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Alpha-gamma decay studies of ^{251,253}No and their daughter products ^{247,249}Fm

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Abstract. The isotopes ^{251}No and ^{253}No were produced in nuclear reactions ^{206}Pb(^{48}Ca,3n)^{251}No and ^{207}Pb(^{48}Ca,2n)^{253}No. Radioactive decay of these isotopes and their daughter products has been investigated by means of α- and α-γ- spectroscopy. An isomeric state ^{251m}No, having a half-life of $T_{1/2} = (0.93 \pm 0.06)$ s and decaying by emission of α particles of $E_\alpha = (8665 \pm 8)$ keV was identified. The measured decay data allowed for the construction of partial level schemes for ^{251}No, ^{247,249}Fm and ^{243,245}Cf and an extrapolation of energy systematics of single particle levels of $N = 145$, 147 and 149 isotones with even Z towards higher atomic numbers up to $Z = 102$.

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

1 Introduction

Information on nuclear structure of transfermium nuclei has been obtained so far almost exclusively from investigation of the most intense α-transitions. Detailed decay studies require the production of a large number of nuclei to measure α-decay fine structure, α-γ- and/or α-conversion electron coincidences and to study electron capture decay. However, due to small production cross-sections, limited beam currents as well as efficiencies of experimental set-ups considerably lower than unity only relatively small numbers of nuclei of transfermium isotopes could be produced in acceptable irradiation times so far. Therefore conclusions on nuclear structure were drawn essentially on the basis of systematics of Nilsson levels in transuranium nuclei in connection with the analysis of hindrance factors for α-transitions. The latter, however, deliver usually only limited information, such as the estimation of the "favoured transitions" between equivalent Nilsson levels in mother and daughter nuclei. Decay studies using α-γ-coincidence measurements have been performed so far only for a few transfermium nuclei, ^{255}Rf [1], ^{253}No [2,3], ^{247}Md [4] or ^{255}Md [5]. Encouraged by the positive results for ^{255}Rf, ^{253}No and ^{247}Md a program to investigate the decay of neutron-deficient isotopes of mendelevium, nobelium and lawrencium was started. In this paper we present the results from the study of the α-decay chains of ^{251,253}No.

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2 Experiment

The experiments were performed at GSI, Darmstadt, using a ^{48}Ca beam delivered by the high charge state injector with ECR-ion source of the UNILAC accelerator. Beam intensities and energies were $\approx 2 \times 10^{12}$ ions/s ($\approx$ 300 pnA) and (218–230) MeV. The targets of ^{206}Pb (isotopic enrichment 99.8%) and ^{207}Pb (92.4%) with thicknesses of ≈ 450 μg/cm^2 were evaporated on carbon layers of 40 μg/cm^2 (upstream) and covered with 5 μg/cm^2 carbon (downstream). They were mounted on a wheel which rotated synchronously to the beam macro structure [6] (5 ms wide pulses at 50 Hz repetition frequency).

The evaporation residues leaving the targets with energies ≈ 40 MeV were separated from the primary beam by the velocity filter SHIP [7]. 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 [8], used to measure the kinetic energies of the residues as well as subsequent α-decays. 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 $124 \times 124 \times 140$ mm^3. Alpha calibration was performed using the literature values of isotopes which were produced either in the reactions or in an irradiation of ^{170}Er and implanted into the stop detector, as described in [9]. Gamma calibration was performed with standard energies from ^{152}Eu and ^{133}Ba sources. The accuracy of these calibration procedures was ±5 keV for α- and ±0.5 keV for γ-energies. In the case of α-decays we have to consider that the calibration was performed using energies below 8 MeV. Extrapolation into the region of interest here, 8–9 MeV, reduces the accuracy to ±10 keV. The width of the α-lines was $\Delta E(\mathrm{FWHM}) \approx 24$ keV with typical fluctuations for individual lines within ±4 keV.

The standard intensities of the γ-lines from the ^{133}Ba decay were used to estimate the relative efficiency of the Ge-detectors in the range $E_\gamma = (80\text{-}390)$ keV, while the absolute α-γ-coincidence efficiency ($\epsilon_{\alpha\gamma}$) was estimated from the ratio $\Sigma n(\alpha - \gamma)/\Sigma n(\alpha)$ from the transitions α(8421 keV)-γ(209.8 keV) of ^{247}Md and α(7539 keV)-γ(295.1 keV) of ^{251}Md. The isotope ^{251}Md was produced via ^{209}Bi(^{48}Ca,2n)^{255}Lr $\xrightarrow{\alpha}$ ^{251}Md in this experiment, while ^{247}Md was produced via ^{209}Bi(^{40}Ar,2n)^{247}Md in a subsequent irradiation using the identical experimental set-up. Both γ-transitions are considered as $E1$, and on this basis corrections of the counting rate for internal conversion were made according to the conversion coefficients of ref. [10]. Values of $\epsilon_{\alpha\gamma} = 0.14 \pm 0.02$ (209.8 keV) and $\epsilon_{\alpha\gamma} = 0.13 \pm 0.04$ (295.1 keV) were obtained.

The hindrance factor for an α-transition is defined as the ratio $T_{\alpha,\mathrm{exp}}$ / $T_{\alpha,\mathrm{theo}}$, with $T_{\alpha,\mathrm{exp}} = T_{1/2}/(b_\alpha \times i_\alpha)$, where $T_{1/2}$ and b_α denote the half-life and the α-branching of the isotope, while i_α is the intensity of the transition. The theoretical half-life was calculated using the formula proposed by Poenaru *et al.* [11] with the parameter modification suggested by Rurarz [12]. Hindrance factors are usually divided into four catagories characterizing "differences" in the initial ("parent") and final ("daughter") states (see, *e.g.*, [13] and references therein). Alpha-transitions in odd-mass nuclei, where the unpaired nucleon remains in the same orbital in the parent and daughter nucleus are characterized by low hindrance factors of (1–4). In the literature they are usually called "favoured transitions".

3 Experimental results

3.1 Decay of ^{253}No, ^{249}Fm and ^{245}Cf

The nucleus ^{253}No was identified more than thirty-five years ago. It has been reported to decay with a half-life of about 100 s ($T_{1/2} = 95 \pm 10$ s [14], $T_{1/2} = 105 \pm 20$ s [15]) by emission of α-particles with an energy of 8.01 MeV [14, 15]. It was, however, remarked in ref. [14] that the α-decay probably populates an excited state in the daughter nucleus, ^{249}Fm, since according to systematics for ^{253}No a higher α-decay energy was expected than for the neighbouring isotope ^{254}No ($E_\alpha = 8.10$ MeV).

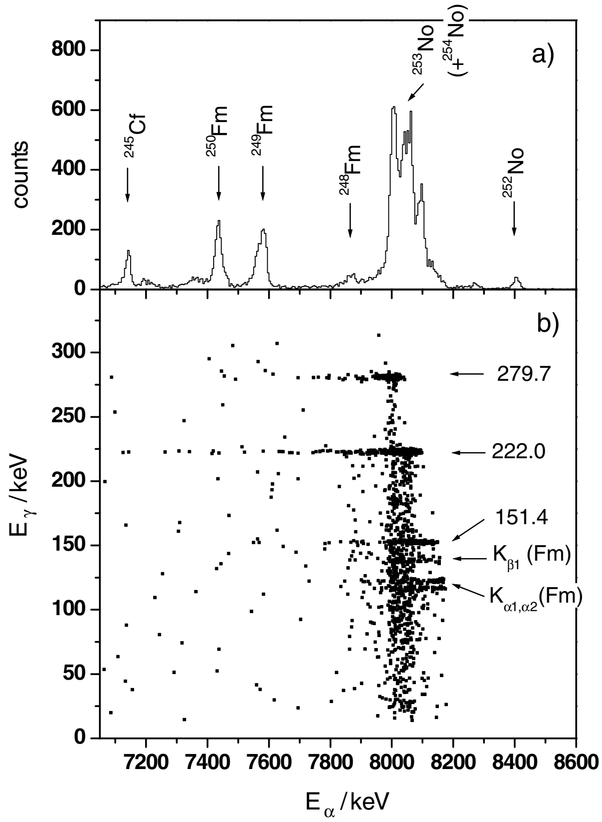

Fig. 1. Alpha singles spectrum (a) and α-γ-coincidence spectrum (b) of evaporation residues and their daughter nuclides from the reaction ^{48}Ca + ^{207}Pb at $E_{\mathrm{lab}} = 221$ MeV.

