

Production of radioactive ion beams at CERN-ISOLDE

Mia Au



Outline: Radioactive beams at CERN-ISOLDE







08.03.24





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DOI 10.17181/cds.2289929 3







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Fig. 1. Target and ion source assembly with plasma ion source MK5. The vacuum valve is part of the assembly.











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Target selection

- **Cross sections** •
- Bulk
- Half-lives •

At ISOLDE

- 1.4-GeV p •
- ²³²Th, ²³⁸U





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Target selectior

- Cross sections
- Bulk
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At ISOLDE

- 1.4-GeV p
- ²³²Th, ²³⁸U

Sof	tware: F	ELUKA 📀	Tar	get type:	U Carbio	le	()	Beam ene	ergy: 14	00 📀	Neutro	n conver	ter	Show	Com	pare									
Go	to:	Go	Sho	w decay i	modes 🔽	Sho	w magic	number	s 🗹																
123 - 95	124	125	126	127	128	129	130	131	132	133	1 134	135	136	1 137	138	139	140	141	142	143	144	145	146	147	14
Pu 21 7 2.08e+4 - 94	+ -	Ction (µC ⁻¹)		□ 1.04e+5	Pu 222 4.16e+4	Pu 223 1.87e+5	Pu 224 6.24e+4	Pu 225 1.04e+5	Pu 226 2.08e+4	Pu 227 4.16e+4 20# ms	Pu 228 4.16e+4 2.1 s 1.3	Pu 229 2.08e+4 91 s 26	Pu 230 4.16e+4 1.70 m 0.17	Pu 231 1.66e+5 8.6 m 0.5	Pu 232 2.29e+5 33.7 m 0.5	Pu 233 7.70e+5 20.9 m 0.4	Pu 234 1.39e+6 8.8 h 0.1	Pu 235 4.31e+6 25.3 m 0.5	Pu 236 8.97e+6 2.858 y 0.008	Pu 237 2.55e+7 45.64 d 0.04	Pu 238 5.14e+7 87.7 y 0.1	Pu 239 2.92e+7 24.11 ky 0.03	Pu 240 1.23e+7 6.561 ky 0.007	Pu 241 5.41e+5 14.329 y 0.029	
Np 21 <mark>6</mark> 6.24e+5 – 93	- 1e	9+12 ^{Np} 218 2.64e+6 9+10	Np 219 1.39e+6 <5 us	Np 220 1.08e+6 30# ns	Np 221 9.78e+5 30# ns	Np 222 1.31e+6 700# ns	Np 223 1.44e+6 1# us	Np 224 1.41e+6 100# us	Np 225 1.41e+6 6 ms 5	Np 226 2.00e+6 35 ms 10	Np 227 1.98e+6 510 ms 60	Np 228 2.85e+6 61.4 s 1.4	Np 229 2.87e+6 4.00 m 0.18	Np 230 6.35e+6 4.6 m 0.3	Np 231 8.61e+6 48.8 m 0.2	Np 232 3.24e+7 14.7 m 0.3	Np 233 5.65e+7 36.2 m 0.1	Np 234 1.03e+8 4.4 d 0.1	Np 235 6.70e+8 396.1 d 1.2	Np 236 6.91e+8 153 ky 5	Np 237 1.08e+9 2.144 My 0.007	Np 238 4.08e+8 2.099 d 0.002	Np 239 9.86e+7 2.356 d 0.003	Np 240 1.41e+7 61.9 m 0.2	Np 2 3.74 13.9 r
U 215 2.64e+7 1 4 92 0. 9	- 1e - 1e - 1e	2+6 U 217 4.26e+7 2+4	U 21.8 4.32e+7 550 us 140	U 219 2.92e+7 55 us 25	U 220 3.64e+7 60# ns	U 221 4.43e+7 660 ns 140	U 222 4.90e+7 4.7 us 0.7	U 223 3.84e+7 21 us 8	U 224 3.92e+7 396 us 17	U 225 3.63e+7 61 ms 4	U 226 3.66e+7 269 ms 6	U 227 4.21e+7 1.1 m 0.1	U 228 3.16e+7 9.1 m 0.2	U 229 1.93e+7 57.8 m 0.5	U 230 5.94e+8 20.23 d 0.02	U 231 3.14e+8 4.2 d 0.1	U 232 2.29e+9 68.9 y 0.4	U 233 3.56e+9 159.2 ky 0.2	U 234 1.05e+10 245.5 ky 0.6	U 235 1.42e+10 704 My 1	U 236 3.26e+10 23.42 My 0.03	U 237 5.48e+10 6.752 d 0.002	U 238 3.52e+11 4.468 Gy 0.006	U 239 6.49e+9 23.45 m 0.02	U 2 6.84 14.1
Pa 214 9.20e+7 1 91 s 3	215 1.31e+7e 14 ms 2	+2 +0 Pa 216 2.14e+8 105 ms 12 modes	Pa 21.7 1.88e+8 3.48 ms 0.09	Pa 218 1.40e+8 113 us 10	Pa 219 1.77e+8 53 ns 10	Pa 220 2.03e+8 780 ns 160	Pa 221 2.37e+8 5.9 us 1.7	Pa 222 2.12e+8 3.2 ms 0.3	Pa 223 2.35e+8 5.1 ms 0.3	Pa 224 2.84e+8 846 ms 20	Pa 225 2.78e+8 1.7 s 0.2	Pa 226 3.66e+8 1.8 m 0.2	Pa 227 3.24e+8 38.3 m 0.3	Pa 228 2.83e+8 22 h 1	Pa 229 1.46e+9 1.50 d 0.05	Pa 230 7.99e+8 17.4 d 0.5	Pa 231 3.25e+9 32.76 ky 0.11	Pa 232 2.53e+9 1.32 d 0.02	Pa 233 6.33e+9 26.975 d 0.013	Pa 234 6.21e+9 6.70 h 0.05	Pa 235 9.50e+9 24.4 m 0.2	Pa 236 6.30e+9 9.1 m 0.1	Pa 237 1.19e+10 8.7 m 0.2	Pa 238 1.75e+8 2.28 m 0.09	Pa 2 8.95 1.81
Th 21 <mark>3</mark> 8.64e+8 +4 90 : 2 <mark>1</mark>	■ a em	nission ²¹⁵ on emission	Th 21 <mark>6 1.36e-9</mark> 26.0 ms 0.2	Th 217 9.22e+8 247 us 4	Th 218 1.22e+9 117 ns 9	Th 219 1.01e+9 1.021 us 0.024	Th 220 1.23e+9 9.7 us 0.6	Th 221 8.25e+8 1.78 ms 0.03	Th 222 9.05e+8 2.24 ms 0.03	Th 223 5.53e+8 600 ms 20	Th 224 1.58e+9 1.04 s 0.02	Th 225 1.03e+9 8.75 m 0.04	Th 226 1.94e+9 30.70 m 0.03	Th 227 1.39e+9 18.697 d 0.007	Th 228 2.18e+9 1.9124 y 0.0008	Th 229 1.66e+9 7.920 ky 0.017	Th 230 2.07e+9 75.4 ky 0.3	Th 231 1.46e+9 25.52 h 0.01	Th 232 1.51e+9 14.0 Gy 0.1	Th 233 9.48e+8 21.83 m 0.04	Th 234 8.40e+8 24.10 d 0.03	Th 235 4.16e+8 7.2 m 0.1	Th 236 2.36e+8 37.3 m 1.5	Th 237 2.87e+6 4.8 m 0.5	
Ac 21 <mark>2</mark> 1.62e+9 19 89 : 28	2-pro Ac 213 2 neutr 738 ms 18 2-neu	ron emission Ac 214 ron emission utron emissior	Ac 21.5 2.19e+9 170 ms 10	Ac 216 1.34e+9 440 us 16	Ac 217 1.54e+9 69 ns 4	Ac 218 1.45e+9 1.00 us 0.04	Ac 219 1.66e+9 11.8 us 1.5	Ac 220 1.24e+9 26.36 ms 0.19	Ac 221 1.36e+9 52 ms 2	Ac 222 1.02e+9 5.0 s 0.5	Ac 223 1.04e+9 2.10 m 0.05	Ac 224 7.71e+8 2.78 h 0.16	Ac 225 7.66e+8 9.920 d 0.003	Ac 226 5.31e+8 29.37 h 0.12	Ac 227 5.24e+8 21.772 y 0.003	Ac 228 3.30e+8 6.15 h 0.02	Ac 229 3.03e+8 62.7 m 0.5	Ac 230 1.72e+8 122 s 3	Ac 231 1.37e+8 7.5 m 0.1	Ac 232 6.27e+7 1.98 m 0.08	Ac 233 3.82e+7 145 s 10	Ac 234 1.35e+7 45 s 2	Ac 235 3.22e+6 62 s 4	Ac 236 2.08e+4 4.5 m 3.6	
Ra 21 <mark>1</mark> 3.25e+9 \$ 388 1.4	 electr 2-ele β- de 	ron capture (? ctron capture) Ra 21 <mark>4</mark> 2.71e+9 (?) 7 s 0.01e	Ra 215 1.63e+9 1.67 ms 0.01	Ra 216 1.54e+9 182 ns 10	Ra 217 9.90e+8 1.63 us 0.17	Ra 218 1.03e+9 25.2 us 0.3	Ra 219 6.08e+8 10 ms 3	Ra 220 6.07e+8 17.9 ms 1.4	Ra 221 3.56e+8 28 s 2	Ra 222 3.23e+8 33.6 s 0.4	Ra 223 1.88e+8 11.4377 d 0.0022	Ra 224 1.70e+8 3.6319 d 0.0023	Ra 225 9.58e+7 14.9 d 0.2	Ra 226 8.45e+7 1.600 ky 0.007	Ra 227 4.30e+7 42.2 m 0.5	Ra 228 3.77e+7 5.75 y 0.03	Ra 229 1.59e+7 4.0 m 0.2	Ra 230 1.11e+7 93 m 2	Ra 231 3.89e+6 104 s 1	Ra 232 2.39e+6 4.0 m 0.3	Ra 233 2.70e+5 30 s 5	Ra 234 1.04e+5 30 s 10		I
Fr 210 1.96e+9 2 87 0.06	 doub β+ de 	ble β- decay ecay ^{200 m 0.6}	Fr 21.3 1.45e+9 34.14 s 0.06	Fr 214 6.71e+8 5.18 ms 0.16	Fr 215 4.40e+8 86 ns 5	Fr 216 2.67e+8 700 ns 20	Fr 217 2.19e+8 16.8 us 1.9	Fr 218 1.26e+8 1.0 ms 0.6	Fr 219 9.98e+7 20 ms 2	Fr 220 5.66e+7 27.4 s 0.3	Fr 221 4.73e+7 4.801 m 0.005	Fr 222 2.67e+7 14.2 m 0.3	Fr 223 2.67e+7 22.00 m 0.07	Fr 224 1.58e+7 3.33 m 0.10	Fr 225 1.66e+7 3.95 m 0.14	Fr 226 9.09e+6 49 s 1	Fr 227 8.28e+6 2.47 m 0.03	Fr 228 3.04e+6 38 s 1	Fr 229 1.91e+6 50.2 s 0.4	Fr 230 4.99e+5 19.1 s 0.5	Fr 231 2.70e+5 17.6 s 0.6	Fr 232 4.16e+4 5.5 s 0.6		I	
tn 209 ^{1.00e+9} 886 ^{1.0}	■ spon	nal transition Rn 211 taneus fission pic abundance	Rn 21 <mark>2</mark> 3.82e+8 23.9 m 1.2	Rn 213 1.89e+8 19.5 ms 0.1	Rn 214 1.06e+8 270 ns 20	Rn 215 4.89e+7 2.30 us 0.10	Rn 216 3.94e+7 45 us 5	Rn 217 1.80e+7 540 us 50	Rn 218 1.71e+7 33.75 ms 0.15	Rn 219 9.72e+6 3.96 s 0.01	Rn 220 1.20e+7 55.6 s 0.1	Rn 221 9.20e+6 25.7 m 0.5	Rn 222 1.37e+7 3.8215 d 0.0002	Rn 223 8.90e+6 24.3 m 0.4	Rn 224 1.00e+7 107 m 3	Rn 225 4.79e+6 4.66 m 0.04	Rn 226 5.24e+6 7.4 m 0.1	Rn 227 1.54e+6 20.2 s 0.4	Rn 228 7.07e+5 65 s 2	Rn 229 1.46e+5 11.9 s 1.3	Rn 230 1.25e+5 10# s > 300ns		1		
At 208 2.98e+8		er At 210 9.77e+7	At 211 5.95e+7	At 212 3.32e+7	At 213 1.44e+7	At 214 7.57e+6	At 215	At 216 3.56e+6	At 217 5.24e+6	At 218 5.12e+6	At 219 8.34e+6	At 220 6.74e+6	At 221 8.80e+6	At 222 4.64e+6	At 223	At 224 2.27e+6	At 225 2.33e+6	At 226 6.24e+5	At 227 2.70e+5	At 228 6.24e+4	At 229 4.16e+4	At 230 2.08e+4			



