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Radioactive decay of ^{217}Pa

F.P. Heßberger[1,a], S. Hofmann[1], I. Kojouharov[1], D. Ackermann[1,2], S. Antalic[3], P. Cagarda[3], B. Kindler[1], B. Lommel[1], R. Mann[1], A.G. Popeko[4], S. Saro[3], J. Uusitalo[5], and A.V. Yeremin[4]

[1] Gesellschaft für Schwerionenforschung mbH, D-64220 Darmstadt, Germany
[2] Institut für Physik, Johannes Gutenberg - Universität Mainz, D-55099 Mainz, Germany
[3] Department of Nuclear Physics, Comenius University SK-84215 Bratislava, Slovakia
[4] Flerov Laboratory of Nuclear Reactions, JINR, 141 980 Dubna, Russia
[5] Physics Department, University of Jyväskylä, FIN-40351 Jyväskylä, Finland

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Abstract. The radioactive decay of ^{217}Pa was investigated by means of α-γ–spectroscopy. Fine structure in the ground-state α-decay was established. Ambiguities in the fine structure of the α-decay of the previously known isomeric state could be clarified by α-γ–coincidence measurements. A previously unknown α-transition of $E_\alpha = (8306 \pm 5)$ keV was detected and identified by means of delayed α-α– and α-γ-γ–coincidence measurements. A second isomeric state decaying by α-emission was not observed. The quality of the previously reported data of the α-decay fine structure of ^{217}Th was improved.

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1 Introduction

For isotopes of elements above lead far off the line of β-stability, α-emission prevails as radioactive decay mode and α-spectroscopy is the most important tool to obtain information on the nuclear structure of the daughter nuclei. Presently the most efficient method to produce isotopes in that region is the complete fusion of heavy ions. However, since the fission barriers are low and the compound nuclei are typically produced with excitation energies of several tens of MeV, the probability for the compound nuclei to de-excite solely by emission of neutrons and γ-rays is small compared to prompt fission or emission of charged particles, mainly protons and α-particles. The decay of these unwanted isotopes produces a large "background" of α-particles in a wide energy range, and therefore, in general, only the strongest α-lines of the isotopes under investigation are visible in single α-spectra, while weak transitions are hidden. Improvement can be achieved in specific cases by measuring delayed α-α–coincidences. However, the most sensitive tool for identifying weak α-transitions, are α-γ–coincidence measurements. Due to low cross-sections of typically a few microbarns or less, the low intensity of α-rays in the case of fine-structure α-decays, reduced detection probability due to the requirement of α-γ–coincidences and often short half-lives, a rapid and efficient separation of the evaporation residues is necessary. A further requirement is the use of a highly sensitive and efficient detector system. Due to these difficulties detailed nuclear decay studies of neutron-deficient isotopes above lead were hardly available until recently, although a large number of nuclei were synthesized and identified already about thirty years ago.

A specific case is the decay of the nucleus ^{217}Pa. First evidence for a successful production of ^{217}Pa was reported by Valli and Hyde [1], who observed an α activity of 8.34 MeV in bombardments of ^{203}Tl and ^{206}Pb with ^{20}Ne. Several years later this activity was unambiguously assigned to ^{217}Pa by means of delayed α-α–coincidences ("α-α–correlations") to the daughter product ^{213}Ac by Schmidt *et al.* [2], who also measured a half-life of $(4.9^{+0.6}_{-0.8})$ ms. In addition, Schmidt *et al.* observed an α activity of 10.16 MeV decaying with $T_{1/2} = (1.6^{+1.0}_{-0.5})$ ms, which they assigned to the decay of an isomeric state. Recently Ikuta *et al.* [3] observed another α-line of 9.54 MeV, $T_{1/2} = (1.5^{+0.9}_{-0.4})$ ms, which they attributed to a second isomeric state in ^{217}Pa, despite the fact that the half-life was consistent with that of the known isomeric state. Energy and half-life of this α-transition could be confirmed in a recent experiment performed at SHIP [4]. However, concerning the assignment we came to a different conclusion. Considering the spin assumptions proposed by Ikuta *et al.*, we concluded on the basis of Weisskopf estima-

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[a] e-mail: `f.p.hessberger@gsi.de`

tions, that the previously known isomeric state $^{217\mathrm{m}1}$Pa at $E^* = 1.85$ MeV would predominantly decay by γ-emission into $^{217\mathrm{m}2}$Pa at $E^* = 1.23$ MeV. In that case an α-decay branch of the isomer at 1.85 MeV would have been hardly detectable. Moreover we observed another α-line of 9.69 MeV, which had the same half-life as the other two transitions [4]. It was thus argued that there exists only one isomeric state, which decays into excited levels of the daughter nucleus.

