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Decay studies of $^{210-214}$Fr using α-γ-coincidences

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Abstract. The α-decay fine structure of $^{210-214}$Fr has been studied by α-γ-coincidence measurements. The nuclei were produced using the ^{12}C on ^{209}Bi reaction. Evaporation residues recoiling out of the target were separated in-flight by the velocity filter SHIP and stopped in a position-sensitive 16-strip PIPS-detector in order to study their subsequent decays. In the present work new and improved results for $^{210-214}$Fr, produced by α-decay of the primary reaction products $^{214-218}$Ac, were extracted. The results are discussed and compared to previously published data.

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1 Introduction

The isotopes $^{210-214}$Fr were identified forty years ago, nevertheless α-decay fine-structure data particularly in the even-neutron cases are rather limited. In both ^{211}Fr and ^{213}Fr only the ground-state–to–ground-state (g.s.–to–g.s.) α-decay has been studied so far [1], though our previous work briefly referred the decay data for ^{213}Fr [2]. In odd-odd cases with one neutron added or removed from the $N = 126$ closed shell the α-decay fine structures are by far better established, while for ^{210}Fr only one α-branch is reported [1].

In our recent α-γ-coincidence study of actinium isotopes at the $N = 126$ closed shell [2] we identified several new α-transitions along with γ-rays emitted from the levels populated in the francium-daughter nuclei. Therefore, it seemed worthwhile to extend our α-γ-coincidence studies to the daughter nuclei using the same data, although some losses in statistics were expected due to electron capture (EC) decay of the parent nuclei. Thus, the aim of the present study was to expand the level schemes of these nuclei and to extract the level energies with improved precision. Furthermore, as our studies improved data for ^{213}Fr and ^{214}Fr these results are also included in this paper. The experimental procedure is already explained in ref. [2] so only the most relevant details are given here.

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2 Experimental details

The experiment was carried out employing the reaction ^{209}Bi(^{12}C$, xn)^{221-x}$Ac. A ^{12}C beam was delivered from the UNILAC at GSI, Darmstadt, with incident beam energies of 7.1 and 9.1 $A \cdot$ MeV and an intensity of ≈ 200 pnA. The targets of a 240 μg/cm^2 thick ^{209}Bi layer on 40 μg/cm^2 of C-backing were mounted on a wheel that rotated synchronously to the beam macro structure (beam pulses of 5 ms followed by 15 ms beam-off periods). Evaporation residues were separated from the primary beam by the velocity filter SHIP [3]. The evaporation residues were implanted into a position-sensitive 16-strip PIPS Si-detector (active area 80×35 mm^2) where their arrival and subsequent decays were registered [4]. The Si-detector was cooled to a temperature of ≈ 258 K to achieve an energy resolution of ≈ 22 keV (FWHM) at 8 MeV for each strip.

The γ-ray studies were carried out using a Ge-Clover-detector (four individual crystals, 70 mm diameter and 140 mm length each) placed behind the Si-detector in close geometry. Coincidences of Ge- and Si-detector signals were recorded within a 5 μs time interval. Energy and relative efficiency calibrations of the Clover-detector were carried out using an ^{152}Eu γ-source. 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-detector was estimated internally using the ratio of α-γ-coincidences and α-decays of ^{216}Ac into the levels at 854 and 938 keV in ^{212}Fr (see ref. [2] for details). The absolute efficiency for γ-rays corresponded to (4.5 ± 0.3)% photo peak efficiency at 1.3 MeV.

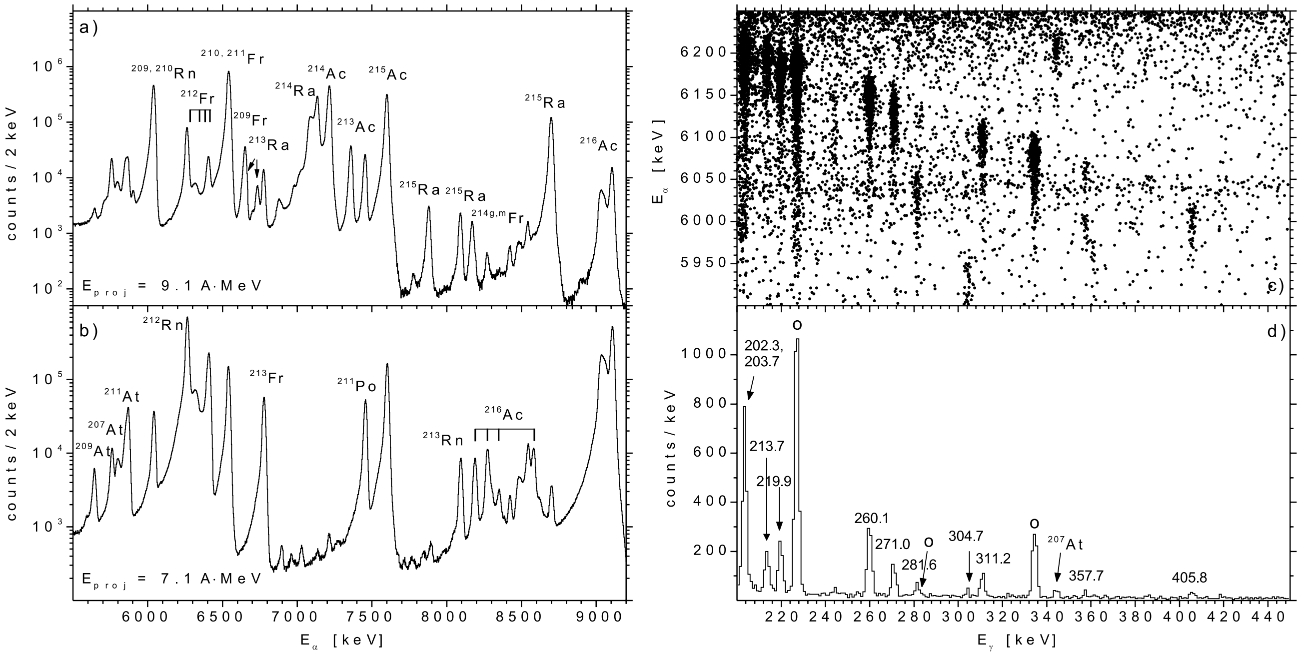

Fig. 1. Singles α-spectra from the ^{209}Bi(^{12}C, xn)$^{221-x}$Ac reaction at a) 9.1 and b) 7.1 $A \cdot$ MeV beam energy. c) Selected α-γ-coincidences observed in α-decay of ^{212}Fr. d) Projection of α-γ-coincidences on the γ-energy axis. The γ-transitions populating the g.s. are denoted by o. The γ-ray energies for transitions connecting excited levels in the daughter nucleus ^{208}At are in keV.

3 Experimental results

3.1 General considerations

The $^{210-214}$Fr nuclei were produced either by α-decay of $^{214-218}$Ac or as αxn-products of the ^{209}Bi(^{12}C, xn)$^{221-x}$Ac reaction. We performed α-γ-coincidence measurements which provide a unique method to identify weak α-transitions hidden in a background of strong transitions. Although invisible in singles α-spectra (shown in fig. 1) their intensities can be extracted using the number of γ-rays in α-γ-coincidences and the absolute efficiency of the Ge-detector.

However, internal conversion hampers γ-ray intensity studies. Moreover, α-decays into excited states undergoing internal conversion are accompanied by conversion electrons. As the residues are implanted into the Si-detector such events may be difficult to identify. They are detected with a probability of $\approx 50\%$ as summing signals of an α-particle and conversion electrons. This results in "artificial" α-lines and losses in α-intensities to the excited levels in singles α-spectra. In the region of interest α-decay in odd-even nuclei often populates levels up to relatively high excitation energies, while energy differences between succeeding levels are often large. These transitions are expected to be only weakly converted. However, for odd-odd cases where level densities are higher, internal conversion and electron summing may result in misinterpretation if not verified by α-γ-coincidences. Furthermore, γ-transitions connecting levels in the daughter nucleus provide additional information about its nuclear structure.

In order to estimate the effects, knowledge about transition multipolarities and structures of conversion electron summed α-lines in α-spectra are important. Unfortunately, often internal conversion coefficients are unknown and difficult to determine. Therefore losses in γ-ray intensities were not taken into account in the present work (if not otherwise noted) but α-intensities estimated using the number of γ-rays in α-γ-coincidences are given as extracted from the original data. Consequently α-decay hindrance factors in these cases are upper limits rather than real values due to lower limits given for α-intensities. However, in each case error bars are given in order to reflect the quality of the data and to provide errors for intensities as multipolarities are settled. The α-decay hindrance factors are calculated according to the method of Rasmussen [5] assuming $\Delta\ell = 0$ if not otherwise noted.