In the course of our investigation of rutherfordium isotopes, ^{253}No was produced by α-decay of ^{257}Rf [16]. The decay properties of ^{253}No reported earlier were essentially confirmed, but it was realized that the energy distribution of the α-particles was quite broad and could be fitted assuming several lines. Definite conclusions on levels populated in the daughter nucleus, however, were not made [16]. Recently in an in-beam spectroscopy study of ^{253}No performed by Herzberg *et al.* [17] also the α-decay was studied. They observed three γ-lines of ≈ 150, 220, and 279 keV in coincidence with α-particles [2]. The intensity ratio of γ-events and conversion electrons strongly suggested to interprete these transitions as $E1$ [2]. This observation motivated us to re-analyze the data from the ^{257}Rf-decay study and to also search for α-γ coincidences. Four γ-lines of $E_\gamma = 120.9$, 151.6, 222.1 and 280.3 keV and conversion electrons in coincidence with α-particles were detected [3]. The energy of the first line is close to the $K_{\alpha1}$-X-ray energy of fermium, while the other three corresponded to those observed by Herzberg *et al.* In accordance with their interpretation, the γ-transitions were assigned to the decay of the $9/2^-[734]$ Nilsson level in the daughter ^{249}Fm, located at $E^* = 280.3$ keV, to the $7/2^+[624]$ ground-state level, and to the $9/2^+$ and $11/2^+$ levels built up on the ground-state rotational band. To

Table 1. Decay properties of ^{253}No. The conversion coefficients given in col. 6-11 are theoretical values from [10].

E_α/keV	E_γ/keV	$i_{\gamma,\mathrm{rel}}$	α_K(exp)	α_L(exp)	$\alpha_K(E1)$	$\alpha_L(E1)$	$\alpha_K(E2)$	$\alpha_L(E2)$	$\alpha_K(M1)$	$\alpha_L(M1)$
8004 ± 5	279.7 ± 0.5	0.48 ± 0.02	<0.35	<0.1	0.04	0.01	0.09	0.22	1.4	0.46
	222.0 ± 0.5	1	<0.17	<0.05	0.07	0.017	0.125	0.61	3.9	0.9
	151.4 ± 0.5	0.18 ± 0.01	<0.98	<0.3	0.16	0.043	0.128	3.08	11.5	2.6

Table 2. Compilation of measured decay data. The errors of the energies do not include a systematic error of ±10 keV due to the calibration procedure (see sect. 2). For completeness also our results for the even-even nuclei ^{252}No, ^{248,250}Fm are given, which are not discussed in the text.

Isotope	E_α/keV	$T_{1/2}$ / s	E_γ/keV
^{253}No	8004 ± 5		151.4 ± 0.5 (0.48 ± 0.02) 222.0 ± 0.5 (1) 279.7 ± 0.5 (0.18 ± 0.01)
^{252}No	8403 ± 8	2.52 ± 0.22	
^{251}No	8608 ± 5	0.78 ± 0.02	
$^{251\mathrm{m}}$No	8665 ± 8	0.93 ± 0.06	
^{250}Fm	7434 ± 6		
^{249}Fm	(7574)$^{(\mathrm{a})}$	96 ± 6	
^{248}Fm	7863 ± 5	36 ± 2	
^{247}Fm	7840 ± 20	29 ± 1	121.5 ± 0.5, 141.4 ± 0.5, 166.2 ± 0.5
$^{247\mathrm{m}}$Fm	8170 ± 5	4.3 ± 0.4	
^{245}Cf	7142 ± 5		

($^{\mathrm{a}}$) Energy value is influenced by energy summing with conversion electrons.

confirm this interpretation also detailed information on the energy of the coincident α-particles and the independence of the γ-lines from each other are required. Since this information was not available from the aforementioned study, a new measurement was performed using the production reaction ^{207}Pb(^{48}Ca,2n)^{253}No. The results are presented in fig. 1 and tables 1, 2. No γ-γ coincidences between any lines were observed which proves that these γ-transitions do not form a cascade.

The structure of the α-spectra indeed suggests to assign the 279.7 keV γ-line to the transition into the ground-state. The coincident α-line has an energy of 8004 ± 5 keV and a widths of $\Delta E = 23.4$ keV (FWHM). It is therefore obviously not influenced by energy summing with conversion electrons. In contrast, we observe broad lines in coincidence with the 222.0 keV and 151.4 keV γ-lines (fig. 2a). The α-spectrum in coincidence with the 220.0 keV γ-line can be fitted by a Gaussian curve of $E = 8045$ keV and $\Delta E = 52.4$ keV (FWHM). The line-broadening and also the energy shift with respect to the α-line in coincidence with the 279.7 keV γ-line is ascribed to energy summing of the α-particles with conversion electrons from the decay of a level in ^{249}Fm populated by the 220.0 keV γ-transition. A detailed analysis suggests that it consists of three components peaking at 8008, 8040 and 8060 keV, which can be interpreted as due to

a) minimum energy summing (conversion electrons escaping the detector) for the 8008 keV component,

b) energy summing with L-conversion electrons accompanied by the emission of L-X-rays (8040 keV component) and

c) energy summing with L-conversion electrons accompanied by absorption of the L-X-rays in the detector, energy summing with L-conversion electrons and Auger-electrons, or energy summing with M-conversion electrons (8060 keV component).

This interpretation is supported by the facts that $L1$-conversion is much stronger than $L2$- and $L3$-conversion [10] and the energy difference of the components b) and c) is within the energy region of the most intense X-rays emitted due to $L1$-vacancies (16–22 keV for fermium) [18].

The energy distribution of the α-particles in coincidence with the 151.4 keV γ-line is more complex. It cannot be simply explained by energy summing with conversion electrons from a single level, *i.e.* the level populated by the 151.4 keV γ-transition must decay to a large extent in at least two steps to the ground state.