To confirm our considerations we decided to perform a more detailed study of the decay scheme of ^{217}Pa. We chose the reaction $^{181}\mathrm{Ta}(^{40}\mathrm{Ar}, 4\mathrm{n})^{217}\mathrm{Pa}$ instead of $^{170}\mathrm{Er}(^{51}\mathrm{V}, 4\mathrm{n})^{217}\mathrm{Pa}$ used in the previous experiment by two reasons: firstly, the production cross-section for $^{181}\mathrm{Ta}(^{40}\mathrm{Ar}, 4\mathrm{n})^{217}\mathrm{Pa}$ is $\sigma = 1.1$ μb [5] which is more than an order of magnitude higher than $\sigma = 82$ nb which was measured for $^{170}\mathrm{Er}(^{51}\mathrm{V}, 4\mathrm{n})^{217}\mathrm{Pa}$ [6], and secondly, about a factor of two higher beam intensity could be expected for ^{40}Ar compared to ^{51}V.

2 Experiment

The experiment was performed at the velocity filter SHIP at GSI, Darmstadt, using a beam of ^{40}Ar. Beam intensities of (1.2–1.5) × 10^{13} ions/s ((2.0–2.5) particle μA) were delivered from the UNILAC accelerator. The incident beam energy was 182 MeV. Taking into account energy loss in the target backing (carbon) and in the first half of the target thickness according to [7] this energy corresponded to an excitation energy of $E^* = 43$ MeV in the centre of the target, a value close to that expected for the maximum cross-section for the 4n de-excitation channel, according to [5]. The targets of natural tantalum (99.988% ^{181}Ta) were produced by sputtering the metal onto a carbon layer of 40 μg/cm^2 thickness. The mean thickness of tantalum was 400 μg/cm^2. Eight targets were mounted on a target wheel that rotated synchronously to the beam macro structure [8]. The evaporation residues, recoiling from the targets with energies of ≈ 25 MeV were separated from the primary beam by the velocity filter SHIP [9]. Behind SHIP they passed three transmission detectors [10], which were used to discriminate between incoming particles and α-decays (anticoincidence). Finally, the residues were implanted into a position-sensitive 16-strip PIPS detector ("stop detector") with an active area of (80 × 35) mm^2, where their kinetic energies as well as subsequent α-decays were measured [11]. Operated at a temperature of 258 K, the energy resolution for individual strips was (20–24) keV(FWHM). Summing all strips in the off-line data analysis we obtained typical overall "stop detector" resolutions of $\Delta E = (22\text{–}28)$ keV. (The slightly worse resolution here compared with the better values (18 keV) published elsewhere results from radiation damage of the detectors in previous irradiations.) Alpha energy calibration was performed using the literature values for known isotopes also produced in the irradiation.

Coincidences between α-particles and γ-rays were measured with a Compton-unsuppressed clover detector. It consisted of four Ge crystals (70 mm ⌀, 140 mm length), which were shaped and assembled to form a block of (124 × 124 × 140) mm^3. The γ detector was mounted directly behind the "stop detector". The energy was calibrated using ^{152}Eu and ^{133}Ba γ sources. The energy resolution for the individual crystals was typically about 2 keV (FWHM) for the 139 keV line of ^{214}Ac and about 3 keV for the 613 keV line of ^{217}Pa.

Table 1. α-γ–coincidence efficiencies of the detector set-up. The values $\epsilon_{\alpha\text{-}\gamma}$ represent the total efficiency summed over all four germanium crystals of the clover detector.

Isotope	E_α/keV	E_γ/keV	$\epsilon_{\alpha\text{-}\gamma}$
^{217}Th	8455	822.1	0.035 ± 0.005
^{217}Th	8725	546.5	0.060 ± 0.009
$^{217\mathrm{m}}$Pa	9697	466.5	0.068 ± 0.021
$^{217\mathrm{m}}$Pa	9552, 9533	613.0, 634.3	0.052 ± 0.006

The efficiency $\epsilon_{\alpha\text{-}\gamma}$ for α-γ–coincidences was estimated for γ-rays from 450 to 825 keV from the ratio of observed α-γ– to–α single rates for the fine-structure α-lines of ^{217}Th (8725, 8455 keV) and the $E_\alpha = 9697$, 9552 and 9533 keV transitions of $^{217\mathrm{m}}$Pa. The results are listed in table 1.

