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Theoretical basics and modern status of radioactivity studies

Lecture 2: Radioactivity

Coefficients

1 year = π x 10^7 s

$\hbar = c = 1$

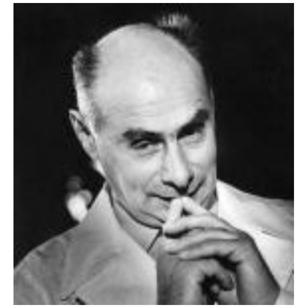
Γ [MeV] = $\frac{4.56 \times 10^{-22} \text{ [MeV s]}}{T_{1/2} \text{ [s]}}$

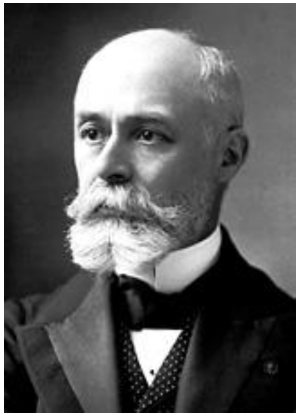
1 ns -> 30 cm

$\frac{\text{[MeV][fm]}}{197.327}$

E (AMeV)	v	
5	0.103	Coulomb barrier
20	0.203	Intermediate
100	0.428	energies
1000	0.875	Relativism

Radioactivity “hall of fame”





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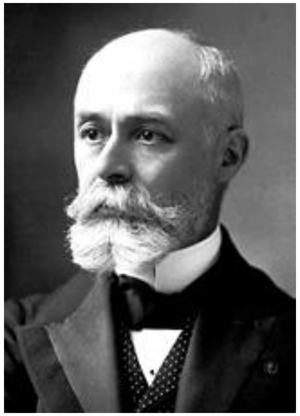

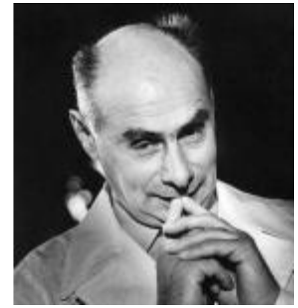

Henri Becquerel: three types of radioactivity - negative, positive, and electrically neutral

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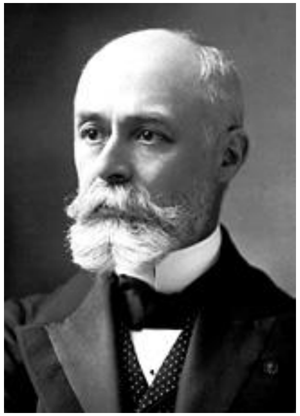

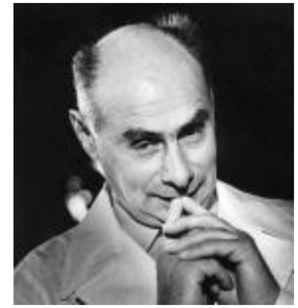

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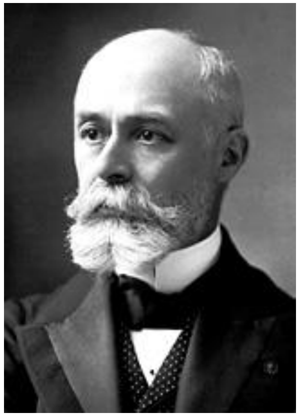

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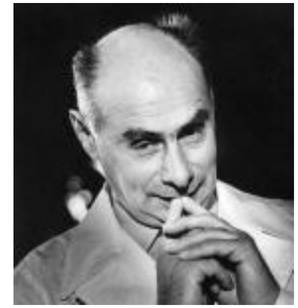

G.N. Flerov and K.A. Petrzhak spontaneous fission

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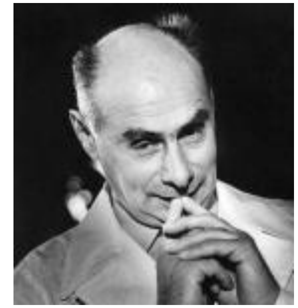

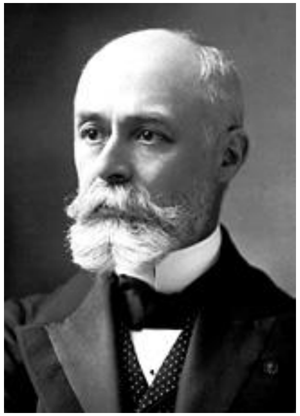

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β-delayed p

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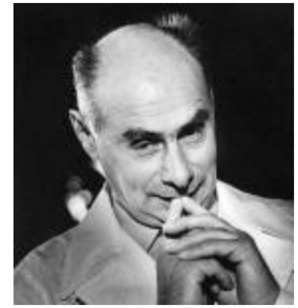

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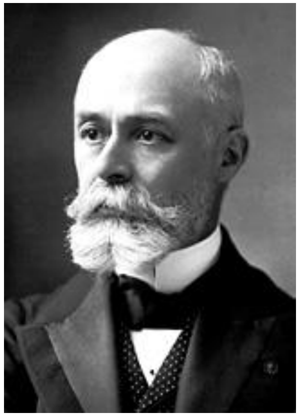

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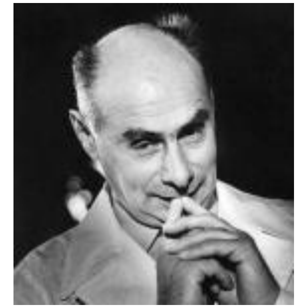