The $E1$-character of the γ-lines was confirmed by comparing our upper limits for the K- and L-conversion coefficients with the expected values according to ref. [10]. K-conversion coefficients were determined from the intensity ratios of the X-rays and the corresponding γ-lines, while for the estimation of the L-conversion coefficients we used the energy summing of α-particles and conversion electrons. With respect to the discussion above events from energy summing with L-conversion electrons from the decay of the 279.7 keV level are expected in the

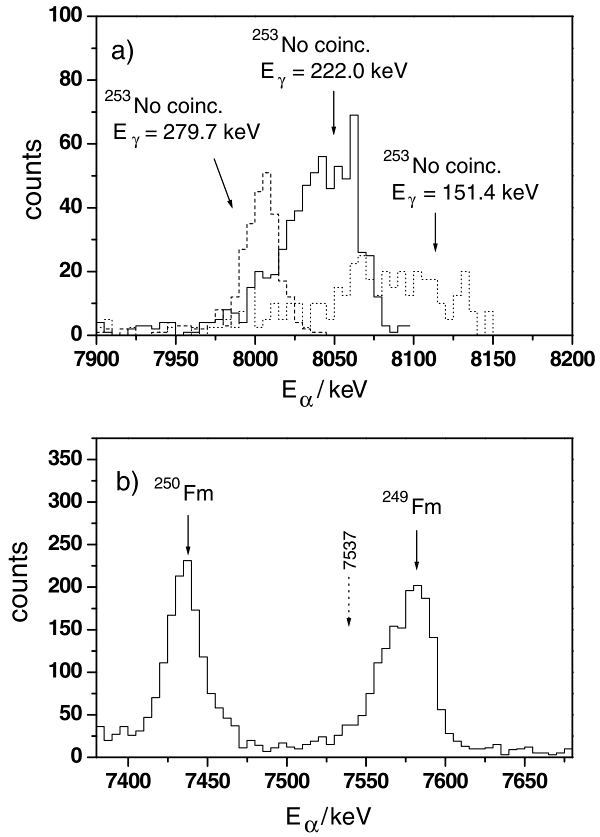

Fig. 2. Comparison of α-spectra from ^{253}No coincident with $E_\gamma = 220.0$ keV (full line), $E_\gamma = 151.4$ keV (dotted line) and $E_\gamma = 279.7$ keV (dashed line) (a) with α-spectrum from ^{249}Fm (b).

interval $E = (8200\text{–}8300)$ keV. Since about half of the conversion electrons are stopped in the Si-detector (the other half escapes in backward direction) the L-conversion coefficient for a transition with the energy E_γ can be given by $\alpha_L \approx 2 \times \Sigma n_\alpha(8200\text{–}8300) \times \epsilon_{\alpha\gamma} / \; \Sigma n_\gamma(E_\gamma)$, where $\Sigma n_\alpha(8200\text{–}8300)$ denotes the number of α-decays in the energy interval (8200–8300) keV, $\epsilon_{\alpha\gamma}$ the efficiency of the Clover detector, and $\Sigma n_\gamma(E_\gamma)$ the number of γ-events. Our experimental values, however, represent upper limits since the contribution of each γ-line to the numbers of X-rays or α-particles (here we also have to respect possible α-decays into the ground state) were not known. So we used for each γ-transition the full number of counts. It is evident from table 1, that our upper limits for the K-conversion coefficients indeed do not exclude $E2$ multipolarity. The upper limits for the L-conversion coefficients, however, clearly are lower than the values expected for $E2$-transitions. So we conclude, that all three γ-lines represent $E1$-transitions.

Decay data of ^{249}Fm were scarce. An α-decay energy of 7.52 ± 0.03 MeV was reported in ref. [14]. It was realized already in our earlier decay study of ^{257}Rf, that our α-energy of ^{249}Fm differed from the value of ref. [14] by about 40 keV to a higher energy. This result was insofar precarious since α energies for other isotopes given in paper [14] were in agreement with our data. So the discrepancy could not be ascribed to insuffiencies of the calibration. But due to the low number of observed decays we did not draw conclusions. In the present experiment about 1550 α-decays of ^{249}Fm were registered. No γ-events in coincidence with α-particles were observed. The shift of the α energy with respect to the value of ref. [14] was confirmed and close similarities with the energy distribution of the α-particles in coincidence with the 222.0 keV γ-line of ^{253}No were observed (see fig. 2b). So it is reasoned that the α-decay of ^{249}Fm populates a low-lying level in ^{245}Cf, that nearly exclusively decays by internal conversion. To estimate the energy of this level we use the quantitative relations obtained for ^{253}No. The α-spectrum of ^{249}Fm can be disentangled into two components of $E_\alpha = (7561 \pm 10)$ keV and $E_\alpha = (7581 \pm 10)$ keV. The differences to the literature value $E_\alpha = (7527 \pm 23)$ keV (we use here the value of the data table [18] instead of the value given in ref. [14]) are $\Delta E = 34$ keV and $\Delta E = 54$ keV, respectively, and thus resemble the results obtained for ^{253}No. In addition, as seen in fig. 2b, we observe in the α-spectrum of ^{249}Fm a slight shoulder towards lower energies, indicating a "peak" at $E = 7537$ keV shown by an arrow in fig. 2b. Interpreting it as originating from minimum summing, the "undisturbed peak" is expected at $E \approx 7530$ keV, in accordance with the literature value. We thus suggest that the energy of the level populated by the α-decay of ^{249}Fm is $E^* = (55 \pm 10)$ keV.

The nucleus ^{245}Cf is reported to decay by emission of α-particles with energies and relative intensities (given in brackets) 7137 keV (0.913), 7084 keV (0.078), 7036 keV (0.0045), 6983 keV (0.0044), 6886 keV (< 0.0001) [18]. An α branch of 0.36 ± 0.03 is given. In our experiment we observed only the three most intense lines. Our results are 7142 keV (0.93), 7086 keV (0.07), 7036 keV (< 0.01). The line at 7086 is seemingly strongly influenced by energy summing with conversion electrons, while the 7142 keV line is narrow with a width of 16.5 keV (FWHM). Our α branching is 0.36 ± 0.05. No γ-events in coincidence with α-decays of ^{245}Cf were observed.

3.2 Decay of ^{251}No and ^{247}Fm

Identification of ^{251}No has been reported by Ghiorso *et al.* [15], who assigned two α-lines of 8.60 MeV ($i_{\rm rel} = 0.8$) and 8.68 MeV ($i_{\rm rel} = 0.2$) to this isotope and gave a half-life of 0.8 ± 0.2 s. In the course of our decay studies of rutherfordium isotopes, ^{251}No was produced by α-decay of ^{255}Rf [19,20,16,1]. While half-life and the 8.60 MeV line were verified, no indication for the line at 8.68 MeV was found.

In these experiments a broad energy distribution of α-particles from the decay of the daughter product ^{247}Fm was observed, while decay energies of 7.87 MeV ($i_{\rm rel} \approx 0.7$) and 7.93 MeV ($i_{\rm rel} \approx 0.3$) were reported by Flerov *et al.* [21]. Our data indicated that α-decay of ^{247}Fm populates a level in ^{243}Cf, that decays into the ground state in at least two steps. To clarify the situation concerning the α-line at 8.68 MeV and to study the decay of ^{247}Fm in more detail, we performed an irradiation of

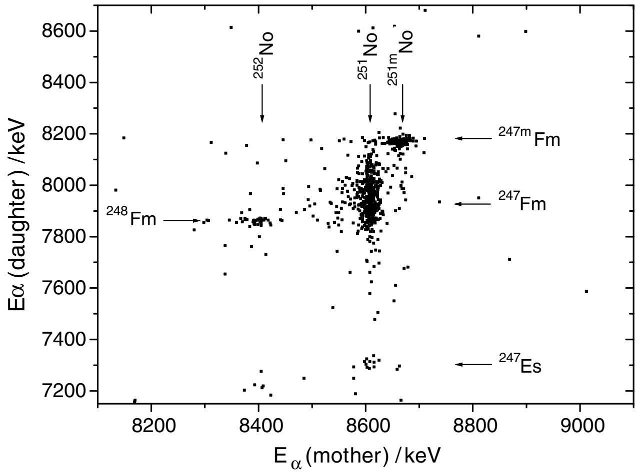

Fig. 3. α-α-correlation plot for decays observed in the reaction ^{48}Ca + ^{206}Pb at E = 4.81 AMeV.