To avoid contaminations in the α-spectra from the decay of ^{217}Pa, which could originate from background of evaporation residues (ER) as well as scattered beam particles and target nuclei that passed SHIP and were not rejected by the anticoincidence, we considered only α-particles which followed the implantation of heavy residues at the same detector position within 15 ms. Since the energy region of the 9552 and 9533 keV transitions of $^{217\mathrm{m}}$Pa overlaps with that of the α energies of ^{218}Pa (9610, 9540 keV), we additionally required in the analysis a subsequent α-decay of ^{213}Ac (7360 keV) within 5 s in order to enhance the $^{217\mathrm{m}}$Pa α-lines in the spectrum relative to the α-lines of ^{218}Pa.

In the discussion, when comparing energies from α-γ–coincidence measurements, we prefer to use the Q_α-value, $Q_\alpha = (1 + m_\alpha/m_\mathrm{d}) \times E_\alpha$ where $(m_\alpha/m_\mathrm{d}) \times E_\alpha$ denotes the recoil energy transferred to the daughter nucleus (m_d) by the α-particle (m_α).

3 Experimental results and discussion

The spectrum of α-particles following the implantation of an evaporation residue within 15 ms is shown in fig. 1 (full line). The shaded area represents those events which are in addition followed by an α-decay of ^{213}Ac within 5 s. It is evident that practically only α-decays from $^{217\mathrm{g},217\mathrm{m}}$Pa are left, while the strong lines from ^{218}Pa, ^{217,216}Th and ^{215}Ac vanished except for a low number of random correlations (see also table 3).

Table 2. Summary of spectroscopic results for ^{217g,217m}Pa and ^{217}Th. The γ-rays coincident to the α transitions are listed in column 6.

Isotope	E_α/keV	Q_α/keV	i_α	$T_{1/2}$/ms	E_γ/keV
^{217g}Pa	8337 ± 5	8494 ± 5	0.99 ± 0.01	3.8 ± 0.2	
	7873 ± 5	8021 ± 5	0.004 ± 0.002		466.1 ± 2.0
	7728 ± 5	7873 ± 5	0.003 ± 0.002		612.5 ± 0.8
	7710 ± 5	7855 ± 5	0.003 ± 0.002		634.3 ± 1.1
^{217m}Pa	10157 ± 5	10348 ± 5	0.72 ± 0.04	1.08 ± 0.02	
	9697 ± 5	9879 ± 5	0.02 ± 0.01	0.95 ± 0.05	466.5 ± 0.2
	9552 ± 5	9731 ± 5	0.09 ± 0.01	0.94 ± 0.09	613.0 ± 0.2
	9533 ± 5	9712 ± 5	0.06 ± 0.01	1.11 ± 0.20	634.3 ± 0.1
	8306 ± 5	8462 ± 5	0.11 ± 0.02	1.03 ± 0.13	450.4 ± 0.1, 612.7 ± 0.1, 820.8 ± 0.2
				1.08 ± 0.03[a]	
^{217}Th	9261 ± 5	9435 ± 5	0.945 ± 0.005	0.237 ± 0.001	
	8725 ± 5	8889 ± 5	0.018 ± 0.001	0.229 ± 0.006	546.1 ± 0.1
	8455 ± 5	8614 ± 5	0.037 ± 0.001	0.245 ± 0.008	822.1 ± 0.1
				0.237 ± 0.002[a]	

([a]) Mean half-lives obtained from all measured events.

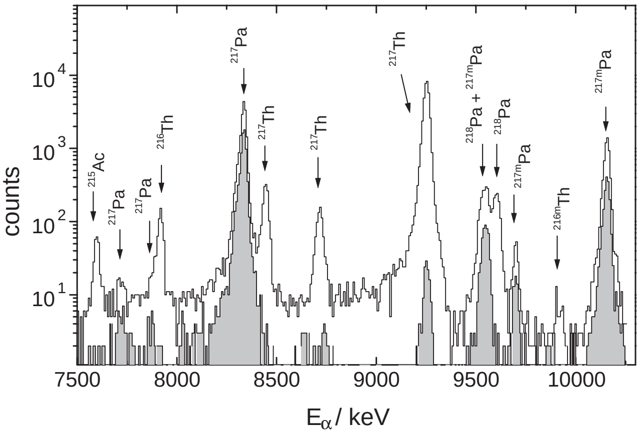

Fig. 1. Alpha-spectra observed in the irradiation of ^{181}Ta with ^{40}Ar at $E_{\text{lab}} = 182$ MeV. Full line: spectrum of α-particles following the implantation of a heavy residue within $\Delta t \leq 15$ ms. Shaded area: spectrum of α-particles following the implantation of a heavy residue within $\Delta t \leq 15$ ms and followed by an α-decay of ^{213}Ac within $\Delta t \leq 5$ s. The selected α energy window for ^{213}Ac was (7340–7380) keV.