In the present work α-particles emitted by the mother nuclei were identified on the basis of $Q_\alpha + E_\gamma$ values close (within ± 5 keV) to the g.s.–to–g.s. α-decay. The Q_α value is calculated using the measured α-particle energy E_α and the equation $Q_\alpha = (1 + m_\alpha/m_d) \times E_\alpha$, where m_α and m_d are the masses of the α-particle and daughter nucleus, respectively. Transitions connecting excited states were placed on the basis of energy balance and observed energy summing of α-particles and conversion electrons.

3.2 ^{210}Fr

The isotopes of ^{210}Fr and ^{211}Fr, having overlapping α-energies were identified by Griffioen and Macfarlane [6] based on the shape of the excitation functions measured

Table 1. α-γ-coincidence data for ^{210}Fr.

E_α (keV)	I_α (%)$^{(a)}$	HF$^{(b)}$	$E_{\rm level}^{\rm daughter}$ (keV)	E_γ (keV)	$N_{\alpha\text{-}\gamma}^{(c)}$	I_γ	$I_{\gamma,\rm rel.}$ (%)
6545 ± 5	99.87 ± 0.03	2.1	0		(d)		
(e),(f)	(g)	(g)	$5.6 \pm 0.4^{(e),(f)}$	(e)	(e)	(e)	(e)
(e),(f)	(g)	(g)	$31.1 \pm 0.3^{(e),(f)}$	(e)	(e)	(e)	(e)
6420 ± 4	$> 0.030 \pm 0.005$	< 2200	126.3 ± 0.1	126.3 ± 0.1	276 ± 19	1000	100 ± 7
				$120.7 \pm 0.3^{(f)}$	44 ± 13	158 ± 48	16 ± 5
$6409 \pm 4^{(f)}$	$> 0.014 \pm 0.004$	< 4200	$137.6 \pm 0.3^{(f)}$	$137.6 \pm 0.3^{(f)}$	127 ± 17	471 ± 71	100 ± 13
				$106.5 \pm 0.2^{(f)}$	27 ± 8	94 ± 29	20 ± 7
6400 ± 4	$> 0.034 \pm 0.007$	< 1600	148.0 ± 0.1	148.0 ± 0.1	256 ± 29	971 ± 129	100 ± 11
				$116.9 \pm 0.3^{(f)}$	98 ± 20	348 ± 75	36 ± 9
$(6348 \pm 5)^{(f),(h)}$	$> 0.0041 \pm 0.0013$	< 7900	$200.9 \pm 0.5^{(f)}$	$195.3 \pm 0.2^{(f)}$	39 ± 11	163 ± 47	100
$6227 \pm 5^{(f)}$	$> 0.010 \pm 0.002^{(i)}$	< 1000	$322.3 \pm 0.1^{(f)}$	$322.3 \pm 0.1^{(f)}$	75 ± 11	399 ± 65	100
6212 ± 4	$> 0.022 \pm 0.003$	< 380	340.4 ± 0.1	340.4 ± 0.1	160 ± 15	878 ± 102	100
6112 ± 7	$> 0.0017 \pm 0.0009$	< 1800	444.2 ± 0.5	444.2 ± 0.5	10 ± 5	65 ± 33	100
$(5900 \pm 5)^{(f),(h)}$	$> 0.010 \pm 0.005$	< 32	$657.3 \pm 0.2^{(f)}$	$651.5 \pm 0.3^{(f)}$	33 ± 9	284 ± 23	100 ± 30
				$626.3 \pm 0.3^{(f)}$	15 ± 5	125 ± 43	40 ± 20

(a) Relative α-intensities for the excited levels were extracted from α-γ-coincidences. The greater sign takes into account that losses in intensities due to internal conversion were not considered.
(b) Half-life of 3.18 min [1] and α-branch of 71% used in the calculation.
(c) Fit of gated γ-rays.
(d) A number of counts in the singles α-spectrum was estimated to be $(66.9 \pm 1.7)\times 10^5$ counts.
(e) γ-rays not observed, see text for details.
(f) Tentative.
(g) α-intensities may be included in the g.s. due to electron summing.
(h) γ-transition feeding the g.s. not observed, E_α calculated from the Q value.
(i) α-intensity for this level may be partly from the level at 340.4 keV due to internal conversion.

using the ^{12}C on ^{203,205}Tl reactions. Valli *et al.* [7] verified the results, but so far only one α-branch for ^{210}Fr with $E_\alpha = 6543 \pm 5$ keV and ^{211}Fr with $E_\alpha = 6534 \pm 5$ keV were reported (see ref. [1] and references therein). The first and up to now most detailed experimental data for levels in the daughter nucleus ^{206}At were measured by Zelinski *et al.* [8] by EC-decay of ^{206}Rn. Although they identified several γ-transitions assigned to ^{206}At, they had difficulties in placing them in the level scheme of ^{206}At (see ref. [8] for details). Therefore, we expected that α-γ-coincidences were useful in probing the low-lying levels in ^{206}At.

The isotope ^{210}Fr was produced using the reaction of ^{209}Bi(^{12}C, 7n)^{214}Ac followed by α-decay of ^{214}Ac to ^{210}Fr. The decay of ^{210}Fr was investigated by α-γ-coincidences. A use of α-γ-γ-coincidences was excluded because α-decay of ^{210}Fr is strongly dominated by the g.s.–to–g.s. decay and/or decays to the level(s) at low excitation energy. The results of our study are listed in table 1 and the proposed decay scheme is shown in fig. 2.

The levels at 126, 148, 340 and 444 keV are assigned to the daughter nucleus ^{206}At on the basis of narrow α-lines with $Q_\alpha + E_\gamma$ values close to that of the g.s.–to–g.s. α-decay of ^{210}Fr whereas the rest of the levels are tentative only. The two low-lying levels at 6 and 31 keV, from which no γ-rays were observed, are based on the (tentatively placed) γ-transitions of 121, 195 and 652 keV and on 107, 117 and 626 keV, respectively. The placements of these transitions are supported by α-energies observed in α-γ-coincidences gated by respective γ-rays.

We observed γ-rays of 121 keV in coincidence with α-particles of 6424 ± 6 keV ($\Delta E = 31$ keV FWHM). The width of the α-line and an energy shifted ≈ 4 keV towards the higher value of 126 keV (the width of the α-line is 24 keV FWHM) are suggesting that the level at 126 keV decays directly to the g.s. by the 126 keV transition and to the level at 6 keV by the 121 keV transition. However, a low-energy transition of 6 keV is expected to be fully converted. Therefore, the evidence for the level at 6 keV is indirect only and should be considered as tentative. From α-γ-coincidences we further noted γ-rays at 195 keV for which the α-energy peaks at 6346 ± 7 keV with $\Delta E = 29$ keV (FWHM). One notes that the $Q_\alpha + E_\gamma$ value with these energies is ≈ 5 keV too low compared to that of the g.s.–to–g.s. decay. A broad energy distribution of α-particles also indicates that the 195 keV transition is not populating the g.s. directly. Therefore, we tentatively conclude that the 195 keV γ-rays originate from a level at 201 keV (for which the $Q_\alpha + E_\gamma$ value fits to that of the g.s.–to–g.s. decay) which is feeding the level at 6 keV.

The level at 31 keV is based on γ-rays at 117 keV observed in coincidence with 6406 ± 6 and 6430 ± 5 keV α-lines. This suggests that the transition occurs from the level at 148 keV. A small shift in α-energy and another α-line slightly above can be explained by summing of 6400 keV α-particles and conversion electrons. We further noted that a difference in energy between the 107 and 138 keV γ-transitions equals 31 keV. The 107 keV γ-rays were in coincidence with 6423 ± 7 keV ($\Delta E = 49$ keV

