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Decay studies of $^{214-216}$Ac by α-γ-γ-coincidences

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Abstract. The α-decay fine structure of ^{214}Ac, ^{215}Ac and ^{216}Ac has been studied using the α-γ-coincidence technique. The nuclei were produced by ^{209}Bi(^{12}C, xn)$^{221-x}$Ac-reactions. Evaporation residues were separated in-flight from the primary beam using the velocity filter SHIP at GSI, Darmstadt. The separated nuclei were implanted into a position-sensitive 16-strip PIPS Si detector and their subsequent decays were measured. In these studies new and improved decay data for $^{214-216}$Ac were obtained.

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1 Introduction

Decay data of actinides near the $N = 126$ closed shell are rather scarce. Even for actinium and thorium isotopes, although first identified three decades ago, only a few α-branches populating levels in daughter nuclei have been reported so far [1]. A recent work in the region by Heßberger *et al.* [2] showed that, apart from a few strong α-transitions, other α-branches are extremely weak. Thus, the most promising way to probe further these short-living nuclei is to use the α-γ-coincidence technique combined with efficient in-flight separation of evaporation residues. The present work takes advantage of this technique in α-decay studies of ^{214}Ac, ^{215}Ac and ^{216}Ac.

Alpha-gamma-coincidence data for these nuclei were established in the previous studies [2]. However, the results were partly tentative but indicated complex decay patterns inspiring further studies. Therefore, as a continuation, the present investigations were performed in order to confirm the earlier results and to study further these nuclei. The aim of the present work was to extract new and improved decay data for $^{214-216}$Ac using in addition α-γ-γ-coincidences and, particularly for ^{214}Ac and ^{216}Ac, to significantly expand the decay schemes of these nuclei.

2 Experimental procedure

The experiments were carried out employing reactions of the type ^{209}Bi(^{12}C, xn)$^{221-x}$Ac. A ^{12}C beam was delivered by the UNILAC accelerator at GSI, Darmstadt, with incident beam energies in the range from 6.6 to 11.4 $A \cdot$ MeV and an intensity of $\approx$ 200 pnA. The targets were 240 μg/cm^2 thick ^{209}Bi foils (with 40 μg/cm^2 carbon backing) which were mounted on a wheel that rotated synchronously to the beam macro structure (pulses of 5 ms followed by beam-off periods of 15 ms). The evaporation residues escaping the target were separated from the primary beam by the velocity filter SHIP [3]. After separation the residues were implanted into a position-sensitive

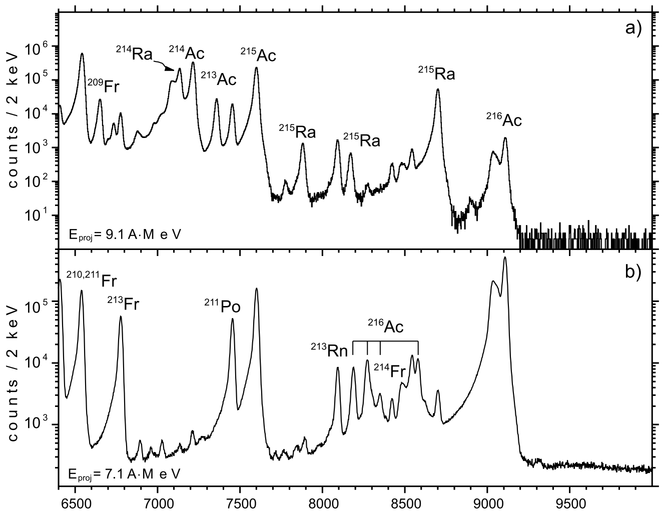

Fig. 1. Singles α-spectra from the ^{209}Bi(^{12}C, xn)$^{221-x}$Ac reaction at a) 9.1 $A \cdot$ MeV (beam off only) and b) 7.1 $A \cdot$ MeV bombarding energies (both beam on and off).

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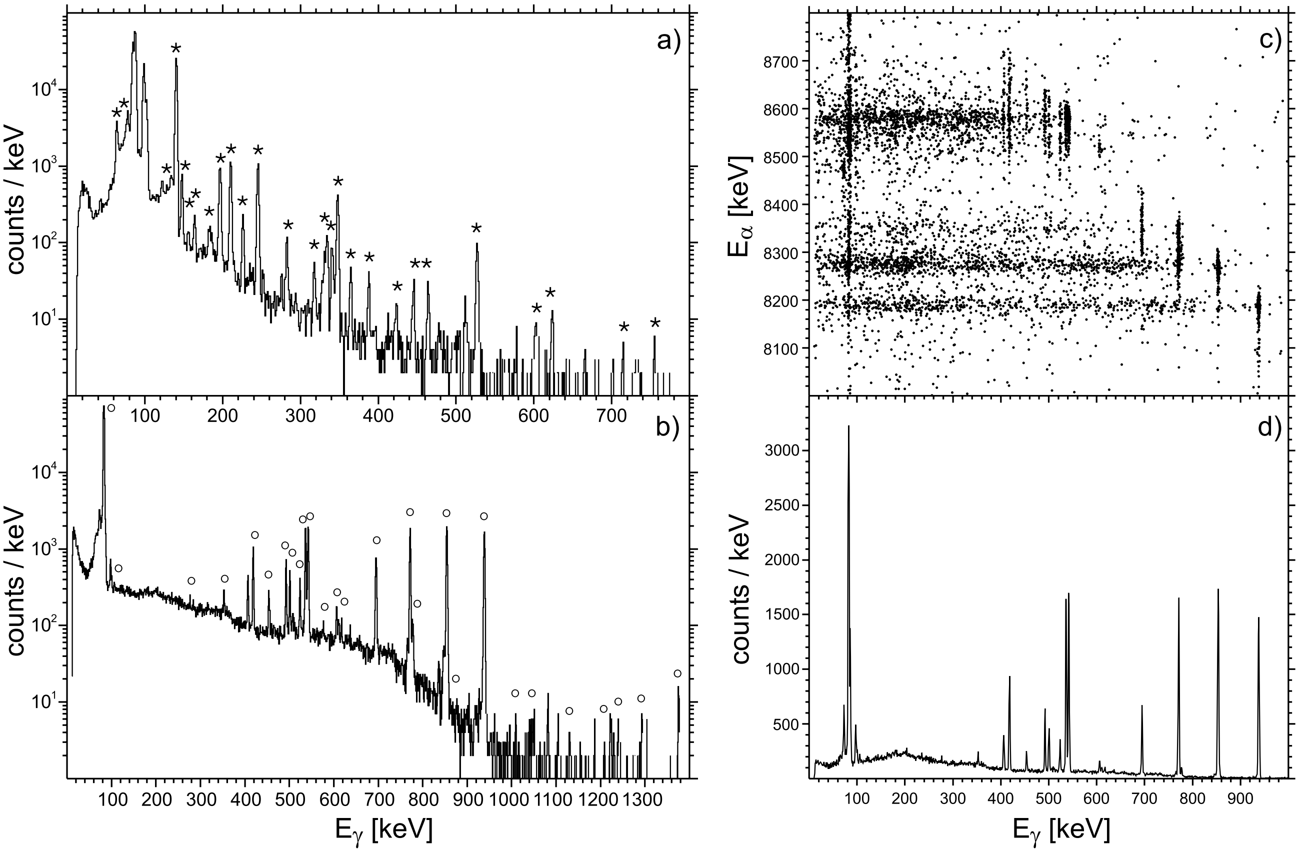

Fig. 2. γ-rays observed in coincidence with α-decays of a) ^{214}Ac and b) ^{216}Ac. γ-rays assigned to the decay of ^{214}Ac measured at 9.1 $A \cdot$MeV and ^{216}Ac at 7.1 $A \cdot$MeV are denoted by $\star$ and $\circ$, respectively. c) α-γ-coincidences observed in α-decay of ^{216}Ac (the scatter plot shows $\approx 5\%$ of total data). d) Projection of all α-γ-coincidences on the γ-energy axis.

16-strip PIPS Si detector (active area 80×35 mm^2), where their kinetic energy, position, time of arrival and subsequent decays were registered [4]. The Si detector was cooled to a temperature of ≈ 258 K to obtain an α-energy resolution of ≈ 22 keV (FWHM) at 8 MeV for each strip. For internal α-particle energy calibration α-decays of ^{209,210,212,213}Rn, ^{213}Fr and ^{215}Ra were used. Their α-energies were taken from ref. [1].

In very asymmetric reactions like ^{12}C on ^{209}Bi, the velocity of the residues is low (kinetic energy ≤ 5 MeV). Therefore they are implanted close to the surface of the stop-detector. This results in tails of the α-lines towards the low-energy part of the spectrum. The effect is related to geometrical reasons and/or incomplete charge collection of the detector due to α-particles stopped in the dead layer of the Si detector. This is illustrated in fig. 1, where singles α-spectra measured at projectile energies of 7.1 and 9.1 $A \cdot$MeV are shown. Another effect worsening the energy resolution is the summing of signals from an α-particle and conversion electrons, which results in a shift of α-lines towards higher energy.

Studies of α-γ(-γ)-coincidences were carried out using a high-purity Ge detector (diameter = 75 mm, length = 71 mm), which was in a later experiment replaced by a Ge Clover-detector consisting of four crystals, 70 mm in diameter and 140 mm in length each. Both detectors were mounted behind the Si detector in close geometry. The Clover-detector covered almost 2π of the solid angle. Gamma-rays in coincidence with Si detector signals

Table 1. Previously published decay data for ^{214}Ac. The results of our experiments are given in table 2.