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Ballof et al. (2020) *NIM B* **463**, 211-215 *cern.ch/isolde-yields*

Target selectior

- Cross sections
- Bulk
- Half-lives

At ISOLDE

- 1.4-GeV p
- ²³²Th, ²³⁸U

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In Ple	ease note, these are not	uct	ion tractable y	ields!						Martin				6		I	n-ta	irge	t pr	odu	ictic	n		
Go	to: So Go	Sho	ow decay n	nodes 🗸	de Sho	w magic	numbers	s 🗸	00 0	Neutron	rconvert		Show	Com	ipare	Ρ	lease i	note, t	hese a	are not	t extra	ctable	e yield:	s!
123 - 95	124 125	1 126	127	128	1 129	130	131	132	133	1 134	135	136	1 137	1 138	139	1 140	1 141	142	143	1 144	1 145	1 146	ı 147	1 148
Pu 217 2.08e+4 - 94	+	U U U U U U U U U U U U U U U U U U U	□ 221 1.04e+5	Pu 222 4.16e+4	Pu 223 1.87e+5	Pu 224 6.24e+4	Pu 225 1.04e+5	Pu 226 2.08e+4	Pu 227 4.16e+4 20# ms	Pu 228 4.16e+4 2.1 s 1.3	Pu 229 2.08e+4 91 s 26	Pu 230 4.16e+4 1.70 m 0.17	Pu 231 1.66e+5 8.6 m 0.5	Pu 232 2.29e+5 33.7 m 0.5	Pu 233 7.70e+5 20.9 m 0.4	Pu 234 1.39e+6 8.8 h 0.1	Pu 235 4.31e+6 25.3 m 0.5	Pu 236 8.97e+6 2.858 y 0.008	Pu 237 2.55e+7 45.64 d 0.04	Pu 238 5.14e+7 87.7 y 0.1	Pu 239 2.92e+7 24.11 ky 0.03	Pu 240 1.23e+7 6.561 ky 0.007	Pu 241 5.41e+5 14.329 y 0.029	
Np 216 6.24e+5 — 93	- 1e+12 ^{Np} 218 - 1e+10	Np 219 1.39e*6 <5 us	Np 220 1.08e+6 30# ns	Np 221 9.78e+5 30# ns	Np 222 1.31e+6 700# ns	Np 223 1.44e+6 1# us	Np 224 1.41e+6 100# us	Np 225 1.41e+6 6 ms 5	Np 226 2.00e+6 35 ms 10	Np 227 1.98e+6 510 ms 60	Np 228 2.85e+6 61.4 s 1.4	Np 229 2.87e+6 4.00 m 0.18	Np 230 6.35e+6 4.6 m 0.3	Np 231 8.61e+6 48.8 m 0.2	Np 232 3.24e+7 14.7 m 0.3	Np 233 5.65e+7 36.2 m 0.1	Np 234 1.03e+8 4.4 d 0.1	Np 235 6.70e+8 396.1 d 1.2	Np 236 6.91e+8 153 ky 5	Np 237 1.08e+9 2.144 My 0.007	Np 238 4.08e+8 2.099 d 0.002	Np 239 9.86e+7 2.356 d 0.003	Np 240 1.41e+7 61.9 m 0.2	Np 241 3.74e+5 13.9 m 0.2
U 215 2.64e+7 -1-4 92 0. 9	- 1e+8 1 e+6 U 217 4.26+7 - 1 e+4 1 e+4 1 e+4	U 218 4.32e+7 550 us 140	U 219 2.92e+7 55 us 25	U 220 3.64e+7 60# ns	U 221 4.43e+7 660 ns 140	U 222 4.90e+7 4.7 us 0.7	U 223 3.84e+7 21 us 8	U 224 3.92e+7 396 us 17	U 225 3.63e+7 61 ms 4	U 226 3.66e+7 269 ms 6	U 227 4.21e+7 1.1 m 0.1	U 228 3.16e+7 9.1 m 0.2	U 229 1.93e+7 57.8 m 0.5	U 230 5.94e+8 20.23 d 0.02	U 231 3.14e+8 4.2 d 0.1	U 232 2.29e+9 68.9 y 0.4	U 233 3.56e+9 159.2 ky 0.2	U 234 1.05e+10 245.5 ky 0.6	U 235 1.42e+10 704 My 1	U 236 3.26e+10 23.42 My 0.03	U 237 5.48e+10 6.752 d 0.002	U 238 3.52e+11 4.468 Gy 0.006	U 239 6.49e+9 23.45 m 0.02	U 240 6.84e+6 14.1 h 0.1
Pa 214 9.20e+7 —1 91 s 3	- 1e+2 - 15 - 1e+0 - 13 - 1e+0 - 14 - 12 - 16 - 12 - 17 -	Pa 21.7 1.88e+8 6.48 ms 0.09	Pa 218 1.40e+8 9 113 us 10	Pa 219 1.77e+8 53 ns 10	Pa 220 2.03e+8 780 ns 160	Pa 221 2.37e+8 5.9 us 1.7	Pa 222 2.12e+8 3.2 ms 0.3	Pa 223 2.35e+8 5.1 ms 0.3	Pa 224 2.84e+8 846 ms 20	Pa 225 2.78e+8 1.7 s 0.2	Pa 226 3.66e+8 1.8 m 0.2	Pa 227 3.24e+8 38.3 m 0.3	Pa 228 2.83e+8 22 h 1	Pa 229 1.46e+9 1.50 d 0.05	Pa 230 7.99e+8 17.4 d 0.5	Pa 231 3.25e+9 32.76 ky 0.11	Pa 232 2.53e+9 1.32 d 0.02	Pa 233 6.33e+9 26.975 d 0.013	Pa 234 6.21e+9 6.70 h 0.05	Pa 235 9.50e+9 24.4 m 0.2	Pa 236 6.30e+9 9.1 m 0.1	Pa 237 1.19e+10 8.7 m 0.2	Pa 238 1.75e+8 2.28 m 0.09	Pa 239 8.95e+5 1.8 h 0.5
