Eur. Phys. J. A **12**, 57–67 (2001)

**THE EUROPEAN
PHYSICAL JOURNAL A**

Decay properties of neutron-deficient isotopes ^{256,257}Db, ^{255}Rf, ^{252,253}Lr

F.P. Heßberger[1,a], S. Hofmann[1], D. Ackermann[1,b], V. Ninov[1,c], M. Leino[2], G. Münzenberg[1,b], S. Saro[3], A. Lavrentev[4], A.G. Popeko[4], A.V. Yeremin[4], and Ch. Stodel[1,d]

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

Received: 10 January 2001
Communicated by J. Äystö

Abstract. Isotopes of dubnium (element 105) with mass numbers $A = 256$, 257, and 258 were produced by the reaction ^{209}Bi(^{50}Ti,xn)$^{259-x}$Db ($x = 1, 2, 3$) at projectile energies of (4.59–5.08) AMeV. Excitation functions were measured for the 1n, 2n and 3n evaporation channels. The same position of the excitation function was observed for the 1n channel as for the previously measured 1n channel of the reaction ^{208}Pb(^{50}Ti,1n)^{257}Rf. The measured α-decay data of ^{257}Db and its daughter products resulted in the identification of α-decaying isomeric states in ^{257}Db and ^{253}Lr. Two new isotopes, ^{256}Db and ^{252}Lr, were produced at the highest bombarding energies of 4.97 AMeV and 5.08 AMeV. They were identified by delayed α-α coincidences. The measured half-lives are $(1.6^{+0.5}_{-0.3})$ s for ^{256}Db and $(0.36^{+0.11}_{-0.07})$ s for ^{252}Lr. Besides α-decay, a spontaneous fission activity of $T_{1/2} = (2.3^{+1.1}_{-0.6})$ s was observed and attributed to an electron-capture branch of ^{256}Db, which feeds the fissioning nucleus ^{256}Rf. A branching ratio of 0.36 ± 0.12 was obtained. The isotope ^{255}Rf was produced by the reaction ^{207}Pb(^{50}Ti,2n)^{255}Rf. Improved decay data have been obtained by means of α- and α-γ spectroscopy.

PACS. 23.60.+e Alpha decay – 25.70.Jj Fusion and fusion-fission reactions – 25.85.Ca Spontaneous fission – 23.20.Lv Gamma transitions and level energies

1 Introduction

The present investigation of evaporation residue production in irradiation of ^{209}Bi targets with ^{50}Ti projectiles was laid out to study the nuclear decay properties of ^{258,257,256}Db and their decay products and to measure excitation functions for 1n, 2n and 3n evaporation channels. The enhanced sensitivity of our experimental set-up compared to previous studies [1] allowed for a more detailed investigation of the decay properties of the produced isotopes. New results have been obtained for the product from 2n de-excitation (^{257}Db) and its α-decay products ^{253}Lr and ^{249}Md. Alpha-decay of the 3n de-excitation product (^{256}Db) and its daughter product ^{252}Lr have been observed for the first time. The spectroscopic results on the product from 1n de-excitation (^{258}Db) are not unambiguous and demand further studies. The nucleus ^{255}Rf was produced in a previous study [2] by the reactions ^{208}Pb(^{50}Ti,3n)^{255}Rf and ^{206}Pb(^{50}Ti,n)^{255}Rf. The analysis of α-α correlations to its daughter product ^{251}No gave indication for an isomeric state decaying by α-emission [2]. This result was insofar unexpected since on the basis of calculated level sequences [3] no isomeric state with a half-life of ≈ 1 s was predicted at excitation energies $E^* \leq 1$ MeV. To clarify this situation we studied more precisely the α-decay of this isotope. Instead of the reactions used in ref. [2] the more efficient reaction ^{207}Pb(^{50}Ti,2n)^{255}Rf was selected. A cross-section of $\sigma_{\max}(2\text{n}) \approx 10$ nb was expected. The region of isotopes investigated in this study is shown in fig. 1.

"Cold" fusion reactions of lead and bismuth target nuclei with projectiles in the range $Z_{\text{p}} = (24\text{–}30)$ have been shown up to be successful for the production of heavy nuclei with $Z > 106$ [4]. Production rates, however, decrease rapidly with increasing proton

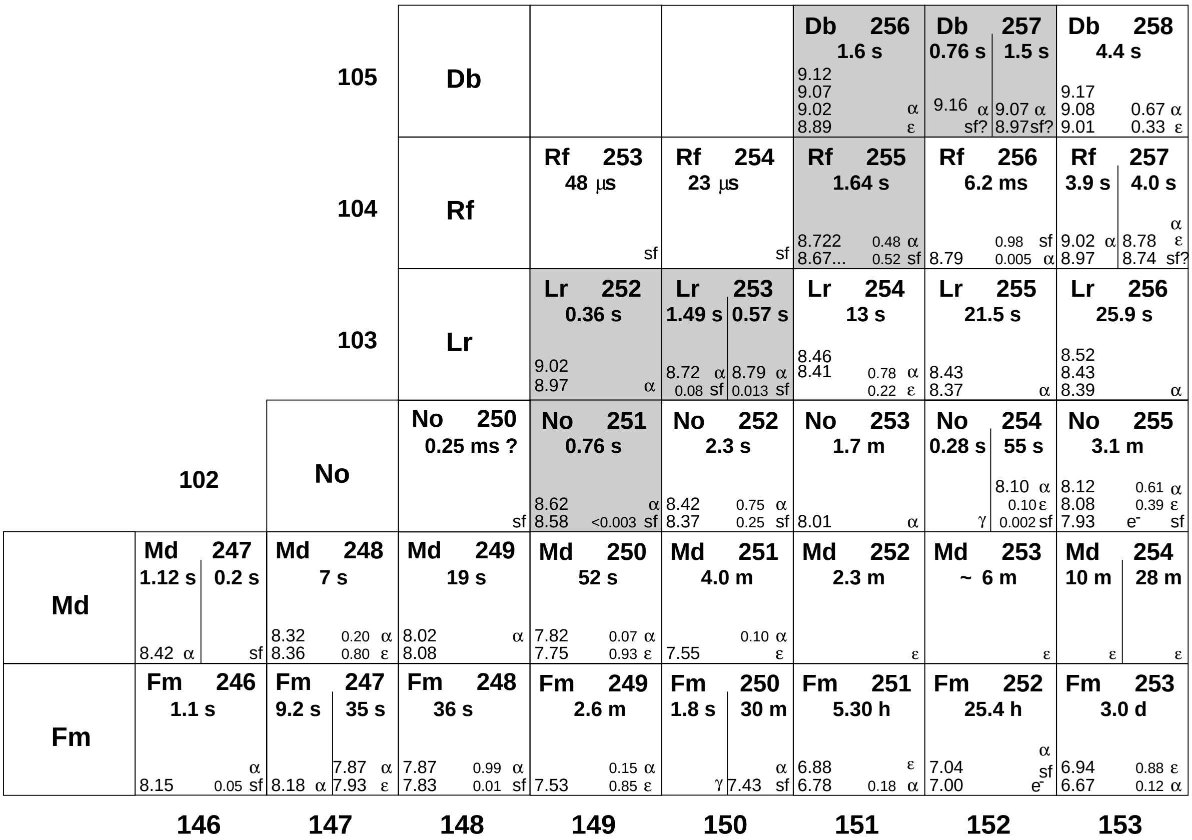
---

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

[b] Also at Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany.

[c] Now at E.O. Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA.

[d] Now at GANIL, F-14076 Caen, France.



105	**Db**						**Db 256** **1.6 s** 9.12 9.07 9.02 α 8.89 ε	**Db 257** **0.76 s** **1.5 s** 9.16 α 9.07 α sf? 8.97 sf?	**Db 258** **4.4 s** 9.17 9.08 0.67 α 9.01 0.33 ε
104	**Rf**				**Rf 253** **48 μs** sf	**Rf 254** **23 μs** sf	**Rf 255** **1.64 s** 8.722 0.48 α 8.67... 0.52 sf	**Rf 256** **6.2 ms** 0.98 sf 8.79 0.005 α	**Rf 257** **3.9 s** **4.0 s** α 9.02 α 8.78 ε 8.97 8.74 sf?
103	**Lr**				**Lr 252** **0.36 s** 9.02 8.97 α	**Lr 253** **1.49 s** **0.57 s** 8.72 α 8.79 α 0.08 sf 0.013 sf	**Lr 254** **13 s** 8.46 8.41 0.78 α 0.22 ε	**Lr 255** **21.5 s** 8.43 8.37 α	**Lr 256** **25.9 s** 8.52 8.43 8.39 α
102	**No**			**No 250** **0.25 ms ?** sf	**No 251** **0.76 s** 8.62 α 8.58 <0.003 sf	**No 252** **2.3 s** 8.42 0.75 α 8.37 0.25 sf	**No 253** **1.7 m** 8.01 α	**No 254** **0.28 s** **55 s** 8.10 α 0.10 ε γ 0.002 sf	**No 255** **3.1 m** 8.12 0.61 α 8.08 0.39 ε 7.93 e^- sf
101	**Md**	**Md 247** **1.12 s** **0.2 s** 8.42 α sf	**Md 248** **7 s** 8.32 0.20 α 8.36 0.80 ε	**Md 249** **19 s** 8.02 α 8.08	**Md 250** **52 s** 7.82 0.07 α 7.75 0.93 ε	**Md 251** **4.0 m** 0.10 α 7.55 ε	**Md 252** **2.3 m** ε	**Md 253** **~ 6 m** ε	**Md 254** **10 m** **28 m** ε ε
100	**Fm**	**Fm 246** **1.1 s** α 8.15 0.05 sf	**Fm 247** **9.2 s** **35 s** 7.87 α 8.18 α 7.93 ε	**Fm 248** **36 s** 7.87 0.99 α 7.83 0.01 sf	**Fm 249** **2.6 m** 0.15 α 7.53 0.85 ε	**Fm 250** **1.8 s** **30 m** α γ 7.43 sf	**Fm 251** **5.30 h** 6.88 ε 6.78 0.18 α	**Fm 252** **25.4 h** α 7.04 sf 7.00 e^-	**Fm 253** **3.0 d** 6.94 0.88 ε 6.67 0.12 α
		146	**147**	**148**	**149**	**150**	**151**	**152**	**153**

