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Alpha-gamma decay studies of ^{255}Rf, ^{251}No and ^{247}Fm

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Abstract. The decay of the isotopes ^{255}Rf, ^{251}No and ^{247}Fm produced in the reactions $^{207}\mathrm{Pb}(^{50}\mathrm{Ti},2\mathrm{n})^{255}\mathrm{Rf} \xrightarrow{\alpha} {}^{251}\mathrm{No} \xrightarrow{\alpha} {}^{247}\mathrm{Fm}$, and $^{206}\mathrm{Pb}(^{48}\mathrm{Ca},3\mathrm{n})^{251}\mathrm{No} \xrightarrow{\alpha} {}^{247}\mathrm{Fm}$ was investigated by means of α-γ spectroscopy. Previously observed γ transitions in coincidence with α decays of ^{255}Rf were confirmed, their energies and line intensities were measured more precisely, and their multipolarities were determined as $E1$. In ^{251}No a new isomeric state at $E^* > 1700$ keV with a half-life of $\approx 2\,\mu$s was identified. The decay of ^{247}Fm was measured more precisely. A partial level scheme of the daughter nucleus ^{243}Cf could be established.

PACS. 23.60.+e α decay – 27.90.+b $220 \leq A$ – 21.10.-k Properties of nuclei; nuclear energy levels

1 Introduction

For many years studies of fine structure in the α decay had been practically the only source of information on the nuclear structure of transfermium isotopes. Technical progress resulting in higher beam intensities from accelerators, in higher efficiencies of electromagnetic devices for separation of the reaction products in-flight, and improvements of detector systems for simultaneous measurement of various decay modes of the produced nuclei opened up a new field of research during the past years, which was mainly concentrated in the region of deformed nuclei around $Z = 102$ and $N = 152$ [1,2]. Certainly, the number of particles (α, conversion electrons) or photons detected in experiments of typically several days to two weeks duration is considerably lower than those obtained in studies of somewhat lighter nuclides where the investigated isotopes had been produced by breeding in a nuclear reactor (see, *e.g.*, [3]) or in reactions using light projectiles having orders-of-magnitude higher cross-sections (see, *e.g.*, [4]). Nevertheless, the results obtained within the last years can be regarded as a breakthrough in the direction of nuclear-structure investigations of superheavy nuclei. Experiments performed so far may be divided into three categories. The first one may be characterized as in-beam studies, suited to investigate the decay of short-lived states in evaporation residues populated by de-excitation of the compound nucleus. The second one may be denoted as investigation of isomeric states having lifetimes long enough to survive in-flight separation from the primary beam, which is typically 1–2 μs. Since it has been found recently that the decay of such isomeric states can also populate rotational bands that have also been observed in in-beam studies, these methods can be regarded as at least partly complementary [5,6].

The third category is α-γ spectroscopy from the decay of the ground state or isomeric states. Since, in general, α decay populates only low-lying states with sufficient intensity, these experiments were performed so far for delivering information on single-particle levels in odd-mass nuclei at $E^* < 500$ keV. In this way, we could establish trends in single-particle level energies for odd-mass einsteinium isotopes produced by α decay of mendelevium precursors [7] and for even-Z isotopes with $N = 145$, 147 and 149 up to $Z = 102$ [8]. In recent studies the decay of ^{255}Rf [9], ^{253,251}No [8] and their α decay daughter nuclides was investigated. Although a couple of new results were presented, the conclusions remained partly specula-

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Table 1. Summary of beam parameters and reactions used for the production of ^{251}No and ^{255}Rf.

Projectile	Target (% enrichment)	Evaporation residue	E_{proj}/AMeV	I/pμA[1]	ϵ_{SHIP}[2]	σ/nb
^{48}Ca	^{206}Pb (98.6)	^{251}No	4.80	0.8	0.4	30
^{50}Ti	^{207}Pb (92.4)	^{255}Rf	4.85	0.33	0.4	10

[1] Average beam intensity.

[2] Calculated value of the separator efficiency.

tive due to the relatively low number of observed decays. Therefore, new experiments were performed aiming at a collection of about five to ten times more decays than previously recorded.

New or improved results for ^{255}Rf, ^{251}No, and ^{247}Fm will be presented in this paper.

2 Experiment

The experiments were performed at GSI, Darmstadt. A beam of ^{48}Ca was delivered by the high-charge state injector with ECR-ion source of the UNILAC accelerator, while the ^{50}Ti beam was delivered from the PIG ion source. Beam parameters and reactions used to produce the investigated nuclides are given in table 1.

The targets were prepared from isotopically enriched material of ^{206}PbS and metallic ^{207}Pb. Layers of 350–450 μg/cm^2 total thickness were evaporated on carbon foils of 40 μg/cm^2 (positioned upstream), which were then covered by evaporation of 5–20 μg/cm^2 carbon. We used ^{206}PbS instead of metallic ^{206}Pb because this compound was found to withstand better highest beam currents due to its higher melting point [10]. The targets were mounted on a wheel which rotated synchronously to the beam macro structure [11] (5 ms wide pulses at 50 Hz repetition frequency). Beam intensities were typically 800–1000 pnA for ^{48}Ca and 300–350 pnA for ^{50}Ti.

The evaporation residues leaving the targets with kinetic energies of ≈ 40–50 MeV were separated from the primary beam by the velocity filter SHIP [12]. In the focal plane of SHIP they were implanted into a position-sensitive 16-strip PIPS detector ("stop detector") with an active area of 80 × 35 mm^2 [13] for measuring the kinetic energies of the residues as well as subsequent α decays [14,15]. Gamma rays emitted in prompt or delayed coincidence with α decays were measured using a clover detector consisting of four Ge crystals (70 mm ⌀, 140 mm length), which were shaped and assembled to form a block of 124 × 124 × 140 mm^3.