Th 213 8.64e+8 -1490: 21	■ a emission 215 ■ proton emission	Th 216 1.36e+9 26.0 ms 0.2	Th 217 9.22e+8 247 us 4	Th 218 1.22e+9 117 ns 9	Th 219 1.01e+9 1.021 us 0.024	Th 220 1.23e+9 9.7 us 0.6	Th 221 8.25e+8 1.78 ms 0.03	Th 222 9.05e+8 2.24 ms 0.03	Th 223 5.53e+8 600 ms 20	Th 224 1.58e+9 1.04 s 0.02	Th 225 1.03e+9 8.75 m 0.04	Th 226 1.94e+9 30.70 m 0.03	Th 227 1.39e+9 18.697 d 0.007	Th 228 2.18e+9 1.9124 y 0.0008	Th 229 1.66e+9 7.920 ky 0.017	Th 230 2.07e+9 75.4 ky 0.3	Th 231 1.46e+9 25.52 h 0.01	Th 232 1.51e+9 14.0 Gy 0.1	Th 233 9.48e+8 21.83 m 0.04	Th 234 8.40e+8 24.10 d 0.03	Th 235 4.16e+8 7.2 m 0.1	Th 236 2.36e+8 37.3 m 1.5	Th 237 2.87e+6 4.8 m 0.5	
Ac 212 1.62e+9 -8989: 28	2-proton emission Ac 213 Ac 214 2-neutron emission 2-neutron emission 2-neutron emission	Ac 21.5 2.19e+9 170 ms 10	Ac 216 1.34e+9 440 us 16	Ac 217 1.54e+9 69 ns 4	Ac 218 1.45e+9 1.00 us 0.04	Ac 219 1.66e+9 11.8 us 1.5	Ac 220 1.24e+9 26.36 ms 0.19	Ac 221 1.36e+9 52 ms 2	Ac 222 1.02e+9 5.0 s 0.5	Ac 223 1.04e+9 2.10 m 0.05	Ac 224 7.71e+8 2.78 h 0.16	Ac 225 7.66e+8 9.920 d 0.003	Ac 226 5.31e+8 29.37 h 0.12	Ac 227 5.24e+8 21.772 y 0.003	Ac 228 3.30e+8 6.15 h 0.02	Ac 229 3.03e+8 62.7 m 0.5	Ac 230 1.72e+8 122 s 3	Ac 231 1.37e+8 7.5 m 0.1	Ac 232 6.27e+7 1.98 m 0.08	Ac 233 3.82e+7 145 s 10	Ac 234 1.35e+7 45 s 2	Ac 235 3.22e+6 62 s 4	Ac 236 2.08e+4 4.5 m 3.6	
Ra 211 3.25e+9 -13 88 1.4	 electron capture (?) 2-electron capture (' β- decay 	Ra 21 <mark>4</mark> 2.71e+9 ?)7 s 0.01e	Ra 215 1.63e+9 6 1.67 ms 0.01	Ra 216 1.54er9 182 ns 10	Ra 217 9.90e+8 1.63 us 0.17	Ra 218 1.03e+9 25.2 us 0.3	Ra 219 6.08e+8 10 ms 3	Ra 220 6.07e+8 17.9 ms 1.4	Ra 221 3.56e+8 28 s 2	Ra 222 3.23e+8 33.6 s 0.4	Ra 223 1.88e+8 11.4377 d 0.0022	Ra 224 1.70e+8 3.6319 d 0.0023	Ra 225 9.58e+7 14.9 d 0.2	Ra 226 8.45e+7 1.600 ky 0.007	Ra 227 4.30e+7 42.2 m 0.5	Ra 228 3.77e+7 5.75 y 0.03	Ra 229 1.59e+7 4.0 m 0.2	Ra 230 1.11e+7 93 m 2	Ra 231 3.89e+6 104 s 1	Ra 232 2.39e+6 4.0 m 0.3	Ra 233 2.70e+5 30 s 5	Ra 234 1.04e+5 30 s 10		
Fr 210 1.96e+9 ⊶1870.00	 doubble β- decay β+ decay internal transition 	Fr 21 <mark>.3</mark> 1.45e+9 54.14 s 0.06	Fr 214 6.71e+8 5.18 ms 0.16	Fr 215 4.40e+8 86 ns 5	Fr 216 2.67e+8 700 ns 20	Fr 217 2.19e+8 16.8 us 1.9	Fr 218 1.26e+8 1.0 ms 0.6	Fr 219 9.98e+7 20 ms 2	Fr 220 5.66e+7 27.4 s 0.3	Fr 221 4.73e+7 4.801 m 0.005	Fr 222 2.67e+7 14.2 m 0.3	Fr 223 2.67e+7 22.00 m 0.07	Fr 224 1.58e+7 3.33 m 0.10	Fr 225 1.66e+7 3.95 m 0.14	Fr 226 9.09e+6 49 s 1	Fr 227 8.28e+6 2.47 m 0.03	Fr 228 3.04e+6 38 s 1	Fr 229 1.91e+6 50.2 s 0.4	Fr 230 4.99e+5 19.1 s 0.5	Fr 231 2.70e+5 17.6 s 0.6	Fr 232 4.16e+4 5.5 s 0.6			
Rn 209 100e+9 - ³⁸ 86 1.0	 spontaneus fission isotopic abundance 	Rn 212 3.82e+8 23.9 m 1.2	Rn 213 1.89e+8 19.5 ms 0.1	Rn 214 1.06e+8 270 ns 20	Rn 215 4.89e+7 2.30 us 0.10	Rn 216 3.94e+7 45 us 5	Rn 217 1.80e+7 540 us 50	Rn 218 1.71e+7 33.75 ms 0.15	Rn 219 9.72e+6 3.96 s 0.01	Rn 220 1.20e+7 55.6 s 0.1	Rn 221 9.20e+6 25.7 m 0.5	Rn 222 1.37e+7 3.8215 d 0.0002	Rn 223 8.90e+6 24.3 m 0.4	Rn 224 1.00e+7 107 m 3	Rn 225 4.79e+6 4.66 m 0.04	Rn 226 5.24e+6 7.4 m 0.1	Rn 227 1.54e+6 20.2 s 0.4	Rn 228 7.07e+5 65 s 2	Rn 229 1.46e+5 11.9 s 1.3	Rn 230 1.25e+5 10# s>300ns				
At 208 2.98e+8 4-6 85 9.02	Acluster 2018-8 9.778-7 8.1h04 7.	At 21.1 5.95e+ 7 214 h 0.00:	At 212 3.32e+7 7 314 ms 2	At 213 1.44e+7 125 ns 6	At 214 7.57e+6 558 ns 10	At 215 5.66e+6 100 us 20	At 216 3.56e+6 300 us 30	At 217 5.24e+6 32.62 ms 0.24	At 218 5.12e+6 1.5 s 0.3	At 219 8.34e+6 56 s 3	At 220 6.74e+6 3.71 m 0.04	At 221 8.80e+6 2.3 m 0.2	At 222 4.64e+6 54 s 10	At 223 5.76e+6 50 s 7	At 224 2.27e+6 2.5 m 1.5	At 225 2.33e+6 2# m >300ns	At 226 6.24e+5 20# s >300ns	At 227 2.70e+5 20# s >300ns	At 228 6.24e+4 5# s >300ns	At 229 4.16e+4 5# s >300ns	At 230 2.08e+4			