Fig. 1. Excerpt from the chart of nuclei, $Z = 100$–105, $N = 146$–153.

number of the compound nuclei, and, moreover are extremely sensitive to the excitation energy. To optimize the bombarding energy for the production of new elements [5–7] extrapolated values from measured excitation functions ^{208}Pb(^{50}Ti,xn)$^{258-x}$Rf ($x = 1, 2, 3$) [2] and ^{208}Pb(^{58}Fe,n)^{265}Hs [5] were used. However, it was questionable if the extrapolated "optimum" excitation energies obtained from projectile-target combinations leading to even-even compound nuclei could also be used for odd-Z compound nuclei. A first rough estimation obtained from ^{209}Bi(^{58}Fe,n)^{266}Mt [8] agreed with the result from ^{208}Pb(^{58}Fe,n)^{265}Hs, but the data suffered from low counting rate. It therefore seemed meaningful to measure in more detail an excitation function over a wide range of excitation energies for a reaction using bismuth targets. Because of the sufficiently high cross-sections [1] and the vicinity to the already precisely measured system ^{208}Pb(^{50}Ti,xn)$^{258-x}$Rf, we chose the reaction ^{209}Bi(^{50}Ti,xn)$^{259-x}$Db.

2 Experiment

The experiment was performed at the velocity filter SHIP at GSI, Darmstadt, using an intense ^{50}Ti-beam of up to 3.1×10^{12} ions/s (≈ 500 pnA) delivered from the UNILAC accelerator. Since the standard technique for identification of heaviest nuclei was used, which is described in detail elsewhere [5], we will point out here only some specific features relevant to the data analysis.

The evaporation residues were implanted into a position-sensitive 16-strip PIPS detector ("stop detector") with an active area of (80×35) mm^2, where their kinetic energies as well as subsequent α-decays or spontaneous fission (sf) were measured. Six silicon detectors of equal shape and size were mounted in the backward hemisphere ("backward detector") facing the "stop detector". They were used to measure α-particles or products from sf escaping the "stop detector" with a solid angle of 85% of 2π.

Calibration was performed using α energies of isotopes in the range from radon to thorium produced by the reaction $^{50}\mathrm{Ti} + {}^{170}\mathrm{Er} \rightarrow {}^{220}\mathrm{Th}^*$. The energy resolution for individual strips was (18–20) keV (FWHM). For α-lines obtained by summing the energy loss signal from the "stop detector" and the "residual" energy signal from the "backward detector" ("sum events") the resolution varied within (40–120) keV depending on the individual strip of the "backward detector". A systematic uncertainty of ± 10 keV was added quadratically to the error obtained from the fitting procedure of Gaussian curves to the data points.

Genetic relationship between implanted evaporation residues (ER) and succeeding α-decays or spontaneous fission (sf) events was established by the method of ER-α-α or ER-sf correlation: after stopped in the detector an implanted nucleus will remain at the position where it came to rest. Since dislocation due to recoil energy transferred to the residual nucleus by an emitted α-particle (typically some μm) and the range of α-particles or fission products (typically some ten μm) are considerably smaller than the position resolution of the detector ($\approx$300 μm (FWHM)), the implanted evaporation residues and succeeding decays will be characterized (within the detector resolution) by the same vertical position within the detector. In our experiment 95% of the events were found within an interval ($y_{\alpha1}$-$y_{\alpha2}$) $\leq \pm$0.5 mm (α-α correlations), or (y_{ER}-y_α) $\leq \pm$1.2 mm (ER-α correlations). The larger value in the latter case was due to the fact that signals for evaporation residues and α-particles were stored in different ADCs using also different main amplifiers for the corresponding detector signals.

^{255}Rf was produced in two experimental runs. In the second one we used a High Purity Germanium (HPGe) Coaxial Detector mounted directly behind the "stop detector" to measure coincidences between α-particles and γ-rays. Energy calibration and estimation of the relative efficiency was performed using known transition energies and intensities of γ-lines from a ^{133}Ba and a ^{152}Eu source. A measurement of the absolute efficiency of the Ge-detector was not performed, it was, however, roughly estimated from the number of ^{213}Ra α-decays into the first excited level of ^{209}Rn ($E^* = 110.1$ keV) [9,10] and the number of α-γ coincidences $E_\alpha = 6624$ keV–$E_\gamma = 110.1$ keV. Internal conversion was taken into account using K-, L- and M-conversion coefficients for $E2$-transition according to [11]. (^{213}Ra was produced by a "test reaction" ^{208}Pb(^{12}C,7n)^{213}Ra.) Scaling the result with the relative values from the source measurements we obtained $\epsilon = 0.06$ at $E_\gamma = 140$ keV and $\epsilon = 0.055$ at $E_\gamma = 200$ keV. We believe these values reliable within a factor of two.

Table 1. Compilation of reaction data; experimental data for ^{50}Ti + ^{208}Pb were taken from refs. [2,12]. The given error bars of the cross-sections result from statistical uncertainties only; systematic uncertainties may change all cross-section values up to a factor of two. The errors of $E(\sigma_{1\mathrm{n,max}})$, $E(\sigma_{2\mathrm{n,max}})$, $\Delta E(\sigma_{1\mathrm{n,max}})$(FWHM), $\Delta E(\sigma_{2\mathrm{n,max}})$(FWHM) represent the uncertainty of the fit procedure and do not include the uncertainty of the binding energies of the compound nuclei which were taken from [13].

	^{50}Ti + ^{208}Pb	^{50}Ti + ^{209}Bi
$\sigma_{1\mathrm{n,max}}$	10 ± 1 nb	4.3 ± 0.4 nb
$\sigma_{2\mathrm{n,max}}$	12 ± 1 nb	2.4 ± 0.3 nb
$E(\sigma_{1\mathrm{n,max}})$	15.6 ± 0.1 MeV	15.8 ± 0.1 MeV
$\Delta E(\sigma_{1\mathrm{n,max}})$(FWHM)	4.3 ± 0.2 MeV	3.4 ± 0.2 MeV
$E(\sigma_{2\mathrm{n,max}})$	21.5 ± 0.1 MeV	22.3 ± 0.2 MeV
$\Delta E(\sigma_{1\mathrm{n,max}})$(FWHM)	6.2 ± 0.6 MeV	5.5 ± 0.5 MeV
Q value	-169.5 MeV	-171.9 MeV

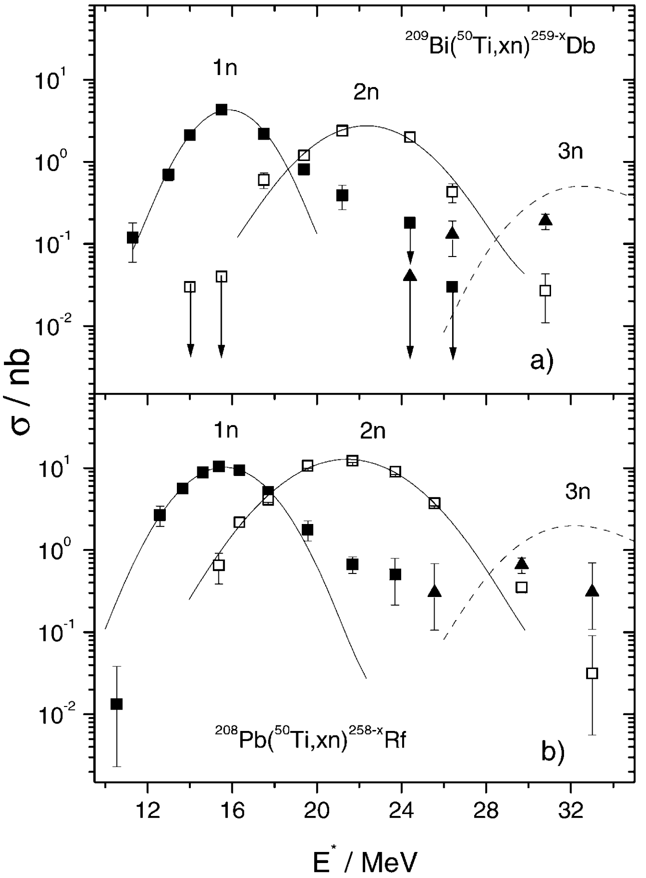


Fig. 2. Experimental excitation functions for ^{50}Ti + ^{209}Bi (a) and ^{50}Ti + ^{208}Pb (b). The full lines are the results from fitting Gaussians to the data (see text); the dashed lines are to guide the eye. Error bars represent statistical errors only. If not visible, error bars are smaller than the size of the symbol.

