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Studies of ^{213g,m}Ra and ^{214g,m}Ra by α and γ decay

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Abstract. The decay of ^{213,214}Ra was studied by α-γ and γ-γ coincidence measurements. The nuclei were produced in the reactions ^{170}Er(^{48}Ca, xn)$^{218-x}$Ra and ^{170}Er(^{50}Ti, 3n)^{217}Th and subsequent α decay of ^{217}Th to ^{213}Ra. Evaporation residues recoiling out of the target were separated in-flight by the velocity filter SHIP and implanted into a position-sensitive 16-strip PIPS detector in order to study their subsequent decays. Associated γ-rays were detected by a four-fold Ge-Clover detector. In the present work we extracted new and improved data for ^{213,214}Ra including isomeric transitions. The results are discussed and compared with previously published data.

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1 Introduction

Isomeric states probed by their decay provide valuable information on nuclear structure. From the point of view of isomeric transitions the region near the $N = 126$ closed neutron shell above lead is of special interest. It provides a wide variety of lifetimes most in the μs range or shorter. While α-γ coincidences are a powerful tool to probe transitions in the daughter nuclei, evaporation residue (ER)-γ coincidences are extremely well suited for studies of short-living isomeric transitions in the mother nuclei, as we have shown in our previous studies in that region (see for example [1,2] and [3,4], respectively).

In this work we concentrate on two nuclei, ^{213}Ra and ^{214}Ra. Alpha-gamma, γ-γ and ER-γ coincidence studies are employed. The latter method, however, is technically difficult to perform due to long lifetimes. On the other hand, long lifetimes could result in measurable α branches, and γ-ray studies can be performed using γ singles and γ-γ coincidences if production cross-sections are sufficiently high, as they are for ^{213,214}Ra. Since we have already explained our experimental methods in above-cited publications, we report here only the most relevant details.

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2 Experimental details

In the present studies we employed reactions using beams of ^{48}Ca and ^{50}Ti and targets of ^{170}Er. Both beams were prepared from enriched material and accelerated by the UNILAC at GSI, Darmstadt. Incident beam energies were 4.25, 4.30 (Ca) and 4.35 (Ti) A·MeV and beam intensities were ≈ 50 and 200 pnA, respectively. The targets of ≈ 0.4 mg/cm^2 thick ^{170}Er layers evaporated on 30 μg/cm^2 carbon backing were mounted on a wheel which was rotated synchronously to the 20 ms beam macro structure (≈ 5 ms pulses followed by ≈ 15 ms beam-off periods). Evaporation residues (ER) were separated in-flight from the primary beam by the velocity filter SHIP [5]. The ERs were implanted into a position-sensitive 16-strip PIPS detector (active area 80×35 mm^2) used to register their arrival and subsequent decays [6,7]. The Si detector was cooled in order to improve energy and position resolution. Energy calibration was performed using the most intense α lines of ^{209,210,213}Rn and ^{214,215}Ra [8].

Gamma ray studies were carried out using a Ge-Clover detector placed behind the Si detector. The Clover detector consisted of four individual crystals, 70 mm diameter and 140 mm length each, which were arranged to a block of 124 × 124 × 140 mm^3. For γ-ray studies we recorded γ singles as follows: γ-rays followed by a particle in the Si detector within 5 μs were recorded as "coincident", the time

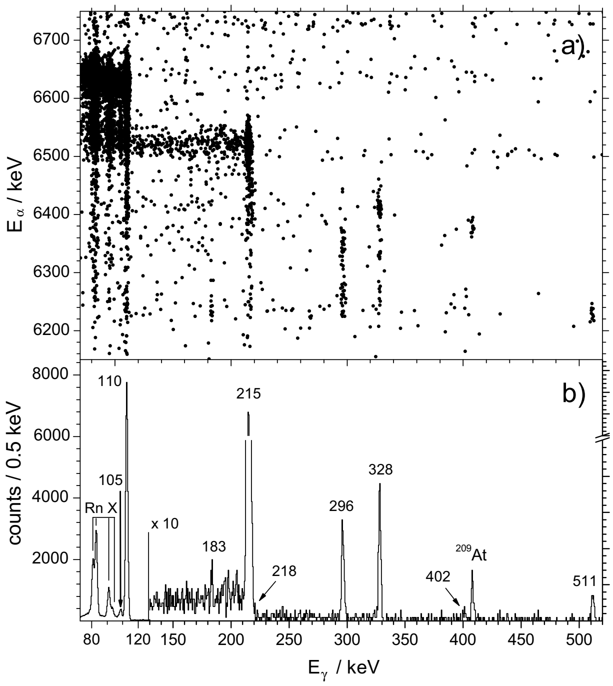

Fig. 1. a) α-γ coincidences associated with the α decay of ^{213}Ra. For clarity, only one third of the total data is shown. b) Projection on the γ-ray energy axis, all data included.

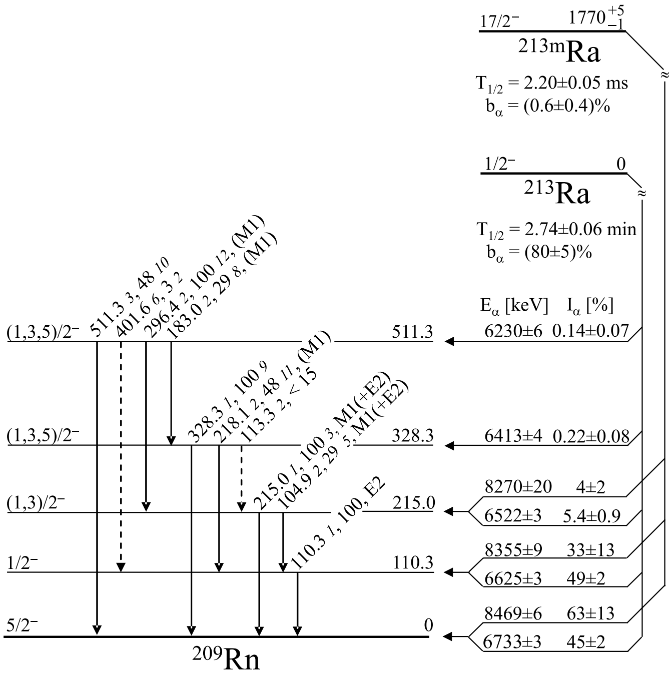

Fig. 2. Decay scheme of ^{213}Ra deduced from the present work. Half-life, b_α and I_α^{rel} to the 110 keV level and the g.s. for ^{213g}Ra are adopted from [8] and $17/2^-$ for ^{213m}Ra from [14,15]. For clarity, errors in γ-ray energies and intensities are given in small *italic* followed by the values. Relative γ intensities followed by energies are in [%]. Dashed lines indicate tentative or inconclusive assignments.

difference extracted using a TAC, γ-rays followed by a particle within 5–16 μs were not recorded due to the dead-time of our data acquisition and for still longer time differences γ-rays were recorded as single events. 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 into the Si detector, absolute efficiency of the Ge-Si detector system was estimated internally using the ratio of α-γ coincidences and α decays of ^{217}Th and ^{213}Ra (see [4] and sect. 3.1, respectively). The absolute efficiency in the ^{50}Ti on ^{170}Er reaction corresponded to a photo-peak efficiency of $(5.0 \pm 0.5)\%$ at 1.3 MeV. Slightly different mean values for absolute efficiencies reported in our previous studies, *e.g.* [1–4], are due to (slightly) different geometries, *i.e.* adjusted distances between the Ge and Si detectors.

