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Decay properties of neutron-deficient nuclei in the region Z = 86–92

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Abstract. Neutron deficient isotopes of elements $Z = 86$–92 have been produced by heavy-ion fusion reactions $^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$, $^{209}\mathrm{Bi}$, $^{22}\mathrm{Ne} + {}^{208}\mathrm{Pb}$, $^{51}\mathrm{V} + {}^{170}\mathrm{Er}$, and $^{50}\mathrm{Ti} + {}^{170}\mathrm{Er}$. The evaporation residues were investigated by means of α- and α-γ-spectroscopy after in-flight separation from the projectile beam by the velocity filter SHIP and implantation into a 16-strip position-sensitive Si-detector. New or improved decay data for $^{225,226}\mathrm{U}$, $^{216,217\mathrm{m},218}\mathrm{Pa}$, $^{215,216,217}\mathrm{Th}$, $^{214,215,216,216\mathrm{m}}\mathrm{Ac}$, $^{214}\mathrm{Ra}$ and $^{213}\mathrm{Rn}$ have been obtained.

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1 Introduction

The study of decay properties and nuclear structure of nuclei close to the $N = 126$ neutron shell above lead is of growing interest. Within our experimental program to synthesize superheavy elements [1] and study their radioactive decay properties we also performed a series of irradiations leading to compound nuclei with atomic numbers $Z = 88$–92. The experimental set-up was laid out for detection and identification of 'rare' events with production cross-sections of some picobarn or lower. We succeeded, especially in combination with measuring γ-rays in coincidence to α-particles, to significantly improve decay data of several isotopes and to identify weak transitions that had not been reported so far.

Subject of this paper is presentation and detailed discussion of the experimental results.

Preliminary data of part of the experiments have already been reported in reference [2].

The complete results are listed in table 1.

2 Experiment

The experiments were performed at the velocity filter SHIP at GSI, Darmstadt, using beams of $^{51}\mathrm{V}$, $^{50}\mathrm{Ti}$, $^{22}\mathrm{Ne}$ and $^{12}\mathrm{C}$. Beam intensities of $(0.6$–$3.1)\times10^{12}$ ions/s ($\approx$(100–500) pnA) were delivered from the UNILAC accelerator. Beam energies were (214–286) MeV for $^{51}\mathrm{V}$, (215–235) MeV for $^{50}\mathrm{Ti}$, (117–123) MeV for $^{22}\mathrm{Ne}$, and (88–100) MeV for $^{12}\mathrm{C}$. The targets of $^{170}\mathrm{Er}$, $^{208}\mathrm{Pb}$, and $^{209}\mathrm{Bi}$ with thicknesses of $\approx$(400–500) $\mu\mathrm{g/cm}^2$, covered with carbon layers of $40\,\mu\mathrm{g/cm}^2$ (upstream) and $5\,\mu\mathrm{g/cm}^2$ (downstream), were mounted on target wheels that rotated synchronously to the beam macro structure [3]. The evaporation residues, recoiling from the targets with energies of ≈ 55 MeV ($^{50}\mathrm{Ti}$, $^{51}\mathrm{V} + {}^{170}\mathrm{Er}$), ≈ 11 MeV ($^{22}\mathrm{Ne} + {}^{208}\mathrm{Pb}$), and ≈ 4.5 MeV ($^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$, $^{209}\mathrm{Bi}$) were separated from the primary beam by the velocity filter SHIP [4] and implanted into a position sensitive 16-strip PIPS detector with an active area of $(80 \times 35)\,\mathrm{mm}^2$ where their kinetic energies as well as subsequent α decays were measured ('stop detector'). Operated at a temperature of 258 K, the energy resolution for individual strips was (18–20) keV (FWHM). Summing all strips in the off-line data analysis we obtained typical 'stop detector' resolutions of $\Delta E = (20$–$24)$ keV (FWHM).

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Table 1. Compilation of measured decay data. For literature data relative intensities of α-lines are given in brackets. Errors for energies and relative intensities of values from literature are ommitted. Definition of Q_α is given in section 2. Assignments marked by (^{a}) are tentative.

Isotope	E_α (keV)	Q_α (keV)	i	$T_{1/2}$	E_γ (keV)	Literature
^{226}U	7555 ± 10	7727 ± 10	0.82 ± 0.05	$281 \pm 9\,\mathrm{ms}$		$E_\alpha = 7570(i = 0.85)$, $7420(i = 0.15)\,\mathrm{keV}$,
	7374 ± 10	7543 ± 10	0.15 ± 0.03			$T_{1/2} = 250^{+150}_{-100}\,\mathrm{ms}$ [9], $E_\alpha = 7565(i = 0.82)$,
	7323 ± 20	7491 ± 10	0.03 ± 0.01			$7385(i = 0.18)\,\mathrm{keV}$, $T_{1/2} = 260 \pm 10\,\mathrm{ms}$ [10,11]
^{225}U	7868 ± 15	8047 ± 10	0.58 ± 0.04	$59^{+5}_{-2}\,\mathrm{ms}$		$E_\alpha = 7880(i = 0.9)$, $7830(i = 0.1)\,\mathrm{keV}$,
	7833 ± 15	8011 ± 10	0.37 ± 0.05			$T_{1/2} = 80^{+40}_{-40}\,\mathrm{ms}$ [13], $E_\alpha = 7870\,\mathrm{keV}$,
	7621 ± 15	7795 ± 10	0.05 ± 0.02			$T_{1/2} = 30^{+20}_{-10}\,\mathrm{ms}$ [9], $E_\alpha = 7879(i = 0.85)$,
						$7821(i = 0.15)\,\mathrm{keV}$, $T_{1/2} = 95 \pm 15\,\mathrm{ms}$ [14]
^{218}Pa	9616 ± 15	9831 ± 10	0.65 ± 0.07	$113 \pm 10\,\mu\mathrm{s}$		$E_\alpha = 9614(i = 0.65)$, $9535(i = 0.35)\,\mathrm{keV}$,
	9544 ± 15	9758 ± 10	0.35 ± 0.05		91.8 ± 0.4	$T_{1/2} = 120^{+40}_{-40}\,\mu\mathrm{s}$ [15]
^{217}Pa	8334 ± 15	8526 ± 15		$3.4 \pm 0.1\,\mathrm{ms}$		$E_\alpha = 8333\,\mathrm{keV}$, $T_{1/2} = 4.9^{+0.6}_{0.4}\,\mathrm{ms}$ [15],
						$E_\alpha = 8330\,\mathrm{keV}$, $T_{1/2} = 2.3^{+0.5}_{0.4}\,\mathrm{ms}$ [17]
$^{217\mathrm{m}}$Pa	10155 ± 15	1038 ± 15	0.80 ± 0.05	$1.5 \pm 0.1\,\mathrm{ms}$		$E_\alpha = 10160\,\mathrm{keV}$, $T_{1/2} = 1.6^{+1.0}_{-0.5}\,\mathrm{ms}$ [15],
	9694 ± 20	9912 ± 20	0.03 ± 0.01	$1.3^{+0.4}_{-0.2}\,\mathrm{ms}$		$E_{\alpha 1} = 10140\,\mathrm{keV}$, $T_{1/2} = 1.7^{+1.7}_{-0.4}\,\mathrm{ms}$ [17],
	9548 ± 15	9763 ± 15	0.17 ± 0.02	$1.4 \pm 0.2\,\mathrm{ms}$		$E_{\alpha 2} = 9540\,\mathrm{keV}$, $T_{1/2} = 1.5^{+0.9}_{-0.4}\,\mathrm{ms}$ [17]
^{216}Pa	7948 ± 15	8134 ± 15	0.51 ± 0.04			$E_\alpha = 7.92, 7.82, 7.72\,\mathrm{MeV}$,
	7815 ± 15	7998 ± 15	0.45 ± 0.05		133.6 ± 0.3	$T_{1/2} = 200 \pm 40\,\mathrm{ms}$ [18], $E_\alpha = 7865(i = 0.7)$,
	7793 ± 15	7976 ± 15	0.04 ± 0.01			$7812(i = 0.3)\,\mathrm{keV}$, $T_{1/2} = 170^{+100}_{-30}\,\mathrm{ms}$ [15],
						$E_\alpha = 7960(i = 0.5)\,\mathrm{keV}$, $E_\alpha = 7830(i = 0.5)\,\mathrm{keV}$,
						$T_{1/2} = 140^{+50}_{-30}\,\mathrm{ms}$ [17], $T_{1/2} = 150^{+70}_{-40}\,\mathrm{ms}$ [17]
^{215}Pa	8091 ± 15	8280 ± 15		$14 \pm 2\,\mathrm{ms}$		$E_\alpha = 8085 \pm 15\,\mathrm{keV}$, $T_{1/2} = 14^{+20}_{-3}\,\mathrm{ms}$ [15]
^{214}Pa	8116 ± 15	8306 ± 15		$17 \pm 3\,\mathrm{ms}$		
^{213}Pa	8236 ± 15	8429 ± 15		$5.3^{+4.0}_{-1.6}\,\mathrm{ms}$		
^{224}Th	7156 ± 10	7321 ± 10	0.87 ± 0.08	$812 \pm 99\,\mathrm{ms}$		$E_\alpha = 7170(i = 0.79)$, $7000(i = 0.19)$,
	6984 ± 15	7146 ± 15	0.13 ± 0.03			$6770(i = 0.012)$, $6700(i = 0.003)\,\mathrm{keV}$,
						$T_{1/2} = 1.05 \pm 0.02\,\mathrm{s}$ [12], $E_\alpha = 7170(i = 0.80)$,
						$7000(i = 0.20)\,\mathrm{keV}$ [9]
^{222}Th	7974 ± 10	8155 ± 10		$2.0 \pm 0.1\,\mathrm{ms}$		$E_\alpha = 7980(i = 0.97)$, $7600(i = 0.03)\,\mathrm{keV}$,
						$T_{1/2} = 2.2 \pm 0.2\,\mathrm{ms}$ [28], $E_\alpha = 7982\,\mathrm{keV}$,
						$T_{1/2} = 2.8 \pm 0.3\,\mathrm{ms}$ [12]
^{221}Th	8458 ± 10	8649 ± 10	0.48 ± 0.09	$2.0^{+0.3}_{-0.2}\,\mathrm{ms}$		$E_\alpha = 8472(i = 0.39)$, $8146(i = 0.56)$,
	8135 ± 10	8320 ± 10	0.48 ± 0.09			$7733(i = 0.06)\,\mathrm{keV}$, $T_{1/2} = 1.68 \pm 0.06\,\mathrm{ms}$ [12]
	7732 ± 15	7910 ± 10	0.04 ± 0.03			$E_\alpha = 8470(i = 0.33)$, $8375(i = 0.11)$,
						$8150(i = 0.51)\,\mathrm{keV}$, $7730(i = 0.05)\,\mathrm{keV}$,
						$T_{1/2} = 1.9 \pm 0.1\,\mathrm{ms}$ [28]
^{217}Th	9268 ± 15	9477 ± 15	0.946 ± 0.006	$247 \pm 3\,\mu\mathrm{s}$		$E_\alpha = 9250\,\mathrm{keV}$, $T_{1/2} = 252 \pm 7\,\mu\mathrm{s}$ [12]
	8731 ± 15	8930 ± 15	0.016 ± 0.001	$293 \pm 28\,\mu\mathrm{s}$		$E_\alpha = 9247(i = 0.923)$, $8713(i = 0.026)\,\mathrm{keV}$,
	8459 ± 15	8653 ± 15	0.038 ± 0.001	$250 \pm 8\,\mu\mathrm{s}$		$8429(i = 0.051)\,\mathrm{keV}$, $T_{1/2} = 261^{+22}_{-18}$ [20]
^{216}Th	7923 ± 10	8108 ± 10	0.9946 ± 0.0040	$27.0 \pm 0.3\,\mathrm{ms}$		$E_\alpha = 7921\,\mathrm{keV}$, $T_{1/2} = 28 \pm 2\,\mathrm{ms}$ [12]
	7302 ± 15	7475 ± 15	0.0054 ± 0.0003	$30 \pm 3\,\mathrm{ms}$	628.3 ± 0.5	
$^{216\mathrm{m}}$Th	9933 ± 15	10156 ± 15		$140 \pm 5\,\mu\mathrm{s}$		$E_\alpha = 9912\,\mathrm{keV}$, $T_{1/2} = 180 \pm 40\,\mu\mathrm{s}$ [27]
^{215}Th	7520 ± 15	7698 ± 15				$E_\alpha = 7524(i = 0.40)$, $7395(i = 0.52)$,
	7387 ± 15	7562 ± 15			133.6 ± 0.4	$7333(i = 0.08)\,\mathrm{keV}$, $T_{1/2} = 1.2 \pm 0.2\,\mathrm{s}$ [12]
	7336 ± 15	6510 ± 15			192.4 ± 1.5	

Table 1. Continued.