3 Excitation functions

The production of evaporation residues (ER) was measured for excitation energies of the compound nuclei ranging from $E^* = 11$ MeV to 31 MeV. The excitation energies were calculated using mass excess data published in ref. [13] for a reaction in the center of the target thickness. The energy loss of the projectiles in the upstream target backing and the first half of the target was $\Delta E \approx 2.8$ MeV according to ref. [14]. The excitation functions are shown in fig. 2. Maximum production cross-sections of σ(1n,max) = (4.3 $\pm$ 0.4) nb and σ(2n,max) = (2.4 $\pm$ 0.3) nb were measured. For the 3n deexcitation channel a cross-section σ(3n) = (0.19 $\pm$ 0.04) nb was measured at $E^* = 30.8$ MeV. This value can be regarded as close to σ(3n,max), although the 3n excitation function is incomplete. Gaussian curves were fitted to the data points for a comparison with the results from ^{50}Ti + ^{208}Pb [2,12]. We obtained for the positions and widths of the curves $E^*(\sigma_{1\mathrm{n,max}}) = (15.8 \pm 0.1)$ MeV, $\Delta E^*(\sigma_{1\mathrm{n}}) = (3.4 \pm 0.2)$ MeV (FWHM) and $E^*(\sigma_{2\mathrm{n,max}}) = (22.3 \pm 0.2)$ MeV, $\Delta E^*(\sigma_{2\mathrm{n}}) = (5.5 \pm 0.5)$ MeV (see also table 1).

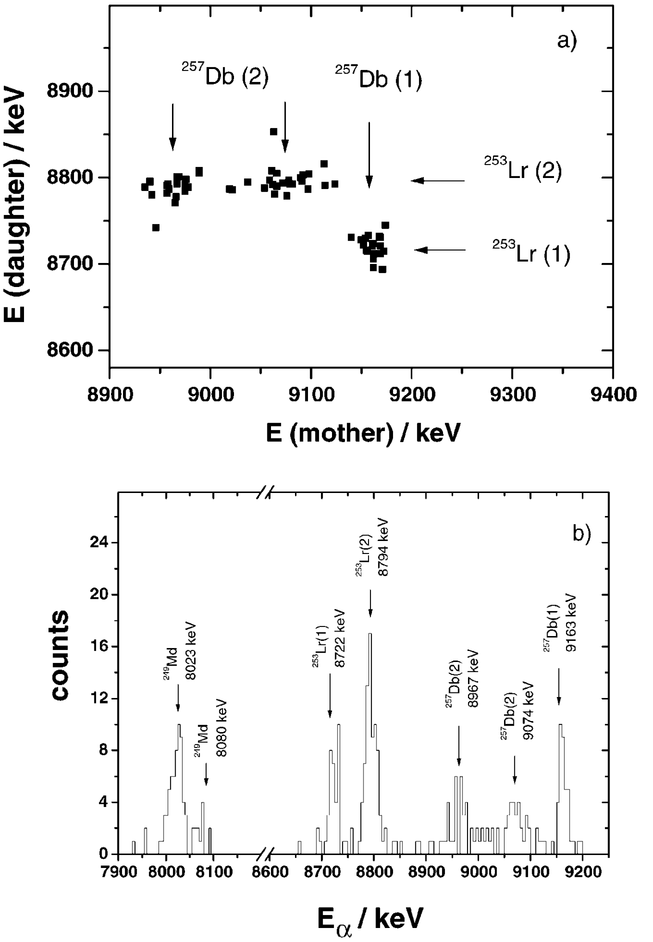


Fig. 3. a) α-α correlation plot for ^{257}Db $\rightarrow$ ^{253}Lr; b) spectrum of α-events attributed to ^{257}Db, ^{253}Lr and ^{249}Md.

A comparison of the Gaussian fits with those obtained for ^{50}Ti + ^{208}Pb resulted in an agreement for $E^*(\sigma_{1\mathrm{n,max}})$ within the error bars, while for $E^*(\sigma_{2\mathrm{n,max}})$ an increase of $\Delta E^* \approx 0.8$ MeV was obtained for ^{50}Ti + ^{209}Bi. Since this value is considerably smaller than the energy loss $\Delta E_{\mathrm{CM}} \approx 3$ MeV of the projectiles in the target [14], it remains unclear if this is a real effect or an artefact due to target inhomogeneities.

4 Decay properties of ^{257}Db, ^{253}Lr and ^{249}Md

4.1 Analysis of the α-decay chains

The isotopes ^{257}Db and ^{253}Lr were first observed in a bombardment of ^{209}Bi with ^{50}Ti at SHIP [1]. They were identified by delayed α-α coincidences with the decays of ^{249}Md and ^{245}Es. Three equally intense α-lines of 9160 keV, 9071 keV and 8970 keV were assigned to ^{257}Db, two α-lines of 8800 keV and 8722 keV were assigned to ^{253}Lr; half-lives were $(1.4^{+0.6}_{-0.3})$ s for ^{257}Db and $(1.3^{+0.6}_{-0.3})$ s for ^{253}Lr. These data were obtained on the basis of only ten observed events. In the present experiment we observed about 120 α-decays of ^{257}Db followed by decays of ^{253}Lr. While the previously reported energies of ^{257}Db and ^{253}Lr could be reproduced within the error bars (see table 2), the α-α correlations between ^{257}Db and ^{253}Lr resulted in new information on the decay properties: α-decays of 9163 keV [^{257}Db(1)] were only followed by α-decays of 8722 keV [^{253}Lr(1)], while α-decays of 9074 keV and 8967 keV [^{257}Db(2)] were only followed by α-decays of 8794 keV [^{253}Lr(2)] as shown in fig. 3a. Upper probability limits for "cross correlations" are p[^{257}Db(1) $\xrightarrow{\alpha}$ ^{253}Lr(2)] ≤ 0.02 and p[^{257}Db(2) $\xrightarrow{\alpha}$ ^{253}Lr(1)] ≤ 0.01.

The analysis of the linewidths showed a striking difference between ^{257}Db(1) and ^{257}Db(2) (see fig. 3a and b). The width of the 9163 keV line of ^{257}Db(1) is $\Delta E = 17.5$ keV (FWHM). This value is, within the uncertainties, in agreement with the results for ^{253}Lr(1): $E_\alpha = 8722$ keV, $\Delta E = 25.3$ keV, for ^{253}Lr(2): $E_\alpha = 8794$ keV, $\Delta E = 20.8$ keV (see fig. 3b), for ^{250}Fm: $E_\alpha = 7448$ keV, $\Delta E = 21.9$ keV, produced by the decay of ^{258}Db, and for ^{216}Th: $E_\alpha = 7923$ keV, $\Delta E = 21.5$ keV, produced by a "calibration reaction" ^{50}Ti + ^{170}Er. The two α-groups of ^{257}Db(2), however, have significantly broader linewidths; we obtained $\Delta E = 41.9$ keV for the 8967 keV group and $\Delta E = 44.6$ keV for the 9074 keV group. This indicates that the latter two are strongly influenced by energy summing of α-particles and conversion electrons. For the same reason it is not unambiguous, if the accumulation of events at $E_\alpha \approx 9021$ keV represents a single transition or is also produced by energy summing of α-particles and conversion electrons.

For ^{249}Md, the α-decay daughter of ^{253}Lr, two α-lines were measured (see fig. 3b): a transition of $E_{\alpha 1} = 8023$ keV, $i_1 = 0.79 \pm 0.12$, already known from the literature, and a weaker new transition of $E_{\alpha 2} = 8080$ keV, $i_2 = 0.21 \pm 0.05$. The common half-life is $T_{1/2} = (19^{+3}_{-2})$ s. However, also another interpretation seems possible since two differences between α-decays following ^{253}Lr(1) or ^{253}Lr(2) are indicated: a) α-particles of $E_{\alpha 1}$ following α-decay of ^{253}Lr(1) have a mean energy of $E_{\alpha 11} = (8025 \pm 2)$ keV, those following ^{253}Lr(2) a value of $E_{\alpha 12} = (8022 \pm 2)$ keV (the errors denote the accuracy of the fitting procedure only); while both energies still agree within the error bars, the line $E_{\alpha 12}$ is definitely broader. We obtain $\Delta E_{\alpha 12} = 40.1$ keV (FWHM) and $\Delta E_{\alpha 11} = 26.3$ keV (FWHM). b) α-decays $E_\alpha > 8060$ keV following the decay of ^{253}Lr(1) show a half-life of $T_{1/2} = (1.5^{+1.2}_{-0.5})$ s, which is one order of magnitude lower than the common half-life of all α-decays in the range 7.95 MeV–8.15 MeV following α-decays of ^{253}Lr(1) or ^{253}Lr(2).

In the case that the differences could be confirmed by more sensitive measurements, we then must conclude, that an isomeric state decaying by α-emission also exists in ^{249}Md.