E_α (keV)	E_γ (keV)	I_α (%)	$T_{1/2}$ (s)	Reference
7.24 MeV		33	12	[5]
7.18 MeV		33	12	
7.12 MeV		33	12	
7212 ± 5		52 ± 2	8.2 ± 0.2	[6]
7080 ± 5		44 ± 2	8.2 ± 0.2	
$7000 \pm 15^{(a)}$		4 ± 1	8.2 ± 0.5	
7210 ± 10				[2]
7154 ± 15	$62.3 \pm 0.5^{(b)}$			
7115 ± 15	$76.5 \pm 0.2^{(b)}$			
7080 ± 15	138.6 ± 0.2			
7021 ± 15	$193.0 \pm 0.2^{(b)}$			
7016 ± 20	$209.0 \pm 1.4^{(b)}$			
6881 ± 10	$348.6 \pm 1.6^{(b)}$			

(^{a}) Reported as probably complex.
(^{b}) Reported as tentative.

Table 2. Decay data for ^{214}Ac extracted from α-singles and α-γ-(γ-)coincidences.

E_α (keV)	Q_α (keV)	I_α (%)$^{(a)}$	HF$^{(b)}$	$E_{\rm level}^{\rm daughter}$ (keV)	E_γ (keV)	$I_{\gamma,\rm rel}$ (%)$^{(c)}$	Multiplicity	Transition
7215±3	7351±3	54±2	7.5	0				
7153±6	7288±5	?	?	62.6±0.1	62.6±0.1	100		→ g.s.
7081±4	7215±4	42±2	3.1	139.0±0.1	139.0±0.1	100±3	$M1$	→ g.s.
					76.3±0.1	6±2$^{(d)}$		→ 62.6
7023±5	7156±5	> 0.35±0.05$^{(e)}$	< 230	195.5±0.1	195.5±0.1	100±4		→ g.s.
					133.1±0.1$^{(f)}$	37±12$^{(f)}$		→ 62.6$^{(f)}$
7011±5	7143±5	> 0.44±0.04$^{(e)}$	< 170	209.0±0.1	209.0±0.1	100±3	$M1+E2^{(f)}$	→ g.s.
					146.4±0.1	59±3		→ 62.6
6998±7$^{(f),(g)}$	7130±7	> 0.04±0.02	< 1600	225.1±0.2$^{(f),(g)}$	225.1±0.2$^{(f),(g)}$	< 15$^{(f),(g)}$		→ g.s.$^{(f)}$
					162.5±0.1$^{(f)}$	100±20$^{(f)}$		→ 62.6$^{(f)}$
6978±5	7110±5	1.1±0.3	50	244.2±0.1	244.2±0.1	100±6	$M1$	→ g.s.
					181.4±0.1	13±11		→ 62.6
6889±6	7019±6	> 0.054±0.010	< 470	333.0±0.1$^{(h)}$	333.0±0.1	100		→ g.s.
6879±6	7009±6	> 0.031±0.008	< 780	339.5±0.1$^{(h)}$	339.5±0.1	100		→ g.s.
6878±5	7008±5	> 0.13±0.02	< 170	346.4±0.1$^{(h)}$	346.4±0.1	100		→ g.s.
6861±6	6992±6	> 0.09±0.02	< 220	363.9±0.2	363.9±0.2	24±4		→ g.s.
					224.7±0.1	100±9	$M1$	→ 139.0
					154.6±0.1	78±12		→ 209.0
6783±7	6911±7	> 0.015±0.004	< 640	444.2±0.2$^{(h)}$	444.2±0.2	100		→ g.s.
6701±5	6827±5	0.14±0.02	33	525.9±0.1	525.9±0.1	100±6		→ g.s.
					463.0±0.2	23±4		→ 62.6
					386.7±0.2	31±4		→ 139.0
					330.1±0.1	57±8		→ 195.5
					316.6±0.2	33±5		→ 209.0
					281.4±0.1	74±7	$M1$	→ 244.2
6626±7	6751±7	> 0.0047±0.0012	< 500	601.4±0.2$^{(h)}$	601.4±0.2	100		→ g.s.
6606±7	6731±7	> 0.0066±0.0013	< 290	622.5±0.2$^{(h)}$	622.5±0.2	100		→ g.s.
6515±15	6638±15	> 0.0022±0.0008	< 380	713.4±0.7$^{(h)}$	713.4±0.7	100		→ g.s.
6478±15	6600±15	> 0.0023±0.0008	< 250	753.7±0.7$^{(h)}$	753.7±0.7	100		→ g.s.

($^{\rm a}$) Relative α-intensities in the transitions of 7215, 7081, 6978 and 6701 keV were obtained from singles α-spectrum. The other intensities were extracted from α-γ-coincidences. The greater sign takes into account that intensity losses due to internal conversion were not considered.
($^{\rm b}$) α-branch of 89% for ^{214}Ac [1] used in calculation.
($^{\rm c}$) Relative intensity ($I_{\gamma,\rm rel}$) is normalized to 100% for the most intense γ-ray from the level.
($^{\rm d}$) Systematic deviation due to the efficiency of Ge-detector at low energies was estimated to be a factor of two.
($^{\rm e}$) For the double α-line at 7011 and 7023 keV we get $I_\alpha = (2.1\pm0.2)$% from singles α-spectrum.
($^{\rm f}$) Tentative placement or assignment.
($^{\rm g}$) E_γ overlaps with 224.7±0.1 keV, E_γ and $E_{\rm level}^{\rm daughter}$ are calculated using a sum of 62.6±0.1 keV and 162.5±0.1 keV.
($^{\rm h}$) γ-transition only to the g.s. observed, may also populate a low-lying level, see text for details.

were recorded within a time interval of 5 μs. Energy and relative-efficiency calibration of the Clover-detector was carried out using an ^{152}Eu γ-source. Due to different geometries of a point-like γ-source and a wide distribution of recoils implanted into the Si detector (width (FWHM) of $\approx$ 40 mm in horizontal and 20 mm in vertical direction), the absolute efficiency of the Clover-detector was estimated internally by the ratio of α-γ-coincidences and α-decays into the 854 and 938 keV daughter levels of ^{216}Ac (for intensities see table 6). We obtained a photo-peak efficiency corresponding to (4.5±0.3)% at 1.3 MeV.

The present study of $^{214-216}$Ac nuclei was carried out in two separate sets of α-γ-measurements, which included excitation function measurements. In the first part complicated decay patterns were observed for ^{214}Ac and ^{216}Ac as expected for odd-odd nuclei. However, the results were partly ambiguous since only α-γ-coincidences were measured. Therefore we performed another study using the Ge Clover-detector, which allowed γ-ray multiplicity measurements for clarification. The beam energies were selected on the basis of earlier studies, where the highest production cross-sections for ^{214}Ac and ^{216}Ac were observed at ^{12}C beam energies of 9.1 and 7.1 $A\cdot$MeV, respectively.

The technique of α-γ-coincidences has shown to be a unique method to identify weak α-transitions which are hidden in the background from strong transitions. In this way weakly populated excited levels in the daughter nuclei can be studied. In addition, transitions observed between excited levels in the daughter nucleus deliver more detailed information about its nuclear structure. Also, in odd-odd nuclei the most intense α-branch is often not the ground-state–to–ground-state (g.s.–to–g.s.) decay, but a decay to one of the low-lying excited levels. Therefore,

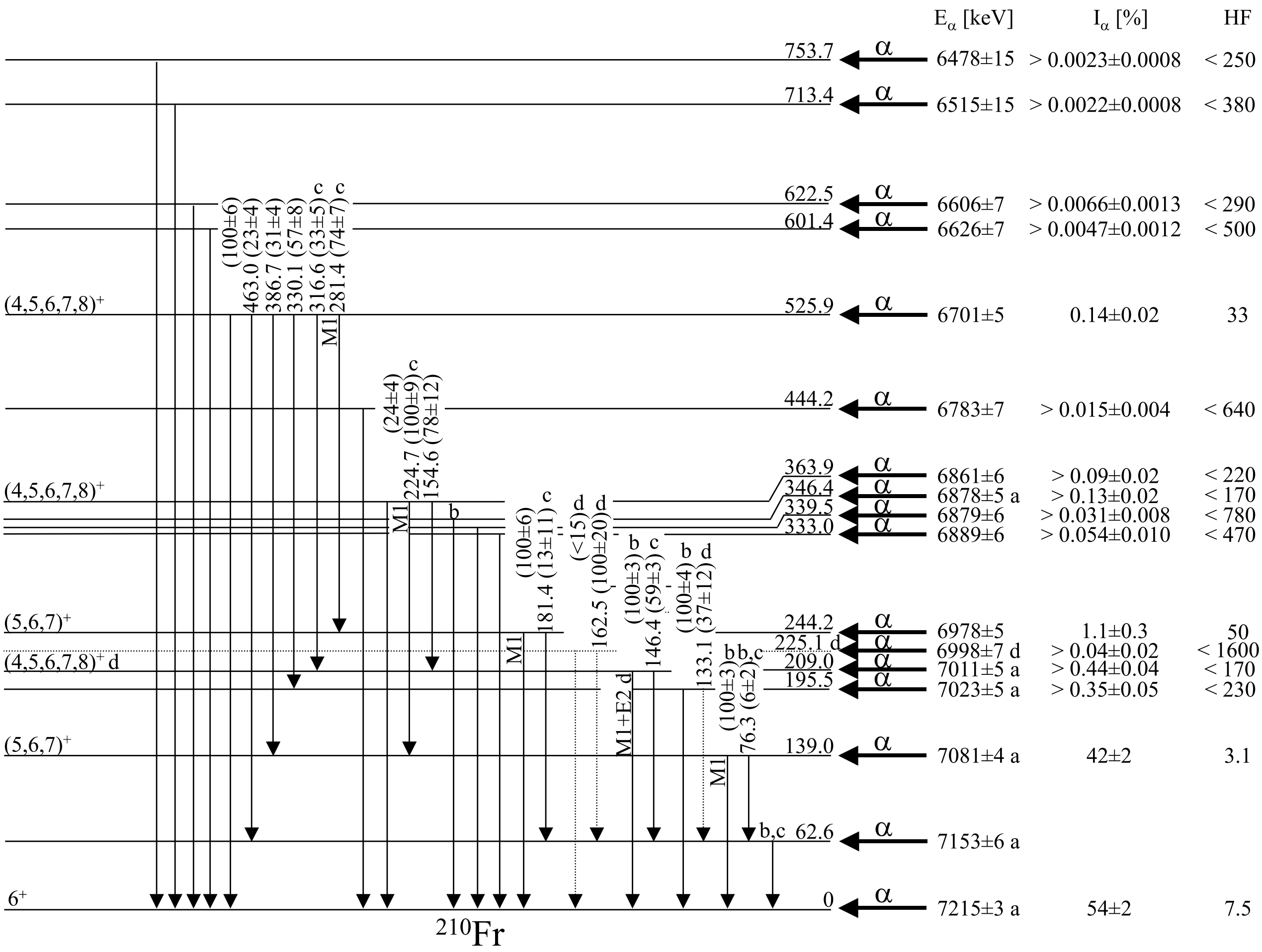

Fig. 3. Proposed decay scheme of ^{214}Ac to ^{210}Fr. [a] Previously observed in α-decay. [b] Previously observed in α-γ-coincidences. [c] From α-γ-γ-coincidences. [d] Tentative. Relative γ-ray intensities (%) are given in brackets. Energies are quoted in keV.