Isotope	E_α (keV)	Q_α (keV)	i	$T_{1/2}$	E_γ (keV)	Literature
^{216}Ac	9052 ± 10	9257 ± 10		$440 \pm 16\,\mu$s		$E_\alpha = 9072(i = 0.09)$, $8992(i = 0.1)$ keV,
						$T_{1/2} \approx 0.33$ ms [12]
$^{216\text{m}}$Ac	9110 ± 10	9316 ± 10		$443 \pm 7\,\mu$s		$E_\alpha = 9108(i = 0.462)$, $9030(i = 0.496)$,
	9026 ± 15	9231 ± 15		$359^{+97}_{-63}\,\mu$s	82.4 ± 0.4	$8200(i = 0.017)$ keV, $8285(i = 0.025)$,
	8586 ± 15	8783 ± 15		$475^{+289}_{-130}\,\mu$s	537 ± 3	$T_{1/2} = 0.33 \pm 0.02$ ms [12]
	8273 ± 15	8464 ± 15		$432 \pm 17\mu$s	826 ± 3^a	
	8198 ± 20^a	8387 ± 20		$463 \pm 180\,\mu$s		
^{215}Ac	7602 ± 10	7781 ± 10	0.992			$E_\alpha = 7604$ keV, $T_{1/2} = 0.17 \pm 0.01$ s [12]
	7214 ± 15	7385 ± 15	≈ 0.0046		399 ± 2^a	
	7026 ± 15	7194 ± 15	≈ 0.0020		582.3 ± 2.3^a	
	6960 ± 15	7127 ± 15	≈ 0.0014		654.0 ± 2.3^a	
^{214}Ac	7210 ± 10	7382 ± 10				$E_\alpha = 7214(i = 0.52)$, $7082(i = 0.44)$,
	7154 ± 15	7325 ± 15			62.3 ± 0.5^a	$7002(i = 0.04)$ keV, $T_{1/2} = 8.2 \pm 0.2$ s [12]
	7115 ± 15	7285 ± 15			76.5 ± 0.2^a	
	7080 ± 15	7249 ± 15			138.6 ± 0.2	
	7021 ± 15	7189 ± 15			193.0 ± 0.2^a	
	7016 ± 15	7184 ± 15			209.0 ± 1.4^a	
	6881 ± 15	7047 ± 15			348.6 ± 1.6^a	
^{213}Ac	7356 ± 10	7531 ± 10		731 ± 17 ms		$E_\alpha = 7362$ keV, $T_{1/2} = 0.80 \pm 0.05$ s [25]
^{212}Ac	7373 ± 10	7549 ± 10		880 ± 110 ms		$E_\alpha 7377$ keV, $T_{1/2} = 0.93 \pm 0.05$ s [25]
^{211}Ac	7472 ± 10	7651 ± 10		200 ± 29 ms		$E_\alpha = 7480$ keV, $T_{1/2} = 0.25 \pm 0.05$ s [25]
^{210}Ac	7462 ± 10	7641 ± 10		335^{+64}_{-46} ms		$E_\alpha = 7462$ keV, $T_{1/2} = 0.35 \pm 0.05$ s [25]
^{209}Ac	7577 ± 10	7759 ± 10		98^{+59}_{-27} ms		$E_\alpha 7585$ keV, $T_{1/2} = 0.10 \pm 0.05$ s [25]
^{220}Ra	7449 ± 10	7621 ± 10	0.95 ± 0.08	18 ± 2 ms		$E_\alpha = 7455(i = 0.99), 6900(i = 0.01)$ keV,
	7393 ± 15	7563 ± 15	0.05 ± 0.03			$T_{1/2} = 25 \pm 5$ ms [12]
						$E_\alpha = 7460$ keV, $T_{1/2} = 17 \pm 2$ ms [28]
^{215}Ra	8700 ± 10	8899 ± 10		1.67 ± 0.01 ms		$E_\alpha = 8699(i = 0.958)$, $8171(i = 0.014)$,
	8171 ± 15	8360 ± 15		1.75 ± 0.07 ms	539.6 ± 0.2	$7882(i = 0.025)$ keV, $T_{1/2} = 1.59 \pm 0.09$ s [12]
	7879 ± 15	8062 ± 10		1.79 ± 0.04 ms	833.5 ± 0.2	
^{214}Ra	7137 ± 10	7307 ± 10	0.998 ± 0.001			$E_\alpha = 7134$ keV, $T_{1/2} = 2.46 \pm 0.03$ s [12]
	6505 ± 15	6663 ± 15	0.002 ± 0.001		641.9 ± 0.2	
^{213}Ra	8088 ± 10	8276 ± 10	0.982 ± 0.002	19.5 ± 0.1 ms		$E_\alpha = 8088(0.99), 7553(0.01)$ keV,
	7550 ± 15	7727 ± 15	0.0067 ± 0.0007	18.0 ± 0.4 ms	540.3 ± 0.4	$T_{1/2} = 25.0 \pm 0.02$ s [12]
	7552 ± 15	7424 ± 15	0.011 ± 0.001	19.0 ± 0.5 ms		

A consequence of implanting the nuclei into the detector is that part of the recoil energy transferred by the α-particle to the residual nucleus contributes to the pulse height. Further α-particles from an external source suffer an energy loss in the deadlayer of the detector. Using external sources for calibrations one therefore obtains for known implanted nuclei α energies typically (40–70) keV higher than reported literature values. Therefore α calibration was performed rather using the literature values of known isotopes also produced in the concerning reactions than using external α sources of 'standard' isotopes (*e.g.* ^{241}Am, ^{239}Pu etc.). Although the energy of these 'standards' is more precisely known the correction for a) the energy loss of the α-particles of external sources in the deadlayer of the detector and b) the contribution of the recoil energy to the pulse height results in larger uncertainties than the method used here. Since the evaporation residues were implanted close to the detector surface due to low kinetic energy in the experiment using the ^{12}C beam, the α-lines showed long tails towards lower energies. As a consequence it turned out to be quite problematic to identify weak α-lines at slightly lower energies than those of intense ones.

To discriminate between incoming particles and α decays of implanted nuclei we used three (^{50}Ti experiment) or two (^{51}V experiment) transmission detectors [5] in anticoincidence with the 'stop detector'. In the experiments using ^{22}Ne or ^{12}C such detectors were not used to avoid stopping of the evaporation residues in the detectors' carbon foils. Coincidences between α-particles and γ-rays were measured either using two planar Ge-detectors each of $(35 \times 35)\,\mathrm{mm}^2$ (^{51}V experiment), or a high-purity Ge-detector (^{12}C experiment) mounted directly behind the 'stop detector'. No α-γ coincidence measurements were performed for the $^{50}\mathrm{Ti} + ^{170}\mathrm{Er}$ and $^{22}\mathrm{Ne} + ^{208}\mathrm{Pb}$ experiments.

Further details on the experimental set-up are given in reference [6].

In the cases of α-γ coincidence measurements for comparison of energies we prefer to use the Q_α-value $Q_\alpha = (1 + m_\alpha/m_d) \times E_\alpha + \Delta E_{\mathrm{scr}}$, where $(m_\alpha/m_d) \times E_\alpha$ denotes the recoil energy transferred to the residual nucleus (m_d) by the α-particle (m_α) and ΔE_{scr} is the screening correction according to [7].

3 Experimental results

3.1 Isotope ^{226}U

Discovery of ^{226}U was first claimed by Viola *et al.* [8], who observed an α-activity of $E_\alpha = (7.43 \pm 0.03)\,\mathrm{MeV}$ and $T_{1/2} = (0.5 \pm 0.2)\,\mathrm{s}$ in a bombardment of ^{232}Th with ^{4}He-ions. The authors were aware that the measured decay properties were similar to that of ^{211}Po, but they definitely excluded this isotope as source of the observed activity and rather assigned it to ^{226}U. Completely different results were later reported by Andreev *et al.* [9], who produced ^{226}U by the reaction ^{208}Pb (^{22}Ne, 4n) ^{226}U and identified it by α-α correlations to its daughter nucleus ^{222}Th. They reported two α energies $E_{\alpha 1} = (7570 \pm 20)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.85 \pm 0.05)$), $E_{\alpha 2} = (7420 \pm 20)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.15 \pm 0.05)$) and a half-life of $T_{1/2} = (250^{+150}_{-100})\,\mathrm{ms}$. A somewhat different result was obtained later by Greenlees *et al.* [10,11] who reported $E_{\alpha 1} = (7565 \pm 5)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.82 \pm 0.04)$, $E_{\alpha 2} = (7385 \pm 5)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.18 \pm 0.02)$ and a half-life of $T_{1/2} = (260 \pm 10)\,\mathrm{ms}$. The difference in $E_{\alpha 2}$ was insofar striking since Greenlees *et al.* observed a γ-line of $E_\gamma = 183\,\mathrm{keV}$ in coincidence to the $E_{\alpha 2}$ line, so it was assigned to α decay into the first excited 2^+-level in ^{222}Th. To prove these results we produced ^{226}U also by the ^{208}Pb (^{22}Ne,4n) ^{226}U reaction at a bombarding energy of $E = 117\,\mathrm{MeV}$. To distinguish it unambiguously from any other isotope that might have one daughter product having at least one decay energy similar to one of the daughter products of ^{226}U, it was identified by 'four-fold' ER-$\alpha_{1'}$-$\alpha_{2'}$-$\alpha_{3'}$ correlations $\mathrm{ER} \rightarrow {}^{226}\mathrm{U} \overset{\alpha_{1'}}{\rightarrow} {}^{222}\mathrm{Th} \overset{\alpha_{2'}}{\rightarrow} ({}^{218}\mathrm{Ra}/{}^{214}\mathrm{Rn}) \overset{\alpha_{3'}}{\rightarrow} {}^{210}\mathrm{Po}$. The time intervals for searching correlated events were ΔT (ER-$\alpha_{1'}$) = 5000 ms, ΔT ($\alpha_{1'}$-$\alpha_{2'}$) = 25 ms and $\Delta T(\alpha_{2'}$-$\alpha_{3'}) = 0.2\,\mathrm{ms}$, defined by the half-life values of the corresponding daughter nuclei.

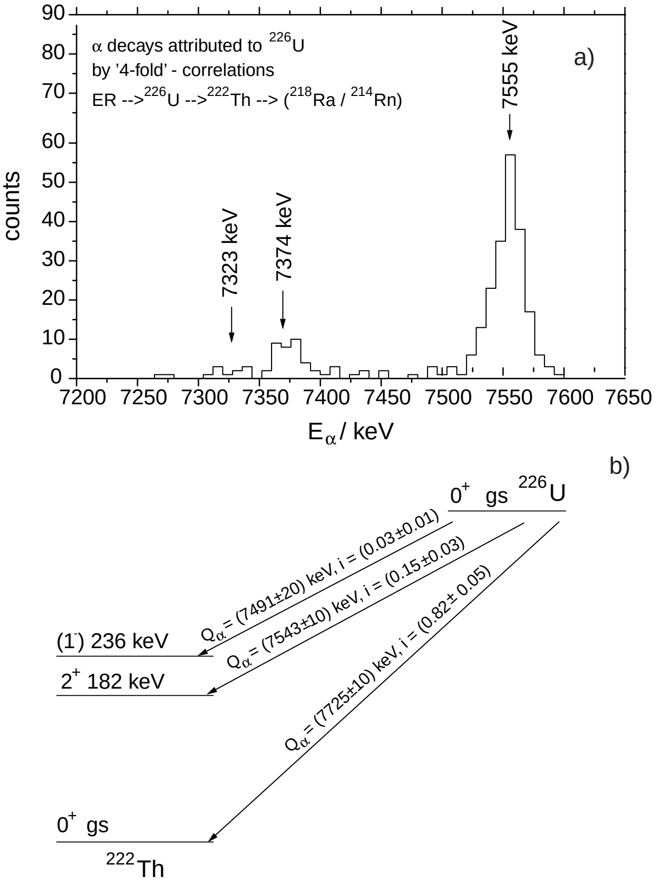

Fig. 1. a) α-spectrum of ^{226}U obtained from 'fourfold' correlations $\mathrm{ER} \rightarrow {}^{226}\mathrm{U} \rightarrow {}^{222}\mathrm{Th} \rightarrow ({}^{218}\mathrm{Ra}/{}^{214}\mathrm{Rn})$, b) decay scheme proposed for ^{226}U.