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Accelerator Systems





*	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	H0	Er	Tm	Yb
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

cern.ch/isolde-yields

Ion sources

- Surface ionization
- Plasma / electron impact ionization

STI

Resonance laser ionization



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*	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	H0	Er	Tm	Yb
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Vacuum valve



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Ion sources

- Surface ionization
- Plasma / electron impact ionization
- Resonance laser ionization

SY

Accelerator Systems

08.03.24

							+	on sourc Surface	e 								2 He
4 Be							hot	FEBIAD Laser	cold			5 B	6 C	7 N	8 O	9 F	10 Ne
12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
20		21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Ca		Sc	Ti	V	Cr	Mn	Fe	C0	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
38		39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Sr		Y	Zr	Nb	Mo	TC	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
56	*	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Ba		Lu	Hf	Ta	W	Re	OS	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
88	**	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Ra		Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	MC	LV	Ts	Og
	4 Be 12 Mg 20 Ca 38 Sr 56 Ba 88 Ra	4 Be 12 Mg 20 Ca 38 Sr 56 Ba 88 Ra **	4 Be 12 F Mg 20 Ca 21 S8 39 56 * Ba ** 88 ***	4 Be 12 21 22 20 Sc Ti 38 39 40 55 * Ti Ti 88 ** 103 104	4 Be 2 Constant 21 Sc 22 Ti 23 V 38 Sr 39 Y 40 Zr 41 Nb 56 Ba * 71 Lu 72 Hf 73 Ta 88 Ra ** 103 Lr 104 Rf 105 Db	4 Be 12 21 22 23 24 Sc Ti V Cr 38 Y Y Zr Nb Mo 56 * Ti Ta W 88 ** 103 104 105 106	4 Be 12 21 22 23 24 25 20 Sc Ti V Cr Mn 38 39 40 41 42 43 56 * Ti 72 Ta W 75 88 ** 103 104 105 106 107	4 Be bot 12 Mg 20 Sc 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 56 Ba * 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 88 Ra ** 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs	4 Be bit FEBIAD 12 Mg 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Ca 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Rh 45 Rh 56 Ba * 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 OS 77 Ir 88 Ra ** 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt	4 Be hot FEBIAD cold 12 Mg 12 22 23 24 25 26 27 28 20 Ca Sc Ti V Cr Mn Fee Co Ni 38 39 40 41 42 43 44 45 46 56 * 71 72 73 74 75 76 77 78 88 ** 103 104 105 106 107 108 109 110 88 ** 103 104 Db Sg Bh Hs Mt Ds	4 Be bot FEBIAD cold 12 Mg 12 22 23 24 25 26 27 28 29 20 Ca Sc Ti V Cr Mn Fe Co Ni Cu 38 39 40 41 42 43 44 45 46 47 56 * 71 72 73 74 75 76 77 78 79 58 ** 103 104 105 106 107 108 109 110 111 88 ** Lr Rf Db Sg Bh Hs Mt Ds 18	4 Be hot FEBIAD cold 12 Mg 12 22 23 24 25 26 27 28 29 30 20 Ca Sc Ti V Cr Mn Fe Co Ni Cu Z1 20 30 Z1 V Cr Mn Fe Co Ni Cu Z1 Z1 V Cr Mn Fe Co Ni Cu Z1 Z1 V Cr Mn K1 K1 K1 K2 X3 X4 K5 K6 K7 K1 K2 K3 K2 X4 K1 K1 K2 K2 K1 K1	4 Be 5 I Laser 13 I Laser 13 V 13 V 13 V 13 V 14 V 25 V 26 V 27 V 28 V 29 V 30 V 31 V 31 V 31 V 44 V 45 V 46 V 47 V 48 V 49 V 30 V 31 V 31 V	4 Bet FebIAD cold 5 6 6 6 12 12 12 12 12 13 14 14 14 14 14	4 Be At FEBIAD cold 12 13 14 15 13 14 15 13 14 15 20 21 22 23 24 25 26 27 28 29 30 31 32 33 38 39 40 41 42 43 44 45 46 47 48 49 50 51 56 7 73 74 75 76 77 78 79 80 81 82 83 88 ** 103 104 105 106 107 108 109 110 111 112 113 114 115	4 6 7 8 12 10	4 6 7 8 9 12 12 12 12 12 12 13 14 15 16 17 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 76 77 78 79 80 81 82 83 84 85 56 * 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 58 ** 103 104 105 106 107 188 109 110 111 112 113 114

*	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	H0	Er	Tm	Yb
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Vacuum valve Magnet coil Target Anode Hot Transfer Target vacuum vessel p+

cern.ch/isolde-yields

Ion sources

- Surface ionization
- Plasma / electron impact ionization
- Resonance laser ionization



SY

Accelerator Systems



08.03.24



*	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	H0	Er	Tm	Yb
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

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Ion sources

- Surface ionization
- Plasma / electron impact ionization

(STI

Resonance laser ionization











*	57	58	59	60	61	62	63	64	65	66	67	68	69	70
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	H0	Er	Tm	Yb
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No



cern.ch/isolde-yields

Ion sources

- Surface ionization
- Plasma / electron impact ionization

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- Resonance laser ionization
 - Resonance ionization spectroscopy (RIS)





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Accelerator Systems



Experimental areas



ISOL

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"On-Line":

Production

Release

Ionization

Extraction



08.03.24

ISOL "On-Line":

- Production
- Release
- Ionization
- Extraction







(STI)



ISOL "On-Line":

- Production
- Release
- Ionization
- Extraction





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STI

ISOL "On-Line":

- Production
- Release
- Ionization
- Extraction











STI



ISOL Step 4: Mass separation Catherall et al. (2017) J. Phys G 44, 094002 isolde.web.cern.ch **Front Ends** HRS Frontend GPS Frontend



SY



STI



ISOL Step 4: Mass separation Catherall et al. (2017) J. Phys G 44, 094002 isolde.web.cern.ch **Front Ends** HRS Frontend Mass separator magnets GPS HRS Frontend Mass separator GPS Mass separator ISCOOL



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ISOL Step 5: Delivery to Experiments

Catherall et al. (2017) *J. Phys G* **44**, 094002 *isolde.web.cern.ch*







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ISOL Step 5: Delivery to Experiments

Catherall et al. (2017) *J. Phys G* **44**, 094002 *isolde.web.cern.ch*





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ISOL Step 5: Delivery to Experiments Cather isolde.

Catherall et al. (2017) *J. Phys G* **44**, 094002 *isolde.web.cern.ch*







																GPS Sc	hedule 2	2023															
		Ар	oril			N	lay				June				Ju	ıly				August				September					October			Nove	mber
WK	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
MO #7	77 Ta LIST 3	10	#818 UC n 17	24	1	8	15	22	2	9 #534 Sn VDS 5	#760 UC VD7 12	15	26	3	10	27M Pb V05 17	#812 Ta 2	4 #824 UC 31		7 14	21	21	0 4	11	18	#835 UC 25	2	9	16	6 23	30	6	13
TU				150182	15688			LOI244				RILIS Cr test						199	199	#776 UC				#776 UC	#534 Sn VD7		W 26-944		0	134In - IDS	7Be col. (night)	#685MW	UC#836
WE				15693	(IS722)	#759 UC q n			IS703 (GLM)	1992				TBC 818 UC	VUV	A		$ \rightarrow $			#811 UC hq n		IS646	Set Isor	1995		MC LL VLI	γ-MRI		83Rb 0.5 shift			
TH r	are earths			#812 Ta	(nights)		Ascension	#727M Pb VDS		2010 Sold State Physics	sel-sli				1.00								Jeune G	Moleauer			IS668 (IS703)	IS691			46.6		
FR	G. Fri	101246									γ-MRI	#818 UC			LAI			IS727 50Ca	IS724			15557	15646	Mag. et al.	IS679 IS713		#760 UC VD7	#836 UC n	IS697	#761 UC			
SA		LO1235	TAS				1501.02	TAS		IS6/9 IS/13 IS732 LOI248	IS691		IS725 IS673		🎇 2C-911	IS563	IS688	@	49Ca @	MIRACLE		80Zn@4.7N	79Zn@3.4M	IS681	LOI249	ROC			12/g,min 1315b, 1335b		IS692 7Be @		IS725 - 226Ra
SU		LO1226	IS693				IS685	IS707		LOI249 LOI250	IS668		Colls		IS715	15699	(nights)	7.5MeV/u	7MeV/u	IS671		eV/u	eV/u	IS683	LOI250 IS738	IS529			@ 4 MeV/u		11MeV/u	15672	(GLM)
		RILIS REs	RILIS In	RILIS In	RILIS Dy		RILIS Cd	RILIS Hg		111Cd	Noble gases		RILIS : In		RILIS : Ac	RILIS Hg	RILIS Dy	RILIS: Ca	RILIS: Ca	RILIS: Mg		RILIS: Zn	RILIS: Zn	RILIS: Mn	111Cd	RILIS: Ca	RILIS: Pb		RILIS: Sb/In	RILIS: In	RILIS: Be	RILIS:Ag	Ra/Rn coll.
																															ISOLD	DE Winter pl	nysics