Further details concerning experimental procedures and methods of data analysis (γ calibrations, efficiency estimations, coincidence conditions, determination of multipolarities of electromagnetic transitions, etc.) are described in detail in previous publications [8,16,17] and shall not be repeated here. Concerning the accuracy of α energies we want to point out that we regard our absolute energies reliable within ±15–20 keV due to three sources of errors: a) a systematic error of ±15 keV due to the accuracy of the literature values used for calibration, b) the accuracy of the calibration, *i.e.* the reproducibility of a given α energy by the linear calibration functions used for the individual detector strips ("detector alignment"); this error is typically ±3 keV; c) the accuracy of the estimation of the peak position, which essentially depends on the detector resolution and the number of observed decays; it typically varies within ±1–10 keV. Energy differences from decays of or into different levels etc. are in general precise within 5–10 keV, since they depend only on error types b) and c). Therefore errors given in the discussion include only the latter ones.

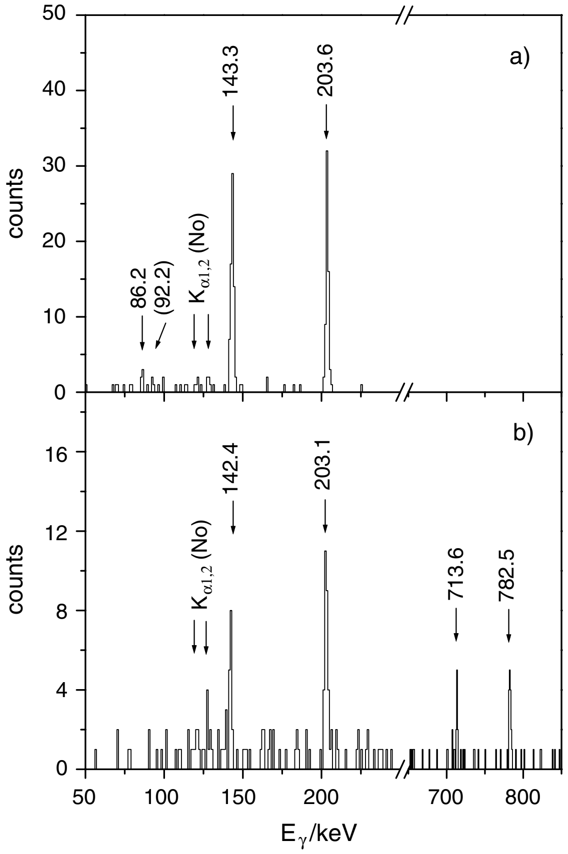

Fig. 1. Gamma-spectra observed in coincidence with a) α decays of ^{255}Rf and b) evaporation residues (Δt (ER-γ) $< 4\,\mu$s) followed by the α decay of ^{251}No.

3 Experimental results and discussion

3.1 Decay of ^{255}Rf

In our previous study two γ transitions had been observed in coincidence with α decays of ^{255}Rf [9]. The

Table 2. Summary of decay data of ^{255}Rf, ^{251,251m1,251m2}No, and ^{247,247m}Fm.

Isotope	E_α/keV[1]	i_{rel}	HF	E^*/keV[2]	E_γ/keV	i_{rel}(trans)[3]	$T_{1/2}$/s
^{255}Rf	8906 ± 8[3]	0.025 ± 0.010	1344				1.68 ± 0.09
	8716 ± 4	0.92 ± 0.05	2.4		143.3 ± 0.2	0.51 ± 0.06	
					203.6 ± 0.2	0.49 ± 0.06	
	8678 ± 8[4]	0.03 ± 0.01	56				
	8646 ± 5[4]	0.015 ± 0.005	90				
	8575 ± 5[4]	0.01 ± 0.005	80				
^{251}No	8612 ± 4	≈ 0.98	1.3				0.80 ± 0.01
	8571 ± 7[4]	≈ 0.005	191				
	8562 ± 7	≈ 0.003	266				
	8552 ± 8[4]	≈ 0.01	82				
	8524 ± 8[4]	≈ 0.005	132				
^{251m1}No	8668 ± 4	≈ 0.98	1.1	106 ± 6			1.02 ± 0.03
	8625 ± 10	≈ 0.02	53				
^{251m2}No				(> 1700)	142.4 ± 0.5		$\approx 2 \times 10^{-6}$
					203.1 ± 0.5		
					713.6 ± 0.5		
					782.5 ± 0.6		
^{247}Fm	7824 ± 10		1		166.6 ± 0.2		31 ± 1
					141.8 ± 0.2		
					121.8 ± 0.2		
					82.2 ± 0.2		
^{247m}Fm	8172 ± 5		2.1	45 ± 7			5.1 ± 0.2

[1] Error bars include the uncertainty of the peak position estimation only and not systematic errors due to uncertainties in the energies of α lines used for calibration (see text for details).

[2] Excitation energy of the isomeric states; values are rounded.

[3] Relative decay of the level including also conversion.

[4] Tentative lines.

aim of the new study was to confirm these results, establish the assumed multipolarity of the transitions and to search for weaker γ transitions. The γ spectrum observed in coincidence with α decays is shown in fig. 1a and data are listed in table 2. Besides the strong transitions at $E_\gamma = 203.6\,\mathrm{keV}$ and $E_\gamma = 143.3\,\mathrm{keV}$, four weaker groups at 86.2 keV (5 events), 92.2 keV (3 events), 121.2 keV (4 events) and 127.4 keV (5 events) are indicated. Analysis of the γ background in the energy interval 60–140 keV resulted in probabilities $p = 0.73$, 0.10 and 0.01 to observe three, four or five events in a 2 keV bin due to statistical fluctuation of the background. Thus, it seems justified to regard the "line" at 86.2 keV as a "real" one, while that at 92.2 keV apparently is not statistically significant. The lines at 121.2 keV and 127.4 keV agree with the values expected for the $K_{\alpha 2}$ (120.95 keV) and $K_{\alpha 1}$ (127.36 keV) X-ray energies of nobelium. Thus, the concentration of counts around 121 keV is considered as real lines.

