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Decay studies of $^{215-217}$Th using ER-γ-α-γ coincidences

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Abstract. The decay of $^{215-217}$Th was investigated by ER-γ-α-γ coincidence measurements. The nuclei were produced by the reaction ^{170}Er(^{50}Ti, xn)$^{220-x}$Th. Evaporation residues recoiling out of the target were separated in flight by the velocity filter SHIP and stopped in a position-sensitive 16-strip PIPS-detector in order to study their subsequent decays. Associated γ-rays were detected by a fourfold Ge-Clover detector. In the present work we extracted new and improved data for $^{215-217}$Th including isomeric decays. The results are discussed and compared to previously published data.

PACS. 23.60.+e α decay – 23.20.Lv γ transitions and level energies – 27.80.+w $190 \leq A \leq 219$

1 Introduction

The measurement of α-γ coincidences presents a unique tool to study the structure of nuclei near the closed neutron shell $N = 126$. Results of our previous work were published in refs. [1–6]. In this work we present new data of an investigation of the isotopes $^{215-217}$Th. In several cases we measured α fine-structure transitions in coincidence with γ transitions. In addition to the technique applied in our previous investigation we also employed delayed γ coincidences enabling the study of isomeric transitions. Apart from that, the experimental procedure is already explained in detail in refs. [5,6], so only the most relevant details are given here.

2 Experimental procedure

The nuclei to be studied were produced in the reaction ^{170}Er(^{50}Ti, xn)$^{220-x}$Th. A ^{50}Ti beam was delivered from the UNILAC at GSI, Darmstadt. The incident beam energy was 4.35 $A \cdot$ MeV at an intensity of $\approx$ 200 pnA. The targets of $\approx$ 0.4 mg/cm^2 thick ^{170}Er evaporated on 30 μg/cm^2 thick carbon foils were mounted on a wheel that rotated synchronously to the beam macro structure (beam pulses of 5 ms followed by 15 ms beam-off periods). Evaporation residues (ER) recoiling out of the targets were separated from the primary beam by the velocity filter SHIP [7] and implanted into a position-sensitive 16-strip PIPS-detector (active area 80 $\times$ 35 mm^2) where their arrival and subsequent decays were registered [8,9]. The Si detector was cooled to a temperature of $\approx$ 258 K to achieve an energy resolution of $\approx$ 25 keV (FWHM) for 8 MeV α-particles. For energy calibration we used most intense α lines from ^{209,210,212}Rn, ^{213}Fr, ^{213,214}Ra, ^{215}Ac and ^{216}Th [10].

For γ-ray studies we used a Ge-Clover detector constituted of four individual crystals, each of 70 mm diameter and 140 mm length. The detector was placed behind the Si detector in close geometry. Coincidences between α-particles and γ-rays were recorded within a 5 μs time interval. Compared with our previous studies (see, for example, [5]) the experimental setup was modified such that γ-rays were recorded without coincidence conditions in order to study γ transitions following ERs, α's and γ's after a time interval considerably longer than the previously used coincidence time window of 5 μs. Energy and relative efficiency calibration of the Ge detector was carried out using ^{133}Ba and ^{152}Eu γ sources. Due to different geometries of a point-like γ source and a broad spacial distribution of implanted recoils at the focal plane of SHIP, the absolute efficiency of the Ge detector was estimated internally using the ratio of α-γ coincidences and α-decays of ^{217}Th (see sect. 3.3). The absolute efficiency corresponded to a photo-peak efficiency of $(5.0 \pm 0.5)\%$ at 1.3 MeV.

The ER-γ-α-γ correlation/coincidence measurements were performed in order to identify γ-rays depopulating isomeric states and to observe weak α transitions hidden among strong ones (see fig. 1 as an example).

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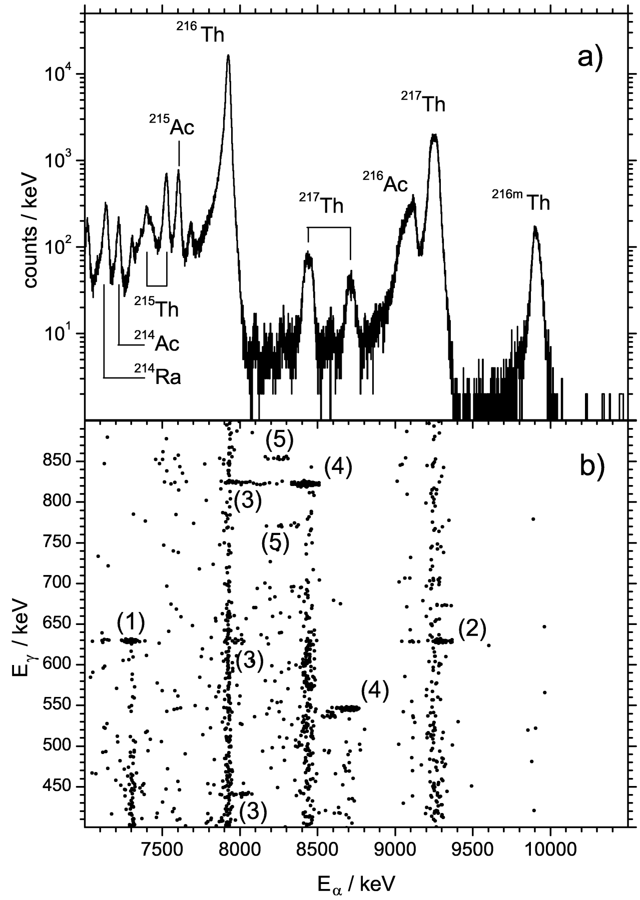

Fig. 1. a) Singles α spectrum recorded in the ^{50}Ti + ^{170}Er reaction at the 4.35 $A \cdot$MeV beam energy. b) α-γ coincidences marked as follows: (1) ^{216g}Th α-decay to the 2^+ state in ^{212}Ra, which depopulates by 629.3 keV γ-rays, (2) ^{216m}Th α-decay to the 2^+ state in ^{212}Ra, (3) ^{216m}Th α-decay to ^{212m}Ra which is depopulated by a cascade of 440.8, 825.0 and 629.3 keV γ-rays, (4) ^{217}Th α-decay to the $(5/2^-)$ and $(3/2^-)$ states in ^{213}Ra, which are depopulated by 546.1 and 822.5 keV γ-rays, respectively, and (5) ^{216}Ac α-decay to the level at 853.7 keV in ^{212}Fr, which is depopulated by 771.3 and 853.7 keV γ-rays.