	HRS schedule 2023																																
		Ap	pril			N	1ay				June				Ju	ly				August				September					October			Nove	mber
WK	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
MO	TBC 3	10		.7 24		1 #816 UC 8	15	22	2 25	#819 LaC Proto 5	#826 UC W 12	19	26	5 3	10	17	24	31	. 7	14	21	28	4	11	18	25	2	9	16	23	i 1	6	13
TU				#791 ThC VD5								TS 30 h	IS712				N/			COLLAPS					~		~	-					
WE					ISOL											#817UC	Ť			LOI245			#816 UC			1					#826 UC W		
TH		for tests to)TRAP		Ascension			KOL	If ready, p+ scan		#827 UC				Ó		#812				Jeune G			#837 UC + S			#817UC	N [±] Z			
FR	G. Fri	CRIS			TISD (days			#817 UC	CRIS	TRAP	yields	αα-		CRIS.			IS733			#780 UC hq n	CRIS.				15656			15702		¥		CRIS	CRIS.
SA				TISD	until	Callaps				Tests for		decav					(daw/mening)								144Cs@		15595 132Sn	130Sn @		6			
SU				FTS/ISOLTRAP	Weekend)	IS718			IS700	ISOLTRAP		IS712		IS714			(aut/creaming)				IS682			4	.5MeV/u	1	@ 3.9MeV/u	4.4MeV/u		15733		IS663	
						RILIS TI			RILIS AI			RaF	RaF	RILIS : Cr			K beams			RILIS: Tm	RILIS: Zn			C	s beams		SnS beam	SnS beam		K beams		RaF	RaF/Fr
																															ISOLD	E Winter ph	ysics



= Yield measurements, proton scans, setup



23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag



08.03.24

Accelerator Systems

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CERN-ISOLDE

>1000 isotopes and isomers

74 elements

Ballof *et.al,* (2020) *NIM B* **463**, 211-215 *cern.ch/isolde-yields*



www.nucleonica.com

Dataset: JEFF-3.1 Nuclear Data Library, NEA (2023)

(ST







• RIS, LIF



Progress in Particle and Nuclear Physics 129 (2023) 104005

Review

Laser spectroscopy for the study of exotic nuclei

X.F. Yang^{a,*}, S.J. Wang^a, S.G. Wilkins^{b,*}, R.F. Garcia Ruiz^{b,*}

^a School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China ^b Massachusetts Institute of Technology, Cambridge, MA 02139, USA



Fig. 1.2. The chart of the nuclides. Stable and long-lived isotopes that exist in large quantities on Earth are indicated in black. The dashed line indicates the region within which bound nuclei are predicted to exist by nuclear theory [65]. Unstable isotopes produced at RIB facilities are shown in gray (for nuclei with $T_{1/2} > 0.5$ ms) and light yellow (for nuclei with $T_{1/2} < 0.5$ ms). Around a thousand ground- and long-lived isomeric states of unstable nuclei have been studied by laser spectroscopy experiments so far, which are indicated with red, blue and green squares, depending on the technique employed.



•



Sensitivity (pps) RILIS 100 TRILIS RIS **IG-RIS** RADRIS In-gas jet 10^{1} CRIS **CLS+RIS COLLAPS** BECOLA 10^{2} **IGISOL-CLS** CLS 10^{3} TRAP/DR Resolution (MHz) 10^{4} 10^{3} 10² 10^{1} "New observables"

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Accelerator Systems

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08.03.24

Sensitivity (pps) RILIS 100 TRILIS RIS **IG-RIS** RADRIS In-gas jet 10^{1} CRIS **COLLAPS** BECOLA 10^{2} **IGISOL-CLS** 10^{3} PI-LIST TRAP/DR Resolution (MHz) 10^{4} 10^{3} 10² 10^{1} "New observables"

SY

Accelerator Systems

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Review

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Review

Progress in Particle and Nuclear Physics 129 (2023) 104005

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184

114

82



Actinium

- Delivered as Ra/Fr: • ²²⁵Ac [1]
- Laser-ionized: ²²⁷Ac • [2] IS637, Data under analysis

Now

Actinium

Laser-ionized: ^{225,227,228}Ac [3] •

Np

212 213 214 215 Ac Ac Ac Ac

Thorium

From Ac/Ra/Fr: ²²⁹Th [6]

[1] Guglielmetti et al, EPJA 12, 383-386 (2002) [2] Jajčišinova et al, D8.1, Zenodo (2023) [3] Andreyev et al, INTC-LOI-216 (2020) [4] Heinke et al, NIM B 541, 8-12 (2023) [5] Heinke, Jaradat, Zenodo, 7824897 (2022) [6] Kraemer et al, Nature 617, 706-710 (2022) [7] Au et al, NIM B 541, 375-379 (2023) [8] Kaja et al, PhD thesis, in preparation (2023) • [9] Au et al, INTC-LOI-243 (2022)

Protactinium

Laser-ionized: tried, failed •

Uranium

^{234,235,238}U [7]



Laser-ionized: ²³⁵⁻²⁴¹Np

Plutonium

Pu

Laser-ionized: ²³⁴⁻²⁴¹Pu •



SY





N=152

Neutrons -



Actinium

- Delivered as Ra/Fr: • ²²⁵Ac [1]
- Laser-ionized: ²²⁷Ac • [2] IS637, Data under analysis

Now

Actinium

Laser-ionized: ^{225,227,228}Ac [3]

Np

212 213 214 Ac Ac Ac

Neptunium

Pu

Laser-ionized: ²³⁵⁻²⁴¹Np

Original figure published in: Block, Laatiaoui Raeder, (2021) Prog. Part. Nucl. Phys. 116

PHYSICAL REVIEW C 107, 064604 (2023)

Production of neptunium and plutonium nuclides from uranium carbide using 1.4-GeV protons

M. Au ,^{1,2,*} M. Athanasakis-Kaklamanakis^{0,1,3} L. Nies^{0,1,4} R. Heinke^{0,1} K. Chrysalidis^{0,1} U. Köster,^{1,5} P. Kunz^{0,6} B. Marsh,¹ M. Mougeot,^{1,7,†} L. Schweikhard,⁴ S. Stegemann,¹ Y. Vila Gracia,¹ Ch. E. Düllmann,^{2,8,9} and S. Rothe,¹ ¹European Organization for Nuclear Research (CERN), Meyrin, 1211 Geneva, Switzerland ²Department of Chemistry, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany ³Katholieke Universiteit Leuven, Instituut voor Kern-en Stralingsfysica, B-3001 Leuven, Belgium ⁴Institut für Physik, University of Greifswald, 17489 Greifswald, Germany ⁵Institut Laue-Langevin, 38000 Grenoble, France ⁶TRIUMF, Vancouver, Canada V6T 2A3 ⁷Max Planck Institut für Kernphysik, 69117 Heidelberg, Germany ⁸GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany ⁹Helmholtz Institute Mainz, 55099 Mainz, Germany

(Received 11 March 2023; accepted 8 May 2023; published 8 June 2023; corrected 7 August 2023)



Accelerator Systems

Thorium

- Protactinium
 - Laser-ionized: tried, failed

From Ac/Ra/Fr: ²²⁹Th [6]

Uranium

^{234,235,238}U [7]

SY



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N=152

Neutrons –



Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

First on-line application of the high-resolution spectroscopy laser ion source **PI-LIST at ISOLDE**

Reinhard Heinke^{a,*}, Mia Au^{a,b}, Cyril Bernerd^{a,c}, Katerina Chrysalidis^a, Thomas E. Cocolios^c, Valentin N. Fedosseev^a, Isabel Hendriks^{a,d}, Asar A.H. Jaradat^a, Magdalena Kaja^e, Tom Kieck^{f,g}, Tobias Kron^e, Ralitsa Mancheva^{a,c}, Bruce A. Marsh^a, Stefano Marzari^a, Sebastian Raeder^{f,g}, Sebastian Rothe^a, Dominik Studer^{f,g}, Felix Weber^e, Klaus Wendt^e