Alpha decays were assigned on the basis of $Q_\alpha + E_\gamma$ values if equal to the Q_α value of the ground-state–to–ground-state (g.s.-to-g.s.) α decay within ± 20 keV (typical error bar of Q_α values). For the Q_α values we used the relation $Q_\alpha = (1 + m_\alpha/m_d) \times E_\alpha$ where m_α and m_d are the masses of the α-particle and daughter nucleus, respectively. Transitions connecting excited states (see, for example, 296 keV in fig. 1) were placed on the basis of γ-γ coincidences and of energy and intensity balances.

3 Results and discussion

3.1 ^{213g}Ra

Raich *et al.* [9] published the so far most detailed studies of low-lying levels in ^{209}Rn using γ-rays subsequent to α decay of ^{213}Ra. Prior to their work Valli *et al.* [10,11] established the levels by α transitions populating the g.s. with $E_\alpha = 6730 \pm 5$ keV and the levels at 109 and 214 keV with $E_\alpha = 6623 \pm 5$ and 6520 ± 5 keV, respectively. Relative α intensities were estimated to be $(45 \pm 2)\%$, $(49 \pm 2)\%$ and $(6 \pm 1)\%$, respectively. A weak $(0.4 \pm 0.2)\%$ α branch at 6408 ± 5 keV feeding the level at ≈ 328 keV was tentatively assigned to the α decay of ^{213}Ra. On the basis of systematics in the $N = 123$ even-Z isotones (see [11] for details) the levels at 110 and 215 keV were tentatively assigned to $1/2^-$ and $3/2^-$ states, respectively, the g.s. being $(5/2^-)$. Raich *et al.* verified the results. Furthermore, they proposed that the 214.7 keV level depopulates, instead of expected $M1$ or mixed $M1 + E2$ transitions, by 104.6 and 214.7 keV transitions of $E2(+M1)$ multipolarity.

To date the g.s. and the level at 110 keV in ^{209}Rn are settled as $5/2^-$ and $1/2^-$ states [8], respectively, while the $(3/2^-)$ state at 215 keV is still based on systematics of the lighter $N = 123$ even-Z isotones. In order to verify and improve the data we used α-γ coincidences. Our study was carried out via two experimental runs using the ^{48}Ca and ^{50}Ti on ^{170}Er reactions. Our results are shown in figs. 1 and 2, and the data are listed in table 1.

An important feature in our study is the use of the recoil-implantation method which suffers from energy summing of α-particles and conversion electrons. This results in modified α energies and relative intensities. The effect cannot be estimated solely by measuring α-particle

Table 1. α decay of ^{213}Ra populating the levels in ^{209}Rn.

E_α [keV]	E_{level} [keV]	E_γ [keV]	I_γ^{rel} [%]	Mult.
6733 ± 3	0			
6625 ± 3	110.3 ± 0.1	110.3 ± 0.1	100	$E2$
6522 ± 3	215.0 ± 0.1	215.0 ± 0.1	100 ± 3	$M1(+E2)$
		104.9 ± 0.2	29 ± 5	$M1(+E2)$
6413 ± 4	328.3 ± 0.1	328.3 ± 0.1	100 ± 9	
		218.1 ± 0.2	48 ± 11	$(M1)^{(a)}$
		$113.3^{(b,c)}$	$< 15^{(b)}$	
6230 ± 6	511.3 ± 0.2	511.3 ± 0.3	48 ± 10	
		$401.6 \pm 0.6^{(b)}$	3 ± 2	
		296.4 ± 0.2	100 ± 12	$(M1)^{(a)}$
		183.0 ± 0.2	29 ± 8	$(M1)^{(a)}$

(^{a}) $M1 + E2$ mixtures not excluded, see text for details.
(^{b}) Tentative.
(^{c}) No γ-rays observed, based on intensity balance, an upper limit was estimated using α-γ coincidences, see text for details.

Table 2. Internal conversion coefficients α for selected transitions in ^{209}Rn.

E_γ	Measured	Theoretical α values [12]				
[keV]	α values	$E1$	$E2$	$E3$	$M1$	$M2$
110.3	$\alpha_{tot} = 5.1 \pm 0.9$	0.38	5.51	125.	10.6	76.6
104.9	$\alpha_K = 8.1 \pm 2.4$	0.33	0.34	0.17	9.95	56.1
183.0	$\alpha_K = 2.5 \pm 1.8$	0.085	0.20	0.45	2.04	8.36
218.1	$\alpha_K = 1.7 \pm 1.6$	0.056	0.14	0.34	1.25	4.68
296.4	$\alpha_K = 0.9 \pm 0.6$	0.028	0.071	0.185	0.535	1.74

energies but α-γ coincidences gated by γ-rays exclude internal conversion and unambiguously reveal α decay energies for given levels. Furthermore, if an α branch for at least one of the levels is reliably available one can use the α-γ coincidences together with the absolute efficiency to extract transition multipolarities and relative intensities for the other α branches.

In ^{213}Ra such a branch is obviously feeding the 110 keV level in ^{209}Rn with $I_\alpha^{rel} = (49 \pm 2)\%$ [10]. Because the total number of α decays is often easier to estimate than the relative α intensity to the excited level, we took advantage of the well-established α decay data for ^{213}Ra. Using the ratio of α-γ coincidences between 110 keV γ-rays and 6625 keV α-particles and the calculated one using the total number of ^{213}Ra α-particles, known relative α intensity and absolute efficiency, we derived a total conversion coefficient of $\alpha_{tot} = 5.1 \pm 0.9$ for the 110 keV transition. This value is in line with an $E2$ transition as listed in table 2.

