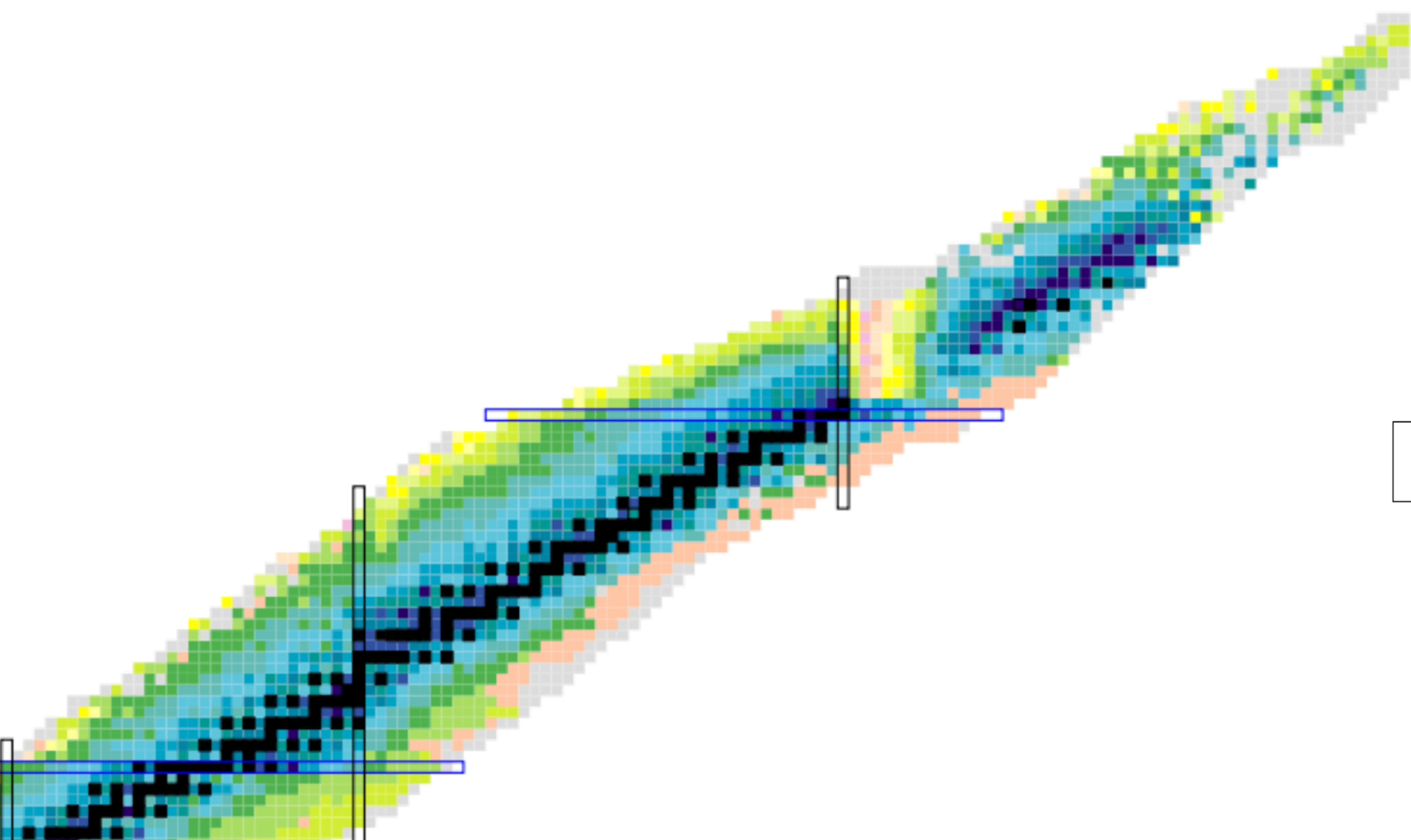


Structure and limits of the superheavy nuclear quantum building

Presentation : Martin BORDEAU
Supervisor : Benoît GALL
« From Nuclei to Stars » group



Université
de Strasbourg

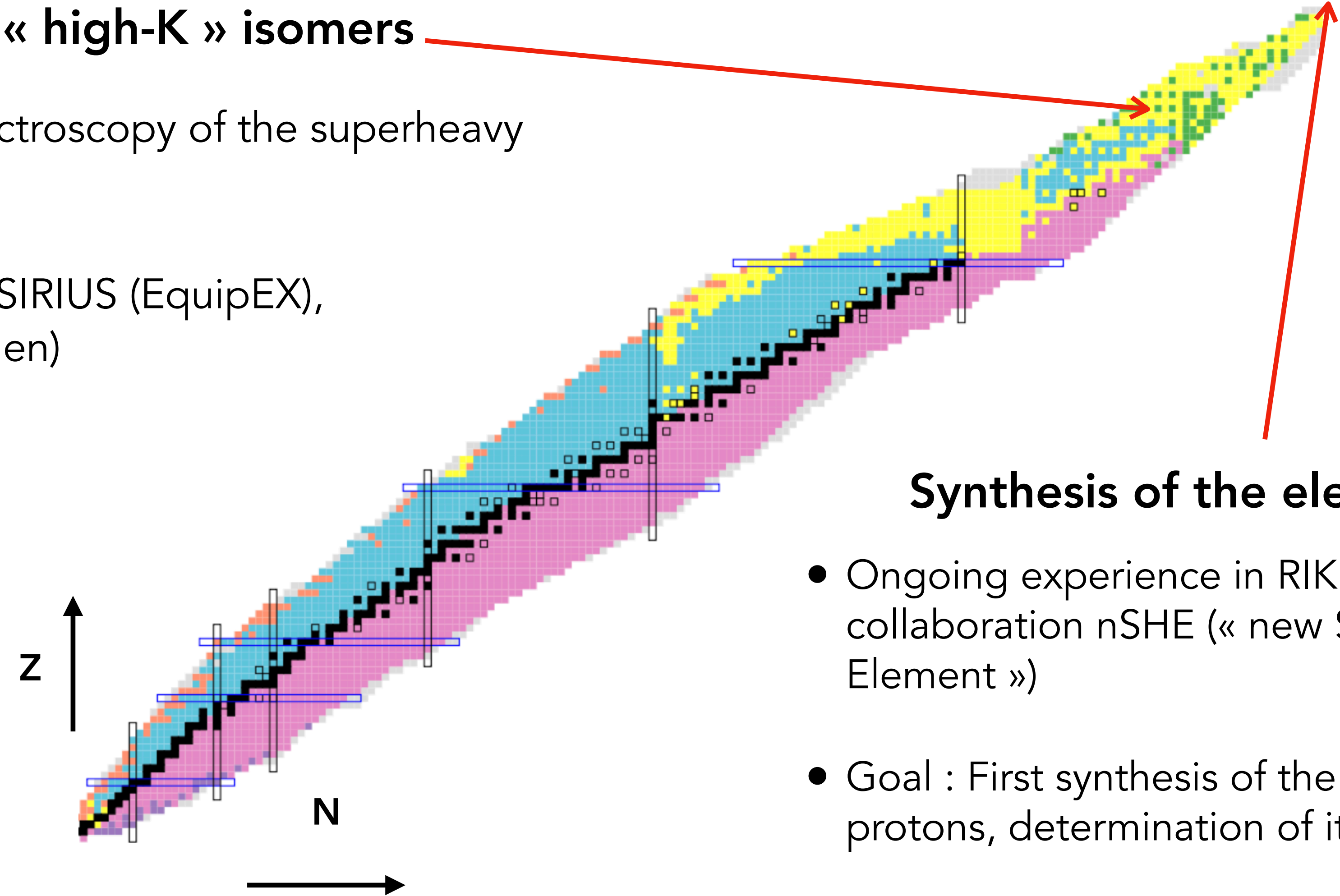


Wednesday 21st of June 2023 / Master 2 PSA

Outline

Study of ^{256}Rf « high-K » isomers

- Goal: delayed spectroscopy of the superheavy nucleus of ^{256}Rf
- Facilities : S^3 and SIRIUS (EquipEX), GANIL, France (Caen)



Synthesis of the element Z=119





- Ongoing experience in RIKEN, Japan, through collaboration nSHE (« new Super Heavy Element »)
- Goal : First synthesis of the element with 119 protons, determination of its lifetime and mass

Synthesis of element 119

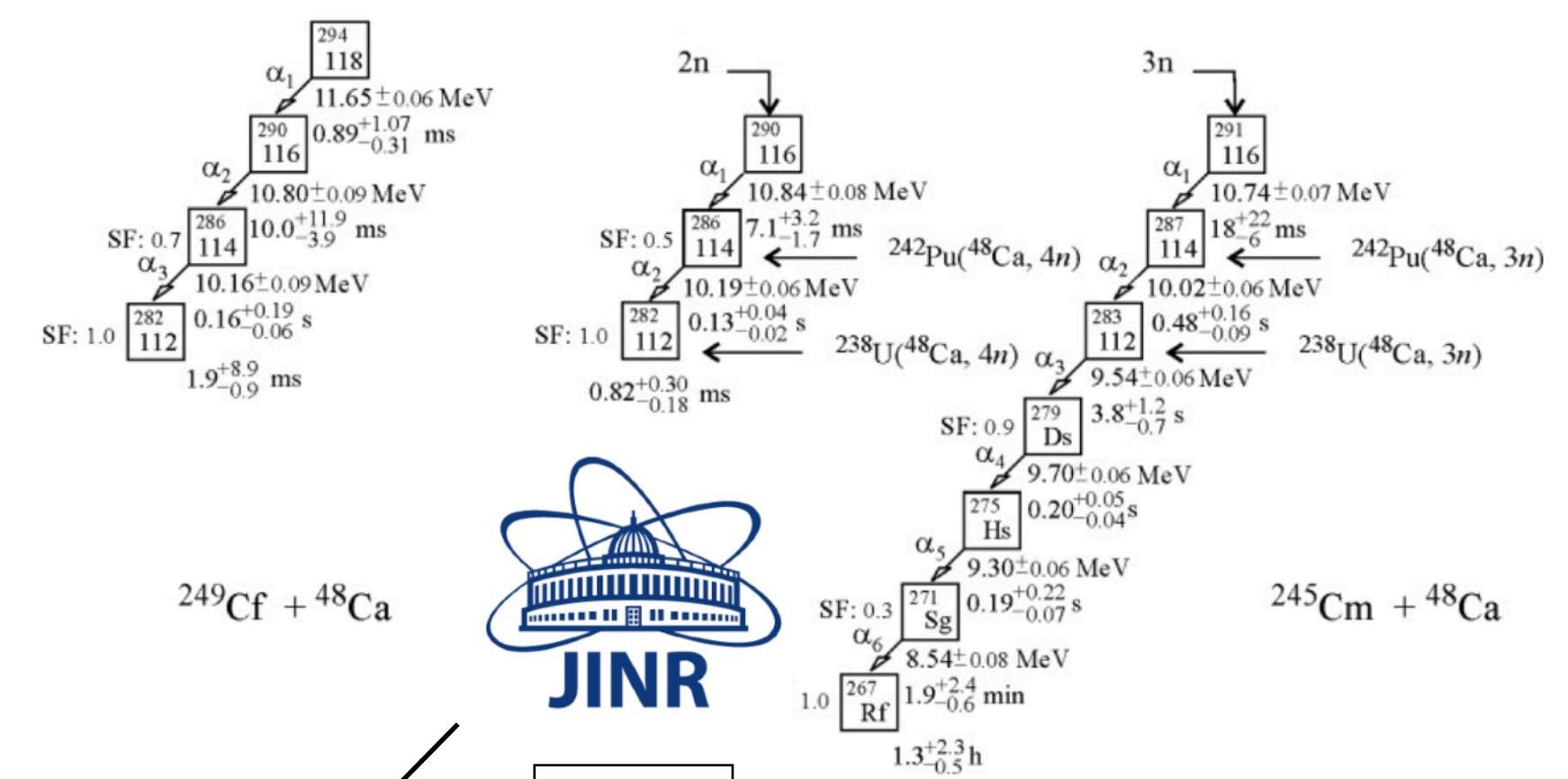
State-of-the-art

IUPAC Periodic Table of the Elements

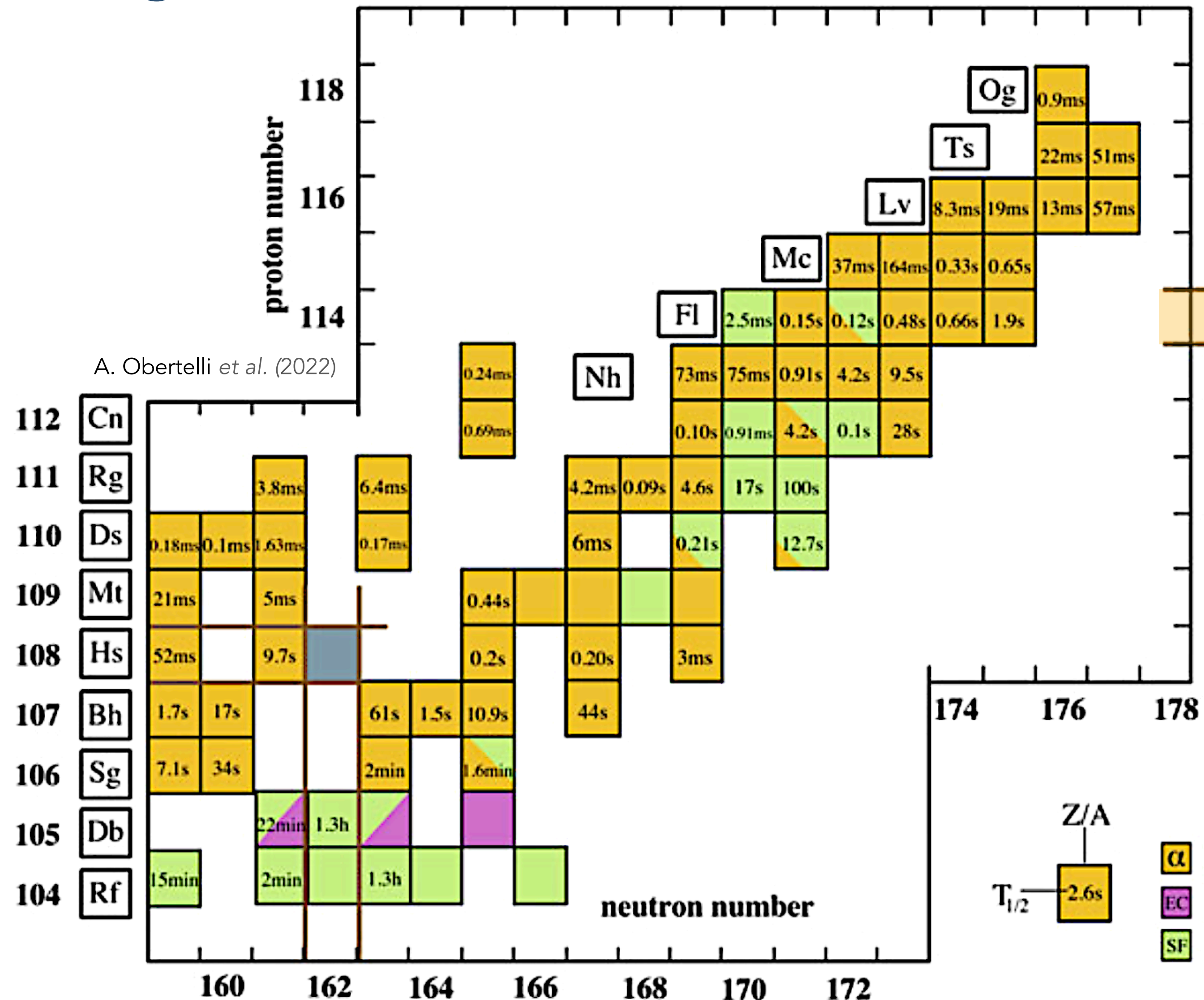
INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

1 H hydrogen 1.008 [1.0078, 1.0082]	2 He helium 4.0026											13 B boron 10.81 [10.806, 10.821]	14 C carbon 12.011 [12.009, 12.012]	15 N nitrogen 14.007 [14.006, 14.008]	16 O oxygen 15.999 [15.999, 16.000]	17 F fluorine 18.998	18 Ne neon 20.180																						
3 Li lithium 6.94 [6.939, 6.997]	4 Be beryllium 9.0122											19 K potassium 39.098	20 Ca calcium 40.078(4)											21 Sc scandium 44.956	22 Ti titanium 47.867	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845(2)	27 Co cobalt 58.933	28 Ni nickel 58.693	29 Cu copper 63.546(3)	30 Zn zinc 65.38(2)	31 Ga gallium 69.723	32 Ge germanium 72.630(6)	33 As arsenic 74.922	34 Se selenium 78.971(8)	35 Br bromine 79.904 [79.901, 79.907]	36 Kr krypton 83.798(2)
11 Na sodium 22.990	12 Mg magnesium 24.305 [24.304, 24.307]											37 Rb rubidium 85.468	38 Sr strontium 87.62											39 Y yttrium 88.906	40 Zr zirconium 91.224(2)	41 Nb niobium 92.906	42 Mo molybdenum 95.95	43 Tc technetium	44 Ru ruthenium 101.07(2)	45 Rh rhodium 102.91	46 Pd palladium 106.42	47 Ag silver 107.87	48 Cd cadmium 112.41	49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60(3)	53 I iodine 126.90	54 Xe xenon 131.29
55 Cs caesium 132.91	56 Ba barium 137.33	57-70 lanthanoids	71 Lu lutetium 174.97	72 Hf hafnium 178.49(2)	73 Ta tantalum 180.95	74 W tungsten 183.84	75 Re rhenium 186.21	76 Os osmium 190.23(3)	77 Ir iridium 192.22	78 Pt platinum 195.08	79 Au gold 196.97	80 Hg mercury 200.59	81 Tl thallium 204.38 [204.38, 204.39]	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium	85 At astatine	86 Rn radon																					
87 Fr francium	88 Ra radium	89-102 actinoids	103 Lr lawrencium	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113 Nh nihonium [204.38, 204.39]	114 Fl flerovium	115 Mc moscovium	116 Lv livermorium	117 Ts tennessine	118 Og oganesson																					
			57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24	61 Pm promethium	62 Sm samarium 150.36(2)	63 Eu europium 151.96	64 Gd gadolinium 157.25(3)	65 Tb terbium 158.93	66 Dy dysprosium 162.50	67 Ho holmium 164.93	68 Er erbium 167.26	69 Tm thulium 168.93	70 Yb ytterbium 173.05																							
			89 Ac actinium 232.04	90 Th thorium 232.04	91 Pa protactinium 231.04	92 U uranium 238.03	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium																							



Synthesis of element 119



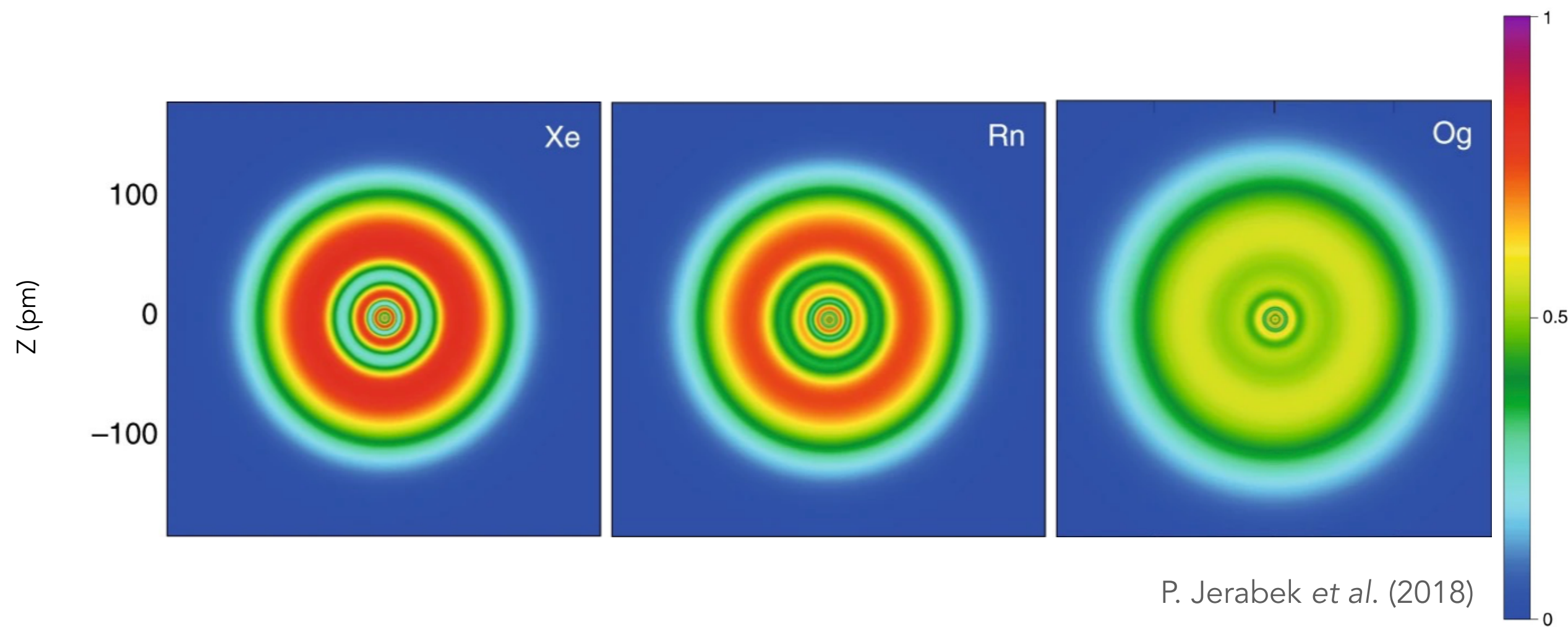
- What is the heaviest nucleus that can be created? How many elements are there?
- New evidence of the existence of the "island of stability"
- New anchor point for theory (constraints thanks to mass and life time)

Model	Z	N
Nilsson	114	184
Wood-Saxon	114	184
Wood-Saxon Universal	126	184
Hartree-Fock-Bogoliubov	126	184
Relativistic Mean Field	120	172

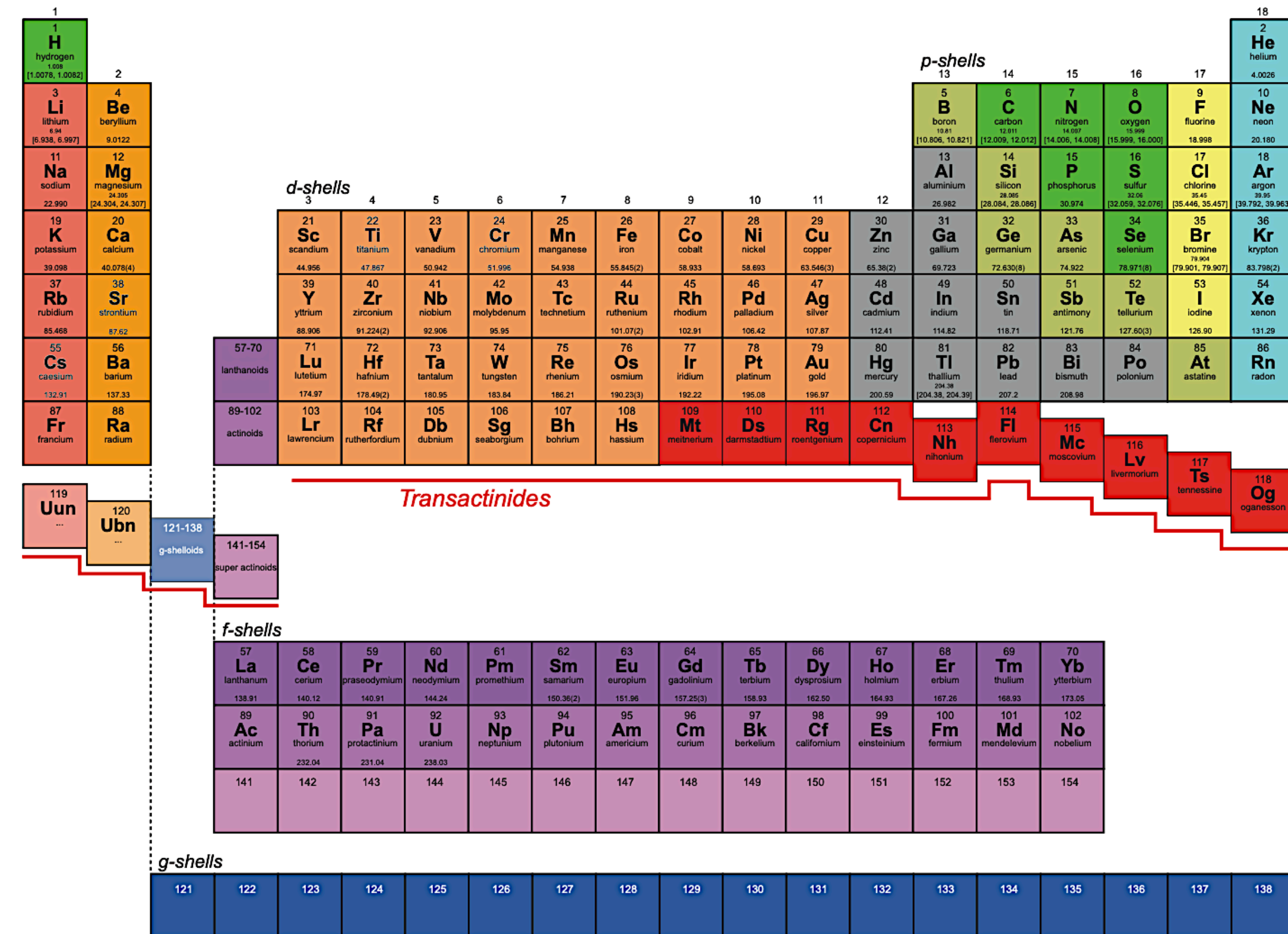
K. Kessaci, Thèse de l'Unistra (2021)

Synthesis of element 119

- 7th period completed → Oganesson (Z=118)
- Chemistry of the nuclei g electronic layer?
- Not negligible relativistic effects from Z=112 → what about the classification of the elements?