Due to the short half-life of ^{214}Rn of $T_{1/2} \approx 270\,\mathrm{ns}$, the $\alpha_{3'}$-events have been observed as α energy sum events of ^{218}Ra and ^{214}Rn. Three groups could be distinguished:

- $E_{\alpha 31'} \approx (8.4$–$9.0)\,\mathrm{MeV}$: registration of the full α energy of ^{218}Ra ($E_\alpha = 8390\,\mathrm{keV}$) plus a ΔE signal from ^{214}Rn, escaping the detector;
- $E_{\alpha 32'} \approx (9.0$–$10.0)\,\mathrm{MeV}$: registration of the full α energy of ^{214}Rn ($E_\alpha = 9037\,\mathrm{keV}$) plus a ΔE signal from ^{218}Ra, escaping the detector;
- $E_{\alpha 33'} \approx 17.4\,\mathrm{MeV}$: full energy summing of the α decay energies of ^{218}Ra and ^{214}Rn.

The energy spectrum for the mother events $E_{\alpha 1}$ attributed to ^{226}U is shown in fig. 1a). Two strong lines at $E_{\alpha 1} = (7555 \pm 10)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = 0.82 \pm 0.05$), and $E_{\alpha 2} = (7374 \pm 10)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = 0.15 \pm 0.03$) were observed. One weak transition is indicated at $E_{\alpha 3} = (7323 \pm 20)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = 0.03 \pm 0.01$). The half-life is $T_{1/2} = (281 \pm 9)\,\mathrm{ms}$. The results for $E_{\alpha 1}$, $E_{\alpha 2}$, and $T_{1/2}$ are in fair agreement with the data of Greenlees *et al.* [10,11]. The slight shift of the energies may be due to a systematic deviation of the energy calibration. A new result is the weak line at $E_{\alpha3} = (7323 \pm 20)$ keV, the energy difference of $\Delta Q = Q_{\alpha1} - Q_{\alpha3} = 236$ keV, however, is inconsistent with a decay into the 4^+-level of the ground state rotational band of ^{222}Th, located at $E^* = 439.8$ keV [12]. A comparison to neighbouring even-even-nuclei $^{222-226}$Ra, ^{224,226}Th [12] shows, that these nuclei have low-lying 1^--states in the energy range $E^* \approx (216–253)$ keV, which are populated weakly by α decay of the corresponding mother nuclei. Hindrance factors HF for these α decays are ≈(4.7–28). The value HF = 4.1 (3.1–6.2 within 1σ) obtained for the $E_{\alpha3}$ line is consistent with these data. Therefore we assign $E_{\alpha3}$ to the decay into a low-lying 1^--state in ^{222}Th. The proposed decay scheme is shown in fig. 1b)

3.2 Isotope ^{225}U

^{225}U was first reported by Heßberger *et al.* [13] ($E_{\alpha1} = (7880 \pm 20)$ keV, ($i_{\rm rel} \approx 0.9$), $E_{\alpha2} = (7830 \pm 20)$ keV, ($i_{\rm rel} \approx 0.1$), $T_{1/2} = (80^{+40}_{-20})$ ms) and Andreev *et al.* [9] ($E_\alpha = (7.87 \pm 0.02)$ MeV, $T_{1/2} = (0.03^{+0.02}_{-0.01})$ s). While in [13] it was produced by ^{180}Hf (^{48}Ca, 3n) ^{225}U, in [9] the ^{208}Pb (^{22}Ne, 5n) ^{225}U-reaction was used. Later Toth *et al.* [14] produced it by ^{209}Bi (^{19}F, 3n) ^{225}U. Their results, $E_{\alpha1} = (7879 \pm 15)$ keV ($i_{\rm rel} \approx 0.85$), $E_{\alpha2} = (7821 \pm 15)$ keV, ($i_{\rm rel} \approx 0.15$), $T_{1/2} = (95 \pm 15)$ ms, were in perfect agreement with the data of reference [13]. In our recent experiment ^{225}U was produced by ^{208}Pb (^{22}Ne, 5n) ^{225}U. In analogy to ^{226}U it was identified by 'four fold' correlations ER→^{225}U $\overset{\alpha_{1'}}{\to}$ (^{221}Th/ ^{217}Ra) $\overset{\alpha_{2'}}{\to}$ ^{213}Rn $\overset{\alpha_{3'}}{\to}$ ^{209}Po. The time intervals for searching correlated events were ΔT (ER-$\alpha_{1'}$) = 600 ms, $\Delta T(\alpha_{1'}$-$\alpha_{2'}) = 10$ ms and $\Delta T(\alpha_{2'}$-$\alpha_{3'}) = 120$ ms defined by the half-life values of the corresponding daughter nuclei.

Our result is shown in fig. 2a). We observed the two previously reported lines $E_{\alpha1} = (7868 \pm 15)$ keV, ($i_{\rm rel} = (0.58 \pm 0.04)$), $E_{\alpha2} = (7833 \pm 15)$ keV, ($i_{\rm rel} = (0.37 \pm 0.05)$) and measured a more precise half-life of $T_{1/2} = (59^{+5}_{-2})$ ms). Although these results are slightly different from our previously reported data they are still in agreement within the experimental accuracy. Especially the relative intensities are expected to be more precise than our previous values which were obtained on the basis of only eight correlated events. As a new result a weak line is indicated at $E_{\alpha3} = (7621 \pm 15)$ keV ($i_{\rm rel} = (0.05 \pm 0.02)$). According to the energy difference $\Delta Q = Q_{\alpha1} - Q_{\alpha3} = 252$ keV it is interpreted as decay into the assumed $11/2^+$ level of the ground-state rotational band of ^{221}Th, which is reported to be located at $E^* = 250.9$ keV [12]. $E_{\alpha1}$ is assumed to populate the ground state (assumed spin and parity: $7/2^+$ [12]) and $E_{\alpha2}$ the first member of the ground-state band of ^{221}Th, a $9/2^+$-state. Since the transition $9/2^+ \to 7/2^+$ is expected to be highly converted, $E_{\alpha2}$ may be strongly influenced by energy summing between α-particles and conversion electrons. So the energy difference $Q_{\alpha1} - Q_{\alpha2}$ does not necessarily reflect the excitation energy of the $9/2^+$-level.

The proposed decay scheme is shown in fig. 2b).

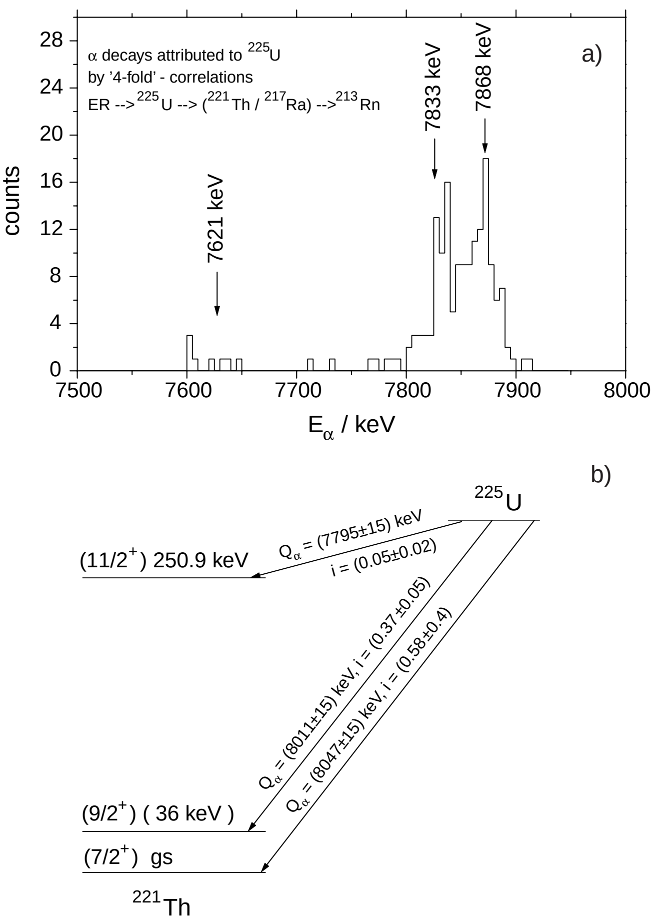

Fig. 2. a) α-spectrum of ^{225}U obtained from 'fourfold' correlations ER→^{225}U→ (^{221}Th/^{217}Ra)→^{213}Rn; b) decay scheme proposed for ^{225}U.

3.3 Isotope ^{218}Pa

^{218}Pa was first identified by Schmidt *et al.* [15], who produced it by ^{181}Ta(^{40}Ar, 3n)^{218}Pa. Two α-lines $E_{\alpha1} = (9614 \pm 20)$ keV, ($i_{\rm rel} = (0.65 \pm 0.10)$), $E_{\alpha2} = (9535 \pm 15)$ keV ($i_{\rm rel} = (0.35 \pm 0.10)$) and a half-life of $T_{1/2} = (120^{+40}_{-20})$ μs were reported. In the present experiment this isotope was produced by ^{170}Er (^{51}V, 3n)^{218}Pa. Our results $E_{\alpha1} = (9616 \pm 15)$ keV ($i_{\rm rel} = (0.65 \pm 0.07)$), $E_{\alpha2} = (9544 \pm 15)$ keV, ($i_{\rm rel} = (0.35 \pm 0.05)$) and a half-life of $T_{1/2} = (113 \pm 10)$ μs are in agreement to those of Schmidt *et al.*. In addition, however, we observed γ- or X-ray events of $E_\gamma = (91.8 \pm 0.4)$ keV in coincidence to the $E_{\alpha2}$ line (see fig. 3a)). We obtain a sum energy $Q_{\alpha2} + E_\gamma = 9850$ keV, while $Q_{\alpha1} = 9831$ keV. The difference $\Delta Q_\alpha = Q_{\alpha2} + E_\gamma - Q_{\alpha1} = 19$ keV is significantly larger than the error in the difference of the peak positions $\Delta E_{\alpha12}$. Neglecting the systematic error due to the calibration, we obtain a value of $\Delta E_{\alpha12} = ((\Delta E_{\alpha1})^2 + (\Delta E_{\alpha2})^2)^{1/2} = 6.8$ keV. So $E_{\alpha1}$ definitely does not represent the α decay into the ground state of the daughter nucleus ^{214}Ac. The energy of the γ-line is about one keV higher than the energy of the $K_{\alpha1}$ line of actinium, which is $E = 90.87$ keV. Although we cannot exclude completely that this difference is affected by the low

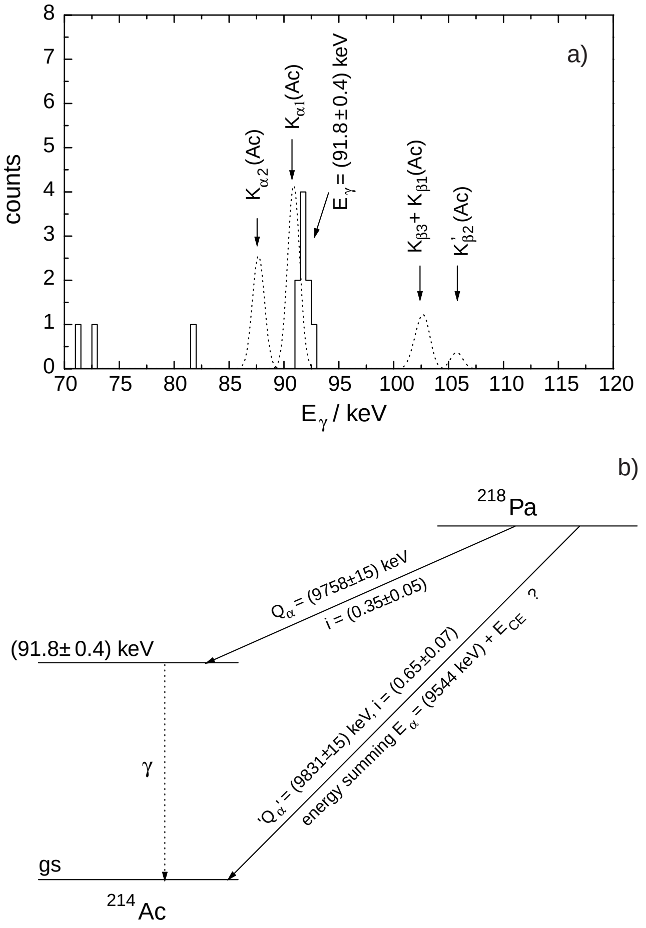

Fig. 3. a) γ-events in coincidence to the $E_\alpha = 9544\,\mathrm{keV}$ line attributed to ^{218}Pa; the dotted lines represent expected energies (referring to a detector resolution of $\Delta E = 2\,\mathrm{keV}$ (FWHM)) and intensities of Ac-X-rays, b) decay scheme proposed for ^{218}Pa.

number of observed events and a possible small systematic error of the calibration, we do not favour such an interpretation, since for ^{216}Pa we observed $K_{\alpha1}$, $K_{\alpha2}$ and $K_{\beta1}$–X-rays in coincidence to α decays (see sect. 3.5). In these cases the differences between the measured energy and the tabulated ones [12] were lower than 0.5 keV, so the value $\Delta E = 0.9\,\mathrm{keV}$ is already significant. In fig. 3a) we further show energies and expected intensities of $K_{\alpha2}$, $K_{\beta1}$ and $K_{\beta'2}$-X-rays assuming the observed γ-events were $K_{\alpha1}$-X-rays. It is evident that the observed spectrum of γ-events is in contradiction to the expected rates for the other X-ray-lines. Thus we conclude that the $E_{\alpha2}$ line feeds an excited level in ^{214}Ac 91.8 keV above the ground state. This energy is lower than the K binding energy of Ac ($E = 106.756\,\mathrm{keV}$) therefore this state cannot decay into the ground state by K-conversion. Since the energy difference $Q_{\alpha2} + E_\gamma - Q_{\alpha1} = 19\,\mathrm{keV}$ is approximately equal to the $L_{1,2}$ binding energy of actinium of $E(L_1) = 19.846\,\mathrm{keV}$ or $E(L_2) = 19.081\,\mathrm{keV}$, $E_{\alpha1}$ probably represents the energy summing between $E_{\alpha2}$-events and L-conversion electrons, so we propose the decay scheme shown in fig. 3b). From the number of observed α-events we obtain an upper limit of $b_{\alpha,\mathrm{gs}} < 0.002$ for populating the ground state of ^{214}Ac directly by α decay.

