Main radioactive processes

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DDEP workshop – 21 to 25 October 2024

1. General concepts

Radioactive decay

A spontaneous process during which the atomic nucleus undergoes transformation(s)

- Each radioactive decay is unambiguously characterized by several properties:
  - Half-life
  - Q-value
  - Emission of, at least, one particle with specific energy and probability distributions

- Two different types of physical processes
  - Involving the nucleus
  - Involving the atomic cloud

Current presentation subject

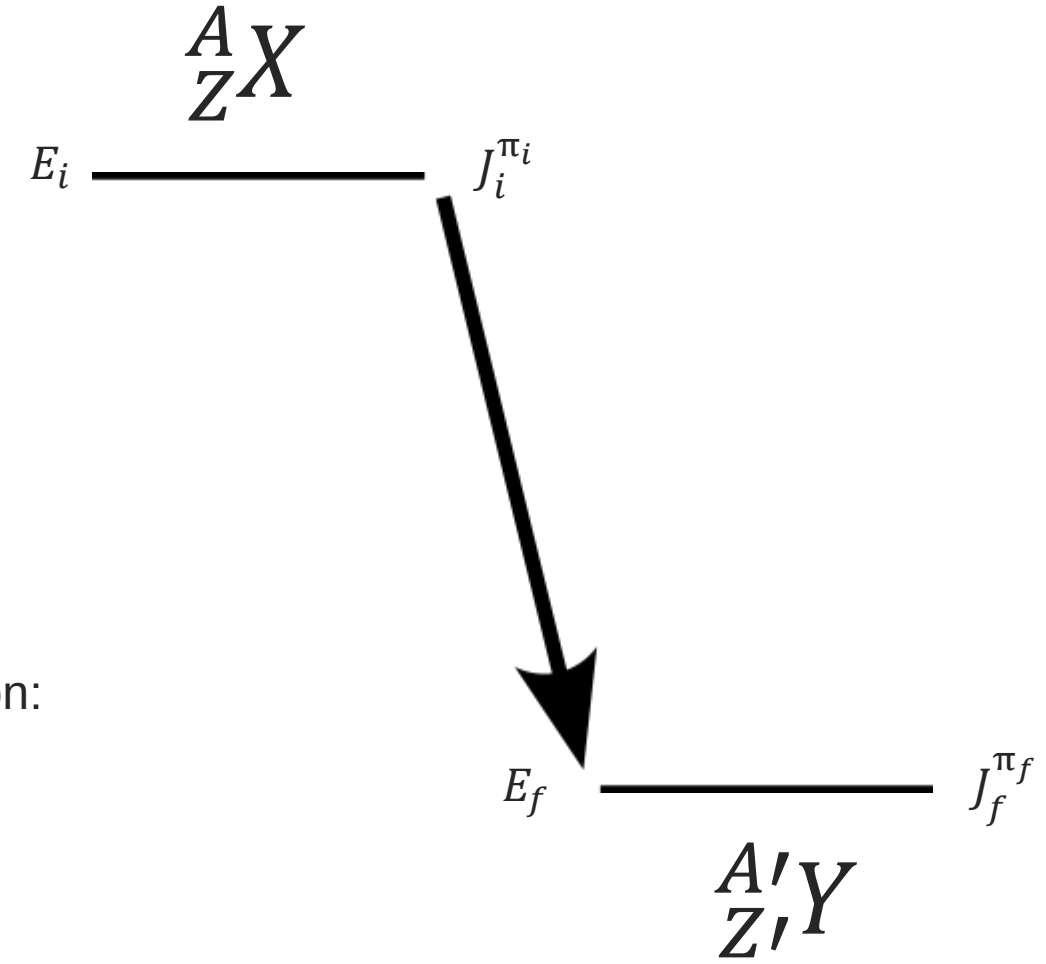
See Xavier’s presentation on atomic emissions

Notation about radioactive decay

A given decay transforms the nucleus

- From an initial state in the parent nucleus defined by
  - An excitation energy E_i
  - A spin-parity $J_i^{\pi_i}$
- From a final state in the daughter nucleus defined by
  - An excitation energy E_f
  - A spin-parity $J_f^{\pi_f}$

- The energy available for the decay (or Q-value) depends on:
  - The relative mass of the parent and daughter nuclei
  - The mass of the particles emitted during the decay
  - The excited energy of the parent and daughter nuclei



General concepts on radioactive decay

A given nucleus can decay

- Through different decay processes
- To different states in the daughter nucleus

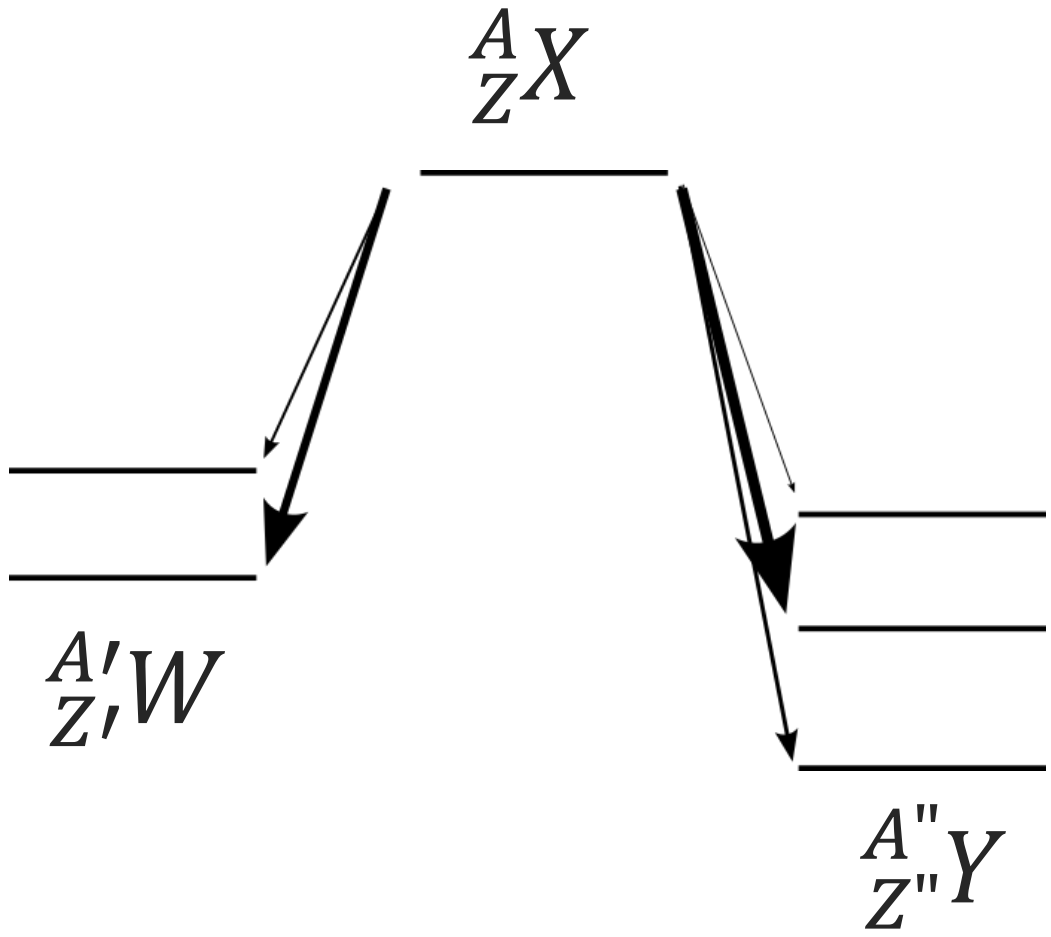
The relative probability of each transition strongly depends on the initial properties of the initial and final state