Another way to estimate the multipolarity of the 110 keV transision is to use the γ-ray spectrum gated by ^{213}Ra α-particles as illustrated in fig. 1b. One notes that radon K-X-ray and 110 keV γ-ray intensities are nearly equal. A closer study reveals that the efficiency corrected ratio of all radon K-X-rays and 110 keV γ-rays is 0.91 ± 0.04, which must be larger than the K-conversion coefficient for the 110 keV transition. Since the theoretical K-conversion coefficient for $M1$ at 110.3 keV is $\alpha_K = 8.60$ [12] the ratio excludes magnetic transitions (the α_K values at 110 keV are close to those for 105 keV listed in table 2). Thus we concluded that the 110 keV transition is $E2$. This combined with the α intensity of $(49 \pm 2)\%$ in our ^{48}Ca on ^{170}Er data results in an absolute efficiency of $(13.9 \pm 1.0)\%$ at 110 keV. The value corresponds to a photo-peak efficiency of $(4.5 \pm 0.4)\%$ at 1.3 MeV.

Table 3. Relative transition rates for transitions depopulating the 215 and 328 keV levels in ^{209}Rn. Errors in intensities are given in parentheses referring to the last digit(s).

E_γ	$I_{\alpha\text{-}\gamma}^{trans}/I_{\alpha\text{-}\gamma}^{total}$ [%]				
[keV]	$E1$	$E2$	$E3$	$M1$	$M2$
	100(18)%$^{(a)}$ using absolute efficiency				
104.9	6.5(15)	36(9)	760(180)	60(14)	430(100)
215.0	16(3)	21(4)	73(14)	39(7)	118(23)
	100(8)%$^{(a)}$ using radon K-X-rays				
104.9	2.5(4)	2.6(4)	1.3(2)	76(9)	430(60)
215.0	1.4(2)	3.4(4)	8.6(8)	32(3)	120(11)
	100(50)%$^{(b)}$ using absolute efficiency				
$113.3^{(c)}$	< 5	< 21	< 396	< 39	< 246
218.1	8(5)	11(6)	35(19)	19(11)	58(32)
328.3	17(10)	19(10)	27(20)	25(13)	45(24)

(^{a}) Sum of 105 and 215 keV must meet the given value.
(^{b}) As (^{a}) but with 218 and 328 keV.
(^{c}) α-γ coincidences not observed but assumed on the basis of lifetime arguments and intensity balance, see text for details.

In order to estimate multipolarities for the 105 and 215 keV transitions depopulating the level at 215 keV we list our data in two sets in table 3. In the upper part we used the $(6 \pm 1)\%$ α branch feeding the level at 215 keV [8,10] and listed calculated relative intensities for the 105 and 215 keV transitions using the total conversion coefficients and absolute efficiency. For this we used the relation $(1 + \alpha_{tot}) \times N_{\alpha\text{-}\gamma}/(\epsilon_{\alpha\text{-}\gamma} \times N_\alpha^{tot})$ where $N_{\alpha\text{-}\gamma}/\epsilon_{\alpha\text{-}\gamma}$ and N_α^{tot} are the numbers of α-γ coincidences corrected by absolute efficiency and α decays feeding the level at 215 keV, respectively, while α_{tot} is the total conversion coefficient taken from [12].

The second part consists of K-conversion (α_K [12]) corrected relative γ intensities for the 105 and 215 keV transitions ($\alpha_K \times I_\gamma$) divided by the total number of radon K-X-rays associated with the level at 215 keV (I_{KXray}^{tot}). The latter is extracted by subtracting the total number of radon K-X-rays by those associated with the 110 keV transition. Due to very small α branches and relatively high transition energies the contribution of K-X-rays associated with the levels at 328 and 511 keV could contribute only by few per cent (see text below). Thus we neglected them together with a small fraction due to fluorescence but included the numbers into error bars listed in table 3.

On the basis of the data in tables 2 and 3 we concluded that the 105 and 215 keV transitions are $M1$ transitions or $M1 + E2$ mixtures. Admixtures of $E2$ were estimated to be $(11^{+16}_{-11})\%$ and $< 58\%$, respectively. Thus, the 215 keV transition could also be $E2 + M1$. However, our data extracted using the absolute efficiency are in best agreement