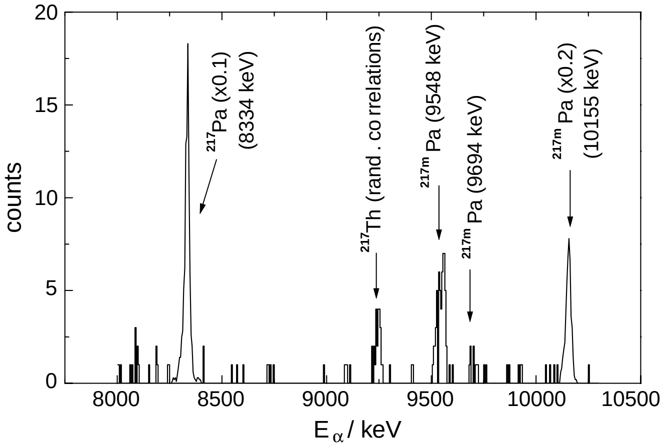

Fig. 4. spectrum of α-particles observed in $^{51}\mathrm{V} + ^{170}\mathrm{Er}$ ($E = 230 - -281\,\mathrm{MeV}$), following the implantation of an ER within $\Delta t \leq 15\,\mathrm{ms}$.

3.4 Isotope ^{217}Pa

Decay data on ^{217}Pa have been reported by Valli *et al.* [16] as well as by Schmidt *et al.* [15]. Two different activities had been observed and attributed to the ground state decay ($E_\alpha = 8.33\,\mathrm{MeV}$, $T_{1/2} = 4.9\,\mathrm{ms}$) and to an isomeric state ($E_\alpha = 10.16\,\mathrm{MeV}$, $T_{1/2} = 1.6\,\mathrm{ms}$) [15]. Recently Ikuta *et al.* [17] observed another α-line, $E_\alpha = (9.54 \pm 0.05)\,\mathrm{MeV}$, $T_{1/2} = (1.5^{+0.9}_{-0.4})\,\mathrm{ms}$, which they attributed to a second isomeric state in ^{217}Pa, although the half-life is consistent with that of the known isomeric state. In our experiment this isotope was produced by ^{170}Er (^{51}V, 4n) ^{217}Pa. Our measured value for the α decay energy of $^{217\mathrm{g}}$Pa $E_\alpha = (8334 \pm 15)\,\mathrm{keV}$ is consistent with the data reported previously [15,17], while our half-life of $T_{1/2} = (3.4 \pm 0.1)\,\mathrm{ms}$ is considerably different from the results of Schmidt *et al.* ($T_{1/2} = (4.9^{+0.6}_{-0.4})\,\mathrm{ms}$) as well as from those of Ikuta *et al.* ($T_{1/2} = (2.3^{+0.5}_{-0.3})\,\mathrm{ms}$).

In addition, three more α lines were observed to be followed by α decays of ^{213}Ac (fig. 4) and assigned to the decay of $^{217\mathrm{m}}$Pa. Energies, relative intensities and half-lives are $E_{\alpha1} = (10155 \pm 15)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.80 \pm 0.05)$), $T_{1/2} = (1.5 \pm 0.1)\,\mathrm{ms}$; $E_{\alpha2} = (9548 \pm 15)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.17 \pm 0.02)$), $T_{1/2} = (1.4 \pm 0.2)\,\mathrm{ms}$; $E_{\alpha3} = (9694 \pm 20)\,\mathrm{keV}$, ($i_{\mathrm{rel}} = (0.03 \pm 0.01)$), $T_{1/2} = (1.3^{+0.4}_{-0.2})\,\mathrm{ms}$. It is worth to note that all three half-lives agree within the error bars. $E_{\alpha1}$ and $E_{\alpha2}$ agree with the α decay energies reported for $^{217\mathrm{m}}$Pa [15,17], while $E_{\alpha3}$ was not reported so far. Contrary to Ikuta *et al.* we do not attribute $E_{\alpha2}$ to a second isomeric state, but due to the similar half-lives we assign all three decays to the same state. Although it is not impossible that two or even three different isomeric states may accidentally have similar half-lives, the assignment of Ikuta *et al.* may be under discussion. Ikuta *et al.* assign $E_{\alpha1}$ to a transition $^{217\mathrm{m}1}$Pa ($29/2^+$) $\rightarrow ^{213}$Ac ($9/2^-$)

and $E_{\alpha 2}$ to a transition $^{217\mathrm{m}2}$Pa ($23/2^-$) $\rightarrow$ ^{213}Ac ($9/2^-$). According to the selection rules for electromagnetic transitions the $29/2^+ \rightarrow 23/2^-$ transition can be assumed as $E3$. The energy difference is $\Delta(E_{\alpha 1} - E_{\alpha 2}) = 607$ keV. A Weisskopf estimation [12] results in $T_{1/2}$ (w.u.) $= 10^{-5}$ s for such a transition. Respecting the recommended relation $T_{1/2}$(w.u.)/$T_{1/2}$(exp) ≈ 100 for $E3$-transitions [12] the half-life $T_{1/2}(29/2^+ \rightarrow 23/2^-) \approx 10^{-7}$ s is expected to be about four orders of magnitude lower than the experimental value for α decay, $T_{1/2,\alpha} \approx 10^{-3}$ s. To conclude: the assumption of an isomeric $23/2^-$-state at $E^* \approx 1.3$ MeV [17] is in conflict to the existence of an isomeric $29/2^+$-state with a half-life $T_{1/2} \approx 1.5$ ms at $E^* \approx 1.9$ MeV.

3.5 Isotope ^{216}Pa

In the course of the present investigations ^{216}Pa was produced in the ^{170}Er(^{51}V, 5n) ^{216}Pa reaction. Previously reported decay data are $E_{\alpha 1} = 7.72$ MeV, $E_{\alpha 2} = 7.82$ MeV, $E_{\alpha 3} = 7.92$ MeV, $T_{1/2} = (200 \pm 40)$ ms [18]; $E_{\alpha 1} = (7812 \pm 20)$ keV, ($i_{\mathrm{rel}} \approx 0.7$), $E_{\alpha 2} = (7865 \pm 20)$ keV, ($i_{\mathrm{rel}} \approx 0.3$), $T_{1/2} = (170^{+100}_{-30})$ ms [15]; $E_{\alpha 1} = (7830 \pm 50)$ keV, $T_{1/2} = (150^{+70}_{-40})$ ms, $E_{\alpha 2} = (7960 \pm 50)$ keV, $T_{1/2} = (140^{+50}_{-30})$ ms [17].

While the half-life of this isotope could not be determined satisfactorily due to problems with random correlations between evaporation residues and α-particles at time distances Δt (ER-α) > 100 ms in this experiment, a detailed investigation of the α decay properties was performed. Three groups of α decays attributed to ^{216}Pa were observed in coincidence to γ- or X-rays (see fig. 5a)). The α decays in coincidence to X-rays are certainly strongly influenced by energy summing of α-particles with conversion electrons. So only the $E_\alpha = (7815 \pm 15)$ keV-line observed in coincidence to $E_\gamma = (133.6 \pm 0.3)$ keV is assumed to represent a 'real' α decay into an excited level of ^{212}Ac that decays by emission of γ-rays into the ground state. On the basis of this assumption one expects an α energy for the ground state to ground state transition of E_α(gs) ≈ 7946 keV. The result of α-α correlations is shown in fig. 5b). Besides the lines, also observed in coincidence to γ-rays, a weak line at $E_\alpha = (7793 \pm 15)$ keV, and a doublet in the range $E_\alpha = (7900$–$8000)$ keV are seen. The α-line at $E_\alpha = (7948 \pm 15)$ keV is attributed to the ground state to ground state α-transition of ^{216}Pa, while the line at $E_\alpha = (7919 \pm 15)$ keV is attributed to ^{216}Th. It is produced by ^{170}Er (^{51}V, p4n) ^{216}Th with a yield more than two orders of magnitude higher than that of ^{216}Pa, and appears here randomly correlated to ^{212}Ac. This interpretation is supported by a) comparing the data with α decays correlated to ^{212}Ra (dotted line in fig. 5b)), where only the α line of ^{216}Th is seen, and b) a half-life analysis: for the line at $E_\alpha = 7919$ keV we obtained $T_{1/2} = (25 \pm 9)$ ms, a value similar to that of ^{216}Th (see sect. 3.7), while for $E_\alpha = 7948$ keV we obtain $T_{1/2} > 100$ ms (fig. 5c)). The proposed decay scheme of ^{216}Pa is shown in fig. 5d).

3.6 Isotope ^{217}Th

Decay properties of ^{217}Th have been first reported by Valli and Hyde [16] who produced it by the ^{206}Pb (^{16}O, 5n) ^{217}Th. An α energy of $E_\alpha = 9250$ keV and an upper limit of $T_{1/2} < 300\,\mu$s were reported. Later a half-life of $T_{1/2} = (251 \pm 7)\,\mu$s was measured by Häusser *et al.* [19]. Very recently fine structure of the decay of ^{217}Th was reported by Nishio *et al.* [20], who observed two weak α-lines at $E_\alpha = (8713 \pm 32)$ keV, ($i_{\mathrm{rel}} = 0.026^{+1.6}_{-1.1}$) and $E_\alpha = (8429 \pm 32)$ keV ($i_{\mathrm{rel}} = 0.051^{+2.0}_{-1.6}$) in addition to $E_\alpha = 9247$ keV.

We used both, the reactions ^{170}Er (^{51}V, p3n) ^{217}Th and ^{170}Er(^{50}Ti, 3n)^{217}Th to produce this isotope. An α energy $E_{\alpha 1} = (9268 \pm 10)$ keV and a half-life of $T_{1/2} = (247 \pm 3)\,\mu$s were measured. Besides this 'main line' two more activities with similar half-lives were observed (fig. 6a),b)): a) $E_{\alpha 2} = (8731 \pm 10)$ keV, $T_{1/2} = (293 \pm 28)\,\mu$s and b) $E_{\alpha 3} = (8459 \pm 10)$ keV, $T_{1/2} = (250 \pm 8)\,\mu$s. Due to the similar half-lives and the fact that the excitation functions for these two activities measured within the ^{51}V $+^{170}$ Er-irradiation (fig. 6c)) are similar in shape and in the position of the maxima to that of the $E_\alpha = 9268$ keV activity they are also attributed to ^{217}Th thus confirming the assignment of reference [20]. The relative intensities of the lines are given in table 1. The levels populated in the daughter nucleus ^{213}Ra can be estimated by the Q-value difference to the $E_\alpha = 9268$ keV line, assuming that it represents the ground state to ground state transition. These values are: E^*_1 (^{213}Ra ($E_\alpha = 8731$ keV))=547 keV and E^*_2 (^{213}Ra ($E_\alpha = 8459$ keV)) $= 824$ keV. Thus E^*_1 evidently represents the α decay into the $E^* = 546.35$ keV-level in ^{213}Ra, known from the literature [12], with an assumed spin and parity of $5/2^-$.