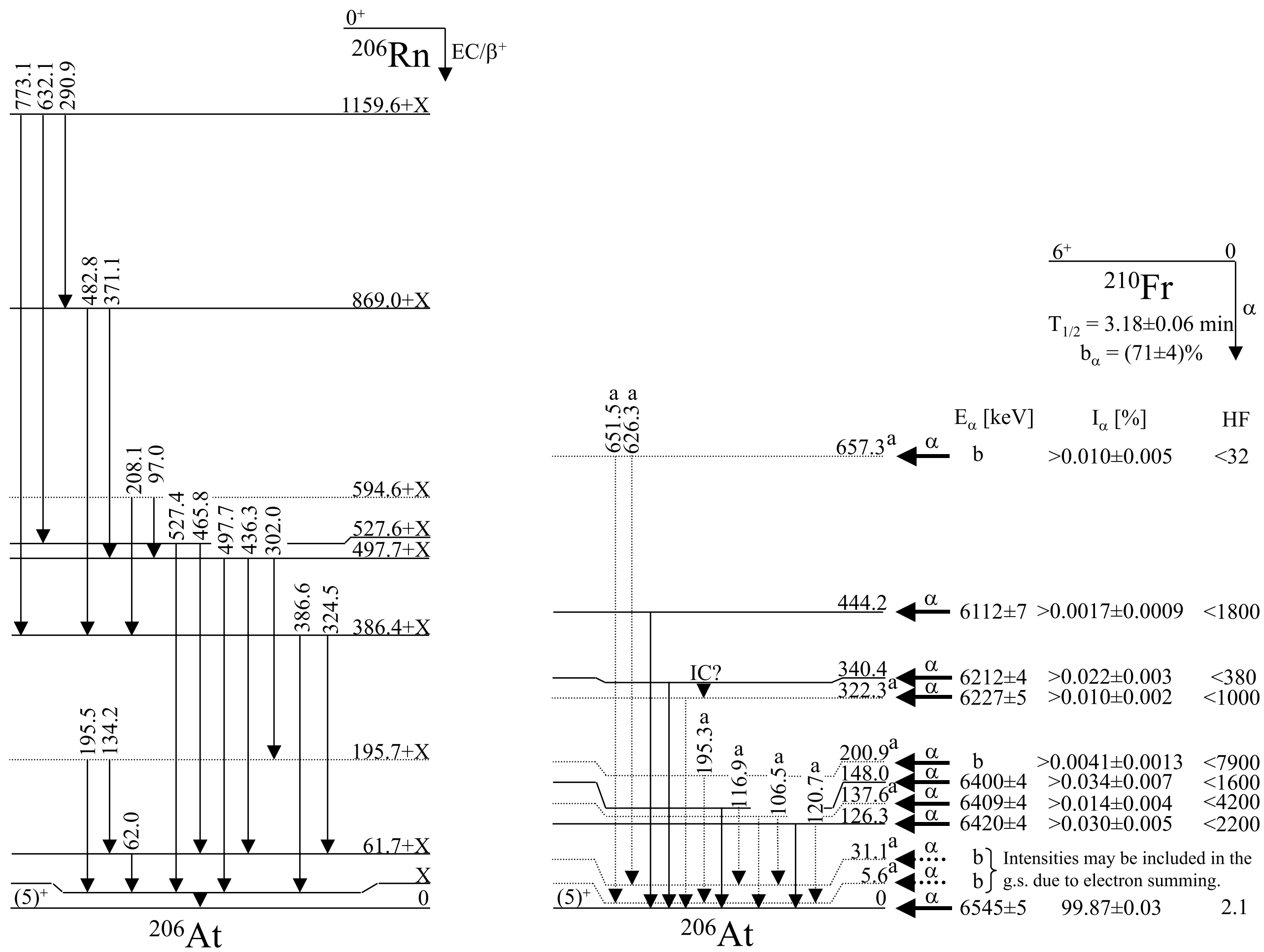

Fig. 2. The level scheme of ^{206}At observed by EC-decay of ^{206}Rn (adopted from refs. [1,8]) and our proposed α-decay scheme of ^{210}Fr to ^{206}At (the (5^+) g.s. for ^{206}At, the 6^+ g.s. and half-life for ^{210}Fr are from ref. [1]). [a] Tentative. [b] No direct γ-transition to the g.s. observed.

FWHM) α-particles and a broad energy distribution indicates that the transition populates a low-lying level rather than the g.s.. The $Q_\alpha+E_\gamma$ value for the tentative level at 138 keV ($E_\alpha = 6409 \pm 4$ keV, $\Delta E = 29$ keV FWHM) fits to that of the g.s.–to–g.s. decay of ^{210}Fr but a rather broad α-energy distribution suggests that 138 keV transition may not populate the g.s. directly. However, as a result of nearly overlapping γ-ray energy with the tail of 139 keV γ-rays from the α-decay of ^{214}Ac may have hampered the study (even if the data are background subtracted). Therefore, we tentatively conclude that 107 and 117 keV transitions feed the low-lying level at 31 keV.

An additional evidence for the levels at 6 and 31 keV is provided by α-particle energies gated by 626 and 652 keV γ-rays. The difference between these two energies equals that of 6 and 31 keV within experimental accuracy. Also, α-particles gated by 626 keV γ-rays peak at 5930 ± 8 keV ($\Delta E = 30$ keV FWHM) which results in a lower $Q_\alpha+E_\gamma$ value than that of the g.s.–to–g.s α-decay of ^{210}Fr. This indicates that the 626 keV transition is feeding a low-lying level, not the g.s.. For γ-rays at 652 keV the situation is different since α-particles gated by 652 keV γ-rays peak at 5904 ± 7 keV ($\Delta E = 26$ keV FWHM) implying that the $Q_\alpha+E_\gamma$ value fits to that of the g.s.–to–g.s. α-decay of ^{210}Fr. However, also in this case the width of the α-line indicates that the transition is not feeding the g.s. directly and the matching of the $Q_\alpha+E_\gamma$ value probably results from the low excitation energy of the level at 6 keV. Therefore we tentatively conclude that the 626 and 652 keV transitions are not populating the g.s. directly but are both from the level at 657 keV populating the levels at 31 and 6 keV, respectively. However, due to overlapping α-energy with ^{211}Fr and small excitation energies we cannot conclude if the two low-lying levels are fed by α-decay.

The $Q_\alpha+E_\gamma$ value for the level at 322 keV ($\Delta E =$ 27 keV FWHM) fits to that of the g.s.–to–g.s. decay of ^{210}Fr within experimental accuracy. However, a broad α-energy distribution may indicate that the state decays to the low-lying level rather than to the g.s. Another explanation is that the level at 322 keV is populated from the level at 340 keV by internal conversion broadening the

α-energy distribution due to electron summing. This interpretation is actually supported by a tail in α-line gated by 322 keV γ-rays which seems wider than that gated by 340 keV γ-rays. This also explains a slightly lower $Q_\alpha + E_\gamma$ value than that of the level at 340 keV or the g.s.–to–g.s. α-decay. Therefore, we conclude that the level at 322 keV is populated by α-decay but the level is also populated from the level at 340 keV by internal conversion. However, on the basis of the present data we cannot rule out the possibility that 322 keV γ-rays populate the low-lying level. In conclusion, the level at 322 keV is only tentative.

Due to overlapping α-energies and unknown multipolarities, the α-intensities for ^{210}Fr could not be extracted from singles α-spectra. Therefore the numbers of observed α-γ-coincidences are also given in table 1. Also, due to a lack of statistics in α-γ-X-ray-coincidences (providing information about internal conversion coefficients) and the vicinity of α-energies from other α-decaying isotopes, *e.g.* ^{212}Fr and ^{213}Ra (implying a significant number of random correlations in α-X-ray-coincidences), we could not determine spins and parities of the levels observed in ^{206}At.

However, from singles α-spectrum we were able to estimate the α-branch of ^{210}Fr ($b_\alpha = (60 \pm 30)\%$ in ref. [1]). This resulted in a value of $(71 \pm 4)\%$ for the main α-line of ^{210}Fr. Here we assumed α-branches of $(87 \pm 3)\%$ and (99.91 ± 0.02) [1] for ^{211}Fr and ^{215}Ac (for details on ^{211}Fr, see next section), and α-intensities of $(54 \pm 2)\%$ and $(99.57 \pm 0.07)\%$ [2] for the g.s.–to–g.s. α-decay of ^{214}Ac and ^{215}Ac, respectively. In addition, we assumed that there is no direct production of ^{210}Fr by α7n-evaporation.

In addition to the transitions explained above, we also observed a γ-line at 100.9 ± 0.2 keV. These γ-rays are probably associated with the decay of ^{210}Fr. Gated by 101 keV γ-rays, α-particles peak at 6405 ± 11 and 6445 ± 5 keV with $\Delta E = 31$ and 15 keV (FWHM), respectively. On the basis of α-energies, the 101 keV γ-rays may derive from the levels at 101 or 148 keV. However, since we did not observe clear evidence for the levels at 47 or 101 keV we did not place the transition to the level scheme. One also notes that the 101 keV transition may be the same as observed by Zelinski *et al.* [8] in EC-decay of ^{206}Rn with $E_\gamma = 101.2 \pm 0.2$ keV, but its placement remains unclear.

3.3 ^{211}Fr

So far the fine structure in the α-decay of ^{211}Fr has not been observed, but the low-lying levels in the daughter nucleus ^{207}At were identified by EC-decay of ^{207}Rn and by in-beam γ-spectroscopy (see ref. [1] and references therein). Therefore, our main interest was to measure α-intensities to the low-lying levels in ^{207}At and to calculate the α-decay hindrance factors. The results of our study are listed in table 2 and the decay scheme of ^{211}Fr is shown in fig. 3.