In the present work α-particles emitted by the mother nuclei were assigned on the basis of $Q_\alpha + E_\gamma$ values if they were within ± 5 keV to that of the ground-state–to–ground-state (g.s.–to–g.s.) α-decay. The Q_α values were calculated using the measured α-particle energy E_α and the relation $Q_\alpha = (1 + m_\alpha/m_\mathrm{d}) \times E_\alpha$, where m_α and m_d are the masses of the α-particle and daughter nucleus, respectively. The α-decay hindrance factors were calculated according to the method of Rasmussen [11]. Transitions connecting excited states were placed on the basis of γ-γ coincidences and of γ-ray energy and intensity balances.

3 Results and discussion

3.1 ^{215}Th

Valli and Hyde [12] reported for the decay of ^{215}Th a half-life of 1.2±0.2 s and α-particle energies of 7524±8, 7395±8 and 7333 ± 10 keV. The relative α intensities were estimated to be (40 ± 3)%, (52 ± 3)% and (8 ± 3)%, respectively. The results were verified by Heßberger *et al.* [1] who were also able to identify the two low-lying levels by α-γ coincidences with γ-rays at 133.6±0.4 and 192.4±1.5 keV.

Table 1. α-decay of ^{215}Th and γ transitions in ^{211}Ra observed in the present work.

E_α (keV)	$E_\mathrm{level}^\mathrm{daughter}$ (keV)	E_γ (keV)	I_γ^rel (%)	Mult.
7523 ± 5	0			
7392 ± 4	133.9 ± 0.1	133.9 ± 0.1	100	$E2$
7335 ± 5	194.5 ± 0.1	194.5 ± 0.1	100 ± 6	$M1$
		60.9 ± 0.3	11 ± 4	
7236 ± 7	295.1 ± 0.3	295.1 ± 0.3	(100)$^{(a)}$	($M1$)

(^{a}) On the basis of the $N = 123$ isotones possible relative γ-ray intensities to the 133.9 and 194.5 keV levels were estimated (after consideration of conversion processes) to be less than 30% and 5%, respectively.

In the present work the decay of ^{215}Th was also studied using α-γ coincidences. In addition to the previously reported energy levels a weak α branch peaking at 7236 ± 7 keV was observed in coincidence with 295 keV γ-rays. Because of electron summing resulting from internal conversion we were not able to extract α intensities reliably for the previously observed levels, but an upper limit for the g.s.–to–g.s. α-decay with 52% and lower limits for α-decays to the 134 and 195 keV levels with 41% and 6%, respectively, could be estimated. However, the relative population for the newly established level was extracted. Since it is well separated from other α lines and its transition energy is relatively high, losses due to internal conversion are expected to be small. The study resulted in an α branch of (1.0±0.4)% for the level at 295.1±0.3 keV. Our results are listed in table 1 and fig. 2.

The total conversion coefficients for the 134, 195 and 295 keV transitions were extracted using the ratio of observed α-γ coincidences and calculated ones expected for the given α line. The expected numbers of α-γ coincidences were calculated using the absolute efficiency of the Ge detector (see sect. 3.3). Furthermore, in order to avoid systematic errors in α intensities due to summing with conversion electrons, we decided to use the α intensities reported in [12] for the previously reported levels and an α intensity of (1.0 ± 0.4)% for the level at 295 keV.

The study resulted in measured conversion coefficients $\alpha_\mathrm{tot} = 2.5 \pm 0.5$, 3.8 ± 1.7 and 1.0 ± 0.5 for the 134, 195 and 295 keV transitions, respectively. These values can be compared with theoretical ones of Rösel *et al.* [13]. For the 134 keV transition the measured value is consistent with $\alpha_\mathrm{tot}^{E2} = 2.8$ while $\alpha_\mathrm{tot}^{E1} = 0.24$, $\alpha_\mathrm{tot}^{M1} = 7.3$ and $\alpha_\mathrm{tot}^{E3} = 51$ are excluded. Therefore, we conclude that the 134 keV transition is $E2$. Our multipolarity assignment is supported by relative intensities of radium K X-rays and ^{211}Ra γ-rays gated by ^{215}Th α-decays. As the relative γ intensities for 134, 195 and 295 keV (normalized to 134 keV γ-rays) are $(100 \pm 3) : (14 \pm 2) : (1.2 \pm 0.4)$ and the relative intensity ratio between radium K X-rays and 134 keV γ-rays is $(77 \pm 7) : (100 \pm 3)$, respectively, a significant contribution