4.2 Isomeric states in ^{257}Db and ^{253}Lr

The lack of cross correlations between the different clusters shown in fig. 3a and discussed in the previous section suggests that besides the ground state ^{257g}Db also an isomeric state ^{257m}Db is populated by the reaction process.

Table 2. Summary of decay properties: ^{a} tentative line, ^{b} this isotope has probably some more weaker α-lines, ^{c} energy probably influenced by summing of α-particles and conversion electrons.

Isotope	E_α/keV	i_{rel}	$T_{1/2}$/s		HF
^{251}No	8621 ± 10	$0.96^{+0.04}_{-0.06}$	0.76 ± 0.03	$b_{\mathrm{sf}} < 0.003$	1.4
	8578 ± 10	0.04 ± 0.015		$b_\alpha = 0.91^{+0.09}_{-0.22}$	24
^{252}Lr	9018 ± 20	≈ 0.75	$0.36^{+0.11}_{-0.07}$		6.9
	8974 ± 20	≈ 0.25			15
^{253}Lr	8794 ± 10		$0.57^{+0.07}_{-0.06}$	$b_{\mathrm{sf}} = 0.013^{+0.030}_{-0.010}$	2.3
^{253m}Lr	8722 ± 10		$1.49^{+0.30}_{-0.21}$	$b_{\mathrm{sf}} = 0.08 \pm 0.05$	2.4
^{255}Rf	8722 ± 10	≈ 0.94	1.64 ± 0.11	$b_{\mathrm{sf}} = 0.52 \pm 0.06$	1.9
	8924 ± 15^a	≤ 0.05			≥ 194
	8670 ± 10^a	≤ 0.05			≥ 31
	8583 ± 10^a	≤ 0.05			≥ 16
^{256}Db	9014 ± 20	≈ 0.67	$1.6^{+0.5}_{-0.3}$	$b_{\mathrm{EC}} = 0.36 \pm 0.12$	11
	9120 ± 20^a	≈ 0.11			114
	9075 ± 20^a	≈ 0.11			86
	8891 ± 20^a	≈ 0.11			22
^{257}Db^b	9074 ± 10^c	≈ 0.5	$1.50^{+0.19}_{-0.15}$	$b_{\mathrm{sf}} \leq 0.06$	11
	8967 ± 15^c	≈ 0.5			5.1
^{257m}Db	9163 ± 10		$0.76^{+0.15}_{-0.11}$	$b_{\mathrm{sf}} \leq 0.13$	5.1

Both states decay by α-emission. The low hindrance factors for the α-decays of ^{257}Db(1), ^{253}Lr(1), ^{253}Lr(2) and the 9109 keV transition of ^{257}Db(2) indicate that they represent favoured transitions into analogous Nilsson levels in the daughter nuclei. (In agreement with fig. 4 we use in the following discussion the Q_α values instead of the energies E_α.) The lack of cross correlations further proves that also ^{253m}Lr predominantly decays by α-emission, while a possible decay into the ground state by γ-emission or internal conversion is a rare process with p($^{253m}\mathrm{Lr} \overset{\gamma,\mathrm{IC}}{\rightarrow} {}^{253g}\mathrm{Lr}$) < 0.02. Under these circumstances it seems reasonable to assign ^{257}Db(1), ^{253}Lr(1) to the isomeric states and ^{257}Db(2), ^{253}Lr(2) to the ground states. Otherwise the 9217 keV transition of ^{257}Db(2) would represent the decay into a nuclear level of ^{253}Lr below the isomeric state. In such a case correlation of both, the 9109 keV and the 9217 keV transition to ^{253}Lr α-decays of the same energy would not occur. Whether the level in ^{249}Md populated by α-decay of ^{253m}Lr is an isomeric one is unclear so far. As discussed in subsect. 4.1 there are some indications of differences in α-decays following those of ^{253}Lr(1) and ^{253}Lr(2), respectively, but the quality of the data does not allow a definite statement on the existence of an isomeric state decaying either by α-emission or, having a half-life $T_{1/2} \ll T_\alpha(^{249}\mathrm{Md})$, by γ-emission or internal conversion.

Support for the existence of isomeric states in ^{257}Db and ^{253}Lr is obtained from calculations of Cwiok *et al.* [3]. Their results for ^{257}Db, ^{253}Lr, and ^{249}Md at excitation energies below one MeV are shown in fig. 4a. Using Weiss-Kopf estimations for lifetimes of γ-transitions [9], the $1/2^-[521]$ level in ^{257}Db and ^{253}Lr is a candidate for an isomeric state decaying by α-emission, provided that the energy difference to the lower-lying $7/2^-[514]$ level is lower than 150 keV and that in ^{257}Db the $5/2^-[512]$ level lies above the $1/2^-[521]$ level.

A possible decay scheme on the basis of the predictions of [3] is shown in fig. 4b. Attributing $1/2^-[521]$ levels to the isomers in ^{257}Db and ^{253}Lr, the assumption of a $1/2^-[521]$ level as the ground state in ^{249}Md as predicted in ref. [3] is in contradiction to our data, regardless if we attribute ^{257}Db(2), ^{253}Lr(2) to the isomeric levels and ^{257}Db(1) and ^{253}Lr(1) to the ground states, or vice versa. As can be seen from the decay scheme in fig. 4b the Q_α values for the isomeric and ground-state decays (favoured transitions) in ^{257}Db and ^{253}Lr have to fulfill the relations:

$$Q^m_{\mathrm{Db}} = (m_{\mathrm{Db}}c^2 + E^m_{\mathrm{Db}}) - (m_{\mathrm{Lr}}c^2 + E^m_{\mathrm{Lr}}) - m_\alpha c^2, \quad (1)$$

$$Q^g_{\mathrm{Db}} = m_{\mathrm{Db}}c^2 - (m_{\mathrm{Lr}}c^2 + E^*_{\mathrm{Lr}}) - m_\alpha c^2, \quad (2)$$

$$Q^m_{\mathrm{Lr}} = (m_{\mathrm{Lr}}c^2 + E^m_{\mathrm{Lr}}) - m_{\mathrm{Md}}c^2 - m_\alpha c^2, \quad (3)$$

$$Q^g_{\mathrm{Lr}} = m_{\mathrm{Lr}}c^2 - (m_{\mathrm{Md}}c^2 + E^*_{\mathrm{Md}}) - m_\alpha c^2. \quad (4)$$

Here Q^m_{Db}, Q^g_{Db}, Q^m_{Lr}, Q^g_{Lr} denote the Q_α values for the favoured transitions of isomeric and ground-state decays of ^{257}Db and ^{253}Lr, m_{Db} and m_{Lr} the ground-state mass excesses of ^{257}Db and ^{253}Lr, m_α the mass excess of the α-particle, E^m_{Db}, E^m_{Lr} the energy of the isomeric levels in ^{257}Db and ^{253}Lr, E^*_{Lr}, E^*_{Md} the energy of excited states in ^{253}Lr and ^{249}Md possibly populated by the ground-state decays of ^{257}Db and ^{253}Lr.

From (1) to (4) one obtains an energy balance of the α-decay sequences $^{257m}\mathrm{Db} \overset{\alpha}{\rightarrow} {}^{253m}\mathrm{Lr} \overset{\alpha}{\rightarrow} {}^{249}\mathrm{Md}$ and ^{257g}Db

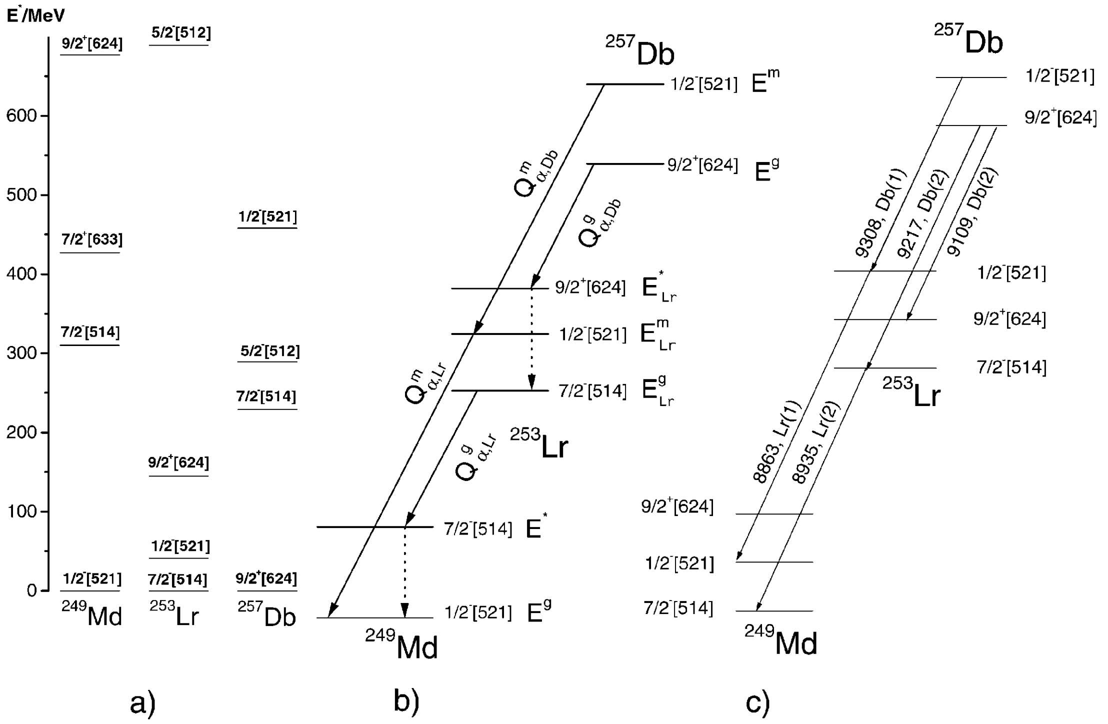


Fig. 4. a) Level schemes predicted for ^{249}Md, ^{253}Lr, ^{257}Db according to [3]; b) symbolic decay scheme for ^{257}Db using level sequences as predicted in ref. [3]; c) tentative decay scheme suggested for ^{257,257m}Db on the basis of the observed α-decay energies. The numbers denote the Q values.