3.7 Isotope ^{216}Th

Even-even isotopes of polonium and radon slightly below the neutron shell at $N = 126$ are known to have their lowest excited levels (2^+) at $E^* \approx (575$–$700)$ keV [12]. For some of these nuclei those levels are known to be populated weakly ($i_{\mathrm{rel}} < 0.01$) by α decay of the corresponding mother nuclei. It therefore seemed meaningful to identify the first excited 2^+-level of ^{212}Ra by searching for fine structure in the α decay of ^{216}Th which was produced by the ^{170}Er(^{51}V, p4n)^{216}Th and ^{170}Er(^{50}Ti, 4n)^{216}Th reactions in the present experiment. A previously unknown α line at $E_\alpha = (7302 \pm 15)$ keV was clearly observed in these reactions (see fig. 7a)). The half-life of this activity was estimated as $T_{1/2} = (30 \pm 3)$ ms (fig. 7b)), which is equal within the error bars to the value of $T_{1/2} = (27.0 \pm 0.3)$ ms obtained for the well-established $E_\alpha = (7923 \pm 10)$ keV-line of ^{216}Th. Literature values for this isotope are $E_\alpha = (7921 \pm 8)$ keV and $T_{1/2} = (28 \pm 2)$ ms [12]. This agreement suggests to assign the line at $E_\alpha = 7302$ keV to the α decay of ^{216}Th into the first excited 2^+-level of ^{212}Ra. This interpretation is supported by the observation of two γ-events with a mean energy of $E_\gamma = (628.3 \pm 0.5)$ keV in coincidence to α decays of $E_\alpha = 7302$ keV in the ^{51}V $+^{170}$ Er-bombardment.

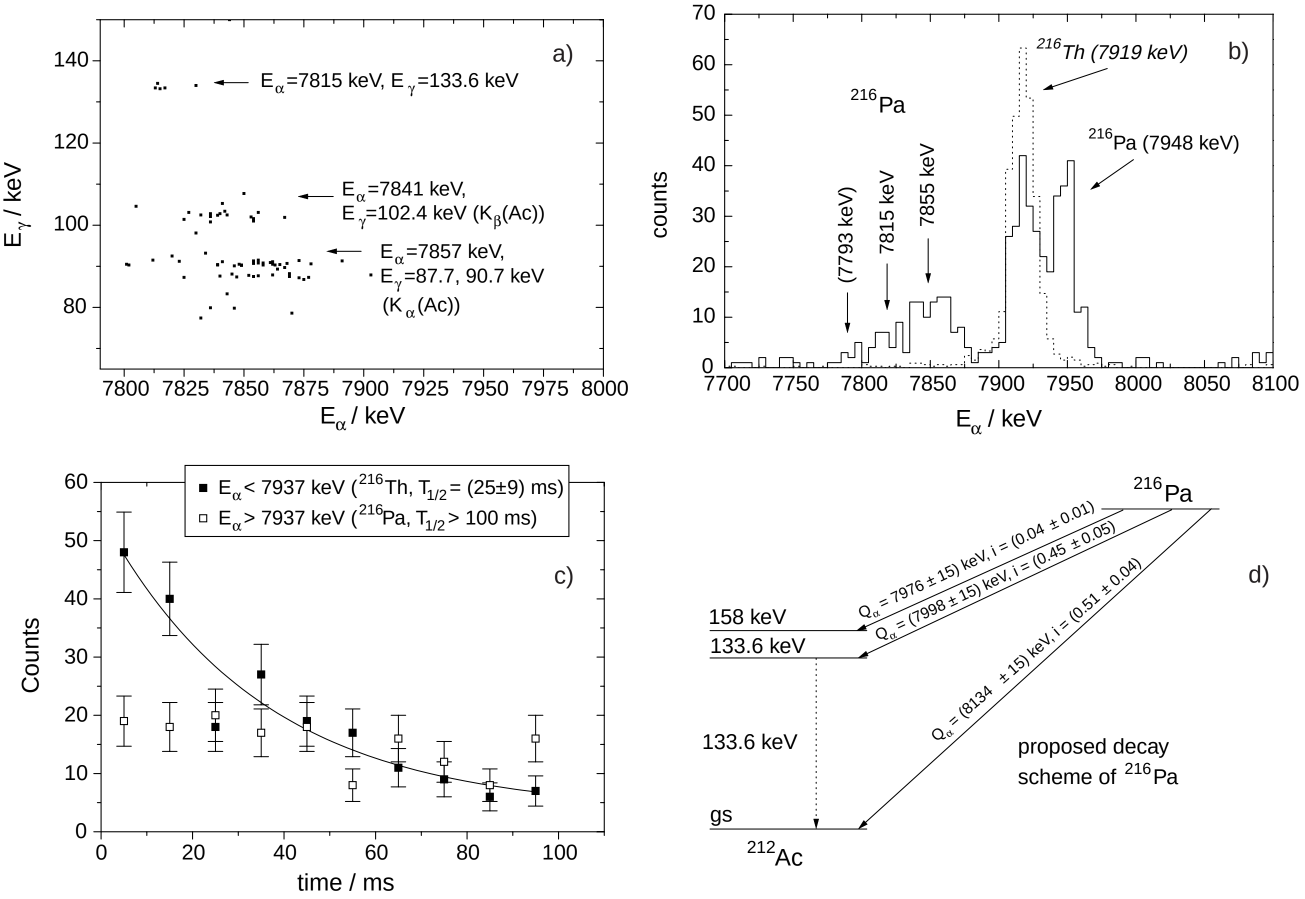

Fig. 5. a) α (E_α = (7800–7900) keV)-γ (E_γ = (70–140) keV) coincidences observed for ^{51}V +^{170} Er and assigned to ^{216}Pa; b) spectrum of α decays from ^{51}V +^{170} Er, followed by α decays of ^{212}Ac; dotted line: spectrum of α decays followed by α decays of ^{212}Ra; c) time distribution Δt (ER-α) of α decays followed by ^{212}Ac; open symbols: events assigned to ^{216}Pa; full symbols: events assigned to ^{216}Th (random correlations); d) decay scheme proposed for ^{216}Pa.

3.8 Isotope ^{215}Th

Decay properties of ^{215}Th have been first reported by Valli and Hyde [16]. They produced it by the ^{206}Pb(^{16}O, 7n)^{215}Th reaction. Three α-lines $E_{\alpha 1}$ = 7522 keV, $E_{\alpha 2}$ = 7393 keV, $E_{\alpha 3}$ = 7331 keV were attributed to this isotope. Its half-life is $T_{1/2}$ = (1.2 ± 0.2) s. In the present experiment it was produced by the ^{170}Er(^{51}V, p5n)^{215}Th reaction. The half-life was not determined, since it was too long to establish ER-α correlations unambiguously. The reported α energies could be reproduced. Our results are $E_{\alpha 1}$ = (7520 ± 15) keV, $E_{\alpha 2}$ = (7387±15) keV, $E_{\alpha 3}$ = (7336±15) keV. We further observed the known [21] γ line at E_γ = (133.6 ± 1.5) keV in coincidence to $E_{\alpha 2}$ and, as a new result, a line E_γ = (192.4 ± 1.5) keV in coincidence to $E_{\alpha 3}$.

3.9 Isotope ^{216}Ac

First observation of ^{216}Ac, having an α decay energy of E_α = 9.14 MeV and a half-life of $T_{1/2}$ = 0.39 ms, was reported by Rotter *et al.* [22]. In principle these results were later confirmed by Valli and Hyde [16], who observed two peaks at $E_{\alpha 11}$ = (9105 ± 10) keV and $E_{\alpha 12}$ = (9020±10) keV, both having a half-life of $T_{1/2} \approx 0.5$ ms. In addition they reported two more lines at $E_{\alpha 14}$ = (8283 ± 10) keV and $E_{\alpha 15}$ = (8198 ± 10) keV. They attributed the lines $E_{\alpha 12}$, $E_{\alpha 15}$ to the ground state decay ^{216g}Ac (assumed spin and parity 1^-), the lines $E_{\alpha 11}$ and $E_{\alpha 14}$ to the decay of an isomeric state ^{216m}Ac (assumed spin and parity 9^-). This assignment was revised by Torgerson and Macfarlane [23]. They carefully analyzed the excitation functions, measured for ^{12}C +^{209} Bi and observed in the α-energy interval E = (8900–9150) two more α lines at $E_{\alpha 21}$ = (9.070±0.008) MeV and $E_{\alpha 22}$ = (8.99±0.02) MeV, whose maxima cross-sections were shifted by ≈ 3 MeV to lower bombarding energies compared to the lines $E_{\alpha 11}$, $E_{\alpha 12}$, $E_{\alpha 14}$, $E_{\alpha 15}$. Consequently they assigned the lines $E_{\alpha 21}$ and $E_{\alpha 22}$ to the ground state decay ^{216g}Ac and in contrast to Valli and Hyde all other lines ($E_{\alpha 11}$, $E_{\alpha 12}$, $E_{\alpha 14}$, $E_{\alpha 15}$) to the decay of the isomeric state ^{216m}Ac. The half-life given in reference [23] is $T_{1/2}$ = (0.33 ± 0.02) ms, equal within the error bars for both, ^{216g}Ac and ^{216m}Ac. In our experiments we obtained the highest yields of ^{216}Ac in the ^{209}Bi(^{12}C, 5n)^{216}Ac-reaction. An α-spectrum, cov-

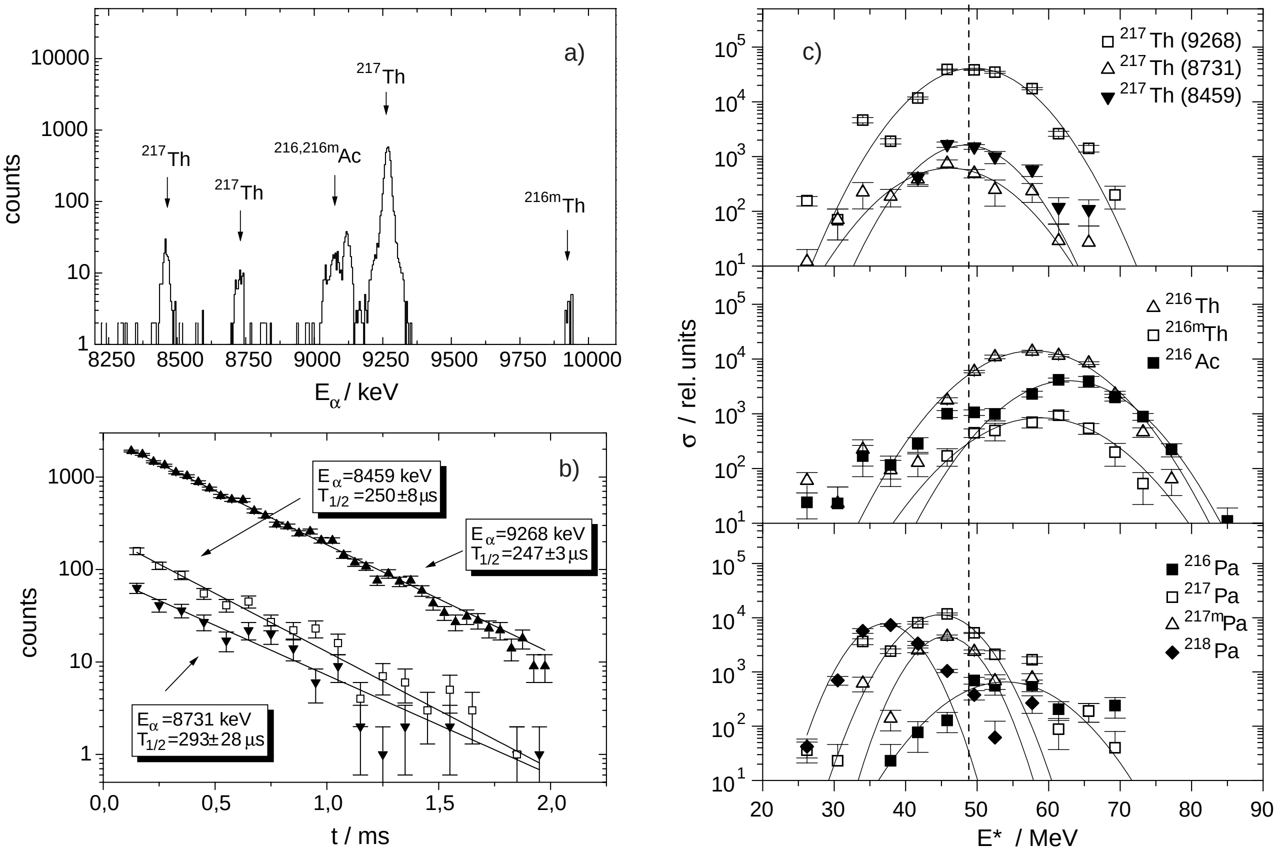

Fig. 6. a) Spectrum of α-particles observed in ^{50}Ti +^{170} Er ($E = 218$ MeV), following the implantation of an ER within 0.6 ms $\leq \Delta t \leq 2$ ms; a lower time limit of 0.6 ms was chosen to avoid distortions in the α-spectrum due to pile-up of pulses from ER with those from succeeding α-particles in cases of small time differences; b) time distribution Δt (ER-α) of α decays attributed to ^{217}Th; c) excitation function for evaporation residue production by ^{51}V +^{170} Er.