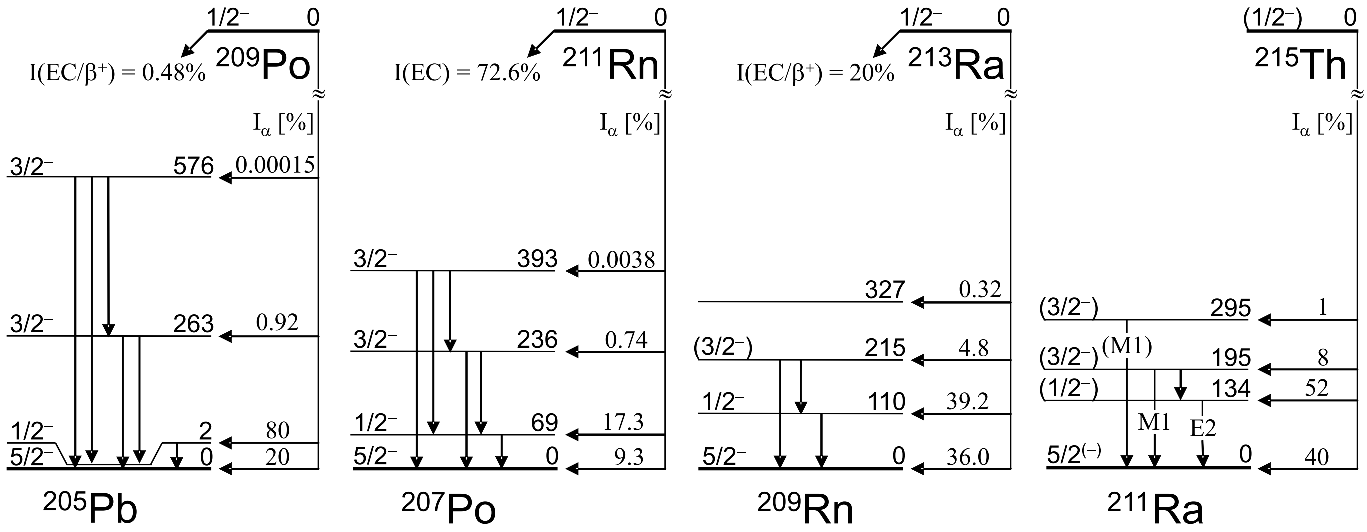

Fig. 2. Partial level schemes (four lowest-lying levels) of the $N = 123$ even-Z isotones. The data for ^{211}Ra including the α intensity for the level at 295 keV, γ transitions and proposed spins and parities for excited states are from the present work, while other data are taken from [10].

to the radium K X-rays results from the 134 keV transition. Since the ratio corresponds to an upper limit of the K-conversion coefficient $\alpha_K < 0.9$, we can exclude magnetic transitions for which $\alpha_K \geq 5.9$ [13].

The measured total conversion coefficient for the 195 keV transition can be compared with the theoretical ones $\alpha_{\rm tot}^{E2} = 0.66$, $\alpha_{\rm tot}^{M1} = 2.5$, $\alpha_{\rm tot}^{E3} = 7.2$ and $\alpha_{\rm tot}^{M2} = 11$. This leads us to conclude that it has an $M1$ character. Finally, the measured conversion coefficient for the 295 keV transition is $\alpha_{\rm tot} = 1.0 \pm 0.5$ which fits to both $M1$ and $E3$ transitions with $\alpha_{\rm tot}^{M1} = 0.8$ and $\alpha_{\rm tot}^{E3} = 1.1$, respectively. Since $\alpha_{\rm tot}^{E2} = 0.16$ and $\alpha_{\rm tot}^{E4} = 5.7$ are excluded, the 295 keV transition is either $M1$ or $E3$. However, the 295 keV γ-rays were observed prompt in the α-γ-TAC spectrum, while an $E3$ transition, according to a Weisskopf estimate (see, for example, [10]), could be expected to have a lifetime of an order of a millisecond. Therefore, we tentatively conclude that the 295 keV transition is $M1$.

As the g.s. of ^{211}Ra is assigned to a $5/2^{(-)}$ level [10], with the given multipolarities we tentatively conclude that the levels at 134, 195 and 295 keV are the $1/2^-$, $3/2^-$ and $3/2^-$ states, respectively. These results can be compared with the $N = 123$ even-Z isotones which have very similar level schemes as illustrated in fig. 2. A smooth change in energies of the low-lying states indicates similar nuclear structures.

In addition, we observed delayed γ-rays at 560.8 ± 0.2 and 860.5 ± 0.2 keV (fig. 5b below) with half-lives of 0.78 ± 0.07 and 0.75 ± 0.11 μs, respectively. Since they coincided in γ-γ and ER-γ-α coincidences gated by ^{215}Th α-particles, we conclude that there is an 0.77 ± 0.06 μs isomeric state in ^{215}Th which de-excites by a cascade of 561 and 861 keV γ-rays. On the basis of the level systematics observed in the lighter $N = 125$ isotones [10] we tentatively assign the level at 561 keV to be the $5/2^-$ state in ^{215}Th, while the 861 keV transition needs further investigation.

In the ^{209}Po, ^{211}Rn and ^{213}Ra isotones the low-lying $5/2^-$ states are populated by the $9/2^-$ states with approximately linearly increasing level energies as proton pairs are added to ^{207}Pb (see, *e.g.*, [10] or fig. 5 in ref. [4]). As each step is ≈ 150 keV, an expected level energy for the $9/2^-$ state in ^{215}Th is ≈ 1750 keV. This would correspond to ≈ 1200 keV for a transition connecting the $9/2^-$ and $5/2^-$ states, which is significantly greater than 861 keV. Thus, on the basis of the level systematics of the $9/2^-$ states observed in the lighter $N = 125$ even-Z isotones, it is not evident that the 861 keV transition connects the $5/2^-$ and $9/2^-$ states in ^{215}Th.