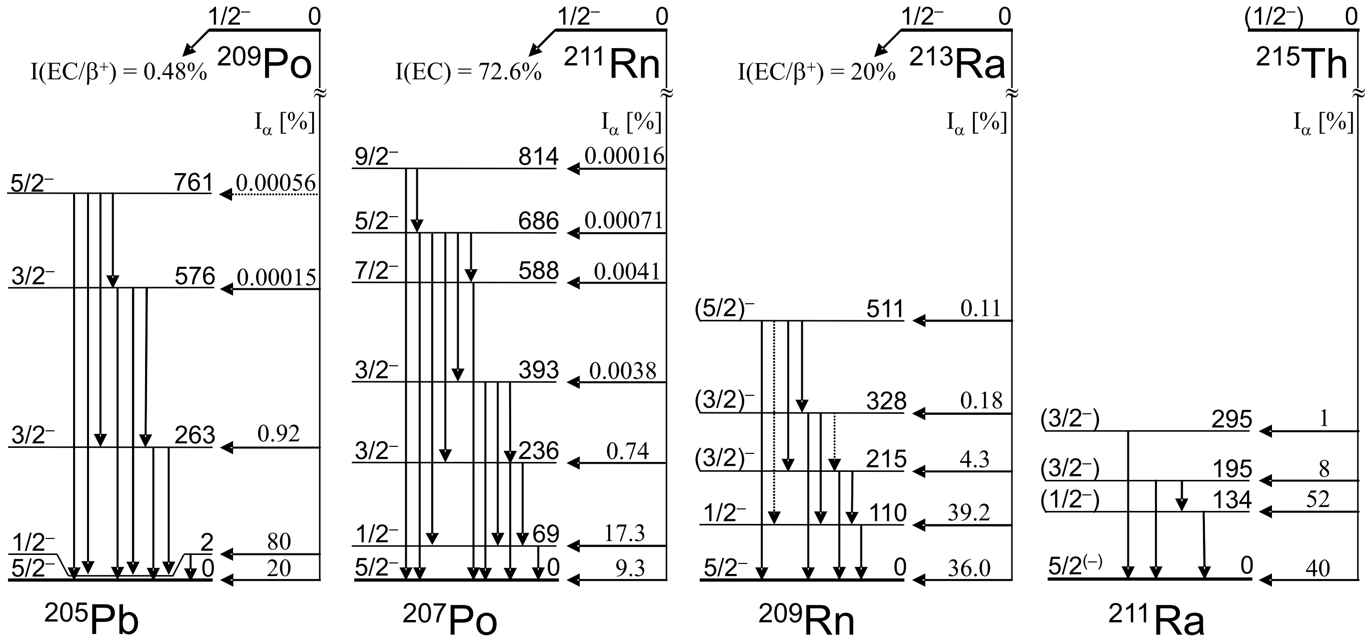

Fig. 3. α decay schemes of the $N = 125$ even-Z isotones. The data for ^{209}Po and ^{211}Rn are adopted from [8], for ^{213}Ra from [8] ($I(EC/\beta^+)$, the g.s. and the level at 110 keV) and the present work and for ^{215}Th from [4,8]. For clarity, only the most probable spins for the levels at 215, 328 and 511 keV in ^{209}Rn are shown, complete spin combinations extracted in the present work are $(1,3)/2$, $(1,3,5)/2$ and $(1,3,5)/2$, respectively, see text for details.

assuming both to be pure $M1$ transitions (table 3). Therefore we expect $E2$ contributions in both cases to be minor. Using the absolute efficiency and the total conversion coefficients extracted from our data we get a relative α intensity of $(5.4 \pm 0.9)\%$ for α decay into the 215 keV level.

Transitions depopulating the 328 keV level are illustrated in the lower part of table 3 where γ feedings are listed in a similar manner as in the upper part, now assuming $I_\alpha^{rel} = (0.4 \pm 0.2)\%$ [8,10]. One notes that the sum intensity fits best for $M2$ or $E3$ while even two pure $M1$ transitions can hardly reach the lower limit of required sum intensity, although our error bars are in this case large. However, $M2$ or $E3$ transitions enabling a positive-parity state at 328 keV would be rather surprising, particularly as 218 and 328 keV γ-rays are prompt ($\tau \ll 100$ ns) in our α-γ-TAC spectrum. Further, $M2$ for 218 keV is excluded by the measured α_K (table 2) which suggests an $M1$, $E2$ or $E3$ multipolarity. A Weisskopf estimate results in a half-life of 20 ms for 218.1 keV $E3$. This is five orders of magnitude longer than our limit. Thus we excluded $E3$ and concluded that the 218 keV transition is $M1$, $E2$ or a mixture, and that the level at 328 keV has a negative parity and a spin of 1/2, 3/2 or 5/2. This assignment is further supported by intensities of the 218 and 328 keV transitions listed in the lower part of table 3, which cannot be explained by two $E1$ transitions and finally, $E1$ and $M2/E3$ transitions from the same level with roughly equal intensities (see table 1) seem very unlike.

Therefore, we concluded that the small sum intensity for the 218 and 328 keV transitions (see the lower part of table 3) may result from the 113.3 ± 0.2 keV transition connecting the levels at 215 and 328 keV, which we do not observe due to its energy close to the very strong one at 110 keV and low γ-ray intensity related to losses by internal conversion. Based on the $N = 123$ isotones (see fig. 3) and on a small difference in expected spins of connected states (feedings to the $5/2^-$ g.s. and the $1/2^-$ state at 110 keV are similar including conversion) such a transition could also appear in ^{209}Rn but its relative γ intensity must be less than 15%. Based on the above discussion and on the intensity balance (see the lower part of table 3) we consider $M1$ assignments the most plausible for the 218, 328 and possible 113 keV transitions while admixtures of $M1 + E2$ cannot be excluded.

A relative intensity for α decay into the 328 keV level was estimated using α singles and α-γ coincidences. From singles we get $I_\alpha^{rel} = (0.11 \pm 0.03)\%$ which is to be considered as a lower limit due to losses by electron summing. Employing α-γ coincidences, absolute efficiency and an assumption that the level depopulates by 113, 218 and 328 keV $M1$ (upper limit) or 218 and 328 keV $E2$ (lower limit) transitions, we extracted a value of $I_\alpha^{rel} = (0.22 \pm 0.08)\%$. Being consistent with $(0.4 \pm 0.2)\%$ by Valli *et al.* [10] we also consider this value more reliable than that of α singles. Compared to the previous relative intensity our slightly lower value suggests that its α decay hindrance factor is actually larger than the previously reported value of ~ 36, which fits better to the systematics of the $N = 123$ even-Z isotones (see [8]).

The level at 511 keV was evidenced by 183–328 and 215–296 keV γ-γ coincidences and by α-γ coincidences gated by 511.3 keV γ-rays (see fig. 1). Using the latter we calculated the $Q_\alpha + E_\gamma$ value consistent with that of the g.s.-to-g.s. α decay of ^{213}Ra. The level feeds all levels below it and again all transitions depopulating it were prompt in the α-γ-TAC spectrum. Due to weak transitions we could estimate transition multipolarities only for the 183 and 296 keV transitions. The measured α_K values fit best for $M1$ while mixtures with $E2$ are not excluded. A relative α intensity was estimated in a similar manner as for the 328 keV level. Our study resulted in values of $(0.06 \pm 0.02)\%$ and $(0.14 \pm 0.07)\%$ using α singles and α-γ coincidences, respectively. Based on the present data we find the latter value more reliable and report it as the relative α intensity for the newly established 511 keV level.

On the basis of the $5/2^-$ g.s. and the $1/2^-$ state at 110 keV [8] we concluded that the 215 keV state depopulated by $M1$ transitions or by $M1 + E2$ mixtures has spin and parity of $(1,3)/2^-$. We further concluded that the 328 keV level depopulates by the 218 and 328 keV $M1$, $M1 + E2$ or $E2$ transitions and thus has spin and parity of $(1,3,5)/2^-$. It also seems likely that it decays in addition via the unobserved 113 keV transition. Based on the 183 and 296 keV $M1$ (or $M1 + E2$, pure $E2$ are ruled out) transitions, the 511 keV state similarly has spin and parity of $(1,3,5)/2^-$. Thus, on the basis of the lighter $N = 123$ even-Z isotones and our data it would be tempting to assign the 215, 328 and 511 keV levels to $3/2^-$, $3/2^-$ and $5/2^-$, respectively. However, due to poor multipolarity data for several transitions we leave conclusive assignments for future studies.

3.2 ^{213m}Ra

Raich *et al.* [9] reported the 2.1 ± 0.1 ms isomeric state in ^{213}Ra based on a cascade of 546.35 ± 0.05, 1062.5 ± 0.2 and 160.87 ± 0.05 keV γ transitions (two tentative $E2$ transitions and an $E2$ transition, respectively) and on α decays feeding low-lying levels of ^{209}Rn. The latter decays to the g.s. and the levels at 110 and 215 keV have α energies of 8467 ± 5, 8358 ± 10 and 8266 ± 10 keV and relative intensities of $(69 \pm 7)\%$, $(28 \pm 6)\%$ and $(3 \pm 2)\%$, respectively.

