for $I(78\,\text{keV})=5/2$]. The levels resulting from the $K=1/2(3/2)$ band are shown by the solid (dashed) lines.

mixed amplitude within a given band which is due to the fact that the members of the two bands alternate in being the lower level at a given spin due to the decoupling term in the energies of the $K=1/2$ band. This feature has an influence on the γ-ray branching ratios as discussed below.

As emphasized previously [8,14] the $K^{\pi}=1/2^{+}$ band is predicted to be the member of a parity doublet and one thus expects a close-lying $K^{\pi}=1/2^{-}$ band. The decoupling parameters of the $K=1/2$ parity doublet bands are expected to be similar in magnitude but opposite in sign, and thus the $K^{\pi}=1/2^{-}$ band should have a $3/2^{-}$ bandhead. This led Liang *et al.* [14] to suggest the 38 keV $3/2^{-}$ state as bandhead of a $K^{\pi}=1/2^{-}$ band, with the 99 and 229 keV levels as $7/2^{-}$ and $5/2^{-}$ members of this band, respectively. As discussed above the 99 keV level has positive parity, but an obvious candidate for the $7/2^{-}$ member of the $1/2^{-}$ band is the 74 keV level: it decays, as expected, by an $E1$ transition to the $5/2^{+}$ member of the parity doublet partner. The assignment of the 229 keV level as the $5/2^{-}$ member of this band is supported by the observed α-decay hindrance factors and the γ decay of this level as discussed below. Since there is no obvious candidate for a close-lying $K^{\pi}=3/2^{-}$ band to Cori-

TABLE II. Energy levels and band constants from Coriolis coupling of the lowest $K^{\pi}=1/2^{+}$ and $3/2^{+}$ bands in ^{227}Th.

Energy level		Level energies and band constants[a]						Wave functions[b]	
K^{π}	I	Expt.	calc(A)	calc(B)	Expt.	calc(C)	calc(D)	$c(1/2)$	$c(3/2)$
$1/2^{+}$	3/2	99.16	99.15	99.16	77.58	77.96	77.79	0.985	0.171
	5/2	9.26	8.76	9.26	9.26	10.32	9.99	0.948	−0.317
	7/2		250.78	249.20		215.00	216.35	0.972	0.234
	9/2	86.78	86.99	86.78	86.78	86.40	86.55	0.962	−0.273
$3/2^{+}$	3/2	24.34	24.47	24.35	24.34	23.91	24.12	−0.171	0.985
	5/2	77.58	77.50	77.57	99.16	99.13	99.19	0.317	0.948
	7/2		117.66	125.79		96.08	109.44	−0.234	0.972
	9/2		214.21	222.20		238.32	252.31	0.273	0.962
Band constants									
$A(1/2)$			8.21	8.08		7.58	7.26		
$A(3/2)$			8.21	8.84		7.58	8.93		
a			2.91	3.00		1.80	2.03		
$\langle 3/2\|h_{+1}\|1/2\rangle$			8.25	7.26		13.76	12.82		
ΔE[c]			27.31	26.52		38.20	35.88		

[a]All energies are in keV. The calculations A and B were performed assuming that the 77.6 keV level is the $5/2^{+}$ member of the $K^{\pi}=3/2^{+}$ band, with equal and different moments of inertia for the two bands, respectively. In the calculations C and D the 77.6 keV level is assumed to be the $3/2^{+}$ member of the $K^{\pi}=1/2^{+}$ band.

[b]Wave functions for calc(B). The matrix element $\langle 3/2|h_{+1}|1/2\rangle$ was arbitrarily assumed to be positive.

[c]Energy difference of the unperturbed bandheads.

TABLE III. Ratios of reduced transition probabilities for transitions among the $K^\pi=1/2^+$, $1/2^-$ and $3/2^+$ bands in ^{227}Th.