Furthermore, a steep drop in half-lives from 2.1 ms observed in ^{213}Ra to 0.77 μs in ^{215}Th is surprising. As the $9/2^-$ state being responsible of the isomeric state is ruled out also on the basis of a too long lifetime (for $E2$) we conclude that in ^{215}Th there is either i) a state slightly above the 1421 keV level (the sum of 561 and 861) which populates the state but the transition is beyond our sensitivity due to internal conversion, or ii) the 861 keV transition is, *e.g.*, $E3$ which would result in a half-life of 1.26 μs using a Weisskopf estimate [10]. While the case i) would require two high-spin states close in energy, the half-life estimate for the $E3$ transition is comparable to that of the measured value. However, a very low-lying $11/2^+$ state feeding mainly the yrast $5/2^-$ state would also be surprising. Unfortunately, on the basis of the present data either possibilities cannot be experimentally inferred or excluded. Therefore, we leave spin and parity assignments for the level(s) at 1421.3 ± 0.3 keV (and $1421.3 + X$ keV) for forthcoming studies.

3.2 ^{216}Th

First, α-decay properties of ^{216}Th were reported by Valli and Hyde [12]. Later, Hingmann *et al.* [14] reported the

Table 2. α-decay data for $^{216\mathrm{g}}$Th and $^{216\mathrm{m}}$Th, respectively.

E_α (keV)	$E_{\mathrm{level}}^{\mathrm{daughter}}$ (keV)	I_α (%)	$T_{1/2}$ (ms)	Ref.
7921 ± 8	0	100	28 ± 2	[12]
7923 ± 10	0	99.46 ± 0.40	27.0 ± 0.3	[1]
7302 ± 15	628.3 ± 0.5	0.54 ± 0.03	30 ± 3	[1]
7919 ± 6	0	100	25.4 ± 0.8	[16]
7923 ± 5	0	99.6 ± 0.1	26.0 ± 0.2	this
7304 ± 4	629.3 ± 0.1	0.4 ± 0.1		work
9912 ± 20	0	$100^{(\mathrm{a})}$	0.18 ± 0.04	[14]
9933 ± 15			0.140 ± 0.005	[1]
9915 ± 15	0	$100^{(\mathrm{b})}$	0.128 ± 0.008	[16]
9930 ± 10	0	$74 \pm 4^{(\mathrm{c})}$	0.135 ± 0.004	this
9312 ± 12	629.3 ± 0.1	$13 \pm 3^{(\mathrm{c})}$		|
7999 ± 10	$1967 \pm 13^{(\mathrm{d})}$	$13 \pm 2^{(\mathrm{c})}$		work

(a) $b_\gamma = (97 \pm 1)\%$ for the level at 2028 keV reported.
(b) $b_\gamma = (95^{+3}_{-5})\%$ for the level at 2032 ± 15 keV reported.
(c) $b_\alpha = (2.8 \pm 0.9)\%$ for the level at 2045 ± 9 keV extracted.
(d) $E_{\mathrm{level}} = 1958.4 \pm 0.5$ keV reported in ref. [15].

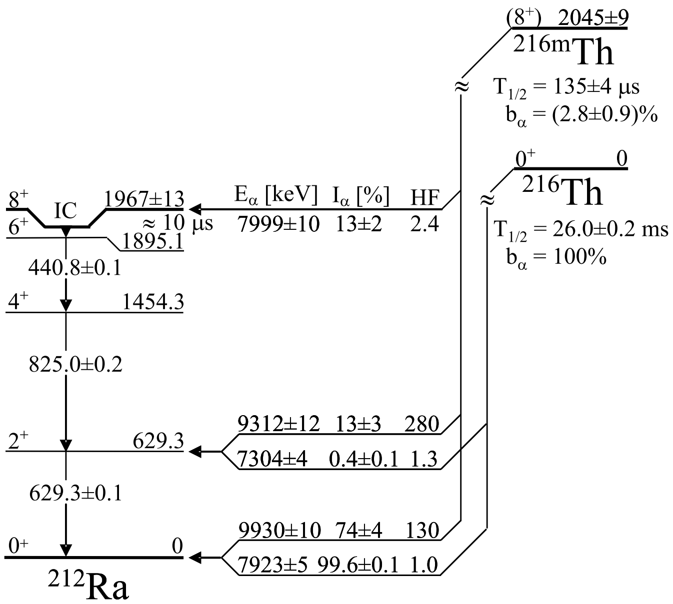

Fig. 3. Decay scheme of ^{216}Th observed in the present work. Ordering of the $6^+ \to 4^+ \to 2^+$ transitions is from [15] where the level energy of 1958.4 ± 0.5 keV for the isomeric 8^+ state with a half-life of 10.9 ± 0.4 μs and connected by a 63.3 keV transition to the 6^+ state at 1895.1 keV is reported. The α-decay hindrance factors (HF) were calculated according to [11] assuming a spin difference of $\Delta I^\pi = |I^\pi_{\mathrm{initial}} - I^\pi_{\mathrm{final}}|$.

α-decay of an isomeric (8^+, 11^-) state in ^{216}Th populating the g.s. of ^{212}Ra. The α-decay results were verified and improved by Heßberger *et al.* [1] who also reported α-decays to the 2^+ state in the daughter nuclei ^{212}Ra. Prior to the work of Heßberger *et al.* the level scheme of ^{212}Ra was established by Kohno *et al.* [15] who used a variety of in-beam techniques and observed also an isomeric 8^+ state at 1958.5 ± 0.5 keV with a half-life of 10.9 ± 0.4 μs. Recently, Hauschild *et al.* [16] studied ^{216}Th by the recoil-decay-tagging (RDT, see, *e.g.*, [17]) technique (see text below) including α-decay investigations. In our studies the α-decay fine structures of $^{216\mathrm{g}}$Th and $^{216\mathrm{m}}$Th were measured by α-γ coincidences. The α-decay data for ^{216}Th are listed in table 2 and its decay scheme extracted from the present work is shown in fig. 3.