Similar to cases in the neighbouring $N = 151$ isotones ^{253}No [8] and ^{251}Fm [4] the lines at 203.6 keV and 143.3 keV are interpreted as transitions from the $9/2^-$[734] level in the daughter nucleus ^{251}No, populated by the α decay, into the $7/2^+$[624] ground state and into the $9/2^+$ member of the rotational band built up on it. In lighter $N = 149$ isotones notable intensities for transitions into the $11/2^+$ member were observed. This level is located at 120–130 keV. So it seems straightforward to assign the 86.2 keV line as the transition into the $11/2^+$ level in ^{251}No, and one obtains an excitation energy of 117.4 keV, which is somewhat lower than in the other $N = 149$ isotones. However, the $11/2^+$ level is expected to decay via two highly converted $M1$ transitions $11/2^+ \overset{IC}{\to} 9/2^+ \overset{IC}{\to} 7/2^+$ into the ground state. It has been shown in our decay study of ^{253}No that in this case the corresponding α energies are strongly influenced by energy summing with conversion electrons and distributed in an interval of $\Delta E \approx 150\,\mathrm{keV}$ [8]. For the transition here, however, we observe a quite "narrow" distribution within an interval $\Delta E = 35\,\mathrm{keV}$ with a mean value of 8710 keV, *i.e.* the energy distribution does not show the behavior expected for the $9/2^-[734] \to 11/2^+$ transitions followed by two steps of internal conversion into the $7/2^+$[624] ground state. So we presently hesitate to attribute this line to the transition into the $11/2^+$ state.

Conversion coefficients (or upper limits) for the 203.6 keV and 143.4 keV transitions were determined as

Table 3. Conversion coefficients and relative intensities for the γ transitions in ^{251}No following the α decay of ^{255}Rf. The conversion coefficients given in columns 6–11 are theoretical values from [18].

E_α/keV	E_γ/keV	$i_{\gamma,rel}$	α_K (exp)	$\alpha_L+\alpha_M$ (exp)	α_K ($E1$)	$\alpha_L+\alpha_M$ ($E1$)	α_K ($E2$)	$\alpha_L+\alpha_M$ ($E2$)	α_K ($M1$)	$\alpha_L+\alpha_M$ ($M1$)
8720 ± 20	203.6 ± 0.2	0.94 ± 0.05	< 0.088	< 0.1	0.04	0.01	0.09	0.22	1.4	0.46
	143.4 ± 0.2	1		< 0.25	0.07	0.017	0.125	0.61	3.9	0.9

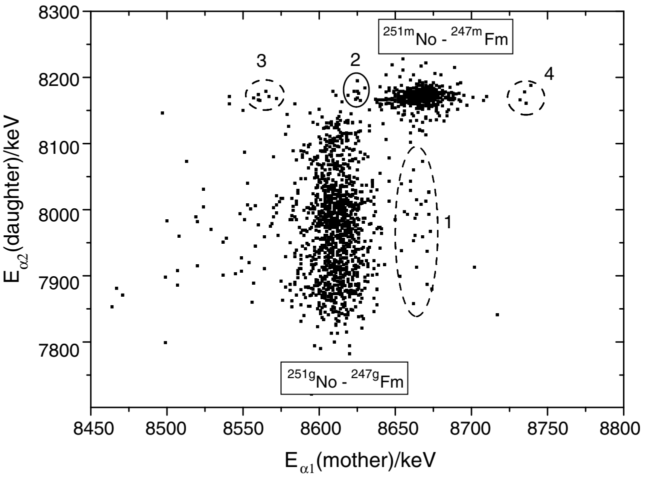

Fig. 2. Alpha-alpha correlation plot for evaporation residues from ^{48}Ca + ^{206}Pb at $E_{lab} = 4.80$ AMeV; the groups denoted by numbers 1–4 are discussed in the text.

described in [8,17] and are listed in table 3. The values clearly establish $E1$ multipolarity.

Search for fine structure in the α decay of ^{255}Rf did not show clear results, which obviously is due to the problem of identifying α lines of low intensity located slightly below strong ones, because of several reasons: a) the corresponding transitions may populate levels that decay predominantly by internal conversion; therefore the α energies are shifted towards the "main" line by energy summing with conversion electrons; b) a small part of α-particles (from the "main" line) escapes the stop detector with low residual energies. Their energy loss in the stop detector produces a tail of the "main" line towards lower energies; c) it is known that Si detectors suffer from radiation damage after some time of irradiation with heavy nuclei, leading to an increase of leakage current and thus to a degradation of energy resolution. To our experience already in the "early" stage of radiation damage a slight broadening of the basis of a line occurs. Statistical fluctuations of count rates in different energy bins may then, in conjunction with b), c) and small deviations of the energy calibrations of the individual detector strips ($\leq \pm 5$ keV), create indications of weak lines, which normally are not reproducible in different experimental runs.

The results of our analysis of ^{255}Rf α decays are presented in table 2. The maximum measured α decay energy of 8906 ± 8 keV is lower than the sum of the transition having $E_\alpha = 8716 \pm 4$ keV and the following γ decay into the ground state, $E_\gamma = 203.6$ keV. Also the hindrance factor is considerably lower than the values obtained in decay studies of the lighter $N = 151$ isotones ^{251}Fm, ^{249}Cf and ^{247}Cm for the decay into the daughter ground state, which are HF = 3800–8700 [19]. The line therefore hardly represents the "pure" ground-state–to–ground-state transition, but rather a mixture with sum events from the 8716 keV transition and L, M conversion electrons. The hindrance factor of the 8678 keV transition is in-line with values typically for decays into the $11/2^-$ member of the band built up on the $9/2^-$[734] level, but the energy difference to the transition into the bandhead is only 35 keV, while it is typically around 50 keV for lighter isotones [19]. This behavior may be due to energy summing with conversion electrons. Hindrance factors and intensities for the 8646 keV and 8575 keV transitions are comparable to the values obtained for transitions into the $7/2^-$[743] level and the $9/2^-$ band member in the decay of ^{251}Fm and ^{249}Cf [19]. The energy difference of 68 keV is somewhat larger than the value of 59 ± 1 keV observed in the lighter isotones, which may be due to the limited accuracy of α energy measurement for lines of low intensity. In summary, although all the lines reported earlier could be reproduced and an indication for a new line at 8646 keV was found, according to the discussion above we still consider them as tentative.