P. Jerabek et al. (2018)

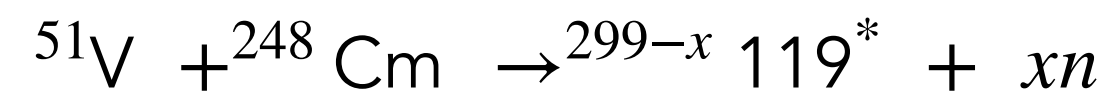


Cf. B. Gall

Synthesis of element 119

Experimental setup @ RIKEN, Japan

- Fusion-evaporation reaction :



- Production cross-section ~ fb !

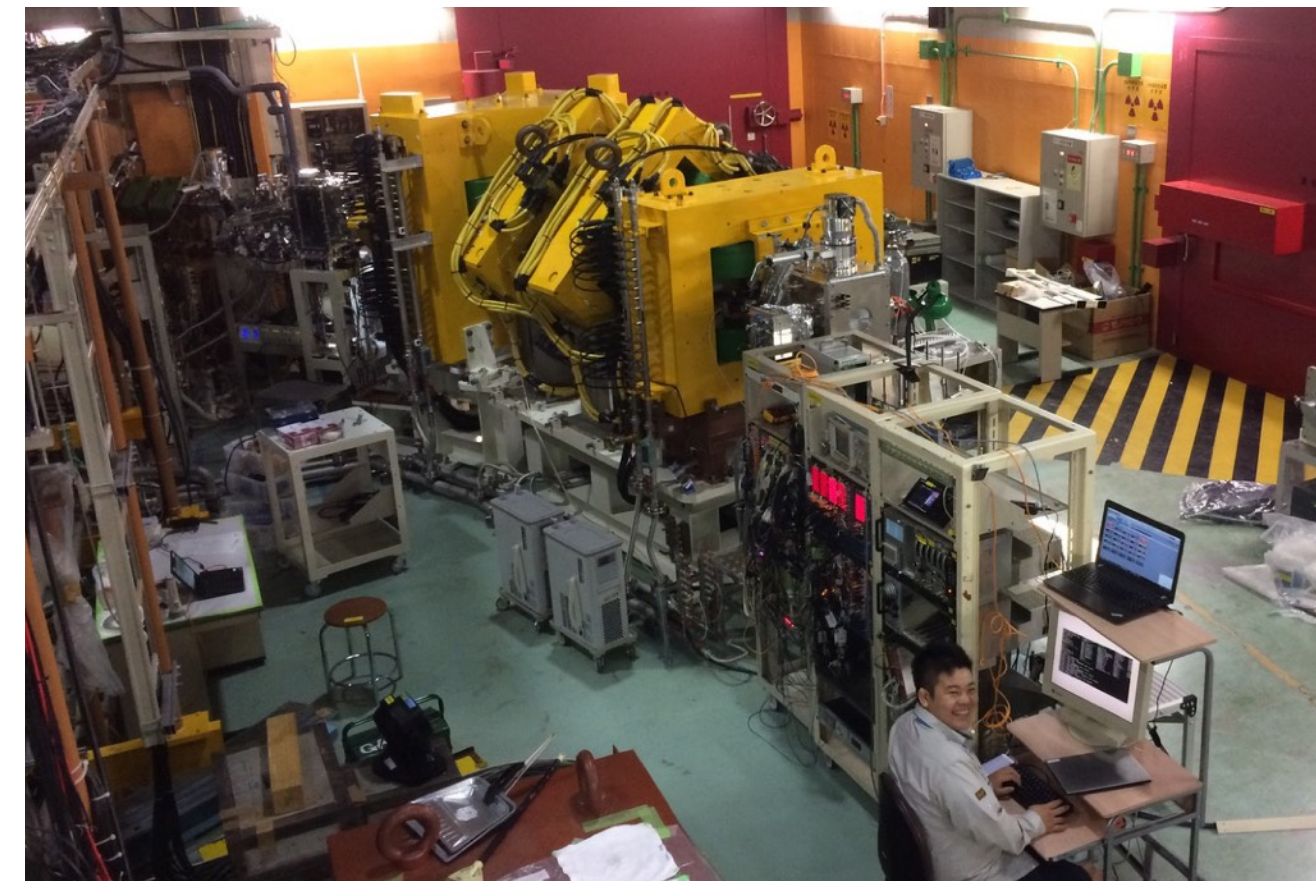
I (pμA)	σ (fb)	Event every:
1	50	2 months
10	50	6 months
1	3	12 years
10	3	15 months

(1pμA ≈ 6 × 10¹² particles/s)

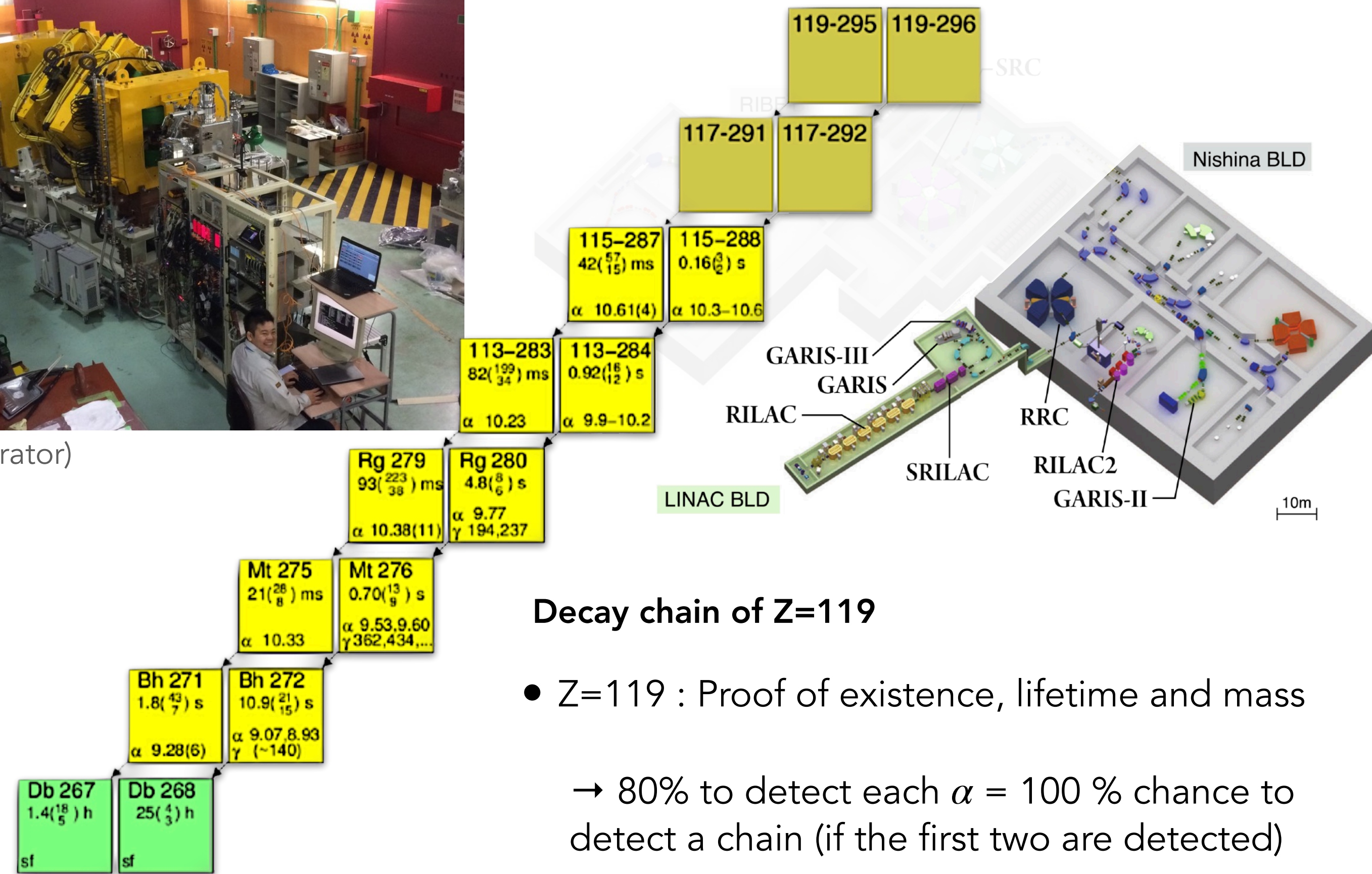
- High intensity

→ Superheavy factory: SRILAC, SHE factory, LINAG

→ New separators : GARIS III, DGFRS II & III, S³



GARIS II (separator)
Cf. B. Gall



Decay chain of Z=119

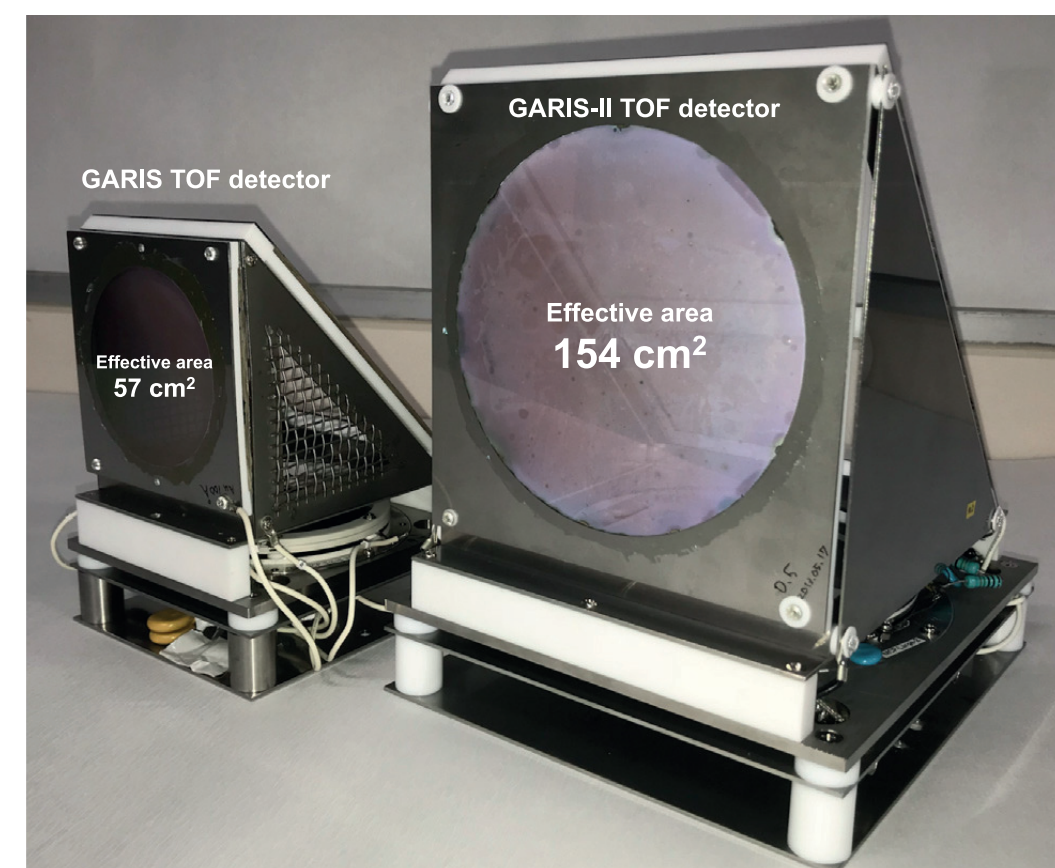
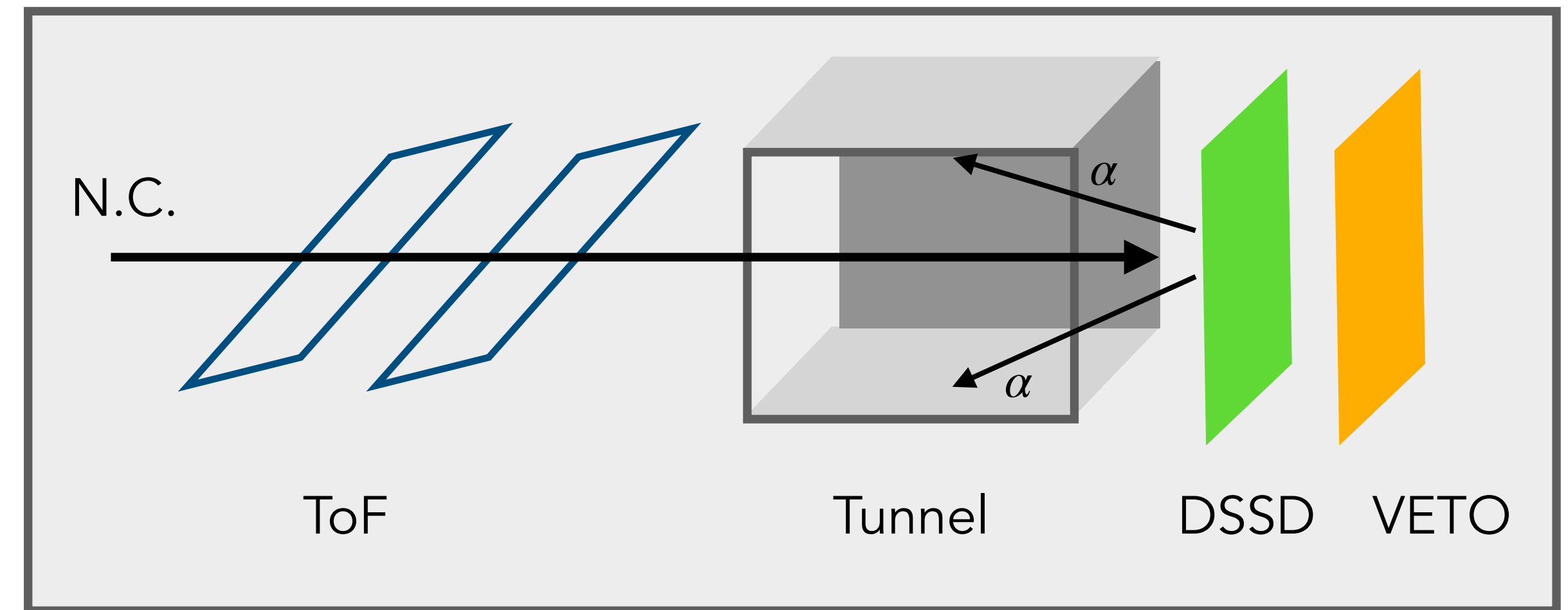
- Z=119 : Proof of existence, lifetime and mass
 - 80% to detect each α = 100 % chance to detect a chain (if the first two are detected)
 - isotopes known except Z=117 (Ts)

Synthesis of element 119

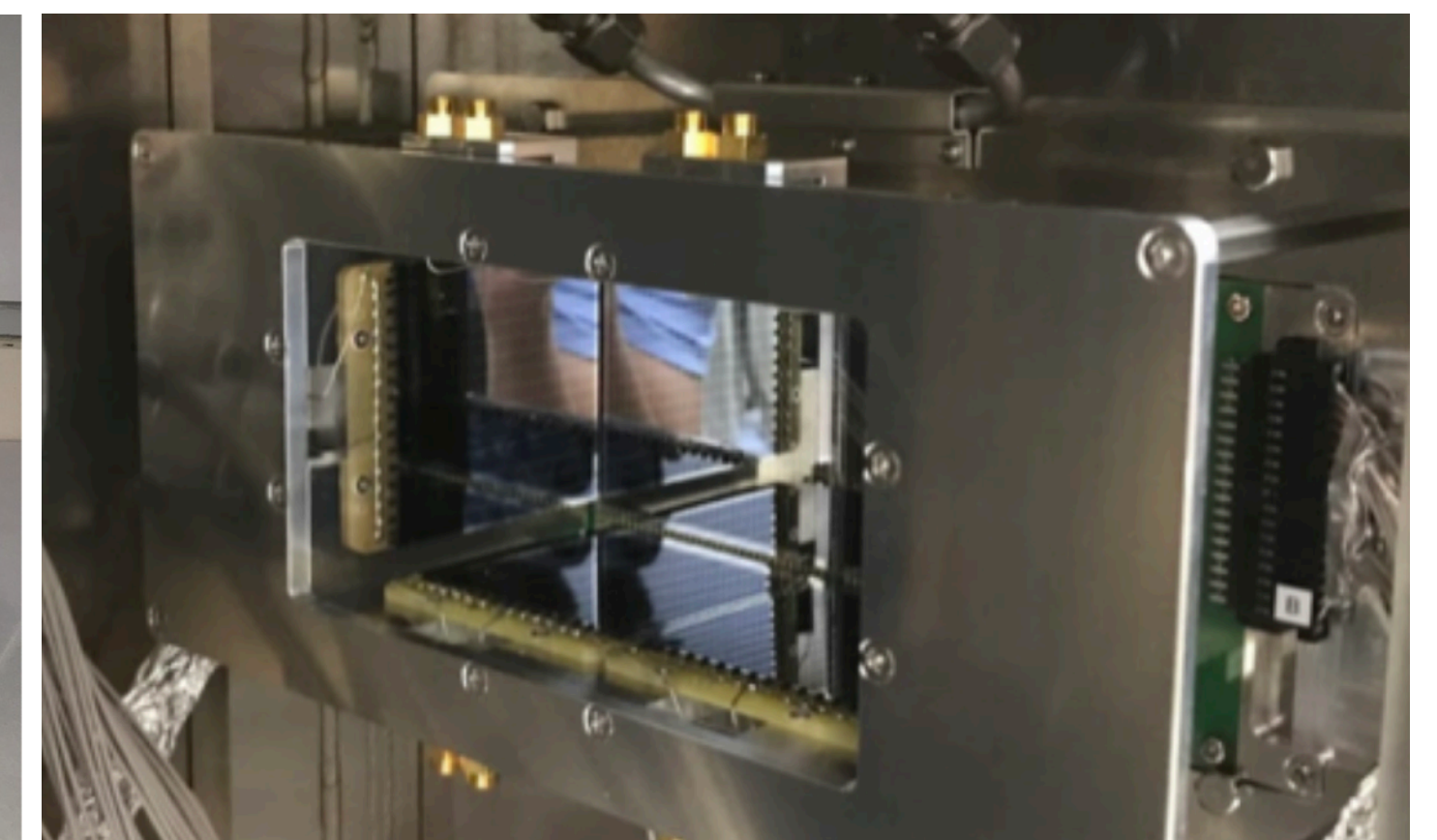
Experimental setup @ RIKEN, Japan

Detection system:

- Time of Flight detector (ToF)
- Double-sided silicon strip detector (DSSD) (e^- and α)
- non-pixelized silicon Tunnel (e^- and α)
- non-pixelized silicon VETO



ToF detector



Detection chamber

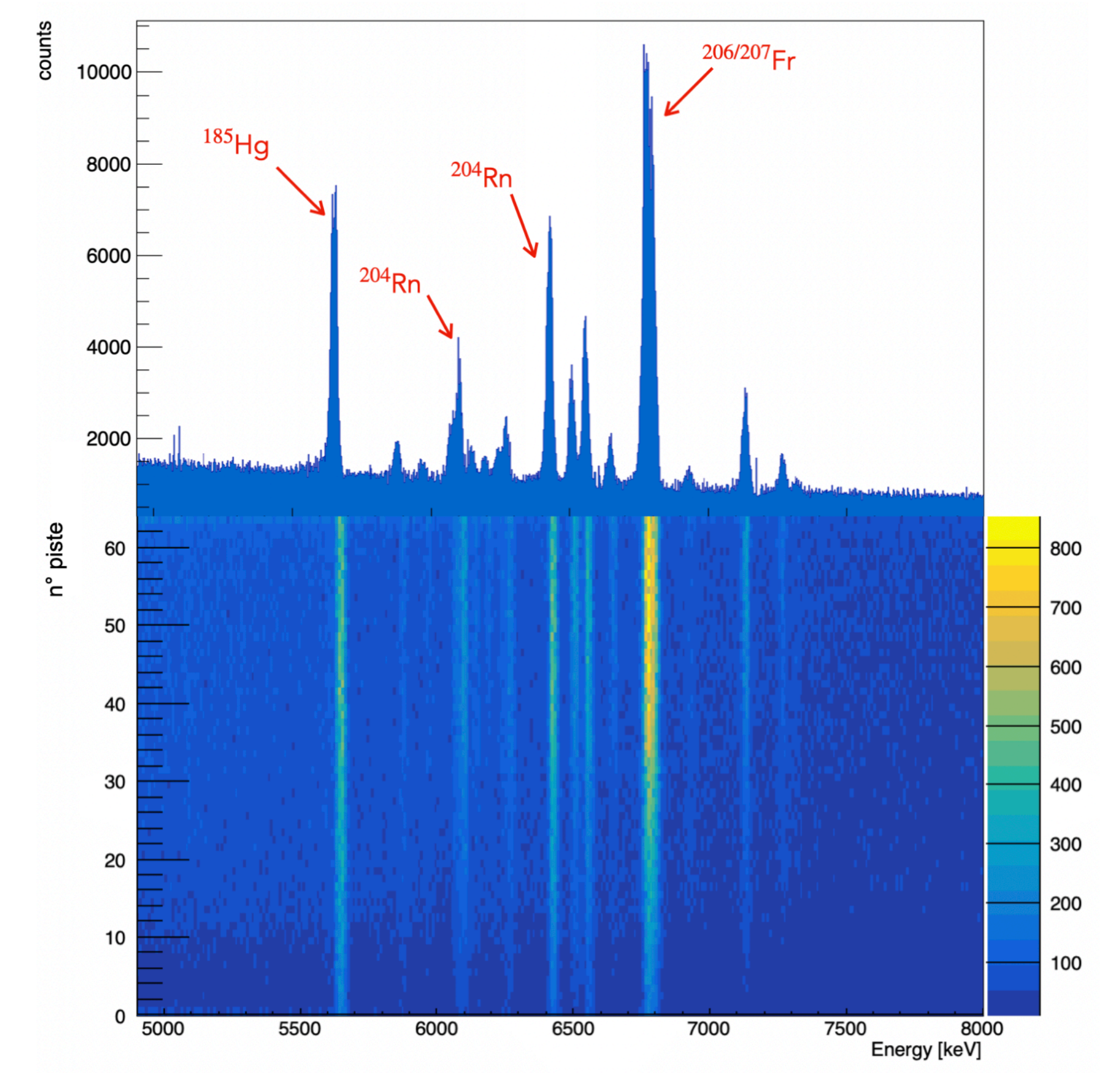
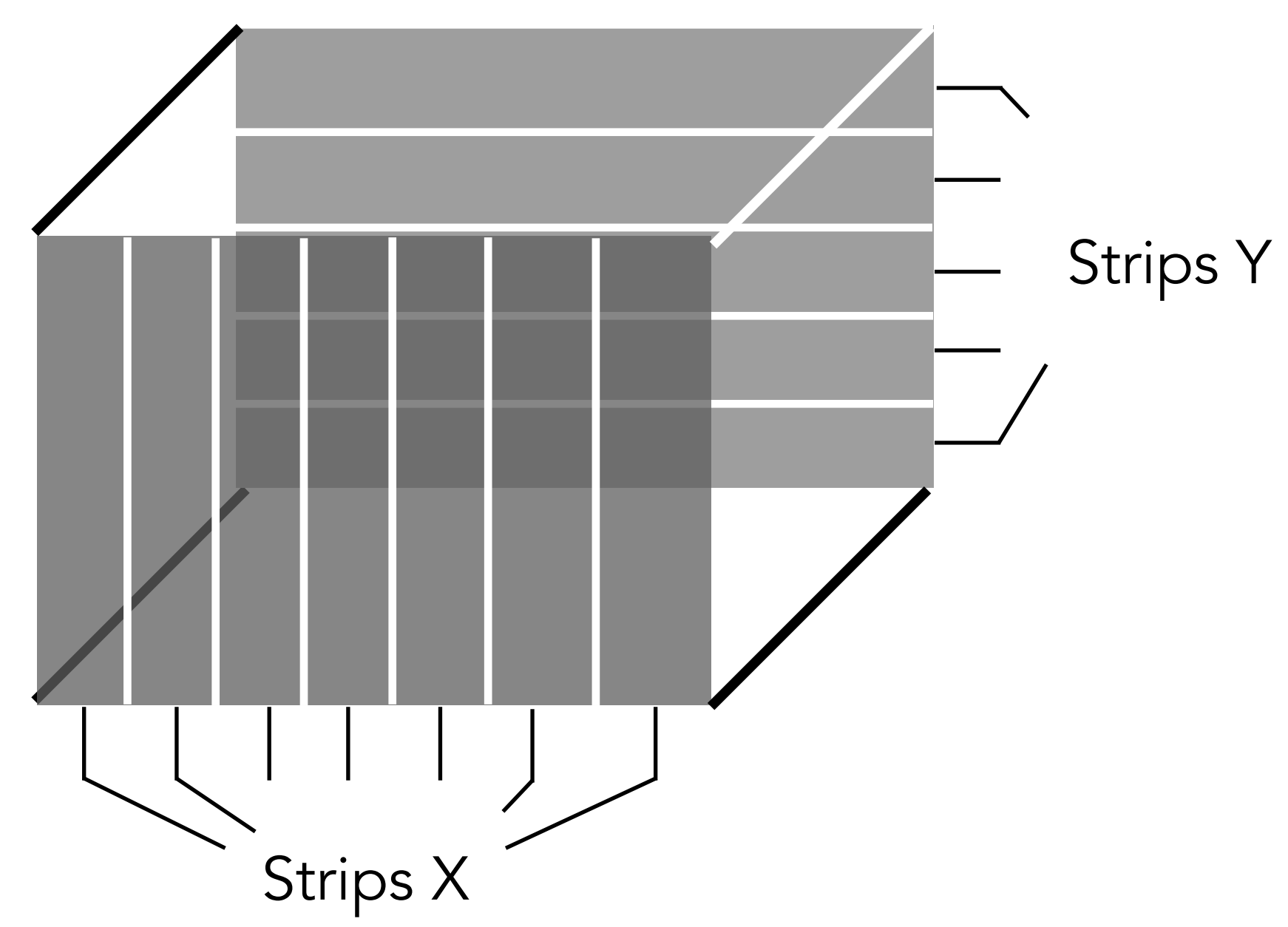
Internship: production of $^{257/258}\text{Db}$