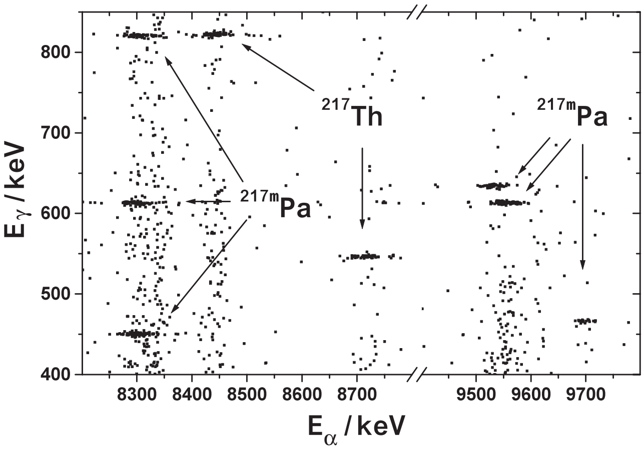

Fig. 2. Two-dimensional plot of α-γ–coincidences for products from complete-fusion reaction of ^{181}Ta with ^{40}Ar projectiles at $E_{\text{lab}} = 182$ MeV. The detector set-up consisting of silicon detectors and a germanium clover detector was mounted behind SHIP.

3.1 ^{217m}Pa

Our previous suggestion [4] to assign the α-line at 9548 keV and to tentatively assign the line at 9694 keV to decays of ^{217m}Pa into excited daughter levels was clearly verified by the current experiment. The results are listed in table 2 and are shown in the two-dimensional plot of the α *versus* γ energy (fig. 2). Three groups of α-γ–coincidences are visible. The tentatively assigned line at 9694 keV could be confirmed, while the line at 9548 keV turned out to be a line doublet, which is not resolved in the one-dimensional α-spectrum (see fig. 1). Also it should be emphasized that each one of these α-lines is coincident only with one γ-line. Besides random events distributed uniformly in energy, no coincidences with γ's were observed for the α-line at 10157 keV. The narrow line width of $\Delta E(\text{FWHM}) = 28$ keV does not suggest that it is effected by energy summing with conversion electrons. It is also evident from table 2, that the Q_α-value for the 10157 keV line perfectly agrees with the sum $Q_\alpha + E_\gamma$ of the other lines. These facts strongly suggest that the 10157 keV line indeed represents the decay into the ground state of ^{213}Ac. The half-life obtained from fitting an exponential function to the distribution of time differences between implantation of the evaporation residue and the succeeding α-decay results in a value of $T_{1/2} = (1.08 \pm 0.02)$ ms for the isomeric state, a value slightly lower but still in agreement with that of the previous experiment.

In addition a group of three γ-lines at energies of 450.4, 612.7, 820.8 keV was observed in coincidence to α-particles

Table 3. α(mother)-α(daughter)–correlation probabilities $\Sigma_{\alpha\text{-}\alpha}/\Sigma_{\mathrm{ER}\text{-}\alpha}$ for different α-lines observed for the fusion products from reactions of ^{181}Ta with ^{40}Ar at $E_{\mathrm{lab}} = 182$ MeV. $\Sigma_{\mathrm{ER}\text{-}\alpha}$ denotes the number of ER-α(mother)–correlations within the time interval $\Delta(t(\alpha(\text{mother})) - t(\text{ER})) \leq 15.0$ ms. $\Sigma_{\alpha\text{-}\alpha}$ denotes the number of α(mother)-α(daughter)–correlations within the time interval $\Delta(t(\alpha(\text{daughter})) - t(\alpha(\text{mother}))) \leq 5.0$ s. The energy range for events respected as daughter decays was (7320–7400) keV corresponding to the α-line of ^{213}Ac, the daughter product of ^{217}Pa, The energy ranges for events respected as mother decays are given in column 3, whereas the peak value of the α-line is given in column 2.

Isotope	E_α(mother)/keV	ΔE_α(mother)/keV	$\Sigma_{\alpha\text{-}\alpha}/\Sigma_{\mathrm{ER}\text{-}\alpha}$
^{217}Th	9261	9215–9295	$(6.7 \pm 0.5) \times 10^{-3}$
$^{217\mathrm{m}}$Pa	10157	10070–10240	0.40 ± 0.01
$^{217\mathrm{m}}$Pa	9697	9660–9720	0.43 ± 0.08
$^{217\mathrm{m}}$Pa (+^{218}Pa)	9552, 9533	9500–9600	0.27 ± 0.02
$^{217\mathrm{m}}$Pa	8306$^{(\mathrm{a})}$	8265–8330	0.437 ± 0.11
^{217}Pa	8337	8265–8410	0.49 ± 0.01
^{217}Pa	7873	7850–7890	0.22 ± 0.08
^{217}Pa	7710, 7728	7690–7750	0.32 ± 0.09