α-γ-coincidences may deliver the total g.s.–to–g.s. decay energies.

In the present work the identification of α-particles emitted by $^{214-216}$Ac (and thus populating energy levels in $^{210-212}$Fr) was based on matching of $Q_\alpha + E_\gamma$ values to that of the g.s.–to–g.s. α-decay (see narrow α-lines in fig. 2c as an example). The Q_α value is obtained from the measured α-energy E_α by $Q_\alpha = (1 + m_\alpha/m_\mathrm{d}) \times E_\alpha$, where m_α and m_d are the masses of the α-particle and daughter nucleus, respectively. Gamma-transitions were assigned on the basis of energy balance, observed energy summing of α-particles and conversion electrons (see broad α-lines in fig. 2c as an example) and in a few cases of α-γ-γ-coincidences.

From the α-spectroscopic point of view a complication related to the summing of α-particle and conversion electron signals is that some information on the intensity of α-decays into excited levels is lost. This may lead to underestimation of α-decay intensities to the excited levels and overestimation of α-intensities in low-lying levels or the g.s., since energy summing may increase numbers of counts in α-lines feeding these levels. However, even when it is evident that energy summing causes a systematic error in α-intensities the effect is difficult to determine quantitatively in detail. Particularly this is the case if multipolarities of the γ-transitions are not known and/or there is feeding from levels above to the level of interest and feeding from that level to the levels below (examples of this are given in the next section). Therefore the effect was not taken into account (if not otherwise noted), but α-intensities are given as extracted from our data.

3 Experimental results

3.1 ^{214}Ac

Identification of ^{214}Ac was reported by Griffioen and Macfarlane [5]. Their results were verified and improved by Valli *et al.* [6] and by Heßberger *et al.* [2] (see table 1). In order to further improve the data of ^{214}Ac we performed α-γ-coincidence measurements at SHIP using the ^{209}Bi(^{12}C, 7n)^{214}Ac reaction at 9.1 $A \cdot$ MeV beam energy. The study was carried out using α-singles and α-γ(-γ)-coincidences. A total of 16 α-branches populating

Table 3. Internal conversion coefficients for selected transitions observed in ^{210}Fr.

E_γ (keV)	Ratio$^{(a)}$ of N_X/N_γ	Measured α_K values	Theoretical $\alpha_K(E1, M1, E2, M2)$ values [7]				Multipolarity
			$E1$	$M1$	$E2$	$M2$	
139.0	5.1±0.3	4.6±0.4	0.167	4.77	0.321	22.5	$M1$
209.0	4/6	0.4±0.3	0.0640	1.54	0.141	5.75	$M1+E2^{(b)}$
224.7	10/5	1.5±0.9	0.0543	1.26	0.122	4.54	$M1$
244.2	8/3	1.9±1.4	0.0450	1.01	0.104	3.47	$M1$
281.4	5/3	1.1±0.9	0.0328	0.683	0.0785	2.20	$M1$

(^{a}) Ratio between a number of observed francium K X-rays and γ-rays.
(^{b}) Tentative.

levels in the daughter nucleus ^{210}Fr were observed and, in addition, one level was assigned tentatively. The measured α-spectrum and the γ-spectrum gated by the ^{214}Ac α-particles are shown in figs. 1a and 2a, respectively. The results of our ^{214}Ac study are listed in table 2 and the proposed decay scheme of ^{214}Ac is shown in fig. 3.

Fifteen excited levels can be attributed to ^{210}Fr on the basis of α-γ-coincidences, characterized by narrow α-lines with a typical width of approximately 25 keV (FWHM) and having total decay energies ($Q_\alpha + E_\gamma$) equal to the value of the g.s.–to–g.s. α-decay of ^{214}Ac within ±5 keV. It is worth noticing again that this could also be the case for the summing of α-particles and L- (M-, ...) conversion electrons which may lead to misinterpretation of the data. A level can decay partly by γ-emission into the g.s. ($E_{\gamma1}$) or into a level lower than the K-binding energy, which then decays into the g.s. predominantly by L- or M-conversion. Due to energy summing with conversion electrons the energy values ($E_\alpha + E_{\gamma1}$) and ($E_\alpha + E_{\mathrm{ce}} + E_{\gamma2}$) are nearly equal and an additional level with $E^* = E_{\gamma2}$ may be mimicked. In the ^{214}Ac decay that is the case for the eight levels listed in table 2 (marked by index (h)). However, since we did not observe any conclusive evidence about a low-lying level matching the energy differences between the observed γ-rays, these levels are attributed to ^{210}Fr.

Several transitions between excited levels were identified on the basis of α-γ-γ-coincidences (marked by index c in fig. 3). For easier reading we omit here and in the following the digits behind the decimal point. For the exact energy values, see tables 2, 4 and 6 for ^{214}Ac, ^{215}Ac and ^{216}Ac, respectively. Due to a lack of statistics in α-γ-γ-coincidences, all the other transitions connecting excited levels were placed on the basis of α-γ-coincidences (see table 2). However, the placement of the 133 keV γ-transition as decay from the 195 keV level is tentative only. This is due to a lack of statistics and Compton scattering in the Ge detector which resulted in difficulties for a study of weak γ-lines below the very intense γ-line at 139 keV. However, since the sum of 62.6±0.1 and 133.1±0.1 keV equals to 195.5±0.1 keV within experimental accuracy, the 133 keV γ-transition is tentatively assigned to ^{210}Fr.

Also a level at 225 keV as well as the placement of a 162 keV transition are tentative. One notes that the 224 keV γ-line (transition connecting the levels at 363 and 139 keV) and the much weaker 225 keV γ-line are overlapping. Therefore the level at 225 keV can be observed only indirectly on the basis of 162 keV γ-rays and α-particle energies gated by the 162 and 224 keV γ-lines. The energy distribution of α-particles gated by the 224 keV γ-rays peaked at 6889±5 and 6998±7 keV with widths (FWHM) of 64 and 30 keV, respectively. One notes that for the 363 keV level (which decays by the 224 keV transition) the $E_\alpha + E_{\mathrm{ce}}$ value equals to the latter α-energy only in case of L- or M-conversion. As the number of α-counts at 6998 keV depends on L- and M-conversion coefficients, the observed number of α-counts at 6998 keV leads to "unusually" high L- or M-conversion coefficients (from this a ratio of the 225 and 224 keV γ-rays is estimated to be less than 10%). Therefore it seems that the 224 keV transition from the level at 363 keV cannot solely explain the number of counts at 6998 keV but there is also another contribution. Thus, we tentatively conclude that there is a level in ^{210}Fr at 225 keV which decays directly to the g.s. by the weak 225 keV transition and to the level at 62 keV by the 162 keV transition.

Using francium K X-rays we were able to extract internal conversion coefficients for five transitions listed in table 3. The conversion coefficient for the 139 keV transition was extracted directly from the (efficiency corrected) numbers of K X-rays and 139 keV γ-rays using α-γ/X-ray-coincidences gated by respective α-particles. This resulted in a measured value of $\alpha_K = 4.6\pm0.4$ which can be compared to the theoretical conversion coefficient $\alpha_K = 4.77$ [7] for $M1$. As the 139 keV line is by far the strongest in the γ-spectrum, contributions of other decays are negligible (see fig. 2a). Thus, the use of α-γ/X-ray-coincidences solely can be considered reliable in the conversion coefficient estimation for this particular transition. The result verifies an earlier conclusion [2].

The other measured conversion coefficients listed in table 3 were extracted using α-γ-X-ray-coincidences. The multipolarity assigned for the 209 keV transition is tentative due to the measured conversion coefficient which fits best for the $M1 + E2$ mixture but a pure $E2$ is not excluded. For the 224 keV transition the measured conversion coefficient is in between the theoretical values of $M1$ and $M2$ but it is still consistent with $M1$. So we conclude that the 224 keV transition is a pure $M1$. This is also the case for the 244 keV transition even though its value is more uncertain. Spin and parity assignments for

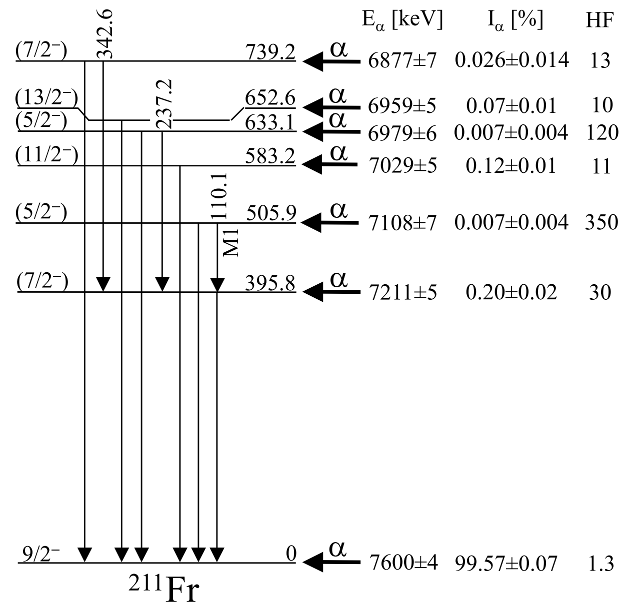

Fig. 4. Proposed decay scheme of ^{215}Ac to ^{211}Fr.