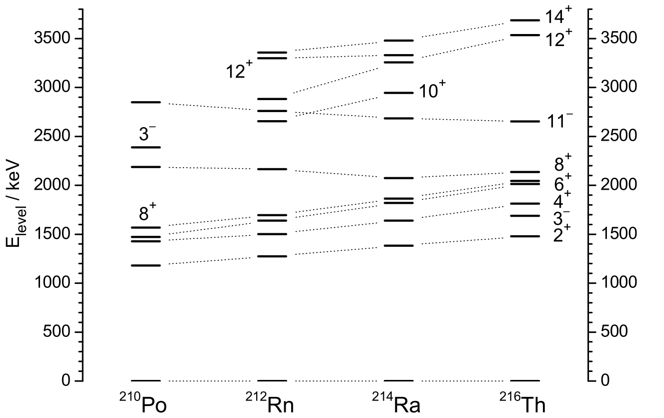

Fig. 4. Level energies of the $N = 126$ even-Z isotones taken from [10,16] and the present work. The dotted lines connect levels of equal spin and parity.

In the present work the isomeric 8^+ state in ^{212}Ra was populated via α-decay. Thus, transitions above the 2^+ state were placed according to [15]. A half-life of the isomeric state was estimated to be ~ 10 μs. This is comparable to that of Kohno *et al.* [15]. The α-decay hindrance factors (HF) shown in fig. 3 were calculated using the data given in the figure. A small hindrance factor for the α-decay connecting the isomeric states in ^{216}Th and ^{212}Ra suggests a similar nuclear structure for both states.

So far the most detailed γ-ray studies for ^{216}Th were performed by Hauschild *et al.* [16]. In their work γ-rays at 126, 200, 209, 335 and 1478 keV were observed below the 2045 keV isomeric state. These transitions were explained by levels at 1478, 1687, 1813 and 2013 keV with tentative spin and parity assignments of 2^+, 3^-, 4^+ and 6^+, respectively, while a weak γ transition at 335 keV was interpreted to connect the 2^+ and 4^+ states (see fig. 4 for details). Furthermore, γ-rays at 607, 883 and 150 keV were observed in the delayed spectrum. These transitions were interpreted to connect the 128 μs isomeric state at 2032 ± 15 keV and the levels at 2639, 3522 and 3672 keV with tentative spin and parity assignments of 8^+, 11^-, 12^+ and 14^+, respectively. Half-lives for the levels at 2639 and 3672 keV were estimated to be 615 ± 55 ns and > 130 ns, respectively. To study further the excited states in ^{216}Th we used ER-γ-(γ)-α correlations and γ-γ coincidences. The previous observations were verified. Our results are listed in table 3.

ER-γ-α correlations gated by the g.s.–to–g.s. α-decays of ^{216}Th within a 200 ms time interval revealed dominating γ-rays at 126, 200, 210 and 1478 keV. On the basis of intensity balance the 126, 200 and 210 keV γ-rays can only be explained by $E1, E2$ and $E1$ transitions, respectively. Using further γ-γ coincidences gated by 1478 keV γ-rays

Table 3. γ-ray data observed in ^{216}Th.

E_{level} (keV)	E_γ (keV)	$\Delta t^{\mathrm{ave}}_{\mathrm{ER}\text{-}\gamma}$ (μs)	I^{rel}_γ (%)	I^π
1478.2 ± 0.1	1478.2 ± 0.1	$180 \pm 30^{(a)}$	100	(2^+)
$1687.7 \pm 0.2^{(b)}$	$209.5 \pm 0.1^{(b)}$	$220 \pm 50^{(a)}$	100	(3^-)
$1813.8 \pm 0.2^{(b)}$	$126.1 \pm 0.1^{(b)}$	$180 \pm 20^{(a)}$	100	(4^+)
2013.7 ± 0.2	$199.9 \pm 0.1^{(b)}$	$270 \pm 80^{(a)}$	100	(6^+)
$2045 \pm 9^{(c)}$		$195 \pm 6^{(c)}$		(8^+)
$2136 \pm 9^{(b),(d)}$	$90.5 \pm 0.3^{(b),(d)}$		100	(8^+)
$2652 \pm 9^{(b)}$	$606.8 \pm 0.1^{(b)}$	0.81 ± 0.04	100 ± 4	(11^-)
	$516.3 \pm 0.2^{(b)}$	0.90 ± 0.09	8 ± 2	
$3535 \pm 9^{(b)}$	$883.4 \pm 0.3^{(b)}$	$1.0 \pm 0.4^{(e)}$	100	(12^+)
$3686 \pm 9^{(b)}$	$151.2 \pm 0.6^{(b)}$	1.1 ± 0.1	100	(14^+)

(^{a}) From ER-γ-α correlations gated by 7923 keV α-particles.
(^{b}) Tentative placement.
(^{c}) From α-decay.
(^{d}) Calculated using the 2652 keV level, no γ-rays observed.
(^{e}) Probably due to depopulation of the 3686 keV level.

three additional but weak γ lines at 325.8 ± 0.3, 335.8 ± 0.3 and 409.0 ± 0.4 keV appeared. Thus, we concluded that the dominating transitions populate the level at 1478 keV which further populates the g.s. directly. Employing gates at 126, 200 and 210 keV we observed weak γ-rays at 409 (the sum of 200 and 210), 336 (the sum of 126 and 210) and 326 (the sum of 126 and 200) keV, respectively. Compared to that of 1478 keV the relative γ intensities for the γ lines at 326, 336 and 409 keV were (4.9 ± 1.0)%, (6.2 ± 1.5)% and (4.8 ± 1.1)%, respectively.