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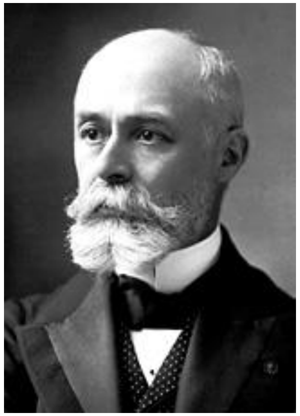

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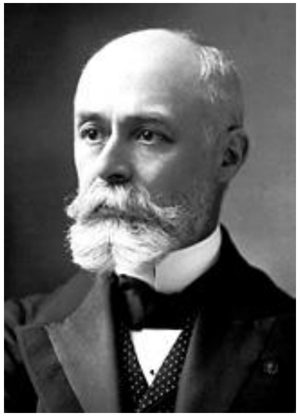

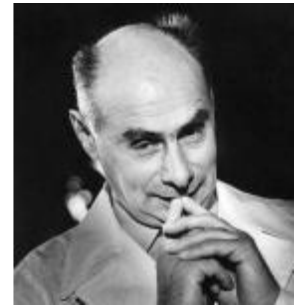

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???
2n radioactivity

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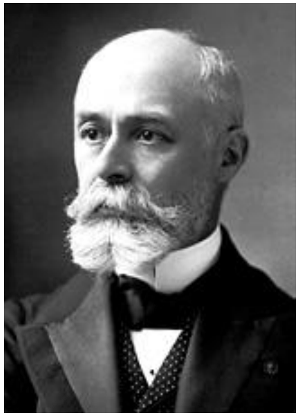
???
4n radioactivity

Discovery of radioactivity 1896. Classical era of radioactivity



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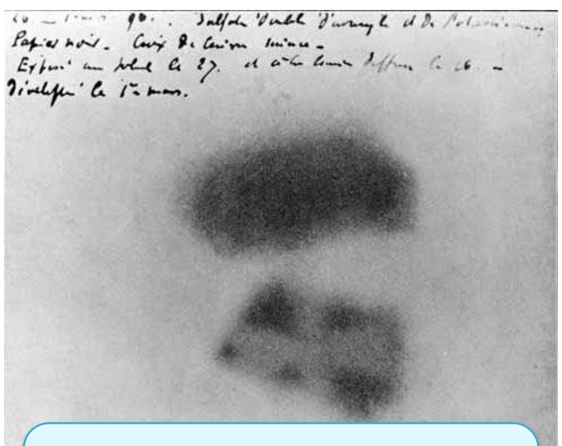
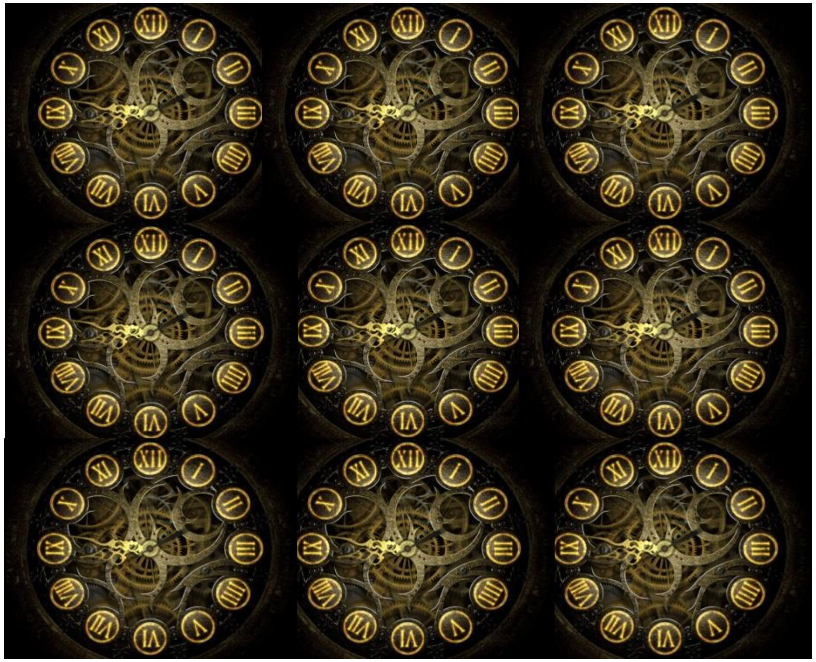