The sum of probabilities of all available transitions is equal to unity

$$\sum_j P_j = 1$$

The overall decay process occurs according the radioactive law

$$N = N_0\, e^{-\lambda t} \quad with\ \lambda = \frac{\log 2}{T_{1/2}}$$



2. Decay process overview

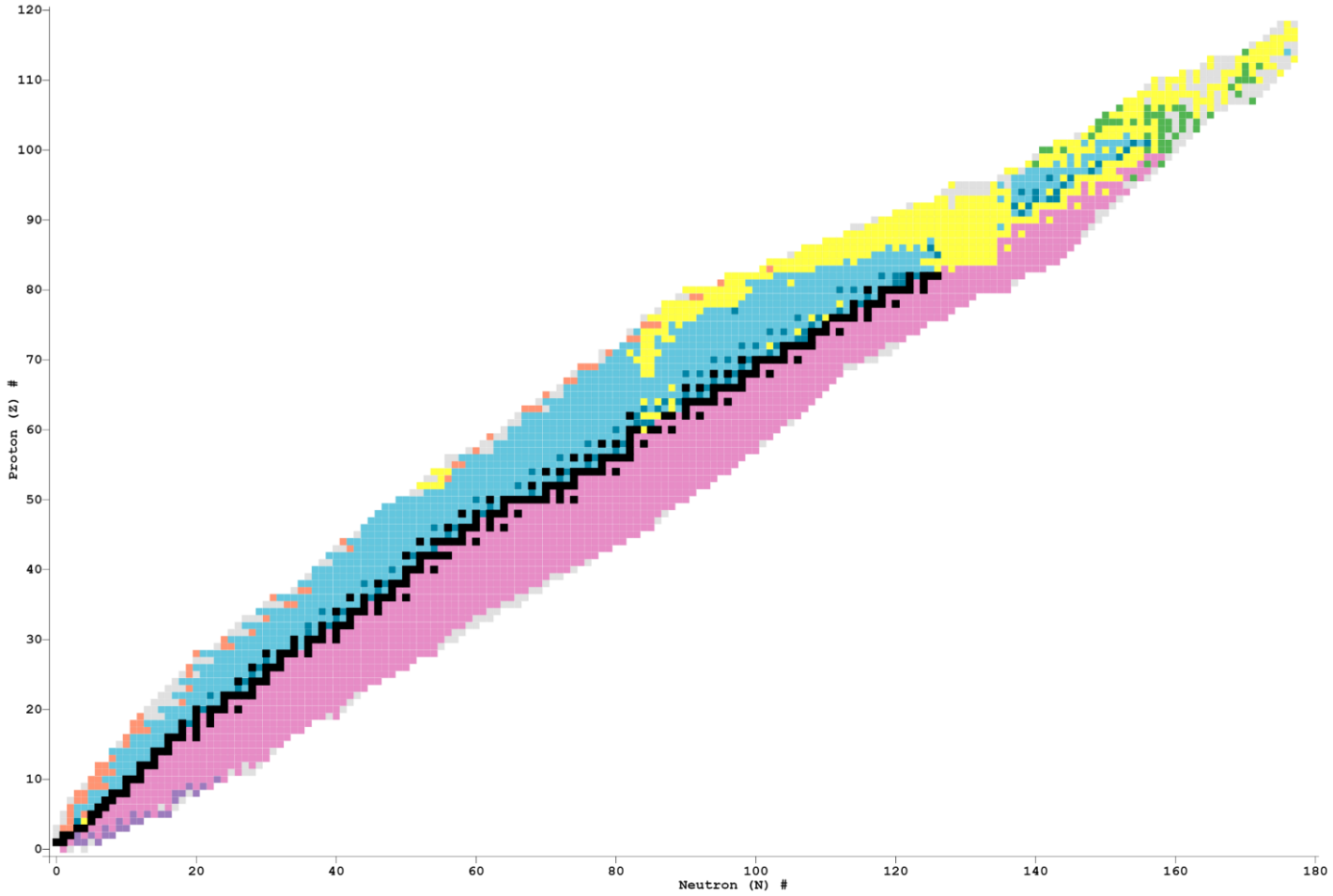
Overview of all decay processes

Main decay processes:

- β^- decay
- β^+ decay / Electron capture
- α decay
- Spontaneous fission

But also

- Neutron-decay
- Proton-decay
- β^-delayed neutron
- Induced fission



Overview of all decay processes

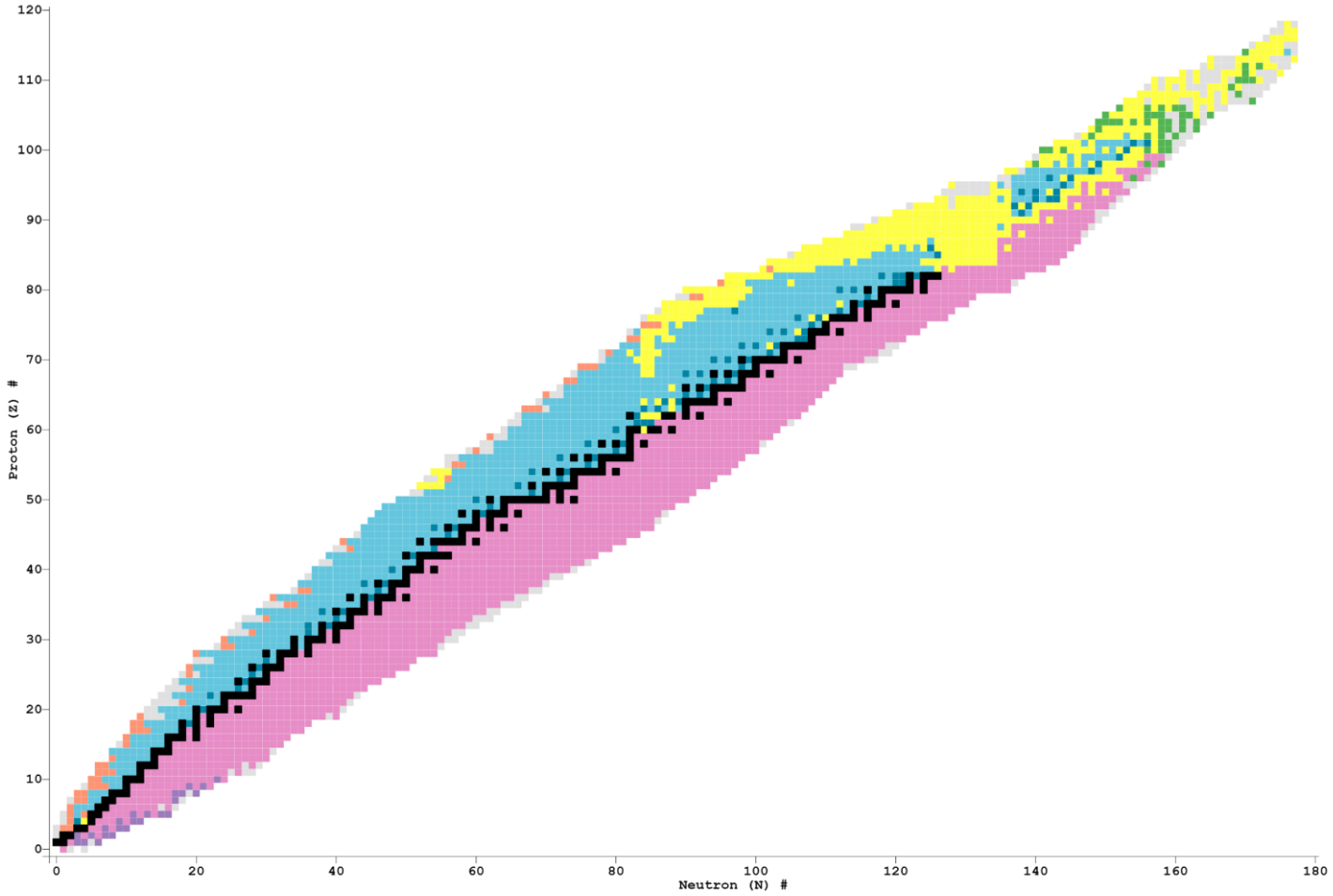
Main decay processes:

- β⁻ decay
- β⁺ decay / Electron capture
- α decay
- Spontaneous fission

But also

- N[illegible]n-d[illegible]
- Pr[illegible]
- β⁻d[illegible]tron
- I[illegible]d fi[illegible]

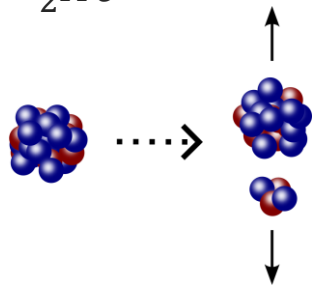
Not in the scope of DDEP



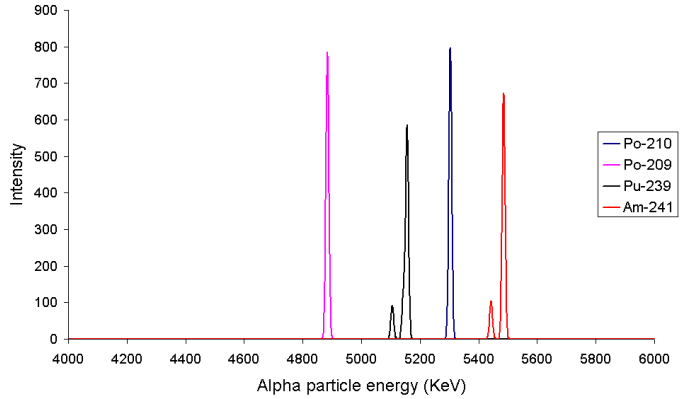
Alpha decay: decay process

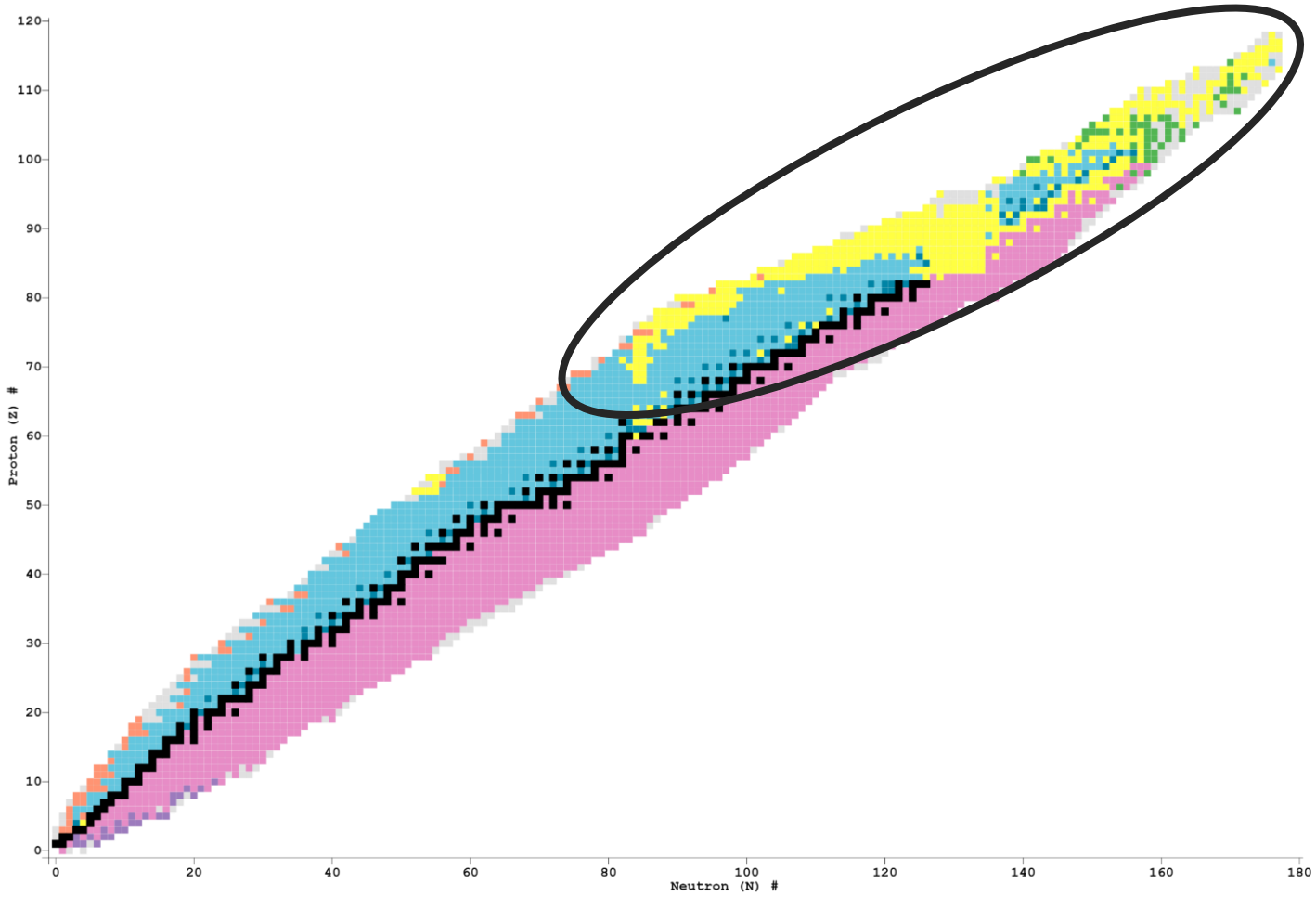
A two-body decay

- A process occurring mainly at Z > 82
- $^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$