Initial level		Final levels				Multipolarity	$\frac{B(\lambda,I_1\to I_2)}{B(\lambda,I_1\to I_3)}$
E_1 (keV)	$I_1^\pi K$	E_2 (keV)	$I_2^\pi K$	E_3 (keV)	$I_3^\pi K$	λ	
24.34	$3/2^+3/2$	0	$1/2^+1/2$	9.26	$5/2^+1/2$	$M1$	0.087 *16*
77.58	$(5/2^+3/2)$	24.34	$3/2^+3/2$	9.26	$5/2^+1/2$	$M1$	1.8 *3*
99.16	$(3/2^+1/2)$	0	$1/2^+1/2$	9.26	$5/2^+1/2$	$M1$[a]	0.19 *6*
		24.34	$3/2^+3/2$	9.26	$5/2^+1/2$	$M1$[a]	0.83 *24*
24.34	$3/2^+3/2$	0	$1/2^+1/2$	9.26	$5/2^+1/2$	$E2$	0.25 *7*
37.88	$3/2^-1/2$	0	$1/2^+1/2$	9.26	$5/2^+1/2$	$E1$	0.49 *7*
228.64	$(5/2^-1/2)$	99.16	$(3/2^+1/2)$	9.26	$5/2^+1/2$	$E1$	4.2 *8*
		24.34	$3/2^+3/2$	77.58	$(5/2^+3/2)$	$E1$	1.06 *11*
		77.58	$(5/2^+3/2)$	99.16	$(3/2^+1/2)$	$E1$	1.0 *2*

[a]The transitions from the 99.16 keV level are assumed to have pure $M1$ multipolarity.

olis couple with the $1/2^-$ band we can only calculate the band constants from the energy equation without Coriolis coupling. The resulting band constants are $A=8.00$ keV, $a=-3.77$, and $E_0=66.15$ keV. These parameters are quite reasonable and thus indicate, that the $K^\pi=1/2^-$ band might be less strongly influenced by Coriolis couplings than the $1/2^+$ band, as was also observed for the analogous bands in ^{225}Ra [22]. Using these band constants we calculate the energies of the $1/2^-$ and $9/2^-$ band members as 104.3 and 417.0 keV, respectively. It is clear that these levels could not have been observed in the ^{231}U α decay.

Another source of information on K-value assignments is generally provided by the γ-ray branching ratios. Unfortunately, in the present case the useful information is rather limited, but we will discuss it briefly. The ratios of reduced transition probabilities for transitions between the members of the $K=1/2$ parity doublet bands and the Coriolis coupled $3/2^+$ band are summarized in Table III. The $B(M1)$ and $B(E2)$ ratios for the 24 keV level are derived from the conversion-electron data of Novikova *et al.* [10] assuming a 20% error in the ratios of electron intensities and the $E2/M1$ mixing ratio for the 24 keV transition given above. The remaining ratios are derived from the γ-ray data of Liang *et al.* [14] and the present work.

The $M1$ transition rates among the members of the $K^\pi=1/2^+$ and $3/2^+$ coupled bands involve four parameters, none of which is predicted to dominate [23,24]. Thus the $B(M1)$ ratios are expected to depend in a complicated way on the details of the Coriolis-coupled wave functions and cannot be predicted reliably. This is most apparent for the $B(M1)$ ratio from the 24 keV $3/2^+$ level, which deviates strongly from the value of 5 expected for pure $K=3/2\to K=1/2$ transitions despite the fact, that the states involved probably still have quite clean wave functions (see the two last columns in Table II). We note here that Leander and Chen [6] briefly discuss this $B(M1)$ ratio and mention a calculation yielding a result of 0.015.

The $E2$ transition probabilities also involve four parameters, although one can expect that the two intrinsic electric quadrupole moments are similar and the signature-dependent term in the $E2$ matrix element [Eq. (4.91) of [24]] is small. The Coriolis coupling gives in general, to first order, only a renormalization of the intrinsic transition moment, without any effect on the relative transition probabilities [24] and in fact the experimental $B(E2)$ ratio for the 24 keV level is in agreement with the theoretical ratio for pure K values of 7/27. However, the renormalization statement is only valid for the normal case where the amplitudes of the admixed component in the wave functions of the coupled bands have the same sign within each band, but this is not so in the present case (see Table II). Therefore, if we neglect the intrinsic $E2$ moment, assume equal Q_0's for the two bands and use the wave functions of Table II we obtain a value of 0.08 for the $B(E2)$ ratio.