Becquerel Bq $1\ s^{-1}$
Curie $1\ Ci = 3.7 \times 10^{10}$ Bq

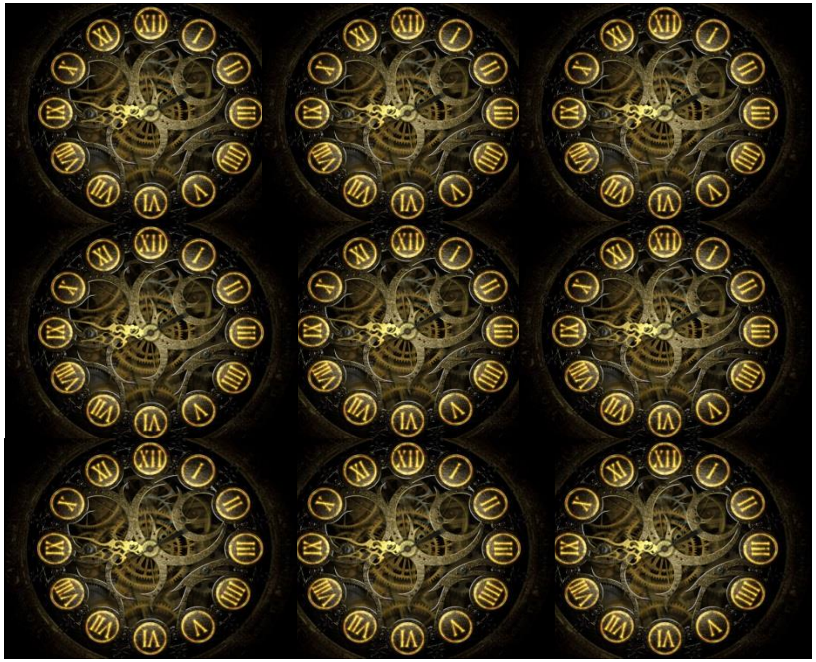
- Polonium and Radium, Curie and Curie, 1898
- α and β rays distinguished by Rutherford, 1899
- γ rays distinguished by Villard, 1900
- Atomic nucleus, Rutherford, 1911
- Explanation of α decay, Gamow, 1928
- Theory of β decay, Fermi, 1934
- β^+ decay discovered by Curie and Joliot, 1934
- Electron capture Wick, Bethe, and Peierls, 1934
- Spontaneous fission, Flerov and Petrzhak, 1940

Impact of radioactivity discovery on the philosophical worldview



What was most important in the discovery of radioactivity?

Impact of radioactivity discovery on the philosophical worldview



Classical physics: world of cause and consequence

Key word: spontaneous

Difficult to imagine nuclei as tiny clockworks counting the time up to decay moment

Paving way for quantum vision of the physical world

These people were to be very open-minded and critical to themselves to overcome the scientific challenge of their epoch. Our times are different – we do not feel that next scientific revolution is close. Could be true. Could be not true. However, lesson to us to be not less creative…

Why to study radioactive decays

“Active” vs “passive” approach

Reactions

Choice of reaction can be very selective for the question of interest

Initial state → Reaction mechanism → Nuclear structure → Decay mechanism → Observables

Decays

Decay provide only one type of information

Nuclear structure → Decay mechanism → Observables

It decay studies there are fever steps from observables to valuable information

Reaction theory is very fuzzy as any strong interaction theory (electron scattering is exception)

Decay mechanism (final state interactions) could be accessible for very precise theoretical investigation

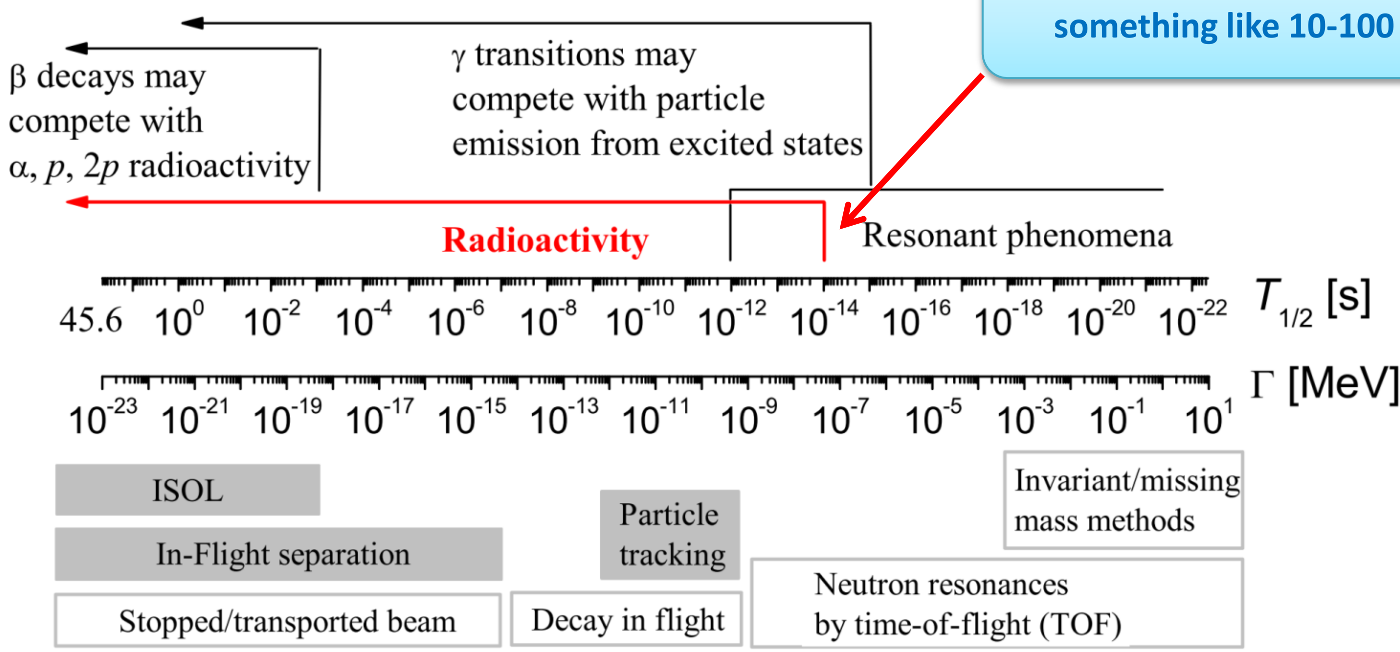
Time scales

Initial idea: radioactivity is process when something is radiated

Modern definition: energy loss by atom

"Atom" in the definition means that process is slow enough that atom (electronic orbitals) can be formed.