($^{\mathrm{a}}$) α-decays coincident to $E_\gamma = 450.4$, 612.7 or 820.8 keV.

having a mean energy of 8306 keV, a value that is slightly, but significantly lower than the energy of the ground-state to ground-state transition of ^{217}Pa at $E_\alpha = 8337$ keV. This activity is assigned to the decay of $^{217\mathrm{m}}$Pa into a high-energy level at $E^* = (1883.9 \pm 0.3)$ keV of ^{213}Ac by the following reasons:

a) An analysis of α-α–correlations proved the 8306 keV decay unambiguously as precursor of ^{213}Ac as seen in table 3, where we have listed the probabilities for observing delayed coincidences. The result for the observed α-α–correlations is comparable to that for $^{217,217\mathrm{m}}$Pa and definitely larger than for ^{217}Th, which is not an α-decay precursor of ^{213}Ac and therefore its value represents the probability for random correlations.
b) A half-life of (1.03 ± 0.13) ms was measured, a value close to that obtained for $^{217\mathrm{m}}$Pa.
c) The total Q-value for the decay, *i.e.* $Q_\alpha + E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3}$ is 10346 keV and thus identical within the error bars to that for the ground-state decay (10348 keV) and the sum of the other α fine-structure lines plus γ-lines as discussed above.
d) Each γ-line was observed in coincidence with the other two lines, proving that the level populated by the α-transition, decays into the ground state by the cascade of the three measured γ-transitions (fig. 3).

3.2 $^{217\mathrm{g}}$Pa

Population of excited levels by α-decay of the isomer $^{217\mathrm{m}}$Pa suggests that also the ground-state decay may populate excited levels notably. Due to the lower Q_α-value, however, lower relative intensities are expected. Estimations for unhindered transitions on the basis of calculated partial α half-lives [12,13] result in relative intensities of $i_{\mathrm{rel}} < 0.05$. Searching for α-γ–coincidences in the energy region in question, $E_\alpha = (7700\text{–}7900)$ keV, we observed three accumulations of events. The results are listed in table 2. The assignment to ^{217}Pa could be confirmed by delayed α-α–coincidences to ^{213}Ac as seen in fig. 1 (shaded areas) and table 3, where similar corre-

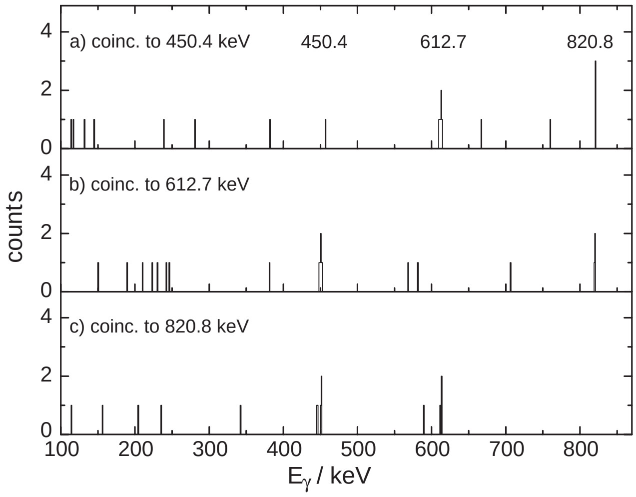

Fig. 3. γ-γ–coincidence spectra observed in coincidence to α-particles in the energy interval $E_\alpha = (8270\text{–}8345)$ keV. The three spectra in a), b), and c) were taken in coincidence to the γ-lines at 450.4, 612.7, and 820.8 keV, respectively.

lation probabilities are obtained as for the main line of the $^{217\mathrm{g}}$Pa decay and the lines attributed to $^{217\mathrm{m}}$Pa. The somewhat smaller values of the correlation probabilities in table 3 of the weaker ^{217}Pa lines may be due to the fact that the rates for ER-α–correlations also contain decays of ^{216}Th (7923 keV) and ^{216}Pa (7948, 7815 and 7793 keV), which is especially significant for the 7873 keV line. (Note that the lines of 7728 keV and 7710 keV are not resolved in the α-spectrum.)

Since due to background from ^{216}Pa the weak lines of ^{217}Pa were not visible in the single α-spectra, the line intensities given in table 2 were estimated on the basis of observed numbers of α-α–correlations to ^{213}Ac, which resulted in larger error bars. Nevertheless it is evident that the intensities are about a factor (3–10) lower than expected for unhindered transitions.