^a STI group, SY department, CERN, Switzerland ^b Chemistry department, Johannes Gutenberg University Mainz, Germany ^c Institute for Nuclear and Radiation Physics, KU Leuven, Belgium ^d Lund University, Sweden e Institute of Physics, Johannes Gutenberg University Mainz, Germany f GSI Helmholtzzentrum für Schwerionenforschung, Germany ⁸ Helmholtz Institute Mainz, Germany

From Ac/Ra/Fr: ²²⁹Th [6]



Protactinium

Laser-ionized: tried, failed

Uranium

^{234,235,238}U [7]

Neutrons – Ac Ac Original figure published in: Block, Laatiaoui Raeder, (2021) Prog. Part. Nucl. Phys. 116

Neptunium

Pu

Np

³Ac [3]

1 =

BEAM MATERIALS AND ATOMS

Check for updates

Laser-ionized: ²³⁵⁻²⁴¹Np

PHYSICAL REVIEW C 107, 064604 (2023)

Production of neptunium and plutonium nuclides from uranium carbide using 1.4-GeV protons

M. Au ,^{1,2,*} M. Athanasakis-Kaklamanakis^{0,1,3} L. Nies^{0,1,4} R. Heinke^{0,1} K. Chrysalidis^{0,1} U. Köster,^{1,5} P. Kunz^{0,6} B. Marsh,¹ M. Mougeot,^{1,7,†} L. Schweikhard,⁴ S. Stegemann,¹ Y. Vila Gracia,¹ Ch. E. Düllmann,^{2,8,9} and S. Rothe,¹ ¹European Organization for Nuclear Research (CERN), Meyrin, 1211 Geneva, Switzerland ²Department of Chemistry, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany ³Katholieke Universiteit Leuven, Instituut voor Kern-en Stralingsfysica, B-3001 Leuven, Belgium ⁴Institut für Physik, University of Greifswald, 17489 Greifswald, Germany ⁵Institut Laue-Langevin, 38000 Grenoble, France ⁶TRIUMF, Vancouver, Canada V6T 2A3 ⁷Max Planck Institut für Kernphysik, 69117 Heidelberg, Germany ⁸GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany ⁹Helmholtz Institute Mainz, 55099 Mainz, Germany

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M. Au | INT-24 | Seattle, USA

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Contents lists available at ScienceDirect Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

First on-line application of the high-resolution spectroscopy laser ion source **PI-LIST at ISOLDE**

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^a STI group, SY department, CERN, Switzerland ^b Chemistry department, Johannes Gutenberg University Mainz, Ger ^c Institute for Nuclear and Radiation Physics, KU Leuven, Belgium ^d Lund University, Sweden

e Institute of Physics, Johannes Gutenberg University Mainz, German f GSI Helmholtzzentrum für Schwerionenforschung, Germany ⁸ Helmholtz Institute Mainz, Germany

[1] Guglielmetti et al, EPJA 12, 38 [2] Jajčišinova et al, D8.1, Zenode [3] Andreyev et al, INTC-LOI-216 [4] Heinke et al. NIM B 541. 8-12 [5] Heinke, Jaradat, Zenodo, 782 [6] Kraemer et al, Nature 617, 70 [7] Au et al, NIM B 541, 375-379 [8] Kaja et al, PhD thesis, in prep [9] Au et al, INTC-LOI-243 (2022)

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

In-source laser resonance ionization spectroscopy of neptunium and plutonium

May 13, 2022

Np

Ac Ac

BEAM MATERIALS AND ATOMS

Check for updates

Mia Au^{1,2}, Anastasia Borschevsky³, Katerina Chrysalidis¹, Raphaël Crosa-Rossa³, Christoph Düllmann^{2,4,5}, Reinhard Heinke¹, Asar Jaradat¹, Magdalena Kaja², Bruce Marsh¹, Iain Moore⁶, Andrea Raggio⁶, Sebastian Rothe¹, Simon Stegemann¹. Darcy van Eerten⁷, Clemens Walther⁷

¹SY-STI, CERN, Switzerland ²Johannes Gutenberg-Universität Mainz, Germany ³Rijksuniversiteit Groningen, Groningen, Netherlands ⁴GSI Helmholtzzentrum für Schwerionenforschung, Germany ⁵Helmholtz Institute Mainz, Germany ⁶University of Jyväskylä, Finland ⁷IRS. Leibniz Universität Hannover, Germany

March 2023

Spokesperson: Mia Au mia.au@cern.ch, Magdalena Kaja mkaja@uni-mainz.de Contact person: Mia Au mia.au@cern.ch

Neptunium

Pu

Laser-ionized: ²³⁵⁻²⁴¹Np

Original figure published in: Block, Laatiaoui Raeder, (2021) Prog. Part. Nucl. Phys. 116

In-source spectroscopy, analysis [8,9]

PHYSICAL REVIEW C 107, 064604 (2023)

Production of neptunium and plutonium nuclides from uranium carbide using 1.4-GeV protons

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(Received 11 March 2023; accepted 8 May 2023; published 8 June 2023; corrected 7 August 2023)







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Neutrons –

Transuranium atomic ion beams



Production of neptunium and plutonium nuclides from uranium carbide using 1.4-GeV protons

M. Au, M. Athanasakis-Kaklamanakis, L. Nies, R. Heinke, K. Chrysalidis, U. Köster, P. Kunz, B. Marsh, M. Mougeot, L. Schweikhard, S. Stegemann, Y. Vila Gracia, Ch. E. Düllmann, and S. Rothe Phys. Rev. C 107, 064604 - Published 8 June 2023

TABLE I. Production mechanisms in % of total events for selected nuclides of interest calculated using GEANT4 QGSP_INCLXX+ABLA with 109 1.4-GeV proton primaries. "Inelastic" and "Decay" columns give the sums over inelastic and radioactive decay processes, respectively. The larger contribution is indicated in bold. Various capture reactions are included in the model but not shown in the table. Some processes with event fractions below 1 % (e.g., photonuclear reactions) are not shown and only the dominant parent nucleus and its corresponding percentage fraction of total events are given. The number of total events is scaled from 10^9 protons to obtain the nuclides per μ C equivalent.

isotope	Inelastic:	р	n	d	t	³ He	α	ions	Decay:	parent		nuclides/µC
²³⁴ U	36.4	28.4	7.2	0.4	-	-	-	-	63.6	²³⁴ Pa	59.4	6.7×10^{9}
²³⁶ U ^a	65.5	52.2	11.8	0.8	-	-	-	-	34.3	²³⁶ Pa	34.3	1.3×10^{10}
²³⁷ U	70.5	61.7	7.4	0.9	0.1	-	-	-	29.0	²³⁷ Pa	29.0	1.9×10^{10}
²³⁹ U ^a	1.9	-	-	1.3	0.5	-	0.1	-	-	-	-	2.2×10^{9}
²⁴⁰ U	100.0	-	-	-	85.7	-	11.9	2.4	-	-	-	2.1×10^{6}
²³¹ Np	99.0	93.1	-	3.5	0.5	-	-	-	1.0	²³¹ Pu	1.0	1.3×10^{6}
²³² Np	100.0	92.3	0.3	5.4	0.3	0.1	-	-	-	-	-	1.3×10^{7}
²³³ Np	99.8	91.1	0.2	6.1	0.5	0.1	-	-	0.2	²³³ Pu	0.2	3.6×10^{7}
²³⁴ Np	100.0	89.9	0.2	7.7	0.7	0.1	-	-	-	-	-	2.0×10^{8}
²³⁵ Np	99.8	88.4	0.2	8.9	1.0	0.2	-	-	0.2	²³⁵ Pu	0.2	3.8×10^{8}
²³⁶ Np	100.0	86.2	0.1	11.1	1.4	0.2	-	-	-	-	-	8.7×10^{8}
²³⁷ Np	3.7	3.0	-	0.6	0.1	-	-	-	96.3	²³⁷ U	96.3	2.0×10^{10}
²³⁸ Np	100.0	61.0	-	27.4	8.8	1.1	0.4	-	-	-	-	3.9×10^{8}
²³⁹ Np	3.0	-	-	2.2	0.6	0.2	0.1	-	97.0	²³⁹ U	97.0	2.2×10^{9}
²⁴⁰ Np	73.0	-	-	-	47.8	5.2	18.8	1.3	27.0	²⁴⁰ U	27.0	7.8×10^{6}
²⁴¹ Np	100.0	-	-	-	-	-	96.3	3.7	-	-	-	6.8×10^{5}
²³⁵ Pu	99.2	62.5	-	-	-	18.8	10.9	-	0.8	²³⁵ Am	0.8	8.0×10^{5}
²³⁶ Pu	97.1	67.8	-	-	-	13.5	12.5	-	2.9	²³⁶ Np	1.9	1.3×10^{6}
²³⁷ Pu	99.5	39.7	-	-	-	15.5	39.7	0.3	0.5	-	-	2.3×10^{6}
²³⁸ Pu	0.9	0.1	-	-	-	0.1	0.7	-	99.1	²³⁸ Np	99.1	4.0×10^{8}
²³⁹ Pu	0.3	-	-	-	-	-	0.3	-	99. 7	²³⁹ Np	99.7	2.2×10^{9}
²⁴⁰ Pu	24.0	-	-	-	-	2.5	20.9	0.6	76.0	²⁴⁰ Np	75.5	1.0×10^{7}
²⁴¹ Pu	53.9	-	-	-	-	-	51.7	2.2	46.1	²⁴¹ Np	46.1	1.4×10^{6}

^{a 236,239}U are 0.2 % and 98.1 % produced by neutron capture reactions, respectively.