Calibration of an experiment and search for α -decay chains

- Calibration of detectors from reactions \longrightarrow

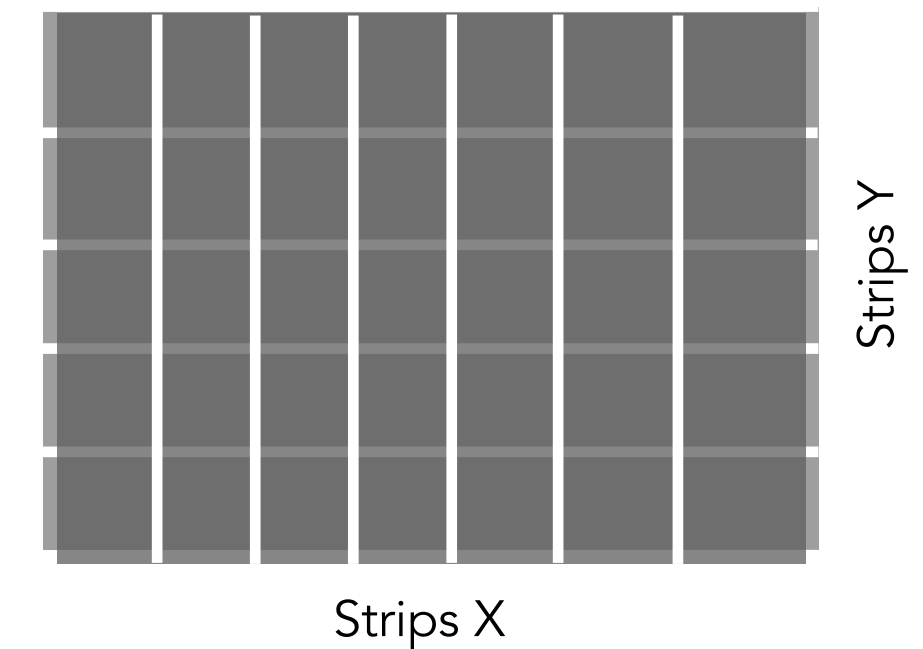


DSSD
64 x 32 x 2 = 4096 pixels



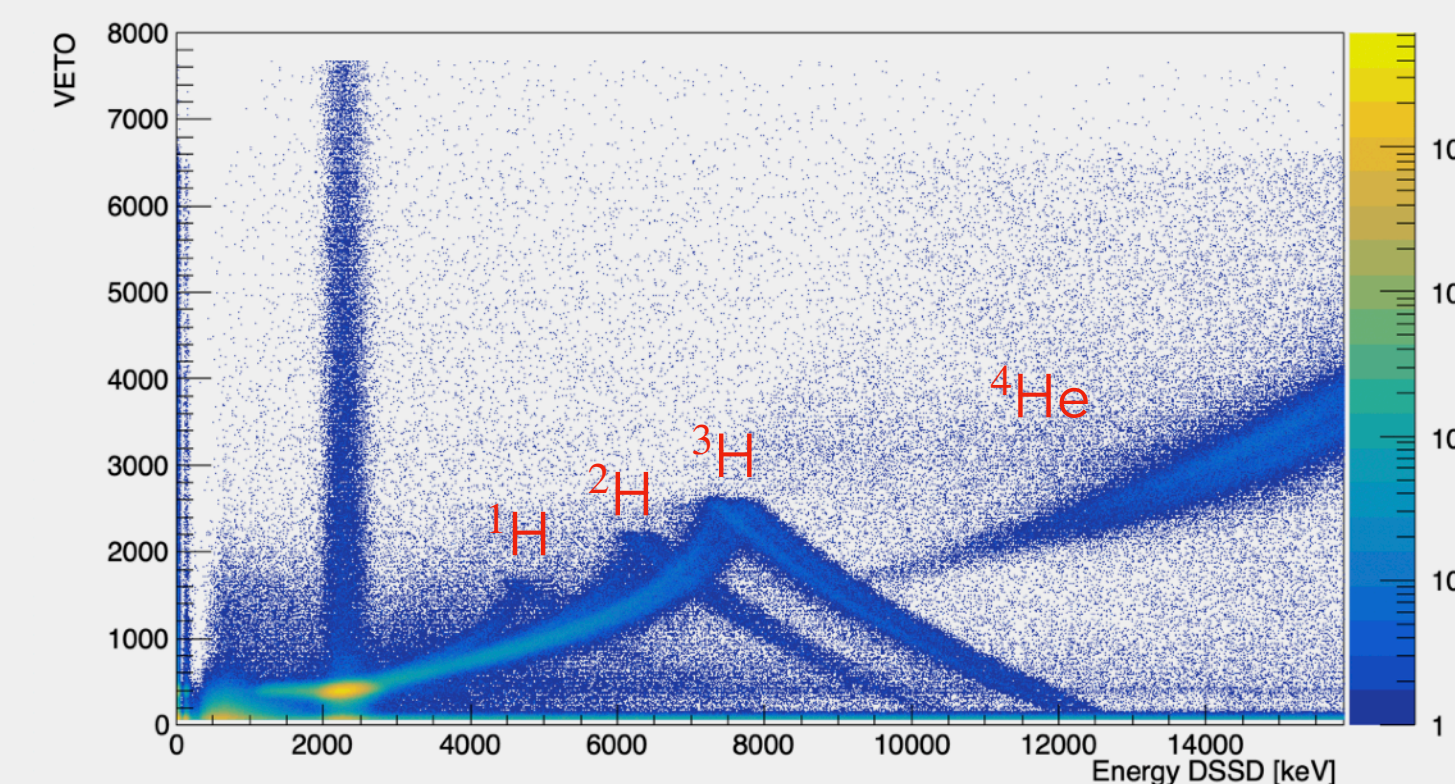
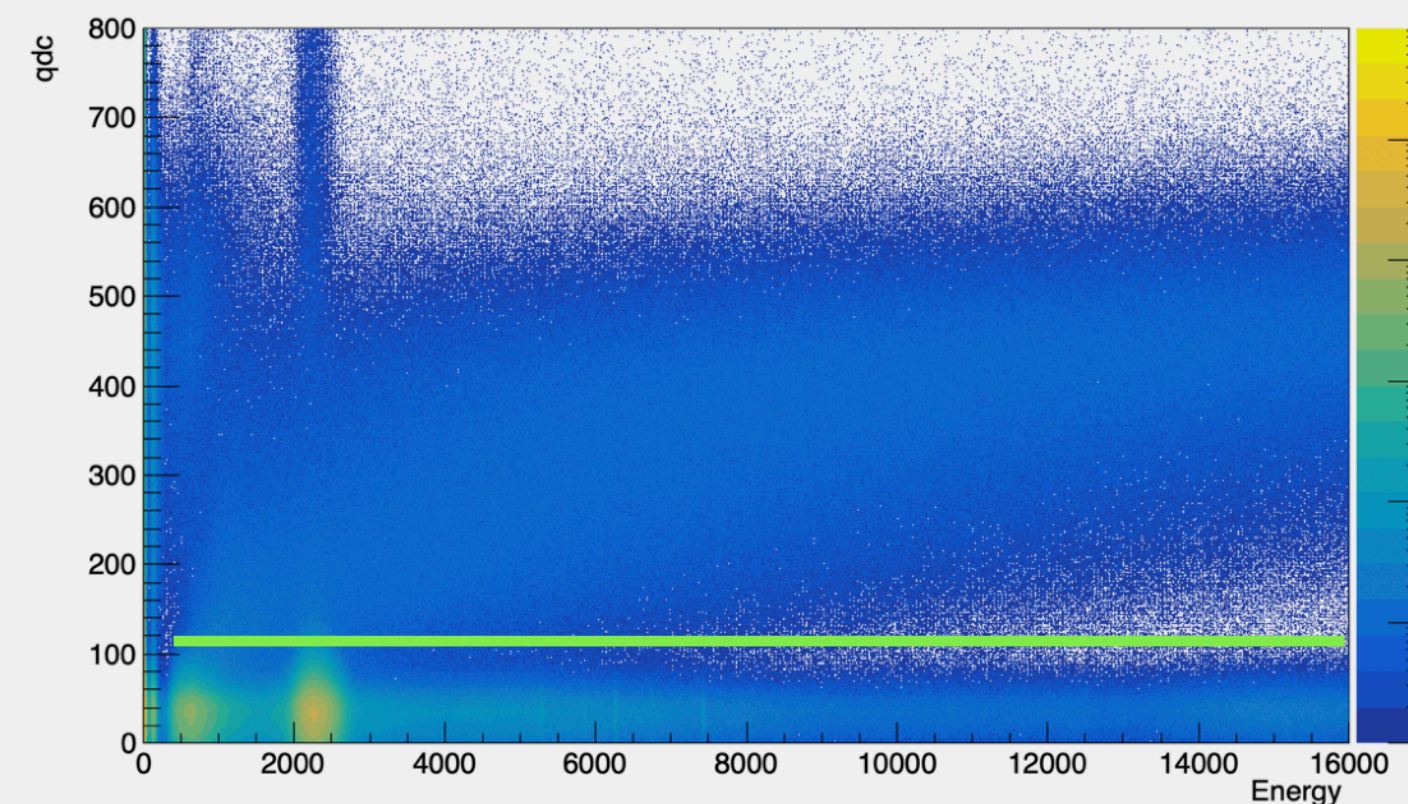
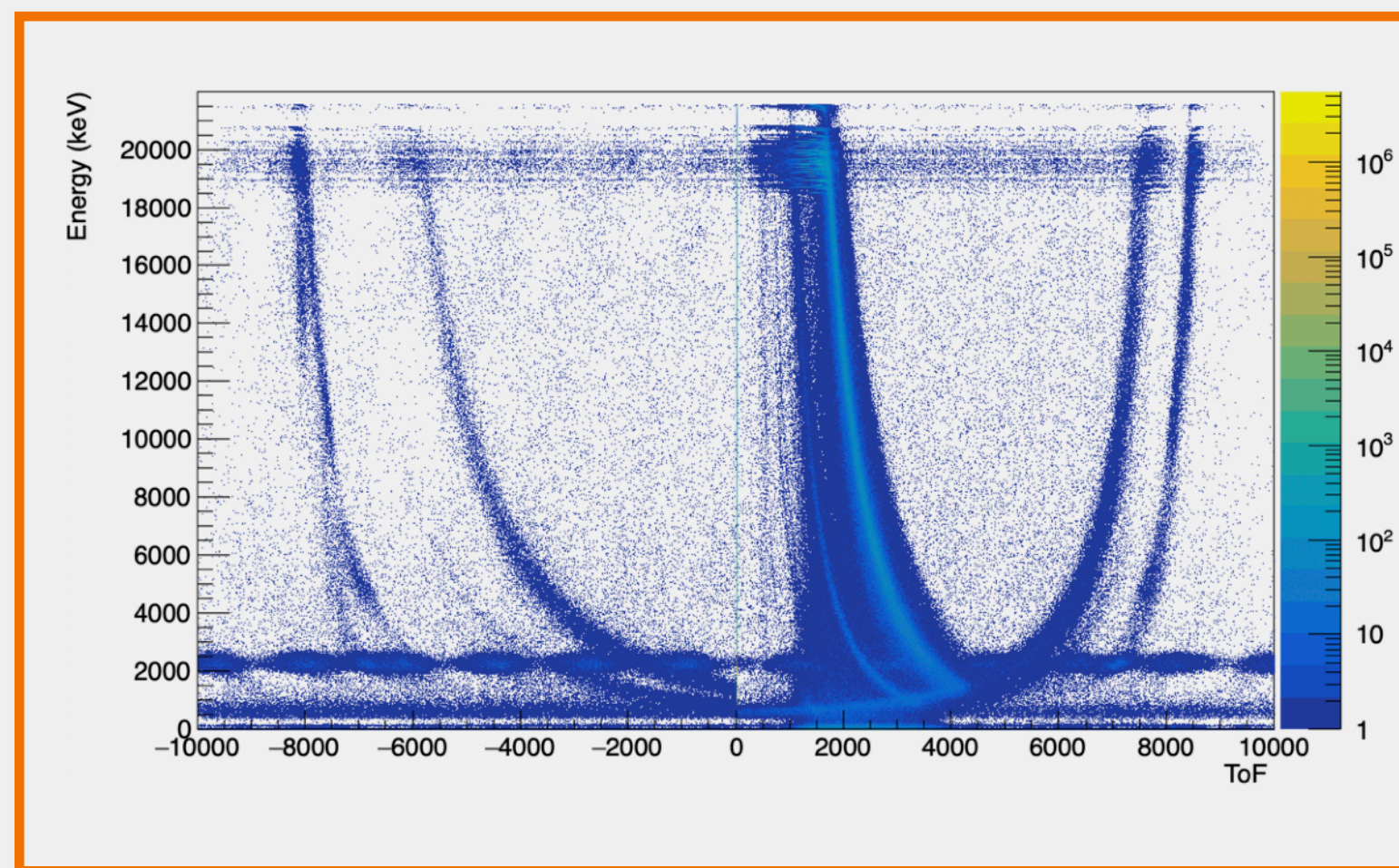
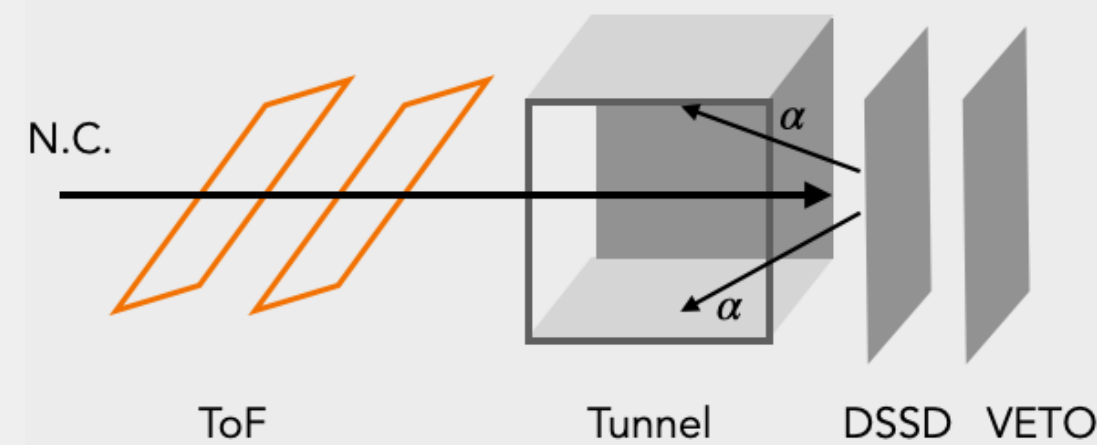
Internship: production of $^{257/258}\text{Db}$

Calibration of an experiment and search for α -decay chains



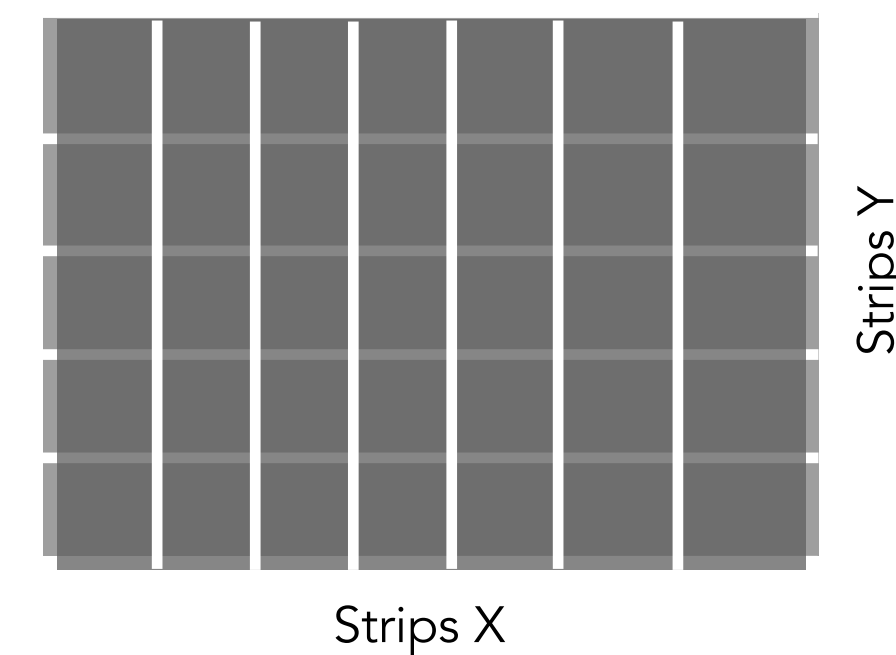
Data flow $\longrightarrow R\alpha R A \alpha \alpha A \alpha A R \alpha \alpha A \alpha A \alpha R R \alpha \alpha R A \alpha$

- $^{51}\text{V} + ^{208}\text{Pb} \rightarrow ^{259-x}\text{Db} + xn$
- Filtering using ToF, QDC et VETO



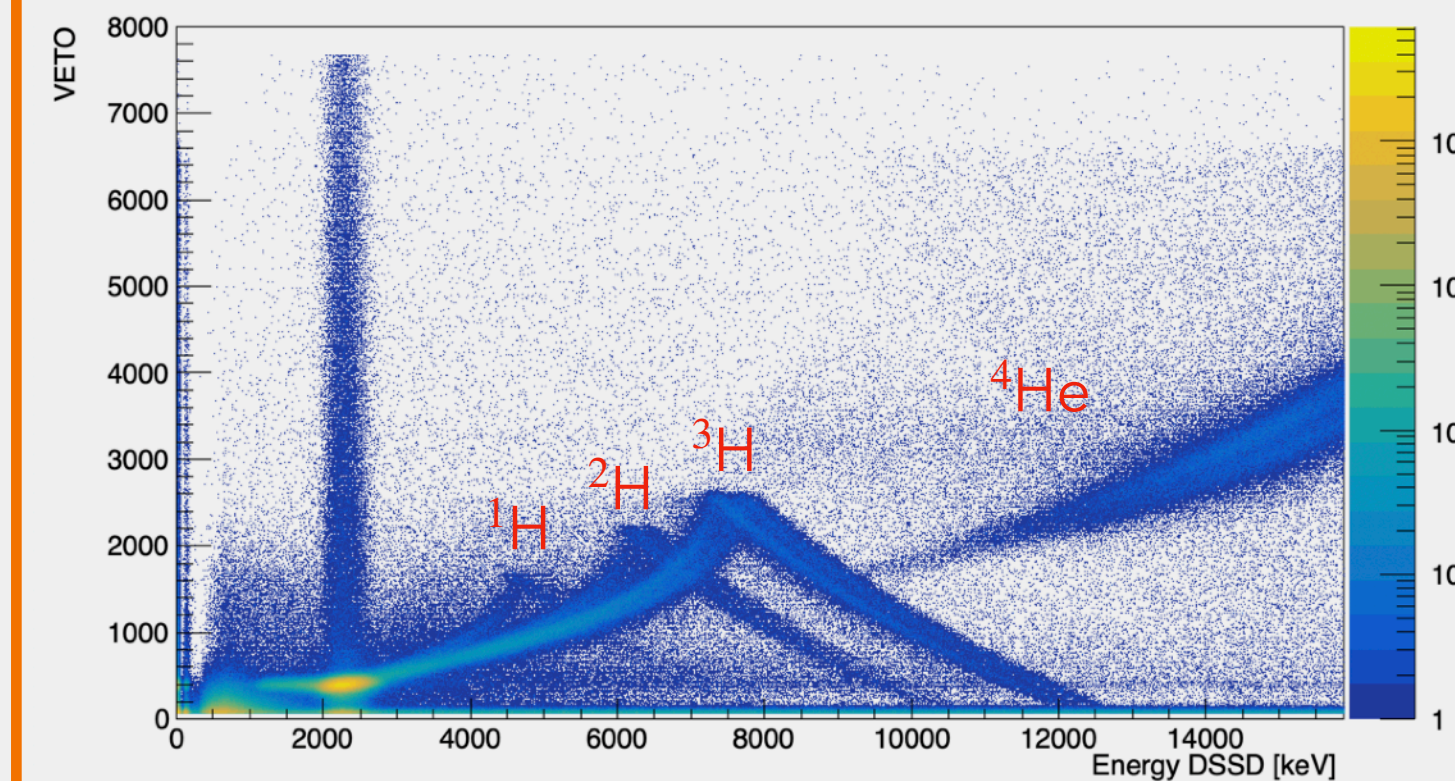
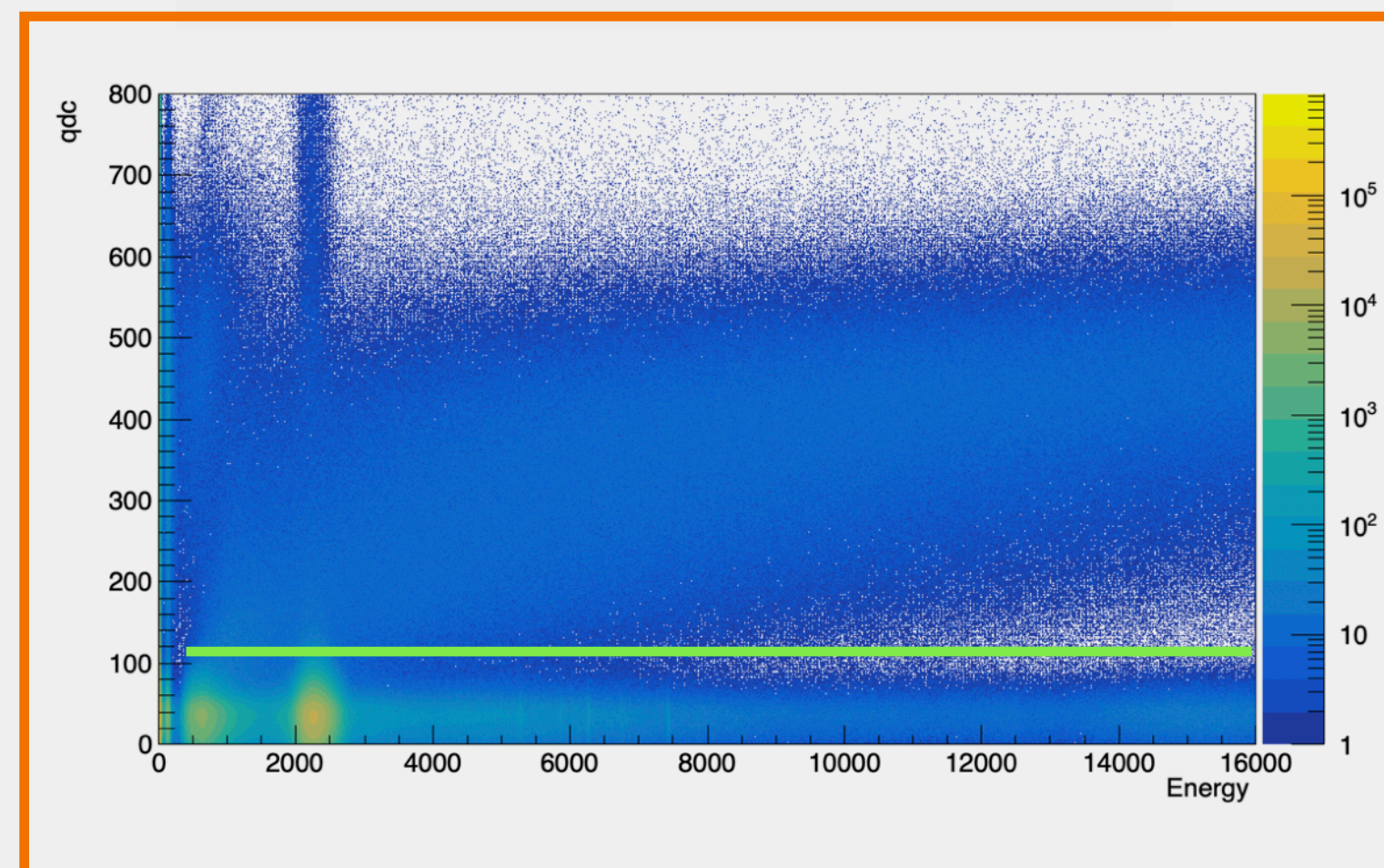
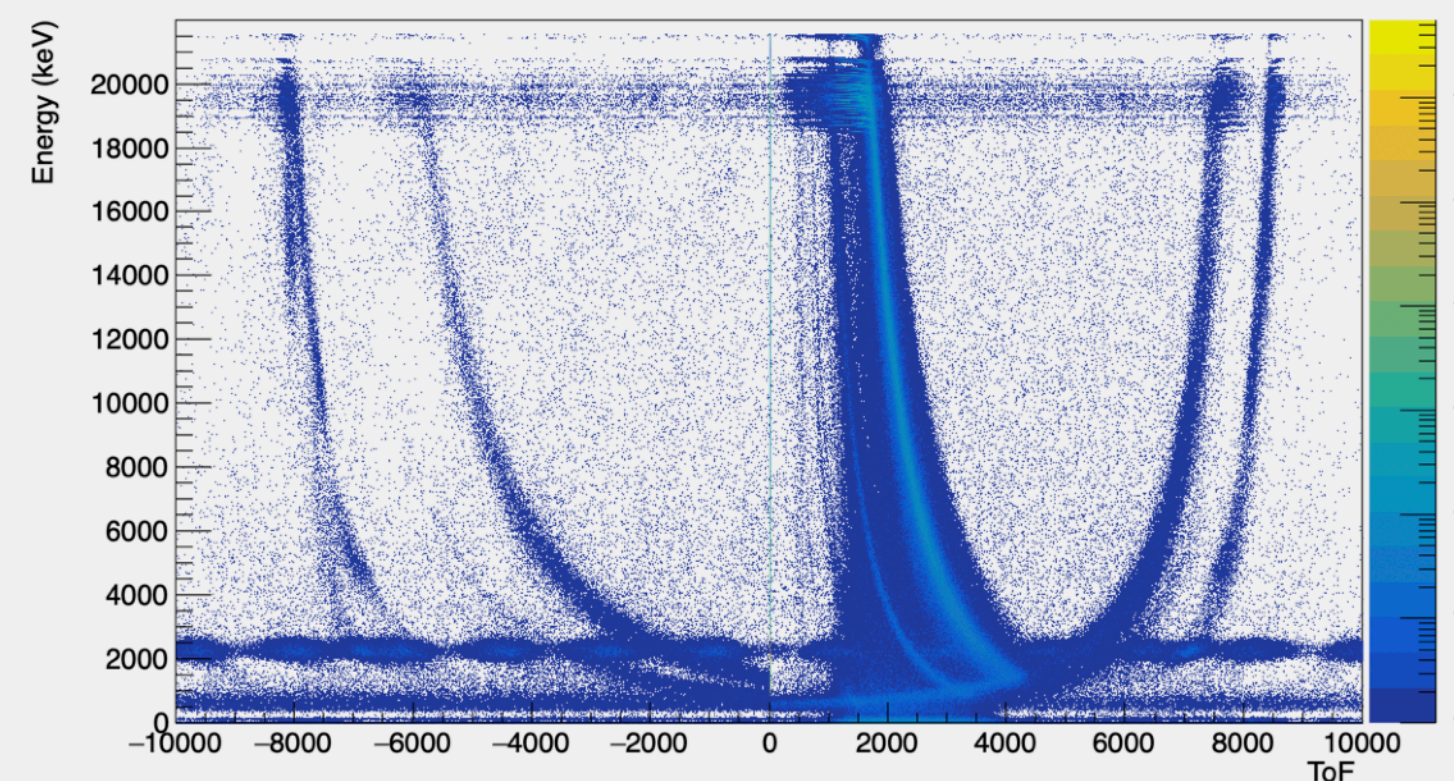
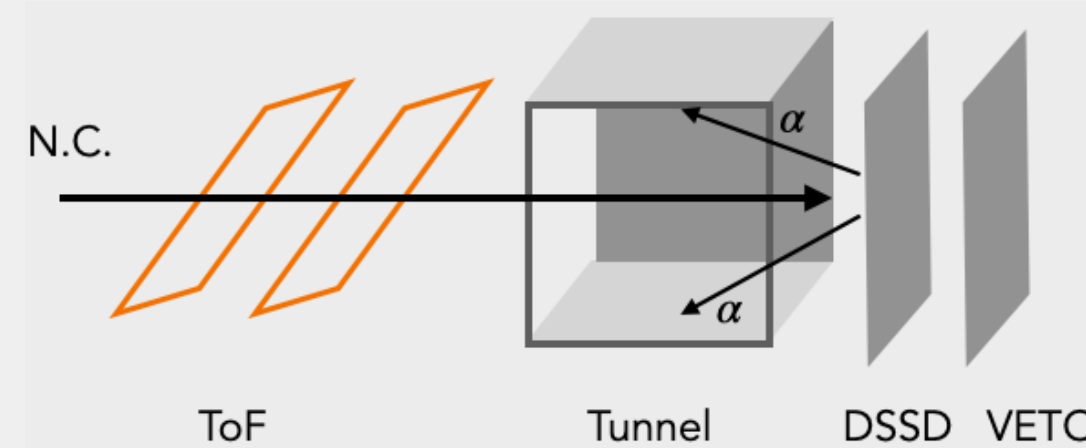
Internship: production of $^{257/258}\text{Db}$