^{210}Fr are made on the basis of these multipolarities taking into account the known 6^+ g.s. of ^{210}Fr [1].

Relative α-intensities for the g.s. and for the levels at 139, 244 and 525 keV were extracted from the singles α-spectrum. Due to the lack of statistics and small energy gaps between the levels at around 200 keV (for the double line of 195 and 209 keV an α-intensity of (2.1 ± 0.2)% was extracted from the singles α-spectrum) and 350 keV, the α-intensities for the rest of the levels were extracted indirectly from the numbers of γ-rays in α-γ-coincidences (for details of the method, see sect. 3.3). Because of unknown multipolarities losses in γ-intensities due to internal conversion were not taken into account. Therefore, even if the α-intensities for these levels represent lower limits, they are given as extracted from original data. However, as the data for multipolarities are available the values can be corrected accordingly.

One notes that α-intensities extracted from the singles α-spectrum may suffer losses due to electron summing. However, for the level at 525 keV the given value can be considered as reliable. This is due to the relatively large transition energies from this level so only small conversion coefficients are expected. When α-intensities of other α-branches are compared to those of Valli *et al.* [6] (whose method without residue implantation does not suffer electron summing and can therefore be considered as reliable), the values are consistent. Small deviations may result from electron summing. Therefore, because the effect of electron summing is not clearly understood and losses due to internal conversion could not be fully taken into account, α-decay hindrance factors (HF) were calculated using the α-intensities listed in table 2, even if it is evident that at least for some of the levels α-intensities are slightly distorted. In these calculations the relation $\mathrm{HF} = \delta^2_{\mathrm{g.s.}}/\delta^2_{\mathrm{ex}}$ was employed. Here $\delta^2_{\mathrm{g.s.}}$ is the average of the reduced α-decay widths of ^{212}Ra, ^{214}Ra, ^{214}Th and ^{216}Th (data are taken from ref. [1]) and δ^2_{ex} is the reduced width for the decay of interest. The reduced widths are calculated according to the method of Rasmussen [8] assuming an α-branch of 89% for ^{214}Ac [1] and $\Delta\ell = 0$ for each α-decay.

In addition to the transitions explained above, we also observed weak γ-lines at 41.5 ± 0.1, 121.0 ± 0.1, 184.8 ± 1.0 and 422.1 ± 0.4 keV. These lines are likely from the ^{214}Ac decay but their placements are unclear. However, from α-γ-coincidences one can conclude that these four γ-lines represent transitions between excited states rather than transitions to the g.s. It is interesting to note that the sum of 41.5 and 121.0 keV is equal to 162.5 keV, *i.e.* to that which was tentatively assigned to the transition between the levels at 62 and 225 keV. Therefore it may be possible that the three transitions are linked together resulting in a level at 104.1 ± 0.2 or 183.6 ± 0.2 keV.

The 184 keV γ-rays were in the tail of those at 181 keV with approximately half of the intensity. These γ-rays were in coincidence with α-particles peaking at 7025 ± 5 keV with a width of 35 keV (FWHM) indicating summing with L-electrons. However, the 184 keV transition does not seem to fit to any energy difference between the low-lying levels and, on the basis of the slightly lower $Q_\alpha + E_\gamma$ value, it also does not seem to populate the g.s. Therefore we did not place it into the level scheme. For a weak γ-transition of 422 keV it is worth noticing that its energy as well as the α-energies from α-γ-coincidences fit to the transition from the level at 525 keV to the possible level at 104 keV. However, since there is no clear evidence for a level at 104 keV, the 422 keV γ-transition was not assigned to ^{210}Fr.

3.2 ^{215}Ac

The ^{215}Ac nucleus was identified by Valli *et al.* [6] who reported an α-particle energy of 7602 ± 5 keV and a half-life of 0.17 ± 0.01 s. Since then the levels in the daughter nucleus ^{211}Fr have been studied using in-beam spectroscopy by Byrne *et al.* [9] and using α-γ-coincidences by Heßberger *et al.* [2] who reported the g.s.–to–g.s. α-decay of ^{215}Ac with an energy of 7602 ± 10 keV and fine-structure α-decays of 7214 ± 15, 7026 ± 15 and 6960 ± 15 keV corresponding to γ-ray energies of 399 ± 2, 582.3 ± 2.3 and 654.0 ± 2.3 keV, respectively. The latter two levels have also been identified in in-beam studies with 583.3 ± 0.2 and 652.6 ± 0.1 keV [9].

In the present work ^{215}Ac was produced employing the ^{209}Bi(^{12}C, 6n)^{215}Ac reaction at 7.1, 8.6 and 9.1 $A\cdot$MeV beam energies, where the maximum production cross-section for ^{215}Ac was observed at 8.6 $A\cdot$MeV beam energy. Due to weak α-branches to the excited levels only α-singles and α-γ-coincidences were available in the analysis. Our results are listed in table 4 and the proposed decay scheme of ^{215}Ac is shown in fig. 4.

In addition to previously published energy levels in ^{211}Fr three more levels were identified. We also observed three linking γ-transitions connecting the excited levels (see fig. 4). Since the α-lines were identified in the singles

Table 4. Decay data for ^{215}Ac extracted from α-singles and α-γ-coincidences.

E_α (keV)	I_α (%)	HF	$E_{\text{level}}^{\text{daughter}}$ (keV)	E_γ (keV)	$I_{\gamma,\text{rel}}$ (%)$^{(a)}$	Transition
7600±4	99.57±0.07	1.3	0			
7211±5	0.20±0.02	30	395.8±0.1	395.8±0.1	100	$(7/2^-)^{(b)} \rightarrow 9/2^-$
7108±7	0.007±0.004$^{(b)}$	350	505.9±0.2	505.9±0.2	100±27	$(5/2^-)^{(b)} \rightarrow 9/2^-$
				110.1±0.4	15±8	$(5/2^-)^{(b)} \rightarrow (7/2^-)^{(b)}$
7029±5	0.12±0.01	11	583.2±0.1	583.2±0.1	100	$(11/2^-) \rightarrow 9/2^-$
6979±6	0.007±0.004$^{(b)}$	120	633.1±0.2	633.1±0.2	100±30	$(5/2^-)^{(b)} \rightarrow 9/2^-$
				237.2±0.4	43±18	$(5/2^-)^{(b)} \rightarrow (7/2^-)^{(b)}$
6959±5	0.07±0.01	10	652.6±0.2	652.6±0.2	100	$(13/2^-) \rightarrow 9/2^-$
6877±7	0.026±0.014$^{(b)}$	13	739.2±0.4	739.2±0.4	68±34	$(7/2^-)^{(b)} \rightarrow 9/2^-$
				342.6±0.5	100±26	$(7/2^-)^{(b)} \rightarrow (7/2^-)$

(a) As for ^{214}Ac.
(b) Tentative.

Table 5. Previously published decay data for ^{216}Ac. The data of our study are given in table 6.

Mother	E_α (keV)	$E_{\text{level}}^{\text{daughter}}$ (keV)	I_α (%)	$T_{1/2}$ (μs)	I^π_{mother}	Reference
^{216}Ac	9140±30			390±30		[10]
$^{216\text{m}}$Ac	9105±10	0	97.0±0.5	~ 500	$9^{-\,(a)}$	[11]
$^{216\text{m}}$Ac	8283±10	837	3.0±0.5	~ 500	$9^{-\,(a)}$	
$^{216\text{g}}$Ac	9020±10	0	98.0±0.5	~ 500	$1^{-\,(a)}$	
$^{216\text{g}}$Ac	8198±10	837	2.0±0.5	~ 500	$1^{-\,(a)}$	
$^{216\text{m}}$Ac	9106±5	0	46.2	330±20	$9^{-\,(a)}$	[12]
$^{216\text{m}}$Ac	9028±5	80	49.6		$9^{-\,(a)}$	
$^{216\text{m}}$Ac	8283±8	839	2.5		$9^{-\,(a)}$	
$^{216\text{m}}$Ac	8198±8	925	1.7		$9^{-\,(a)}$	
$^{216\text{g}}$Ac	9070±8	0	90	≈ 330	$1^{-\,(a)}$	
$^{216\text{g}}$Ac	8990±20	80	10		$1^{-\,(a)}$	
$^{216\text{m}}$Ac	9110±10			443±7		[2]
$^{216\text{m}}$Ac	9026±15	82.4±0.4$^{(b)}$		359^{+97}_{-63}		
$^{216\text{m}}$Ac	8586±15	537±3$^{(b)}$		475^{+289}_{-130}		
$^{216\text{m}}$Ac	8273±15	826±3$^{(b),(c)}$		432±17		
$^{216\text{m}}$Ac	8198±20$^{(c)}$			463±180		
$^{216\text{g}}$Ac	9052±10			440±16		

(a) Assumed (ref. [11]) or probable (ref. [12]) spin and parity.
(b) From α-γ-coincidences, $E_{\text{level}}^{\text{daughter}}$ given as E_γ.
(c) Reported as tentative.

α-spectrum, we were able to estimate the intensities and α-decay hindrance factors (HF) of the transitions. The hindrance factors were calculated as in the case of the ^{214}Ac α-decay but $\delta^2_{\text{g.s.}}$ was taken as the average of the reduced α-decay widths of ^{214}Ra and ^{216}Th (decay data are taken from ref. [1]) assuming $\Delta\ell = 0$ for each α-decay.