In spite of consistent level energies of the isomer at ≈ 1770 keV extracted from α and γ decay, Raich *et al.* concluded that the decays do not depopulate the same state. This was due to the 161 keV $E2$ transition placed on the top of the cascade on the basis of the lighter $N = 125$ even-Z isotones, which cannot result in a ms range lifetime (its Weisskopf estimate is several orders of magnitude shorter). Thus, the level energy for the isomer was settled slightly above 1769.7 keV as calculated from the cascade. On the basis of α decay properties, shell model predictions and the lighter $N = 125$ even-Z isotones, the isomeric state was assigned to a $13/2^+$ or $17/2^-$ state, the latter being the most preferred (see [9,13] for details). Later, Neyens *et al.* [14,15] verified the $17/2^-$ assignment using the level mixing spectroscopy (LEMS) method and Heßberger *et al.* [3] verified the half-life and γ energies.

We studied the isomer using α-γ, γ-γ coincidences and α, γ singles. Our α singles spectrum is shown in fig. 4. The data are summarized in fig. 2 and γ-ray data are listed in table 4. Using α and γ decays the level energies are 1769 ± 6 and $1769.5 \pm 0.2 + X$ keV, respectively. This verifies the

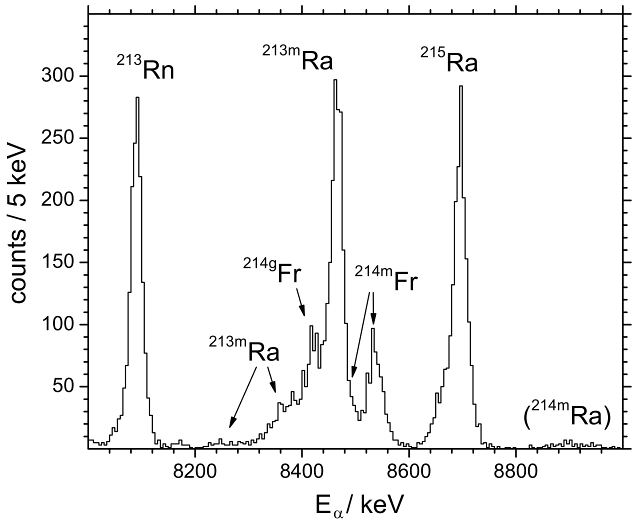

Fig. 4. High-energy ($E_\alpha > 8000$ keV) α singles spectrum recorded in the ^{48}Ca + ^{170}Er reaction at 4.30 A·MeV.

Table 4. Measured K-conversion coefficients α_K and relative transition rates (normalized to 546 keV) for ^{213m}Ra. Errors are given in parentheses referring to the last digit(s).

E_γ	Measured	Theoretical α_K values [12]			
[keV]	α_K	$E1$	$E2$	$E3$	$M1$
161.2(1)	0.26(6)	0.120	0.237	0.450	3.47
546.2(1)	0.024(9)	0.0082	0.0215	0.0529	0.123
1062.1(1)	0.014(9)$^{(a)}$	0.0024	0.0063	0.0138	0.021
	I_γ^{rel} [%]	$I_\gamma^{rel}(1+\alpha_{tot})$ [%]			
161.2	41(2)	47(2)	96(5)	830(30)	219(8)
546.2	100(1)	101(1)	103(1)	111(1)	115(1)
1062.1	97(6)	98(6)	98(6)	99(6)	100(6)

$(^a)$ Mean value could be overestimated, see text for details.

findings of Raich *et al.* Lifetimes were estimated using ER-α correlations and decay curves of gated γ-rays during the ≈ 15 ms beam-off period. The study resulted in half-lives of 2.2 ± 0.2 ms and 2.20 ± 0.05 ms, respectively, which are consistent with the previously published values [3,9].

Transition multipolarities (table 4) were estimated using the total transition rates and measured K-conversion coefficients extracted from γ-γ-γ coincidences. Based on our data the 161 and 546 keV transitions have $E2$ characters while 1062 keV needs further examination. Although our measured value of $\alpha_K = 0.014 \pm 0.009$, excluding other than $E2$, $E3$ and $M1$ [12], matches best to $E3$ (which would require a positive-parity state at a very low energy, not observed in the other $N = 125$ isotones, see [8,16] and fig. 5) we hesitated to conclude so. This is due to the small number of radium K-X-rays (single counts) coinciding with 1062 keV γ-rays in γ-γ-γ coincidences gated by 161 and 546 keV γ-rays (see table 4 for small K-conversion coefficients). Our estimation of the conversion coefficient was rather sensitive to background subtraction. For ex-