$\xrightarrow{\alpha}$ ^{253g}Lr $\xrightarrow{\alpha}$ ^{249}Md:

$$E^m_{\rm Db} = (Q^m_{\rm Db} + Q^m_{\rm Lr}) - (Q^g_{\rm Db} + Q^g_{\rm Lr}) - E^*_{\rm Lr} - E^*_{\rm Md} \qquad (5)$$

and from (3) and (4) an energy balance for the α-decays ^{253m}Lr $\xrightarrow{\alpha}$ ^{249}Md and ^{253g}Lr $\xrightarrow{\alpha}$ ^{249}Md:

$$E^m_{\rm Lr} = (Q^m_{\rm Lr} - Q^g_{\rm Lr}) - E^*_{\rm Md}. \qquad (6)$$

Assuming ^{257}Db(2), ^{253}Lr(2) as the decays of the isomeric levels and ^{257}Db(1) and ^{253}Lr(1) as the ground-state decays we obtain for (5) using the measured energies for the favoured transitions

$$E^m_{\rm Db} = -127\ \text{keV} - E^*_{\rm Lr} - E^*_{\rm Md}$$

and hence a negative value for $E^m_{\rm Db}$.

Assuming, on the other hand, ^{257}Db(1), ^{253}Lr(1) as the decays of the isomeric levels and ^{257}Db(2) and ^{253}Lr(2) as the ground-state decays and a lower limit $E^*_{\rm Lr} = 108$ keV, *i.e.* the energy difference between the two α-lines attributed to ^{257}Db, we can fulfill (5) by

$$E^m_{\rm Db} \leq 19\ \text{keV} - E^*_{\rm Md}$$

but obtain from (6)

$$E^m_{\rm Lr} = -72\ \text{keV} - E^*_{\rm Md}$$

and hence $E^m_{\rm Lr} < 0$. We therefore assign the $7/2^-[514]$ level to the ground state of ^{249}Md, as it was done also for heavier mendelevium isotopes [9].

Our proposed decay scheme is shown in fig. 4c. Yet, we want to point out that this scheme is tentative and needs to be confirmed by more detailed measurements, since it still exhibits a not understood peculiarity. Interpreting the 9109 keV line of ^{257}Db(2) as decay into the $9/2^+[624]$ level of ^{253}Lr and the 9217 keV line as decay into the $7/2^-[514]$ level of ^{253}Lr, the transition $9/2^+[624] \rightarrow 7/2^-[514]$ would be $E1$, for which conversion coefficients $k_L \approx 0.1$ and $k_M \approx 0.03$ are expected [11]. So the α-lines could not be noticeably influenced by energy summing of α-particles and conversion electrons. One may of course speculate that decay of the $9/2^+[624]$ level in ^{253}Lr populates the excited $9/2^-$ more strongly than the $7/2^-[514]$ ground state. The transition $9/2^- \rightarrow 7/2^-[514]$ is $M1$ and will be highly converted. Such a behavior has been observed for the decay $9/2^-[734] \rightarrow 7/2^+[624]$, $9/2^+$ in ^{247}Cf, populated by α-decay of ^{251}Fm [15] (see also sect. 6). Yet the amount of data does not allow to draw definite conclusions. More sensitive measurements are necessary.

4.3 Spontaneous-fission properties of ^{257}Db and ^{253}Lr

Four spontaneous-fission events following α-decays within $\Delta t = 5$ s were observed in this experiment. Based on the energies of the preceding α-particles three of the fission events were attributed to ^{253}Lr(1) and one to ^{253}Lr(2), resulting in spontaneous fission branchings $b_{\rm sf} = 0.08 \pm 0.05$ for ^{253m}Lr and $b_{\rm sf} = 0.013^{+0.030}_{-0.010}$ for ^{253g}Lr.

Search for spontaneous fission of ^{257}Db was difficult. Due to "background" of fission events of ^{256}Rf (produced by EC-decay of ^{256}Db (see sect. 5 and fig. 1)) and ^{258}Rf (produced by EC-decay of ^{258}Db) we had to restrict the search to the bombarding energies $E = 4.85$ AMeV and $E = 4.92$ AMeV at which the production cross-sections of ^{256}Db (3n channel) and ^{258}Db (1n channel) were lower than 10% of that for ^{257}Db (2n channel). At these energies the observed number of five fission events was reduced by two events, the numbers of fission events expected for the 1n and 3n channels, respectively, on the basis of the number of the observed α-events and the EC-branchings measured in this experiment, $b_{\mathrm{EC}} = 0.26 \pm 0.03$ for ^{258}Db and $b_{\mathrm{EC}} = 0.35 \pm 0.12$ for ^{256}Db (see sect. 5). Under these conditions we obtained an upper limit of three spontaneous-fission events that could be attributed to ^{257g}Db or ^{257m}Db. A definite assignment to one of these states is not possible due to the similar half-lives. So, as an upper limit we took the ratio of the total number of fission events that could be attributed to ^{257}Db (3 events) and the number of observed α-decays; the results are $b_{\mathrm{sf}} \leq 0.13$ for ^{257m}Db and $b_{\mathrm{sf}} \leq 0.06$ for ^{257g}Db.

5 Identification of ^{256}Db and ^{252}Lr

The identification of the isotopes ^{256}Db and ^{252}Lr was based on a total of 16 α-decay chains, that were followed down to ^{244}Cf according to the sequences $^{256}\mathrm{Db} \xrightarrow{\alpha} {}^{252}\mathrm{Lr} \xrightarrow{\alpha} {}^{248}\mathrm{Md} \xrightarrow{\alpha} {}^{244}\mathrm{Es} \xrightarrow{\mathrm{EC}} {}^{244}\mathrm{Cf} \xrightarrow{\alpha} {}^{240}\mathrm{Cm}$ or $^{256}\mathrm{Db} \xrightarrow{\alpha} {}^{252}\mathrm{Lr} \xrightarrow{\alpha} {}^{248}\mathrm{Md} \xrightarrow{\mathrm{EC}} {}^{248}\mathrm{Fm} \xrightarrow{\alpha} {}^{244}\mathrm{Cf} \xrightarrow{\alpha} {}^{240}\mathrm{Cm}$. Three chains consisted only of decays of ^{256}Db and ^{252}Lr, while in 13 cases they were followed by decays of ^{248}Md, ^{248}Fm or ^{244}Cf (fig. 5). In 4 cases either the energy of ^{256}Db (1 event) or ^{252}Lr (3 events) was smaller than 5 MeV. These events are regarded as α-particles escaping the "stop detector" but not being registered in one of the strips of the "backward detector". They are marked by arrows in fig. 5. It should be noticed that due to its long half-life, to avoid random correlations, only ^{244}Cf α-decays with full energy release in the "stop dectector" and occurring between the beam pulses were considered. Therefore, about 40 per cent of the ^{244}Cf-α-decays were lost.

Eight α-events assigned to ^{256}Db were registered with full energy release in the "stop detector" (small squares in fig. 5). They can be divided into four groups: each one event with an energy of $E_\alpha = 8891$ keV, 9075 keV and 9120 keV and five events in the interval $E_\alpha = (8996$–$9039)$ keV resulting in a mean energy of $E_\alpha = 9014$ keV. The decay pattern of this isotope might be more complex since a) the energy interval $E_\alpha = (8996$–$9039)$ keV is rather large, so the events may represent a line doublet, and b) two of the "sum events" ($E_\alpha = 8681$ and 9251 keV) are definitely outside these groups also with respect to the limited energy resolution. Yet, on the basis of the poor statistics, we presently will not postulate additional lines. Due to the limited energy resolution the six α-decays which were registered as "sum events" and the one escape event were only included in the half-life determinations but not respected in the estimates of the decay energy. The half-life determined from the time differences between implantation and decay is $T_{1/2} = (1.6^{+0.5}_{-0.3})$ s.