 10^{4}



233 234 235 236 237 238

Mass (u)

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240

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239

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241

FC Δ

Actinium PI-LIST [2]

• Octupole deformation



[1] Verstraelen et al., Phys. Rev. C. 100, 044321 (2019)
[2] Heinke et al. (2023) *NIM B.* 541 (8-12)
[3] Heinke et al., CERN-INTC-2020-029, INTC-P-556, <u>https://cds.cern.ch/record/2717945</u> (2020)
[4] Heinke *et al.*, in preparation (2024)

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https://cds.cern.ch/record/2717945 (2020) [4] Heinke *et al.*, in preparation (2024)





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Image published in EP Newsletter, CERN (2020)

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Z=88

Radium









Th

bp 1680°C

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F

bp 55°C



Radioactive molecular beams



F

F

Np

F



U

bp 56.5°C













- 1. Volatilization
- 2. Sideband extraction
- 3. Research opportunities

(STI



INT Workshop 24-87W Schedule Fundamental Physics with Radioactive Molecules









- **Volatilization**
- **Sideband extraction**
- **Research opportunities** 3.



INT Workshop 24-87W Schedule Fundamental Physics with Radioactive Molecules **Opportunities for** Fundamental Physics Research with Radioactive Molecules, arXiV 2302.02165 (2023)



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Molecular beams

1. Formation

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2. Detection and identification

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3. Characterization

Accelerator Systems









Au and Ballof, (2022) Zenodo 10.5281/zenodo.6884293 DOI 10.5281/zenodo.6884293



Formation: how do we make the molecules?

In-source

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Accelerator Systems

Reactive gas \bullet



In-trap

Radio-frequency quadrupole coolerbuncher (RFQ-cb)



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Z

Detection and identification



[1] Au, *PhD thesis* (2023)





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Ion sources and effects





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Ion sources and effects



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Ion sources and effects





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RaF production and CRIS

Collinear Resonance Ionization Spectroscopy (CRIS) technique

- Fast (10s keV) beams reduce velocity spread
- Collinear geometry: linewidth dominated by laser linewidth





RaF characterization





[1] Udrescu et al., Research Square 10.21203/rs.3.r.
2648482/v1 accepted in Nat. Phys. (2023)
[2] Athanasakis-Kaklamanakis *et al.*, arXiv
2308.14862 submitted to PRL (2023)
[3] Athanasakis-Kaklamanakis *et al.*, in preparation (2024)

[4] Wilkins *et al.,* arXiV 2311.04121 submitted to Science (2024)

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Excited states [2]

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• agreement ≥ 99.64% (~12 meV)



State lifetimes [3]

• Radiative lifetime of A ${}^{2}\Pi_{1/2}$ state

Nuclear magnetization effect [4]

• μ(²²⁵Ra)



Actinium

T- α T (targeted alpha therapy)

- Damage to cancer cells
 - DNA double strand breaks, membrane, mRNA damage
 - Ionization through free radicals
- High linear energy transfer

Production routes

- ²²⁶Ra
 - ²²⁶Ra(p,2n)²²⁵Ac

²²⁵Ra (generator)

- ²²⁶Ra(γ,n)²²⁵Ra → ²²⁵Ac
- ²²⁶Ra(n,2n)²²⁵Ra → ²²⁵Ac

Actinide

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- ^{nat}Th(p,x)²²⁵Ac, ²²⁵Ra (^{nat}Th(p,x)²²⁷Ac, ²²⁷Ra)
- nat/depU(p,x)²²⁵Ac, ²²⁵Ra (Nat/depU(p,x)²²⁷Ac, ²²⁷Ra)

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Figure published in: Kratchowil *et al.* (2016) J. Nucl. Med. **57** 1941-1944



Figure published in: Robertson et al. (2018) Current Radiopharmaceuticals. 11 156-172

Actinium (Fluoride)

Ac: Nuclear properties

- Octupole deformation ۲
- Low-lying opposite parity states •
- Schiff moment enhancement

AcF: molecular enhancement

Enhanced sensitivity to CP-violating observables?

Production

IP: ? D_a: ? ullet

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[1] Verstraelen et al., Phys. Rev. C. 100, 044321 (2019) [2] Heinke et al., CERN-INTC-2020-029, INTC-P-556, https://cds.cern.ch/record/2717945 (2020) [3] Flambaum, Feldmeier, Phys. Rev. C. 101, 015502 (2020) [4] Flambaum, Dzuba, Phys. Rev. A. 101, 042504 (2020)



Accelerator Systems



The interaction constant W_S for the effective T,P-violating interaction in ²²⁷Ac-containing molecules is

$$W_S \approx 46000 \text{ a.u.} \tag{55}$$

The energy shift is

[3]

$$2W_S S = 5 \times 10^7 \bar{\theta} \, h \, \text{Hz.} \tag{56}$$

Actinium (Fluoride)

Ac: Nuclear properties

- Octupole deformation
- Low-lying opposite parity states
- Schiff moment enhancement

AcF: molecular enhancement

• Enhanced sensitivity to CP-violating observables?

Production

• IP: ? D_e: ?

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 [2] Heinke et al., CERN-INTC-2020-029, INTC-P-556, <u>https://cds.cern.ch/record/2717945</u> (2020)
 [3] Flambaum, Feldmeier, Phys. Rev. C. 101, 015502 (2020)
 [4] Flambaum, Dzuba, Phys. Rev. A. 101, 042504 (2020)



SY Accelerator Systems



TABLE IV. Schiff moments (*S*) and EDMs (d_A) of some atoms in terms of the QCD θ -term constant $\bar{\theta}$. We remind the reader that the current experimental limit is $|\bar{\theta}| < 10^{-10}$.

		S	$d_A[e\mathrm{cm}]$]
Ζ	Atom	$[e\mathrm{fm}^3\bar{\theta}]$	$10^{-17}S[e{\rm fm}^3]$	$10^{-17}\bar{ heta}$
63	¹⁵³ Eu	-3.7	-1.63	6
63	$^{153}Eu^{3+}$	-3.7	0.33	-1.2
66	161 Dy	$\lesssim 4$	-2.23	$\lesssim 9$
80	¹⁹⁹ Hg	0.005	-2.50	-0.013
81	205,203 Tl ⁺	0.02	-2.79	-0.06
82	207 Pb $^{2+}$	0.005	-2.99	-0.015
86	²²³ Rn	-3	3.3	-10
87	223 Er+	1.6	2.87	1.6
88	²²⁵ Ra	-1	-8.25	8
89	²²⁷ Ac	-6	-10.1	60
89	$^{227}Ac^{+}$	-6	-9.8	60
90	$^{229}\text{Th}^{2+}$	$\lesssim 2$	-6.93	$\lesssim 14$
91	²²⁹ Pa ^a	-40	-11.4	460
92	²³³ U	$\lesssim 2$	-12.1	$\lesssim 20$
93	²³⁷ Np	-4	-7.5	30
94	²³⁹ Pu	$\lesssim 0.1$	-9.2	$\lesssim 1$

^aEstimates for ²²⁹Pa are presented assuming that the existence of a very close nuclear doublet level will be confirmed.