Calibration of an experiment and search for α -decay chains



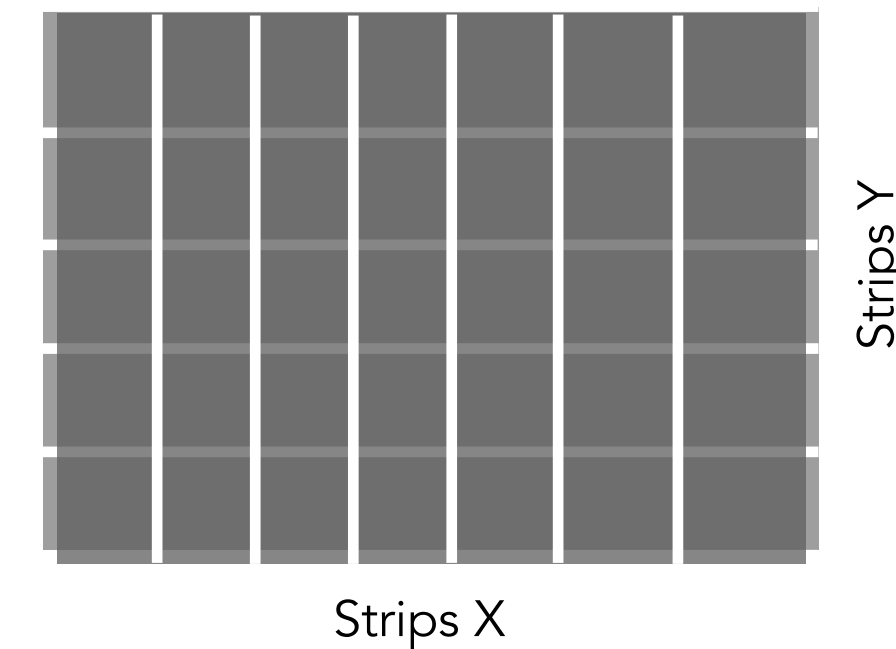
Data flow $\longrightarrow R\alpha R A \alpha \alpha A \alpha R \alpha \alpha A \alpha A \alpha R R \alpha \alpha R A \alpha$

- $^{51}\text{V} + ^{208}\text{Pb} \rightarrow ^{259-x}\text{Db} + xn$
- Filtering using ToF, QDC et VETO



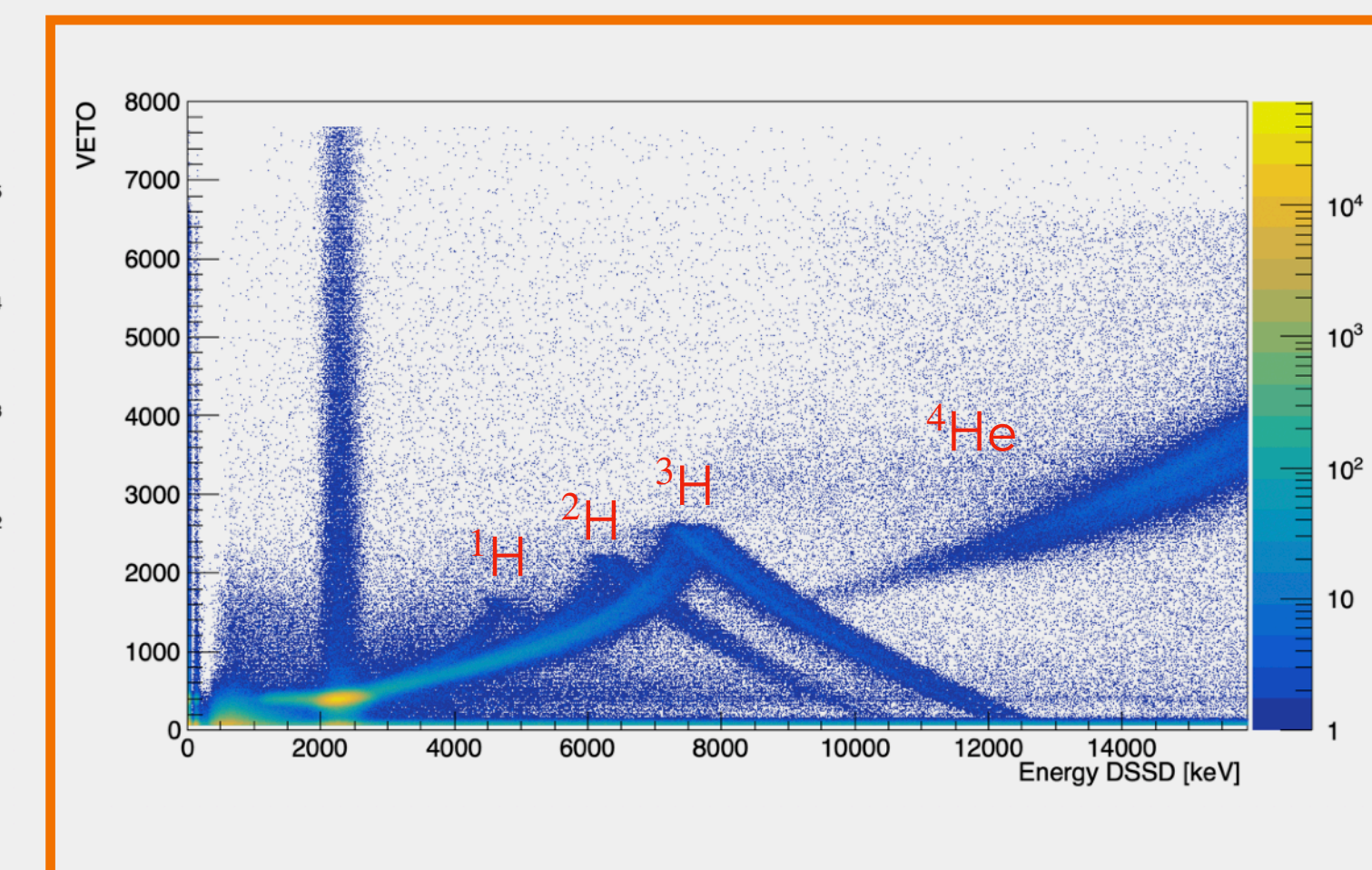
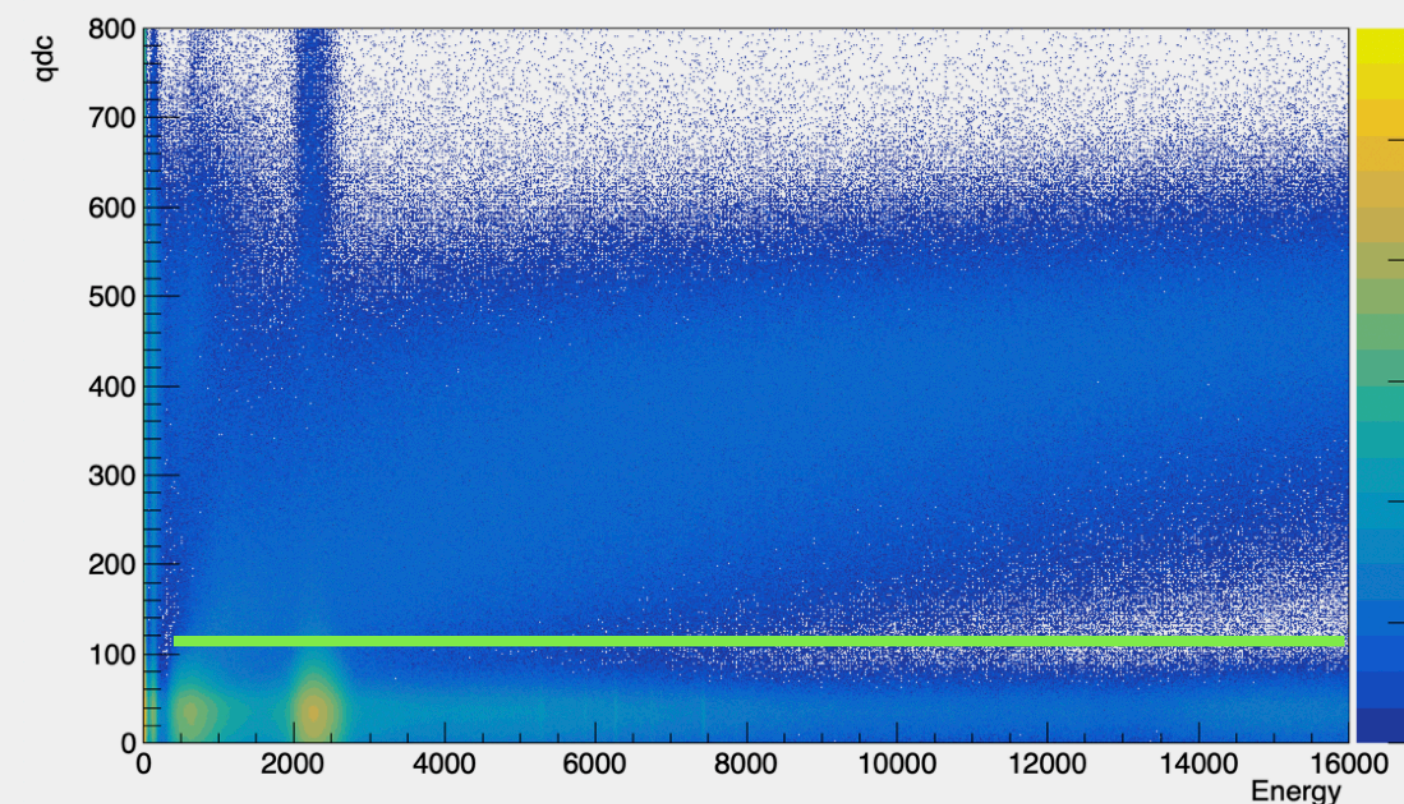
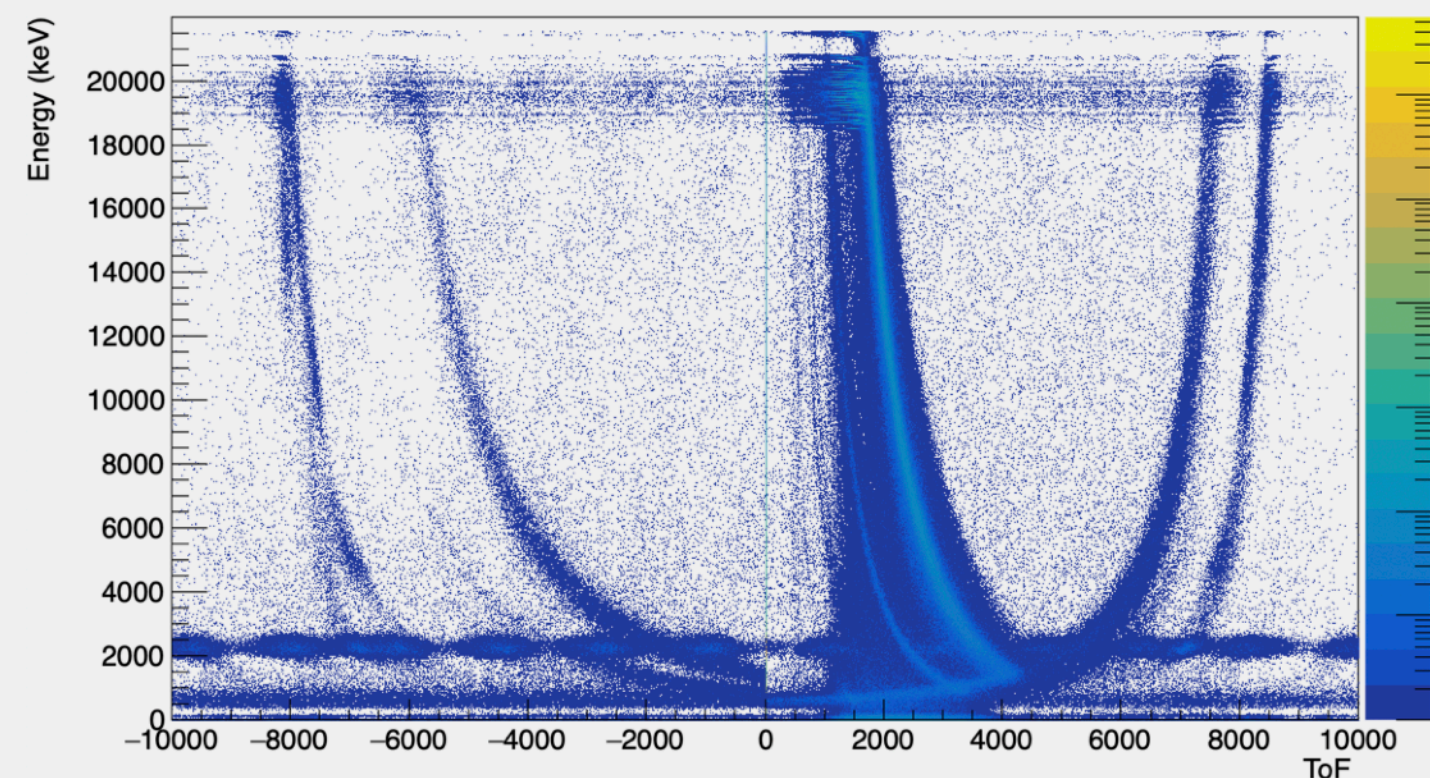
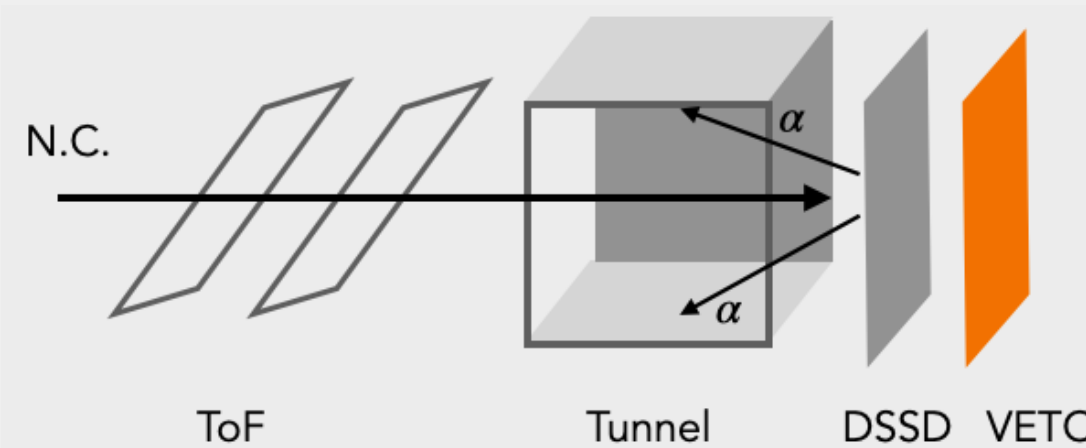
Internship: production of $^{257/258}\text{Db}$

Calibration of an experiment and search for α -decay chains



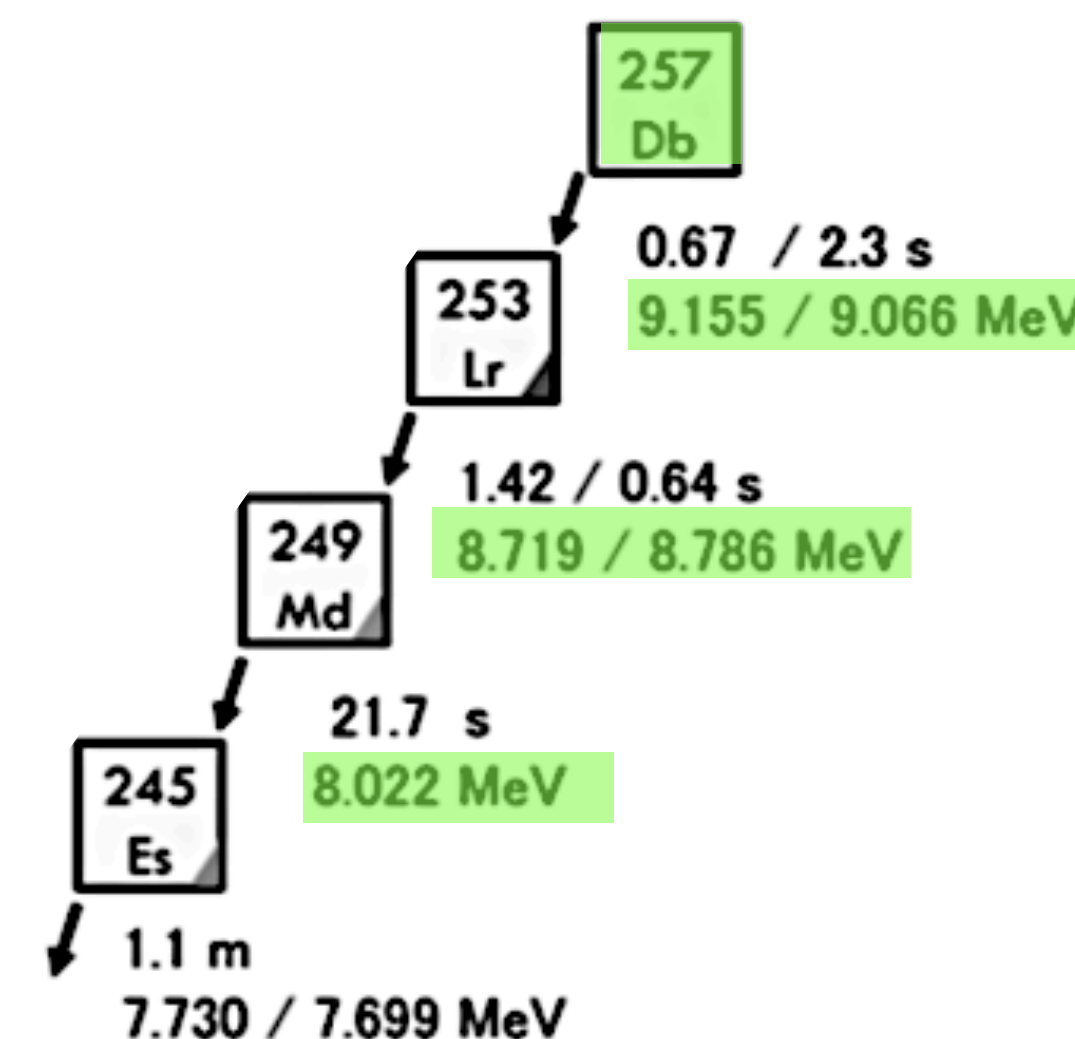
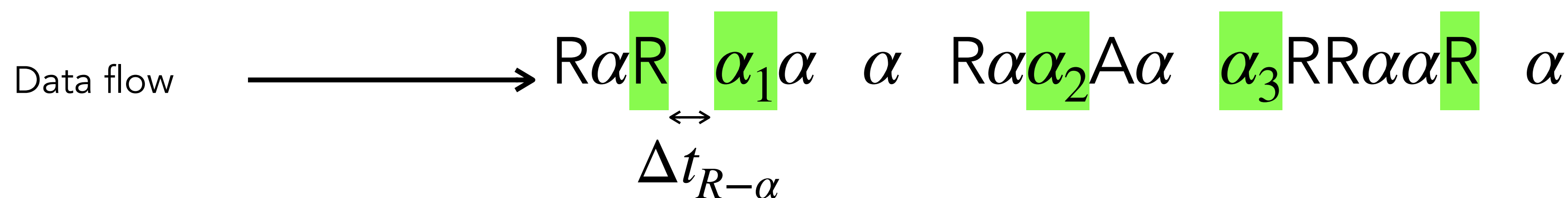
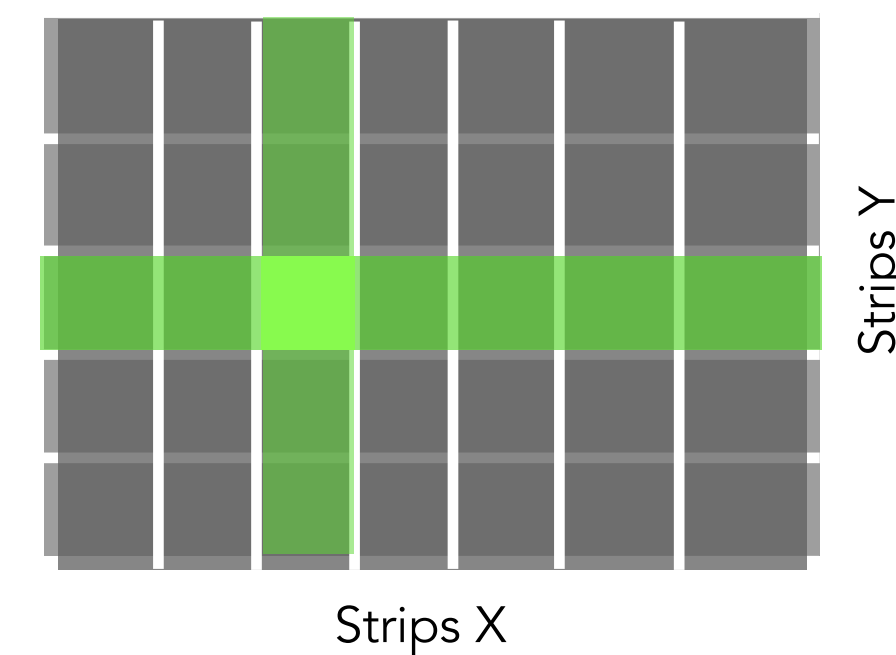
Data flow \longrightarrow $R\alpha R \quad \alpha\alpha \quad \alpha \quad R\alpha\alpha A\alpha \quad \alpha RR\alpha\alpha R \quad \alpha$