ering the energy range 8.8 MeV to 9.25 MeV is shown in fig. 8a). The most prominent line is found at $E_{\alpha 11} = (9110 \pm 10)$ keV, the half-life obtained from the time intervals between implantation of evaporation residues and subsequent α-particles is $T_{1/2} = (443 \pm 7)\,\mu$s. The broad energy distribution at lower energies seems to have a more complex structure. We observed coincidences between γ-events of $E_\gamma = (82.4 \pm 0.4)$ keV and α-particles of $E_\alpha = (9026 \pm 15)$ keV. The half-life of this activity is $T_{1/2} = (359^{+97}_{-63})\,\mu$s. Although E_γ is close to $E(K_{\alpha 2})$ of francium, the γ-events do not seem to be due to X-rays emitted after internal conversion, because our measured spectrum is in contradiction to the expected X-ray spectrum since the $K_{\alpha 1}$ and K_β lines are missing (see fig. 8b)). On the other hand, E_γ is lower than the K binding energy in francium ($E_{B_k} = 101.14$ keV), so K conversion is energetically not possible. Thus the broad energy distribution at $E_\alpha = (9000$–$9080)$ keV is not caused by energy summing of α-particles and conversion electrons, but due to a second activity. Taking $E_{\alpha 11} = 9110$ keV and a line width of $\Delta E = 24.1$ keV (FWHM), as obtained for this line, and also for $E_{\alpha 12}$, we obtain the 'three-line' fit displayed in fig. 8a). The fitted value $E_{\alpha 12} = (9032 \pm 2)$ keV (in this specific case the error only includes the accuracy of the fitting procedure and not the systematic error due to the calibration) is slightly higher than the value obtained from the α decays coincident to γ-events. Another line appears at $E_{\alpha 21} = (9052 \pm 15)$ keV; its width, however, is $\Delta E = (59.4 \pm 1.9)$ keV (FWHM), which is more than twice that for the other lines. $E_{\alpha 21}$ is regarded as due to the same activity observed by Torgerson and Macfarlane and assigned to ^{216g}Ac, although our energy is about 20 keV lower. At $E_\alpha < 9000$ keV we observe a tail in the energy distribution. Therefore the probably weak line $E_{\alpha 22}$ is not clearly observed in our experiment. The large linewidth of $E_{\alpha 22}$, however, which indicates an unresolved line doublet is not quite understood. In [23] it is assumed, that the decays from the ground state ($E_{\alpha 11}$, $E_{\alpha 12}$) as well as from the isomeric state in ^{216}Ac ($E_{\alpha 21}$, $E_{\alpha 22}$) populate the assumed 5^+ ground state and a 4^+-level at low excitation energy in the daughter nucleus ^{212}Fr. So the α spectra for ^{216g}Ac and ^{216m}Ac should have the same structure, which is indeed indicated by about the same energy difference between $E_{\alpha 11}$ and $E_{\alpha 12}$ as well as between $E_{\alpha 21}$ and $E_{\alpha 22}$ [23]. From this point of view it is not understandable, why $E_{\alpha 21}$ should be a line doublet. Also possible energy summing between α-particles and conversion electrons should influence both lines in the same manner. A half-life analysis of α decays in the interval $E_\alpha = (9035$–$9070)$ keV results in $T_{1/2} = (440 \pm 16)\,\mu$s.

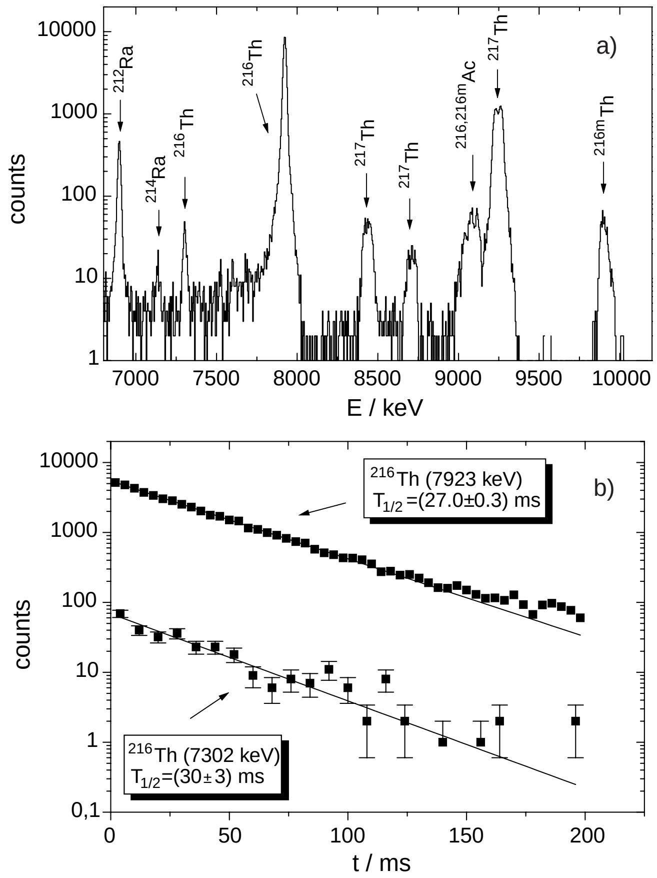

Fig. 7. a) Spectrum of α-particles observed in $^{50}\mathrm{Ti}+^{170}\mathrm{Er}$ ($E = 218\,\mathrm{MeV}$); b) time distribution Δt (ER-α) of α decays attributed to ^{216}Th.

Three more lines which were attributed to $^{216\mathrm{m}}$Ac, $E_{\alpha 14}$, $E_{\alpha 15}$ already reported in [16,23] and a new line at $E_{\alpha 13} = (8586 \pm 15)$ keV, were observed at $E_\alpha < 8900\,\mathrm{keV}$.

For $E_{\alpha 14}$ we obtained $E_{\alpha 14} = 8273\,\mathrm{keV}$ and $T_{1/2} = (432 \pm 17)\,\mu\mathrm{s}$.

The α-line $E_{\alpha 15}$ interfered with the more intense $E_\alpha = 8172\,\mathrm{keV}$ line of ^{215}Ra and thus could not be clearly separated. However, we found an indication for this activity from an analysis of the time distribution from delayed coincidences between evaporation residues and α-particles in the range $E_\alpha = (8150\text{–}8220)\,\mathrm{keV}$, which could be fitted only assuming two activities of $T_{1/2} = (1.68 \pm 1.24)\,\mathrm{ms}$ (^{215}Ra) and $T_{1/2} = (463 \pm 190)\,\mu\mathrm{s}$ ($^{216\mathrm{m}}$Ac). The energy is $E_{\alpha 15} = (8198 \pm 25)\,\mathrm{keV}$

The previously unknown α-line $E_{\alpha 13}$=8586 keV was observed in coincidence to γ-events of $E_\gamma = (537 \pm 3)\,\mathrm{keV}$. Since this line was found on the low energetic tail of the $E_\alpha = 8698\,\mathrm{keV}$ line of ^{215}Ra, the half-life estimation was restricted to using α-events in coincidence to γ-events only. We obtained a value $T_{1/2} = (475^{+289}_{-130})\,\mu\mathrm{s}$. We attribute $E_{\alpha 13}$ to $^{216\mathrm{m}}$Ac since a) $Q_{\alpha 13} + E_\gamma = (9320 \pm 15)\,\mathrm{keV}$ and thus close to $Q_{\alpha 11} = (9316 \pm 15)\,\mathrm{keV}$ and b) the half-life is within the error bars equal to that of the $E_{\alpha 11}$ line. We further want to remark that this assignment is in line with results from in-beam γ-investigations of ^{212}Fr, where a 7^+-state at $E^* = 542.2\,\mathrm{keV}$ was identified [24].

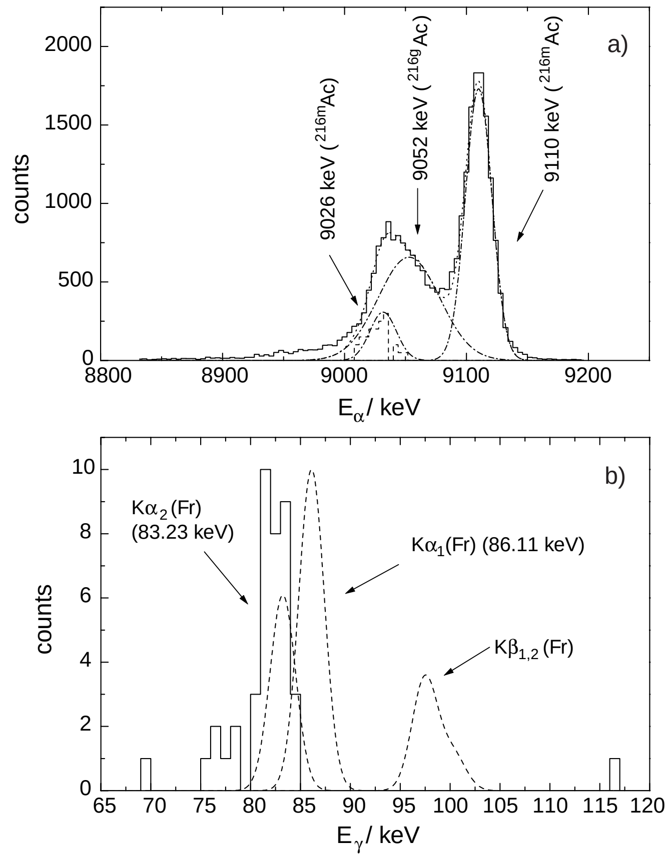

Fig. 8. a) Spectrum of α decays attributed to ^{216}Ac; full line: all events, dashed line: events coincident to γ-events of $E_\gamma = 82.4\,\mathrm{keV}$; dotted and dashed-dotted lines: results from fits (see text) b) γ-events in coincidence to the $E_\alpha = 9026\,\mathrm{keV}$ line attributed to $^{216\mathrm{m}}$Ac; the dashed lines represent expected energies (referring to a detector resolution of $\Delta E = 2\,\mathrm{keV}$ (FWHM)) and intensities of Fr-X-rays.

3.10 Isotope ^{215}Ac

^{215}Ac was first identified by Valli *et al.* [25] in bombardments of ^{203,205}Tl with ^{16}O and of ^{209}Bi with ^{12}C. They reported a half-life of $T_{1/2} = (0.17 \pm 0.01)\,\mathrm{s}$ and an α energy of $E_{\alpha 1} = 7602\,\mathrm{keV}$.

In our bombardment of ^{209}Bi with ^{12}C at $E = 100\,\mathrm{MeV}$, besides the known transition a second line at $E_{\alpha 2} = (7214 \pm 15)\,\mathrm{keV}$ was observed in coincidence to a γ-line of $E_\gamma = (399 \pm 2)\,\mathrm{keV}$. Since the α energy is close to that of the ground-state to ground-state transition of ^{214}Ac ($E_\alpha = (7210 \pm 10)\,\mathrm{keV}$, see sect. 3.11) one cannot exclude *a priori* chance coincidences between α-particles and γ-events. But this seems unprobable on the basis of the observed α rates. We obtained $\Sigma\alpha(^{215}\,\mathrm{Ac}, E_\alpha = 7602\,\mathrm{keV})/\Sigma\alpha(^{214}\mathrm{Ac}, E_\alpha = 7210\,\mathrm{keV}) = (3.86 \pm 0.04)$ for single events but $\Sigma\alpha(E_\alpha = (7595\text{–}7625)\,\mathrm{keV})/\Sigma\alpha(E_\alpha = (7200\text{–}7230)\,\mathrm{keV}) = (0.57 \pm 0.50)$ for α decays coincident to γ-events in the interval $E_\gamma = (390\text{–}410)\,\mathrm{keV}$. If the α-γ coincidences were accidental we would expect the same ratio as for the single events, since there is no reason why the probability for chance coincidences should be higher for the $E_\alpha = 7210\,\mathrm{keV}$ line of ^{214}Ac than for the $E_\alpha = 7602\,\mathrm{keV}$ line of ^{215}Ac. Therefore, the lower ratio indicates that the observed α-γ coincidences are predominantly 'real' events, the background contribution is about 15%. Since $Q_{\alpha 2} + E_\gamma = (7784 \pm 15)\,\mathrm{keV}$ and thus close to $Q_{\alpha 1} = (7781 \pm 15)\,\mathrm{keV}$ we tentatively attribute it to ^{215}Ac. This result is insofar interesting, since nuclear structure of the daughter nucleus ^{211}Fr has been investigated by in-beam γ-spectroscopy by Byrne *et al.* [24]. A nuclear level at $E^* \approx 399\,\mathrm{keV}$ or a γ transition of $E_\gamma \approx 399\,\mathrm{keV}$ has not been reported.