The interaction constant W_S for the effective T,P-violating interaction in ²²⁷Ac-containing molecules is

$$W_S \approx 46000 \text{ a.u.} \tag{55}$$

The energy shift is

3

$$2W_S S = 5 \times 10^7 \bar{\theta} \, h \, \text{Hz.} \tag{56}$$

Production of AcF⁺

- ²²⁵Ac: Targeted-alpha therapy
- Ac: enhanced extraction
- AcF spectroscopy characterization



[1] Au, *PhD thesis* (2023)[2] Au, *submitted to Nat. Comms* (2024)





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AcF spectroscopy

Experimental [1,3]

• (8) $\Pi_1 \leftarrow X \ ^1\Sigma_0$

Nuclear theory

- previous values from scaling factors
- $S_{int} \leftrightarrow Q_0^3 [2]$
- DFT: S_{int}(²²⁷Ac) vs. S_{int}(²²⁵Ra) = 26.6(19) e fm³[3]

Molecular theory

- IH-FS-RCCSD
- IP = 48,866 cm⁻¹
- $D_e = 57,214 \text{ cm}^{-1}$

Athanasakis-Kaklamanakis and Au, (2023) CERN EP newsletter
 Dobaczewski, Engel, Kortelainen, Becker, Phys. Rev. Lett. **121**, 232501 (2018)
 Athanasakis-Kaklamanakis, Au, Kyuberis, Zülch, Wibowo, Skripnikov, Reilly, Lalanne et al., in prep. (2024)
 Skripnikov et al., J. Chem. Phys **159** 124301 (2023)
 Skripnikov et al., Phys. Chem. Chem. Phys **22** 18374-18380 (2020)



FIG. 3. The strongest transitions (blue arrows) from the $X(1)0^+$ ground state of AcF and the strongest transitions for stimulated emission (green arrows). Levels accessible with two-step excitations are shown with solid gray lines. Dotted lines depict electronic states that are hardly accessible from the ground state with either direct or two-step excitations. It is noted that all transitions to the $\Omega = 0^-$ states have low probabilities and are not shown here. T_e values (cm⁻¹) are shown.



Table 2 Molecular constants X and $W_{\rm S}^{(2)} = 6X/r^{\rm sp}$ ($e/a_{\rm B}^4$, $a_{\rm B} = 1$ Bohr) calculated at different levels of theory, given in square brackets

Mol.	State	X [HF]	X [CCSD]	X [CCSD(T)]	r ^{sp}	$W_{\rm S}^{(2)}$ [CCSE) (T)]
AcF	$^{1}\Sigma^{+}$	-2022	-1569	-1593	1.16	-8240	
AcN	${}^{1}\Sigma^{+}$	-10580	-9415	-8950	1.16	-46295	
AcO^+	${}^{1}\Sigma^{+}$	-13362	-11600	-11302	1.16	-58461	
ThO	${}^{1}\Sigma^{+}$	-3965	-3187	-3332	1.17	-17085	
EuO^+	$(\mathbf{f}^6)^a$	-2475^{a}	-2140^{a}	-2114^{a}	1.09	-11677^{a}	
EuN	$(\mathbf{f}^6)^a$	-1975^{a}	-1847^{a}	-1890^{a}	1.09	-10419^{a}	
TlF	$1\Sigma^{+}$	9111	7262	7004	1.13	37 192	

^{*a*} The spin–orbit part of the GRECP operator has been omitted in the calculation. Therefore, we give only the configuration of the molecular state.







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ISOLDE OFFLINE 2 © 2019-2022 CERN

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Behind the scenes: Offline developments







Material developments

Gas injection

Reactive/corrosive gases

Reactants

Mass markers •

Target materials

- Particle size •
- Open porosity •







Adapted from: J.P. Ramos. EMIS XIII, CERN, Geneva, 2018.



Beam Intensity = $\sigma \cdot j \cdot N_t \cdot \varepsilon$

- N_t Number of target atoms
- j Proton flux [cm⁻²]
- σ Cross section [mb]
- ε Efficiency [%]

 $\mathcal{E} = \mathcal{E}_{diff} \mathcal{E}_{eff} \mathcal{E}_{is} \mathcal{E}_{ext} \mathcal{E}_{sep} \mathcal{E}_{trans}$







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- μ diffusion delay parameter
- *G* grain size

 $\mathcal{E} = \mathcal{E}_{diff} \mathcal{E}_{eff} \mathcal{E}_{is} \mathcal{E}_{ext} \mathcal{E}_{sep} \mathcal{E}_{trans}$

 $\varepsilon_{\rm diff} \propto \sqrt{\mu \cdot T_{1/2}} \propto \frac{1}{G}$



Adapted from: J.P. Ramos. EMIS XIII, CERN, Geneva, 2018.



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Beam Intensity = $\sigma \cdot j \cdot N_t \cdot \varepsilon$

- N_t Number of target atoms
- j Proton flux [cm⁻²]
- σ Cross section [mb] ε – Efficiency [%]
- μ diffusion delay parameter
- G grain size

Small G, high T \square Increased ε_{diff}

Increased ε_{diff} (Increased sintering and grain growth

 $\mathcal{E} = \mathcal{E}_{diff} \mathcal{E}_{eff} \mathcal{E}_{is} \mathcal{E}_{ext} \mathcal{E}_{sep} \mathcal{E}_{trans}$

 $\varepsilon_{\rm diff} \propto \sqrt{\mu \cdot T_{1/2}} \propto \frac{1}{G}$

 $\mu = \frac{\pi^2 D}{C^2}$

Adapted from: J.P. Ramos. EMIS XIII, CERN, Geneva, 2018.





Non-actinide development and characterization lab

Planetary ball mill – Powder particle size reduction

Date: 2021-07-09











Laser diffraction particle size analyzer



Gas pycnometry Apparent density determination

Carburization pumpstand Target development, sintering studies



Gas sorption – Pore size distribution (BET)





TGA-MS - Reaction kinetics

Reactor setup









Photos courtesy of V. Berlin, E. Reis, L. Lambert, S. Rothe

The Nanolab: Production and Research



Carbide lab



Oxide lab

5 Glove boxes

- 4 connected in T shape: non-pyrophoric
- 1 inert atmosphere: carbides

Production alternating with development

Photos courtesy of L. Lambert









Storage capsules

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Ion source developments

Molecular breakup and characterization studies

- FEBIAD-type ion sources [1,2] ۲
- Electron energy and source optimization •
- lon source systematics •

Photocathode ion sources [3]

Cold (room-temperature) environments ۲

In-source spectroscopy [4]

- PI-LIST: sub-Doppler hot-cavity in-source spectroscopy
- **CERN-ISOLDE** implementation •

[1] Maldonado (2023) PhD thesis [2] Martinez Palenzuela (2020) PhD thesis [3] Ballof . et al., 2022) J. Phys.: Conf. Ser. 2244 012072 [4] Heinke et al. (2023) NIM B. 541 (8-12)





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Gas





Offline upgrades for molecular beam development

Calibrated

gas leak

Implantation

flange

Detection, implantation, ion counting

RILIS for molecules

Gas injection and mixing

Remote control of HV gas systems and partial • pressures







Tb-IRMA-V E 6. 10-12 Diffusion without CF4 Diffusion of Tb out of Ta 1. Tb was implanted in Ta foil (extracted as a terbium fluoride beam with FEBIAD ion source) The chamber was isolated and baked 3. The foil was heated in vacuum to 2100°C to observe Tb release 4 The foil was cooled down lime (s) 5. 1bar of CF, was injected into Diffusion with CE the gas line 6. The foil was heated again to 2100°C to observe Tb release There is ~100x more Tb species released before CF, injection. 10-10 Bakeout after diffusion with CF The shape of Tb species release TbO (175.00 before CF. injection closly corresponds to that of F at the



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During bake out that followed the diffusion tests, the signal of Tb species was comparable to that during the tests - some Tb condensed on chamber walls ----- after CF4 during the release out of the foi

The system has been successfully used for diffusion studies. Qualititaive insight complementary to mass scans on FC, has been gained into Tb diffusion out of Ta. This insight will be used in future online tests using molecular extraction Several upgrades are planned to allow the chamber to remain hot during the isotope release to prevent species from condensing on the chamber - this will be most important for refractory species.

[1] Au et al. (2023) NIM B. 541 (144-147) [2] Wojtaczka et al. (2023) ICIS'23, Victoria, Canada

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Acknowledgements





NFUTRONS

FOR SOCIETY

Dinko Atanasov, Michail Athanasakis-Kaklamanakis, Jochen Ballof, Ermanno Barbero, Robert Berger, Cyril Bernerd, Mathieu Bovigny, Katerina Chrysalidis, Bernard Crepieux, James Cruikshank, Christoph Düllmann, Paul Florian Giesel, Paul Fischer, Simone Gilardoni, Reinhard Heinke, Jake Johnson, Ulli Köster, Laura Lambert, Daniel Lange, Bruce Marsh, Maxime Mougeot, Lukas Nies, Bianca Reich, Jordan Reilly, Edgar Reis, Moritz Schlaich, Christoph Schweiger, Simon Stegemann, Yago Nel Vila Gracia, Julius Wessolek, Frank Wienholtz, Shane Wilkins, Wiktoria Wojtaczka, ISOLDE operations team, ISOLDE targets and ion sources team,

Sebastian Rothe

This project has received funding from the European's Union Horizon 2020 Research and Innovation Programme under grant agreement number 861198 project 'LISA' (Laser Ionization and Spectroscopy of Actinides) Marie Sklodowska-Curie Innovative Training Network (ITN)









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