However, one notes that the three γ-rays at 126, 200, 210 keV cannot result in three transitions at 326, 336 and 409 keV in the cascade. Due to close geometry and high efficiency of the Ge detector we concluded that our data may suffer from γ-ray energy summing. Therefore, a simulation as described in [18] was performed in order to estimate the effect. According to the simulation the measured intensities for the 326, 336 and 409 keV γ lines are in line with summing. Thus, we did not place them in the level scheme but left possible single γ transitions open for future experiments.

The transitions above the 2045 keV isomeric state were studied using ER-γ(-γ) coincidences and ER-γ(-γ)-α/γ correlations. In a γ-ray spectrum gated by the g.s.–to–g.s. α-decays of $^{216\mathrm{g}}$Th and ER-γ coincidences within a 5 μs time interval three γ-rays at 516, 607 and 883 keV are dominating while that at 151 keV is weak. Observed γ intensities for the three transitions are $(8 \pm 2) : (100 \pm 4) : (5 \pm 1)$, respectively. Based on γ intensities (see figs. 5 and 6a), ER-γ coincidences followed by γ-rays of 126, 200, 210 and 1478 keV having lifetimes consistent with those listed in table 3 (fig. 6b), and the $N = 126$ even-Z isotones (fig. 4), it seems justified to assume that the 607 keV transition feeds the isomeric 8^+ state at 2045 keV. Therefore, we tentatively placed the yrast 11^- state with a half-life of 0.57 ± 0.03 μs at 2652 ± 9 keV in agreement with [16].

On the basis of γ-γ coincidences with 607 and 883 keV γ-rays we concluded, similar to Hauschild *et al.*, that the

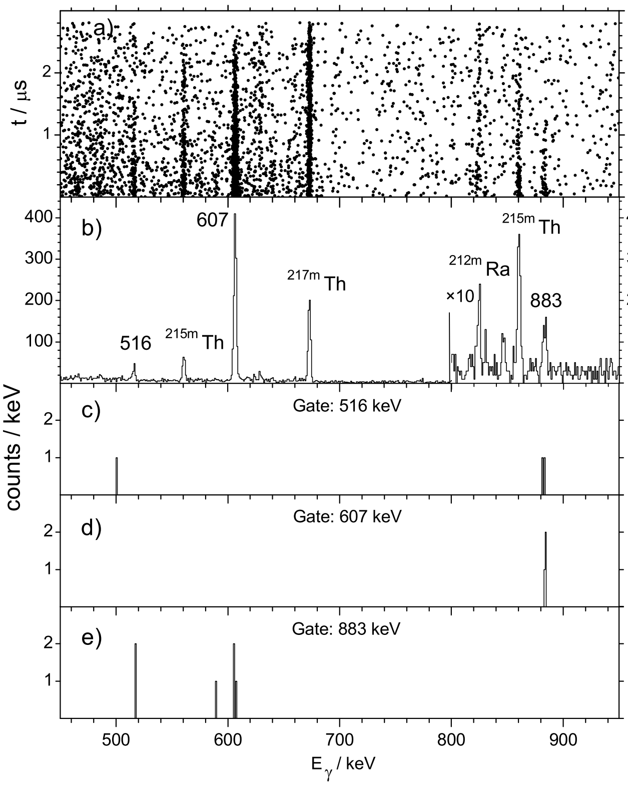

Fig. 5. a) Time *versus* energy scatter plot of ER-γ delayed coincidences. b) Projection on γ-ray energy axis. c)-e) γ-ray energy spectra coincident within 2 μs to $^{216\mathrm{m}}$Th γ-rays at 516, 607 and 883 keV, respectively.

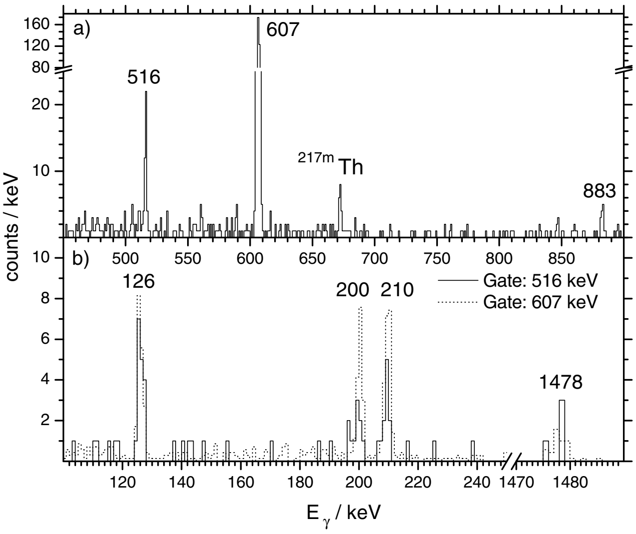

Fig. 6. a) γ-rays gated by ERs within 5 μs and correlated to the 126, 200, 210 and 1478 keV γ-rays with a time window of 550 μs. b) γ-rays followed by 516 and 607 keV ER-γ coincidences with time windows as in part a) normalized to 126 keV γ-ray intensity.

883 keV transition feeds the level at 2652 ± 9 keV. Therefore, we tentatively placed the 12^+ level at 3535 ± 9 keV. Due to poor statistics no γ-γ coincidences with the 151

and 883 keV γ-rays or with 151 and 607 keV were observed. However, on the basis of consistent relative transition intensities ($\alpha_{\text{tot},E2}^{151.2\text{ keV}} = 1.95$ and $\alpha_{\text{tot},E1}^{883.4\text{ keV}} = 0.00434$ [13]) and similar lifetimes (see table 3), we tentatively placed the 151 keV transition above the 883 keV transition, which assumably de-excites the isomeric 14^+ level at 3686 ± 10 keV similar to the lighter $N = 126$ even-Z isotones (see also [10,16,19]). A half-life of 0.74 ± 0.07 μs for the 14^+ state was extracted.