In addition two more α-γ coincidence pairs were observed: a) $E_{\alpha 3} = (7026 \pm 15)\,\mathrm{keV}$, $E_\gamma = (582.3 \pm 2.3\,\mathrm{keV}$, and b) $E_{\alpha 4} = (6960 \pm 15)\,\mathrm{keV}$, $E_\gamma = (654.0 \pm 2.3)\,\mathrm{keV}$. Since the γ energies perfectly agree with the excitation energies of the $11/2^-(583\,\mathrm{keV})$ and $9/2^-(653\,\mathrm{keV})$ levels in ^{211}Fr reported in [24] and also the sum of the Q_α values and the coincident E_γ values fit to Q_α of the ground-state transition, we also tentatively assign these lines to ^{215}Ac.

3.11 Isotope ^{214}Ac

Three α-lines attributed to ^{214}Ac have been reported so far [12]: $E_{\alpha 1} = (7214 \pm 5)\,\mathrm{keV}$ ($i_{\mathrm{rel}} = 0.52$), $E_{\alpha 2} = (7082 \pm 5)\,\mathrm{keV}$ ($i_{\mathrm{rel}} = 0.44$), $E_{\alpha 3} = (7002 \pm 15)\,\mathrm{keV}$ ($i_{\mathrm{rel}} = 0.04$). We have produced this isotope by α decay of ^{218}Pa, ^{170}Er (^{51}V, α3n) ^{214}Ac and by the reaction ^{209}Bi (^{12}C, 7n) ^{214}Ac. The results of our α-γ coincidence measurements are shown in fig. 9a). We observed the $E_{\alpha 2}$ line in coincidence to a γ line of $E_\gamma = (138.6 \pm 0.2)\,\mathrm{keV}$, and at a somewhat higher energy $E_\alpha \approx 7125\,\mathrm{keV}$ coincidences to X-ray events assigned to the $K_{\alpha 2}$-line ($E = 83.16\,\mathrm{keV}$), $K_{\alpha 1}$-line ($E = 86.02\,\mathrm{keV}$), $K_{\beta 1}$-line ($E = 97.11\,\mathrm{keV}$), $K_{\beta' 2}$-line ($E = 100.33\,\mathrm{keV}$) of francium. These α-events are interpreted as summing events of α-particles and conversion electrons. With respect to a fluorescence yield of $\omega_k = 0.967$ for francium [12], the numbers of X-ray and γ-ray events and assuming the same detection efficiency for the X-ray and γ-ray events, we obtain $N_e/N_\gamma = 6.94$. According to the conversion coefficients at $E = 141\,\mathrm{keV}$ published by Hager and Seltzer [26] $\alpha_k(M1) = 4.57, \alpha_k(M2) = 21.6$, $\alpha_k(E1)$, $\alpha_k(\mathrm{E2})$, $\alpha_k(\mathrm{E3})$, $\alpha_k(\mathrm{E4}) < 1$, our value is in best agreement with an $M1$-transition. Thus assuming a spin of $I = 6^+$ for the ground state of ^{210}Fr [12], a value of $I = 5^+$ or $I = 7^+$ is expected for the excited level at $E = 138.6\,\mathrm{keV}$.

Besides the strong γ transition at $E_\gamma = 138.6\,\mathrm{keV}$ five weaker γ-lines were observed in coincidence to α-particles in the interval $E_\alpha = (6850 - 7200)\,\mathrm{keV}$. Since for all transitions $Q_\alpha + E_\gamma \approx 7385\,\mathrm{keV}$, *i.e.* close to the value $Q_{\alpha 1}$ they were attributed to ^{214}Ac. Due to the small number of events, this assignment is likely, but is not completely unambiguous. So it should be regarded as tentative.

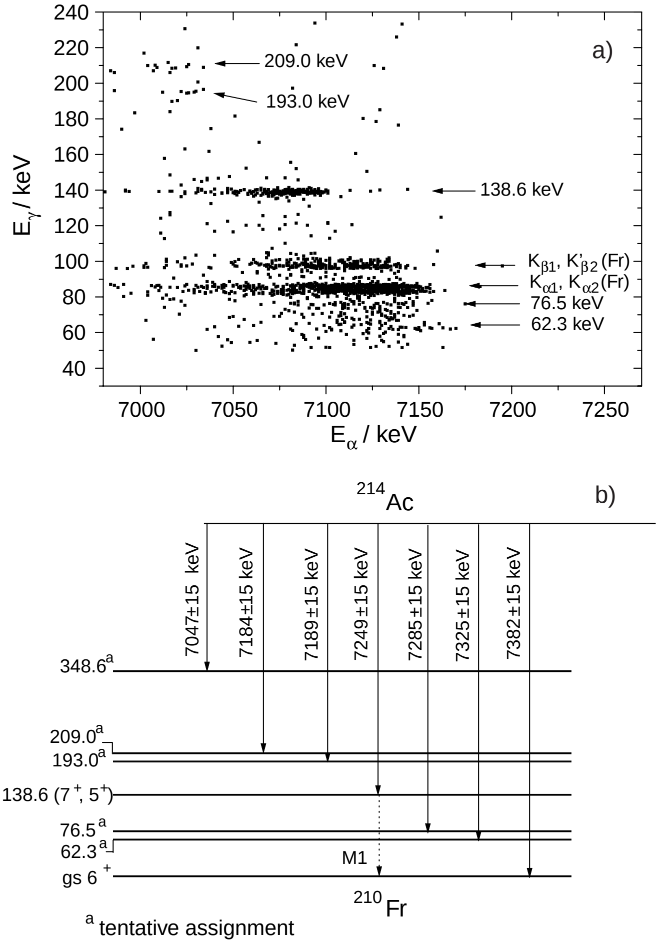

Fig. 9. a) Observed α-γ coincidences ($E_\gamma = (60$–$240)\,\mathrm{keV}$) assigned to ^{214}Ac from $^{12}\mathrm{C} +^{209}$ Bi, $E = 100\,\mathrm{MeV}$; b) decay scheme proposed for ^{214}Ac; the energies refer to the Q_α values.

Below the energies of K-X-rays of francium two γ-lines of $E_\gamma = (62.3 \pm 0.5)\,\mathrm{keV}$ and $E_\gamma = (76.5 \pm 0.5)\,\mathrm{keV}$ were found in coincidence to α-particles of $E_\alpha = (7154 \pm 15)\,\mathrm{keV}$ or $E_\alpha = (7115 \pm 15)\,\mathrm{keV}$, respectively. The existence of two low-lying levels at $E^* < 100\,\mathrm{keV}$ is not unreasonable *a priori*. It is, however, striking that the sum of both energies is $E_{\gamma,s} = (138.8 \pm 0.5)\,\mathrm{keV}$ and thus within the error bars equal to the energy ($E_\gamma = (138.6 \pm 0.2)\,\mathrm{keV}$) of the γ-events coincident to $E_{\alpha 2} = (7080 \pm 15)\,\mathrm{keV}$. It seems therefore possible that the level at $E^* = 138.6\,\mathrm{keV}$ (in the following denoted as E1386) decays with a small probability in a two step process via an intermediate level (in the following denoted as IL) into the ground state. The excitation energy of IL would be $E^* = 76.5\,\mathrm{keV}$ or $E^* = 62.3\,\mathrm{keV}$. Under this assumption the observed coincidences can be understood as a) $^{210}\mathrm{Fr}\ (E1386) \xrightarrow{\gamma} {}^{210}\mathrm{Fr(IL)} \xrightarrow{IC} {}^{210}\mathrm{Fr(gs)}$ and b) $^{210}\mathrm{Fr}\ (E1386) \xrightarrow{IC} {}^{210}\mathrm{Fr(IL)} \xrightarrow{\gamma} {}^{210}\mathrm{Fr(gs)}$. So in one case we would observe the γ-events from the decay $^{210}\mathrm{Fr}\ (E1386) \xrightarrow{\gamma} {}^{210}\mathrm{Fr(IL)}$ in coincidence to the sum energy of α-particles from the $^{214}\mathrm{Ac(gs)} \xrightarrow{\alpha} {}^{210}\mathrm{Fr}\ (E1386)$ transition and the conversion electrons from $^{210}\mathrm{Fr(IL)} \xrightarrow{IC} {}^{210}\mathrm{Fr(gs)}$, while in the other case we would observe the γ-events from the decay $^{210}\mathrm{Fr(IL)} \xrightarrow{\gamma} {}^{210}\mathrm{Fr(gs)}$ in coincidence to the sum energy of α-particles from the $^{214}\mathrm{Ac(gs)} \xrightarrow{\alpha} {}^{210}\mathrm{Fr}\ (E1386)$ transition and the conversion electrons from $^{210}\mathrm{Fr}\ (E1386) \xrightarrow{IC} {}^{210}\mathrm{Fr(IL)}$.

In the region of α energies $E_\alpha < 7050\,\text{keV}$ we observed nineteen γ-events in the energy interval $E_\gamma = (189\text{–}212)\,\text{keV}$ in coincidence with α decays of $E_\alpha \approx 7020\,\text{keV}$. These may be divided into two groups: five events with energies of $E_\gamma = (193.0 \pm 2.5)\,\text{keV}$ and $E_\alpha = (7021 \pm 15)\,\text{keV}$ and fourteen events having $E_\gamma = (209.0 \pm 1.4)\,\text{keV}$ $E_\alpha = (7016 \pm 15)\,\text{keV}$. Due to the small energy difference between α-particles in coincidence to $E_\gamma = 193\,\text{keV}$ and $E_\gamma = 209\,\text{keV}$ it is questionable if the α decays populate two different levels in ^{210}Fr. It may also be possible that at least the γ-events of the lower energy do not represent transitions into the ground state, but in low-lying excited states.

We further registered a small number (four events) of α-γ coincidences having $E_\alpha = (6881 \pm 15)\,\text{keV}$ and $E_\gamma = (348.6 \pm 1.6)\,\text{keV}$. Since $Q_\alpha + E_\gamma = (7396 \pm 15)\,\text{keV}$, a value close to Q_α (gs) $= (7382 \pm 10)\,\text{keV}$, we tentatively assign this line to ^{214}Ac.

Although these new decay data seem to reflect interesting information on the nuclear structure of ^{210}Fr, they are not fully conclusive. More sensitive measurements are necessary. The proposed tentative decay scheme of ^{214}Ac is shown in fig. 9b).

3.12 Isotope ^{214}Ra

Up to now only one α decay line ($E_\alpha = 7137\,\text{keV}$) has been known for ^{214}Ra [12], but according to the result for ^{216}Th (see sect. 3.7), also a small α decay branch into the first excited 2^+-level of ^{210}Rn ($E^*(2^+) = 643.8\,\text{keV}$ [12]) could be expected. To identify the decay $^{214}\text{Ra} \overset{\alpha}{\rightarrow} {}^{210}\text{Rn}$ $(2^+, E^* = 643.8\,\text{keV})$ we searched for coincidences between α-particles and γ-events of $E_\gamma \approx 644\,\text{keV}$, ^{214}Ra was produced by the ^{208}Pb (^{12}C, 6n) ^{214}Ra reaction. The result is shown in fig. 10. A clear concentration of coincident events is seen at $E_\alpha = (6505 \pm 15)\,\text{keV}$ and $E_\gamma = (641.9 \pm 0.2)\,\text{keV}$. The energy of the γ-line as well as the sum $Q_\alpha + E_\gamma = (7305 \pm 15)\,\text{keV}$, which is almost equal to the Q_α value for the ground-state transition, suggests to assign the α-line to the decay into the first excited 2^+-level of ^{210}Rn. The relative intensity of this transition was estimated as $i_{\text{rel}} = (0.0020 \pm 0.0010)$ on the basis of an α-γ coincidence efficiency of $\epsilon_{\alpha\gamma} \approx 0.0037$, obtained as the mean value from the numbers of α decays and α-γ coincidences observed for ^{215}Ra and ^{211}Po.