- $^{51}\text{V} + ^{208}\text{Pb} \rightarrow ^{259-x}\text{Db} + xn$
- Filtering using ToF, QDC et VETO



Internship: production of $^{257/258}\text{Db}$

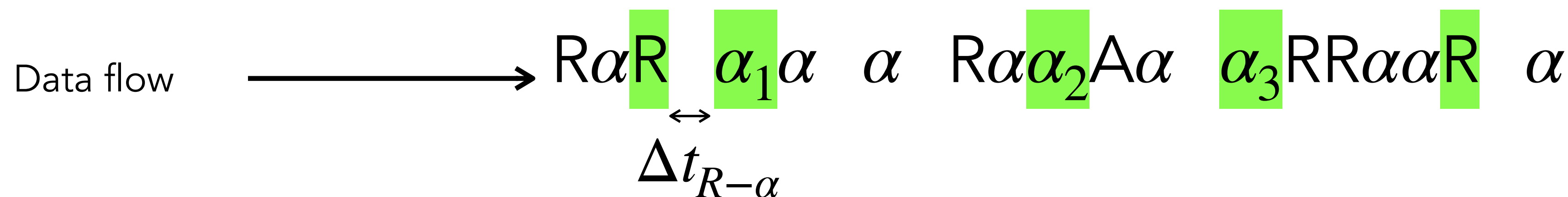
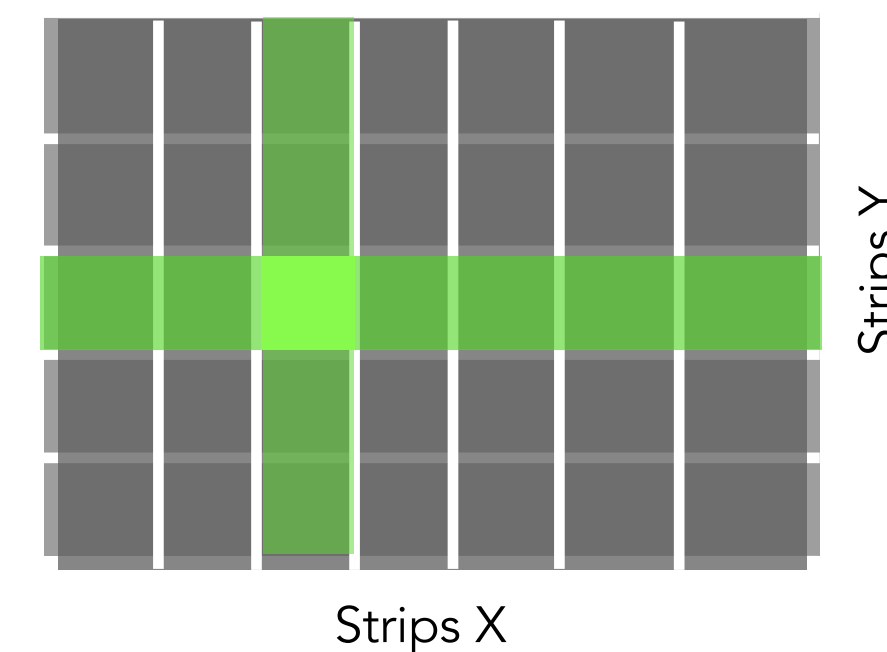
Calibration of an experiment and search for α -decay chains



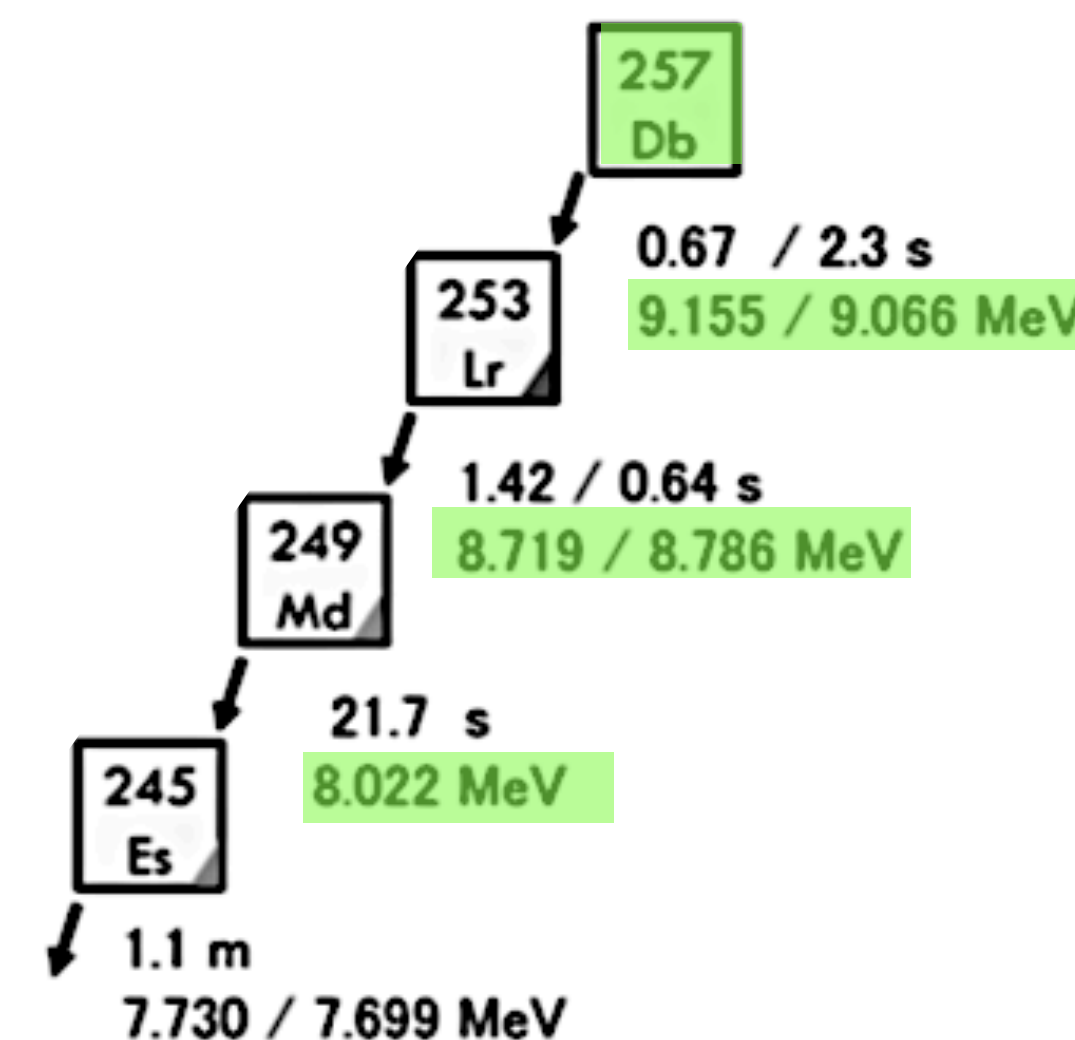
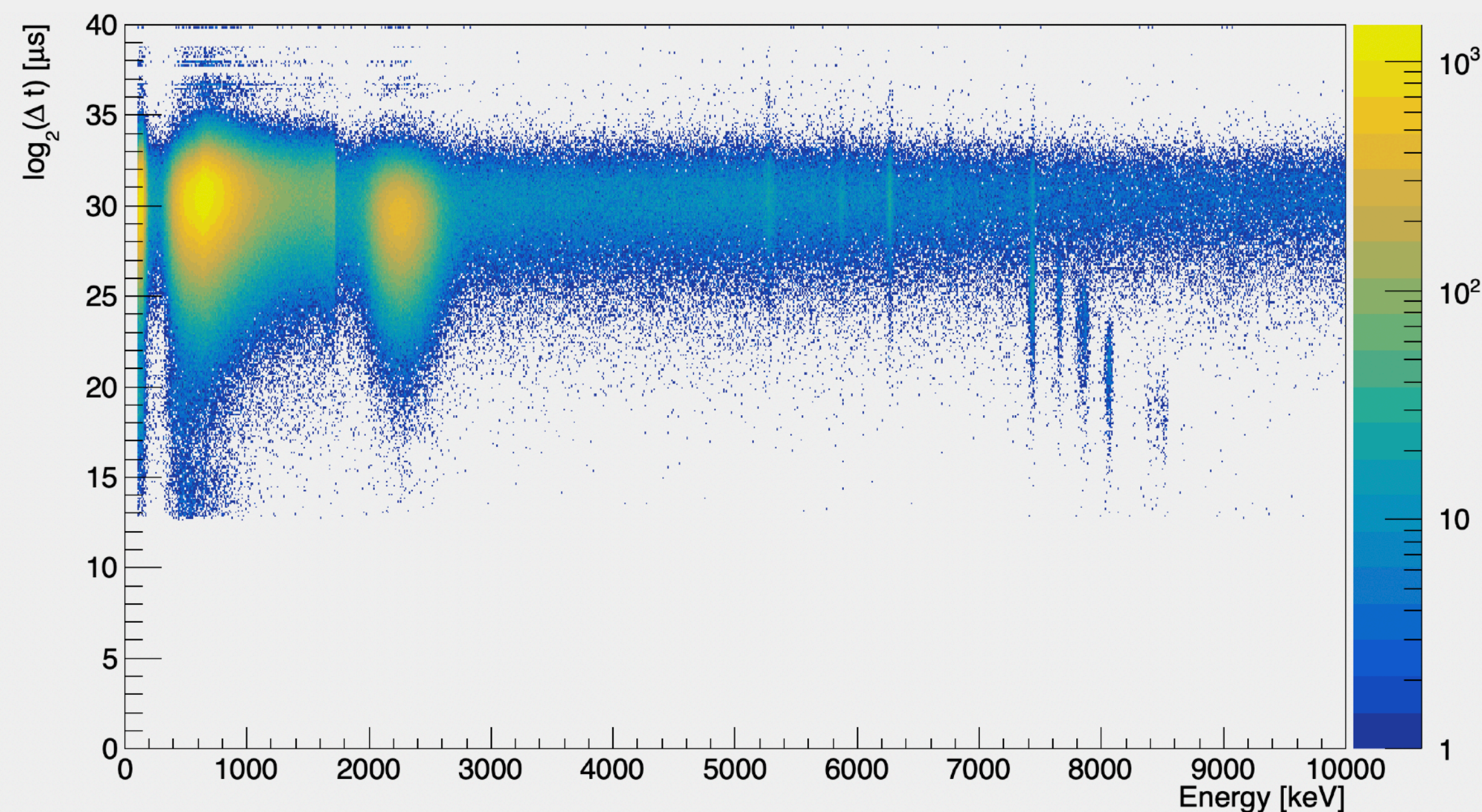
^{257}Db decay chain

Internship: production of $^{257/258}\text{Db}$

Calibration of an experiment and search for α -decay chains



● Recoils lifetimes as function of E_α

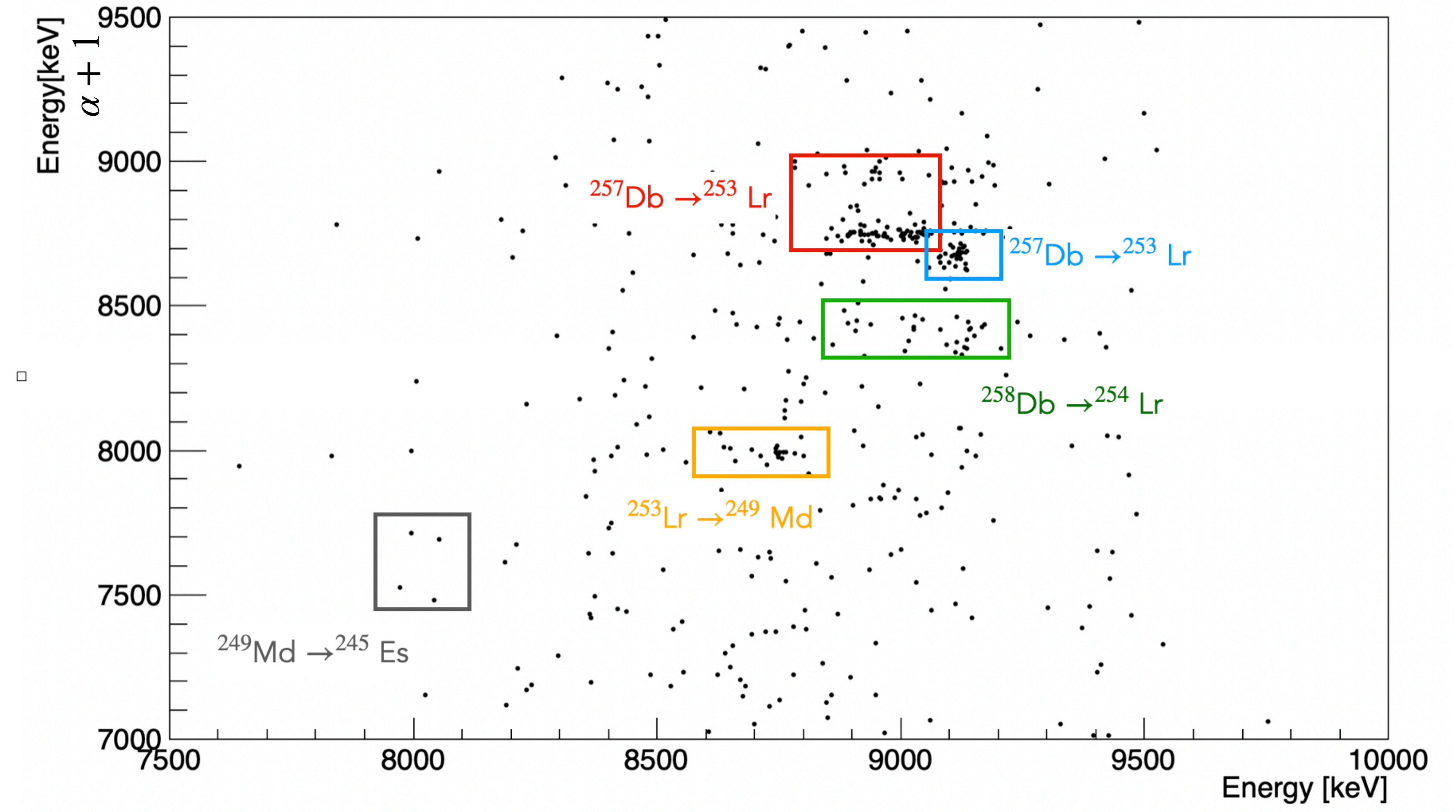
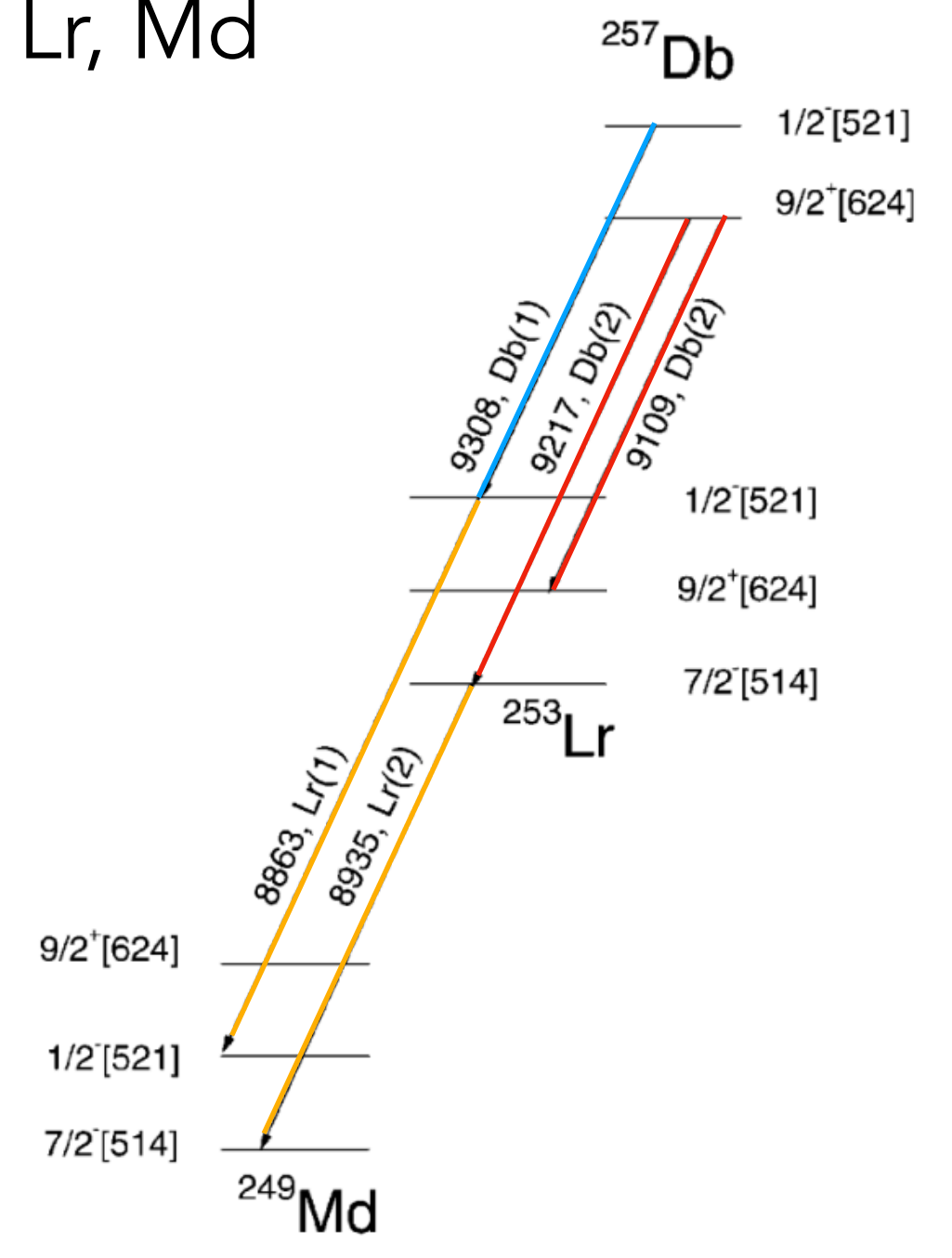


^{257}Db decay chain

Internship: production of $^{257/258}\text{Db}$

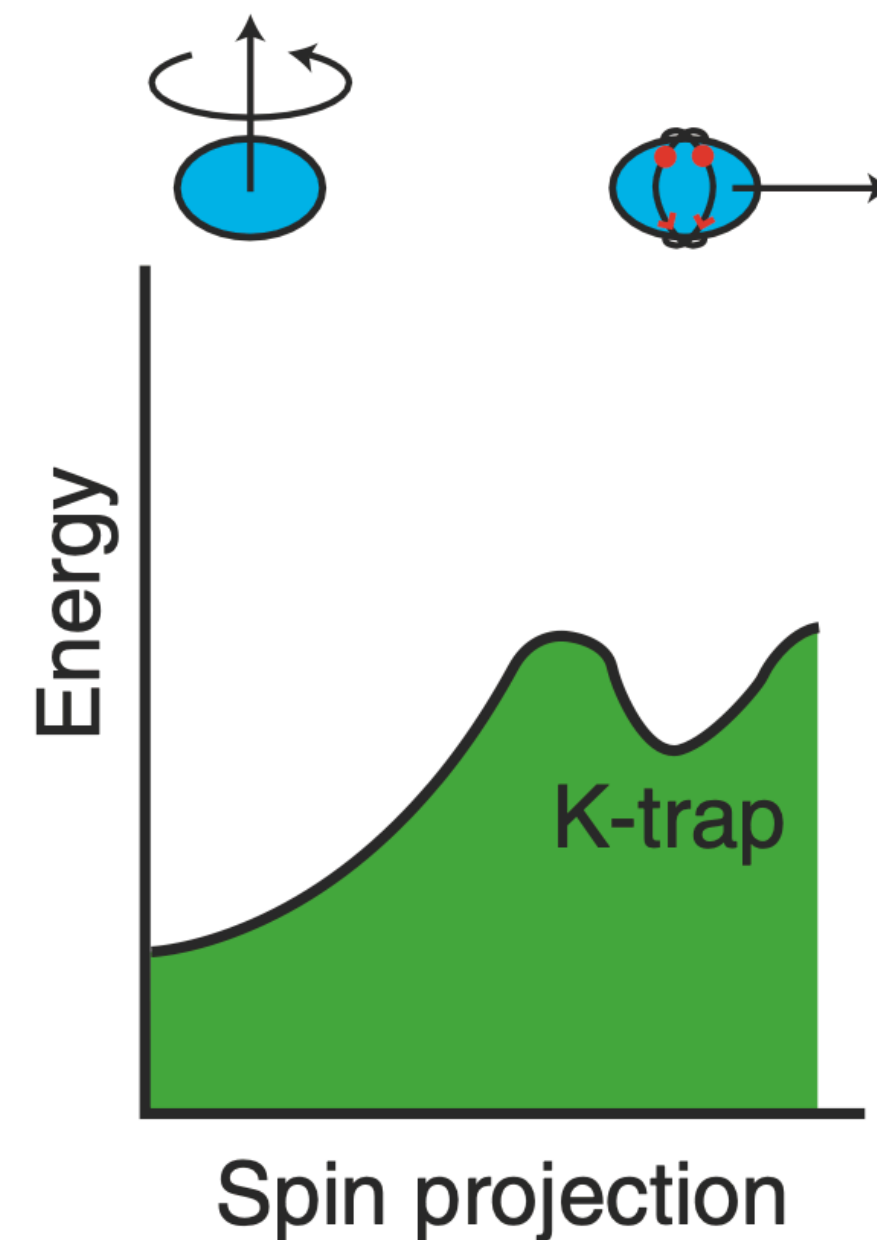
Analysis of decay chains and delayed spectroscopy

- Reconstruction of decay chains
- Delayed spectroscopy for Db, Lr, Md



Study of ^{256}Rf « high-K » isomers

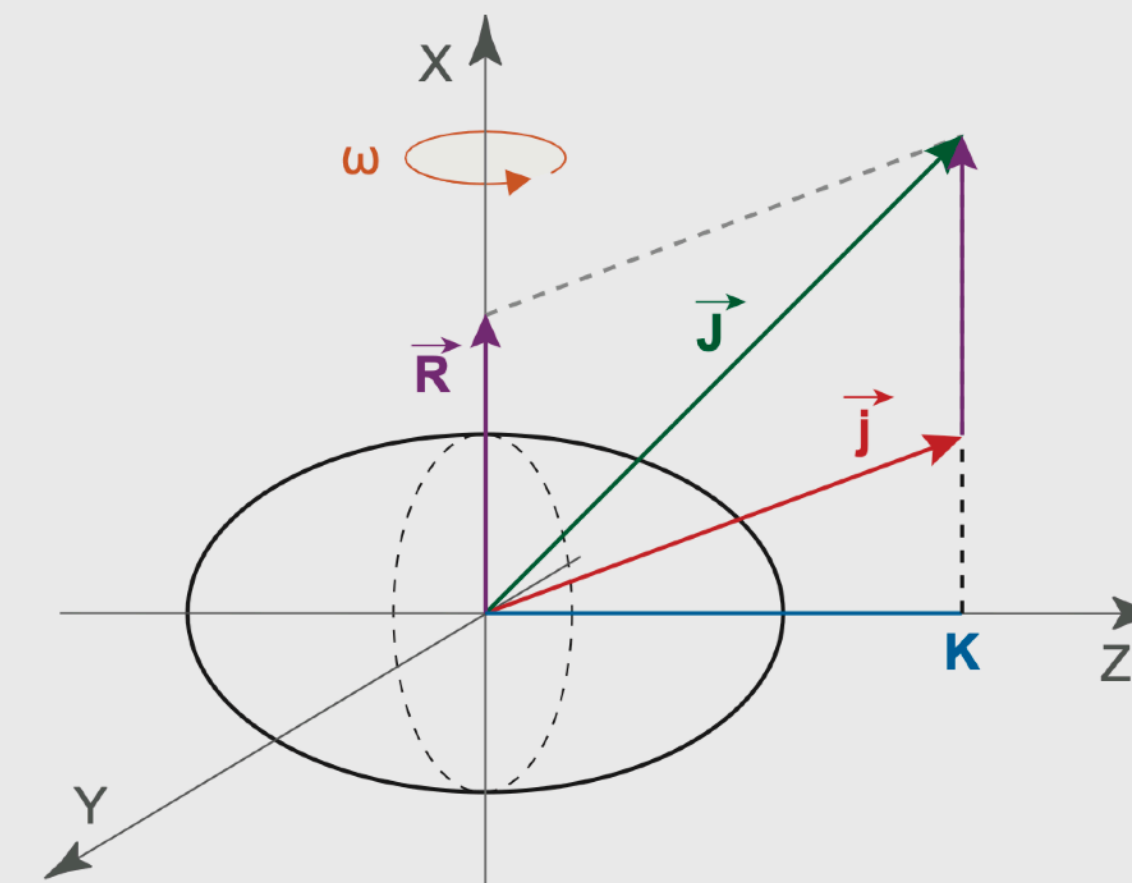
- Metastable excited state of a nucleus
 - SHE region → "high-K" isomers
- Useful to probe the quantum structure of the nucleus