The ^{211}Fr nuclei were produced using the reaction of ^{209}Bi(^{12}C, 6n)^{215}Ac followed by the α-decay of ^{215}Ac. The excited levels were identified on the basis of known γ-ray energies as the $7/2^-$, $11/2^-$ and $13/2^-$ states in ^{207}At [1]. Due to weak α-branches to the excited levels α-intensities

Table 2. Data for ^{211}Fr extracted from α-γ-coincidences.

E_α (keV)	I_α (%)$^{(a)}$	HF$^{(b)}$	E_γ (keV)	I^π
6537 ± 4	99.943 ± 0.022	1.3		$9/2^-$
6199 ± 5	$> 0.041 \pm 0.013$	< 120	344.5 ± 0.2	$7/2^-$
5905 ± 7	$> 0.006 \pm 0.004$	< 38	643.9 ± 0.5	$11/2^-$
5866 ± 6	$> 0.009 \pm 0.005$	< 16	686.7 ± 0.6	$13/2^-$

(^{a}) For lower limits in α-intensities, see (^{a}) in table 1.
(^{b}) 3.10 min [1] half-life and 87% α-branch used in the calculation.

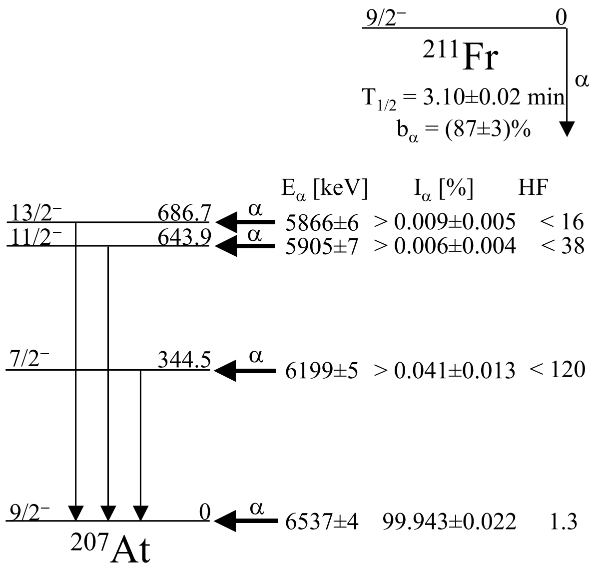

Fig. 3. The decay scheme of ^{211}Fr observed in the present work. The spins, parities and half-life are from ref. [1].

for the fine-structure α-decay were estimated indirectly using the numbers of γ-rays in α-γ-coincidences.

Unfortunately only limited information is available for the mixing ratios of the 345 and 644 keV transitions (both $M1 + E2$ mixtures with a mixing ratio of $\delta = 3^{+2}_{-1}$ and of no reported value [1], respectively), which we were not able to improve due to a lack of statistics. However, using the available information, the total internal conversion coefficients for the two transitions are expected to be $\alpha_{\mathrm{tot}} \leq 0.2$ and $\alpha_{\mathrm{tot}} \leq 0.1$ [9], respectively, but with large uncertainty. Therefore, α-decay intensities were calculated assuming no losses in numbers of γ-rays due to internal conversion. This implies that α-intensities for the excited states represent lower limits and corresponding α-decay hindrance factors upper limits rather than real values. However, corrections are small and as soon as the data are available, intensities and α-decay hindrance factors can be corrected accordingly. The reduced α-decay widths are calculated according to the method of Rasmussen [5] assuming $\Delta\ell = 0$ for each decay. The reduced width for the g.s.–to–g.s. decay is an average of the α-decay widths of ^{210}Rn and ^{212}Ra (data are taken from ref. [1]).

We also estimated an α-branch of ^{211}Fr for which a value of $b_\alpha > 80\%$ is reported [1]. In the study we used the data measured at the 7.1 $A \cdot$ MeV bombarding energy in which a fraction of ^{214}Ac as well as direct production of ^{210}Fr were negligible ($< 0.5\%$). The α-branch of ^{211}Fr was estimated using the ratio of the number of α-counts of ^{211}Fr and ^{215}Ac in the singles α-spectrum. In the calculation we used an α-branch of $(99.91 \pm 0.02)\%$ [1] and an intensity of $(99.57 \pm 0.07)\%$ for the g.s.–to–g.s. α-decay of ^{215}Ac [2]. This resulted in an α-branch of $b_\alpha = (87 \pm 3)\%$ for ^{211}Fr, which is consistent with the previously reported lower limit.

3.4 ^{212}Fr

The ^{212}Fr nucleus was identified by Momyer *et al.* [10] who reported three α-decay energies populating the g.s. and two low-lying levels in the daughter nucleus ^{208}At. Up to now the α-decay of ^{212}Fr has been studied by several authors and, in addition, its daughter nucleus ^{208}At has been investigated by γ-ray spectroscopy and EC-decay of ^{208}Rn (see refs. [1,11] and references therein).

In the present work ^{212}Fr was produced via the reaction ^{209}Bi(^{12}C, 5n)^{216}Ac and α-decay to ^{212}Fr. In the study we verified so far published α-energies on the basis of α-γ-coincidences. In addition we identified two more levels in the daughter nucleus ^{208}At, although one only as tentative. The levels were connected by linking γ-transitions, including several transitions also observed in the EC-decay of ^{208}Rn to ^{208}At. The results of our study are listed in table 3. The decay scheme of ^{212}Fr observed in the present work is shown in fig. 4 where levels populated by EC-decay of ^{208}Rn are also shown.

The α-decay of ^{212}Fr is dominated by decays to the g.s. and to the levels at 24, 64, 72 and 148 keV which take up $\approx 97\%$ of the total α-intensity (see ref. [1] for details). This results in weak α-intensities for levels above 148 keV and thus hamper α-γ-γ-coincidence studies for those transitions. Also, the most intensive α-transition populates the level at 148 keV which decays with strong $M1$ components resulting in emission of K-conversion electrons. As a result a large number of astatine X-rays were observed in α-X-ray-coincidences within a wide range of α-energies hampering conversion studies. Therefore, weak γ-lines with nearly overlapping energies of astatine K_α and K_β X-rays were unresolved. Thus, all γ-transitions were placed on the basis of α-energies observed in α-γ-coincidences gated by respective γ-rays.

Since α-intensities for ^{212}Fr are already studied in detail (see ref. [1] and references therein) and being aware of overlapping α-energies of neighbouring nuclei and summing of α-particles and conversion electrons we did not extract α-intensities for ^{212}Fr. However, for the newly established level at 682 keV the α-intensity can be estimated using the number of α-γ-coincidences from the level at 588 keV ($I_\alpha = (0.05 \pm 0.03)\%$ [1]). As the numbers of α-γ-coincidences from the level at 682 keV and those of 361 keV from the level at 588 keV were 9 and 72±5 counts, respectively, the α-intensity for the level at 682 keV can be expected to be $\approx 0.002\%$, including the efficiency correction and assuming no losses in α-γ-coincidences due to internal conversion.

Table 3. α-γ-coincidence data for ^{212}Fr.

E_α (keV)	$E_{\text{level}}^{\text{daughter}}$ (keV)	E_γ (keV)	$I_{\gamma,\text{rel}}$ (%)
$6406 \pm 4^{(a)}$	0		
$6383 \pm 5^{(a)}$	$23.5 \pm 0.2^{(a),(b)}$	$23.5 \pm 0.2^{(a),(b)}$	100
$(6342 \pm 3)^{(a),(c)}$	$63.6 \pm 0.2^{(a),(b),(d)}$	$40.1 \pm 0.2^{(a),(b)}$	100
$6337 \pm 4^{(a)}$	$71.9 \pm 0.2^{(a),(e)}$	$71.9 \pm 0.2^{(a),(e)}$	100
$()^{(c)}$	$113.9 \pm 0.4^{(b),(d)}$	$50.3 \pm 0.3^{(b)}$	100
$6264 \pm 4^{(a)}$	$147.9 \pm 0.1^{(a)}$	$147.9 \pm 0.1^{(a)}$	5 ± 1
		$124.5 \pm 0.1^{(a)}$	100 ± 10
$()^{(c),(f)}$	$208.3 \pm 0.3^{(d),(f)}$	$184.7 \pm 0.1^{(f),(g)}$	71 ± 11
		$144.6 \pm 0.2^{(f),(g)}$	100 ± 10
$6185 \pm 4^{(a)}$	$227.2 \pm 0.1^{(a)}$	227.2 ± 0.1	100 ± 3
		203.7 ± 0.1	51 ± 4
		163.5 ± 0.2	6 ± 2
$(6173 \pm 4)^{(a),(c)}$	$237.2 \pm 0.2^{(a),(b),(d)}$	$213.7 \pm 0.2^{(b)}$	84 ± 10
		$173.6 \pm 0.1^{(b)}$	100 ± 9
$6122 \pm 9^{(a)}$	$283.5 \pm 0.1^{(a),(d)}$	283.2 ± 0.5	2 ± 1
		260.1 ± 0.1	100 ± 5
		219.9 ± 0.1	53 ± 6
		169.9 ± 0.2	99 ± 9
$6080 \pm 5^{(a)}$	$334.7 \pm 0.1^{(a)}$	334.7 ± 0.1	100 ± 6
		311.2 ± 0.1	31 ± 3
		271.0 ± 0.2	35 ± 4
$(5983 \pm 3)^{(a),(c)}$	$429.5 \pm 0.2^{(a),(d)}$	405.8 ± 0.2	77 ± 14
		357.7 ± 0.2	65 ± 14
		281.6 ± 0.2	100 ± 13
		202.3 ± 0.8	28 ± 20
$5828 \pm 6^{(a)}$	$587.9 \pm 0.3^{(a)}$	587.9 ± 0.3	53 ± 13
		524.2 ± 0.3	75 ± 17
		$440.6 \pm 0.7^{(f)}$	24 ± 8
		$361.3 \pm 0.3^{(g)}$	100 ± 14
		304.7 ± 0.2	40 ± 18
5738 ± 6	681.7 ± 0.5	681.7 ± 0.5	100