We observed coincidences of 607 and 883 keV γ-rays as well as of 516 and 883 keV γ-rays, while coincidences of 516 and 607 keV were absent (see fig. 5). The result is interesting but puzzling. On the one hand, it indicates that the 516 and 607 keV γ-rays depopulate the same state, assumably the 11^- state. On the other hand, the prompt γ-ray spectrum shown by Hauschild *et al.* in [16] indicates that the 516 and 607 keV γ-rays do not de-excite the same level since the 516 keV transition is rather strong in the prompt spectrum, while the 607 keV one is hardly present. However, on the basis of γ-γ coincidences, γ-ray intensities and the lighter $N = 126$ even-Z isotones (see figs. 4, 5 and 6a) it is unlikely that the decay sequence is $883 \rightarrow 516 \rightarrow 607$, $516 \rightarrow 883 \rightarrow 607$ or any other combination of the three transitions. Therefore, we propose the 516 keV γ-ray as a candidate for the 11^- to 8^+ transition. This would place the second 8^+ state ($h_{9/2}^2$) 91 keV above the isomeric 8^+ ($h_{9/2}f_{7/2}$) state at 2045 keV.

We did not observe γ-rays which could be assigned to a linking transition between the two 8^+ levels or to the 6^+ level. Therefore, we were not able to directly extract the γ branch of the isomeric state. A precise level energy for the isomeric 8^+ state remains open since we have to extract it from the α-decay energy, resulting in an excitation energy $E^* = 2045$ keV with an accuracy of ± 9 keV. Using this value we may assume that the 8^+ state above the isomeric state populates the 6^+ state by an $E \approx 120$ keV transition. This is close to the very strong one at 126 keV. In the present work we did not observe γ-rays associated with ^{216}Th next to 126 keV. This can be explained by a weak γ branch or by the fact that its energy overlaps with the 126 keV transition. Furthermore, the total conversion coefficient for an $E2$ transition at 120 keV is $\alpha_{\text{tot}} \approx 5$ and ≈ 90 keV $M1$ connecting the two 8^+ states has $\alpha_{\text{tot}} \approx 5$ [13], which hamper the study. Therefore, the weak γ branch bypassing the isomeric state is difficult to determine, particularly with an uncertain ($\Delta E \approx 10$ keV) level energy. The answer may be found in fig. 6b which shows that intensities of 200 and 210 keV γ-rays gated by 516 and 607 keV γ-rays and normalized to 126 keV are significantly higher with the latter gate. On the basis of our data we cannot explain the result but it could indicate that the 126 γ-ray is actually a double peak.

Due to possible, unobserved transitions bypassing the isomeric state at 2045 keV its γ branch was estimated indirectly. The lower limit was calculated using the relative α intensities of $^{216\text{m}}$Th and $^{216\text{g}}$Th. This resulted in a limit of $b_\alpha > (2.1 \pm 0.2)\%$. The upper limit was estimated using the ratio of the expected number of α-decays associated with γ singles at 1478 keV corrected by absolute efficiency and the number of α-decays associated with $^{216\text{g}}$Th, which takes into account the number of $^{216\text{g}}$Th α-decays following the γ decay of $^{216\text{m}}$Th. This resulted in a limit of $b_\alpha < 3.7\%$. Thus, the α branch for the isomeric state at 2045 keV can be estimated to be $b_\alpha = (2.8 \pm 0.9)\%$. This is consistent with the previously reported values (see table 2).

Table 4. α-decay fine structure of ^{217}Th to ^{213}Ra.

E_α (keV)	$T_{1/2}$ (μs)	I_α (%)	$E_{\text{level}}^{\text{daughter}}$ (keV)	Ref.
9247 ± 15	261^{+22}_{-18}	$92.3^{+0.6}_{-0.6}$	0	[20]
8713 ± 32	290^{+240}_{-90}	$2.6^{+1.6}_{-1.1}$	546	[20]
8429 ± 32	210^{+100}_{-50}	$5.1^{+2.0}_{-1.6}$	834	[20]
9261 ± 5	237 ± 1	94.5 ± 0.5	0	[2]
8725 ± 5	229 ± 6	1.8 ± 0.1	546.1 ± 0.1 (a)	[2]
8455 ± 5	245 ± 8	3.7 ± 0.1	822.1 ± 0.1 (a)	[2]
9269 ± 9	257 ± 2	95.5 ± 0.3	0	this
8727 ± 8	250 ± 30	1.5 ± 0.1	546.3 ± 0.1 (a)	|
8460 ± 7	260 ± 50	3.0 ± 0.2	822.5 ± 0.1 (a)	work

(a) From α-γ coincidences.

To conclude, based on the consistent lifetimes observed in (ER-γ)-α and -γ correlations it is evident that the 126, 200, 210 and 1478 keV γ-rays result from the isomeric state at 2045 keV. We also conclude that the 516, 607 and 883 keV transitions feed the isomeric state. It also seems evident that further studies for the transitions above, bypassing and below the isomeric state at 2045 keV would significantly benefit from γ-γ-γ coincidences.

3.3 ^{217}Th

Valli and Hyde [12] reported the α-decay of ^{217}Th. Later its α-decay fine structure was studied by Nishio *et al.* [20] and Heßberger *et al.* [1,2]. In the present work the decay of ^{217}Th was studied by ER-γ-(γ)-α(-γ) correlations. The α-decay data are listed in table 4 where also selected previously published data are given for comparison.