- Energy of emitted particle is discrete





More on alpha spectrometry during Sylvie's presentation

Alpha decay: energy considerations

- Q value of the decay is express as

$$Q_\alpha = \left(m\left({}^{A}_{Z}X^*\right) - m\left({}^{A-4}_{Z-2}Y^*\right) - m\left({}^{4}_{2}He\right)\right)c^2$$

- The energy is spread between the two emitted particle

$$E_{{}^{4}_{2}He} = \frac{Q_\alpha}{\left(1 + \frac{m\left({}^{4}_{2}He\right)}{m\left({}^{A-4}_{Z-2}Y^*\right)}\right)} \qquad E_{{}^{A-4}_{Z-2}Y^*} = \frac{m\left({}^{4}_{2}He\right)}{m\left({}^{A-4}_{Z-2}Y^*\right)} E_{{}^{4}_{2}He}$$

- Emitted alpha energy is typically between 4 and 10 MeV

- The shorter is the half-life, the larger is the alpha energy

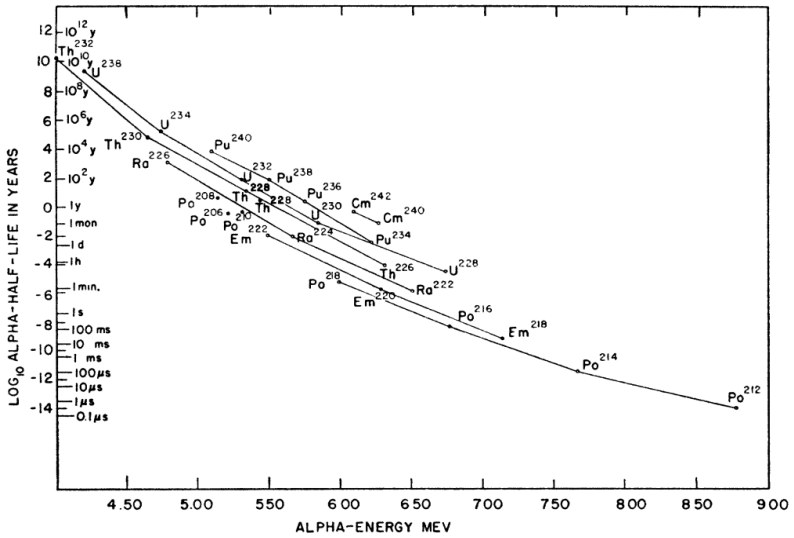
$^{241}_{95}\mathrm{Am}_{146}$

2.1 α Transitions

	Energy keV	Probability × 100
$\alpha_{0,36}$	4838,00 (13)	0,00004 (3)

4 α Emissions

	Energy keV	Probability × 100
$\alpha_{0,36}$	4757,58 (13)	0,00004 (3)



I. Perlman et al. Physical Review 75, 1096 (1949)

Alpha decay: Hindrance factor

- In case of alpha decay, it was shown that transitions between ground states of even-even nuclei follow the rule

$$\log(T_{1/2_i}) = A\, Q_{\alpha_i}{}^{1/2} + B$$

$$where\ A\ and\ B\ are\ free\ parameters\ ajusted\ and\ T_{1/2_i}\ is\ the\ partial\ half-life$$

- The hindrance factor F is defined as

$$F_i = \frac{\log(T_{1/2_i})_{exp}}{\log(T_{1/2_i})_{th}}$$

- Hindrance factor provides information on the nuclear structure of initial and final states