P. Walker & G. Dracoulis, Nature,
1996

« high-K » isomers

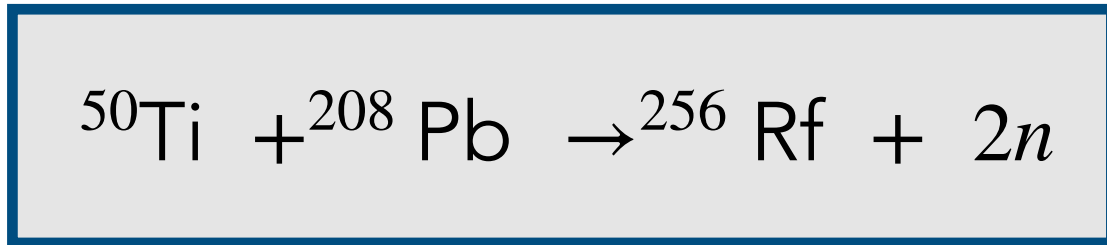
- K : Projection of the total angular momentum along the axis of deformation of the nucleus
- If $|\Delta K| > \lambda$ (Multipolarity of the transition), the transition is "forbidden" but possible decay by tunnel effect



Deformed nucleus with quantum numbers
 K, j, J

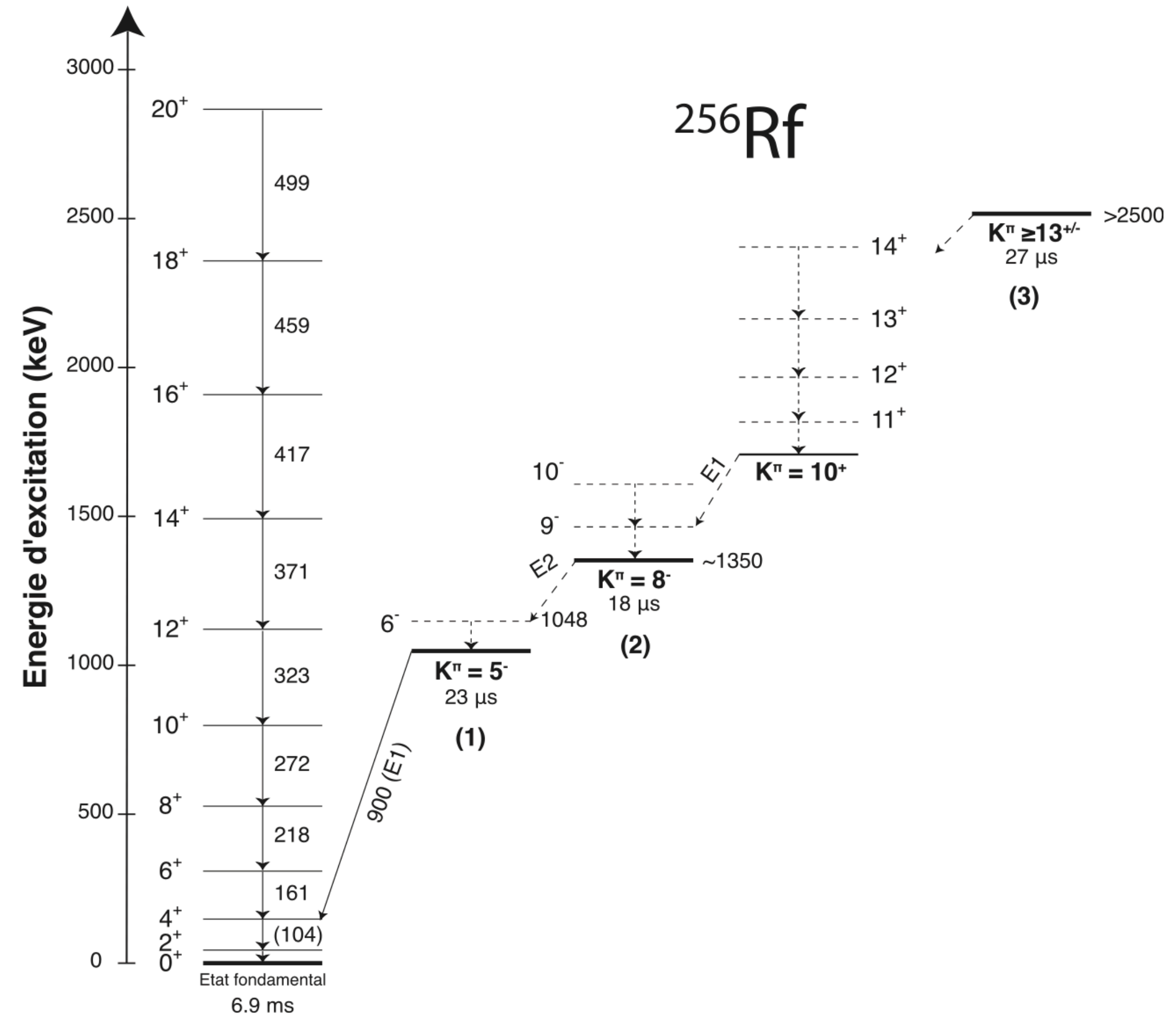
Study of ^{256}Rf « high-K » isomers

- Before 2011: several discordant delayed spectroscopy experiments
- 2011: experiments by IPHC and JYU physicists



↳ low cross-section = 17 nb

↳ Important statistics with S^3 separator and the SIRIUS detection system



J. Rubert, Thèse de l'Unistra (2013)

Study of ^{256}Rf « high-K » isomers

Experimental setup @ **GANIL**
laboratoire commun CEA/DRF **soiral2** CNRS/IN2P3

Université

de Strasbourg



LINAG

Super Separator Spectrometer S^3

- Separator + Spectrometer (1/350)
- High resolution mode and convergent mode
- Intense beam from LINAG

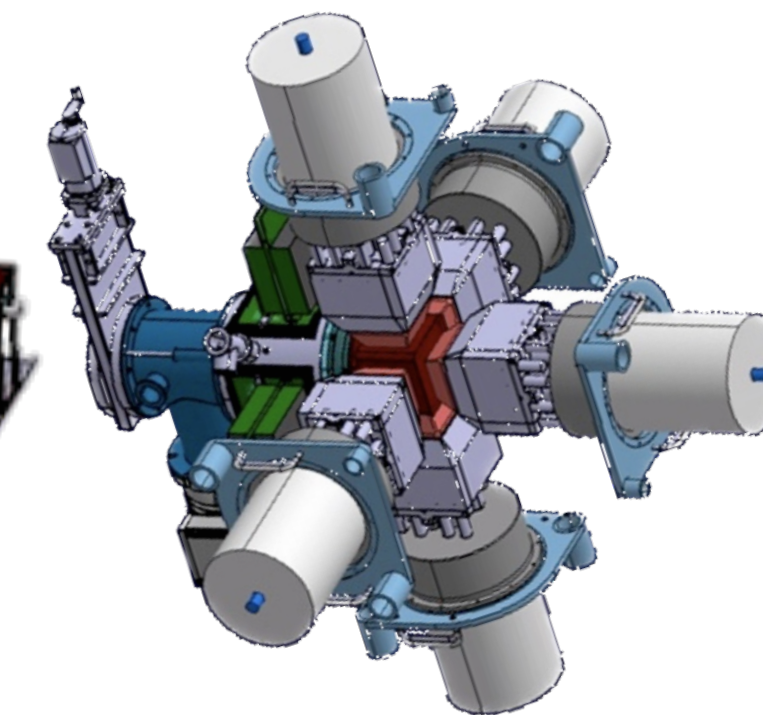
SIRIUS (Spectroscopy & Identification of Rare Isotopes Using S^3)

- Detection system placed at the focal plane:

Tracker (ToF) + DSSD (R, α, e^-) + pixelated Tunnel (α) + VETO + 5 germaniums Clover (γ)

S^3

SIRIUS

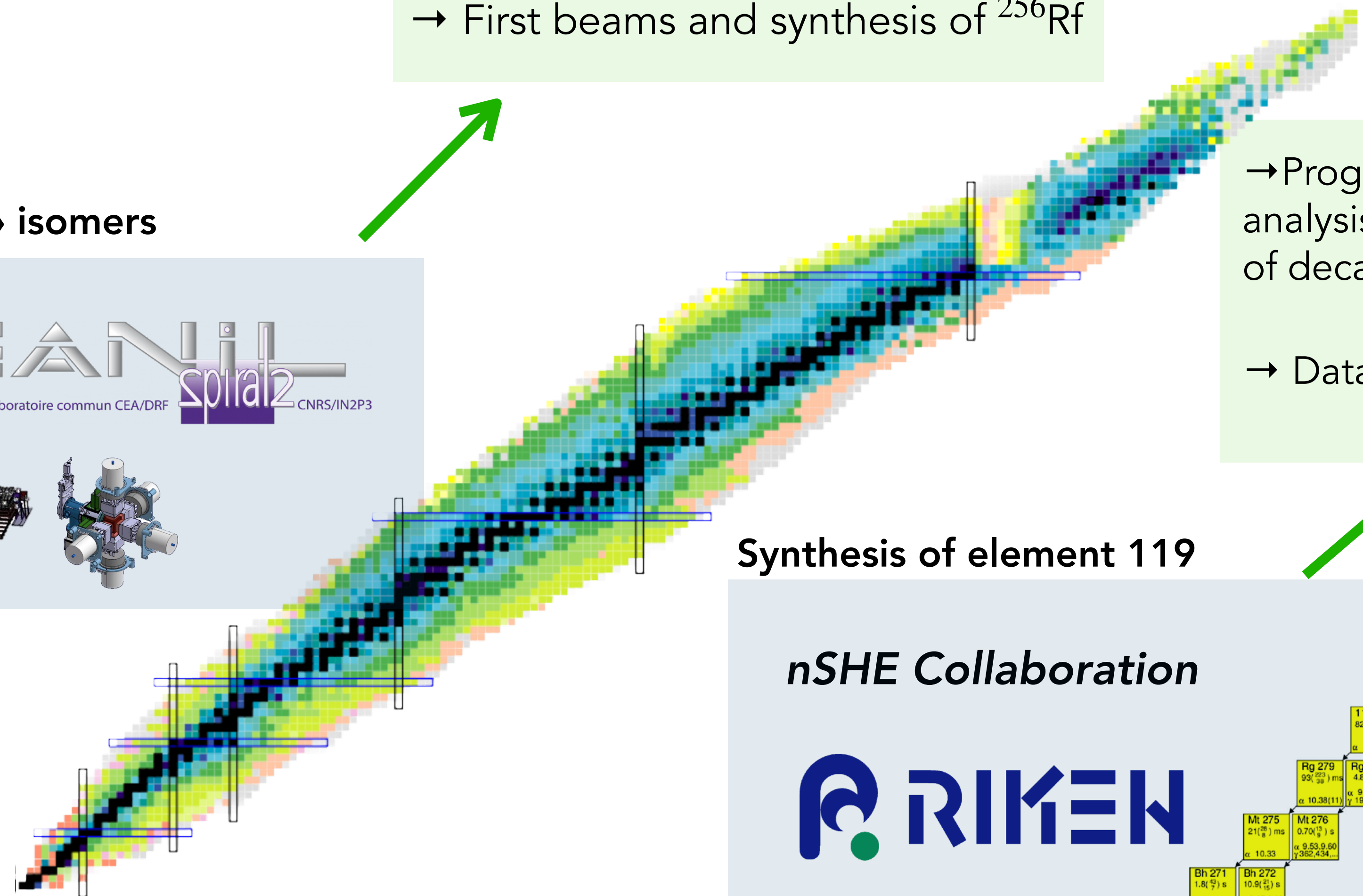


Conclusion

From internship to thesis ...

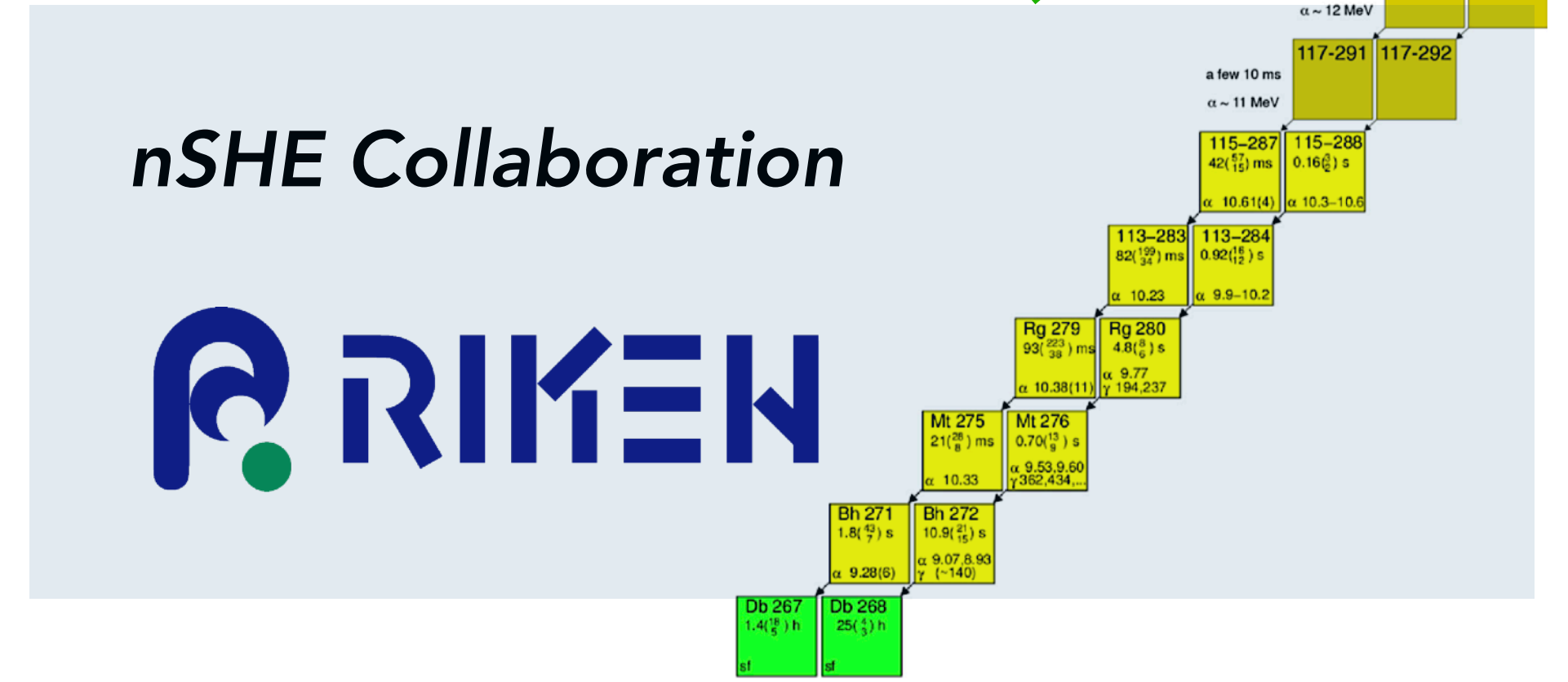
- Installation and testing of S³ and SIRIUS at GANIL, Caen
- First beams and synthesis of ²⁵⁶Rf

Study of ²⁵⁶Rf « high-K » isomers



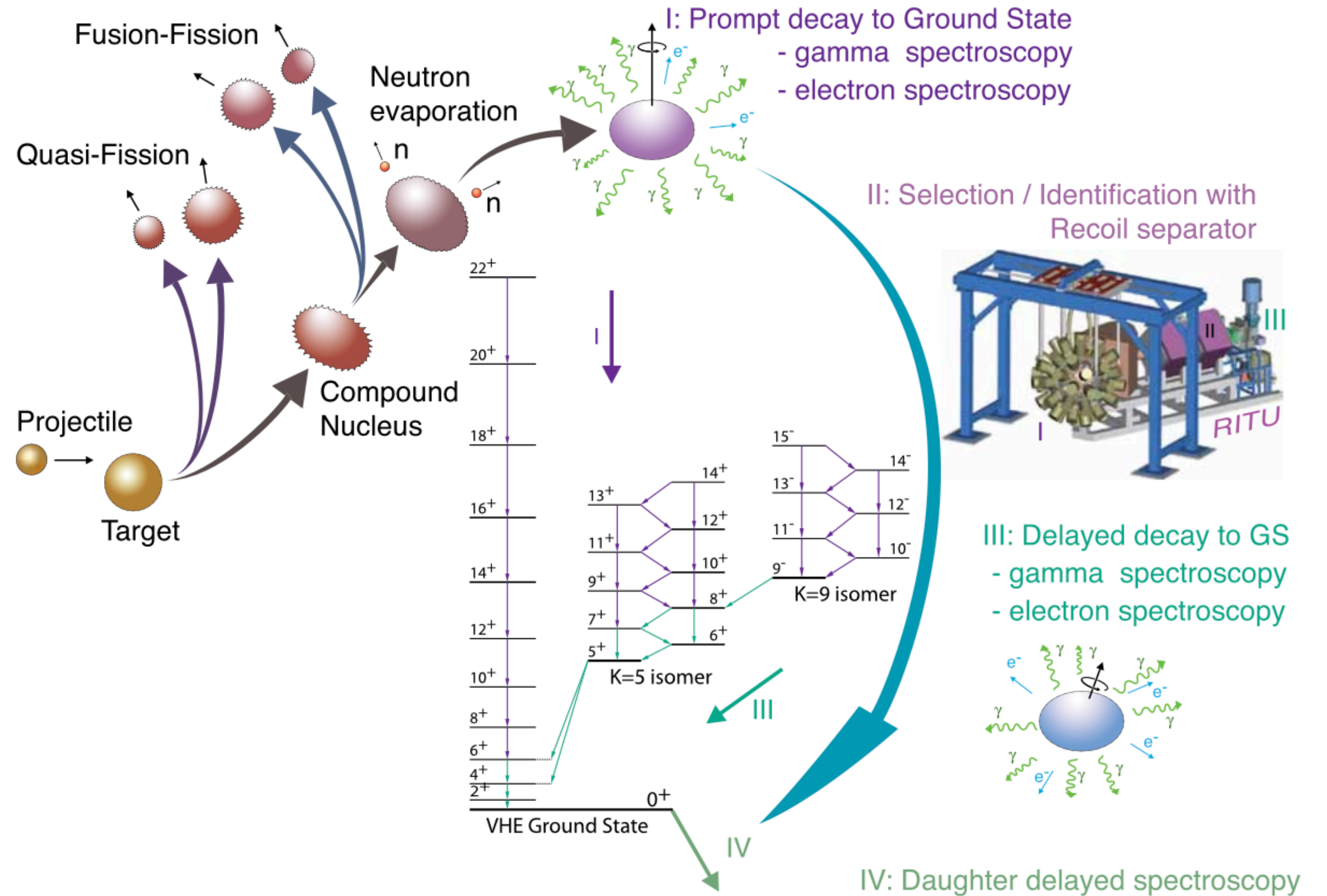
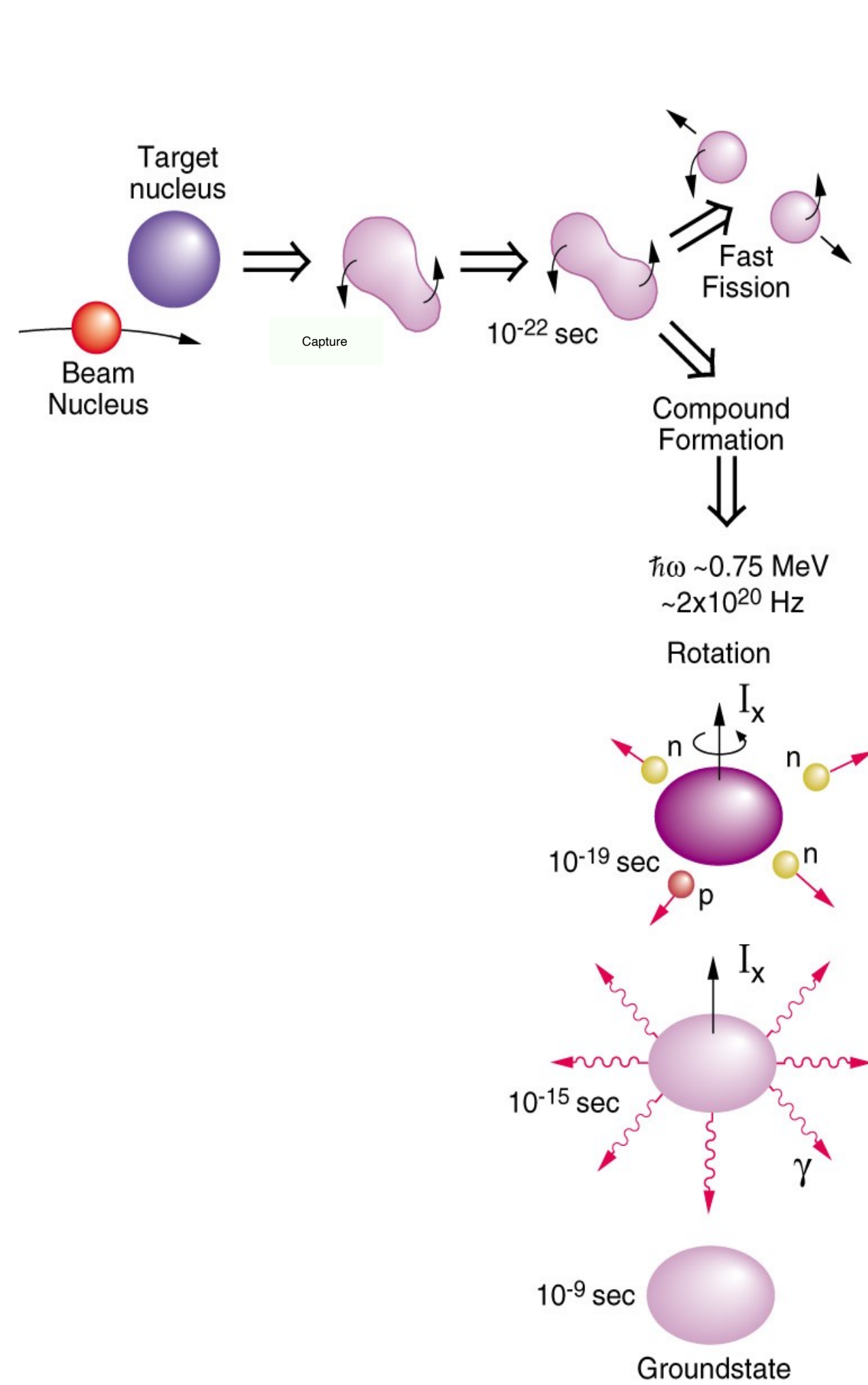
- Programming of the analysis code for the search of decay chains of the Z=119
- Data taking at RIKEN

Synthesis of element 119



Backup slides

Reaction mechanisms.



Deformed nuclei

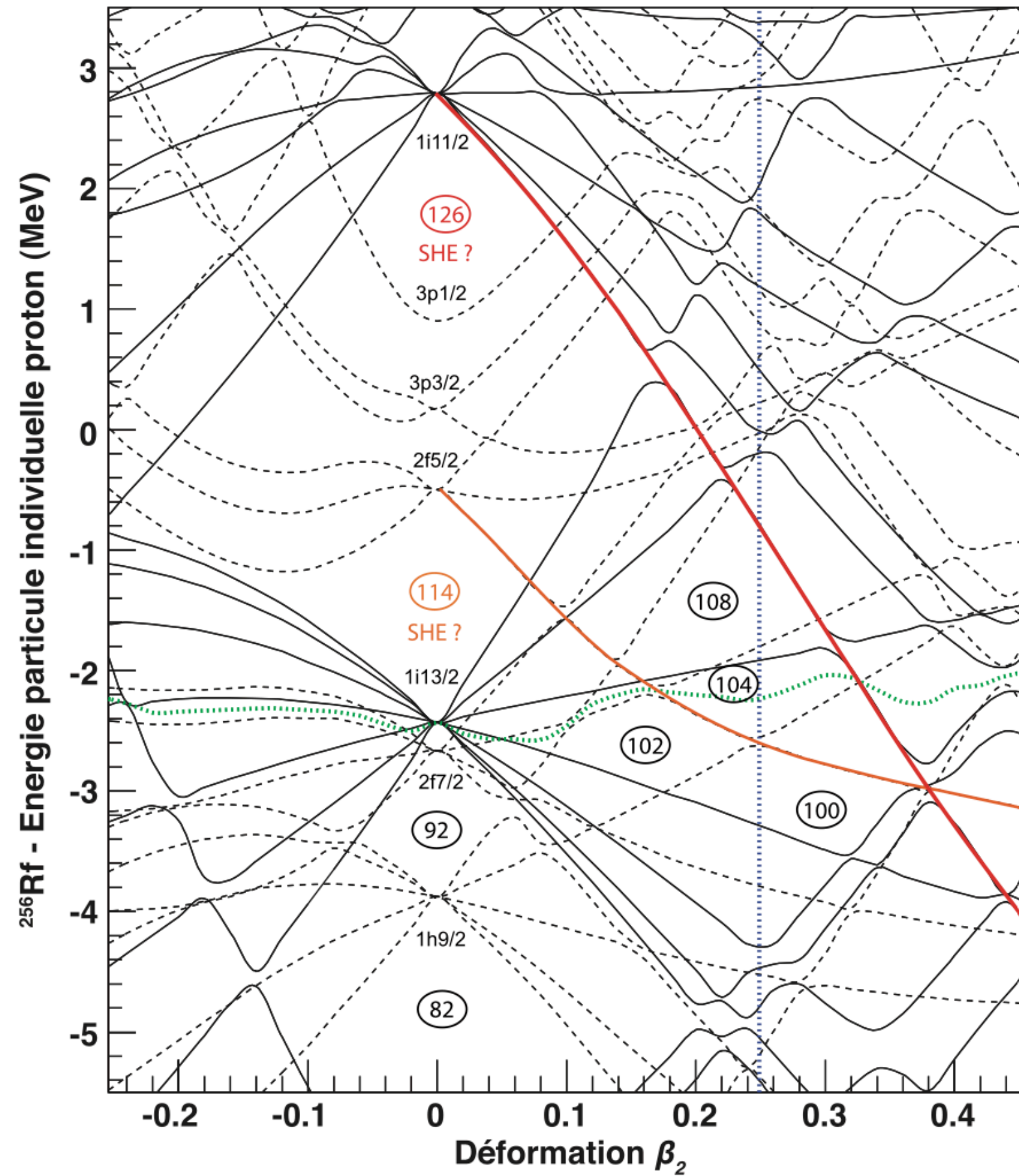


Figure 1.6: Schéma des orbitales des particules individuelles protons pour le noyau de ^{256}Rf en fonction du coefficient de déformation quadrupolaire β_2 . Il a été calculé grâce au modèle "Woods-Saxon Universal" [Rou13]. Des gaps candidats superlourds sont situés à $Z = 114$ et à $Z = 126$. Par l'action de la déformation, les orbitales fermant ces gaps sont rapprochées de la surface de Fermi des noyaux transférma.