3.2 Decay of ^{251}No

In our previous study we observed the α decay from two levels in ^{251}No, produced in the reaction ^{206}Pb(^{48}Ca, 3n)^{251}No [8]. Both transitions were characterized by "narrow" α lines, which excluded energy summing with conversion electrons, and the lack of γ-rays in prompt coincidence with α-particles. It was thus concluded that the transitions populate the ground state and an isomeric state in ^{247}Fm, and that the latter nearly exclusively decays by α emission. In the present study, about a factor of fifteen higher number of decays was measured. As well in "prompt" coincidence as in "delayed" coincidence (Δt = 15–300 μs) with α decays of ^{251m,251g}No only a small number (16 and 13, respectively) of γ events (E = 20–1000 keV) were observed. They are regarded as random coincidences, as they did not show indication for one or more γ lines.

The higher number of observed decays also enabled a more detailed search for both, fine structure in the α decay of ^{251g,251m}No and decay of ^{247m}Fm by internal transitions. A plot of observed α-α correlations is shown in fig. 2. In case of weak transitions, however, one has to consider that ambiguities may arise from random correlations. The probability for random correlations was obtained from the numbers of ^{251g,251m}No decays and their mutual chance correlations. On this basis we expected random correlation probabilities of $(4.1 \pm 2.0) \times 10^{-4}$ for correlations $\alpha_1(^{251g}\text{No})$-$\alpha_2(^{247m}\text{Fm})$ within a time interval $\Delta t = 50\,\text{s}$, and $(2.4 \pm 1.1) \times 10^{-3}$ for correlations $\alpha_1(^{251m}\text{No})$-$\alpha_2(^{247g}\text{Fm})$ within a time interval $\Delta t = 150\,\text{s}$. The time intervals were set at $5 \times T_{1/2}$ of ^{247m}Fm and ^{247g}Fm, respectively. The observed probabilities are $(5.3 \pm 3.1) \times 10^{-4}$ and $(28 \pm 5) \times 10^{-3}$, *i.e.* in case of $\alpha_1(^{251g}\text{No})$-$\alpha_2(^{247m}\text{Fm})$ correlations the observed rate can be explained as random, while in the case of $\alpha_1(^{251m}\text{No})$-$\alpha_2(^{247g}\text{Fm})$ correlations the observed rate is an order of magnitude higher. We attribute it to a notable decay branch b_{IT} of ^{247m}Fm by internal transitions. On the basis of the observed numbers of correlations $\alpha_1(^{251m}\text{No})$-$\alpha_2(^{247m}\text{Fm})$ and $\alpha_1(^{251m}\text{No})$-$\alpha_2(^{247g}\text{Fm})$ (group 1 in fig. 2) we obtained a value $b_{IT} = 0.12 \pm 0.02$, considering an α branching of $b_\alpha = 0.64$ for ^{247g}Fm as obtained in this experiment. In addition to the cases discussed above which referred to the "main" α lines three more groups of correlations are indicated in fig. 2. Group 2 is located close to the region of random correlations $\alpha_1(^{251g}\text{No})$-$\alpha_2(^{247m}\text{Fm})$, but a detailed analysis shows that the energy of the mother decays is $E_\alpha = 8625 \pm 10$ keV and hence higher than that for the main line of ^{251g}No. It is thus tentatively assigned to ^{251m}No. Group 3 in fig. 2 is located at $E_{\alpha 1} = 8563\,\text{keV}$, $E_{\alpha 2} = 8167\,\text{keV}$ and has a half-life of $T_{1/2} = 0.6^{+0.3}_{-0.2}\,\text{s}$. The origin of the α line may be twofold: a) decay of the isomeric state into an excited level above the isomer in ^{247m}Fm, which requires another low-spin state, since the de-excitation of this level must predominantly feed the isomeric state; b) α decay from the ground state of ^{251}No into the isomer ^{247m}Fm, which would fix the energy of the isomeric state at $E^* \approx 50\,\text{keV}$, in agreement with the result from the decay study of ^{247g,247m}Fm (see sect. 3.3). Tentatively, we prefer the latter interpretation since the half-life agrees rather with that of ^{251g}No than with that of ^{251m}No, although this cannot be regarded as a proof due to the large error bars for the 8563 keV transition and the similar values for ^{251g}No and ^{251m}No. From the differences of the Q-values $Q_\alpha(^{251m}\text{No}\text{-}^{247m}\text{Fm}) - Q_\alpha(^{251g}\text{No}\text{-}^{247m}\text{Fm})$ we obtain for ^{251m}No an excitation energy $E^* = 106 \pm 6$ keV.

A small decay branch with an energy of $E_\alpha = 5370.3\,\text{keV}$ ($i_{rel} = 0.0002$) into the $1/2^+[631]$ level of ^{241}Pu at $E^* = 161.68\,\text{keV}$ is reported for the $N = 149$ isotone ^{245}Cm, resulting in a hindrance factor of 5950 [20, 19], while we obtain for the above-mentioned transition a much lower value of 267. However, another weak α transition of $E_\alpha = 5370.8\,\text{keV}$ ($i_{rel} = 0.0026$) feeding the (assumed) $11/2^+$ member of the rotational band built up on the ground state ($E^* = 161.314\,\text{keV}$) is reported for ^{245}Cm. The hindrance factor for this transition is 270 [20, 19]. Although the energy difference of these levels is only 0.37 keV, they could be discriminated on the basis of γ-rays connected to their decay. The $1/2^+[631]$ level was found to be isomeric with a half-life of 0.88 ± 0.5 μs decaying into the ground state via a 161.4 ± 0.2 keV $E2$ transition [21], while a 65.36 keV γ was attributed to the decay of the $11/2^+$ level into the $9/2^+$ member of the rotational band built up on the ground state [22]. Alpha decays into both levels were observed as an unresolved line doublet. Their relative intensities were evaluated numerically from intensity balances at both levels [20]. This procedure, however, may exhibit uncertainties leading to an underestimation of the decay intensity into the $1/2^+$ level and hence to an overestimation of the hindrance factor. So there might be no striking discrepancy for ^{251}No and ^{245}Cm.