(a) Previously observed by α-decay.
(b) Previously observed by EC-decay of ^{208}Rn.
(c) No direct γ-transition to the g.s. observed, α-energy adopted from ref. [1] (if reported).
(d) Level energy calculated using energies from other levels.
(e) Previously observed in in-beam.
(f) Tentative.
(g) As (b) but with uncertain assignment.

A tentative level at 208 keV (no γ-rays at this energy were observed) is placed on the basis of α-energies observed in respective α-γ-coincidences and of a 40.1 keV energy difference between the transitions of 144.6 (probably feeding the level at 64 keV) and 184.7 keV (probably feeding the level at 24 keV). The 145 keV γ-rays were observed in coincidence with broad α-energy distributions at 6189±15 and 6228±5 keV ($\Delta E = 83$ and 35 keV FWHM respectively, a double-Gaussian fit was used although the structure of the "α-lines" may be more complex). The observed energy distribution can be explained by electron summing of converted 24 and 40 keV transitions resulting in

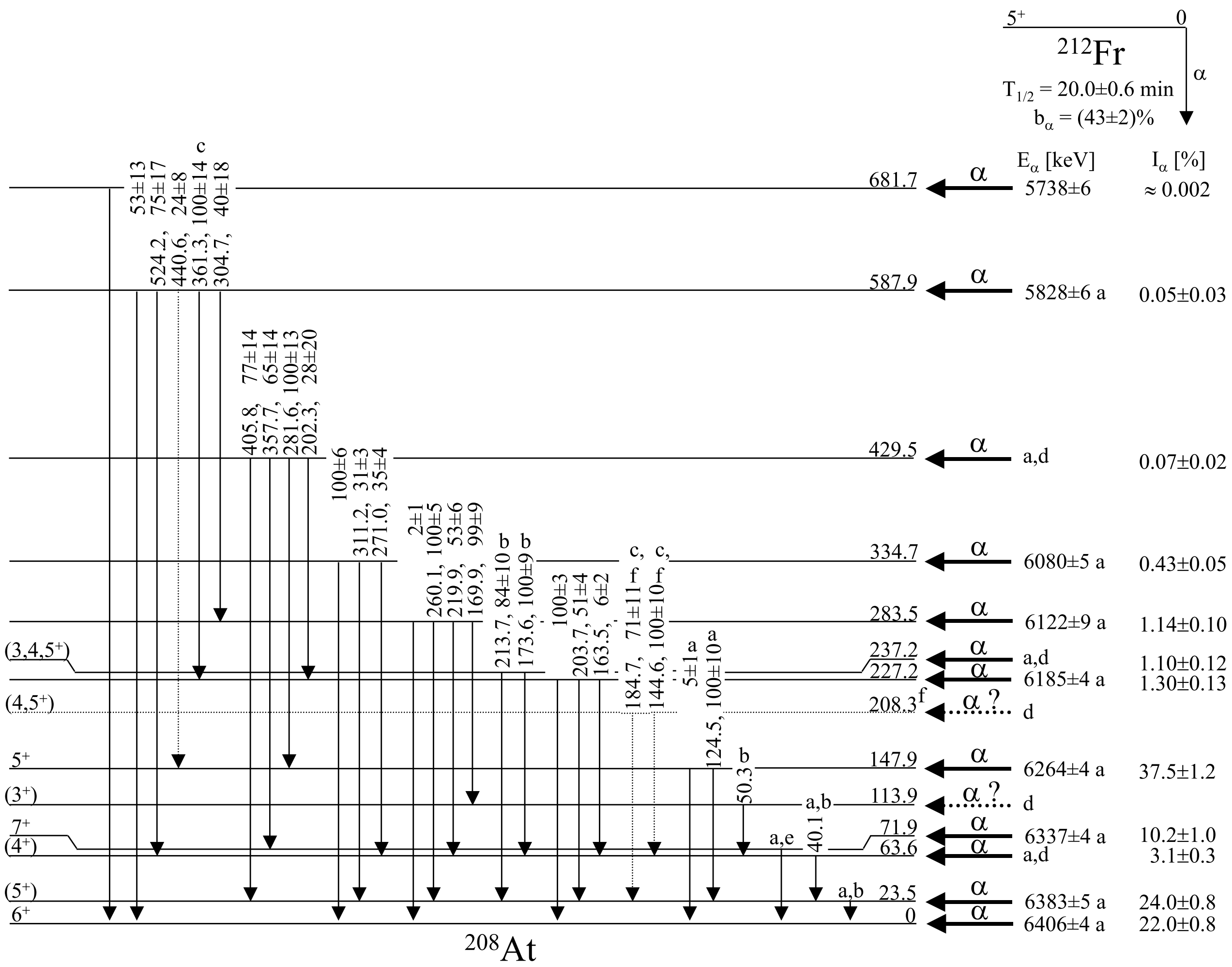

Fig. 4. The decay scheme of ^{212}Fr (the 5^+ g.s., half-life and α-branch are from ref. [1]) observed in the present work. Spins and parities, except for the level at 208.3 keV, and α-intensities are adopted from ref. [1], except for the level at 681.7 keV. [a] Previously observed in α-decay. [b] Previously observed in EC-decay of ^{208}Rn. [c] As [b] but with uncertain assignment. [d] No direct γ-transition to the g.s. observed. [e] Previously observed in in-beam. [f] Tentative.

broad distributions for detected α-particles. The 185 keV γ-rays were in coincidence with α-energies of 6209 ± 12 and 6225 ± 6 keV ($\Delta E = 39$ and 19 keV FWHM, respectively, a double-Gaussian fit was used although the real energy distribution may be more complex) with nearly equal relative intensities. The latter $Q_\alpha+E_\gamma$ value is equal to the g.s.–to–g.s. decay of ^{212}Fr and the narrow α-line suggests a direct transition to the g.s. However, sharp α-lines can also be expected from electron summing if the transition energy is small. This is evidenced by other transitions populating the level at 24 keV. Furthermore, the broad hump lower in energy suggests that the 185 keV transition populates a low-lying level and/or it is linked by converted transition(s) from the level(s) above close in energy.

Our interpretation is that both effects are present. This is supported by the lower part of the α-energy distributions gated by the 145 and 185 keV γ-rays, which are broader than one can expect from electron summing of the converted 24 and 40 keV transitions. Therefore, it seems probable that both the 145 and the 185 keV transitions are linked with transitions from the levels at 227 and/or 237 keV. Also, for the level at 208 keV (if existing) a number of α-γ-coincidences gated by the 145 and 185 keV γ-rays is comparable to that of the level at 237 keV. However, even in the most detailed α-decay intensity study of ^{212}Fr so far performed by Vakhtel *et al.* [12] no α-line at ≈ 6200 keV (corresponding to the level at 208 keV) was observed (see refs. [1,12] for details). Therefore, it seems that the 208 keV level is fed mainly from levels above and only a little if at all by α-decay. As the origin of the two γ-transitions is not fully understood, the level at 208 keV as well as the transitions of 145 and 185 keV are placed tentatively. For the 441 keV transition tentative assignment is due to a lack of statistics.