The $E1$ transition probabilities between $K=1/2$ bands involve two parameters. For the parity doublets in octupole-deformed nuclei one expects enhanced $E1$ transitions [6], and therefore the signature-dependent term can be expected to be small. This is borne out by the $B(E1)$ ratio for the transitions depopulating the 38 keV $3/2^-$ level: the theoretical ratio is

$$B(E1,3/2^-1/2\to 1/2^+1/2)/B(E1,3/2^-1/2\to 5/2^+1/2)$$
$$=(5/9)\cdot[(1-r)/(1+r)]^2$$

with

$$r=(1/\sqrt{2})\cdot\langle 1/2|M(E1,1)|1/2\rangle/\langle 1/2|M(E1,0)|1/2\rangle$$

yielding from the experimental $B(E1)$ ratio $r=0.03(4)$.

For the $B(E1)$ ratios from the 229 keV level to the members of the $K^\pi=1/2^+$ and $3/2^+$ bands listed in Table III the theoretical values for pure K and $r=0$ are 14 and 7/48, respectively. The agreement with the experimental results is not very good, but this might result from the fact, that in both branching ratios one transition probability is very small and therefore sensitive to additional mixings.

If the 73.6 keV level is the $7/2^-$ member of the $K^\pi=1/2^-$ band one expects it to decay also by a 35.8 keV $E2$ transition to the 37.9 keV $3/2^-$ bandhead. For the $[7/2^-(E2)3/2^-]$ to $[7/2^-(E1)5/2^+]$ branching ratio one obtains (with total conversion coefficients of 1614 and 0.384 for the 35.8 keV $E2$ and 64.4 keV $E1$ transitions, respectively)

$$I_{tot}(E2,7/2^-\to 3/2^-)/I_{tot}(E1,7/2^-\to 5/2^+)$$
$$=19.7\times 10^{-8}\cdot B(E2,7/2^-\to 3/2^-)/B(E1,7/2^-\to 5/2^+)$$

with $B(E2)/B(E1)$ in fm^2.

If the levels involved are members of a $K=1/2$ parity doublet the $B(\lambda)$'s can be expressed in terms of intrinsic electric dipole (D_0) and quadrupole (Q_0) moments as

$$B(E1,7/2^- \to 5/2^+)/B(E2,7/2^- \to 3/2^-) = 4\cdot(D_0/Q_0)^2.$$

A lower limit for D_0/Q_0 can be obtained from the γ-ray intensities of the $E1$ transitions depopulating the $3/2^-$ and $7/2^-$ levels. With total conversion coefficients of 3.29 and 1.56 for the 28.6 and 37.9 keV transitions, respectively, one obtains

$$I_{\text{tot}}(E2,7/2^- \to 3/2^-)/I_{\text{tot}}(E1,7/2^- \to 5/2^+) < 4$$

and thus $|D_0/Q_0| > 1.1\times10^{-4}$ fm^{-1}. This result can be compared with the values of 3.7×10^{-4} fm^{-1} and 1.4×10^{-4} fm^{-1} for ^{226}Th and ^{228}Th, respectively [25]. Thus the γ-ray intensities of the $E1$ transitions depopulating the 37.9 and 73.6 keV levels are consistent with the interpretation of these levels as $3/2^-$ and $7/2^-$ members of a $K=1/2$ parity doublet.

We conclude that the γ-ray branching ratios are not inconsistent with the assignments of the $K=1/2$ parity doublet and $3/2^+$ bands. The $E1$ transition rates support the interpretation of the 39 keV $3/2^-$ level as bandhead of a $K=1/2^-$ band.

We observe two additional levels below 150 keV, at 76 and 127 keV, which cannot be associated with the three bands discussed so far. The theoretical calculations predict a $K=5/2$ parity doublet at an excitation energy of 65 keV (see Fig. 9). The α population and γ depopulation of the 76 and 127 keV levels is not inconsistent with spin-parity assignments of $5/2^-$ and $5/2^+$, respectively. We therefore very tentatively assign these levels as bandheads of the 5/2 parity doublet, although it has to be stressed that the experimental evidence is too limited to strongly suggest such an interpretation. We note, however, the exceptionally strong population of the 127 keV level by $E1$ transitions from the 184 and 200 keV levels (see discussion below). It would be interesting to investigate theoretically whether this feature gives a hint about the structure of the levels involved.