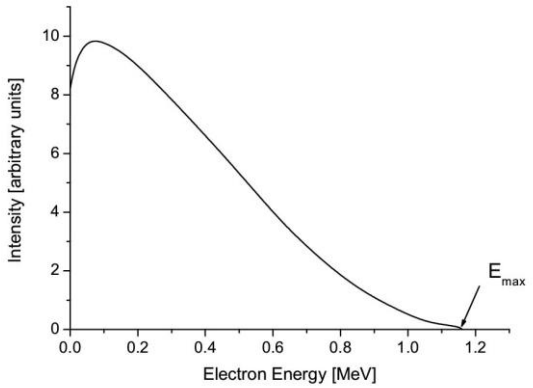
$^{214}_{84}\mathrm{Po}_{130}$

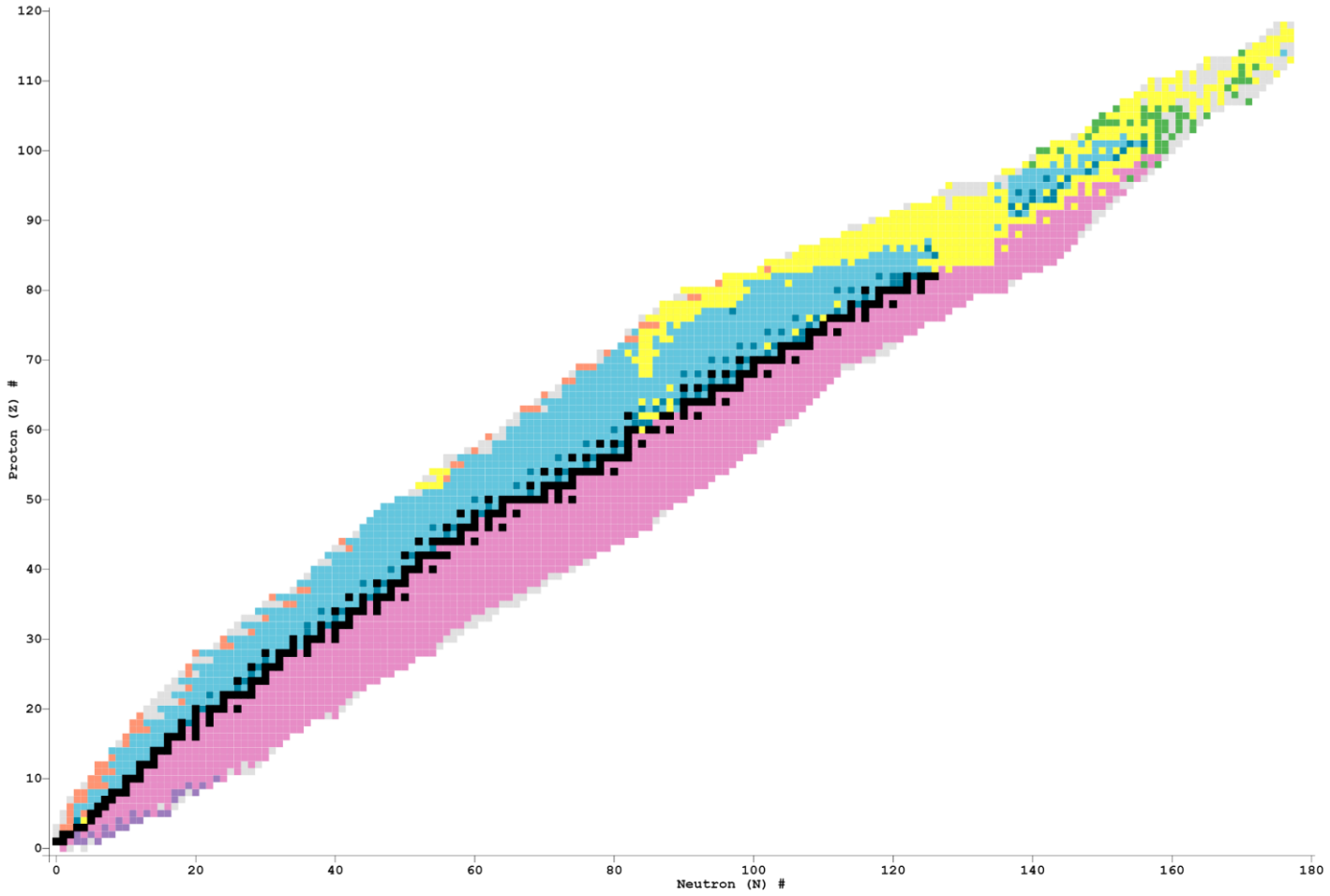
	Energy keV	Probability × 100	F	
$\alpha_{0,2}$	6735,8 (10)	0,000058 (2)	400	$0^+ \rightarrow 4^+$
$\alpha_{0,1}$	7033,76 (21)	0,0105 (7)	27	$0^+ \rightarrow 2^+$
$\alpha_{0,0}$	7833,46 (6)	99,9895 (7)	1	$0^+ \rightarrow 0^+$

Beta decay: decay process

A three-body decay

- For neutron deficient nuclei: β^+
  - ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \nu_e$
- For neutron rich nuclei: β^-
  - ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}_e$
- Energy of emitted particle is continuous





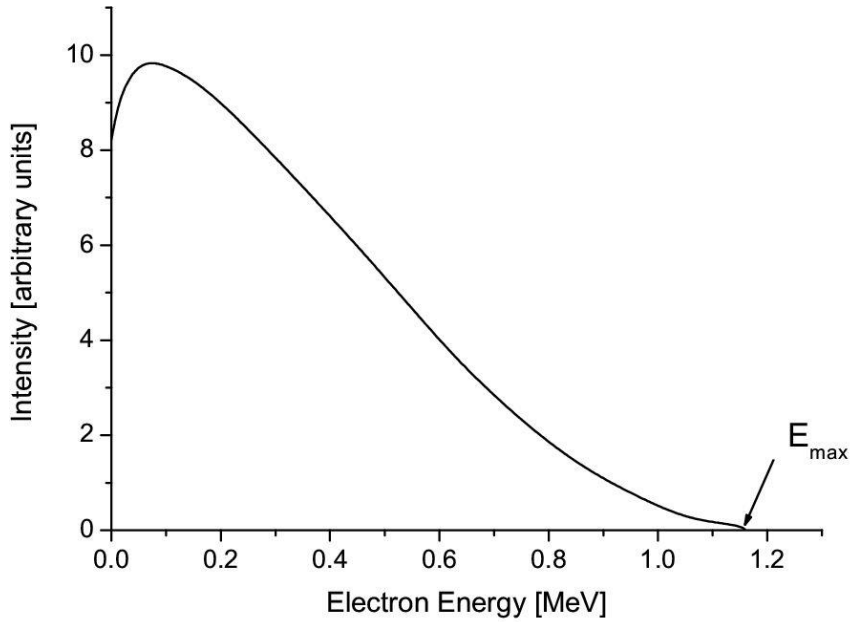
Beta decay: energy considerations

- Q value of the decay is express as
  - $Q_{\beta^-} = \left(m\left({}^{A}_{Z}X^*\right) - m\left({}^{A}_{Z+1}Y^*\right)\right)c^2$
  - $Q_{\beta^+} = \left(m\left({}^{A}_{Z}X^*\right) - m\left({}^{A}_{Z-1}Y^*\right) - 2m_e\right)c^2$

    $\left(m\left({}^{A}_{Z}X^*\right) - m\left({}^{A}_{Z-1}Y^*\right) \geq 2m_e\right.$ required to decay by β^+)

- Beta spectrum shape is described by

$$\frac{dN}{dW} \propto pWq^2 \; F(Z,W)\, C(W)$$

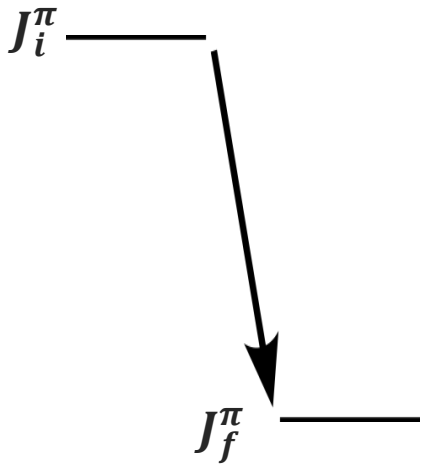


- The *log ft* value of a transition is calculated from
  - f_i the integral of the beta spectrum of the given transition
  - The partial half-life $t_i = \frac{T_{1/2}}{P_{\beta_i}}$

More details during Xavier's presentation

Beta decay: classification

- β transitions are classified according the variation of spin and parity during the process



- Similarly to the Hindrance factor, the *log ft value* can provide information on the nuclear structure of initial and final states

Type	Order of forbiddenness	ΔJ	$\pi_f\,\pi_i$
Super-allowed		0	+1
Allowed		0,+1	+1
Forbidden unique	1	±2	−1
	2	±3	+1
	3	±4	−1
	4	±5	+1
	$(\Delta J-1)$ nth	>1	$(-1)^{(\Delta J-1)}$
Forbidden (non-unique)	1	0, ±1	−1
	2	±2	+1
	3	±3	−1
	4	±4	+1
	(ΔJ) nth	>1	$(-1)^{\Delta J}$