Spins and parities shown in fig. 4 are adopted from ref. [1]. However, the spin combination for the level at 208 keV is based on the $M1(+E2)$ transitions of 145 and 185 keV [13] probably feeding the $(4)^+$ and $(5)^+$ levels at

Table 4. Decay data of ^{213}Fr, levels and γ-transitions in the daughter nucleus ^{209}At with energy levels below 750 keV.

E_α (keV)	I_α (%)	HF	$E_{\text{level}}^{\text{daughter}}$ (keV)	E_γ (keV)	Multipolarity	I^π	Reference
6775.0 ± 1.7	100	1.32	0			$9/2^-$	[1]
			408.33 ± 0.03	408.32 ± 0.04	$E2$	$7/2^-$	
			577.10 ± 0.05	577.10 ± 0.05	$M1 + E2^{(a)}$	$(11/2^-)$	
			725.06 ± 0.06	725.05 ± 0.07	$E2$	$(13/2^-)$	
				148.00 ± 0.09	$M1$		
			745.78 ± 0.04	745.78 ± 0.04	$M1(+E2)$	$7/2^-$	
				337.45 ± 0.04	$M1$		
6775 ± 4	99.78 ± 0.17	1.4	0				this work
6378 ± 5	0.12 ± 0.03	28	408.2 ± 0.2	408.2 ± 0.2			
6211 ± 5	0.10 ± 0.03	6.6	577.1 ± 0.2	577.1 ± 0.2			

(^{a}) Mixing ratio $\delta = 0.83 \pm 0.08$ [1].

64 and 24 keV, respectively. In addition to the γ-rays explained above, we also observed α-γ-coincidences with a γ-ray energy of 244.4 ± 0.3 keV and a widely distributed α-energy ($E_\alpha \approx 6060$–6175 keV) suggesting that the transition occurs between the excited levels in ^{208}At. This is probably the same transition as observed in EC-decay of ^{208}Rn by Vasharosh *et al.* (see refs. [11,13]) with $E_\gamma = 244.31 \pm 0.04$ keV but with uncertain placement. Therefore it is probable that the 244 keV γ-rays are from the ^{212}Fr decay but the placement remains unclear.

3.5 ^{213}Fr

Griffioen and Macfarlane [6] identified ^{213}Fr with an α-energy of $E_\alpha = 6.77 \pm 0.01$ MeV and 33.7 ± 1.5 s half-life. Since then ^{213}Fr has been investigated, *e.g.*, by Valli *et al.* [7] and Hornshøj *et al.* [14], but so far only one α-branch for ^{213}Fr has been observed, while low-lying levels in the daughter nucleus ^{209}At are identified by γ-spectroscopy and EC-decay of ^{209}Rn (see ref. [1] and references therein). The results of our study of ^{213}Fr together with previously published low-lying levels in the daughter nucleus ^{209}At are listed in table 4 and the decay scheme of ^{213}Fr observed in the present work is shown in fig. 5.

Due to overlapping α-particle energies with ^{212}Fr the α-intensities were extracted indirectly from the α-γ-coincidences. As a result of relatively poor statistics we were able to extract α-intensities only for the g.s.–to–g.s. α-decay and for α-decays to the earlier published levels at 408.33 and 577.10 keV (energies are taken from ref. [1]). However, since in this case multipolarities for the 408 and 577 keV transitions are known ($E2$ and $M1 + E2$ with a mixing ratio $\delta = 0.83 \pm 0.08$ [1]) losses in γ-intensities due to internal conversion and thus also in α-intensities could be taken into account. The α-decay hindrance factors are calculated taking δ^2_{gs} as an average reduced width of ^{212}Rn and ^{214}Ra (data are taken from ref. [1]) assuming $\Delta\ell = 0$ for each α-decay.

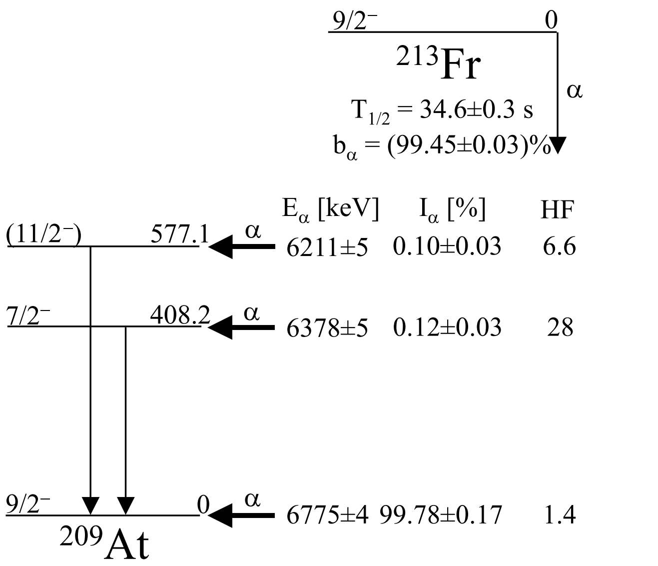

Fig. 5. The decay scheme of ^{213}Fr deduced from the present work. The spins, parities, half-life and α-branching ratio are from ref. [1].

3.6 ^{214}Fr

Griffioen and Macfarlane [15] identified ^{214}Fr. Since then several authors have investigated ^{214}Fr and its daughter nucleus ^{210}At by α-decay of ^{214}Fr and its isomeric state $^{214\text{m}}$Fr, EC-decay of ^{210}Rn and in-beam γ-spectroscopy of ^{210}At and ^{214}Fr (see refs. [1,16,17] and references therein). In the present work the decay of ^{214}Fr was studied using data from the 7.1 $A \cdot$ MeV bombardment. However, the ^{12}C on ^{209}Bi reaction favours xn- and pxn-evaporation channels, which results in low production rate for ^{214}Fr. Furthermore, our beam energy was optimized for the 5n channel. Therefore, the production rate for ^{218}Ac in the 3n channel was small. Also, the half-life of ^{218}Ac is only ≈ 1.1 μs [1]. So a large fraction of residues decay in-flight lowering the transmission for ^{218}Ac. Therefore, our

Table 5. α-γ-coincidence data for ^{214m}Fr.

E_α (keV)	$E_{\text{level}}^{\text{daughter}}$ (keV)	E_γ (keV)	$I_{\gamma,\text{rel}}$ (%)
8545 ± 5	0		
8472 ± 5	72.8 ± 0.2	72.8 ± 0.2	100
$(8058 \pm 6)^{(a)}$	$496.6 \pm 0.6^{(b)}$	496.6 ± 0.6	64 ± 18
		423.1 ± 0.6	100 ± 45
8046 ± 5	507.4 ± 0.2	507.4 ± 0.2	100 ± 11
		434.4 ± 0.6	10 ± 4
$(8024 \pm 6)^{(a)}$	$531.1 \pm 0.4^{(b),(c)}$	458.3 ± 0.3	100
$7979 \pm 5^{(d)}$	$576.7 \pm 0.3^{(d)}$	576.7 ± 0.3	100
$(7953 \pm 6)^{(a),(d)}$	$603.5 \pm 0.5^{(c),(d)}$	530.7 ± 0.4	100
7715 ± 5	846.9 ± 0.3	846.9 ± 0.3	100 ± 17
		774.7 ± 0.4	78 ± 21
7591 ± 15	966.2 ± 0.6	966.2 ± 0.6	100

(^{a}) Calculated from Q values.
(^{b}) Level is possibly not fed by α-decay.
(^{c}) Calculated using energies from other levels.
(^{d}) Previously probably observed as a doublet at 7963 ± 5 keV [1,18].

study was limited to verify the earlier results. Our data are listed in table 5.

Using α-γ-coincidences we were able to verify eight excited levels in the daughter nucleus ^{210}At, including three at 604, 847 and 966 keV with improved precision. While most of the levels are unambiguous on the basis of known energies for the observed α-γ-coincidences, those at 497, 531 and 604 keV need further discussion. The levels at 531 and 604 keV decay (at least) to the level at 73 keV while γ-transitions from these levels to the g.s. were not observed. It seems that the 497 keV level is not populated by α-decay of ^{214m}Fr, but observed γ-rays can be explained by internal conversion from levels at 507 and/or 531 keV.

For the level at 497 keV the population from the level(s) above is supported by α-particles in coincidence with 497 keV γ-rays, which peak at 8049 ± 9 keV with a width of 38 keV (FWHM). Both, the low energy as compared to the one calculated using the Q value, and a broad energy distribution indicate that the level is fed by internal conversion from the level(s) above close in energy. Using the Q values, α-energies for the levels at 507 and 531 keV are 8047 ± 5 and 8024 ± 5 keV, respectively. Therefore both levels could populate the level at 497 keV resulting in a broader energy distribution than expected for the g.s.–to–g.s. decay. Thus we cannot definitely conclude whether the level at 497 keV is populated by α-decay (of ^{214m}Fr) or by converted transitions from the level(s) above, but the α-energy distribution for the level at 497 keV is difficult to explain based on direct α-decay only.