The measured decay curve, *i.e.* the distribution of the time differences between implantation of the ER's and the succeeding α-decays, essentially from the 8337 keV transition, could not be fitted by a single exponential function indicating that the ground state of ^{217}Pa is notably fed by γ-transitions of the isomeric state. A fit using two exponential functions resulted in $T_{1/2} = (3.8 \pm 0.2)$ ms, which is attributed to the half-life of the ground state and $T_{1/2} = (0.93 \pm 0.18)$ ms, which is in agreement with the half-life of the isomeric state. From the fit we further extracted a ratio 0.15 ± 0.02 of $^{217\mathrm{g}}$Pa produced by decay of the isomeric state to the total number of $^{217\mathrm{g}}$Pa. Using this value and the numbers of α-decays observed for $^{217\mathrm{g}}$Pa (27000 events) and $^{217\mathrm{m}}$Pa (10800 events) we obtained an α-branching of the isomeric state of 0.73 ± 0.04.

3.3 ^{217}Th

The isotope ^{217}Th was produced by the ^{181}Ta(^{40}Ar, p3n)^{217}Th reaction in this experiment. Fine structure in the α-decay of its ground state has been already reported by Nishio *et al.* [14] and in our recent paper [4], where we also succeeded to measure a few α-γ–coincidences, which allowed a better estimation of the energy of the daughter levels populated by the α-decays. In the present study the quality of the data could be improved. The new results are listed in table 2.

4 Discussion

The measured spectroscopic data can be used to construct a partial decay scheme for $^{217\mathrm{g}}$Pa and $^{217\mathrm{m}}$Pa. For the discussion we will use theoretical α-decay half-lives according to the formula proposed by Poenaru [12] as modified by Rurarz [13], which perfectly reproduces the half-lives for even-even isotopes of uranium, thorium and radium at $N = 126$ as seen in table 4. Hindrance due to nonzero angular-momentum difference between mother and daughter is included according to the formula proposed by Rasmussen [15]. For comparisons with published values we mostly refer to the data compilation [16].

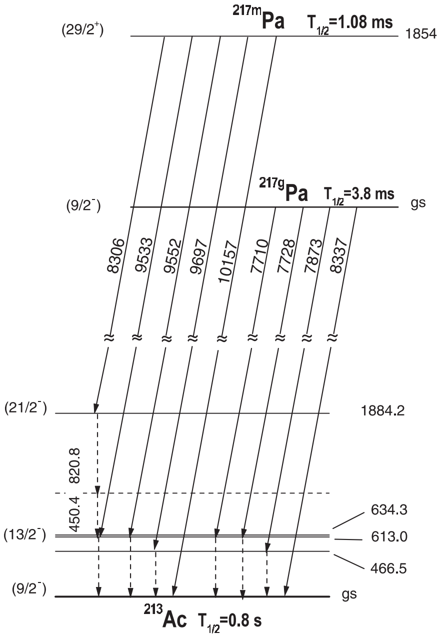

Fig. 4. Tentative partial decay scheme suggested for the decay of ^{217}Pa into ^{213}Ac.

Ground-state spins and parities of odd-Z, even-N nuclei at the neutron shell $N = 126$ above lead are usually characterized as $9/2^-$. The α-decay chain of $^{217\mathrm{g}}$Pa proceeds through $^{217\mathrm{g}}\mathrm{Pa}(b_\alpha \approx 1) \rightarrow {}^{213\mathrm{g}}\mathrm{Ac}(b_\alpha \approx 1) \rightarrow {}^{209\mathrm{g}}\mathrm{Fr}(b_\alpha \approx 0.9) \rightarrow {}^{205\mathrm{g}}\mathrm{At}(b_\alpha \approx 0.1) \rightarrow {}^{201\mathrm{g}}\mathrm{Bi}(b_\alpha < 10^{-6})$. The α-decays of these isotopes are characterized by one dominating α-transition with an intensity of ≥ 0.99, for which no γ-rays in coincidence have been observed so far. This is the reason why they are assigned to ground-state to ground-state transitions. As seen in table 4, experimental half-lives are reproduced perfectly by the calculations. Therefore the transitions are regarded as unhindered transitions connecting levels of equal spin and parity. Thus, a spin and parity assignment of $9/2^-$ for $^{217\mathrm{g}}$Pa and $^{213\mathrm{g}}$Ac as done for the ground states of their decay products ^{209}Fr, ^{205}At and ^{201}Bi is reasonable.