Due to weak γ-ray intensities between the connecting excited levels the multipolarity could be extracted only for the 110 keV transition. This was done from α-γ-coincidences resulting in a measured conversion coefficient $\alpha_K = 14\pm7$. As the theoretical values for $E2$ and $M1$ are $\alpha_K = 0.320$ and $\alpha_K = 9.42$ [7], respectively, our measured value fits best for an $M1$ transition (even though an $M1 + E2$ mixture is not excluded).

Losses in α-intensities due to electron summing were not taken into account. This was due to the fact that only small conversion coefficients were expected as the transitions are expected to be $E1$, $M1$, $E2$ or $M1 + E2$. This was also evidenced by the small number of francium K X-rays. The by far largest fraction of K X-rays is associated with the 505 or 110 keV transitions and by some fraction also with the 633 and 739 keV transitions. Therefore α-intensities for these levels are probably underestimated and their α-decay hindrance factors overestimated. However, for the low-energy transition of 110 keV, electron summing does not severely hamper the α-intensity study due to the small energy of K-electrons. As theoretical conversion coefficients at 110.1 keV for $M1$ are $\alpha_K = 9.42$ and $\alpha_{\text{tot}} = 11.7$ [7], the main contribution is expected from K-conversion. Thus, one cannot explain its large hindrance factor only by losses in α-intensity due to electron summing but it must be related to the nuclear structure.

Table 6. Decay data for ^{216}Ac extracted from α-singles and α-γ-(γ-)coincidences.

E_α (keV)	$Q_\alpha + E_\gamma$ (keV)	I_α (%)$^{(a)}$	HF	$E_{\text{level}}^{\text{daughter}}$ (keV)	E_γ (keV)	$I_{\gamma,\text{rel}}$ (%)$^{(b)}$	Transition
9105±7	9277±7	47.5±0.5	320	0			
9029±7	9282±7	48.8±1.0$^{(c)}$	200	82.6±0.1	82.6±0.1	100	→ g.s.
8616±6	9279±6	0.23±0.05	3.7×10^3	500.7±0.1	500.7±0.1	53±4	→ g.s.
					418.3±0.1	100±6	→ 82.6
8581±6	9279±6	$>$ 0.51±0.06	$< 1.4\times10^3$	536.3±0.1	536.3±0.1	100±6	→ g.s.
					453.9±0.1	9±1	→ 82.6
8576±6	9280±6	$>$ 0.46±0.05	$< 1.5\times10^3$	542.0±0.1	542.0±0.1	100	→ g.s.
8536±15$^{(d)}$	9272±15	$>$ 0.12±0.02	$< 4.4\times10^3$	575.0±0.4$^{(e)}$	575.0±0.4$^{(e)}$	1.3±0.4	→ g.s.$^{(e)}$
					492.4±0.1$^{(e)}$	100±4	→ 82.6$^{(e)}$
8514±6	9281±6	$>$ 0.11±0.02	$< 4.1\times10^3$	606.2±0.1	606.2±0.1	60±7	→ g.s.
					523.7±0.1	100±7	→ 82.6
					105.8±0.2	11±3	→ 500.7
8509±7	9280±7	$>$ 0.017±0.001	$< 2.6\times10^4$	610.6±0.2	610.6±0.2	100	→ g.s.
8346±7$^{(f)}$	9281±7	$<$ 0.1$^{(f)}$	$> 1.6\times10^4$	777.3±0.2	777.3±0.2	14±2	→ g.s.
					694.8±0.1	100±5	→ 82.6
					276.6±0.2	1.3±0.6	→ 500.7
8270±5	9280±5	1.40±0.07	68	853.7±0.1	853.7±0.1	100±4	→ g.s.
					771.3±0.1	77±4	→ 82.6
					352.9±0.2	1.2±0.5	→ 500.7
8187±5	9280±5	0.74±0.02	75	938.2±0.1	938.2±0.1	100±2	→ g.s.
					855.8±0.7	$<$ 5$^{(e)}$	→ 82.6
8114±9	9276±9	$>$ 0.0020±0.0003	$< 1.7\times10^4$	1008.7±0.4	1008.7±0.4	100	→ g.s.
8001±15	9282±15	$>$ 0.0024±0.0016	$< 6.5\times10^3$	1129.9±0.5	1129.9±0.5	100±40	→ g.s.
					1047.5±0.9	85±50	→ 82.6
7924±15	9283±15	$>$ 0.0013±0.0002	$< 7.0\times10^3$	1209.5±0.5	1209.5±0.5	100	→ g.s.
7892±10	9281±10	0.021±0.002	350	1239.9±0.4	1239.9±0.4	100	→ g.s.
7846±15	9281±15	0.016±0.003	330	1287.1±0.8	1287.1±0.8	100	→ g.s.
7776±15	9281±15	$>$ 0.0010±0.0004	$< 3.2\times10^3$	1356±2	1356±2	100	→ g.s.
7758±6	9280±6	0.011±0.003	250	1375.3±0.3	1375.3±0.3	100±20	→ g.s.
					1293.1±0.4	45±17	→ 82.6
					436.8±0.6	17±6	→ 938.2

(^{a}) Relative α-intensities in the transitions of 9105, 9029, 8616, 8270, 8187, 7892, 7846 and 7758 keV were obtained from singles α-spectrum. The other intensities were extracted from α-γ-coincidences. The greater sign takes into account that intensity losses due to internal conversion were not considered.

(^{b}) As for ^{214}Ac.

(^{c}) α-intensity taken as a sum of fits of two peaks at the low-energy part of the triple line, see fig. 1 and text for details.

(^{d}) No γ-transition to the g.s. observed.

(^{e}) Tentative.

(^{f}) Level is fed by internal conversion from levels above, not necessarily directly by α-decay.

Spin and parity assignments for ^{211}Fr are based on the observed tentative $M1$ transition, comparison with the ^{207}Bi and ^{209}At isotones, α-decay hindrance factors, and on known ($11/2^-$) and ($13/2^-$) states at 583.2 and 652.62 keV [1], respectively. In the ^{209}At isotone there are ($11/2^-$) and ($13/2^-$) states at 577.10 and 725.06 keV, respectively, and $7/2^-$ states at 408.33 and 745.78 keV [1], so its level scheme resembles very much that of ^{211}Fr. Therefore, on the basis of these similarities and small α-decay hindrance factors for the levels at 395 and 739 keV, ($7/2^-$) is assigned to both states. The level at 505 keV is tentatively assigned to the ($5/2^-$) state on the basis of the (tentative) $M1$ transition to the ($7/2^-$) state, and of a larger hindrance factor than that of the ($7/2^-$) state (a large HF rules out $7/2^-$ and $9/2^-$). Finally, the level at 633 keV is tentatively assigned to ($5/2^-$) due to a rather similar hindrance factor as that of the level at 505 keV (a large HF rules out $7/2^-$ and $9/2^-$).

3.3 ^{216}Ac

The ^{216}Ac nuclide was reported by Rotter *et al.* [10]. The data was later improved by Valli *et al.* [11], Torgerson and Macfarlane [12], and by Heßberger *et al.* [2] (see table 5 for details). In the present work the ^{216}Ac nuclide was studied via the ^{209}Bi(^{12}C, 5n)^{216}Ac reaction at a bombarding energy of 7.1 $A \cdot$ MeV. The study was carried out using α-singles and α-γ(-γ)-coincidences in a similar manner as for ^{214}Ac. A total of 16 levels were identified in the daughter nucleus ^{212}Fr populated by the α-decay of ^{216}Ac. One more level is possibly not populated by α-decay and another is tentative. Our results of ^{216}Ac are