No absolutely strict value, but something like 10-100 fs…



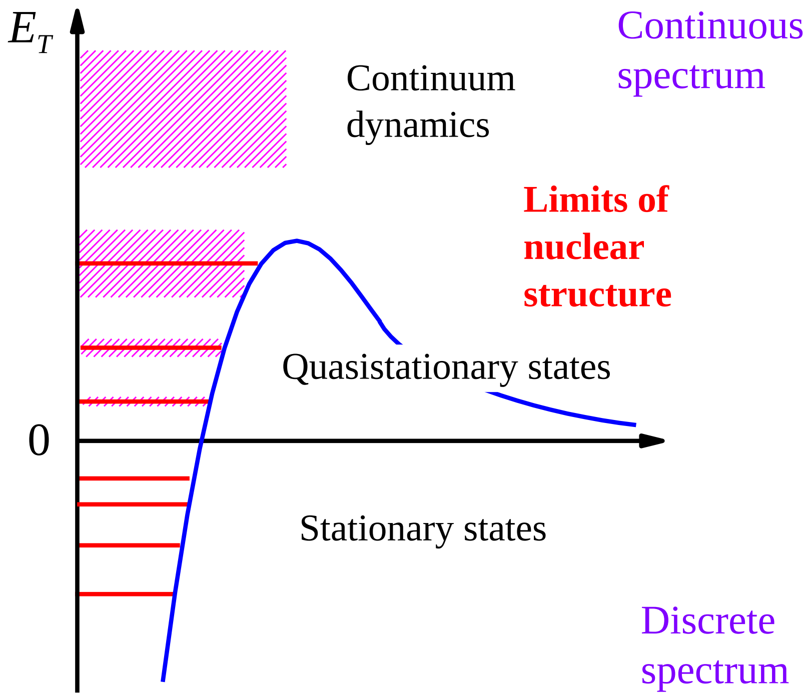
Extremely broad lifetime scale – 25 orders of the magnitude

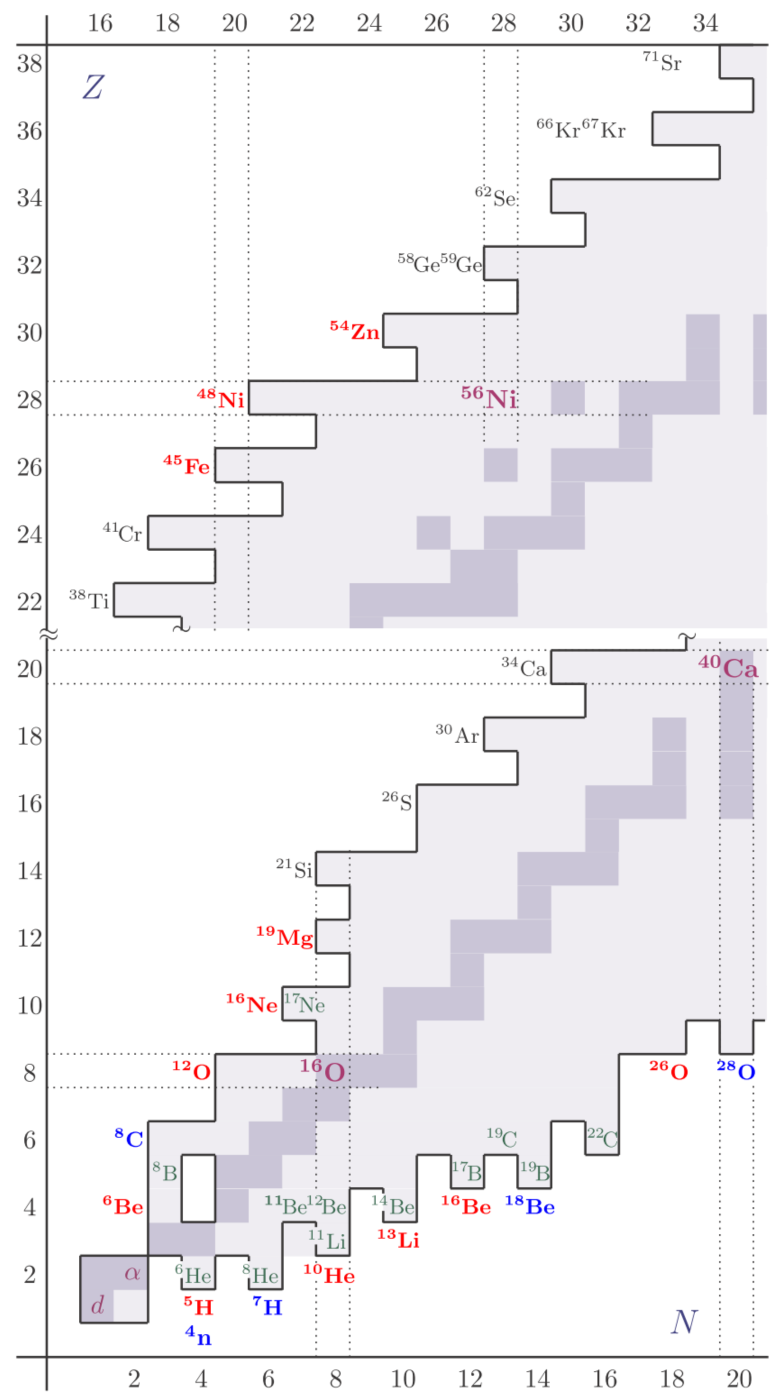
1 sec vs. Universe lifetime – 17-18 orders of the magnitude