Concerning the isomeric state it was already pointed out by Schmidt *et al.* [2] that its long half-life must be due to a strong hindrance of the α-decay caused by a large angular-momentum difference betwen the initial and final state. Since the hindrance factor deduced in [2], as our value in table 4, was in accordance with $\Delta l = 10$, a $29/2^+$ state, also known in some lighter odd-Z, even-N nuclei at $N = 126$, was suspected as the isomeric state. This assumption was adopted later also by Ikuta *et al.* [3]. For the lighter $N = 124$ and $N = 126$ nuclei these levels are located at $E^* = (2400–2650)$ keV. They decay by $E3$ transitions to $23/2^-$ states at $E^* = (1800–1950)$ keV [16]. In ^{217}Pa the isomeric state is located at $E^* = (1854 \pm 7)$ keV, which is close to the energies of the $23/2^-$ states known in the lighter nuclei. Assuming a stable energy of the $23/2^-$ state, a low energy difference to the $29/2^+$ state in ^{217}Pa follows, which is necessary for the existence of an isomeric state of 1 ms half-life. For energy differences greater than

Table 4. Comparison of theoretical and experimental α-decay half-lives as a function of the change in angular momentum. b_α denotes the α-branching, i_α the relative intensity of the transition, $T_{1/2}$(exp) the experimental half-life of the isotope, T_α(exp) and T_α(calc) the experimental and calculated partial α half-lives, Δl the change in angular-momentum quantum number, HF $= T_\alpha(\text{exp})/T_\alpha(\text{calc})$ is the hindrance factor for the transition.

Isotope	E_α/keV	b_α	i_α	$T_{1/2}$(exp)	T_α(exp)	T_α(calc)	Δl	HF
^{218}U	8630	1.0	1.0	1.5 ms	1.5 ms	1.1 ms	0	1.3
^{214}Th	7680	1.0	1.0	0.1 s	0.1 s	0.16 s	0	0.6
^{216}Th	7923	1.0	1.0	28 ms	28 ms	27.5 ms	0	1.0
^{218}Th	9670	1.0	1.0	0.1 μs	0.1 μs	0.13 μs	0	0.8
^{212}Ra	6901	1.0	1.0	13 s	13 s	15.6 s	0	0.8
^{214}Ra	7136	1.0	1.0	2.46 s	2.46 s	2.16 s	0	1.1
^{216}Ra	9349	1.0	1.0	0.18 μs	0.18 μs	0.15 μs	0	1.2
^{217}Pa	8337	1.0	1.0	3.8 ms	3.8 ms	4.3 ms	0	0.9
^{213}Ac	7360	1.0	1.0	0.8 s	0.8 s	0.81 s	0	1.0
^{209}Fr	6648	0.89	1.0	50 s	56 s	54 s	0	1.0
^{205}At	5902	0.1	1.0	0.44 h	4.4 h	3.1 h	0	1.4
^{217}Pa	7873	1.0	0.004	3.8 ms	950 ms	98 ms	0	9.7
						164 ms	2	5.8
						554 ms	4	1.7
						1318 ms	5	0.72
^{217}Pa	7728	1.0	0.003	3.8 ms	1266 ms	297 ms	0	4.3
						500 ms	2	2.5
						1681 ms	4	0.8
^{217}Pa	7710	1.0	0.003	3.8 ms	1266 ms	342 ms	0	3.7
						575 ms	2	2.2
						1936 ms	4	0.65
$^{217\text{m}}$Pa	10157	0.73	0.72	1.1 ms	2.1 ms	9×10^{-5} ms	0	24400
						0.044 ms	8	48
						0.21 ms	9	10
						1.2 ms	10	1.8
						8.0 ms	11	0.3
						62 ms	12	0.03
$^{217\text{m}}$Pa	9697	0.73	0.02	1.1 ms	76 ms	9×10^{-4} ms	0	82600
						13 ms	10	6
						86 ms	11	0.9
						685 ms	12	0.1
$^{217\text{m}}$Pa	9552	0.73	0.09	1.1 ms	17 ms	2.0×10^{-3} ms	0	8500
						1.0 ms	8	17
						4.9 ms	9	3.5
						27 ms	10	1.6
$^{217\text{m}}$Pa	9533	0.73	0.06	1.1 ms	26 ms	2.2×10^{-3} ms	0	11800
						1.1 ms	8	24
						5.4 ms	9	4.8
						31 ms	10	1.2
$^{217\text{m}}$Pa	8306	0.73	0.11	1.1 ms	14 ms	4.2 ms	0	3.3
						7.0 ms	2	2.0
						12 ms	3	1.2
						24 ms	10	0.6