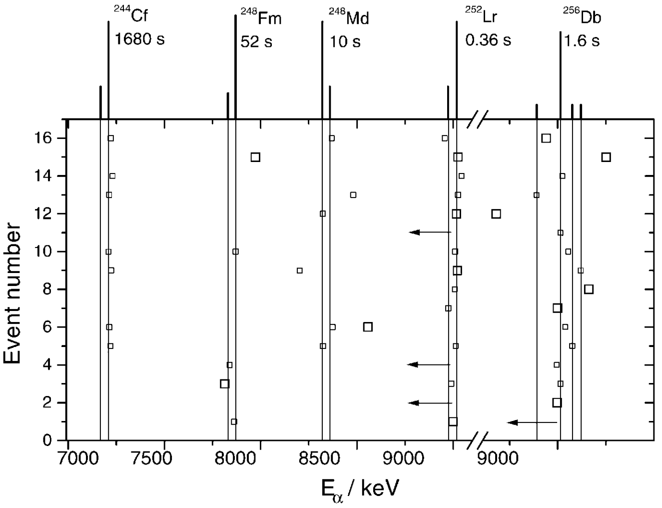


Fig. 5. Plot of the observed decay sequences of ^{256}Db; small symbols: full energy release in the "stop detector"; large symbols: energy taken as the sum of the energy losses in the "stop detector" and the "backward detector"; arrows: only energy loss in the stop detector registered; the lines in the plot refer to the α-energies, the lines at the top of the plot refer to the line intensities; ^{244}Cf, ^{248}Fm, ^{248}Md literature values, ^{252}Lr, ^{256}Db this work. In order to separate the α-decays of ^{256}Db and ^{252}Lr, we interrupted the abscissa at 9100 keV.

From the α-decays of the daughter ^{252}Lr five α-events were registered as "sum events". For three cases the energy value fits quite well to the energies for particles registered with their full energy in the "stop detector". For a fourth event of 8999 keV it was not clear to which of the energy intervals discussed below it should be attributed, while for the third event at 8557 keV only an energy signal in the "backward detector" was observed. Therefore these two events will not be respected in the further discussion. The remaining decays can be divided in two groups: three events in the interval $E_\alpha = (8956$–$8991)$ keV resulting in a mean energy of 8974 keV, and eight events in the interval $E_\alpha = (9008$–$9044)$ keV resulting in a mean energy of 9018 keV. The half-life calculated from the time differences between the α-decays of ^{256}Db and ^{252}Lr is $T_{1/2} = (0.36^{+0.11}_{-0.07})$ s.

Besides the 16 α-decays nine sf events were observed. Seven events at a beam energy of 5.08 AMeV and two events at 4.97 AMeV. The half-life deduced from these nine sf events is $T_{1/2} = (2.3^{+1.1}_{-0.6})$ s including all events. A somewhat lower value, but still agreeing within the error bars, is obtained when only the events at 5.08 AMeV are respected: $T_{1/2} = (1.7^{+0.9}_{-0.4})$ s. Due to its half-life and production characteristics this activity is attributed to the 3n channel, ^{256}Db.

Spontaneous fission of nuclei having unpaired nucleons is known to be hindered compared to neighbouring even-even nuclei. To get a rough estimate of the sf half-life of ^{256}Db we calculated an "unhindered" fission half-life, which was obtained as the geometric mean of the values for the neighbouring even-even nuclei, and multiplied with the hindrance factors (HF) for the neighbouring odd-mass nuclei having the same neutron number, ^{255}Rf ($N = 151$), or the same proton number, ^{257}Db, according to the following relations: $T_{\mathrm{sf}}(^{256}\mathrm{Db}) = T_{\mathrm{sf,unh.}}(^{256}\mathrm{Db}) \times \mathrm{HF}(^{255}\mathrm{Rf}) \times \mathrm{HF}(^{256}\mathrm{Db})$, using $T_{\mathrm{sf,unh.}}(^{256}\mathrm{Db}) = [T_{\mathrm{sf}}(^{254}\mathrm{Rf}) \times T_{\mathrm{sf}}(^{256}\mathrm{Rf}) \times T_{\mathrm{sf}}(^{256}\mathrm{Sg}) \times T_{\mathrm{sf}}(^{258}\mathrm{Sg})]^{1/4}$ and $\mathrm{HF} = T_{1/2} \times [b_{\mathrm{sf}} \times T_{\mathrm{sf,unh.}}]^{-1}$ for both ^{255}Rf and ^{257}Db with $T_{\mathrm{sf,unh.}}(^{255}\mathrm{Rf}) = [T_{\mathrm{sf}}(^{254}\mathrm{Rf}) \times T_{\mathrm{sf}}(^{256}\mathrm{Rf})]^{1/2}$ and $T_{\mathrm{sf,unh.}}(^{257}\mathrm{Db}) = [T_{\mathrm{sf}}(^{256}\mathrm{Rf}) \times T_{\mathrm{sf}}(^{258}\mathrm{Sg})]^{1/2}$.

$T_{\mathrm{sf}}(^{254}\mathrm{Rf})$, $T_{\mathrm{sf}}(^{256}\mathrm{Rf})$, $T_{\mathrm{sf}}(^{258}\mathrm{Sg})$, $b_{\mathrm{sf}}(^{255}\mathrm{Rf})$ and $T_{1/2}(^{255}\mathrm{Rf})$ are experimentally known and were taken from [2] or from this work (table 2); for $T_{\mathrm{sf}}(^{256}\mathrm{Sg})$ the calculated value from [16] was taken. For ^{257}Db the situation is more complicated. Our experiments showed the presence of two decaying levels with half-lives different by roughly a factor of two. We took for our estimation the longer half-life of the assumed ground-state transition, $T_{1/2} = 1.5$ s (^{257m}Db) and as fission branch the ratio of fission events to the total number of α-events assigned to ^{257g}Db, $b_{\mathrm{sf}} \approx 0.06$. Resulting values are $T_{\mathrm{sf,unh.}}(^{256}\mathrm{Db}) \approx 0.2$ ms, $\mathrm{HF}(^{255}\mathrm{Rf}) \approx 7000$, $\mathrm{HF}(^{257}\mathrm{Db}) \approx 6000$ and hence $T_{\mathrm{sf}}(^{256}\mathrm{Db}) \approx 8000$ s, which results in an expected fission branch $b_{\mathrm{sf}}(^{256}\mathrm{Db}) \approx 0.0002$. On the basis of this result it is not justified to attribute the observed events to sf of ^{256}Db. We therefore assume a strong EC branch leading to ^{256}Rf. Since the half-life of the former isotope $T_{\mathrm{sf}} = (6.2 \pm 0.2)$ ms [2] is much shorter than that of ^{256}Db, the observed half-life obtained from the time difference between implantation of the evaporation residue and decay by sf will be equal to that of ^{256}Db. On the basis of the number of the observed α-decays and sf events a branching value of $b_{\mathrm{EC}} = 0.36 \pm 0.12$ was obtained. A notable EC branch is also expected from theory; recent calculations of Möller *et al.* [17] result in $T_{1/2,\beta} = 22.9$ s.

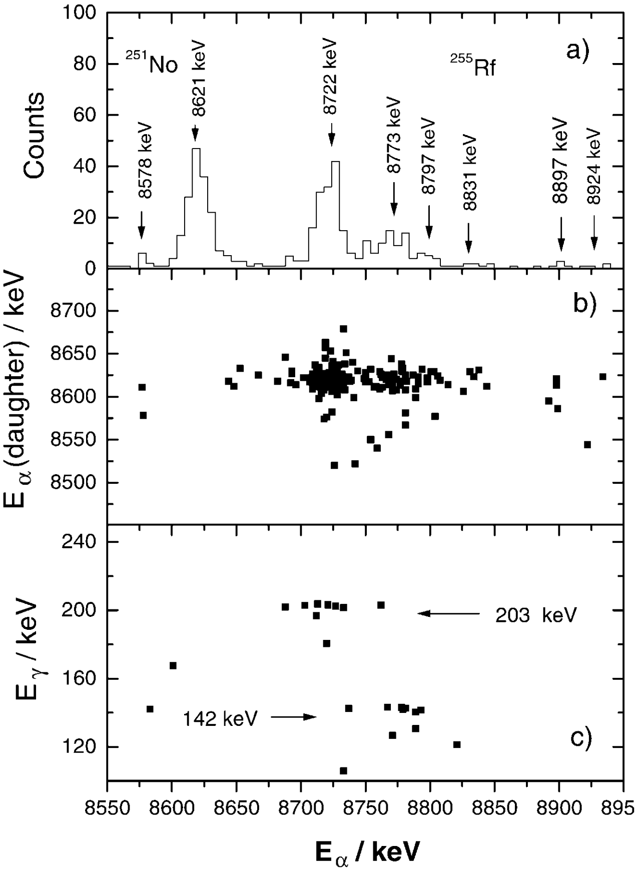


Fig. 6. Decay spectra of ^{255}Rf; a) spectra of α-events following the implantation of a heavy residue within $\Delta t = 20$ s; b) α-α correlation plot for $^{255}\mathrm{Rf} \to {}^{251}\mathrm{No}$; c) plot of α-γ coincidences attributed to the decay of ^{255}Rf.