The last group of correlations (denoted by 4 in fig. 2) is characterized by $E_{\alpha 1} = 8734 \pm 5\,\text{keV}$, $E_{\alpha 2} = 8174 \pm 10\,\text{keV}$ and $T_{1/2} = 0.50^{+0.30}_{-0.14}$ s. The α energies do not suggest an assignment of $E_{\alpha 1}$ to ^{251g}No, while the half-life does not suggest an assignment to ^{251m}No. Speculations on one more level decaying by α emission, on the other hand, seem too vague on the basis of the small number of six correlated events. So, we presently leave this group as unassigned.

Search for further fine structure in the α decay of ^{251g}No did not show clear results, which obviously is due to the problem of identifying α lines of low intensity located slightly below strong ones as discussed in sect. 3.1 and indicated in fig. 2 by α-α correlations having $E_{\alpha 1} < 8.6\,\text{MeV}$. "Lines" indicated below the 8612 keV transitions are listed in table 2 for completeness, but with respect to the discussion above we have to stress their tentative character. Nevertheless, the line at 8578 keV reported earlier [9] seems also present here, but with an intensity being about an order of magnitude lower, while the small line at 8552 keV does not seem to be identical to the 8562 keV transition observed in correlation to decays of ^{247m}Fm. An α line at 8524 keV has not been reported so far. Further, the possibility of energy summing with conversion electrons has to be taken into account, which leads not only to a "change" of the energy but also to uncertainties in estimating transition rates into specific levels and hence to uncertainties of the hindrance factors [17, 23]. Therefore the common method to assign α decays on the basis of similarities with α decay patterns of lighter isotones is questionable. Moreover, a change of the ground-state spin and parity within the $N = 149$ isotone line was concluded from ^{247}Cf to ^{249}Fm and again to ^{251}No [8]. So also the α decay pattern may change. Therefore, we omit a spin and parity assignment of levels populated by these week lines.

A very low fission branch of ^{251}No of $b_{sf} < 0.003$ has been reported previously [9]. In this study one fission event following α decay of ^{255}Rf within 10 s was observed, from which a fission branch $b_{sf} = 1.4^{+3.1}_{-1.2} \times 10^{-3}$ was estimated in agreement with the previous value.

3.3 Decay of ^{251m2}No

In addition to the new and enhanced α-γ decay data a second isomeric state in ^{251}No with a half-life of about $2\,\mu$s was observed. In fig. 1b the γ spectrum measured in delayed coincidence ($1\,\mu\text{s} < \Delta t(\gamma\text{-ER}) < 4\,\mu\text{s}$) with implanted nuclei followed by the α decay of ^{251g}No is shown. The γ lines of 142.4 keV and 203.1 keV are evidently identical to the lines observed in prompt coincidence with α decays of ^{255}Rf (see fig. 1a) which were interpreted as decays from the $9/2^-[734]$ level in ^{251}No. This means that this level is populated by decays connected to the 713.6 keV and 782.5 keV transitions. (The level emitting the 142.4 keV and 203.1 keV γ-rays cannot be isomeric, since these lines were observed in prompt coincidence with α decays of ^{255}Rf and in delayed coincidence here.) The lack of γ-rays above 800 keV indicates that the ground state and the isomer at $E^* = 106$ keV are not significantly populated directly by the decay of the second isomeric state, in other words, population of the $9/2^-[734]$ level is preferred over populating the $7/2^+[624]$ ground state or the $1/2^+[631]$ isomeric state. Efficiency-corrected yields for the different transitions are 320 ± 65 for the sum intensity of the 142.4 keV and 203.1 keV lines and 625 ± 175 for the sum intensity of the 713.6 keV and 782.5 keV lines. These values do not suggest an emission of the latter lines from the same nuclear level, but rather indicates that they belong to a decay cascade. So the energy of the isomeric state may be settled as $E^* > 203.1 + 713.6 + 782.5\,\text{keV} > 1699.2\,\text{keV}$. Vice versa, the energy of the state decaying into the $9/2^-[734]$ level can be settled at $E^* = 203.1 + 713.6\,\text{keV} = 916.7\,\text{keV}$ or $E^* = 203.1 + 782.5\,\text{keV} = 985.6\,\text{keV}$. (Definitely we have to admit that the argument based on the counts is somewhat weak, since due to the low number of observed decays statistical fluctuations may be larger than expressed by a 68% confidential interval. Indeed, we observed here an intensity ratio of ≈ 0.6 for the 142.4 keV and 203.1 keV lines, while both lines were observed with almost equal intensity in coincidence with the α decays of ^{255}Rf.)

Some information on this state can be obtained by comparing different possibilities to decay into low-lying levels with the observed transition. For the latter we have to consider the $7/2^+[624]$ ground state, the $9/2^+$ and the $11/2^+$ members of the rotational band built on it, the $1/2^+[631]$ isomeric state and the $9/2^-[734]$ level at 204 keV. According to Weisskopf estimations only $E1$, $E2$, $E3$, $M1$ and $M2$ transitions are expected to have half-lives below 10 μs, *i.e.* they are expected to be observed notably within our coincidence window. $E3$ and $M2$ multipolarity can be excluded since they require spin and parity assignment of the emitting state that favours $M1$ or $E2$ transitions into the ground-state rotational band or the $1/2^+$ isomeric state. From the remaining candidates $E1$ transitions are the fastest. They require different parities of initial and final states. Under this restriction the parity of the emitting state may be assumed as positive, so it may be settled as $7/2^+$, $9/2^+$, $11/2^+$. With respect to known Nilsson levels in lighter $N = 149$ isotones the $7/2^+[613]$ seems a meaningful candidate. In ^{245}Cm this level was identified at $E^* = 722$ keV [19], while in ^{243}Pu, so far, only the $9/2^+$ band member was assigned to a level at $E^* = 626$ keV [19]. Typical energy differences between the $9/2^+$ member and the $7/2^+$ bandhead are ≈ 60 keV, so the energy difference of 69 keV between the 713.6 keV line and 782.5 keV does not suggest to assign the lower line to the transition $7/2^+ \rightarrow 9/2^-$ and the higher one to the transition $9/2^+ \rightarrow 9/2^-$ as an alternative to the interpretation that they form a cascade as discussed above.