500 keV Weisskopf estimations result in $E3$ lifetimes of < 0.1 ms. Under this aspect a steep decrease of the $29/2^+$ state in the case of ^{217}Pa can explain the occurrence of the observed isomeric state. This interpretation is supported by the characteristics of the 8306 keV α-line. As seen in table 4, the partial α half-life of this transition is in line with an angular-momentum difference $\Delta l = 2$, 3 or 4. However, the values in table 4 do not include hindrance due to the change of parity or other nuclear structure effects. From the values for the 10157 keV transition one could expect a hindrance factor of three. Similar values are obtained for the $9/2^+ \rightarrow 3/2^-$ α-transitions for $^{217}\mathrm{Th} \rightarrow {}^{213}\mathrm{Ra}$, $^{215}\mathrm{Ra} \rightarrow {}^{211}\mathrm{Rn}$, $^{213}\mathrm{Rn} \rightarrow {}^{209}\mathrm{Po}$, $^{211}\mathrm{Po} \rightarrow {}^{207}\mathrm{Pb}$, which are the transitions with the lowest hindrance factors in these nuclei [4]. Thus, one can conclude that parity change introduces a hindrance of at least a factor of three. Under these circumstances a partial α-decay half-life of 14 ms seems surprisingly small at least for $\Delta l = 3$ or 4 transition. It fits better to $\Delta l = 0$, 1 or 2 transitions. On the other hand, in ^{211}Fr, ^{209}At, the lighter $N = 124$ isotones of the daughter ^{213}Ac, $21/2^-$ states are known, decaying by a series of three $E2$ γ-transitions of 106.1, 596.5, 725.05 keV (^{209}At) or 233.4, 800.3, 652.62 keV (^{211}Fr) to the $9/2^-$ ground state indicating some similarity to the situation here, which, vice versa, means the population of a $21/2^-$ state by a $\Delta l = 4$ transition, since population of a level with a higher spin, *e.g.*, $23/2^-$, $25/2^-$, $27/2^-$ or $29/2^-$ is not supported by the experimental data. Since the sum of the γ energies and the Q-value for the 8306 keV transition equals the Q-value for the transition into the ground state of ^{213}Ac and the α-line does not show broadening due to conversion electrons (from, *e.g.*, an $M1$ transition) the level being the starting point of the γ-cascade is certainly not fed by the decay of higher levels. It also seems unlikely that one of the transitions refers to a larger angular-momentum difference, *e.g.*, $\Delta l = 3$, since in such a case much faster $M1$ transitions would dominate and we rather would expect a two-step decay via $M1$ and $E2$ than a single $M3$ transition. Therefore on the basis of the present data we regard the low partial α half-life as an oddity and propose a decay scheme as shown in fig. 4. The assignments, however, as the discussion has shown, are not free of ambiguities and are regarded as tentative.

Due to the agreement of the 612.7 keV line of the γ-cascade with the energy of the lines observed in coincidence to $E_\alpha = 7728$ keV ($^{217\mathrm{g}}$Pa) and to $E_\alpha = 9552$ keV ($^{217\mathrm{m}}$Pa), we attribute it to the last member of the cascade, *i.e.* to the transition $13/2^- \rightarrow 9/2^-$. For the corresponding α-decays this results in $\Delta l = 2$ (7728 keV) or $\Delta l = 8$ (9552 keV) transitions. It is evident from table 4, that the hindrance factor for the 7728 keV transition is, also with respect to the uncertainty of the partial α half-life due to the large error bar for the relative intensity, in-line with an angular-momentum change of $\Delta l = 2$. For the $E_\alpha = 9552$ keV transition from the isomeric state, however, the partial α half-life is still about a factor of six longer than expected for a $\Delta l = 8$ transition even if a hindrance factor for parity change of three is considered. Such a deviation is not unusual, but indicates that additional nuclear structure effects have to be considered. Therefore, spin and parity assignments for the levels populated by the other α-decays cannot be given.

5 Summary

The radioactive decay of $^{217\mathrm{g}}$Pa and $^{217\mathrm{m}}$Pa has been studied in detail by means of α-γ–coincidence measurement. The question of the origin of weak transitions in the energy range $E_\alpha = (9.5$–$9.7)$ MeV from a second high-spin isomer in ^{217}Pa or from fine structure in the α-decay of the known isomeric state could be clearly answered in favor of the latter interpretation. In addition, a notable α-decay branch of $^{217\mathrm{m}}$Pa into a high-spin level of ^{213}Ac at $E^* = 1884$ keV was observed. Fine structure in the α-decay of $^{217\mathrm{g}}$Pa has been observed for the first time.

A partial decay scheme for $^{217\mathrm{g}}$Pa, $^{217\mathrm{m}}$Pa could be constructed including a tentative assignment of spin and parity to the ground state of ^{217}Pa and ^{213}Ac and to the isomeric state $^{217\mathrm{m}}$Pa as well as some excited levels in ^{213}Ac populated by α-decay. More information could be obtained by studying the γ-decay of the isomeric state, which can be done by measuring triple delayed coincidences between implantation of the residue, γ-decay of $^{217\mathrm{m}}$Pa, and α-decay of $^{217\mathrm{g}}$Pa, using an experimental setup which includes highly efficient clover detectors for the γ-ray detection, as was the case in this work.

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