So far a multipolarity is reported only for the 546 keV transition which is tentatively assigned to $E2$ by Raich *et al.* [10,21]. Due to chance X-rays resulting from energy summing of α-particles and conversion electrons associated with the level at 822 keV, we could not verify the result. However, the 822 keV level is populated by α-particles with the lowest α energy in ^{217}Th, so energy summing does not distort the number of radium X-rays observed in coincidence with α-particles. Thus, we extracted the measured conversion coefficient $\alpha_K = 0.07 \pm 0.05$ for the 822 keV transition. The value rules out $E1$ ($\alpha_K = 0.0038$) and $E2$ ($\alpha_K = 0.010$) transitions, while it is consistent with $M1$ ($\alpha_K = 0.041$). Unfortunately, this is also the case for $\alpha_K^{M2} = 0.096$, $\alpha_K^{E3} = 0.023$ and even for $\alpha_K^{E4} = 0.047$. However, the g.s. and low-lying levels in the $N = 125$ isotones are expected to be single-particle states with a neutron hole in the $p_{1/2}$, $f_{5/2}$ and $p_{3/2}$ orbitals, respectively. Therefore, transitions from the two latter states

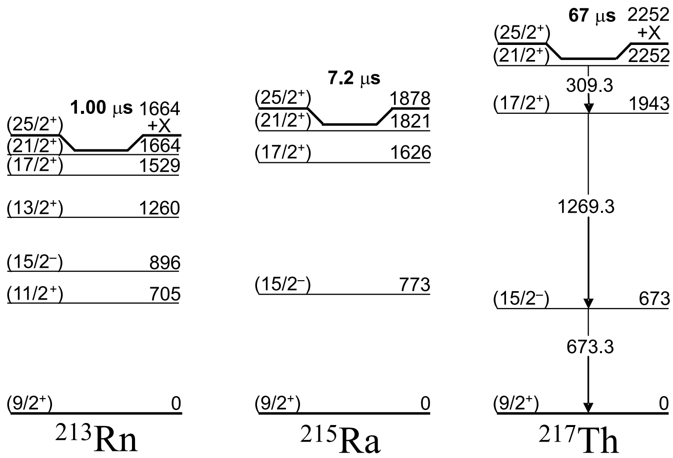

Fig. 7. Partial level schemes of the $N = 127$ even-Z isotones above polonium. The levels in ^{217}Th are tentatively placed on the basis of the lighter isotones [10].

to the g.s. are expected to be low-multipolarity transitions. For the 822 keV transition this is supported by a prompt time structure ($\tau < 50$ ns) observed in the α-γ-TAC spectrum, which favours the $M1$ interpretation. As $M1$ is also favoured by the $N = 125$ even-Z isotone ^{209}Po [10], we tentatively conclude that this is the case. Since the g.s. of ^{213}Ra is $1/2^-$, the level at 822 keV could be a $3/2^-$ state as expected and observed in the lighter $N = 125$ even-Z isotones.

The α-decay fine structure of ^{217}Th also allowed us to estimate an absolute efficiency of the Si-Ge detector system. The outcome was essential for the α-decay study of ^{215}Th as was shown in sect. 3.1. The study was carried out using the ratio of counts in α-γ coincidences and α-decays observed for a given α-decay (see, for example, [4] for details). The study resulted in absolute efficiencies of $(7.4 \pm 1.0)\%$ and $(6.6 \pm 0.7)\%$ for the conversion corrected 546 and 822 keV transitions, respectively. From these values a photo-peak efficiency of $(5.0 \pm 0.5)\%$ at 1.3 MeV is extracted.

In addition to the α-decay studies we were also able to identify delayed γ transitions in ^{217}Th. Prior to the present work, γ-ray studies of ^{217}Th were established by Dracoulis *et al.* [22] who reported an ($E3$) transition at 673.8 keV ($T_{1/2} = 141 \pm 50$ ns) as a candidate for a transition from the $15/2^-$ state to the $9/2^+$ g.s. We employed ER-γ(-γ)-α correlations and γ-γ coincidences, and observed γ-rays of 309.3±0.1, 673.3±0.1 and 1269.3±0.1 keV with relative intensities of $(18\pm3) : (100\pm7) : (84\pm10)$, respectively. The transitions were assigned to ^{217}Th on the basis of ER-γ coincidences followed by α-decay of ^{217}Th. They were placed on the basis of level systematics of the lighter $N = 127$ isotones. Half-lives were extracted using ER-γ-α correlations gated by the g.s.–to–g.s. α-decays of ^{217}Th within 1 ms time interval for both α and γ decays. This resulted in values of 64^{+64}_{-22}, 69^{+32}_{-17} and 66^{+27}_{-15} μs for the 309, 673 and 1269 keV transitions, respectively. From these data a mean half-life of 67^{+17}_{-11} μs follows. The results together with the level systematics of the $N = 127$ isotones are shown in fig. 7.

Unfortunately, we did not observe γ-rays connecting the isomeric state and the state at 2252 keV. However, based on a rather small number of thorium K X-rays observed in γ-γ coincidences gated by the 309, 673 or 1269 keV γ-rays we conclude that the transition energy is probably below the K-electron binding energy ($\approx$ 110 keV [10]). This would place the isomeric state in ^{217}Th between 2252 and 2362 keV prompting further studies.

4 Conclusion

The α-decay fine-structure data for $^{215-217}$Th are improved, particularly concerning the transition multipolarities. For the even-odd cases the results are in line with the level systematics of the lighter isotones, and with the shell model predictions for the nuclei near to the $N = 126$ closed neutron shell. Furthermore, new or improved γ-ray data for the isomeric transitions in $^{215-217}$Th are extracted.

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