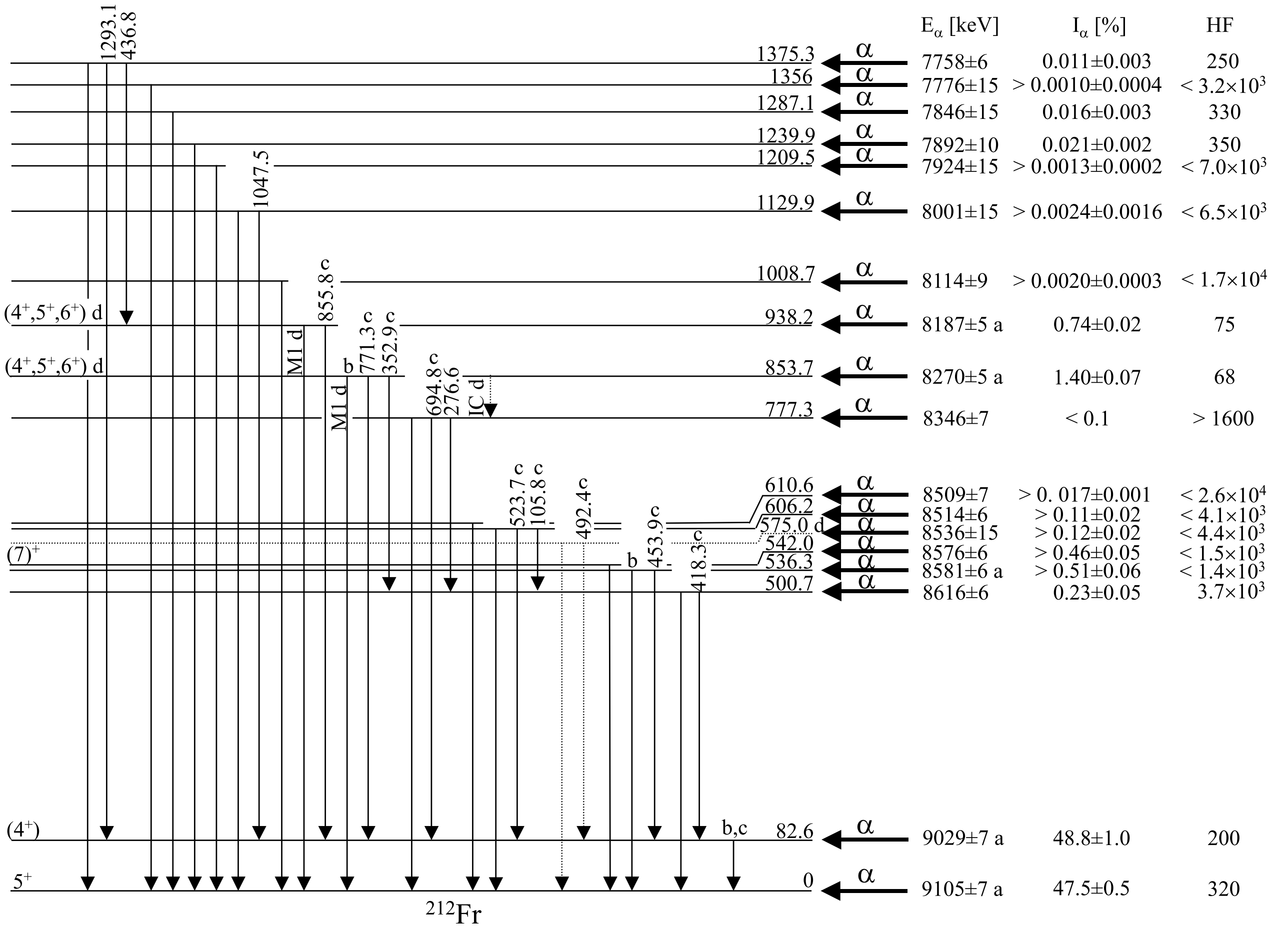

Fig. 5. Proposed decay scheme of ^{216}Ac to ^{212}Fr. [a] Previously observed in α-decay. [b] Previously observed in α-γ-coincidences. [c] From α-γ-γ-coincidences. [d] Tentative.

listed in table 6 and the proposed decay scheme is shown in fig. 5.

Excited levels can be attributed to ^{212}Fr on the basis of $Q_\alpha + E_\gamma$ values and α-γ(-γ)-coincidences. Furthermore, several γ-transitions between excited levels were identified on the basis of α-γ-γ-coincidences (marked by index c in fig. 5). Weak transitions were placed on the basis of energy balance and α-energies observed in α-γ-coincidences gated by the respective γ-rays.

The tentatively placed level at 575 keV is based on α-γ-γ-coincidences gated by 492 keV γ-rays. These γ-rays were observed in coincidence with 82 keV γ-rays while α-γ-coincidences of 8540 keV and 575 keV were weak. Thus, possibly the state at 575 keV decays almost purely via the 82 keV level (as it seems) but then the γ-transition from the level at 575 keV to the g.s. must be strongly hindered. Therefore we assigned the level at 575 keV and the 492 keV γ-transition only tentatively to ^{212}Fr. We further noted that, on the basis of α-γ-coincidences gated by 777 keV γ-rays, it seems that the level at 777 keV is fed weakly if at all by α-decay but rather by internal conversion from the levels above close in energy. This interpretation is due to α-particles gated by 777 keV γ-rays (the same effect is observed with the 694 keV γ-rays) which peak at 8302±6 keV ($\Delta E = 22$ keV (FWHM), $I_{\rm rel} \approx 72\%$) and 8346±7 keV ($\Delta E = 28$ keV (FWHM), $I_{\rm rel} \approx 28\%$). The latter $Q_\alpha + E_\gamma$ value agrees to that of ^{216}Ac, but the α-line is rather broad for a transition to the g.s. Thus it can be a result of electron summing. Therefore we give only an upper limit for a relative α-intensity for this particular level.

Concerning α-intensity (see table 6) losses due to summing of α-particle and conversion electrons were not taken into account. This was due to the unknown transition multipolarities and summing effects which are difficult to determine. Intensities for the α-lines at 9029 keV and 9105 keV were extracted using the data obtained at 7.1 $A \cdot$ MeV bombarding energy, assuming that a tail in the 9029 keV α-line towards the higher energy is due to summing of 9029 keV α-particles and conversion electrons associated with the 82 keV transition (see fig. 8). Intensities also for the seven other levels (see table 6) were extracted directly from the singles α-spectrum. For the rest of the levels α-intensities were determined indirectly from the α-γ-coincidences by normalising the number of γ-ray counts to those of α- and γ-lines observed for the 853 and 938 keV levels which yielded identical values.

The indirect method was used because of overlapping energies (mainly with ^{214}Fr) and weak α-transitions invisible in the singles α-spectrum but visible in α-γ-coincidences. Since, for example, the number of ^{214}Fr α-particles was large (see fig. 1b for details) and $^{214\mathrm{m,g}}$Fr have relatively short half-lives (3.35 ms and 5.0 ms [1], respectively), we also realized that even a use of recoil-α-correlations did not provide a solution for overlapping energies. A reliability test for α-intensities extracted using α-γ-coincidences was performed using α-particles feeding the levels at 536 and 542 keV (an unresolved doublet in the singles α-spectrum at $E_\alpha = 8578\pm6$ keV with a width (FWHM) of 21 keV). This study resulted in a value of $I_\alpha = (0.84\pm0.06)\%$ which is consistent with the sum of $(0.51\pm0.06)\%$ and $(0.46\pm0.05)\%$ extracted using α-γ-coincidences. The error bars for α-intensities extracted using the indirect method are statistical only. When transitions occur via internal conversion or levels are fed from above by internal conversion or γ-rays, the α-intensities listed in table 6 should be corrected accordingly.

As the observed transitions between excited levels in ^{212}Fr have relatively high energy or populate the level at 82 keV, the number of francium K X-rays is small (see francium K_β X-rays slightly above the 82 keV γ-line in fig. 2d and compare to that of ^{214}Ac in fig. 2a). Therefore we were able to estimate conversion coefficients only for the 853 and 938 keV transitions. The measured conversion coefficient for the level at 938 keV was extracted from the ratio between $K_{\alpha1}$ X-rays and 938 keV γ-rays gated by the 8187 keV α-line. This resulted in a measured conversion coefficient $\alpha_K = 0.027\pm0.017$. The theoretical conversion coefficients for the 938.2 keV transition are $\alpha_K(E1) = 0.00286$, $\alpha_K(M1) = 0.0272$, $\alpha_K(E2) = 0.00755$ and $\alpha_K(M2) = 0.0622$ [7]. As our measured value fits best to the $M1$ transition, we tentatively conclude that the 938 keV transition is $M1$. For the 853 keV transition the measured conversion coefficient was extracted by gating on α-particles with energies between 8230 keV and 8320 keV which resulted in a value of $\alpha_K = 0.063\pm0.057$. As the theoretical conversion coefficients for the 853 keV transition are $\alpha_K(E1) = 0.00339$, $\alpha_K(M1) = 0.0348$, $\alpha_K(E2) = 0.00900$ and $\alpha_K(M2) = 0.0805$ [7], we tentatively conclude an $M1$ character also for this transition.

Spin and parity assignments for ^{212}Fr are based, in addition to the two (tentative) $M1$ transitions, on the known (from ref. [1]) 5^+ g.s., the 4^+ state at 79 ± 7 keV and the 7^+ state at 542.2 ± 0.1 keV. The α-decay hindrance factors listed in table 6 are calculated taking $\delta^2_{\mathrm{g.s.}}$ as the average of the reduced α-decay widths of ^{214}Ra, ^{216}Ra, ^{216}Th and ^{218}Th (decay data are taken from ref. [1]). As the differences in spins are not known, all calculations were performed assuming no change in spin ($\Delta\ell = 0$) between the connecting states.

In addition to the transitions explained above, we observed α-γ-coincidences with γ-ray energies of 406.2 ± 0.1, 617.3 ± 0.3, 765.3 ± 0.2 and 1081.3 ± 0.3 keV. These γ-rays are probably associated with the ^{216}Ac decay but their placements are unclear.

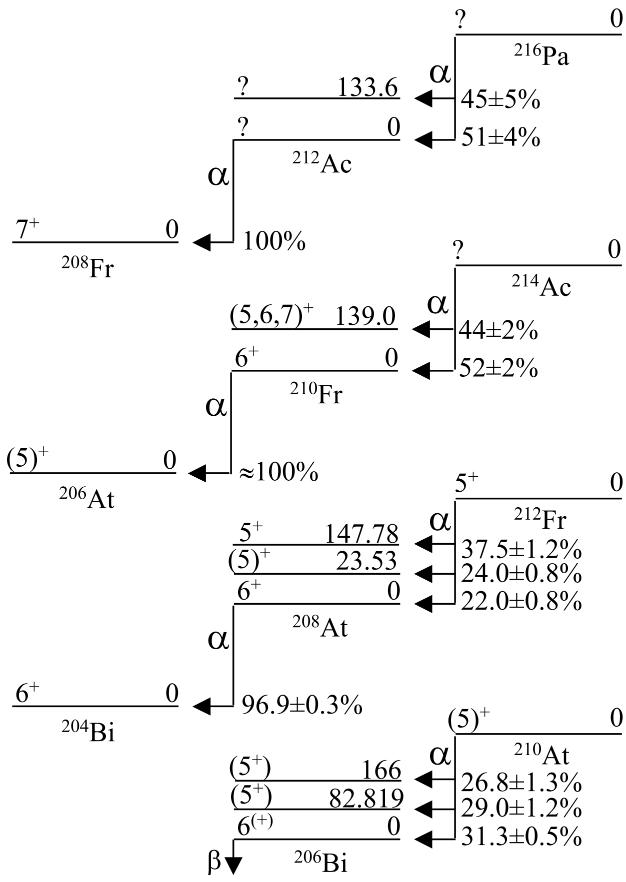

Fig. 6. Partial decay schemes of α-decay chains of $N = 125$ isotones where only the most intense α-branches are shown. Apart from α-decay of ^{216}Pa (from ref. [2]) and the 139.0 keV level in ^{210}Fr (from the present work) the data are adopted from ref. [1].