Two higher-lying groups of levels are observed in ^{227}Th in the ^{231}U α decay which have properties suggesting that they belong to common bands. The three levels at 184, 200, and 231 keV have almost identical α-decay hindrance factors. All three levels decay to the 74 keV ($7/2^-$) level. And, most significantly, the 184 and 200 keV levels decay preferentially by $E1$ transitions to the 127 keV level: the reduced $E1$ transition probabilities from these levels to the 127 keV level are almost 100 times larger than those to the members of the $K=1/2^+$ and $3/2^+$ bands. It is interesting to note that these three levels could be the lowest members of a $3/2^-$ rotational band with $A\sim3.4$ keV. Of course this would yield an unreasonably high moment of inertia, but the levels could be disturbed by the Coriolis coupling to a higher-lying $K^\pi=5/2^-$ band. We finally note that Liang *et al.* [14] interpret the 184 keV level as the $5/2^-$ member of a $K=3/2^-$ band which they interpret as a strongly Coriolis-distorted member of a $K=3/2$ parity doublet.

The two levels at 289 and 319 keV with positive parity are populated with similar α-decay hindrance factors. Their γ decay is consistent with spin-parity assignments of $5/2^+$ and $7/2^+$, respectively, suggesting an interpretation as lowest members of a $K^\pi=5/2^+$ band in accordance with the theoretical prediction (see Fig. 9). Again, the resulting $A\sim4.3$ keV would yield an unreasonably large moment of inertia, but this could be due to a coupling with a close-lying $K^\pi=7/2^+$ band, which is in fact predicted to lie just above the $5/2^+$ band.

V. CONCLUSION

We have identified 16 excited levels below 400 keV in ^{227}Th from a study of the ^{231}U α decay, of which 8 were not known previously. The lowest levels are interpreted in terms of two Coriolis-coupled $K^\pi=1/2^+$ and $3/2^+$ bands and a $1/2^-$ band. The two $K=1/2$ bands have decoupling parameters of similar absolute value, but opposite sign, suggesting an interpretation as parity doublet bands in a reflection-asymmetric average nuclear field. Three levels at ~200 keV are tentatively interpreted as lowest members of a $K^\pi=3/2^-$ band. Two different interpretations have been suggested for the low-lying $K^\pi=3/2^+$ and $3/2^-$ bands: they could be just normal Nilsson orbitals being accidentally close in energy [8] or members of a parity doublet in a reflection-asymmetric nuclear field [14]. We feel that the experimental evidence does not yet allow a distinction between these two possibilities. The crucial evidence for the parity doublet interpretation of the $K=3/2$ bands would probably be the observation of enhanced $E1$ transitions between these bands. The existing experimental evidence indicates that such transitions do not occur, and we therefore favor an interpretation of the low-lying $K=1/2$ and 3/2 bands in terms of the coexistence of reflection-symmetric ($K=3/2$ bands) and reflection-asymmetric ($K=1/2$ bands) shapes.

One comment seems necessary in connection with the tentatively proposed 86.8 keV $9/2^+$ level. This level is based solely on the assignment of a 77.5 keV γ ray as a transition to the 9.3 keV level. This γ ray could also be placed as a transition from the 77.6 keV level to the ground state, but the coincident α spectrum seems to exclude such a placement (see Sec. II A). If the assignment of the 87 keV level is correct one would expect a strong population of this level in the ^{226}Ra(α,3n) reaction. However, in our recent extensive investigation of this reaction we observe no trace of such a 77.5 keV $E2$ transition [26] which makes the assignment of the 87 keV level questionable.

Very tentative evidence is also found for a $K=5/2$ parity doublet at ~100 keV and a $K^\pi=5/2^+$ band at ~300 keV, as predicted theoretically.

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