Qualitatively different experimental techniques

Where the decay is taking place

From borderline of nuclear stability to Limits of nuclear structure existence



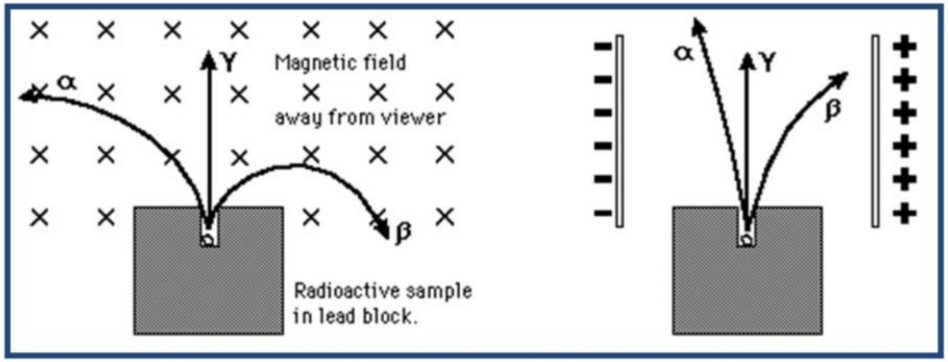


Dripline is achieved for Z<32 and N<22

Dripline is only studied for lightest nuclei

Limits of the nuclear structure are not solidly established even for the lightest isotopes. ^{7}H, ^{12}He, ^{13}Li, ^{5}Be - ???

Types of radioactivity: since 1896



	Interaction domain	Decay suppression reason
Alpha	Strong	Electromagnetic
Beta	Weak	Coupling constant
Gamma	Electromagnetic	Strong

Types of radioactivity: isomers

Typical gamma-decay lifetime is in fs range.
However, there exist very slow gamma transitions

Definition of isomeric state: $T_{1/2} > 10^{-9}$ s
– if you produce it in some reaction, the isomer survive long enough to be spatially separated from production target

Classical example ^{180m}Ta

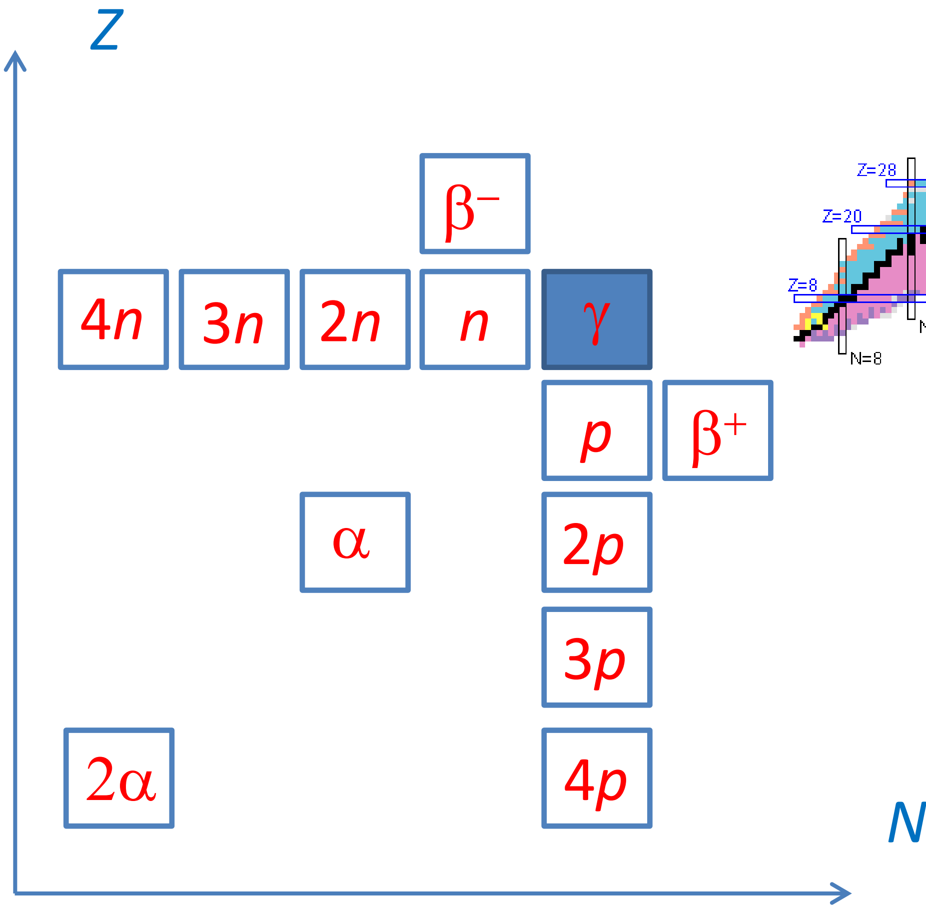
^{180}Ta is abundant in nature (< 0.01%)