^{206}Pb with ^{48}Ca at $E_{\rm lab}$ = 230.5 MeV which should correspond to the cross-section maximum for the reaction ^{206}Pb(^{48}Ca,3n)^{251}No. The result of the measurement is shown in fig. 3 and table 2. Two groups of α-α correlations are evident in fig. 3. Group one consists of a sharp line $E_{\alpha 11}$ = 8608 keV and of a broad distribution $E_{\alpha 12}$ = (7800–8130) keV, representing the sequence ^{251}No $\overset{\alpha}{\to}$ ^{247}Fm $\overset{\alpha}{\to}$ ^{243}Cf, already known from the decay studies of ^{255}Rf. Group two consists of the pair ($E_{\alpha 21}$ = 8665 keV, $E_{\alpha 22}$ = 8170 keV). An activity with the latter energy had been observed by Flerov *et al.* [21] and attributed to the decay of an isomeric state ^{247m}Fm. It thus seems straightforward to equate $E_{\alpha 21}$ with the line observed by Ghiorso *et al.* and to attribute it to the decay of an isomeric state ^{251m}No. The assignment to the decay from a level different from that emitting the 8608 keV α-particles is further based on

a) that the α-line was not observed within the α-decay chain of ^{255}Rf, *i.e.* it must originate from a level not populated by the decay of ^{255}Rf,

b) a half-life of 0.93 s, which is slightly but significantly different from that of the level emitting the 8608 keV α-particles, and

c) the correlation to the 8170 keV group and not to the (7800–8130) group.

Both α-lines attributed to ^{251}No are found to be "narrow" with widths of ΔE(FWHM) = 18.1 keV (8608 keV) and ΔE = 20.1 keV (8665 keV). Thus they are obviously not influenced by energy summing with conversion electrons. No γ-decays have been observed in coincidence with either of these lines.

The 8170 keV-line attributed to ^{247m}Fm was also found to be narrow ΔE = 15.5 keV; no coincident γ-rays were observed.

The interpretation of the α-decays attributed to ^{247g}Fm is more complicated. The following features are important for the further discussion:

a) The α-particles attributed to the decay of ^{247g}Fm exhibit a broad distribution in energy covering the range (7800–8130) keV (fig. 4a, "singles spectrum").

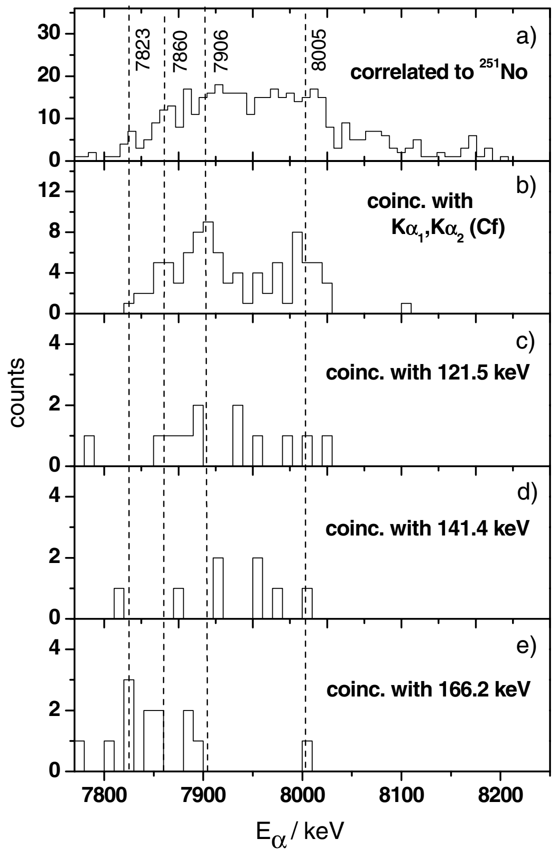

Fig. 4. α-spectrum of ^{247}Fm correlated to ^{251}No (a), coincident with X-rays (b), coincident with 121.5 keV (c), coincident with 141.4 keV (d), and coincident with 166.2 keV (e).

b) In the energy region attributed to the α-decays of ^{247g}Fm, several γ-lines were found in coincidence with α-decays (see fig. 5). Those with the strongest intensities can be attributed to $K_{\alpha 1,\alpha 2}$-X-rays of californium. Furthermore three weaker lines are found at E_γ = 166.2 keV, 141.4 keV and 121.5 keV.

c) The singles spectrum is more or less structureless, while the α-spectrum in coincidence with X-rays exhibits two pronounced peaks at ≈ 7906 keV and ≈ 8005 keV and a weaker one at ≈ 7860 keV (fig. 4b).

d) The α-spectra in coincidence with X-rays or γ-rays end at ≈ 8025 keV (figs. 4b-d), while the singles spectrum extends up to ≈ 8130 keV. Alpha-particles of higher energy may be interpreted as random correlations between ^{251g}No and ^{247m}Fm. Towards lower energies the singles spectrum ends at about 7800 keV, thus (respecting the energy resolution of the detector) an upper excitation energy limit for the level(s) populated by the α-decay can be given as $E^* \leq$ 330 keV.

e) The broad distribution of α energies suggests that the level(s) populated by the α-decay de-excites to the ground state by at least two internal transitions, since in the case of a one-step process one would expect rather three distinct α-lines (minimum summing with conversion electrons, summing with K-conversion electrons, summing

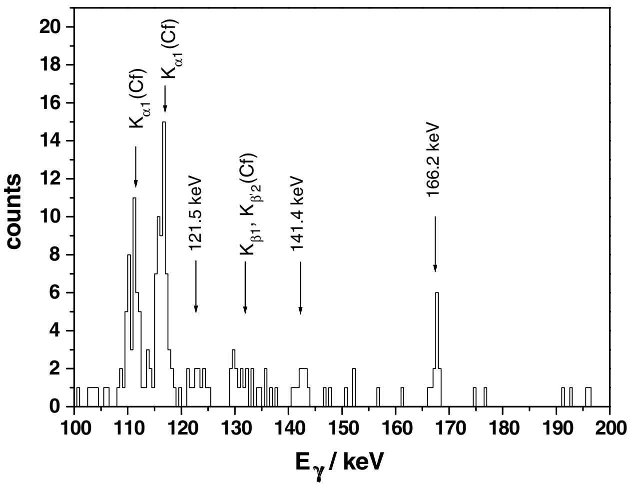

Fig. 5. Gamma-spectrum in coincidence with alpha-decays of ^{247}Fm.

with L/M-conversion electrons), similar to ^{253}No, but more pronounced due to the higher transition energy.

f) The difference between the upper limits of the energy of α-particles in the singles spectrum and those in coincidence with X-rays or γ-rays indicates that the spectrum is significantly influenced by L- and M-conversion electrons. On the other hand, we observed about 95 α–X-ray–coincidences. With respect to a Clover efficiency of 0.15 one obtains a total number of about 630 decays accompanied by K-conversion, while the total number of observed ^{247}Fm α-decays amounts to about 910. Thus about two-third of the α-decays are accompanied by K-conversion. Since at energies around the K binding energy (134.939 keV [18]) K-conversion coefficients for californium are lower than 0.2 for $E1$- or $E2$-transitions and larger than 10 for $M1$- or $M2$-transitions, our observed K-X-ray rate suggests that at least one of the transitions above the K binding energy is a magnetic transition. Taking the ratio of (X-ray/γ)-events for each of the two γ-transitions (neglecting K-conversion of the other one) we obtain $\alpha_K(166.2) = 6.7\pm2.5$ and $\alpha_K(141.4) = 11\pm5$. Both values therefore may be regarded as upper limits and thus suggest rather $M1$- than $M2$-transitions, since for the latter K-conversion coefficients > 20 are expected [10].