6 Decay properties of ^{255}Rf

An indication for the existence of a low-lying isomeric state in ^{255}Rf decaying by α-emission with $T_{1/2} \approx 0.9$ s was obtained in a previous study of evaporation residues from $^{50}\mathrm{Ti} + {}^{206,208}\mathrm{Pb}$, where ^{255}Rf was produced in 1n and 3n evaporation channels. In these experiments an abnormally low number of α-decays in the interval $E_\alpha = (8720$–$8730)$ keV was followed by daughter decays (^{251}No) [2]. However, neither from theoretical predictions [3] nor from the known levels of lighter $N = 151$ nuclei with even-Z numbers (^{251}Fm, ^{249}Cf, ^{247}Cm, ^{245}Pu) [9] which have a similar structure the existence of an isomeric state of $T_{1/2} \approx 1$ s could be expected. To clarify this problem we used the more efficient $^{207}\mathrm{Pb}(^{50}\mathrm{Ti},2\mathrm{n})^{255}\mathrm{Rf}$ reaction to produce an order of magnitude more events of ^{255}Rf. The result is shown in figs. 6a and b. On the basis of the considerably improved statistics no "abnormal low" correlation rate for $E_\alpha = (8720$–$8730)$ keV is evident.

In addition, a few γ-events in coincidence to the α-decays of ^{255}Rf were observed. Two different groups are indicated (fig. 6c), a) nine γ-events with a mean energy of $E_{\gamma1} = (203 \pm 3)$ keV are essentially in coincidence to α-decays of $E_\alpha = (8722 \pm 10)$ keV ($Q_\alpha = (8904 \pm 10)$ keV), while b) seven events of $E_{\gamma2} = (142 \pm 3)$ keV are coincident to $E_\alpha = (8773 \pm 10)$ keV. For a) the sum $Q_\alpha + E_{\gamma1} = (9107 \pm 10)$ keV is equal to the value $Q_\alpha = (9109 \pm 15)$ keV for a group of α-decays in the interval $E_\alpha = (8908$–$8936)$ keV having a mean energy $E_\alpha = (8924 \pm 10)$ keV ($Q_\alpha = (9109 \pm 10)$ keV). These are the α-decays with the highest energies followed by decays of ^{251}No. So we conclude that the γ_1-transitions leads to the ground state of ^{251}No (fig. 7). Due to the lowest hindrance factor of HF = 3 the $E_\alpha = (8722 \pm 10)$ keV transition is assigned to the "favored" transition. According to the calculations of Cwiok *et al.* [3] and the assignments for lighter $N = 151$ and $N = 149$ isotones, we tentatively set the ground state of ^{255}Rf as $9/2^-[734]$ and that of ^{251}No as $7/2^+[624]$. Striking, however, is the low hindrance factor of HF = 7 for the $E_\alpha = (8773 \pm 10)$ keV transition. In the lighter $N = 149$ isotones (^{247}Cf, ^{245}Cm, ^{243}Pu [9]) the first excited Nilsson level is settled as $5/2^+[622]$. Relative intensities of decays into this level (or the first excited member of the rotational band built up on it) are <0.05, hindrance factors are typically >100. Therefore, the properties of the $E_\alpha = 8773$ keV line do not sug-

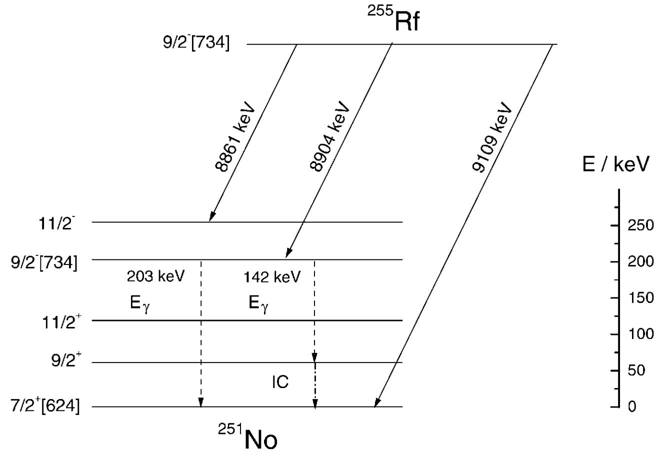


Fig. 7. Decay scheme proposed for ^{255}Rf. The numbers denote the Q values.

gest a transition $9/2^-[734]$ (^{255}Rf) → $5/2^+[622]$ (^{251}No). On the other hand, its linewidth of $\Delta E = 39$ keV hints at an energy summation of α-particles of 8722 keV and conversion electrons. Paying attention to the known α-γ-decay patterns of lighter $N = 151$ isotones ^{251}Fm, ^{249}Cf, ^{247}Cm [9], we therefore interpret the $E_\gamma = 142$ keV line as the transition $9/2^-[734] \rightarrow 9/2^+$, the first excited member of the ground-state rotational band of ^{251}No. The succeeding transition $9/2^+ \rightarrow 7/2^+[624]$ is preferably $M1$ and highly converted ($k_M \approx 14$, $k_L \approx 60$ [11]). Thus the α-line at 8773 keV is interpreted as due to energy summing of α-particles from the favored transition $9/2^-[734]$ (^{255}Rf) → $9/2^-[734]$ (^{251}No) and conversion electrons from the $9/2^+ \rightarrow 7/2^+[624]$ transition. Hence the excitation energy of the $9/2^+$ level is $E^* = (61 \pm 4)$ keV.

Whether the α-events above the $E_\alpha = 8773$ keV line represent just signals from energy summing or a single α transition cannot be stated with certainty so far on the basis of the present data: the accumulation of events around 8831 keV and the small peak indicated at $E_\alpha = 8797$ keV might be due to energy summing with conversion electrons connected to the transitions (a) $9/2^-[734] \xrightarrow{\gamma} 11/2^+ \xrightarrow{\mathrm{IC}} 7/2^+[624]$ or (b) $9/2^-[734] \xrightarrow{\gamma} 11/2^+ \xrightarrow{\mathrm{IC}} 9/2^+ \xrightarrow{\mathrm{IC}} 7/2^+[624]$. The transition $11/2^+ \rightarrow 7/2^+[624]$ is preferably $E2$ for which a K-conversion coefficient ≈ 0.1 is expected, which results in only a small number of events. The transitions $11/2^+ \rightarrow 9/2^+$ and $9/2^+ \rightarrow 7/2^+[624]$ are preferably $M1$ and are expected to be highly converted. Total summation of both conversion electrons with α-particles will also contribute to the $E_\alpha = 8831$ keV line, while partial summation may be the reason for the line indicated at $E_\alpha = 8797$ keV.

The transitions $9/2^-[734] \rightarrow 7/2^+[624]$, $9/2^+$, $11/2^+$ are $E1$ for which conversion coefficients ≤ 0.02 are expected. Although the probability for energy summing is therefore low, a few events can be expected. Especially the peak indicated at $E_\alpha = 8897$ keV is most likely due to energy summing with L conversion electrons. This assumption is supported by a) an energy difference of $\Delta E = 27$ keV to the supposed ground-state transition, which is about the L-binding energy of nobelium ($E(L1) = 29.22$ keV, $E(L2) = 28.26$ keV, $E(L3) = 21.85$ keV [9]) and b) a conversion coefficient of 0.05 ± 0.03 estimated from the number of α-decays, which is close the theoretical value of $k_L(E1) = 0.022$ according to [11].

From comparison to ^{251}Fm, ^{249}Cf, and ^{247}Cm also weak transitions $9/2^-[734]$ (^{255}Rf) → $11/2^-$ (^{251}No) can be expected. Since typical energy differences $\Delta E = E(11/2^-) - E(9/2^-[734])$ are $\Delta E \approx 50$ keV, we would expect a weak line at $E_\alpha \approx 8670$ keV ($Q_\alpha \approx 8861$ keV) where indeed some α-decays are present in both, the single and the coincidence spectrum. Predominantly the $11/2^-$ level, however, will decay by internal conversion into the $9/2^-[734]$ level, so the α-decays into the $11/2^-$ level will be strongly influenced by energy summing with conversion electrons and have resulting energies close to the $E_\alpha = 8722$ keV line; possibly its small shoulder at $E \leq 8700$ keV is effected by these "sum events".

We finally want to remark that on the basis of the γ efficiencies obtained in sect. 2 and the number of observed α-decays in the intervals $E_\alpha = (8700\text{–}8740)$ keV and $E_\alpha = (8740\text{–}8840)$ keV we would expect nine α-γ coincidences with $E_\gamma = 203$ keV and six events with $E_\gamma = 142$ keV, which is in good agreement with the observed numbers of nine and seven events. The discussion above is summarized in table 3.

7 Decay properties of ^{251}No

^{251}No was first identified in irradiation of ^{244}Cm with ^{12}C by Ghiorso *et al.* [18], who reported two α-energies of $E_{\alpha 1} = 8.60$ MeV, $i_{\alpha 1} \approx 0.8$, $E_{\alpha 2} = 8.68$ MeV, $i_{\alpha 2} \approx 0.2$, and a half-life of (0.8 ± 0.3) s. In our experiment it was produced by α-decay of ^{255}Rf. We observed the main α-transition at $E_{\alpha 1} = (8621 \pm 10)$ keV and a low intensity line at $E_{\alpha 2} = (8578 \pm 10)$ keV. An α-line at 8680 keV was not observed at a level of $i_{\mathrm{rel},8680} \leq 0.03$ (68% confidential limit). Our measured half-life is (0.76 ± 0.03) s. Hints for EC-decay of ^{251}No could be obtained in principle from α-α correlations of the type $^{255}\mathrm{Rf} \xrightarrow{\alpha} {}^{251}\mathrm{No} \xrightarrow{\mathrm{EC}} {}^{251}\mathrm{Md} \xrightarrow{\alpha} {}^{247}\mathrm{Es}$, where α-decay of ^{255}Rf and ^{251}Md are observed. However, the α-branch of ^{251}Md is expected to be $b_\alpha \leq 0.1$; no correlations of the above type have been observed. An estimation for the α-branching of ^{251}No is $0.91^{+0.09}_{-0.22}$ obtained from the total number of ^{255}Rf-α-decays and the number of correlations $^{255}\mathrm{Rf} \xrightarrow{\alpha} {}^{251}\mathrm{No} \xrightarrow{\alpha} {}^{247}\mathrm{Fm}$. Spontaneous fission of ^{251}No can be identified by correlations of the type $^{255}\mathrm{Rf} \xrightarrow{\alpha} {}^{251}\mathrm{No} \xrightarrow{\mathrm{sf}}$. No correlations of this type were observed, giving a limit $b_{\mathrm{sf}} \leq 0.003$.