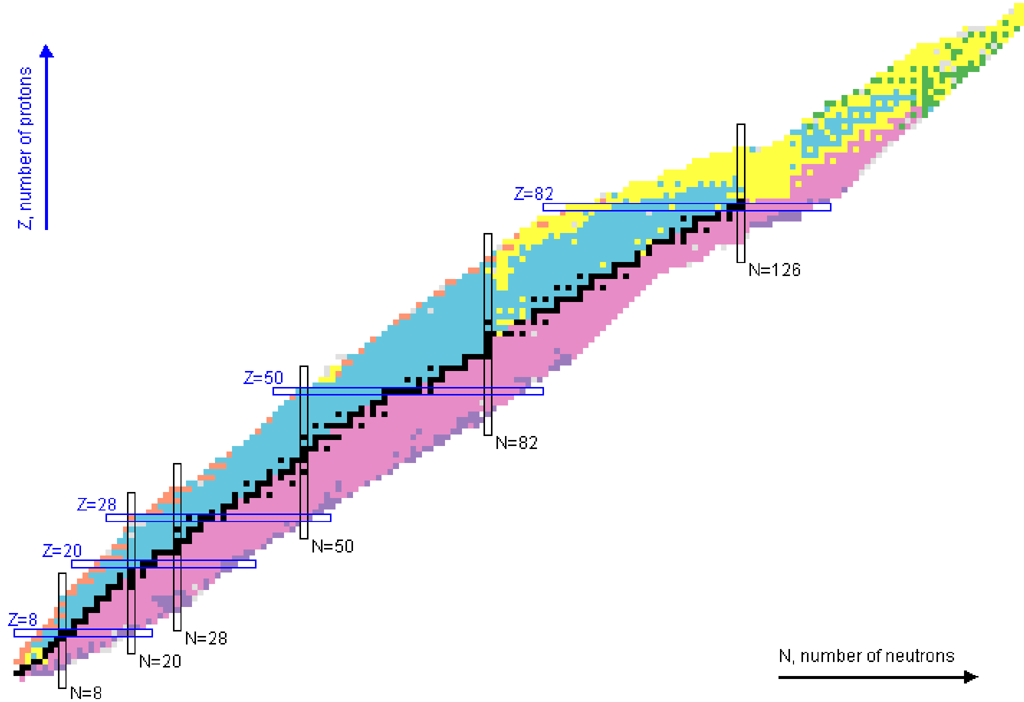
	E* (MeV)	J^{π}	$T_{1/2}$	
^{180}Ta	0	1^+	8	hours
^{180m}Ta	0.07	9^-	$>10^{15}$	years

So, all ^{180}Ta isotope is in isomeric state which has survived since secondary nucleosynthesis in our galaxy