4 Discussion

4.1 ^{214}Ac

In-beam studies for ^{208}At have shown that there is only one low-lying yrast level below the yrast 8^+ state at 788.1 keV populated by α-decay [1]. That is the 7^+ state at 71.7 keV with $I_\alpha = (10.2\pm1.0)\%$ (see ref. [1] and cf. fig. 6). Therefore it seems probable that almost all the levels observed in the α-decay of ^{214}Ac are non-yrast and so far the best candidate for the yrast 7^+ state in ^{210}Fr is the state at 62.6 keV.

On the basis of similarities in the nuclear properties of $N = 125$ isotones, *e.g.* a neutron hole in the $N = 126$ closed shell, one expects similarities in the α-decay schemes of these nuclei. This is indeed observed since to some extent the α-decay schemes of ^{210}At, ^{212}Fr, ^{214}Ac and ^{216}Pa are fairly similar, although some clear differences are also observed (see fig. 6 and refs. [1,2] for details). In all four nuclei the most favoured α-decay is not the g.s.–to–g.s. but the α-decay to a low-lying level (in ^{210}At to the 5^+ state at 166 keV [1], in ^{212}Fr to the 5^+ state at 147.7 keV [1], in ^{214}Ac to the $(5,6,7)^+$ state at

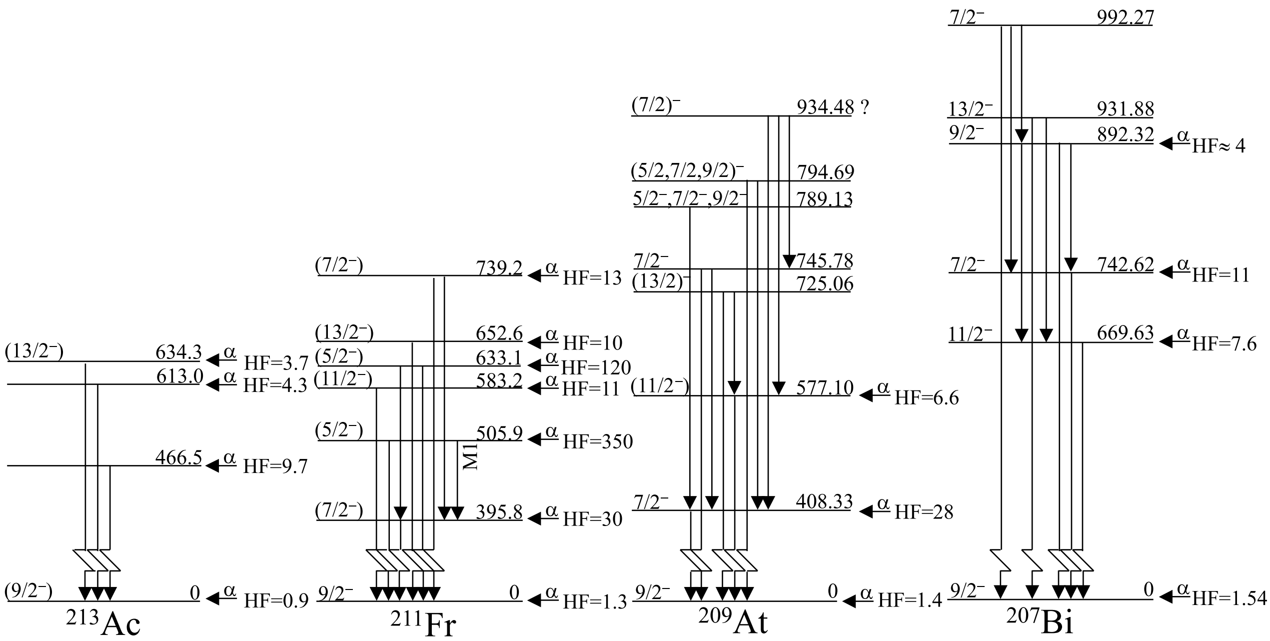

Fig. 7. Partial level schemes of ^{213}Ac (data are adopted from ref. [14]), ^{211}Fr (data are taken from ref. [1] and the present work), ^{209}At (α-decay data are taken from ref. [13] and other data from ref. [1]) and ^{207}Bi (adopted from ref. [1]) isotones, see text for details. Observed α-decays populating different levels in the daughter nuclei are indicated by horizontal arrows and, apart from ^{207}Bi, hindrance factors (HF) are calculated assuming $\Delta\ell = 0$ for each α-decay.

139.0 keV and in the ^{216}Pa to the level at 133.6 keV [2]). Furthermore, the g.s. in ^{206}Bi, ^{208}At and ^{210}Fr is 6^+, whereas in ^{212}Ac it remains unknown.

In this respect it is worth noting that in ^{212}Ac only one α-branch to the daughter nucleus of ^{208}Fr (having 7^+ g.s.) has been observed so far [1,2]. This suggests that other α-branches may be very small (in an odd-odd nucleus one expects at least few low-lying levels to be fed by α-decay) or α-decay populates levels with a very small excitation energy as observed in ^{204}Bi (see ref. [1]). However, if the α-decay observed in ^{212}Ac is the g.s.–to–g.s. transition, one expects the 7^+ g.s. also for ^{212}Ac. If this is the case, there is a change in spin from the 6^+ g.s. in ^{210}Fr to the (possible) 7^+ g.s. in ^{212}Ac. This could indicate that the spin sequences in the ^{206}Bi, ^{208}At, ^{210}Fr and ^{212}Ac isotones are different (even if α-intensities to the g.s. and to the levels at 147.7, 139.0 and 133.6 keV in ^{208}At, ^{210}Fr and ^{212}Ac, respectively, are rather similar). Therefore we hesitate to assign the level at 139 keV in ^{210}Fr to the 5^+ state even if the 5^+ state is suggested by the ^{208}At isotone and the evidence for the 7^+ g.s. in ^{212}Ac is weak. This interpretation implies that the g.s. of ^{214}Ac remains unknown even if 5^+ seems the most probable.

Another interesting detail is that in the ^{208}At isotone the 5^+ state decays to the g.s. mainly via the (5^+) state at 23.53 keV by the 124.2 keV γ-transition [1], whereas in ^{210}Fr the $(5, 6, 7)^+$ state decays mainly directly to the g.s. via the transition of 139 keV. Furthermore, it seems there are fewer low-lying levels populated by α-decay into ^{210}Fr than in the case of ^{208}At (see ref. [1]). Therefore it is possible that the spin sequence of the lowest-lying states in these two isotones is not identical, but an additional proton-pair in ^{210}Fr affects the spin sequence of the lowest-lying levels. Furthermore, in the ^{208}At isotone there are low-lying states populated by α-decay, which, however, have not been observed to decay directly to the g.s. by γ-transitions (see ref. [1] for details). This may also be the case in ^{210}Fr since cascades of low-energy transitions are difficult to detect because of a poor γ-ray detection efficiency and losses in γ-ray intensities due to internal conversion. Therefore we want to remark that the decay sequences to the low-lying levels in the ^{214}Ac α-decay may still not be fully conclusive but need further studies. This is also the case for spins and parities of several states observed in ^{210}Fr.

4.2 ^{215}Ac and odd-even N = 126 isotones

From the nuclear shell model for $82 < Z$ (odd) < 92 nuclei the valence proton is expected to lie in the $h_{9/2}$ orbital. Therefore the g.s.–to–g.s. α-decays in the ^{211}At, ^{213}Fr, ^{215}Ac and ^{217}Pa isotones are expected to occur predominantly between the two $9/2^-$ states (favoured α-decays). This is indeed observed as nearly 100% α-branches in the g.s.–to–g.s. decays, while α-branches to the excited states are very small. This is due to structural differences between the initial and final states, and to unfavourable Q_α values (the levels in ^{207}Bi, ^{209}At, ^{211}Fr and ^{213}Ac isotones are relatively high in energy). For the g.s.–to–g.s. decays the α-decay hindrance factors in all isotones are close to unity as expected for α-decay with no change in spin and

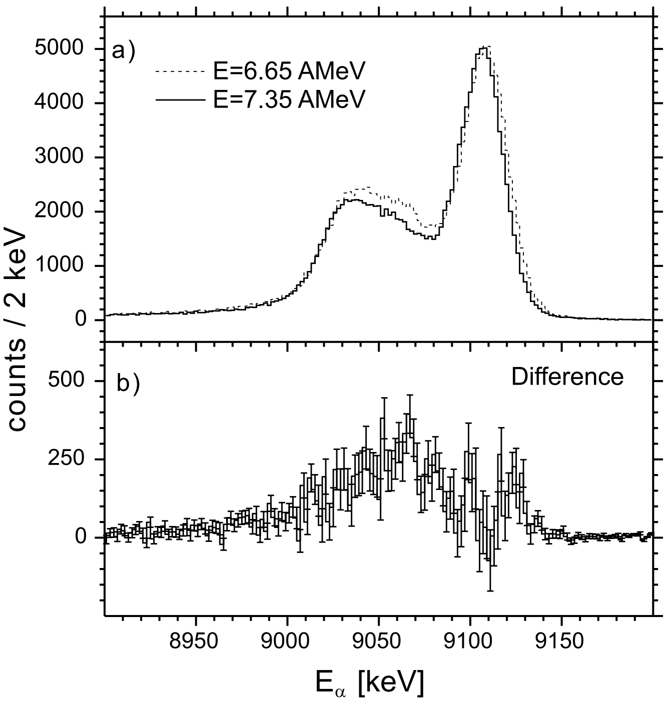

Fig. 8. a) Singles α-spectra of ^{216}Ac to the g.s. and to the level at 82.6 keV in the daughter nucleus ^{212}Fr (normalized to the maximum of the 9105 keV α-line) measured at 6.65 $A \cdot$ MeV (solid line) and 7.35 $A \cdot$MeV (dotted line) bombarding energies. b) Difference in counts between the two spectra in part a).

parity (see refs. [1,13,14] for details and fig. 7 for comparison).