3.13 Isotope ^{213}Rn

The situation for ^{213}Rn is somewhat similar to that for ^{214}Ra. Excited levels at $E^* = 544.95\,\text{keV}$ $(5/2^-)$ and $E^* = 854.32\,\text{keV}$ $(3/2^-)$ are known in the daughter nucleus ^{209}Pb [12], but besides the ground state to ground state α transition at $E_\alpha = 8088\,\text{keV}$ only the $^{213}\text{Rn} \overset{\alpha}{\rightarrow} {}^{209}\text{Po}$ $(5/2^-)$ transition having $E_\alpha = 7553\,\text{keV}$ ($i_{\text{rel}} = 0.001$) has been reported. In our irradiation of ^{208}Pb with ^{12}C at $E = 100\,\text{MeV}$ we observed some α-γ coincidences of $E_\alpha = (7550 \pm 15)\,\text{keV}$ and $E_\gamma = (540.3 \pm 0.4)\,\text{keV}$ which may be assigned to the decay into the $5/2^-$-state, but had no unambiguous indication of α decays coincident to $E_\gamma \approx 854\,\text{keV}$. At lower bombarding energies where we did not measure α-γ coincidences, an α activity having an energy $E_\alpha = (7252 \pm 10)\,\text{keV}$ and $T_{1/2} = (19.0 \pm 0.5)\,\text{ms}$ was observed. The energy dependence of its production cross-section is similar to that of the $E_\alpha = 8088\,\text{keV}$ and $E_\alpha = 7550\,\text{keV}$ activities attributed to ^{213}Rn (fig. 11). Also the half-life is similar; we obtained values of $T_{1/2} = (19.5 \pm 0.1)\,\text{ms}$ for ^{213}Rn ($E_\alpha = 8088\,\text{keV}$) and $T_{1/2} = (18.0 \pm 0.4)\,\text{ms}$ for ^{213}Rn ($E_\alpha = 7550\,\text{keV}$). We want to remark, however, that these values are about 25% lower than those reported in the literature [12]. The Q value difference of the $E_\alpha = 8088\,\text{keV}$ line and the $E_\alpha = 7252\,\text{keV}$ line is $\Delta Q = (852 \pm 4)\,\text{keV}$, which perfectly fits to the excitation energy of the $3/2^-$-level in ^{209}Po. We therefore assign the $E_\alpha = 7252\,\text{keV}$ line to the decay $^{213}\text{Rn} \overset{\alpha}{\rightarrow} {}^{209}\text{Po}$ $(3/2^-)$.

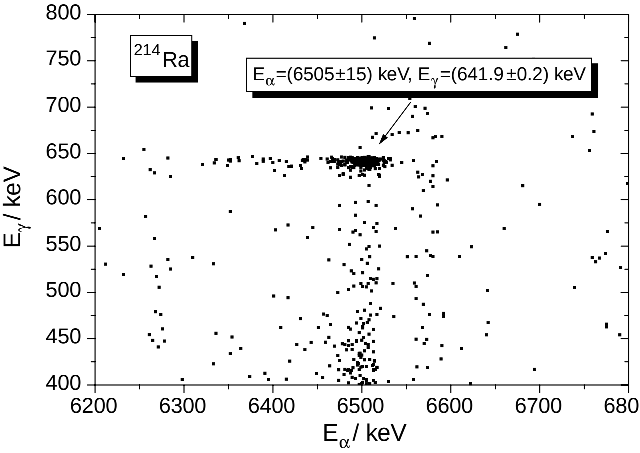

Fig. 10. observed α-γ coincidences from $^{12}\text{C} + {}^{208}\text{Pb}$, $E = 88\,\text{MeV}$ assigned to ^{214}Ra.

3.14 Isotopes ^{215,214,213}Pa, ^{224,222,221,216m}Th, ^{213,212,211,210,209}Ac, ^{220}Ra

For various isotopes produced in these experiments decay data reported in literature [12,25,15,27,9,28] could be reproduced or just slightly improved. For completeness we will here report our results without further discussion in table 1.

^{213,214}Pa were identified in the irradiations of ^{170}Er with ^{51}V at bombarding energies $E_{\text{lab}} = (265\text{–}286)\,\text{MeV}$ for the first time. These results have been already published [29] and thus shall not be discussed here again.

4 Discussion

4.1 α decay of N = 127 even-Z isotones

Our results deliver additional information on general trends in the α decay of even-Z nuclei with $N = 127$ and on the nuclear structure of their $N = 125$ daughter products. From nuclear shell model calculations for $N = 127$,

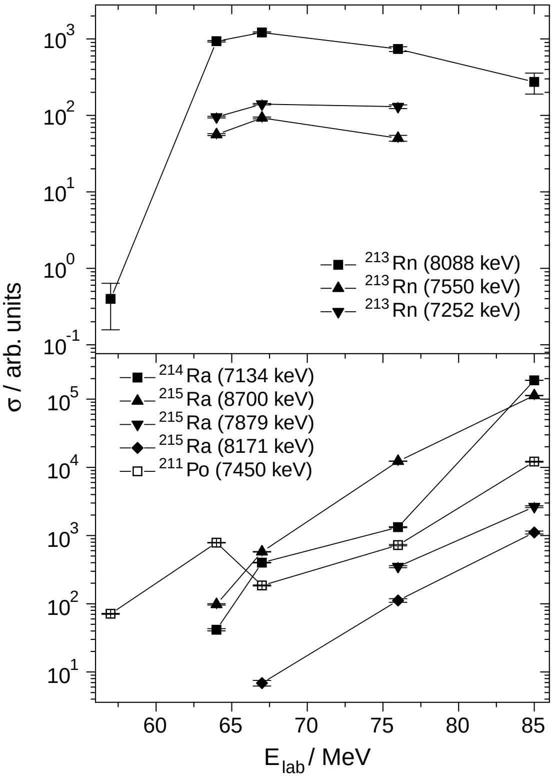

Fig. 11. Excitation function for evaporation residue production by $^{12}\mathrm{C} + ^{208}\mathrm{Pb}$, upper figure: data for the α+lines attributed to ^{213}Rn; lower figure: data for ^{214,215}Ra and ^{211}Po.

one neutron above the closed-shell, the valence neutron in the ground state is expected to be in the single-particle orbital $2g_{9/2}$. For the daughter nuclei the $N = 125$ configuration is assigned to a neutron hole state in the $3p_{1/2}$ orbital. Low-lying levels are expected to be $2f_{5/2}$ and $3p_{3/2}$ hole states. Consequently spin and parity assignments for the ground states are $9/2^+$ and $1/2^-$ for $N = 127$ and $N = 125$ odd-even nuclei, respectively, and $5/2^-$ and $3/2^-$ for low-lying excited levels in $N = 125$ odd-even nuclei. Where experimental data are available these assignments have been confirmed. As shown in fig. 12, the decay properties for ^{217}Th, ^{215}Ra, ^{213}Rn and ^{211}Po show a regular pattern in which the new data for ^{217}Th and ^{213}Rn fit well. Evidently the α decays $9/2^+ \to 3/2^-$ are favored by nuclear structure as can be seen from the largest values of the reduced width $\delta^2 = h \times \ln 2 \times b_\alpha/(\mathrm{T}_{1/2} \times \mathrm{P}_\alpha)$, using the method described in reference [30,31] for calculation of the transmission coefficient P_α. The δ^2 values for the ground state transitions $9/2^+ \to 1/2^-$ are roughly a factor of two lower, but the transitions are favoured by their higher Q-value, while the δ^2 values for $9/2^+ \to 5/2^-$ are lower by typically a factor of twenty and thus exhibit a structural hindrance. It is notable that the reduced widths for corresponding transitions are almost equal for ^{217}Th and ^{215}Ra, but decrease slightly towards the lower Z nuclei ^{213}Rn and ^{211}Po. This may be a hint of an enhanced structural hindrance due to the closed proton shell at $Z = 82$.

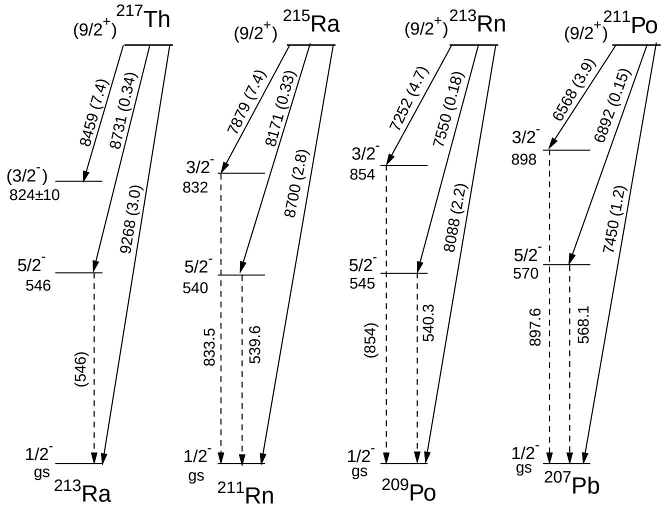

Fig. 12. α decay schemes of $N = 127$ isotones (even Z) reduced α widths in terms of $\delta \times 10^3$ are given in brackets behind the α energies. The γ energies refer to results of this work; values in brackets refer to literature values.

4.2 α decay of N = 126 even-even isotones

α decay of ^{216}Th and ^{214}Ra into the first excited 2^+-levels of their daughter nuclei was observed in the present experiments for the first time. Notable is the strong increase of the relative intensities of the decays into the 2^+-level with increasing atomic number by a factor of about forty from ^{210}Po to ^{216}Th (fig. 13). Calculations of hindrance factors using the formula proposed by Poenaru *et al.* [32] with a parameter modification suggested in [33] for theoretical α half-lives result in hindrance factors of 1.35 (^{216}Th), 1.68 (^{214}Ra), 1.5 (^{212}Rn), and 2.2 (^{210}Po). Respecting experimental uncertainties these values are in-line with hindrance factors of ≈ 1.7 for $\Delta L = 2$-transitions to $\Delta L = 0$ according to [31]. This suggests that the observed increase of the intensities for the transitions into the 2^+-level is not due to a nuclear structure effect but predominantly a Q_α value effect. Indeed the ratio $Q_\alpha(2^+)/Q_\alpha(\mathrm{gs})$ increases from 0.85 for ^{210}Po to 0.92 for ^{216}Th. This assumption is confirmed by comparing the ratios of the barrier transmission coefficients $P(2^+)/P(0^+)$ calculated according to [30, 31]. The results of the calculations reproduce the measured intensities (fig. 13) fairly well.

5 Conclusions

We have measured new decay data and considerably improved existing data of neutron deficient isotopes in the range of the elements with $Z = 86$–92 by means of α- and α-γ spectroscopy. Although part of the isotopes were discovered already thirty years ago, their α decay properties were known only in a rudimentary way in most cases. We have shown that a rapid and efficient separation technique in combination with highly sensitive α and α-γ decay measurements provide not only complementary results to in-beam γ-spectroscopy and β^+, EC decay measurements,

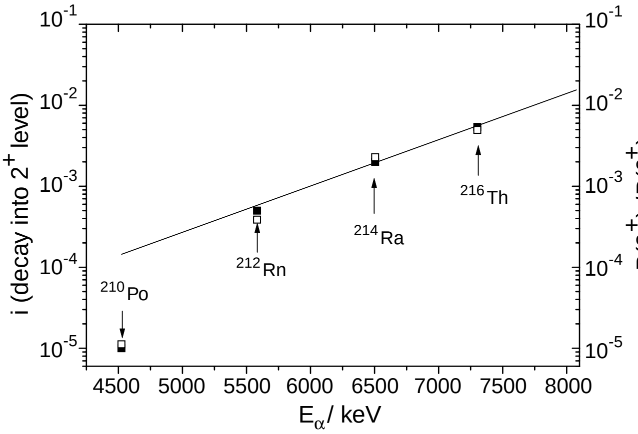

Fig. 13. Full symbols (left axis): relative α decay intensities of even-even $N = 126$ isotones for decays into the first excited 2^+ daughter level; open symbols (right axis): ratio of transmission coefficients for gs-gs transitions $P(0^+)$ to gs-2^+ transitions $P(2^+)$ of $N = 126$ even-Z isotones. The line is to guide the eye.

but also allow for the identification of very weak transitions. Therefore this method provides a valuable tool to obtain more detailed information on nuclear structure of these nuclei.

Note added in proofs:
In an experiment performed after submission of this paper we made an attempt to measure α-γ-coincidence for the fine structure lines of ^{217}Th. We found six γ-events with a mean energy of $E = (822.7 \pm 0.7)$ keV in coincidence with the 8459 keV α-line, and eight γ-events with a mean energy of $E = (546.9 \pm 0.9)$ keV in coincidence with the 8731 keV α-line

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