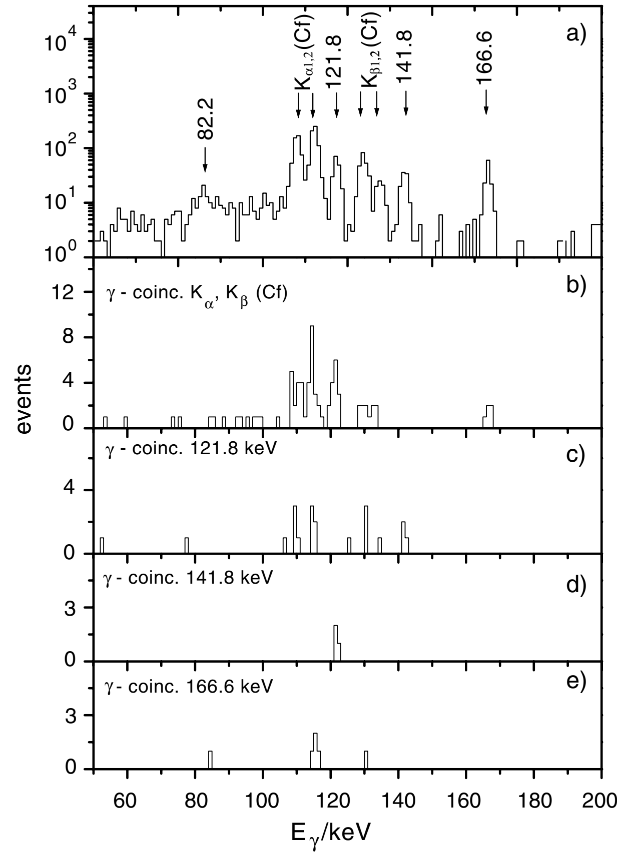

Fig. 3. Gamma spectra observed in prompt coincidence with α decays of ^{247g}Fm (7.8–8.1 MeV); a) single γ spectrum; b)–e) α-γ-γ coincidence spectra.

Moreover, does the energy difference of the two γ lines also not suggest decay from one level into the $9/2^-[734]$ level and the $11/2^-$ band member, since for the lighter $N = 149$ isotones ^{247}Cf, ^{245}Cm, and ^{243}Pu a mean energy difference between these levels of 53 ± 2 keV is obtained [19].

3.4 Decay of ^{247}Fm

In our previous study [8] three γ lines at $E_\gamma = 121.5$, 141.4, and 166.2 keV had been observed besides K-X-rays in coincidence with α-particles from the decay of ^{247g}Fm. On the basis of these results and the systematics of low-lying levels in $N = 145$ isotones, a partial level scheme of the daughter nucleus ^{243}Cf was suggested. In particular, it was concluded that a) on the basis of Q-value arguments, the excitation energy of the level populated by the α decay had to be $E^* \leq 330$ keV, *i.e.* that only two of the three γ lines are emitted within the decay cascade, b) from a comparison of observed numbers of K-X-rays and α decays of ^{247}Fm, the 166.2 keV and 141.4 keV transitions

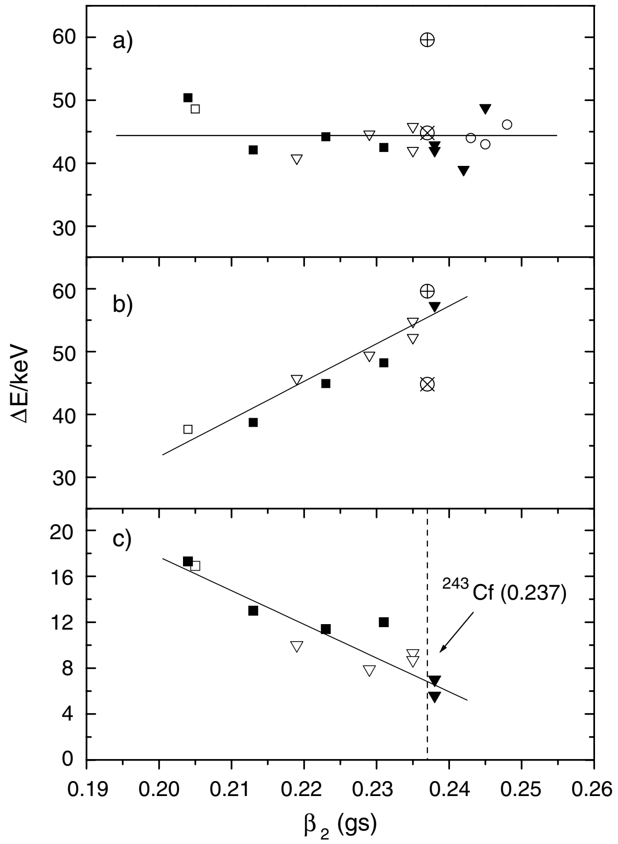

Fig. 4. Systematics of energy differences between a) $7/2^+$ and $5/2^+$ states of the band built up on the $5/2^+[622]$ Nilsson level, b) same as a) but for $5/2^+$ and $3/2^+$ states of $1/2^+[631]$, c) same as a) but for $3/2^+$ and $1/2^+$ states of $1/2^+[631]$; $\otimes$ denotes the energy difference of the γ lines at $E = 166.6$ keV and $E = 121.8$ keV, $\oplus$ denotes the energy difference of the γ lines at $E = 141.8$ keV and $E = 82.2$ keV.

are of $M1$ multipolarity and belong to a cascade, c) on the basis of hindrance factors, the α decays of ^{247,247m}Fm both represent "favoured" transitions between analog Nilsson levels in mother and daughter nuclei. On the basis of the systematics of $N = 145$ isotones, we suggested spin and parity assignments $1/2^+[631]$ for the ground state of ^{243}Cf and $7/2^+[624]$ for the level populated by α decay of ^{247g}Fm. It should decay into the ground state via the $5/2^+[622]$ Nilsson level (or members of the rotational band built up on it).