g) The sum energy of the three weak γ-lines observed amounts to 429 keV. Since according to the discussion above, item d), the level populated by the α-decay is expected at $E \leq 330$ keV only two of the lines can belong to a decay cascade, *i.e.* one of the levels must decay via different γ-transitions into different levels.

h) The α-spectrum in coincidence with the X-rays exhibits two pronounced maxima at ≈ 7906 keV and ≈ 8005 keV and a weaker one at ≈ 7860 keV (fig. 4b). This finding suggests that the peak with the lowest energy is effected by energy summing with K-electrons, while the other two peaks are effected by energy summing with K- and L-electrons or L-electrons from at least two transitions. The energy shift (compared to the lower energy end of the α-spectrum) of the peak at ≈ 7906 keV is too low to be explained by energy summing with conversion electrons from the 121.5 keV transition. This indicates an additional transition for which no γ-decay has been observed. On the other hand, the energy shift of the peak at ≈ 8005 keV is too high to be explained by energy summing with L-conversion electrons from the 166.2 keV transition and K-electrons from the 141.4 keV transition. This indicates that the sum $E = 166.2$ keV + 141.4 keV = 307.6 keV does not represent the excitation energy of the level populated by the α-decay of ^{247}Fm, but that there is another component of (10–30) keV. The affiliation of the γ-lines to the deexcitation steps can be estimated by analyzing the energy distribution of the α-particles in coincidence with the 166.2 keV-line (fig. 4e). It is concentrated in the range (7800–7900) keV and is thus seemingly not affected by energy summing with L-conversion electrons from transitions with energies above 100 keV. Thus the 121.5 keV transition, for which K-conversion is energetically not possible, cannot be attributed to the second step. On the other hand, the energy of K-conversion electrons from the 141.4 keV transition is too low to affect an energy shift of ≈ 70 keV as indicated in fig. 4e. This is another argument, that there must be a contribution from summing with L-conversion electrons from a transition for which no γ-events have been observed.

i) Alpha-decays coincident with 141.4 keV are essentially concentrated in the range (7900–8000) keV (fig. 4d). Since the energy difference to 166.2 keV is 24.8 keV, one would expect an energy distribution of the coincident α-particles similar to that for those coincident with $E_\gamma = 166.2$ keV but shifted by ≈ 25 keV due to the larger energy of the conversion electrons, if the level emitting the $E = 141.4$ keV γ-rays is essentially fed by or feeding the level emitting the $E = 166.2$ keV γ-rays. The different appearance of the spectra in figs. 4d and 4e suggests that another transition plays an important role. We therefore conclude that the 121.5 keV transition is an alternative to the 166.2 keV transition in the de-excitation of ^{243}Cf after beeing produced by α-decay of ^{247}Fm.

j) Principally, however, one cannot exclude that different levels in ^{243}Cf are populated by the α-decay, which decay via 121.5 keV or 166.2 keV transitions into the level which then decays (inter alia) by emission of 141.4 keV γ-rays. From the number of α- and γ-events, but neglecting internal conversion, we obtain an upper intensity ratio limit of 10 for α-decays into different levels. Calculations of partial α half-lives using decay energies of (7800–7900) keV deliver values of $T_\alpha = (26–58)$ s, which are comparable with our experimental partial α half-life of 41 s (on the basis of $b_\alpha \approx 0.7$). Therefore one of these α-transitions must be the favoured transition into the Nilsson level corresponding to the ground state of the mother nucleus. Since α energies are similar, the other transition must have a hindrance factor lower than 10. Such low hindrance factors, however, are not expected for the decay into a different Nilsson orbital. This strongly suggests that the 166.2 keV transition and the 121.5 keV transition are connected to the decay of the same nuclear level in ^{243}Cf, which is populated by the favoured α-decay.

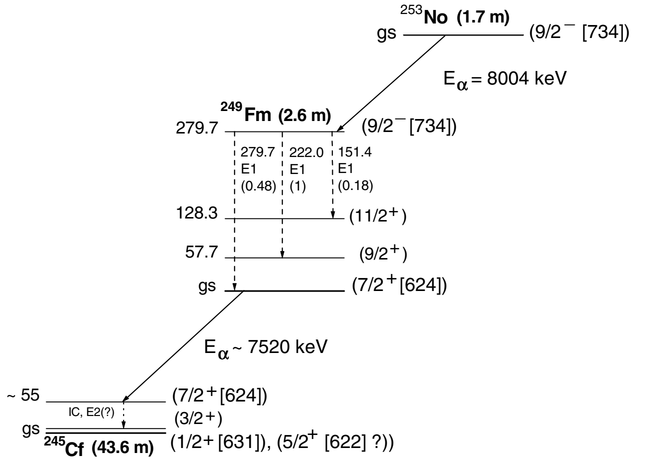

Fig. 6. Decay scheme suggested for ^{253}No. Level energies are given in keV.

k) Our data thus indicate that the deexcitation of ^{243}Cf after α-decay of ^{247}Fm occurs via (at least) two paths, one including transitions of 121.5 keV and 141.4 keV and another one including transitions of 141.4 keV and 166.5 keV. Yet, it should be pointed out, that in each path additional transitions, not observed here, have to be considered.

4 Discussion

Systematic trends in nuclear structure of even-Z isotones have been realized for a long time. Our results extend these trends to nobelium ($N = 149$), fermium ($N = 147$) and californium ($N = 145$). To facilitate the discussion we firstly present (sect. 4.1, 4.2) our suggested decay schemes for ^{251,253}No and systematic trends known from literature. Details will be discussed in sects. 4.3-4.5.

4.1 Decay scheme of ^{253}No

Ground states of even-Z isotones in the transuranium region are identified or estimated as $9/2^-$[734] ($N = 151$), $7/2^+$[624] ($N = 149$) and $5/2^+$[622] ($N = 147$). It thus seems straightforward to assign respective values also to ^{253}No and its α-decay products ^{249}Fm and ^{245}Cf. But such an assignment is in conflict with the measured decay properties of these isotopes. The decay scheme suggested on the basis of our experimental results is shown in fig. 6. Alpha-decay of ^{253}No populates the $9/2^-$[734] Nilsson level in ^{249}Fm (favoured transition), which decays into the $7/2^+$[624] ground state and into the $9/2^+$, $11/2^+$ excited states by γ-rays of 279.7 keV, 222.0 keV or 151.4 keV. Gamma-transitions are $E1$, which is in-line with our interpretation, since the assumed spins and parities of mother and daughter levels require $E1$-transitions. Alpha-decay of ^{249}Fm is interpreted to populate the $7/2^+$[624] Nilsson level in ^{245}Cf (favoured transition). Based on systematics the ground state of ^{245}Cf is tentatively assigned $5/2^+$[622] [18]. Such an interpretation requires a highly converted $M1$-transition $7/2^+[624] \rightarrow 5/2^+[622]$, which could explain the energy shift of the ^{249}Fm α-line and its width, and thus would be in-line with our data.