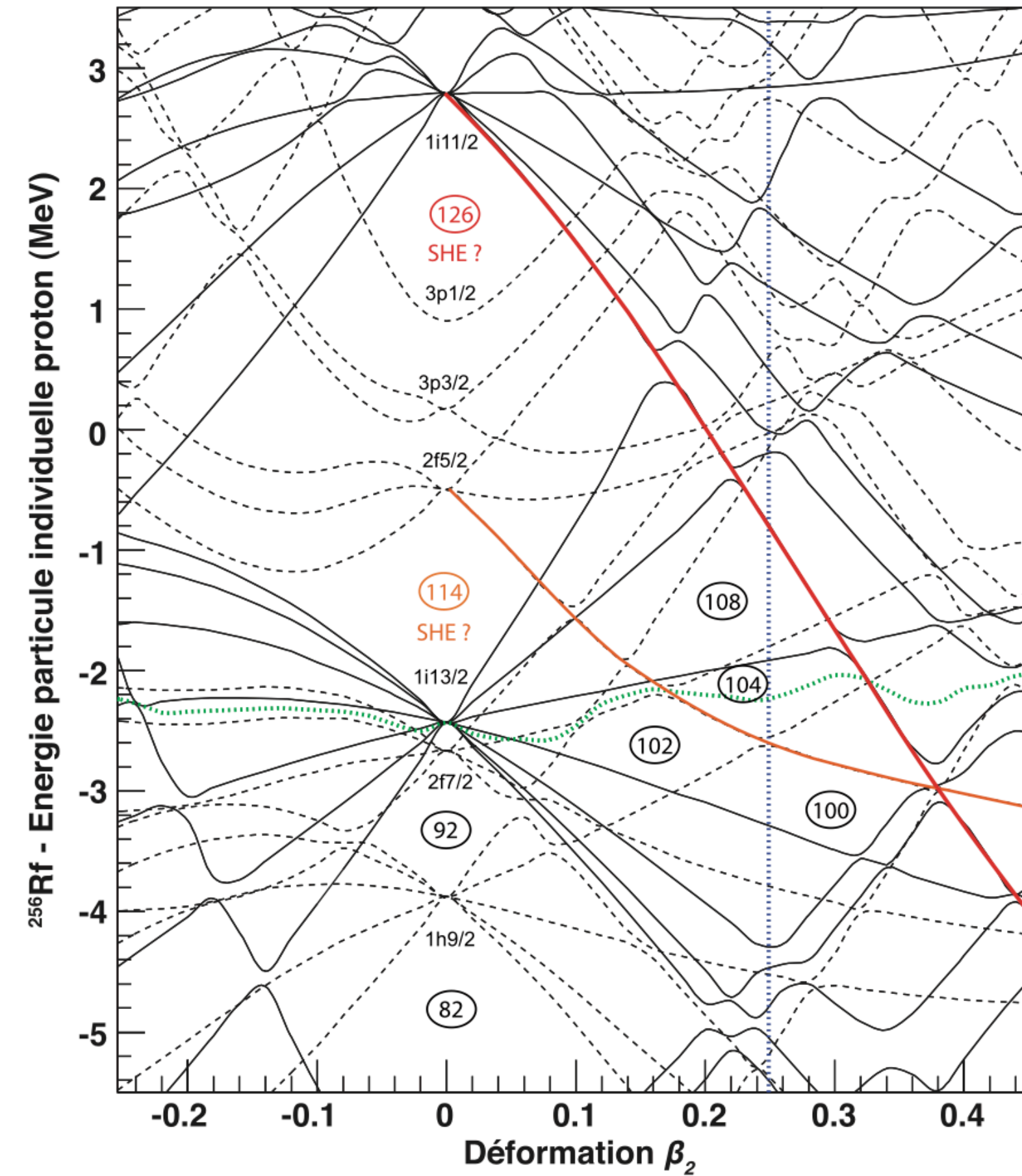
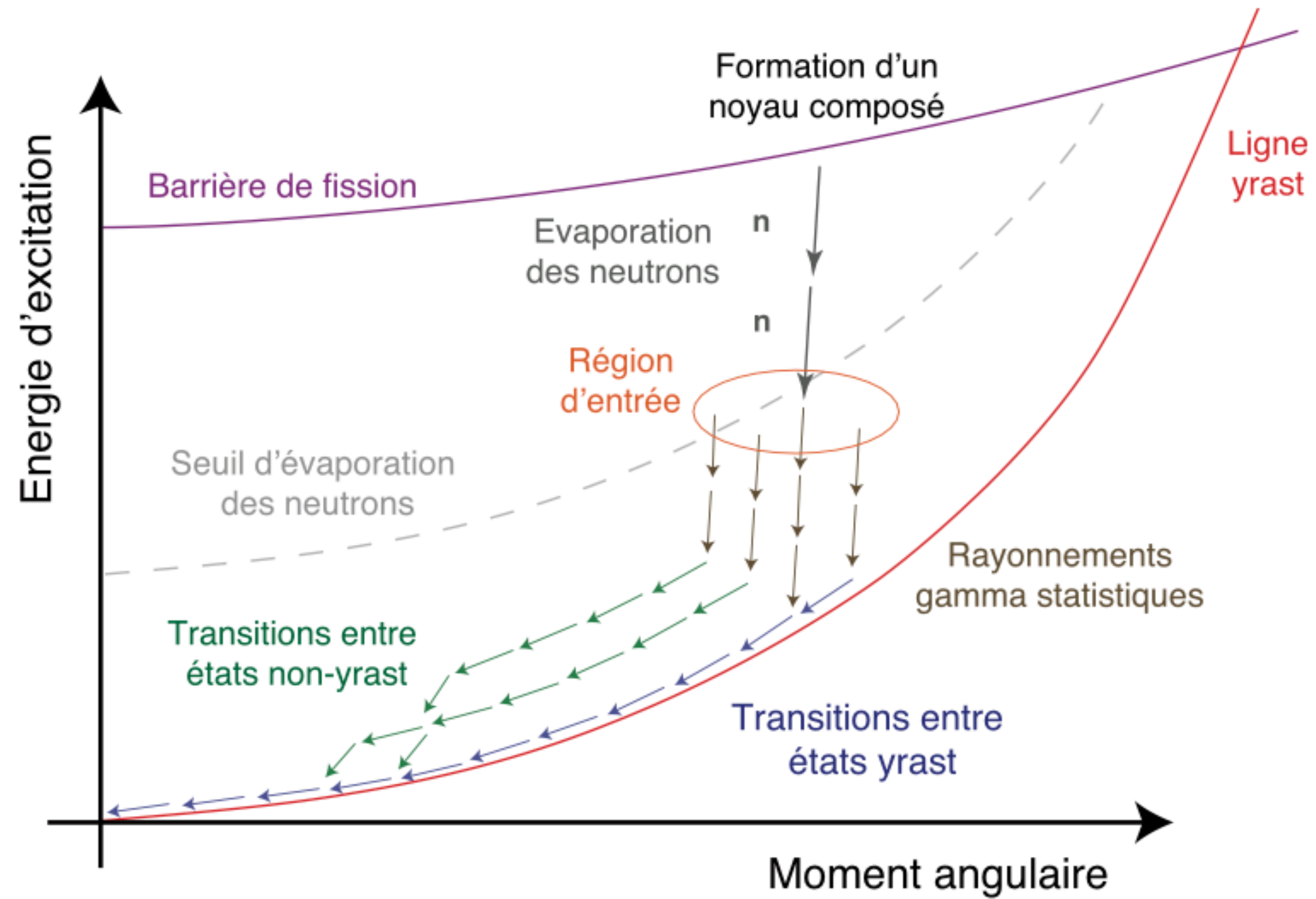
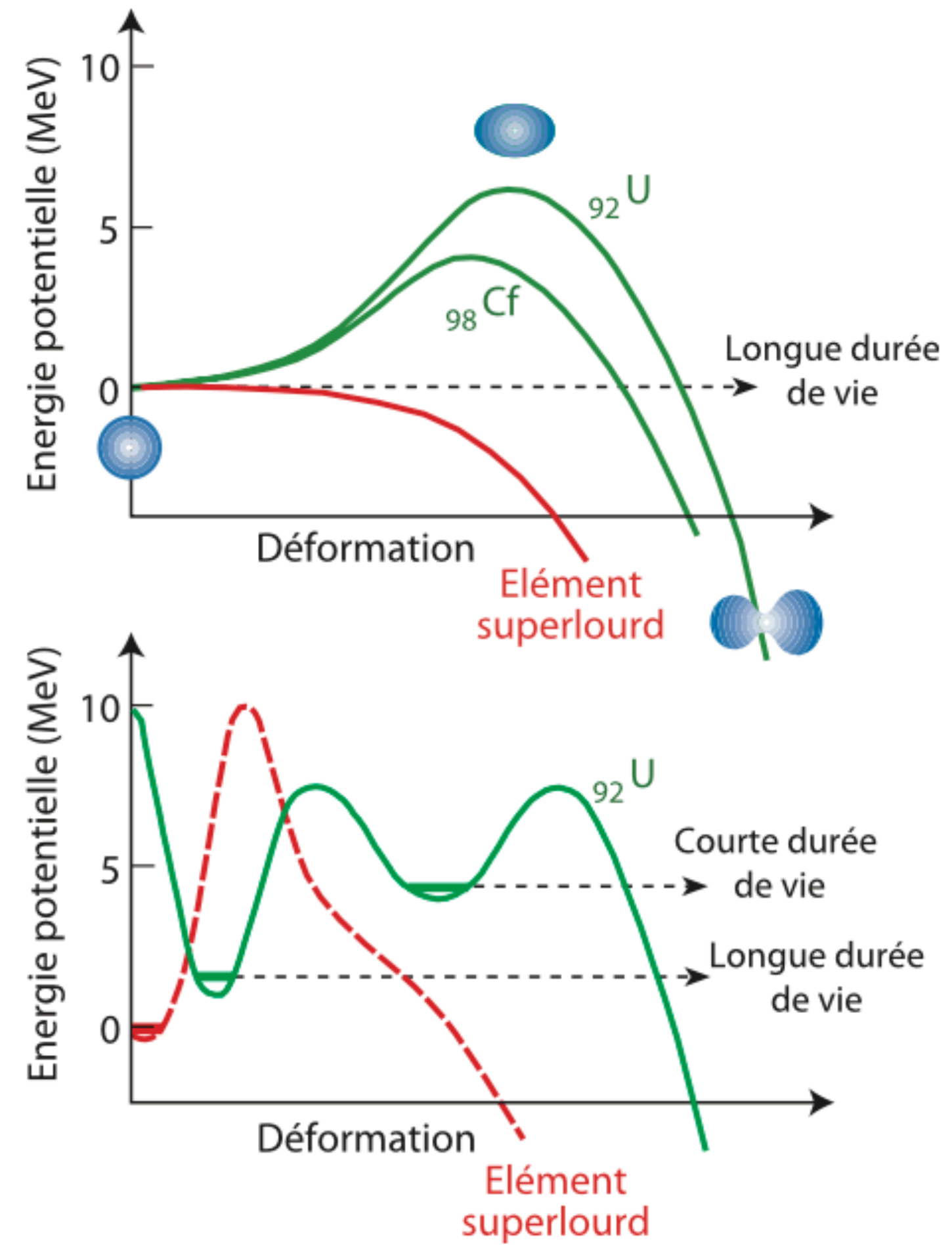


Figure 1.6: Schéma des orbitales des particules individuelles protons pour le noyau de ^{256}Rf en fonction du coefficient de déformation quadrupolaire β_2 . Il a été calculé grâce au modèle "Woods-Saxon Universal" [Rou13]. Des gaps candidats superlourds sont situés à $Z = 114$ et à $Z = 126$. Par l'action de la déformation, les orbitales fermant ces gaps sont rapprochées de la surface de Fermi des noyaux transférma.

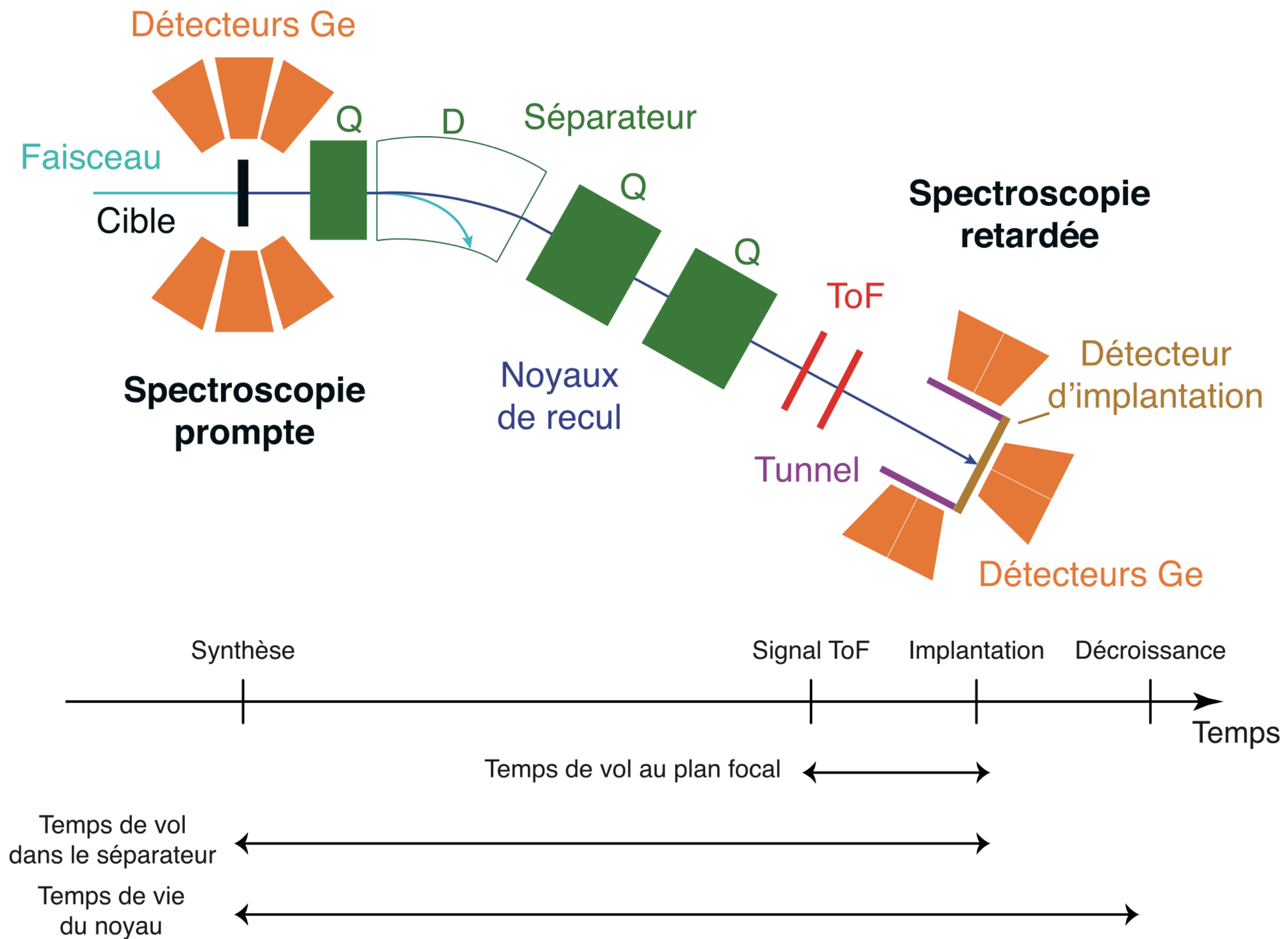
Desexcitation of a CN



Shell Model



prompte vs delayed Spectroscopy

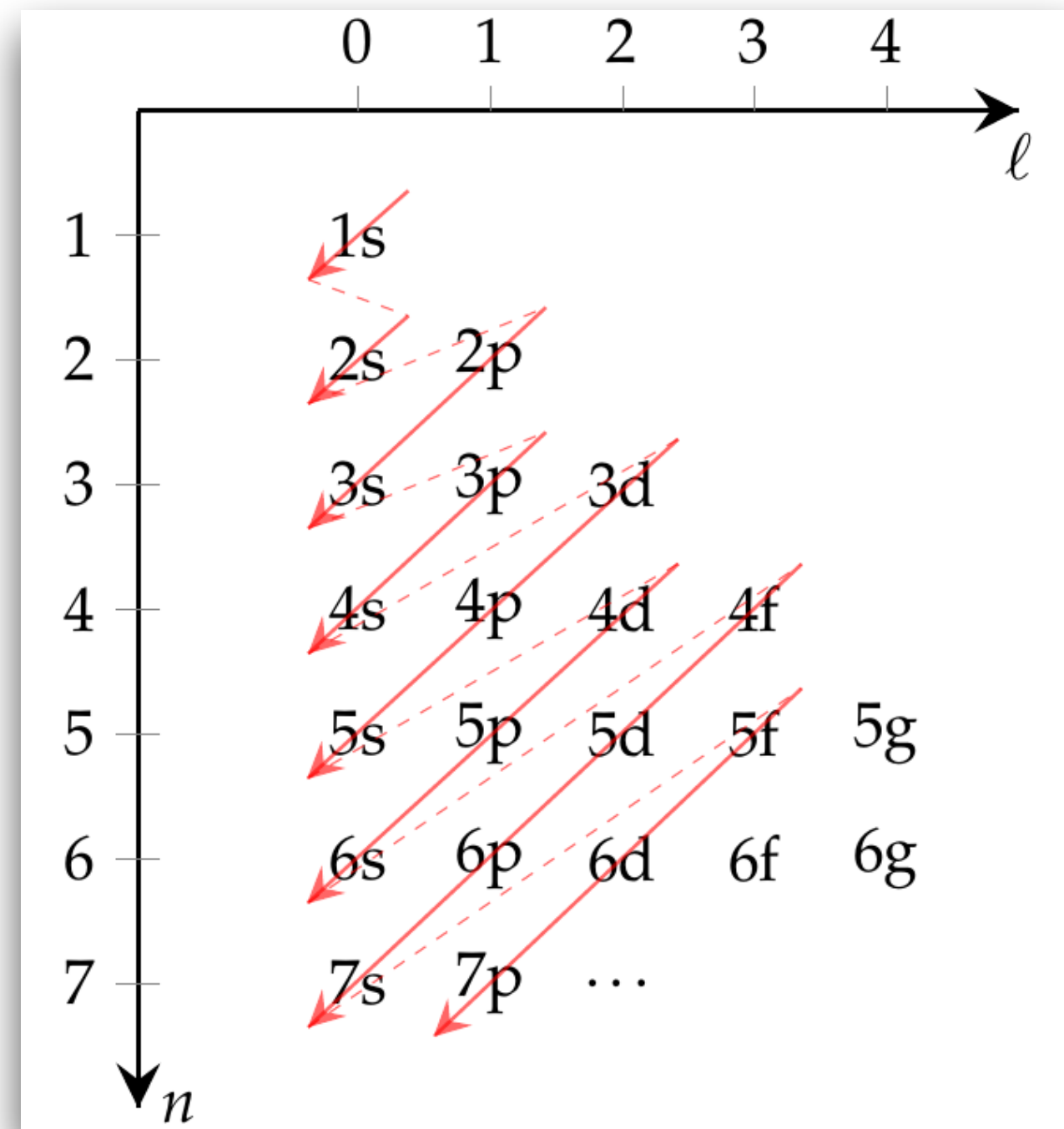


SHE elements

Table 1
Decay properties of nuclei.

	Z	N	A	No. observed ^a	Decay mode, branch (%) ^{b,c}	Half-life ^c	E_α (MeV)	Q_α^{exp} (MeV)	Refs.
Og	118	176	294	d:4	α	$0.69^{+0.64}_{-0.22}$ ms	11.66 ± 0.06	11.82 ± 0.06	[71,73,74]
Ts	117	177	294	d:3, t:2	α	51^{+38}_{-16} ms	10.81–11.07	11.18 ± 0.04	[74,86–89]
		176	293	d:15	α	22^{+8}_{-4} ms	10.60–11.20	11.32 ± 0.05	[74,86–88]
Lv	116	177	293	d:4, s:1	α	57^{+43}_{-17} ms	10.56 ± 0.02	10.71 ± 0.02	[68–70,72]
		176	292	d:5, s:4	α	13^{+7}_{-4} ms	10.63 ± 0.02	10.78 ± 0.02	[70,72]
		175	291	d:3, s:1	α	19^{+17}_{-6} ms	10.74 ± 0.07	10.89 ± 0.07	[49,71,72]
		174	290	d:11	α	$8.3^{+3.5}_{-1.9}$ ms	10.85 ± 0.07	11.00 ± 0.07	[49,71,73,74]
Mc	115	175	290	d:4, t:2	α	650^{+490}_{-200} ms	9.78–10.31	10.41 ± 0.04	[74,86–89]
		174	289	d:16	α	330^{+120}_{-80} ms	10.15–10.54	10.49 ± 0.05	[74,80,81,86–88]
		173	288	d:27, t:19	α	164^{+30}_{-21} ms	10.29–10.58	10.63 ± 0.01 ≈ 10.7 [83]	[75,76,80,81,83,84]
		172	287	d:2, t1	α	37^{+44}_{-13} ms	10.61 ± 0.05	10.76 ± 0.05	[75,76,81,83,84]
Fl	114	175	289	d:10, s:1, t:4, tc:1	α	$1.9^{+0.7}_{-0.4}$ s	9.84 ± 0.02 9.48 ± 0.08	9.98 ± 0.02	[45,48,49,62,65,68–70,72]
		174	288	d:17, s:4, t:11, ic:2, tc:1	α	$0.66^{+0.14}_{-0.10}$ s	9.93 ± 0.03	10.07 ± 0.03	[45,49,56,61,62,65,70,72]
		173	287	d:16, s:1, b:1, ic:1	α	$0.48^{+0.14}_{-0.09}$ s	10.03 ± 0.02	10.17 ± 0.02	[46,49,56,61,70–72]
		172	286	d:25, b:2	$\alpha: 60^{+10}_{-11}$	$0.12^{+0.04}_{-0.02}$ s	10.21 ± 0.04	10.35 ± 0.04	[46,47,49,56,70,71,73,74]
Nh	113	171	285	b:1	α	$0.13^{+0.60}_{-0.06}$ s			[47]
		165	278	d:3	α	2 ms	11.52 -		
		173	286	d:4, t:2	α	$9.5^{+6.3}_{-2.7}$ s	9.61–9.75	9.79 ± 0.05	[74,86–89]
		172	285	d:17	α	$4.2^{+1.4}_{-0.8}$ s	9.47–10.18	10.01 ± 0.04	[74,80,81,86–88]
		171	284	d:27, t:20	α	$0.91^{+0.17}_{-0.13}$ s	9.10–10.11	10.12 ± 0.01 ≈ 10.3 [83]	[75,76,80,81,83,88,84]
Cn	112	173	285	d:10, s:1, t:4, ic:1, tc:1	α	28^{+9}_{-6} s	9.19 ± 0.02	9.32 ± 0.02	[45,48,49,60,62,65,68–70,72]
		172	284	d:19, s:4, t:11, ic:2, tc:1	SF	98^{+20}_{-14} ms			[45,49,56,61,62,65,70,72]
		171	283	d:22, s:4, b:1, ic:6	$\alpha: \geq 93$	$4.2^{+1.1}_{-0.7}$ s	9.53 ± 0.02 9.33 ± 0.06 8.94 ± 0.07	9.66 ± 0.02	[46,49,56–59,61,63,70,71]