The results of the follow-up study fully confirmed our earlier conclusion [8]. The γ spectrum obtained in coincidence with α decays of ^{247g}Fm is shown in fig. 3a. Besides the already known lines a new one at $E_\gamma = 82.2$ keV was observed. The number of observed γ events was high enough to enable a few α-γ-γ coincidences as shown in fig. 3b–e). The results can be summarized as follows: a) K-X-rays are observed in coincidence with K-X-rays, the 121.8 keV and the 166.6 keV γ lines; b) the 121.8 keV line is observed in addition in coincidence with the 141.8 keV line. The observation of coincidences between K-X-rays confirm our previous assumption, that two transitions above the K binding energy of californium ($E_B = 134.9$ keV) contribute to the cascade. Since no other significant γ lines are observed, we attribute them to the transitions at 141.8 keV and 166.6 keV. The coincidence between the 141.8 keV transition and that at 121.8 keV, on the other hand, proves that both lines are emitted from different levels, *i.e.* this finding strongly suggests that the 166.6 keV and 121.8 keV lines are "emitted in parallel" and that the 141.8 keV and 82.2 keV are "emitted in parallel". The assignment of the γ lines to a specific transition was made on the basis of systematics. In fig. 4a we have plotted the energy differences between the $7/2^+$ member and the $5/2^+$ bandhead of the Nilsson level $5/2^+[622]$ in odd-mass even-Z nuclei as a function of the ground-state deformation. The energies are taken from [19]. The β_2 values were obtained either by interpolating the values for neighbouring even-even nuclei from [24] or from [25] when available. In figs. 4b and 4c the same is shown for $\Delta E = E^*(5/2^+) - E^*(3/2^+)$ (fig. 4b) and $\Delta E = E^*(3/2^+) - E^*(1/2^+)$ (fig. 4c) for the $5/2^+$ and the $3/2^+$ members and the $1/2^+$ bandhead of the Nilsson level $1/2^+[631]$. Evidently, $\Delta E(1) = 166.6 - 121.8\,\text{keV} = 44.8\,\text{keV}$ ($\otimes$) fits to the systematics of $7/2^+ - 5/2^+$ energy differences (fig. 4a), while $\Delta E(2) = 141.8 - 82.2\,\text{keV} = 59.6\,\text{keV}$ ($\oplus$) fits to the systematics of $5/2^+ - 3/2^+$ energy differences (fig. 4b). This leads us to place the four transitions into the partial level scheme of ^{243}Cf as shown in fig. 5. To determine the excitation energy of the Nilsson levels the location of the ground state should be established. Having assigned the ground-state band one can use the systematics for the energy differences $\Delta E = E^*(3/2^+) - E^*(1/2^+)$. From fig. 4c one obtains for ^{243}Cf an extrapolated value of 7 ± 2 keV, leading to the excitation energies shown in fig. 5.

To obtain the excitation energy of the isomeric state ^{247m}Fm the α decay energy of the ground state has to be known in addition. Unfortunately, no clean line is observed due to energy summing with conversion electrons. A reliable estimate, however, can be obtained from the mean energy of α-particles in α–K_α-X-ray–K_α-X-ray coincidences for which we obtained $E_\alpha = 7887 \pm 5$ keV (including the contribution of energy summing with conversion electrons). As reported previously [17], the energy shift due to electron summing can be given by the relation $\Delta E \approx (E - E_B) + 0.5 \times (E_B - E_x)$. Using $E = 141.8$ keV and 166.6 keV, $E_B = 134.9$ keV (K binding energy in Cf) and $E_x = 117.1$ keV ("averaged" K-X-ray energy), we obtain $\Delta E_1 = 16$ keV for conversion electrons from the 141.8 keV transition and $\Delta E_2 = 41$ keV for those from the 166.6 keV transition. Assuming, further, simply that the transition energy $3/2^+ \rightarrow 1/2^+[631]$, for which we extrapolated a value of 7 ± 2 keV for ^{243}Cf, contributes fully to the energy summing, we obtain a total correction energy of 64 keV and hence a corrected α transition energy of $E_\alpha(\text{corr}) = 7887 - 64\,\text{keV} = 7823$ keV. Using the level energies indicated in fig. 5, we obtain a total Q-value for the ground-state decay of ^{247}Fm of $Q_{gs} = 8267$ keV, while for the isomeric decay, we obtain $Q_{iso} = Q_\alpha = 8307$ keV. So we end up in an excitation energy of $E^* = 40 \pm 9$ keV for the isomeric state. Using, on the other hand, the interpre-

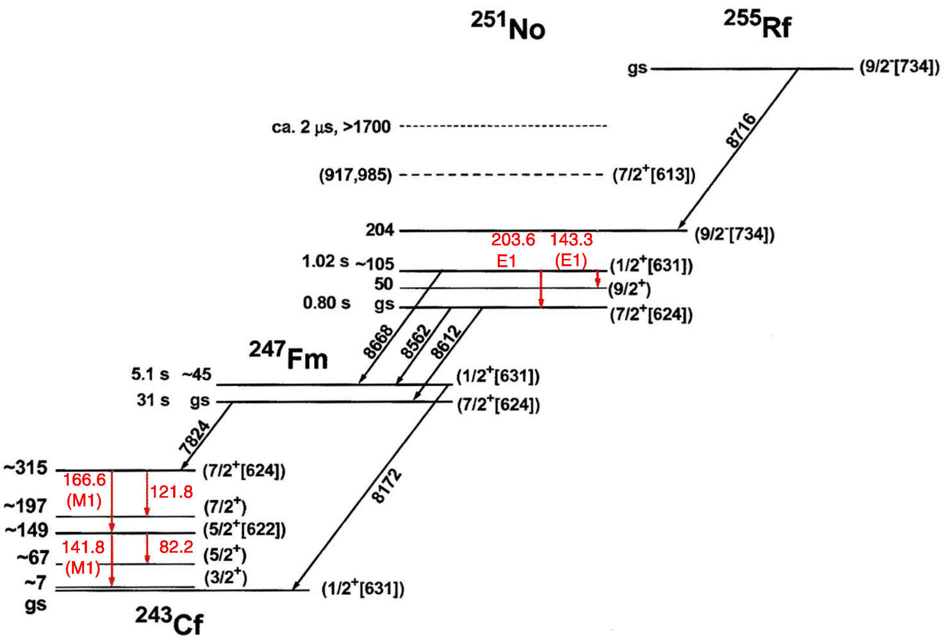

Fig. 5. Decay schemes of ^{255}Rf, ^{251g,251m}No, and ^{247g,247m}Fm derived from the present experiments. Energy values are given in keV.

tation that the 8563 keV transition of ^{251g}No represents the α decay into ^{247m}Fm, as discussed in sect. 3.2, we obtain an excitation energy of $E^* = 49 \pm 7$ keV from the difference of the Q_α values for the ground-state–to–ground-state and the ground-state–to–isomeric-state transitions. Both values agree within the error bars and can be combined to a mean value $E^* = 45 \pm 7$ keV. On the basis of this value, we obtain an excitation energy $E^* = 106 \pm 7$ keV for the $1/2^+[631]$ isomeric state in ^{251}No, in agreement with the result obtained in sect. 3.2.