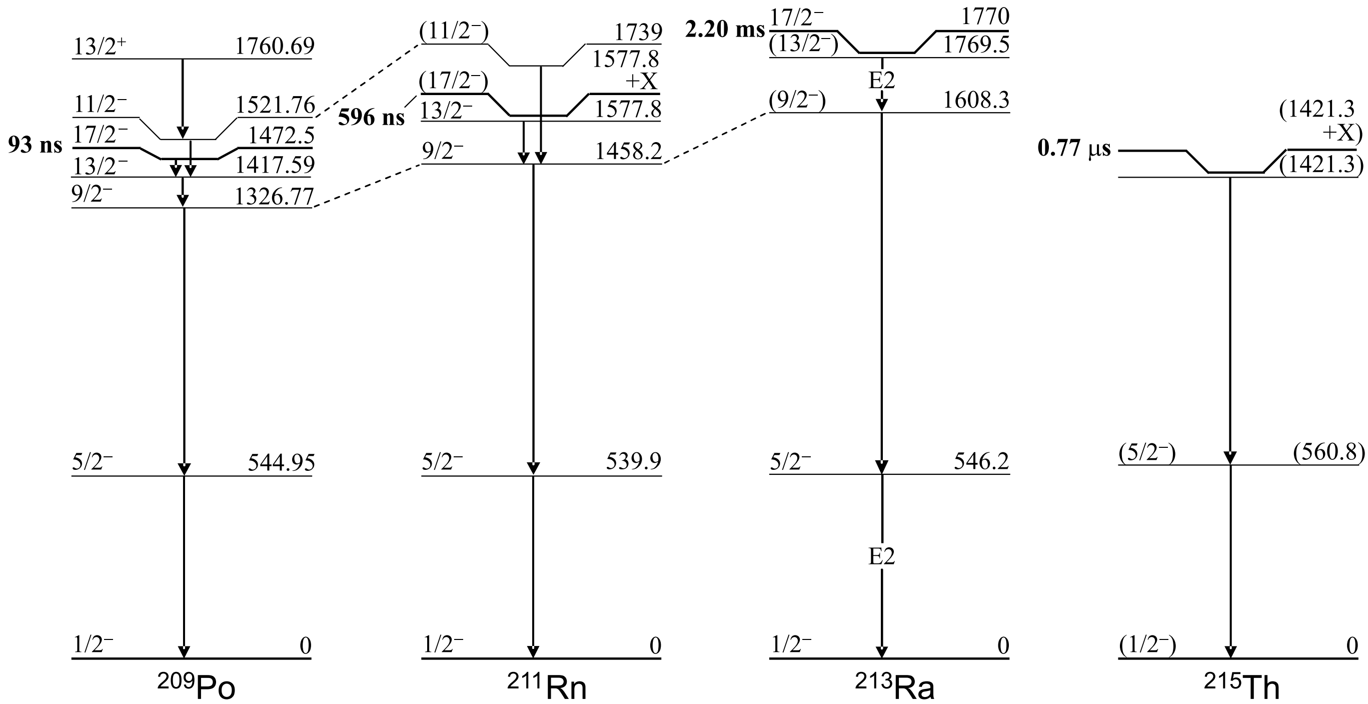

Fig. 5. Partial level schemes of the $N = 125$ even-Z isotones. The most intense transitions in ^{209}Po [16], ^{211}Rn [8], ^{213}Ra (from this work, see also [8,9,14,15]) and ^{215}Th [4] are indicated by arrows.

ample, ^{209}Po has a strong 544.95 keV γ-ray feeding its g.s. [8], and it is produced by a large amount in α decay of ^{213}Ra followed by EC/β^+ decays of ^{209}Rn and ^{209}At. This together with 161 keV γ-rays close to the maximum efficiency of our Ge detector could have resulted in some random coincidences with energies close to those of radium K-X-rays hampering our study. Therefore our measured α_K for the 1062 keV transition could be biased towards a higher value favouring $E3$ and even $M1$ assignments by the cost of $E2$ or even $E1$, the latter however being unlikely. Fortunately, this was not the case for the other two transitions since high-energy γ-rays at 1062 keV provided a clean gate for γ-γ-γ coincidences.

Prior to the present study α decay and α-γ coincidence studies of ^{217}Th established two low-lying levels in ^{213}Ra at 546 and 822 keV (see [4] and references therein). Therefore it is straightforward to assign the 546 keV level to the lowest member of the cascade (shown in fig. 5 together with the other $N = 125$ even-Z isotones) and establish it as the $5/2^-$ state. Unfortunately, the other two transitions cannot be unambiguously placed to the level scheme.

However, as concluded by Raich *et al.* it is likely that the 1062 keV transition feeds the 546 keV level and the 161 keV $E2$ transition cannot result in a half-life of 2.2 ms for the isomeric state, *i.e.* 161 keV does not directly depopulate the isomer but α-particles do (competition between α decay and emission of 161 keV $E2$ γ-rays with $t_{1/2}$(Weisskopf) $\approx$ 70 ns [8] from the same 2.2 ms state would result in an extremely small α branch, which is not supported by the present data). Thus the isomeric $17/2^-$ state $(\pi(h^6_{9/2})_{8+}\nu p^{-1}_{1/2})$ is very likely connected to the $13/2^-$ state within the multiplet by a low-energy $E2$ transition.

On the basis of the measured level energies of 1769.5±0.2 and 1769 ± 6 keV the level energy of the isomer is 1770^{+5}_{-1} keV and an upper limit for the low-energy transition is 6 keV. Assuming that this is correct the transition energy of $\leq$ 6 keV turns into an $E2$ strength lower limit of 2×10^{-4} W.u. This value can be compared to that of ^{214m}Ra (8^+ to 6^+) for which $B(E2) = (1.4 \pm 0.1) \times 10^{-3}$ W.u. [17] is reported. Assuming further that the $E2$ strengths for ^{213m}Ra and ^{214m}Ra are approximately equal we expect the transition energy to be $\approx$ 3 keV ($B(E2) \approx 1 \times 10^{-3}$ W.u.) rather than 6 keV.

An α branch for the isomeric state was estimated using α and γ singles spectra. A value of $(0.23 \pm 0.05)\%$ was extracted using α singles which is however a lower limit due to a fraction of produced ^{213g}Ra by-passing the isomer. The upper limit, on the other hand, was estimated using the ratio of γ-ray singles corrected by absolute efficiency and α decays associated with ^{213g}Ra, *i.e.* using the number of ^{213g}Ra α decays resulting from γ decay of ^{213m}Ra. This resulted in a limit of $b_\alpha < 0.9\%$. Thus, the data combined, we get a branching ratio of $b_\alpha = (0.6 \pm 0.4)\%$ for ^{213m}Ra, which is in-line with $\approx 1\%$ estimated by Raich *et al.* [9].

Finally, we would like to remark that we did not observe γ-rays in ER-γ coincidences gated by ^{213m}Ra α decays. This could indicate short lifetimes for states above the isomer ($\ll 1\,\mu$s, *i.e.* decay in-flight) enabling in-beam studies for transitions feeding and by-passing the 2.2 ms isomer (see [8] and fig. 5 for the lighter $N = 125$ isotones).

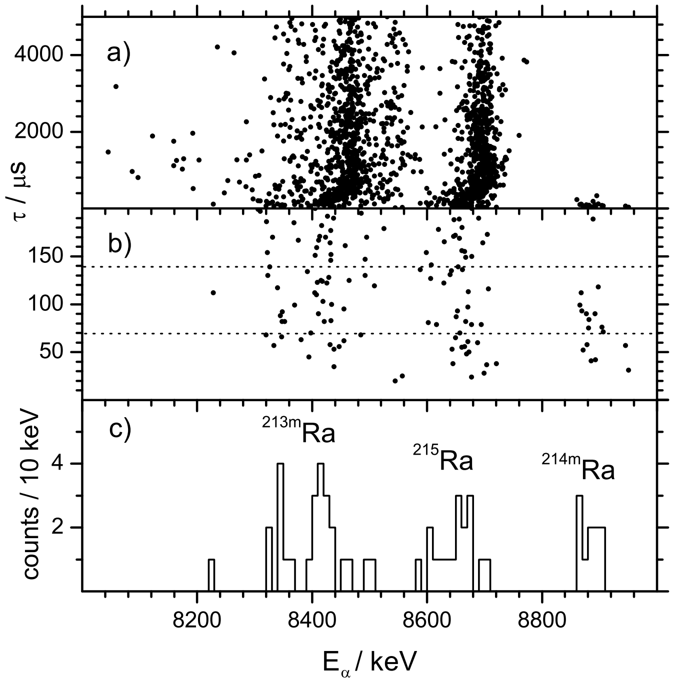

Fig. 6. a) ER-α correlations observed in the ^{48}Ca + ^{170}Er reaction at 4.30 A·MeV beam energy. b) Lifetimes (τ) less than 200 μs. c) Projection of lifetimes between 70 and 140 μs on the energy axis.