The assumption of a $5/2^+$[622] ground state, however, is not quite in-line with our measured α-decay data of ^{245}Cf. The ground state of the daughter nucleus ^{241}Cm has been assigned to $1/2^+$[631]. Since α-decay of ^{245}Cf is only slightly hindered with a hindrance factor HF = 2.5 (using an experimental half-life of 45 min [18], our α-branching value and an α half-life of 51 min according to [11,12]), it represents a favoured transition and thus should populate the $5/2^+$[622] level in ^{241}Cm. In the $N = 145$ isotones ^{237}U and ^{239}Pu the $5/2^+$[622] levels predominantly decay by $M1$ $(+E2)$ transitions into the $3/2^+$ members of the rotational band built up on the $1/2^+$[631] ground-state configuration, which are typically at $E^* = \approx 10$ keV. Since we do not observe γ-events in coincidence with α-decays of ^{245}Cf nor have indication for influence of energy summing with conversion electrons it seems not likely that an excited level in ^{241}Cm is populated by α-decay of ^{245}Cf. Thus we are tempted to tentatively interprete the 7142 keV α-line as a ground-state to ground-state transition and to assign the ground state of ^{245}Cf rather to $1/2^+$[631] than to $5/2^+$[622]. However, we have to admit, that this conclusion is not unambiguous: in case of a low energy difference ($\Delta E \leq 20$ keV) energy shift of the α-line can be assumed to be lower than the error bars defined by the accuracies of the literature value and our calibration procedure ($\Delta E \approx 25$ keV) and the broadening may be smaller than the statistical fluctuations of the widths of individual α-lines. For explanation of the ^{249}Fm decay this has the consequence, that the $7/2^+$[624] will decay via the transition $7/2^+[624] \rightarrow 3/2^+ \rightarrow 1/2^+[631]$ into the ground state. In the region of nuclei considered here the $3/2^+$ level typically lies (5–10) keV above the $1/2^+$ level. The transition $7/2^+[624] \rightarrow 3/2^+$ is $E2$, for which at excitation energies below 100 keV conversion coefficients are more than a factor of two higher then for $M1$-transitions. Additionally, we here should notice, that for $M1$-transitions of $E \approx 55$ keV a total conversion coefficient of ≈ 50 is expected. On the basis of our number of ^{249}Fm α-decays (≈ 1550) and an α-γ-coincidence efficiency of ≈ 0.08 at 55 keV we would expect three events in case of $M1$, while we observed zero (see fig. 1). Therefore the scenario discussed above also is in-line with the observed decay properties of ^{249}Fm. With respect to the expected low excitation energy of the $3/2^+$ level and the limited accuracy of transition energies derived from energy summing of α-particles with conversion electrons, we regard our value of 55 ± 10 keV derived for the transition energy in sect. 3.1 also in this scenario as a reliable value for the excitation energy of the $7/2^+$[624] level.

4.2 Decay scheme of ^{251}No

According to systematics of ground-state Nilsson levels for $N = 151$, 149 and the observed decay properties of ^{255}Rf [1], the ground state of ^{251}No was assigned to $7/2^+[624]$.

The occurrence of an isomeric state with a half-life of $\approx$ 1 s requires a strong hindrance for internal transitions. On the basis of Weisskopf estimations one must expect an angular-momentum difference of $\Delta L \geq 3$. With respect to this condition the only Nilsson level expected at low energies that can form a one-second isomeric state is $1/2^+[631]$. Since the α-decay from the isomeric state represents an unhindered transition, the same level is attributed also to the isomeric state in ^{247}Fm. Ground states of $N = 145$ isotones having even proton numbers (^{237}U, ^{239}Pu, ^{241}Cm) are assigned to $1/2^+[631]$. So it is straightforward to assign this level also to the ground state of ^{243}Cf. Alpha-decay of $^{247\mathrm{m}}$Fm is unhindered, is not accompanied by γ-rays and the α-line obviously is not influenced by energy summing with conversion electrons. Therefore it is interpreted as a transition into the ground state of ^{243}Cf.

The ground-state assignment of ^{247}Fm requires a more detailed discussion. From the systematics one would expect the Nilsson level $5/2^+[622]$. However, the α-decay of ^{251}No is unhindered. It exhibits a "narrow" α-line which is not accompanied by γ-rays. It is thus obvious to interprete it as a transition into the ground state of ^{247}Fm, which suggests to assign its ground state to $7/2^+[624]$. Another argument that $5/2^+[622]$ cannot be the ground state of ^{247}Fm comes from the existence of the 4.3 s isomeric state. For the $N = 147$ isotones ^{241}Pu and ^{243}Cm $1/2^+[631]$ isomeric states of $T_{1/2} = 0.88$ μs and $T_{1/2} = 1.08$ μs decaying by $E2$-transitions into the $5/2^+[622]$ ground states are known [18]. Evidently the situation is completely different in $^{247\mathrm{m}}$Fm. The half-life of 4.3 s is more than six orders of magnitude higher than expected for $E2$-transitions. Therefore the existence of the 4.3 s isomeric state excludes a $5/2^+[622]$ level below the $1/2^+[631]$ and thus supports the ground-state assignment $7/2^+[624]$.

The explanation of the ground-state decay of ^{247}Fm is complicated and cannot be solved satisfactorily on the basis of our data. Nevertheless we want to discuss a possible scheme, which is based on a comparison with the nuclear structure of the lighter $N = 145$ isotone ^{239}Pu. However, it should not be understood as a tentative decay scheme, but as a basis for more detailed investigations, requiring about ten times more counts to enable also γ-γ-coincidence measurements.

The ground state of ^{239}Pu is $1/2^+[631]$, the Nilsson levels $5/2^+[622]$ and $7/2^+[624]$ are found at $E^* = 285.4$ keV and 511.8 keV [22]. In between the Nilsson levels $1/2^-[631]$ and $7/2^-[743]$ have been located at 469.8 keV and 391.6 keV, which do not play a role for the following discussion. The $7/2^+[624]$ level decays predominantly via $M1$-transitions into the $5/2^+[622]$ level ($i_{\mathrm{rel}} = 1$) and the $7/2^+$ member of its rotational band ($i_{\mathrm{rel}} = 0.6$) [22]. The latter then decays into the band-head. The energy difference between $7/2^+$ and $5/2^+$ is 44.7 keV; values of (40–46) keV are typical energy differences for the $5/2^+[622]$ band-head and the $7/2^+$ member in odd-N–even-Z isotopes of U, Pu, Cm, Cf [18]. The $5/2^+[622]$ level decays with

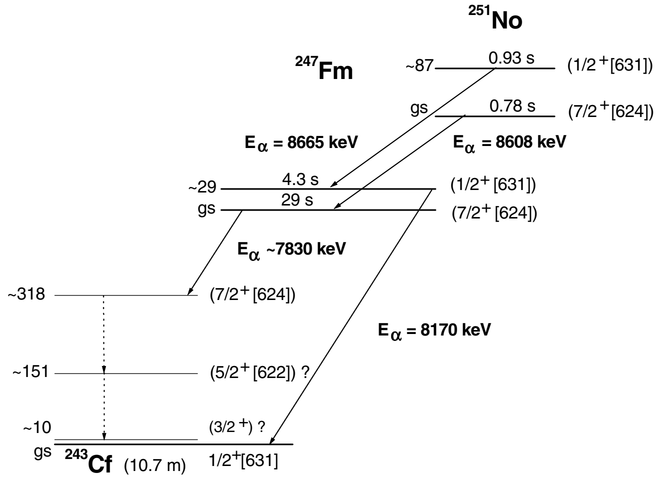

Fig. 7. Decay scheme suggested for ^{251}No. Level energies are given in keV.

about equal intensities into the $3/2^+$ and $5/2^+$ members of the ground-state rotational band located at 7.9 and 57.2 keV, and only weakly directly into the $1/2^+[631]$ ground state. While there is no correlation between the energy difference of the $7/2^+$ and $5/2^+[622]$ levels and ground-state deformation of the nucleus is evident, a slight increase of the difference between the $5/2^+$ and $3/2^+$ levels (built up on $1/2^+[631]$) with increasing deformation is observed. With respect to this, for ^{243}Cf ($\beta_2 = 0.234$ [23]) an about 10 keV higher difference than for ^{239}Pu ($\beta_2 = 0.223$ [23]) can be expected.