Atomic Data and Nuclear Data Tables 152 (2023) 101584

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

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

Systematics of log *ft* values for $\beta-$, and EC/$\beta+$ transitions

Steffen Turkat [a,*], Xavier Mougeot [b], Balraj Singh [c], Kai Zuber [a]

Electron capture: decay process

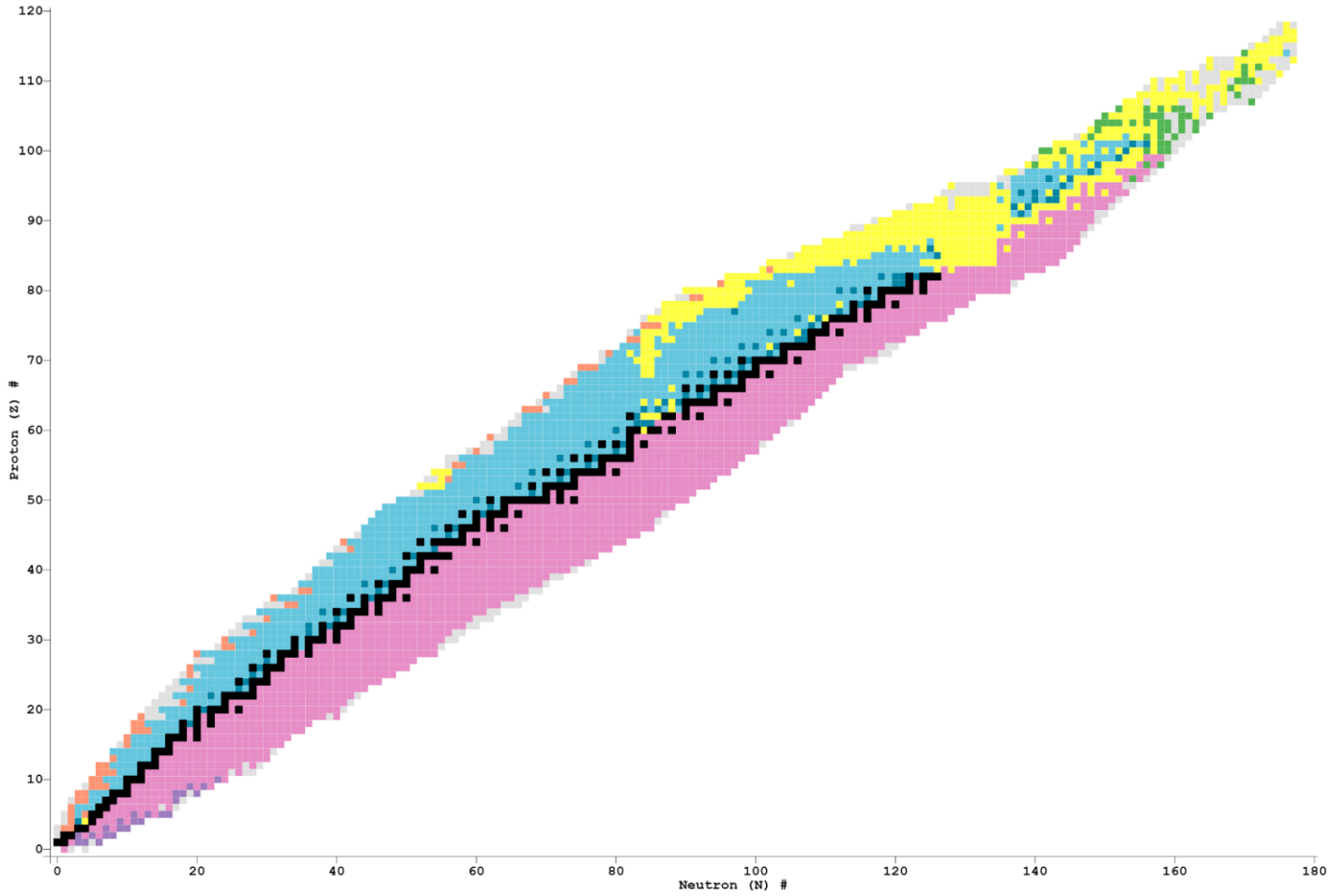
A two-body decay

- For neutron deficient nuclei
  - ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \nu_e$
  - $p + e^- \rightarrow \mathrm{n} + \nu$

- This process competes with β^+ decay

- The process affects the atomic cloud
  - Induces atomic rearrangement

⇨ Emission of atomic radiations



Electron capture: additional information

- Q value of the electron capture is express as

$$Q_{EC} = \left(m\left({}^{A}_{Z}X^{*}\right) - m\left({}^{A}_{Z-1}Y^{*}\right)\right)c^{2} - B(e_i)$$

$$where\ B(e_i)\ is\ the\ binding\ energy\ of\ the\ captured\ electron$$

(Electron capture transition can occur while β^+ decay is energetically impossible)

- The recoil energy of the nucleus can be neglected (except ^{7}Be where E_r = 57 eV)

- The capture process can occur with all available shell and subshells of the atomic nucleus
  - The probability to capture a specific shell depends on the transition type and properties
  - The relative capture probability are calculated such as

$$P_K + P_L + P_M + P_N + \cdots = 1$$

  - Capture probability are often calculated as ratio : $\frac{P_L}{P_K}, \frac{P_M}{P_L}$...