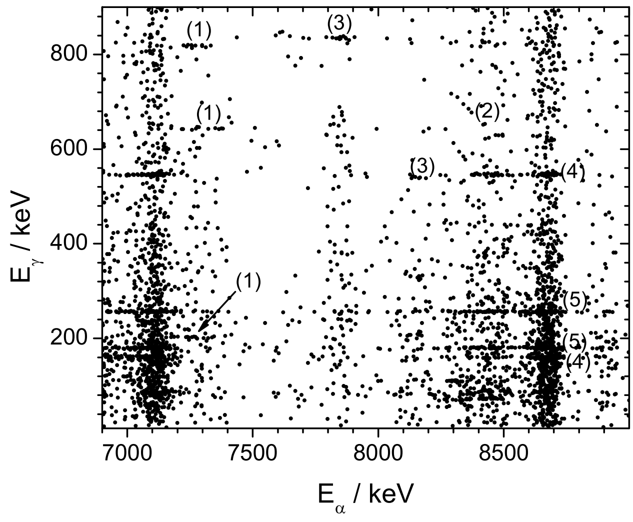

Fig. 7. ER-correlated α-γ coincidences within a searching time of 500 μs produced in the ^{48}Ca + ^{170}Er reaction at 4.25 A·MeV beam energy. Coincident events are marked as follows: (1) ^{214m}Ra α decay to ^{210m}Rn which is depopulated by a cascade of 180, 257 and 1382 keV γ-rays, (2) tentative ^{214m}Ra α decay to the 2^+ state in ^{210}Rn, (3) ^{215}Ra α decay to the $5/2^-$ and $(3/2^-)$ states in ^{211}Rn, which are depopulated by 539.9 and 835.2 keV γ-rays (within ± 0.1 keV, *ibidem*), respectively, (4) isomeric transitions from ^{213}Ra and (5) isomeric transitions from ^{214}Ra. Note that the latter two are scattered within broad α energy windows due to their random nature.

Table 5. α decay of ^{214g}Ra and ^{214m}Ra to the levels in ^{210}Rn, respectively, observed in the present work. Spins and parities (I^π) are adopted from [20] which also reports γ-ray energies within ± 0.1 keV (see text).

E_α [keV]	I_α^{rel} [%]	E_{level} [keV]	E_γ [keV]	I^π
7135 ± 4	99.84 ± 0.03	0		0^+
6505 ± 5	0.16 ± 0.03	643.7 ± 0.2	643.7 ± 0.2	2^+
8950 ± 30	$91 \pm 6^{(a)}$	0		0^+
$\approx 8350^{(b)}$	$\leq 3^{(b)}$	643.7 ± 0.7	643.7 ± 0.7	2^+
			817.8 ± 0.5	4^+
			203.0 ± 0.5	6^+
7290 ± 30	6 ± 3	$1710 \pm 30^{(c)}$		8^+

(^{a}) $b_\alpha = (0.09 \pm 0.07)\%$ extracted for the isomer.
(^{b}) Tentative.
(^{c}) From α decay.

3.3 ^{214g,m}Ra

Prior to the present work spectroscopic studies of ^{214}Ra including an isomeric state at 1865.2 keV with a half-life of $67 \pm 3\,\mu$s were established (see [3,8,18] and references therein). Despite its rather long half-life facilitating α decay to be competitive with γ decay such a branch has not been reported so far. In the present work we observed α decays depopulating the state. Our experimental results are shown in figs. 6 and 7, and summarized in table 5.

In our experiments the isotope was produced by the ^{170}Er(^{48}Ca, 4n)^{214}Ra reaction at 4.25 and 4.30 A·MeV. Its decay was studied using α, γ singles, α-γ coincidences and ER-α, ER-γ correlations. Relative α intensities were extracted using absolute efficiency. Energies for γ-rays depopulating the isomer were determined using γ singles (intensities in the cascade are consistent only with $E2$'s as previously concluded, see [8,17] and references therein). The study resulted in values of 1382.3 ± 0.1, 257.0 ± 0.1 and 180.4 ± 0.1 keV which are consistent with those of [17] within ± 0.1 keV. The 45.5 ± 0.3 keV $E2$ transition ($8^+ \to 6^+$ [8,17]) is highly converted ($\alpha_{tot} \approx 420$ [12]). No γ-rays from this transition were observed. A half-life of ^{214m}Ra was extracted in a similar manner as for ^{213m}Ra but here using γ-γ coincidences gated by 1382 keV γ-rays. This resulted in a value of $68.6 \pm 2.0\,\mu$s which is consistent with the previously reported value.

A search for α decay of ^{214m}Ra was triggered by α-particles scattered around 8900 keV (see fig. 4) for which ER-α correlations resulted in a half-life of $72 \pm 6\,\mu$s. Since a short lifetime results in a broad α energy distribution due to undershooting of energy signals after large pulses of preceding implanted ERs, we investigated the α decay data in more detail. The effect was estimated using the most intense α lines of ^{213m}Ra and ^{215}Ra [8] ($T_{1/2} \approx 1.6$ ms) at 8469 ± 6 and 8699 ± 4 keV, respectively. Events with lifetimes between 70 and 140 μs, *i.e.* within an approximately time-independent region in the E_α *vs.* τ plot (see fig. 6), resulted in α energies of 8398 ± 15 and 8645 ± 10 keV, respectively, with FWHM of ≈ 80 keV. On average the values are reduced by 60 ± 10 keV. Assuming that the energy shifts of ^{213m}Ra, ^{214m}Ra and ^{215}Ra are linear (*i.e.*, average velocities of ERs depend linearly on the mass number) we concluded that the real energy of α-particles observed around 8900 keV is 8950 ± 30 keV. The error bars were estimated taking into account uncertainties in α energies of ^{213m,215}Ra, FWHM of α lines and the number of counts at around 8900 keV. Based on a Q value calculated using energies of 1865.2 ± 0.4 and 7137 ± 3 keV for ^{214m}Ra and α decay of ^{214g}Ra to ^{210g}Rn [8], respectively, we expected an α energy of ≈ 8970 keV for ^{214m}Ra to ^{210g}Rn. Thus, on the basis of matching α energies and half-lives we concluded that α-particles observed at 8950 ± 30 keV likely depopulate the isomeric state in ^{214}Ra. In order to verify our result we performed another, more detailed investigation on α decay of ^{214m}Ra at a slightly lower beam energy of 4.25 A·MeV. The study resulted in α-γ coincidences shown in fig. 7 where α-γ coincidences following implantation of ERs within 500 μs are plotted.