Relativistic effects



IUPAC Periodic Table of the Elements

1																		2																															
H hydrogen 1.008 [1.0078, 1.0082]																		He helium 4.0026																															
3			4															5		6		7		8		9		10		18																			
Li lithium 6.94 [6.938, 6.997]			Be beryllium 9.0122															B boron 10.81 [10.806, 10.821]		C carbon 12.011 [12.009, 12.012]		N nitrogen 14.007 [14.006, 14.008]		O oxygen 15.999 [15.999, 16.000]		F fluorine 18.998		Ne neon 20.180																					
11			12															13		14		15		16		17		18																					
Na sodium 22.990			Mg magnesium 24.305 [24.304, 24.307]															Al aluminium 26.982		Si silicon 28.085 [28.084, 28.086]		P phosphorus 30.974		S sulfur 32.06 [32.059, 32.076]		Cl chlorine 35.45 [35.446, 35.457]		Ar argon 39.95 [39.792, 39.963]																					
19			20															21		22		23		24		25		26		27		28		29		30		31		32		33		34		35		36	
K potassium 39.098			Ca calcium 40.078(4)															Sc scandium 44.956		Ti titanium 47.867		V vanadium 50.942		Cr chromium 51.996		Mn manganese 54.938		Fe iron 55.845(2)		Co cobalt 58.933		Ni nickel 58.693		Cu copper 63.546(3)		Zn zinc 65.38(2)		Ga gallium 69.723		Ge germanium 72.630(8)		As arsenic 74.922		Se selenium 78.971(8)		Br bromine 79.904 [79.901, 79.907]		Kr krypton 83.798(2)	
37			38			57-70 lanthanoids												39		40		41		42		43		44		45		46		47		48		49		50		51		52		53		54	
Rb rubidium 85.468			Sr strontium 87.62			lanthanoids												Y yttrium 88.906		Zr zirconium 91.224(2)		Nb niobium 92.906		Mo molybdenum 95.95		Tc technetium 101.07(2)		Ru ruthenium 101.07(2)		Rh rhodium 102.91		Pd palladium 106.42		Ag silver 107.87		Cd cadmium 112.41		In indium 114.82		Sn tin 118.71		Sb antimony 121.76		Te tellurium 127.60(3)		I iodine 126.90		Xe xenon 131.29	
55			56			89-102 actinoids												71		72		73		74		75		76		77		78		79		80		81		82		83		84		85		86	
Cs caesium 132.91			Ba barium 137.33			actinoids												Lu lutetium 174.97		Hf hafnium 178.49(2)		Ta tantalum 180.95		W tungsten 183.84		Re rhenium 186.21		Os osmium 190.23(3)		Ir iridium 192.22		Pt platinum 195.08		Au gold 196.97		Hg mercury 200.59		Tl thallium 204.38 [204.38, 204.39]		Pb lead 207.2		Bi bismuth 208.98		Po polonium		At astatine		Rn radon	
87			88			actinoids												103		104		105		106		107		108		109		110		111		112		113		114		115		116		117		118	
Fr francium			Ra radium			actinoids												Lr lawrencium		Rf rutherfordium		Db dubnium		Sg seaborgium		Bh bohrium		Hs hassium		Mt meitnerium		Ds darmstadtium		Rg roentgenium		Cn copernicium		Nh nihonium		Fl flerovium		Mc moscovium		Lv livermorium		Ts tennessine		Og oganesson	
119			120			119												119		120		121		122		123		124		125		126		127		128		129		130		131		132					
uun			ubn			ubu												La lanthanum 138.91		Ce cerium 140.12		Pr praseodymium 140.91		Nd neodymium 144.24		Pm promethium		Sm samarium 150.36(2)		Eu europium 151.96		Gd gadolinium 157.25(3)		Tb terbium 158.93		Dy dysprosium 162.50		Ho holmium 164.93		Er erbium 167.26		Tm thulium 168.93		Yb ytterbium 173.05					
89			90			91		92		93		94		95		96		97		98		99		100		101		102																					
Ac actinium			Th thorium 232.04			Pa protactinium 231.04		U uranium 238.03		Np neptunium		Pu plutonium		Am americium		Cm curium		Bk berkelium		Cf californium		Es einsteinium		Fm fermium		Md mendelevium		No nobelium																					

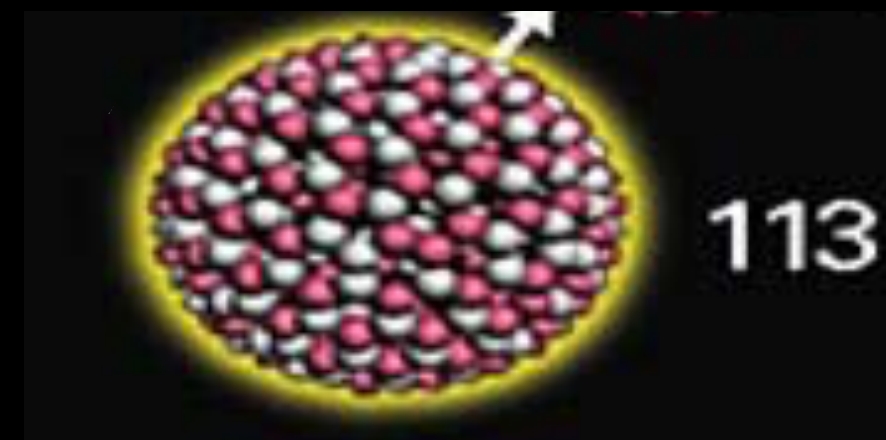
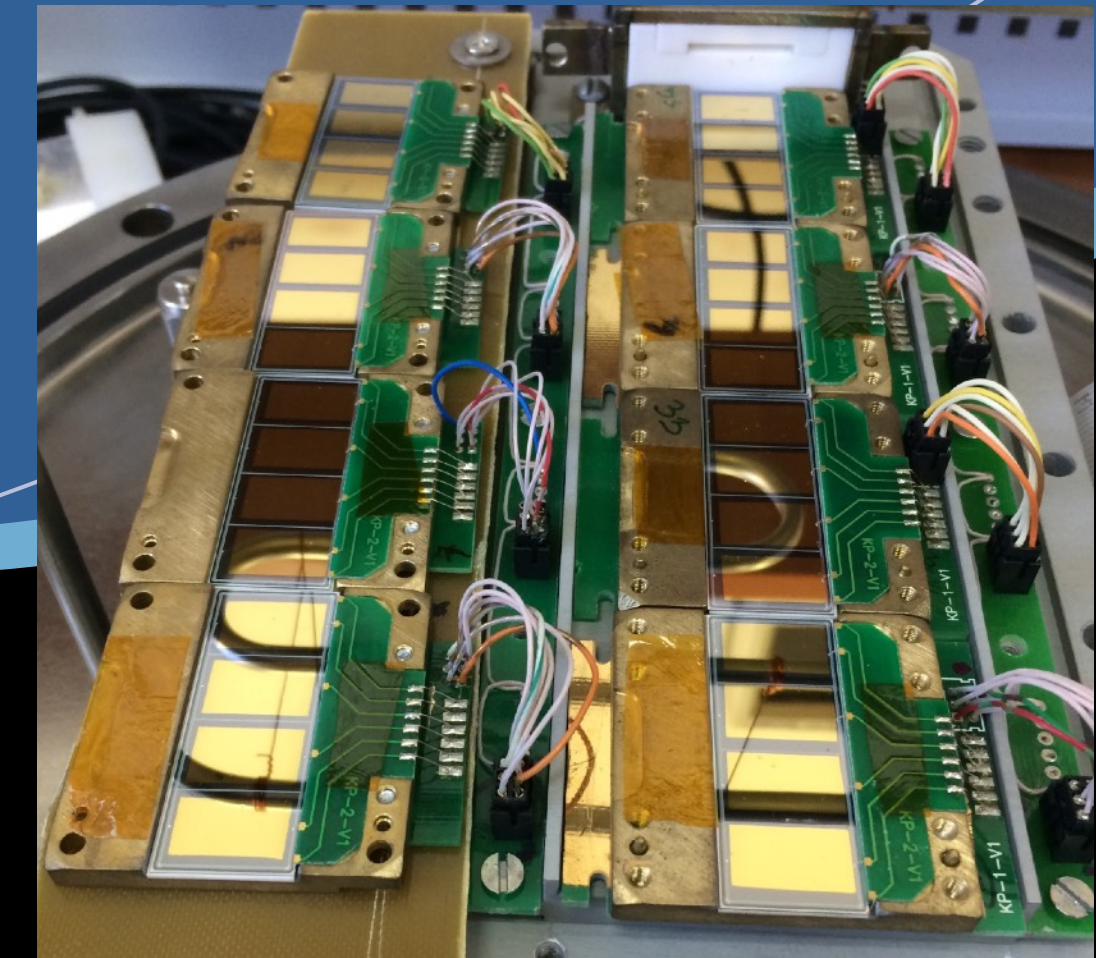
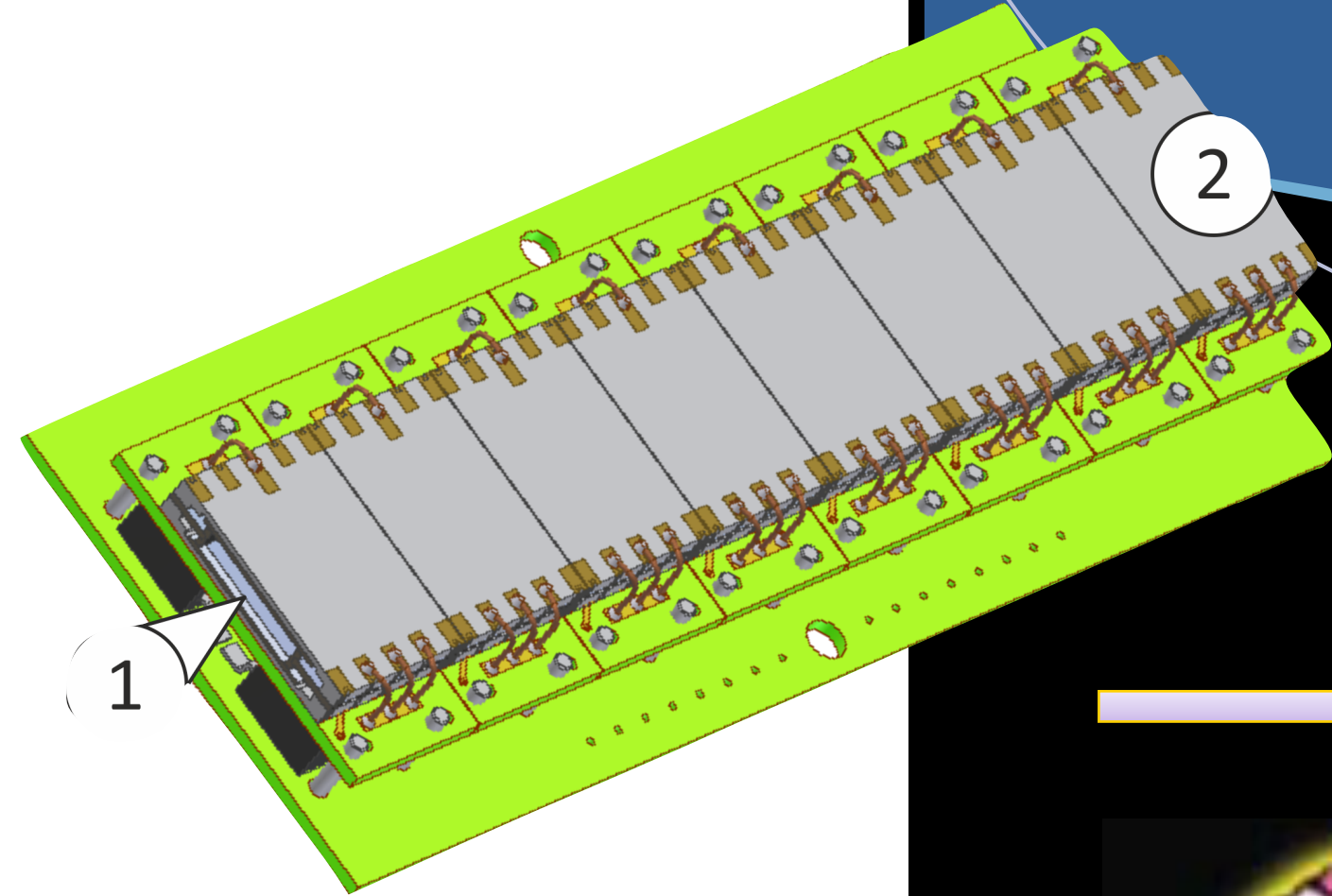
Key:
atomic number
Symbol
name
conventional atomic weight
standard atomic weight

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Chimie des SHE

Mesure de volatilité



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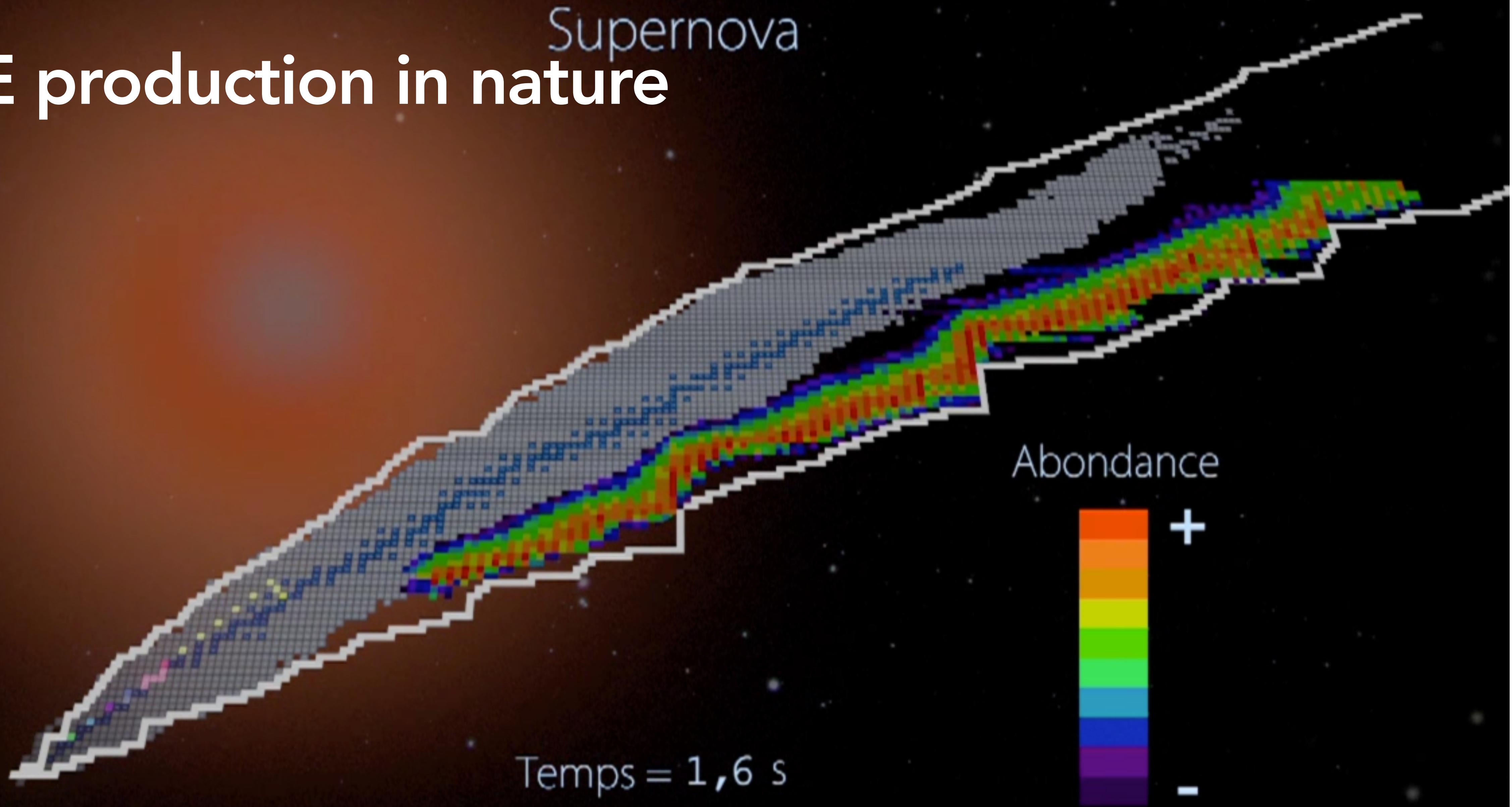
T- Δ T

T-2 Δ T

T-3 Δ T

à l'échelle de l'atome

SHE production in nature



Measurement of target like particle through GARIS I

In order to study the nucleus–nucleus interactions for syntheses of superheavy nuclei, we measured excitation functions for the quasielastic scattering of $^{48}\text{Ca}+^{208}\text{Pb}$, $^{50}\text{Ti}+^{208}\text{Pb}$, and $^{48}\text{Ca}+^{248}\text{Cm}$ using the gas-filled-type recoil ion separator GARIS. The quasielastic scattering events were clearly separated from deep-inelastic events by using GARIS and its focal plan detectors, except for high-incident-energy points. The quasielastic barrier distributions were successfully extracted

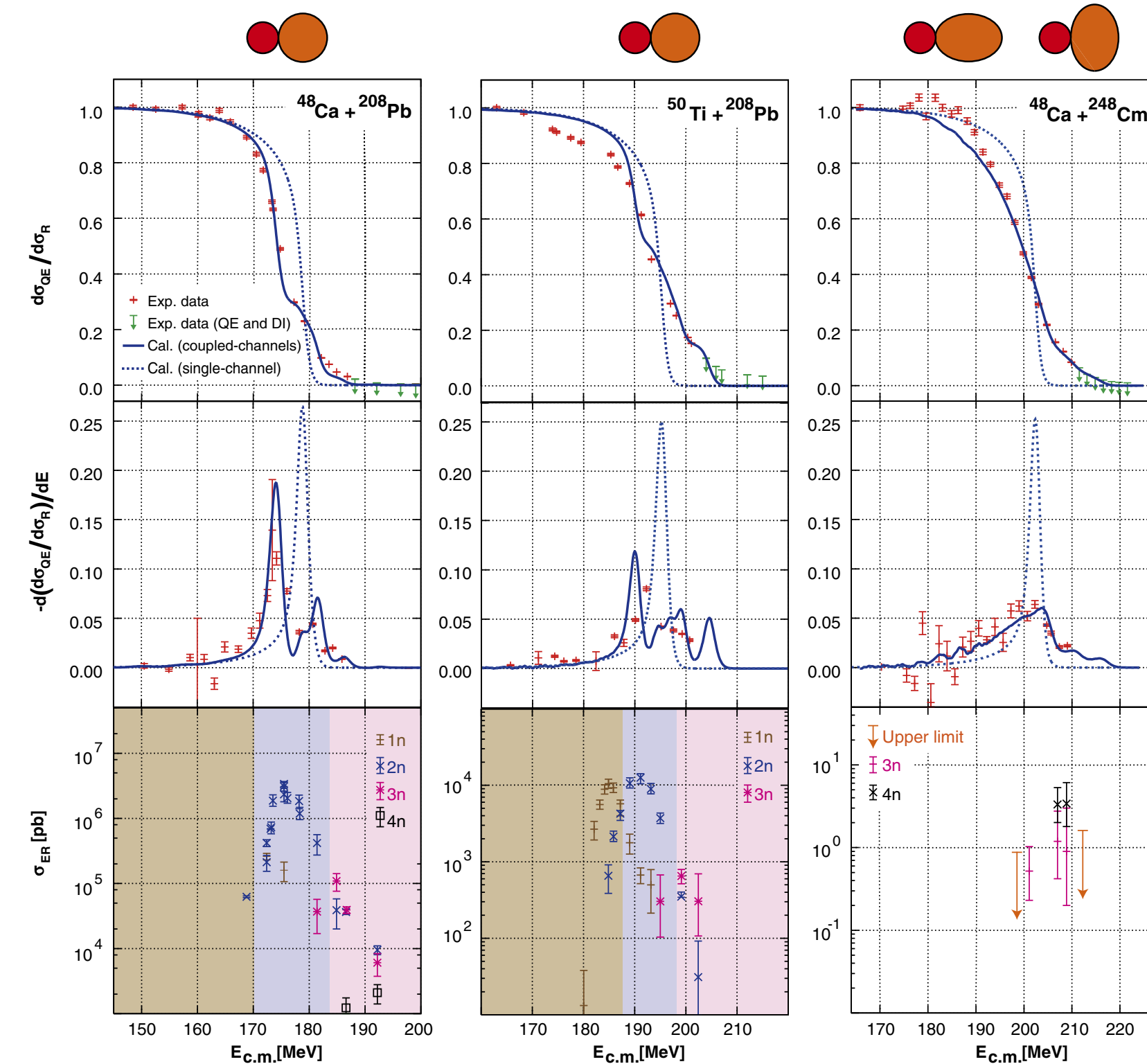
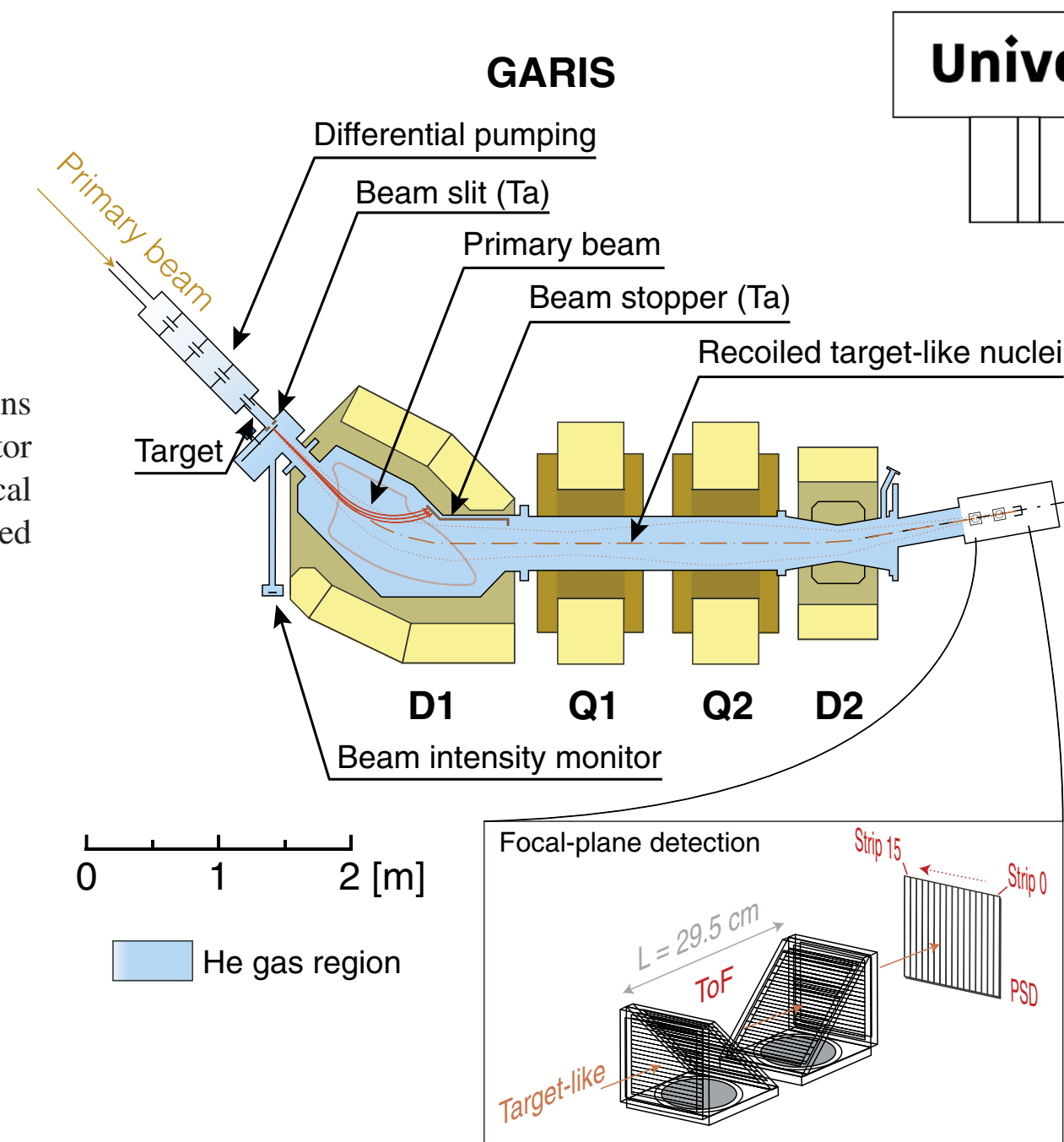


Fig. 7. (Color online) Measured excitation function for the QE scattering cross section relative to the Rutherford cross section (top panels). Left, middle, and right panels are for the $^{48}\text{Ca}+^{208}\text{Pb}$, $^{50}\text{Ti}+^{208}\text{Pb}$, and $^{48}\text{Ca}+^{248}\text{Cm}$ systems, respectively. The corresponding QE barrier distribution (middle panels) and the evaporation residue cross sections reported at different center-of-mass energies from the syntheses of No, Rf, and Lv evaporation residues^{15,16,38–40} (lower panels) are also shown. Red symbols indicate the experimental data from this work, for which the error bars include only the statistical uncertainty. Green symbols indicate the experimental data of mixed QE and DI events. These data points provide an upper limit for $d\sigma_{QE}/d\sigma_R$ (see Sect. 2.3). Blue solid curves indicate the best fit of the coupled-channels calculation with the parameters shown in Table II. Blue dashed curves show the results of the single-channel calculations with the same internuclear potential as that used for the blue solid lines.

Fig. 1. (Color online) Schematics of GARIS and detectors. GARIS consists of a first dipole magnet (D1), followed by two quadrupole magnets (Q1) and (Q2), and a final dipole (D2) magnet. The lower figure shows the focal plane detector system composed of two ToF detectors and a 16-strip PSD.

One measures the barrier distribution and determine E_{cm} for side collision (=optimal bombarding energy for synthesis)

→ get optimal energy