Applying these findings to the decay of ^{247}Fm, we find a difference $\Delta E = (166.2 - 121.5)$ keV $= 44.7$ keV for two of the γ-lines. Since the 166.2 keV transition could be assigned to $M1$ as discussed above, the 166.2 keV and 121.5 keV lines may represent the transitions $7/2^+[624] \rightarrow 5/2^+[622]$ and $7/2^+[624] \rightarrow 7/2^+$, since their energy difference rather fits to these transitions than to $5/2^+[622] \rightarrow 3/2^+$ and $5/2^+[622] \rightarrow 5/2^+$ of the members of the band built up on the ground state $1/2^+[631]$.

The 141.4 keV line then should represent rather the $M1$-transitions $5/2^+[624] \rightarrow 3/2^+$ or $5/2^+[624] \rightarrow 5/2^+$ than the $E2$-transition $5/2^+[622] \rightarrow 1/2^+[631]$. This is in-line with the α-spectrum observed in coincidence with 166.2 keV. As mentioned above there is only a tiny contribution from above 7900 keV, indicating that conversion electrons have energies below $\approx$ 80 keV. Electrons from K-conversion, having energies $E_\gamma - E_{\mathrm{binding}}(K) = (141.5 - 134.9)$ keV $= 6.6$ keV, may effect the "peak" around 7850 keV, but not the one at 7890 keV in fig. 4e. On the other hand electrons from L-conversion have energies around 120 keV and thus would produce sum events above 7900 keV. Since for $M1$-transitions at 141.5 keV the K-conversion dominates ($\alpha_K/\alpha_L = 4$), while for $E2$-transitions L-conversion dominates (α_K / $\alpha_L = 0.04$) the 141.5 keV transition is rather $M1$ than $E2$. Since we observe only one γ-line we cannot state *a priori* the 141.5 keV line to represent the transition into the $5/2^+$ or the $3/2^+$ level. Both transitions are expected as $M1$. Our

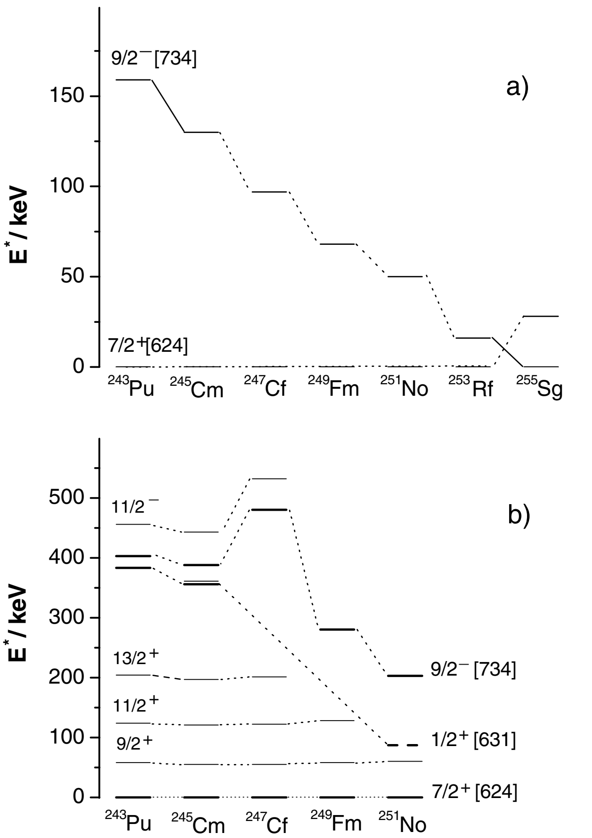

Fig. 8. Systematics of low-lying levels of $N = 149$ isotones; calculated by Cwiok *et al.* [24] (a), experimental data (b).

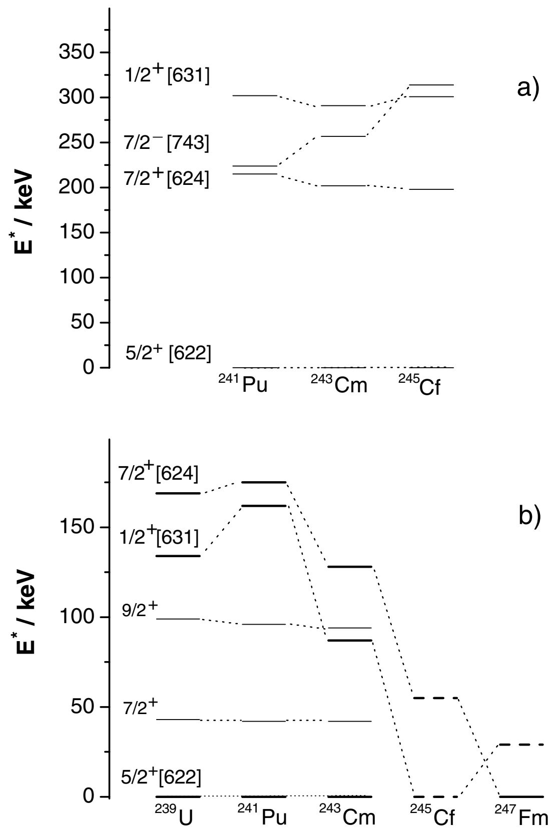

Fig. 9. Systematics of low-lying levels of $N = 147$ isotones; calculated by Cwiok *et al.* [24] (a), experimental data (b). Tentative assignments are marked by levels drawn dashed.

assignment to the decay into the $3/2^+$ is based on the non-observation of a γ-line above the 166.2 keV line and the energy balance. We have to admit, that this is a weak point in our discussion. However, from energy systematics of the levels built up on the $1/2^+[631]$ Nilsson level the $5/2^+$ state can be expected at $E^* \approx 65$ keV. The α-energy of the transition (undisturbed from energy summation with conversion electrons) can be equated with the small peak at $E = 7823$ keV (see fig. 4a,e). Thus we would obtain a total Q-value ($Q_\alpha + E^*(5/2^+) + E_{\gamma 1}(166.2) + E_{\gamma 2}(141.4)$) of 8313 keV, which exceeds the Q-value of the isomeric decay (8302 keV), *i.e.* if the 141.4 keV line would represent the decay into the $5/2^+$ level the ground state of ^{247}Fm would be located above the isomeric state. Our suggested decay scheme is shown in fig. 7. Due to the discussion above the decay scheme of the level in ^{243}Cf populated by α-decay of $^{247\mathrm{g}}$Fm is shown only symbolically. The approximate level energies are based on a typical energy of ≈ 10 keV of the $3/2^+$-state above the $1/2^+[631]$ band head.

4.3 Nuclear levels in N = 149 isotones

Ground states of the $N = 149$ isotones ^{243}Pu, ^{245}Cm and ^{247}Cf have been assigned to $7/2^+[624]$ [18] in accordance with theoretical calculations (fig. 8). The $9/2^-[734]$ levels which represent the ground states of the α-decay mother nuclei are predicted to decrease in energy with increasing proton number and finally should form the ground state of ^{255}Sg. In the experimental data of ^{243}Pu, ^{245}Cm and ^{247}Cf such a trend is not evident. There is a slight decrease from ^{243}Pu to ^{245}Cm, but a steep increase from ^{245}Cm to ^{247}Cf. The recently measured data for ^{251}No, obtained from α-decay studies of ^{255}Rf [1], locate the $9/2^-[734]$ level in this isotope at a considerable lower excitation energy of 203 keV. The data for ^{249}Fm, which place the $9/2^-[734]$ level at 279.7 keV, support the general trend of decreasing energies with increasing proton numbers. Thus the local maximum in ^{247}Cf, which evidently breaks the trend, appears as a peculiarity. Quantitatively, however, predictions underestimate the energy by about (150–250) keV, except in the case of ^{247}Cf, where the difference is ≈ 400 keV. For the $1/2^+[631]$ level no systematic predictions are given in ref. [24]. Experimentally a similar trend of decreasing energies as for the $9/2^-[734]$ level seems evident, although data are scarce.