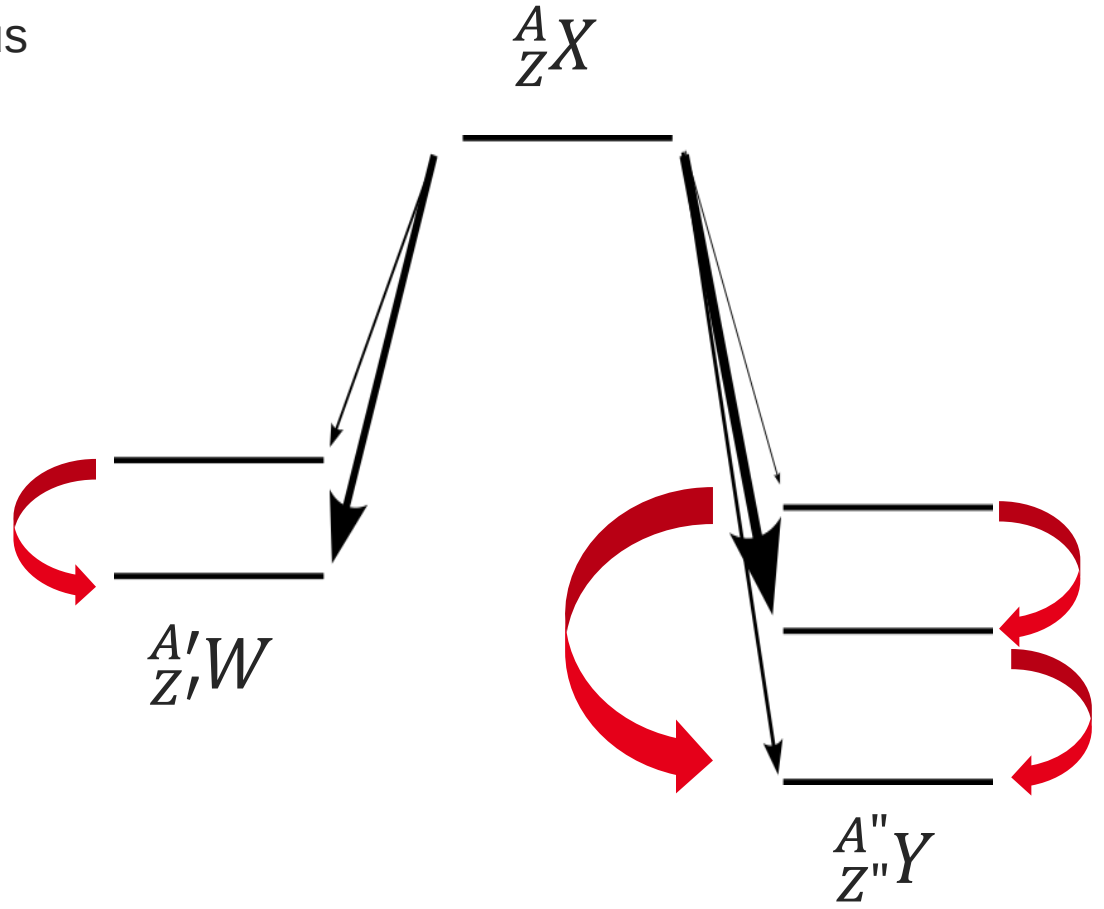
3. De-excitation of a nucleus

Gamma transition: an overview

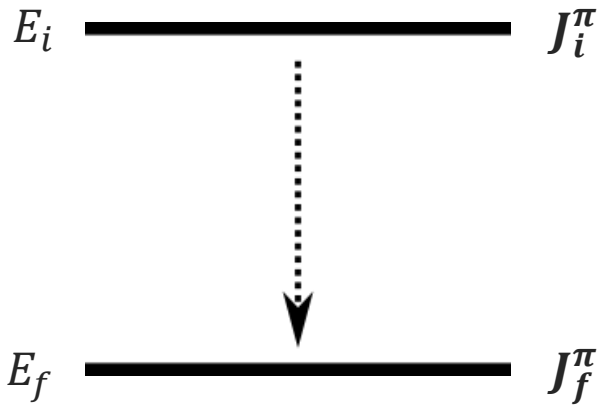
The previous decay processes can leave the daughter nucleus in an excited state

- The nucleus will deexcite through one of these processes
  - Photon (gamma) emission
  - Internal conversion
  - Pair creation
- The process can go directly to the ground state or to an intermediate excited state
- The overall gamma transition probability is expressed:

$$P_g = I_\gamma + I_{ce} + I_{e^\pm}$$



Gamma transition: multipolarity



The gamma transitions are classified according a multipole order expansion

- The order of the transition is determined by ΔJ
- Depending on the parity change, the transition is said
  - *Electric* parity change for $(-1)^L$
  - *Magnetic* parity change for $(-1)^{L-1}$
- A transition can be a mixture of two transitions and characterized by the mixing ratio δ defined as

$$\delta^2 = \frac{P(EL)}{P(ML')} \; if \; E \; is \; dominant \; (respectively \; \delta^2 = \frac{P(ML)}{P(EL')})$$

$L = \lvert J_i - J_f \rvert$	$\pi_f/\pi_i = -1$		$\pi_f/\pi_i = +1$	
	Transition	Possible mixture	Transition	Possible mixture
0 $(0 \to 0)$	Forbidden		Forbidden	
0 $(1/2 \to 1/2)$	E1		M1	
0 $(1 \to 1)$	E1	M2	M1	E2
1	E1	M2	M1	E2
2	M2	E3	E2	M3
3	E3	M4	M3	E4
4	M4	E5	E4	M5
even L $(J_i$ or $J_f = 0)$	ML		EL	
odd L $(J_i$ or $J_f = 0)$	EL		ML	

Gamma transition: photon emission

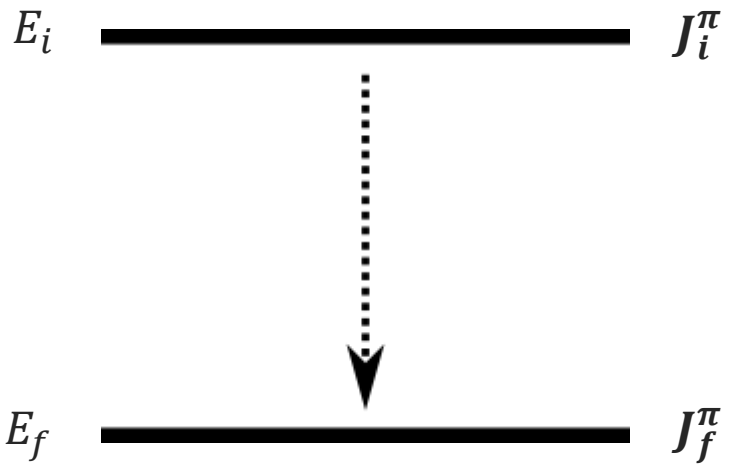
Photon emission is a two body process

- The photon energy is calculated as:

$$E_\gamma = E_i - E_f - E_r$$

$$with\ E_r = \frac{{E_\gamma}^2}{2m(^A_Z X)c^2}$$

  - In practice E_r is often negligible (E_r = 42 eV for 1369 keV of ^{24}Na)



- One as to be careful regarding the differences between emission and transitions information provided

$^{152}_{63}Eu_{89}$

2.4 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ × 100	Multipolarity	α_K	α_L (10^{-3})	α_M (10^{-3})	α_T
$\gamma_{1,0}$(Sm)	121,7818 (3)	61,5 (10)	E2	0,676 (20)	378 (11)	87,5 (26)	1,165 (35)
$\gamma_{5,3}$(Sm)	125,69 (13)	0,038 (13)	(E2)	0,616 (18)	329 (10)	76,0 (23)	1,042 (31)
$\gamma_{10,9}$(Sm)	148,010 (17)	0,055 (8)	(M1+50%E2)	0,430 (13)	115,0 (34)	26,0 (8)	0,578 (17)

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Sm)	121,7817 (3)	28,41 (13)
$\gamma_{5,3}$(Sm)	125,69 (13)	0,019 (6)
$\gamma_{10,9}$(Sm)	148,010 (17)	0,035 (5)