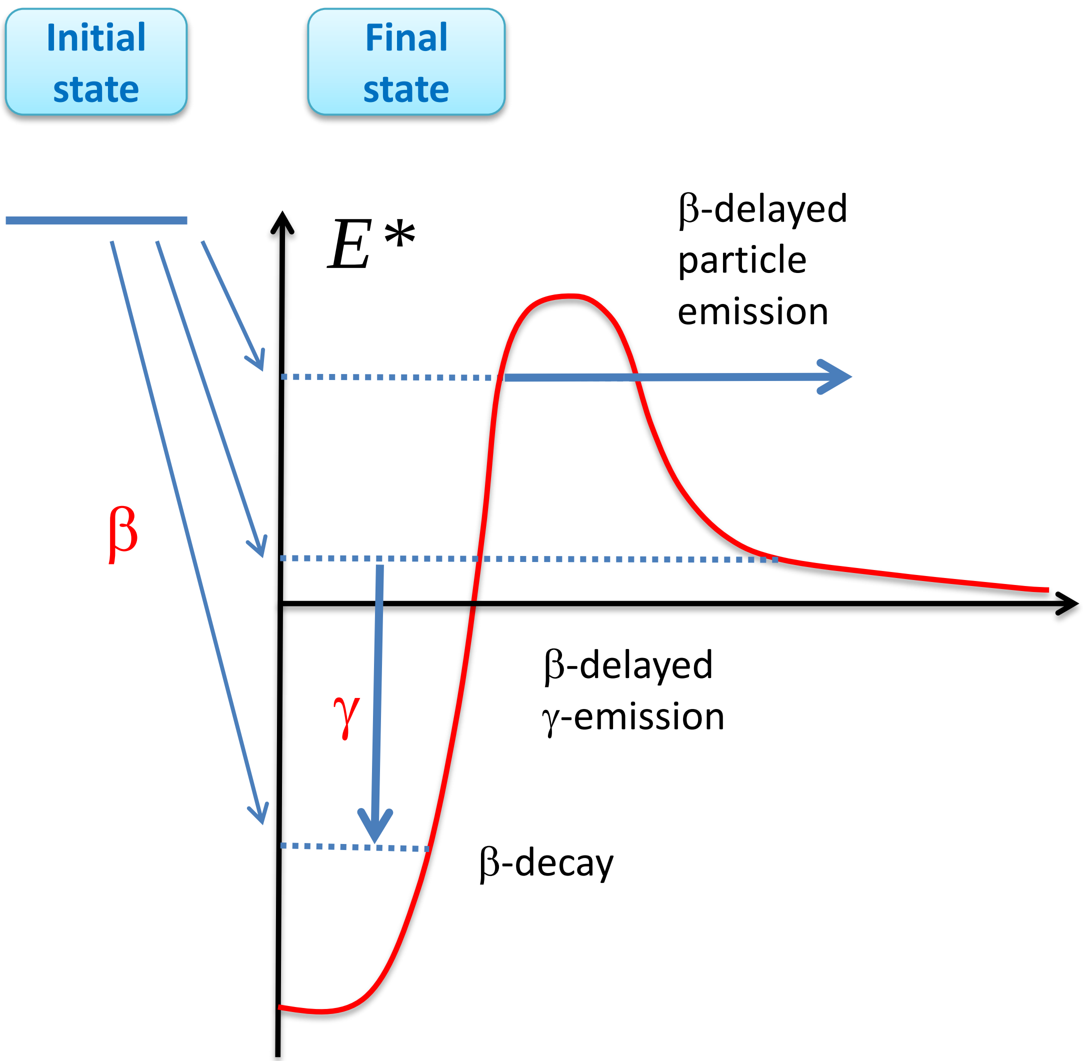
Types of radioactivity: more details

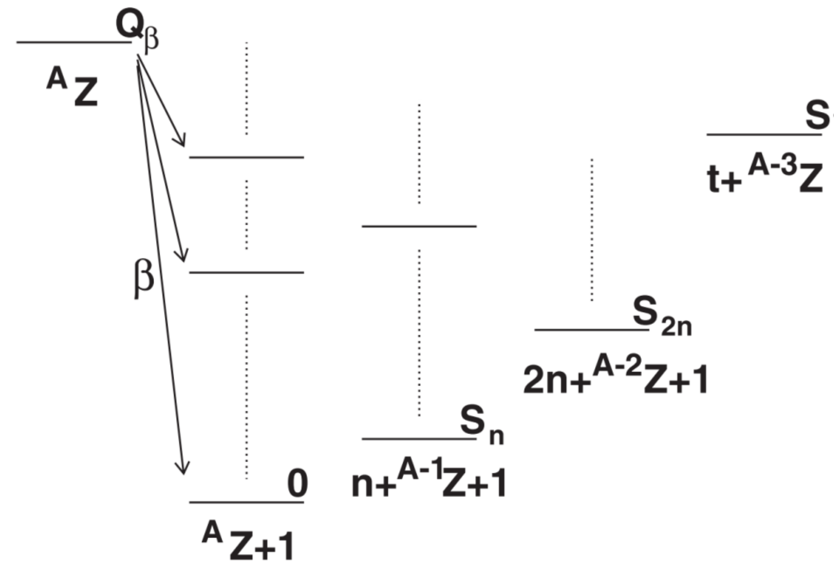
Transmutation networks in the map of nuclides





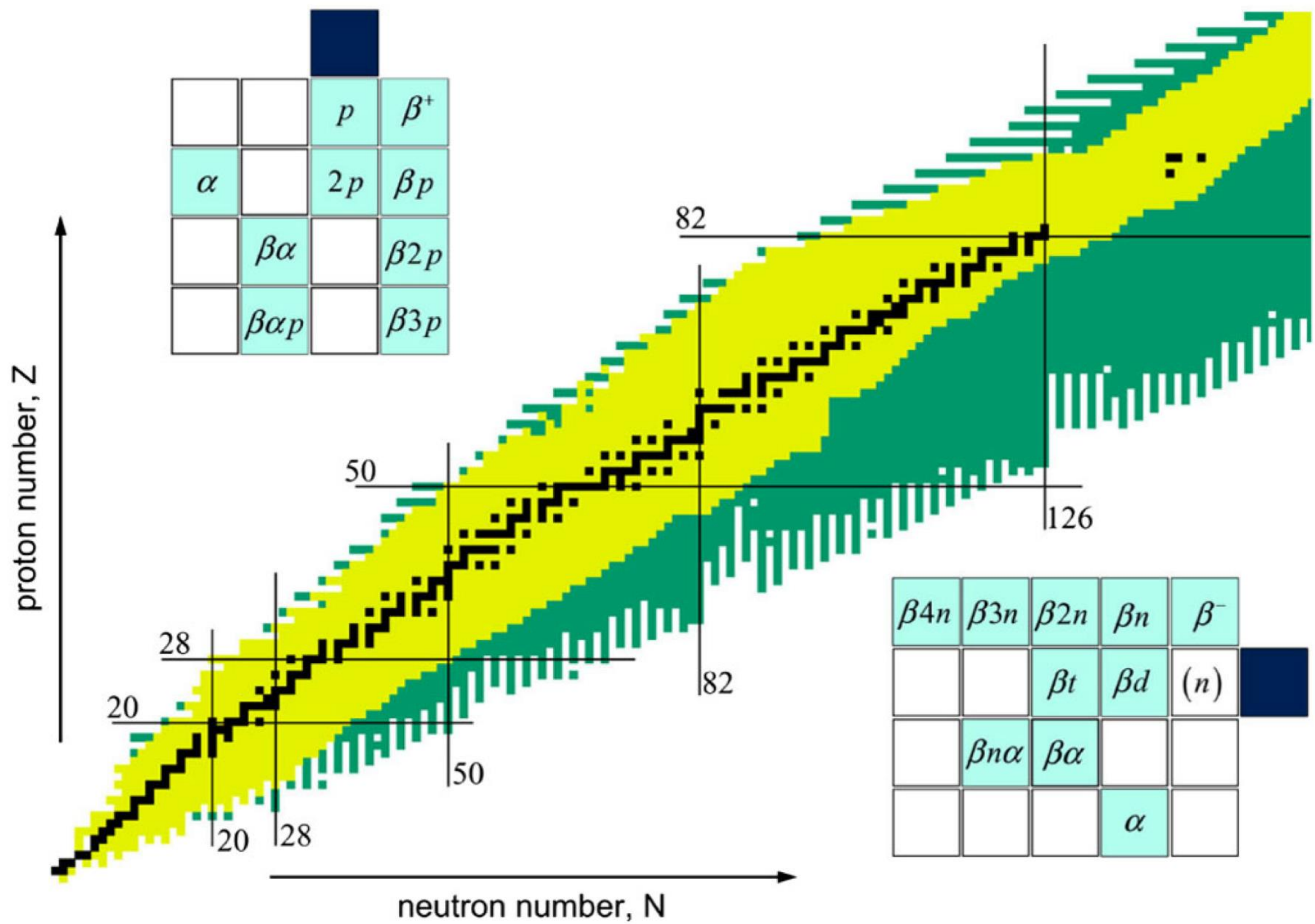
Types of radioactivity: β-delayed particle emission