Prior to the present study the 644 ± 40 ns low-lying isomeric state in ^{210}Rn was established at $1664.6 \pm 0.1 + X$ keV with $X < 50$ (see [8,19,20] and references therein). The isomeric state was observed to depopulate by a cascade of 203.1, 817.8 and 643.9 keV γ-rays (energies are reported within ± 0.1 keV). As shown in fig. 7 our data revealed clear groups of α-γ coincidences scattered between 7200 and 7400 keV with γ-ray energies of 203.0 ± 0.5, 817.8 ± 0.5 and 643.7 ± 0.7 keV. For these transitions we extracted a half-life of 480^{+170}_{-100} ns. Since their γ-ray energies and half-lives perfectly match those previously reported for ^{210}Rn, we concluded that the observed α-γ coincidences result from α decays of ^{214m}Ra to ^{210m}Rn. From our data we estimated an α energy of 7290 ± 30 keV for the transition of ^{214m}Ra to ^{210m}Rn. Our value includes corrections in α energy resulting from short lifetimes and electron summing of low-energy conversion electrons connecting the 8^+ and 6^+ states. The latter was estimated by taking into account only α energies from the beginning of their energy distribution, which neglects events suffering from electron summing. Thus, we place the isomeric state in ^{210}Rn at 1710 ± 30 keV. This is consistent with the previously reported upper limit.

As shown in fig. 7 an α intensity from ^{214m}Ra to the 2^+ state in ^{210}Rn is clearly weaker than that of ^{210m}Rn (assuming equal intensities for the isomer and the 2^+ state the number of α-γ coincidences must be equal). Since the former is hardly visible among background we assign these α-γ coincidences only tentatively to decays from ^{214m}Ra to the 2^+ state in ^{210}Rn, and report only an upper limit of 3% for its α intensity. Based on the present data we have constructed the decay scheme of ^{214}Ra shown in fig. 8.

An α branch (b_α) for the isomer was estimated in a similar manner as for ^{213m}Ra. Our α decay studies resulted in a lower limit of (0.021 ± 0.003)% and an upper limit of 0.15% was extracted using γ singles. Thus we get an α branch of $b_\alpha = (0.09 \pm 0.07)$% for the isomeric state. In order to estimate transition probabilities we used the method of Rasmussen [21]. The α decay hindrance factors (HF) were extracted employing the relation $\mathrm{HF} = \delta^2_{gs}/\delta^2_{ex}$, where δ^2_{gs} and δ^2_{ex} are the reduced α decay widths of the g.s.-to-g.s. α decay of ^{214}Ra and those of the other α decays, respectively. The data for the former (E_α, $T_{1/2}$ and b_α) were taken from [8] and the other data used for the calculation are shown in fig. 8, including differences in spins, $\Delta I^\pi = |I^\pi_{final} - I^\pi_{initial}|$.

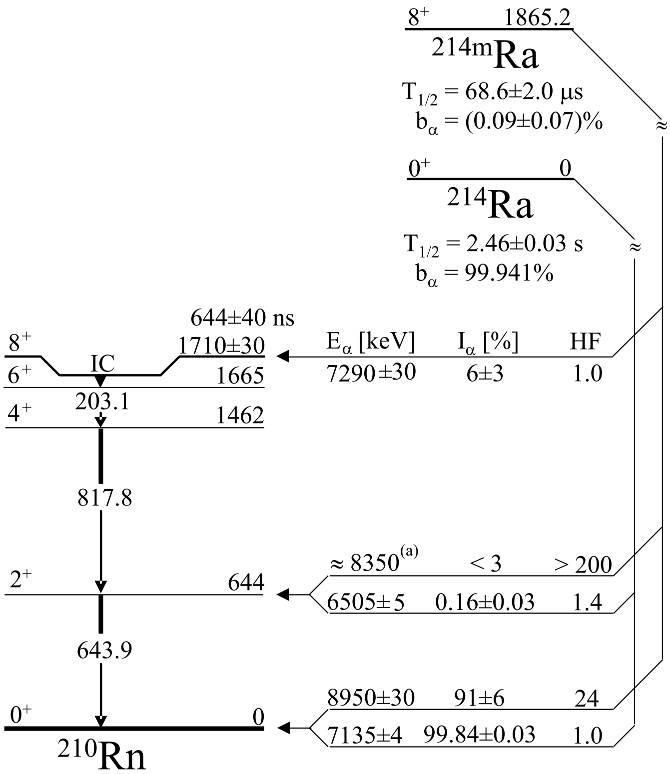

Fig. 8. Decay scheme of ^{214}Ra observed in the present work ($(^a)$ tentative). A half-life ($T_{1/2}$) and α branch (b_α) of ^{214g}Ra and the 8^+ state in ^{214m}Ra are adopted from [8] and the data for ^{210}Rn, apart from the 8^+ level energy, from [20].

The values shown in fig. 8 can be compared with a rather similar α decay of ^{216m}Th to the g.s., 2^+ and the isomeric state of ^{212}Ra for which Kuusiniemi *et al.* [4] recently extracted the values of 130, 280 and 2.4, respectively. One finds that i) the small HF for the ^{214m}Ra to ^{210m}Rn α decay indicates similar nuclear structures for both states and ii) the HFs for ^{214m}Ra appear low compared to those of ^{216m}Th. The latter could indicate that its b_α is actually closer to the value extracted from α decay. However, based on our large error bars we leave further conclusions open for future studies.

4 Conclusion

The present work shows that high-detection efficiencies for α and γ decays combined with low background at the focal plane of SHIP provide an excellent tool to probe nuclear structure. In this work we have improved the decay data for ^{213g,m}Ra and ^{214m}Ra, particularly concerning their α decay properties and transition multipolarities. The results are in line with the level systematics of the $N = 123$, 125 and 126 isotones and with the shell model predictions as expected for the nuclei close to the $N = 126$ neutron shell.

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