4.4 Nuclear levels in N = 147 isotones

For the $N = 147$ isotones the experimental trends are less straightforward, partly because of the limited quality of our data. Theory predicts the $5/2^+[622]$ Nilsson level as the ground state and the levels $7/2^+[624]$, $7/2^-[743]$, and $1/2^+[631]$ in the range of $E^* = (200–350)$ keV (fig. 9).

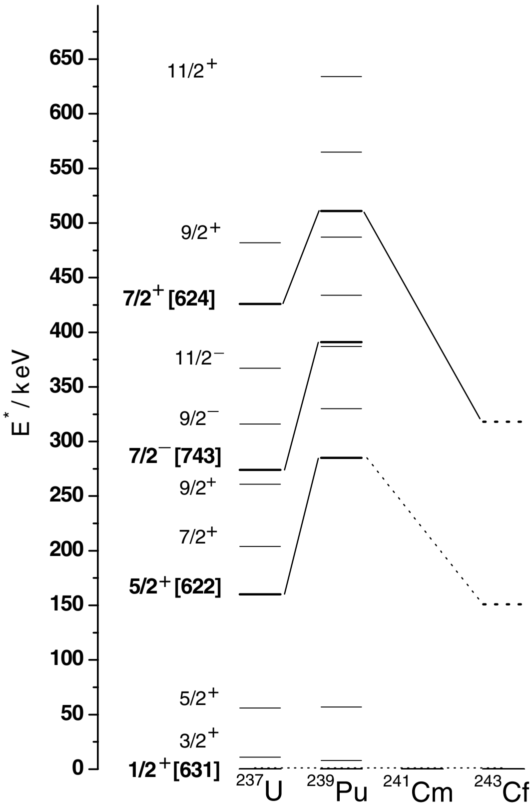

Fig. 10. Experimental systematics of low-lying levels of $N = 145$ isotones; tentative assignments are marked by levels drawn dashed.

While the energy of the $7/2^-[743]$ is increasing with the proton number, those of the other two levels depend only weakly on it. Our experimental data do not support a ground-state level assignment $5/2^+[622]$ for ^{245}Cf and ^{247}Fm. Moreover, they indicate the continuation of the decrease of the $7/2^+[624]$ and $1/2^+[631]$ levels with increasing proton number as already observed for the step from ^{241}Pu to ^{243}Cm, while the energies increase from ^{239}U to ^{241}Pu. Our data indicate for ^{245}Cf already the location of the $1/2^+[631]$ level below the $5/2^+[622]$ level, thus forming here the ground state. Towards ^{247}Fm the $7/2^+[624]$ level sinks below the $1/2^+[631]$, forming the ground state in this isotope. No experimental data on the location of the $5/2^+[622]$ level in ^{245}Cf and ^{247}Fm are available so far.

4.5 Nuclear levels in N = 145 isotones

Data for $N = 145$ isotones are even more scarce, only for ^{237}U and ^{239}Pu detailed data are reported in the literature. The ground states are assigned to $1/2^+[631]$, the Nilsson levels $5/2^+[622]$, $7/2^-[743]$ and $7/2^+[624]$ are located in the excitation energy range (150-450) keV in ^{237}U. Their energies increase by roughly 100 keV towards ^{239}Pu (see fig. 10). Because of this behaviour it seems not justified to assume an extremely steep decrease of any of these levels towards ^{241}Cm. Therefore the ground state of ^{241}Cm is also assigned to $1/2^+[631]$ in the literature [18]. This, however, has the consequence, that due to the structure of the α-spectrum of ^{245}Cf, as discussed in sect. 3.1, we tentatively assign the ground state of the latter isotope also to $1/2^+[631]$ (fig. 9). Since this Nilsson level is the only meaningful candidate to form an isomeric state in ^{247}Fm and ^{251}No, the ground state of ^{243}Cf is also assigned to $1/2^+[631]$ on the basis of the α-decay properties of $^{247\mathrm{m}}$Fm. Our interpretation of the complicated α-decay pattern of $^{247\mathrm{g}}$Fm resulted in a tentative location of the $5/2^+[622]$ and $7/2^+[624]$ levels in ^{243}Cf. This interpretation indicates a general decrease of these levels with increasing atomic number in the $N = 145$ isotones.

5 Summary and conclusion

Alpha-decay chains of ^{251,253}No were investigated by means of α-γ-spectroscopy. The γ-lines observed in coincidence with α-decays of ^{253}No were verified and the suggested $E1$-character was proven. The α-decay energy measured for ^{249}Fm was found to be shifted by about (40–50) keV towards higher energy as compared to literature values. This observation could be explained as due to energy summing of α-particles with conversion electrons emitted from a level populated by the α-decay, which is located about 55 keV above the ground state. The summing effect was registered with our set-up but not with that used in ref. [14].

Analysis of α-α correlations in the irradiations leading to the production of ^{251}No led to the identification of an isomeric state $^{251\mathrm{m}}$No decaying by α-emission into an isomeric state $^{247\mathrm{m}}$Fm. On the basis of systematics the isomeric states were attributed to the $1/2^+[631]$ Nilsson level.

Progress has been achieved in understanding the complicated α-decay pattern of $^{247\mathrm{g}}$Fm. However, our data are not fully satisfying and so our suggested interpretation requires confirmation by more sensitive measurements. A factor of ten in statistics is needed. Thus our interpretation still has to be understood rather as a working hypothesis. The α-decay of $^{247\mathrm{g}}$Fm is interpreted to populate the $7/2^+[624]$ Nilsson level in ^{243}Cf by a favoured transition. This level decays to the $1/2^+[631]$ ground state possibly via the $5/2^+[522]$ Nilsson level in at least three steps. Three γ-lines were observed. Meaningful assignments (needed to be confirmed, however) are the transitions $7/2^+[624] \to 5/2^+[622]$ (166.2 keV), $7/2^+[624] \to 7/2^+$ (121.5 keV), which is a band member built up on the $5/2^+[622]$ level, and $5/2^+[622] \to 3/2^+$ (141.4 keV) member of the band built up on the $1/2^+[631]$ level.

In summary, our data show the continuation of the ground-state spin systematics of $N = 145$, 149, and 151 even-Z isotones up to ^{243}Cf ($N = 145$, $1/2^+[631]$), ^{251}No ($N = 149$, $7/2^+[624]$), and ^{255}Rf ($N = 151$, $9/2^-[734]$). A different behavior is observed for the $N = 147$ isotones. Our observed decay properties of ^{245}Cf are not in line with a $5/2^+[622]$ ground-state configuration as attributed to the lighter isotones, but suggest $1/2^+[631]$, while for the next heavier isotone ground state is assigned to $7/2^+[624]$.

Our data rates show, that with respect to available beam currents, detection efficiencies and acceptable long irradiation times, α-γ-spectroscopy in the present state of the art is a tool for detailed investigation of radioactive decay for nuclei with production cross-sections down to 100 pb, which roughly refers to the production cross-section of ^{265}Hs in the reaction ^{208}Pb(^{58}Fe,n)^{265}Hs [8]. Already slight improvements of the experimental techniques will certainly push this limit down to at least 10 pb within the next few years.

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