Gamma transition: internal conversion

During the internal conversion, the energy is transferred to a shell electron which is ejected

- The energy of the ejected electron is calculated as

$$E_{ce} = E_\gamma - B(e_i)$$

$$where\ B(e_i)\ is\ the\ binding\ energy\ of\ the\ ejected\ electron$$

- The relative intensity between internal conversion and photon emission is defined by the conversion coefficient:

$$\alpha = \frac{I_{ce}}{I_\gamma}$$

- The total conversion coefficient can be expressed as a function of the various available shells

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \alpha_N + \ ...$$

- Internal conversion is high for low energy gamma transition with high order of multipolarity
  - This process is usually negligible beyond few hundreds of keV

Gamma transition: pair creation

The electric field of a nucleus can create a pair $e^+ - e^-$ from a photon of high energy

- In this three-body process
  - The energy transfer to the particle is : $E_{e^+} + E_{e^-} = E_\gamma - 2\,m(e^-)$
  - The gamma energy needs to verify $E_\gamma \geq 1{,}022\ MeV$

- The relative probability to the gamma emission is expressed as

$$\alpha_\pi = \frac{I_{e^\pm}}{I_\gamma}$$

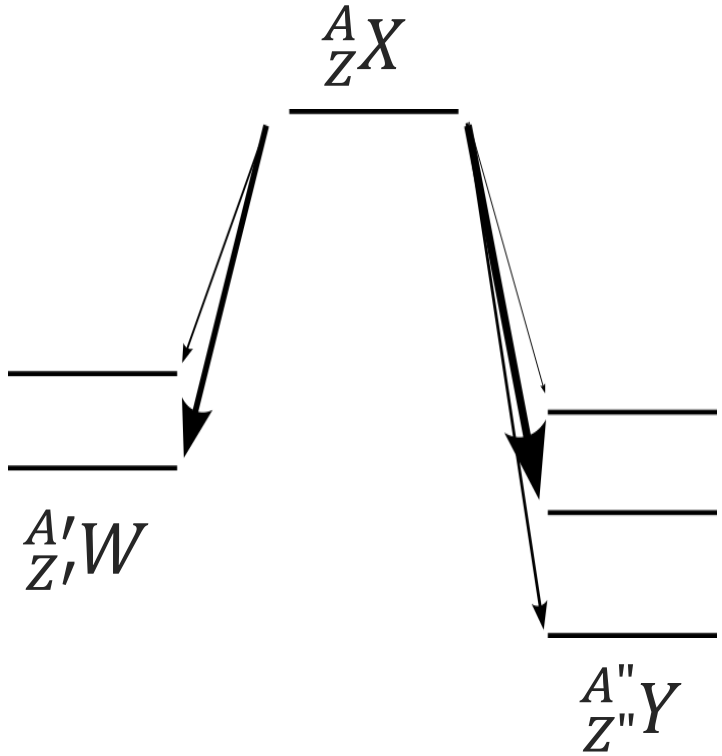
- α_π increases for large gamma energy and with Z of the nucleus

4. Conlcusion

Overview

Radioactivity: a spontaneous process during which the atomic nucleus undergoes transformation(s)

- Four main processes are usually
  - β- decay
  - β+ decay / Electron capture
  - α decay
  - Spontaneous fission
- The excited states of daughter nuclei decay to ground state through
  - Photon (gamma) emission
  - Internal conversion
  - Pair creation



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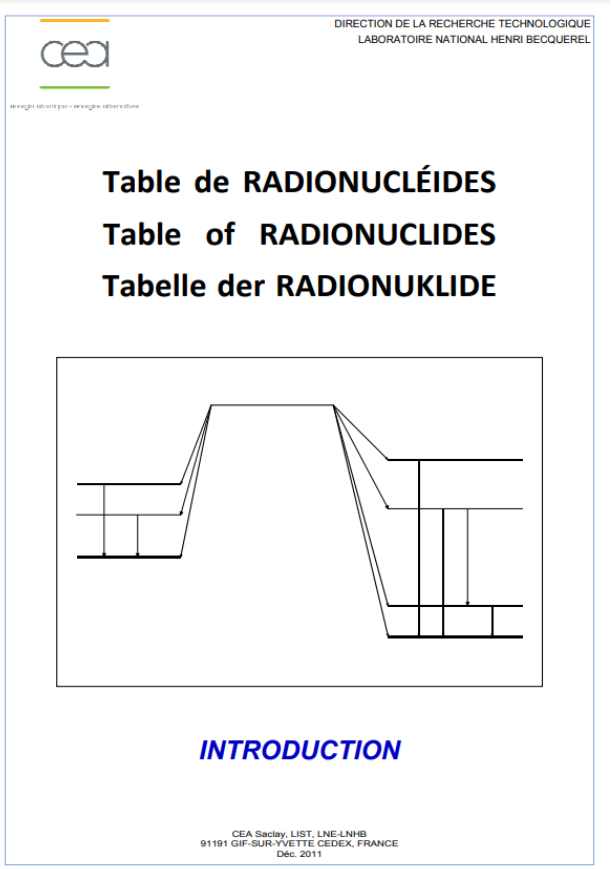
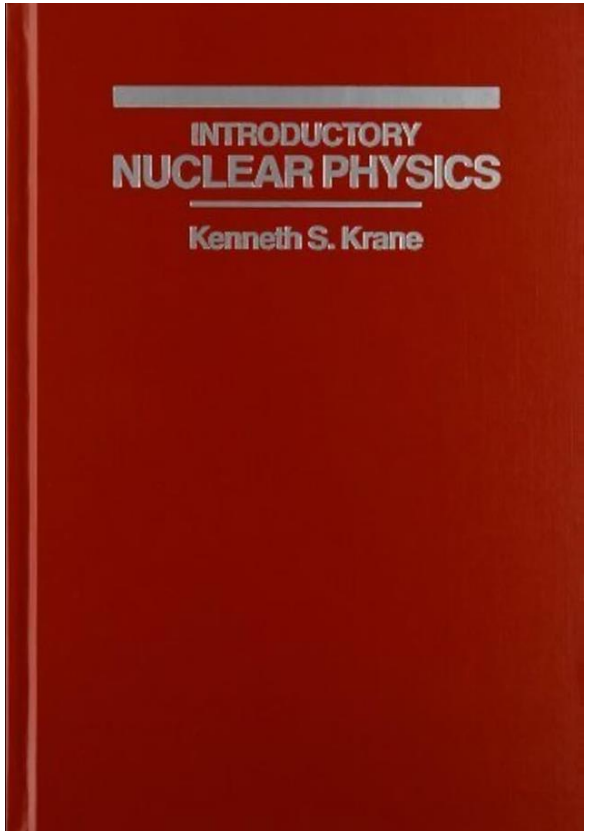


Available at
http://www.lnhb.fr/pdf/DDEP/Introduction_2011.pdf



Thank you for your attention