8 Summary and conclusions

The complete fusion reaction ^{50}Ti + ^{209}Bi → ^{259}Db* was used to measure excitation functions for the 1n and 2n de-excitation channels. Of principal interest was to study —with respect to the reaction ^{50}Ti + ^{208}Pb → ^{258}Rf*— the change of the cross-section ratio $\sigma_{1\mathrm{n,max}}/\sigma_{2\mathrm{n,max}}$ and

Table 3. Decay properties and most probable decay mode of the daughter level populated by α-decay of ^{255}Rf; $^+$ = α-lines are most probably due to energy summing of α-particles and conversion electrons. Note that for reasons of discussion (see text) the division into lines here is somewhat different to the summary in table 2; consequently, relative intensities and hindrance factors are also different.

E_α/keV	$i_{\rm rel}$	HF	Decay (of daughter levels)
8583	0.0125	67	?
8684	0.0094	145	?
8670	0.0094	173	$11/2^- \xrightarrow{\gamma} 7/2^+[624]$
8692^+	0.0406	47	$11/2^- \xrightarrow{\rm IC} 7/2^+[624]$
8722	0.57	4	$9/2^-[734] \xrightarrow{\gamma} 7/2^+[624]$
8773^+	0.26	13	$9/2^-[734] \xrightarrow{\gamma} 9/2^+ \xrightarrow{\rm IC} 7/2^+[624]$
8797^+	0.0313	131	$9/2^-[734] \xrightarrow{\gamma} 11/2^+ \xrightarrow{\rm IC} 9/2^+ \xrightarrow{\rm IC} 7/2^+[624]$
8831^+	0.0313	163	$9/2^-[734] \xrightarrow{\gamma} 11/2^+ \xrightarrow{\rm IC} 7/2^+[624]$
8897^+	0.0156	509	$9/2^-[734] \xrightarrow{\rm IC} 7/2^+[624]$
8924	0.0188	520	$9/2^-[734] \xrightarrow{\rm IC} 7/2^+[624]$??

the influence of the additional, unpaired proton in the target nucleus on the position of the maximum of the 1n de-excitation function. The latter is of specific interest for the extrapolation of the optimum bombarding energies for the production of odd-Z isotopes in the region of heaviest nuclei at $Z \geq 110$. Within our experimental limits no change in $E^*(\sigma_{\rm 1n,max})$ was observed compared to ^{208}Pb(^{50}Ti,1n)^{257}Rf.

A careful analysis of the observed α-spectra revealed the existence of an isomeric state in ^{257}Db decaying by α-emission into an isomeric state in ^{253}Lr, which again decays by α-emission. Possible spin assignments for the ground states of ^{257}Db, ^{253}Lr, and ^{249}Md and the isomeric states ^{257m}Db and ^{253m}Lr were discussed on the basis of the observed α-decay characteristics and theoretical predictions. The results are, however, not free of ambiguities. More detailed measurements are necessary. At the highest bombarding energies the new isotopes ^{256}Db and ^{252}Lr could be identified. Two α-lines of (9018 ± 20) keV and (8974 ± 20) keV were attributed to ^{252}Lr. The spectrum of ^{256}Db appears more complicated. Besides a strong α-line at (9014 ± 20) keV some weaker transitions in the energy interval $E_\alpha = (8.89$–$9.12)$ MeV are indicated. The half-life of ^{256}Db is $(1.6^{+0.5}_{-0.3})$s. Fission events of a similar half-life of $(2.3^{+1.1}_{-0.6})$s were also attributed to ^{256}Db. They are interpreted as spontaneous fission of ^{256}Rf, produced by electron capture decay of ^{256}Db. It is likely that this spontaneous-fission activity is identical to those of similar half-lives that were observed in bombardments ^{51}V + ^{207}Pb, $T_{1/2} = (1.2^{+0.6}_{-0.3})$ s [19], ^{51}V + ^{206,207}Pb, $T_{1/2} =$ 1.5 s [20], and ^{48}Ti + ^{209}Bi, $T_{1/2} = (1.6^{+0.6}_{-0.4})$ s [21]. While no assignment of this activity was made in ref. [19], it was attributed to ^{255}Db in ref. [20], and to ^{256}Db in ref. [21].

Motivated by the hint for a low excited isomeric state in ^{255}Rf decaying by α-emission in a recent experiment [2], which was not expected on the basis of a calculated level scheme [3], we studied the decay of this isotope in more detail by means of α- and α-γ-spectroscopy. A first level scheme of ^{251}No was obtained. The existence of an isomeric state, however, could not be confirmed.

With respect to the necessity to study the nuclear structure of transactinide nuclei in more detail to obtain a reasonable basis of experimental data as support for theoretical prediction of properties of superheavy nuclei, our experiments show that despite low cross-sections of $\sigma \approx (1$–$10)$ nb, using improved experimental techniques, counting rates and sensitivity are high enough for detailed investigation of decay properties.

References

1. F.P. Heßberger, G. Münzenberg, S. Hofmann, Y.K. Agarwal, K. Poppensieker, W. Reisdorf, K.-H. Schmidt, J.R.H. Schneider, W.F.W. Schneider, H.J. Schött, P. Armbruster, B. Thuma, C.-C. Sahm, D. Vermeulen, Z. Phys. A **322**, 557 (1985).
2. F.P. Heßberger, S. Hofmann, V. Ninov, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, A.N. Andreyev, S. Saro, Z. Phys. A **359**, 415 (1997).
3. S. Cwiok, S. Hofmann, W. Nazarewicz, Nucl. Phys. A **575**, 356 (1994).
4. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
5. 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).
6. 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**, 281 (1995).
7. S. Hofmann, V. Ninov, F.P. Heßberger, P. Armbruster, H. Folger, G. Münzenberg, H.J. Schött, A.G. Popeko, A.V. Yeremin, S. Saro, R. Janik, M. Leino, Z. Phys. A **354**, 229 (1996).
8. S. Hofmann, F.P. Heßberger, V. Ninov, P. Armbruster, G. Münzenberg, C. Stodel, A.G. Popeko, A.V. Yeremin, S. Saro, M. Leino, Z. Phys. A **358**, 377 (1997).

9. R.B. Firestone, V.S. Shirley, C.M. Baglin, S.Y. Frank Chu, J. Zipkin, *Table of Isotopes* (John Wiley & Sons, Inc., New York, Chichester, Brisbane, Toronto, Singapore, 1996).
10. D.G. Raich, H.R. Bowman, R.E. Eppley, J.O. Rasmussen, I. Rezanka, Z. Phys. A **279**, 301 (1976).
11. R.S. Hager, E.C. Selzer, Nucl. Data A **4**, 1 (1968).
12. S. Hofmann, *Proceedings of the Experimental Nuclear Physics in Europe (ENPE99), Sevilla, Spain, 1999, AIP Conf. Proc.*, Vol. **495**, edited by B. Rubio, M. Lozano, W. Gelletly (Melville, New York, 1999) 137.
13. G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nucl. Phys. A **624**, 1 (1997).
14. F. Hubert, R. Bimbot, H. Gauvin, At. Data Nucl. Data Tables **46**, 1 (1990).
15. I. Ahmad, J. Milsted, R.K. Sjoblom, J. Lerner, P.R. Fields, Phys. Rev. C **8**, 737 (1974).
16. R. Smolanczuk, J. Skalski, A. Sobiczewski, Phys. Rev. C **52**, 1871 (1995).
17. P. Möller, J.R. Nix, K.-L. Kratz, At. Data Nucl. Data Table **66**, 131 (1997).
18. A. Ghiorso, T. Sikkeland, M.J. Nurmia, Phys. Rev. Lett. **18**, 401 (1967).
19. Yu.Ts. Oganessian, A.G. Demin, N.A. Danilov, G.N. Flerov, M.P. Ivanov, A.S. Iljinov, N.N. Kolesnikov, B.N. Markov, V.M. Plotko, S.P. Tretyakova, Nucl. Phys. A **273**, 505 (1976).
20. G.N. Flerov, *Proceedings of the 3rd International Conference on Nuclei far from Stability, Cargese, Corsica (France), 19-26 May 1976*, Institute Report CERN 76-19, 542 (1976).
21. Yu.Ts. Oganesyan, *International School Conference on Heavy Ion Physics, Alushta, 14-21 April 1983*, Institute Report Dubna D 7-83-644, 55-75 (1983).