Up to date the most detailed study for the low-lying levels in α-decay of odd-proton $N = 126$ isotones is available for ^{211}At. In the daughter nucleus ^{207}Bi there are three excited levels observed to be populated by α-decay with hindrance factors of 7.6, 11 and ≈ 4 for the $11/2^-$, $7/2^-$ and $9/2^-$ states [1], respectively. In ^{211}At α-decay to the $7/2^-$ state at 742.62 keV is slightly more hindered than to the $11/2^-$ state, while α-decay to the excited $9/2^-$ state at 892.32 keV is, as expected, favoured. For the $7/2^-$ and $11/2^-$ states a similar trend is also observed in ^{211}Fr. It further does not seem that there are low-lying $9/2^-$ states beside the g.s. in ^{211}Fr. Moreover, in the α-decay of ^{213}Fr, hindrance factors for decays to the $7/2^-$ and $(11/2^-)$ states in ^{209}At [1] have values of 28 and 6.6 [13], respectively. The hindrance factor of 28 for the decay into the low-lying $7/2^-$ state in ^{209}At is in line with the value for the decay into the $(7/2^-)$ state in ^{211}Fr with nearly equal energy.

So far the $5/2^-$ states fed by α-decay have not been observed in odd-proton $N = 124$ isotones. Therefore our tentative spin and parity assignments for the two $5/2^-$ states are based mainly on large α-decay hindrance factors. However, taking into account small hindrance factors observed for the $7/2^-$ and $9/2^-$ states in the α-decay of ^{215}Ac, one can conclude that the difference in spin between the $9/2^-$ g.s. of ^{215}Ac and the two states in ^{211}Fr is larger than that of the $7/2^-$ state. Furthermore, the $9/2^-$ to $3/2^-$ decay with $\Delta\ell = 3$ is expected to be very hindered due to the parity selection rule. However, for example in the α-decay of ^{211}Rn from the $1/2^-$ g.s. to the $7/2^-$ state at 588.3 keV in ^{207}Po, the hindrance factor is only 17.5 [1] and therefore this possibility cannot be excluded.

4.3 ^{216}Ac

The latest interpretation of spins and parities of ^{216}Ac was derived by Torgerson and Macfarlane [12], who identified two groups of ^{216}Ac α-decays (see table 5 for details). These α-decays were interpreted to be from ^{216g}Ac (probable 1^- state) and ^{216m}Ac (probable 9^- state), respectively, based on odd-proton $N = 127$ isotones and a measured excitation-function shift of the low-spin and high-spin members of the ^{216}Ac isomer pair (in ref. [12] the maximum production cross-section for ^{216g}Ac is observed ≈ 3 MeV lower in bombarding energy than that of ^{216m}Ac, *i.e.* at ≈ 80 MeV bombarding energy).

One of our aims in the decay study of ^{216}Ac was to observe α-decays to the 5^+ g.s. and the (4^+) state at 82 keV in the daughter nucleus ^{212}Fr in order to verify the partial decay scheme of ^{216g,m}Ac. From the α-spectroscopic point of view it is interesting that in the α-decay of ^{216m}Ac the hindrance factor for the (4^+) state at 82 keV is smaller than that of the 5^+ g.s., even though the difference in spin from the 9^- state is larger for the 4^+ state than the 5^+ g.s. As also pointed out by Torgerson and Macfarlane, the same trend is observed in the ^{212}At and ^{214}Fr isotones where α-decays from isomeric states to the 4^+ states are more favoured than the ones to the 5^+ g.s., whereas in the g.s.–to–g.s. α-decays the situation is opposite. This trend is summarized in table III in ref. [12].

However, this interpretation needs to be updated since the later γ-ray and electron spectroscopy study of ^{214}Fr by Byrne *et al.* proposed the isomeric state to be 8^- instead of 9^- based on shell model arguments (see ref. [15] for details). Therefore it may not be evident that the spin and parity for the heavier $N = 127$ isotones follow the trend of the 1^- g.s. and the 9^- isomeric state as observed in ^{210}Bi and ^{212}At. Furthermore, in our work we did not observe any evidence for the 8990 keV α-line or any conclusive evidence for the one at 9070 keV even at the lowest bombarding energy of 6.65 $A \cdot$ MeV but all observed α-decays can be explained by 9105 keV α-particles and 9029 keV α-particles accompanied by 82 keV γ-rays or conversion electrons. This is illustrated in fig. 8a where singles α-spectra in the region of interest at 6.65 and 7.35 $A \cdot$ MeV bombarding energies are shown (the same structure for α-lines is observed also in fig. 1).

Due to a small energy difference between the g.s. of ^{212}Fr and its first-excited level at 82 keV, the $M1$ transition between the two states is highly converted (the theoretical total conversion coefficient for $M1$ at 82.6 keV is $\alpha_{\rm tot} = 5.24$ [7]). Hence summing of 9029 keV α-particles and conversion electrons results in a tail in the 9029 keV α-line towards the high-energy part of the α-spectrum. Consequently, the intensities for the two α-lines at 9029 and 9105 keV were extracted assuming that the tail towards the higher energy in the 9029 keV α-line belongs to the 9029 keV line. This resulted in values of (48.8±1.0)% and (47.5±0.5)% for the 9029 and 9105 keV α-lines, respectively, which are close to the values 49.6% and 46.3% for $E_{\alpha 2} = 9028$ keV and $E_{\alpha 1} = 9108$ keV, respectively, as reported by Torgerson and Macfarlane [12]. A slightly higher relative number of counts for the 9029 keV α-line at 6.65 and 7.35 $A \cdot$MeV bombarding energies, also shown in fig. 8a, can be interpreted as a result of different penetration depths of recoils with different beam energies. The deeper recoils penetrate into the detector the more energy conversion electrons lose in the detector when they escape. That is why the 9029 keV α-line is lower in intensity at higher bombarding energy.

However, taking into account different widths for the tail of the 9029 keV α-lines, the intensities for the two α-lines extracted from the 7.1 and 9.1 $A \cdot$ MeV bombarding energies are consistent. The values for the relative intensities for the 9029 keV (+ tail) and 9105 keV α-lines are: (48.8 ± 1.0)% and (47.5 ± 0.5)% at $E_{\mathrm{beam}} =$ 7.1 $A \cdot$ MeV and, (48.9 ± 1.0)% and (47.4 ± 0.6)% at $E_{\mathrm{beam}} = 9.1$ $A \cdot$MeV, respectively. From α-γ-coincidences assuming a pure $M1$ we get $I_\alpha = (50 \pm 5)$% for 9029 keV α-particles. Furthermore, as shown in fig. 8b the α-spectrum recorded at 6.65 $A \cdot$ MeV bombarding energy (close to the maximum production cross-section for ^{216g}Ac), subtracted by the one at 7.35 $A \cdot$MeV bombarding energy, indicates that there is no clear evidence for an α-line around 9070 keV. The remaining hump can be explained on the basis of electron summing. Therefore, on the basis of the intensity balance in the 7.1 and 9.1 $A \cdot$ MeV bombardments (the excitation energy at 9.1 $A \cdot$MeV should be high enough to cut more of ^{216g}Ac than of ^{216m}Ac) and the absence of an α-line around 9070 keV, one concludes that a possible fraction of 9070 keV α-particles in all spectra is small or at least beyond the sensitivity of our experiment.

Results worth noticing are also the very large hindrance factors (HF $\sim 10^3$) for all decays to the levels between 500 and 611 keV. Unfortunately among them the spin/parity is known only for the level at 542 keV which was assigned to the 7^+ state by Byrne *et al.* [9] based on an in-beam study of ^{212}Fr. This assignment is also supported by the fact that a γ-transition from this level to the (4^+) state at 82 keV was not observed (as probable $M3$), neither by Byrne *et al.* nor in our work. Therefore, assuming all α-decays in ^{216}Ac to be from the isomeric 9^- state, the question of a very high hindrance factor for an α-decay from the 9^- (or 8^-) state to the 7^+ state remains still open.

Furthermore, the hindrance factors for α-decays into the 7^+ state, the 5^+ g.s. and the 4^+ state (see fig. 5) are 1500, 320 and 200, respectively. If we now assume the emitting state in ^{216}Ac to be 9^- (or 8^-) we obtain a spin variation of $\Delta\ell = 2$ (or $\Delta\ell = 1$) for the decay into the 7^+ state, $\Delta\ell = 4$ (or $\Delta\ell = 3$) for that into the 5^+ g.s. and $\Delta\ell = 5$ (or $\Delta\ell = 4$) for the one into the 4^+ state. With the assumption of 1^- as spin and parity of this state the sequence would be $\Delta\ell = 6$, $\Delta\ell = 4$ and $\Delta\ell = 3$, respectively. Thus, the hindrance factor is increasing with increasing $\Delta\ell$ as expected in case of the 1^- g.s., whereas the emitting high-spin state is difficult to explain on the basis of hindrance factors. Furthermore, assuming the emitting state to be 8^- as proposed by Byrne *et al.* for ^{214}Fr, the smallest hindrance factor is observed for the decay which is forbidden by the parity selection rule (for both 1^- and 9^- states forbidden decays are those which have large hindrance factors), and this seems unlikely. Therefore, on the basis of the comparison of the α-spectra measured at different bombarding energies, of the lack of α-lines at around 8990 and 9070 keV and of the calculated hindrance factors, we observe no clear indication for the isomeric state in ^{216}Ac but all decays can be explained by the low-spin g.s.

5 Conclusions

Our results provide improved information on the decay schemes of ^{214}Ac, ^{215}Ac and ^{216}Ac. The results also show that the study of α-decay combined with γ-spectroscopy is an extremely sensitive tool to probe nuclear structure. As α-decay is in many cases (so far) the only way to populate low-lying non-yrast states in the heavy nuclei with measurable intensities, the use of α-γ-coincidences combined with the efficient separation of nuclei of interest provides a unique method to obtain information on these states.

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