The level at 531 keV was observed by α-γ-coincidences with known γ-ray energy at 458 keV populating the level at 73 keV [1,19]. From α-γ-coincidences gated by 458 keV γ-rays α-energies were scattered over energies between 8000 and 8100 keV peaking at around 8030 keV verifying the previous result. However, due to rather poor statistics we cannot definitely conclude whether the level at 531 keV is populated directly by α-decay or by internal conversion from the level(s) above.

The level at 604 keV was identified on the basis of γ-rays at 531 keV feeding the level at 73 keV. It is worth noticing that energies for the level at 531 keV and γ-rays from the level at 604 keV overlap within experimental accuracy. However, on the basis of the present data this happens by chance since, first, the α-energies gated by 458 and 531 keV γ-rays cannot result from the same level and, second, from EC-decay of ^{210}Rn studied in detail by Jonson *et al.* [19] the level at 531 keV was observed by 458 keV γ-rays populating the level at 73 keV but no indication of 531 keV γ-rays were observed, while in the present work the γ-rays at 458 and 531 keV were observed with nearly equal intensities. We also observed α-γ-coincidences at α- and γ-ray energies around 7950 keV and 73 keV, respectively, which further suggests a level at 604 keV energy.

The level at 604 keV is also supported by α-energies gated by γ-rays at 531 and 775 keV (the latter populates the level at 73 keV from the level at 847 keV). For both transitions we observed double humped α-energy distributions, which had identical shapes within statistical deviations, including similar energy differences ($\Delta E \approx 60$ keV) between the two humps. The structures of summing α-lines can be explained for the lower-energy part as resulting from summing of α-particles and escaped conversion electrons while the higher-energy part results from full summing of conversion/Auger electrons and X-rays. The intensity ratio between the two humps was consistent with the one expected from the highly converted 73 keV $M1$ transition ($\alpha_{\text{tot}} = 6.21$ [9]). Therefore, it seems probable that the level at 604 keV has a low spin since both states at 531 keV (having $(3)^+$ [1]) and 604 keV decay to the 4^+ state at 73 keV while γ-transitions to the 5^+ g.s. were not observed.

4 Discussion

4.1 ^{210}Fr

So far α-decay fine structure for the $N = 123$ isotones was observed only for ^{208}At [1]. The two low-lying levels in ^{204}Bi at 15.08 and 53.40 keV are populated by α-decay of ^{208}At and the level at 5.55 keV is possibly populated also by α-decay (see ref. [1] and references therein). Furthermore, the low-lying levels in ^{204}Bi were verified by Brabec *et al.* [20] employing conversion electron spectroscopy. On the basis of the low-lying levels observed in ^{204}Bi, Zelinski *et al.* [8] also assumed a low-lying level in the ^{206}At isotone. Our data supports this assumption, although only indirectly.

A worth noting result is the exceedingly small number of common γ-transitions observed in EC-decay of ^{206}Rn and α-decay of ^{210}Fr. In fact, from the data measured by Zelinski *et al.* and by us, the only common γ-ray energies are at 195 and 444 keV. However, this result is not surprising since levels in the daughter nucleus populated by α- and EC-decay are expected to be different due to the different nuclear structure of the mother nuclei. This is demonstrated, *e.g.*, by the difference in their g.s. spins with 0 and 6 for ^{206}Rn and ^{210}Fr, respectively.

Another striking result, also indicated prior to our study, is the small hindrance factor for the g.s.–to–g.s. α-decay of ^{210}Fr. The g.s. of ^{206}At and ^{210}Fr are $(5)^+$ [1,21] and 6^+ [1,22], respectively. For ^{206}At the g.s. spin was assigned by Lingeman [21] on the basis of β^+-branches feeding the 4^+ and 6^+ states in ^{206}Po with nearly equal log ft values. The g.s. spin of ^{210}Fr along with several other francium isotopes was measured by Ekström *et al.* [22] using an on-line atomic-beam magnetic-resonance technique. Therefore, the hindrance factor of around two for the 6^+ to $(5)^+$ α-decay seems surprisingly small.

One possible explanation is that in ^{206}At the level at 6 keV is the 6^+ state which is populated by α-decay and decays to the g.s. by internal conversion. This results in a summing α-line close to that of the g.s.–to–g.s. decay energy. Furthermore, as the energy of electrons is as small as a few keV, summing of electrons with α-particles does not necessarily result in broadening in α-lines but pushes the summing energy up, close to the value expected for the g.s.–to–g.s. α-decay energy. This would result in an α-line at the energy consistent to that extracted from α-γ-coincidences when γ-transition populates the g.s. directly.

Another explanation is that the g.s. of ^{206}At is 6^+ while the low-lying levels at 6 and 31 keV are, similar to the ^{204}Bi isotone, 5^+ and 4^+ states, respectively. However, this interpretation is not supported by the data of Lingeman [21]. Therefore, we want to remark that on the basis of the present data the low-lying levels in ^{206}At are not understood but need further studies.

4.2 ^{211}Fr

Fine structure α-decay data for the odd-proton $N = 124$ isotones are scarce (data are available only for ^{211}Fr) and for the $N = 122$ isotones level energies are reported only for ^{205}Bi and ^{207}At [1]. This is illustrated in fig. 6 where the decay schemes of the odd-proton $N = 124$ isotones are shown. Furthermore, the α-branch of ^{209}At (to ^{205}Bi) is only $(4.1\pm0.5)\%$ [1]. Therefore, assuming that the g.s.–to–g.s. transition takes up $> 99\%$ of the total α-intensity as in ^{211}Fr, it seems justified to extend the α-decay systematics to the heavier $N = 124$ isotones.

One also notes that α-decay hindrance factors for the decay of ^{211}Fr are in line with the odd-proton even N isotones observed in this region of nuclei (see, *e.g.*, ^{213}Fr and ^{215}Ac [2]). However, it seems that internal conversion takes up a relatively large fraction of the 344.5 keV γ-rays since the hindrance factor of 120 for α-decay between the $9/2^-$ and $7/2^-$ states is rather large. Therefore the reported mixing ratio of $\delta = 3^{+2}_{-1}$ [1] with the theoretical total conversion coefficients of $\alpha_{\rm tot}(M1) = 0.402$ and $\alpha_{\rm tot}(E2) = 0.0917$ [9] may be overestimated, although the error bars are large. This is also the case for the $11/2^-$ to $9/2^-$ g.s. transition at 643.9 keV ($M1 + E2$ for which the mixing ratio is not reported, see ref. [1]) since, on the basis of the $N = 126$ isotones, the hindrance factors for the yrast $11/2^-$ and $13/2^-$ states can be expected to be nearly equal.

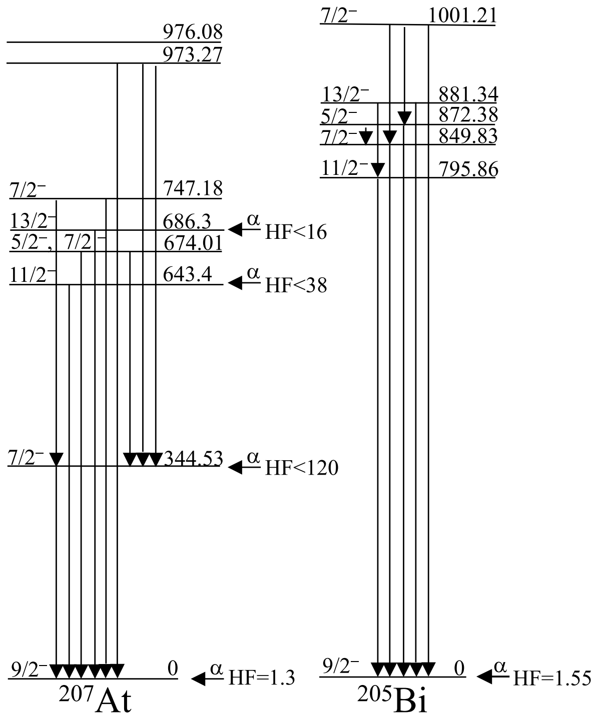

Fig. 6. Partial level schemes of the isotones ^{207}At (α-decay data are taken from the present work and other data from ref. [1]) and ^{205}Bi (data are adopted from ref. [1]). Observed α-decays populating different levels are indicated by horizontal arrows. The hindrance factor (HF) for the ^{209}At decay to ^{205}Bi is adopted from ref. [1] and the HFs for the ^{211}Fr decay to ^{207}At are calculated assuming $\Delta\ell = 0$ for each α-decay.