4 Summary and conclusion

Our experiments delivered new or enhanced quality data for the decay of ^{255}Rf, ^{251}No, and ^{247}Fm which improved the level schemes of ^{251}No, ^{247}Fm, and ^{243}Cf at low excitation energies. Trends in single-particle level energies of $N = 145$, 147 and 149 isotones that had been discussed in our previous paper [8], but were partly speculative, could be fully established on the basis of the data of higher quality obtained in this study. Energies of some levels could be determined more precisely, but no new trends were observed. Therefore, the discussion presented in [8] will not be repeated here. A new isomeric state with a half-life of about 2 μs was identified in ^{251}No. Although excitation energy and spin are uncertain so far, its decay properties gave already some information on the levels in ^{251}No at $E^* > 500$ keV.

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References

1. M. Leino, F.P. Heßberger, Annu. Rev. Nucl. Part Sci. **54**, 175 (2004).
2. R.-D. Herzberg, J. Phys. G **30**, R123 (2004).
3. I Ahmad, J.P. Greene, E.F. Moore, F.G. Kondev, R.R. Chasman, C.E. Porter, L.K. Felker, Phys. Rev. C **72**, 054308 (2005).
4. I. Ahmad, J. Milsted, R.K. Sjoblom, J. Lerner, P.R. Fields, Phys. Rev. C **8**, 735 (1973).
5. R.-D. Herzberg, P.T. Greenlees, P.A. Butler, G.D. Jones, M. Venhart, I.G. Darby, S. Eeckhaudt, K. Eskola, T. Grahn, C. Gray-Jones, F.P. Heßberger, P. Jones, R. Julin, S. Juutinen, S. Ketelhut, T.L. Khoo, W. Korten, M. Leino, A.-P. Leppänen, S. Moon, M. Nyman, R.D. Page, J. Pakarinen, A. Pritchard, P. Rahkila, P. Reiter. J. Saren, C. Scholey, A. Steer, Y. Sun, Ch. Theisen, S. Tandel, J. Uusitalo, Nature **44**, 896 (2006).
6. F.P. Heßberger, Int. J. Mod. Phys. E **15**, 284 (2006).
7. F.P. Heßberger, S. Antalic, B. Streicher, S. Hofmann, D. Ackermann, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, S. Saro, B. Sulignano, Eur. Phys. J. A **26**, 233 (2005).
8. F.P. Heßberger, S. Hofmann, D. Ackermann, P. Cagarda, R.-D. Herzberg, I. Kojouharov, P. Kuusiniemi, M. Leino, R. Mann, Eur. Phys. J. A **22**, 417 (2004).
9. F.P. Heßberger, S. Hofmann, D. Ackermann, V. Ninov, M. Leino, G. Münzenberg, S. Saro, A. Lavrentev, A.G. Popeko, A.V. Yeremin, Ch. Stodel, Eur. Phys. J. A **12**, 57 (2001).

10. B. Kindler, D. Ackermann, W. Hartmann, F.P. Heßberger, S. Hofmann, B. Lommel, R. Mann, J. Steiner, Nucl. Instrum. Methods Phys. Res. A **561**, 107 (2006).
11. H. Folger, W. Hartmann, F.P Heßberger, S. Hofmann, J. Klemm, G. Münzenberg, V. Ninov, W. Thalheimer, P. Armbruster, Nucl. Instrum. Methods A **362**, 64 (1995).
12. G. Münzenberg, W. Faust, S. Hofmann, P. Armbruster, K. Güttner, H. Ewald, Nucl. Instrum. Methods **161**, 65 (1979).
13. S. Hofmann, V. Ninov, F.P. Heßberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, A.N. Andreyev, S. Saro, R. Janik, M. Leino, Z. Phys. A **350**, 277 (1995).
14. S. Hofmann, W. Faust, G. Münzenberg, W. Reisdorf, P. Armbruster, K. Güttner, H. Ewald, Z. Phys. A **291**, 53 (1979).
15. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
16. F.P. Heßberger, S. Hofmann, D. Ackermann, Eur. Phys. J. A **16**, 365 (2003).
17. F.P. Heßberger, S. Hofmann, D. Ackermann, S. Antalic, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, A.G. Popeko, B. Sulignano, S. Saro, B. Streicher, M. Venhart, A. Yeremin, Eur. Phys. J. A **29**, 165 (2006).
18. R.S. Hager, E.C. Seltzer, Nucl. Data A **4**, 1 (1968).
19. R.B. Firestone, V.S. Shirley, C.M. Baglin, S.Y. Frank Chu, J. Zipkin, *Table of Isotopes* (John Wiley & Sons, Inc., New York, Chicester, Brisbane, Toronto, Singapore, 1996).
20. M.J. Martin, Nucl. Data Sheets **106**, 89 (2005).
21. S.W. Yates, I. Ahmad, A.M. Friedman, F.J. Lynch, R.E. Holland, Phys. Rev. C **11**, 599 (1975).
22. J.K. Dickens, J.W. McConnell, Phys. Rev. C **22**, 1344 (1980).
23. F.P. Heßberger, S. Hofmann, G. Münzenberg, K.-H-Schmidt, P. Armbruster, R. Hingmann, Nucl. Instrum. Methods Phys. Res. A **274**, 522 (1989).
24. A. Sobiczewski, I. Muntian, Z. Patyk, Phys. Rev. C **63**, 034306 (2001).
25. A. Parkhomenko, A. Sobiczewski, Acta Phys. Pol. B **36**, 3095 (2005).