4.3 ^{212}Fr

So far the most detailed data for low-lying levels (below the yrast 8^+ state at 788.1 keV) in ^{208}At was determined on the basis of α-decay and α-γ-coincidences of ^{212}Fr and EC-decay of ^{208}Rn (see ref. [11,13] and references therein). Furthermore, the yrast 7^+ state at 71.7 keV was verified by in-beam spectroscopy [11,23].

In the present work we were able to extend the decay scheme of ^{212}Fr. However, due to a lack of statistics we were not able to extract conversion coefficients. Therefore, even if we identified and verified several transitions in ^{208}At, the spin and parity assignments are based on the earlier published data. An exception is the (tentatively) placed level at 208 keV which seems to decay by the 145 and 185 keV transitions. On the basis of similar γ-ray energies and relative intensities the two transitions are probably those observed in the EC-decay of ^{208}Rn by Vasharosh *et al.* [13]. Furthermore, the two transitions are probably directly connected since EC-decay of ^{208}Rn and α-decay of ^{212}Fr populates different levels in the daughter nucleus ^{208}At with different intensities. Both transitions are reported as $M1(+E2)$ transitions with mixing ratios of $\delta_{144.6\ \rm keV} \le 0.90$ and $\delta_{184.7\ \rm keV} \le 0.88$ [11,13]. Therefore, the state at 208 keV can have spin and parity of 4^+ or 5^+.

One also notes that the sum of the 184.7 ± 0.1 keV transition and the unplaced 244.4 ± 0.3 keV transition (see sect. 3.4) is close to that of the level at 429.5 ± 0.2 keV. This would suggest a level at 184.7 keV. However, on the basis of precisely (within 0.05 keV) measured γ-ray energies for the two transitions by Vasharosh *et al.* [13], one concludes that the level energy for the state at 429.5 keV does not equal the sum within experimental accuracy. This and a lack of evidence for the 329.3 keV level (the sum of 144.6 and 184.7 keV) further support the level at 208 keV.

Two more γ-ray energies observed in the EC-decay of ^{208}Rn overlapping with transitions observed in the present work are at 163.5 and 169.9 keV from the levels at 227 and 284 keV, respectively. However, it seems unlikely that the two transitions are those observed in EC-decay of ^{208}Rn, although the energies are rather similar (163.2 ± 0.4 and 169.7 ± 0.5 keV in ref. [13], 163.5 ± 0.2 and 169.9 ± 0.2 keV in the present work). For the 163.5 keV transition this is due to non-observed γ-rays at 203.7 and 227.2 keV (from the level at 227 keV) in EC-decay of ^{208}Rn even though, on the basis of the present data, those have higher relative intensities than that of 163.5 keV.

The situation for the 169.9 keV transition from the level at 283.5 keV is rather similar to that of 163.5 keV since in the EC-decay of ^{208}Rn γ-rays at 169.7 ± 0.5 and 259.649 ± 0.033 keV [13] were observed. The latter energy is close to that of the 260.1 ± 0.1 keV transition from the same level observed in the present work. However, the intensity ratio between the 169.9 and 260.1 keV γ-transitions observed in EC-decay of ^{208}Rn and α-decay of ^{212}Fr are very different. In the present work γ-transitions were observed with equal intensities while in EC-decay of ^{208}Rn the intensity of the 259.6 keV γ-rays was a factor of four higher than that of 169.7 keV. Therefore it seems that the two transitions are not the same although they have nearly equal energies. Based on the present data it is also unlikely that the levels at 227 and 284 keV are populated by EC-decay of ^{208}Rn.

On the basis of our α-γ-coincidence measurements we conclude that the 2^+ state at 173.76 keV is not populated by α-decay of ^{212}Fr. We also cannot conclude that the 3^+ state at 113.79 keV is populated by α-decay. The 50.09 keV $M1(+E2)$ transition from the level at 113.79 keV [13] is probably due to feeding from the level at 284 keV by the 169.9 keV transition. It is also interesting to note that the level at 284 keV populates all four states with spin 3^+ to 6^+. On the basis of relative γ-ray intensities from this level, the weak transition to the g.s. ($I_{\gamma,\mathrm{rel}} = (2 \pm 1)\%$) is probably $E2$ while the others are $M1$ or $M1+E2$ transitions. This suggests that the state at 284 keV is the 4^+ state. However, due to the absence of internal-conversion data our interpretation lacks concrete evidence. Therefore, we leave these assignments for future studies.

4.4 ^{213}Fr

The low-lying levels in the odd-proton $N = 124$ isotones ^{207}Bi, ^{209}At, ^{211}Fr and ^{213}Ac have been identified and, except for ^{209}At, α-decay to some of these states has also been observed (see refs. [1,2,24] for details). However, we could identify only two levels above the g.s. populated by α-decay. These were the $7/2^-$ and $11/2^-$ states at 408.33 and 577.10 keV [1], respectively. The α-decay hindrance factors of ≈ 10 and ≈ 30 for the $11/2^-$ and $7/2^-$ states, respectively, are in line with those of the neighbouring isotones ^{207}Bi and ^{211}Fr. The absence of the $13/2^-$ state at 725.06 keV [1] in our decay data can be explained on the basis of an unfavourable Q value resulting in weak α-intensity. The $13/2^-$ level has also not been observed in the α-decay of ^{211}At to ^{207}Bi [1]. One also notes that, on the basis of the ^{211}Fr isotope, the α-decay hindrance factors for the $11/2^-$ and $13/2^-$ levels can be expected to be nearly equal. This provides an estimate for the α-intensities of the $13/2^-$ levels in the $N = 126$ isotones.

4.5 ^{214}Fr

Prior to the present study the decay schemes of $^{214\mathrm{g}}$Fr and $^{214\mathrm{m}}$Fr, and the low-lying levels in the daughter nucleus ^{210}At were already well established. Nevertheless our α-γ-coincidence studies, although incomplete, still provide new information on the low-lying levels in ^{210}At. Unfortunately our attempt to extract the transition multipolarities failed due to the lack of statistics.

One also notes that the levels populated by α-decay of $^{214\mathrm{g}}$Fr and $^{214\mathrm{m}}$Fr are different (see ref. [1] for details). As shown, for example, by Torgerson and Macfarlane [25], direct production of ^{214}Fr favours the isomeric state while $^{214\mathrm{g}}$Fr is produced with high yield via α-decay of short living ^{218}Ac ($T_{1/2} \approx 1.1$ μs, $b_\alpha = 100\%$ [1]). In the present work all α-γ-coincidences of ^{214}Fr were assigned to the isomeric state, which suggests a production by ^{209}Bi(^{12}C, α3n)^{214}Fr reaction rather than a production by α-decay of ^{218}Ac (see also sect. 3.6). Therefore, a complete decay study of ^{214}Fr needs investigation of two different reactions.

Another interesting detail in ^{214}Fr are the spins of the isomeric pair. Based on the lighter odd-proton $N = 127$ isotones these were interpreted to be 1^- and 9^- for $^{214\mathrm{g}}$Fr and $^{214\mathrm{m}}$Fr [18,26], respectively. However, Byrne *et al.* [17] proposed the isomeric state to be 8^- instead of 9^- based on an in-beam study of ^{214}Fr and shell model arguments. Therefore, as spins and parities for several levels in ^{210}At remain unknown or uncertain as well as the spin of the isomeric state in ^{214}Fr, it seems that further studies are needed for both nuclei.

5 Conclusion

An efficient separation technique combined with sensitive α-particle and γ-ray detection provides a powerful tool to probe nuclear structure. In addition to yrast states, in some cases α-decay populates non-yrast states which are not fed by EC/β-decay or de-excitation of compound nuclei. However, the technique has its limitations. Its efficiency is low for transitions with low energies (≤ 50 keV) for which internal conversion results in severe losses in a number of γ-rays. For the investigation of these transitions planar Ge-detectors or Si(Li)-detectors permitting also the registration of conversion electrons are more suited.

Among the nuclei studied in the present work, this is particularly the case for the low-lying levels in ^{206}At. This is due to overlapping α-energies with the neighbouring ^{209}Fr and low excitation energies of the lowest-lying levels. Therefore, in order to verify the tentatively assigned low-lying levels in ^{206}At, one needs an electron spectroscopy study, *e.g.*, similar to that of Brabec *et al.* [20] for the ^{204}Bi isotone.

Despite the physical limitations in low-energy transitions, the α-γ-coincidence technique is a powerful tool for detailed spectroscopy when transition energies are high enough. Another advantage is that the emission of γ-rays rules out internal conversion while the emission of X-rays verifies it. Therefore, structures of "artificial" and complicated "α-lines" resulting from electron summing can be studied in detail. While often the interpretation of such events is difficult if based on "α-energies" only, they can be understood better using α-γ-coincidences.

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