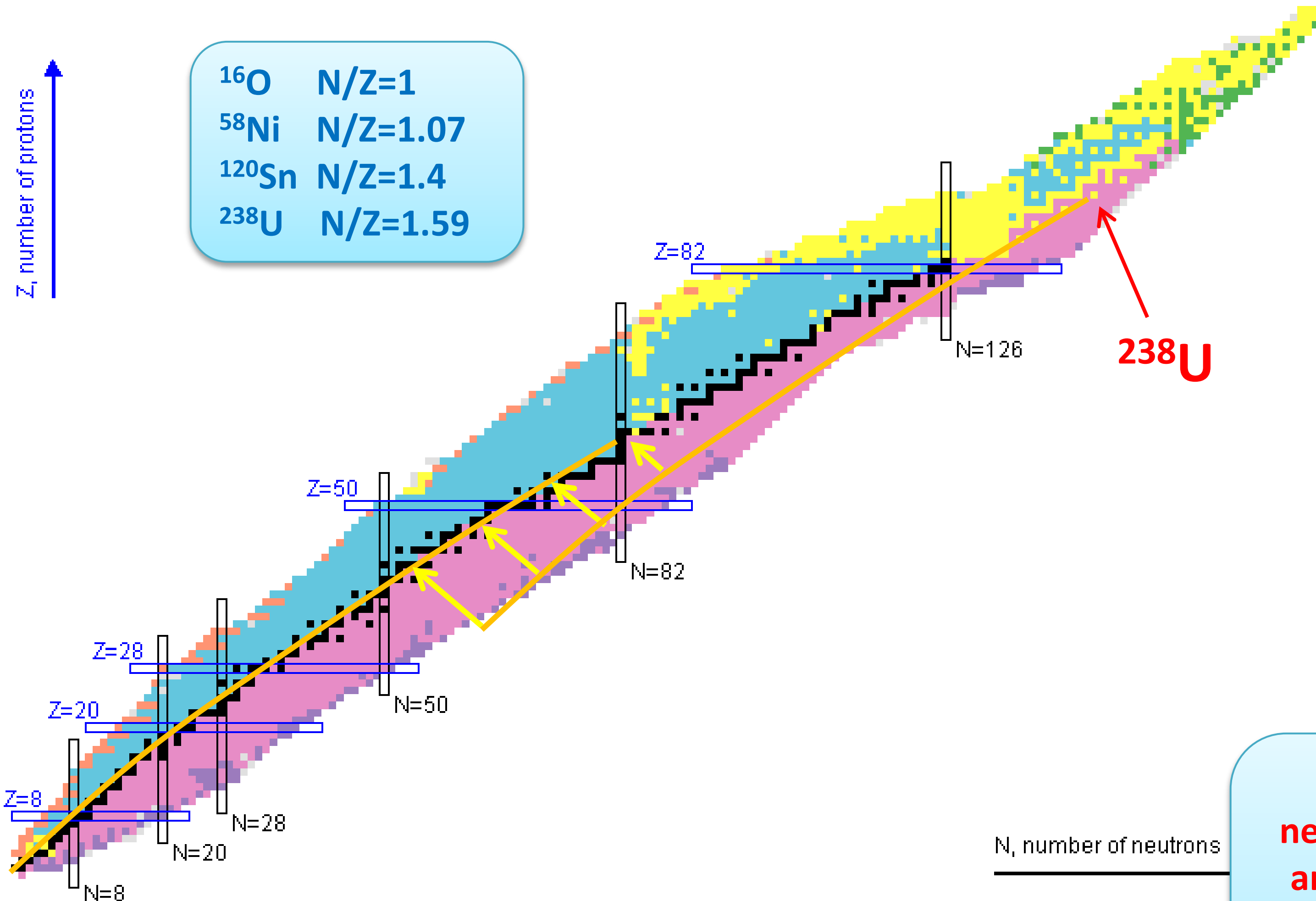
If emitted particle is well excited or particle-unstable we get to situation of multi-particle emission

Types of radioactivity: β-delayed particle emission



Types of radioactivity: spontaneous fission

^{16}O N/Z=1
^{58}Ni N/Z=1.07
^{120}Sn N/Z=1.4
^{238}U N/Z=1.59



Heavy nuclides are increasingly neutron excessive

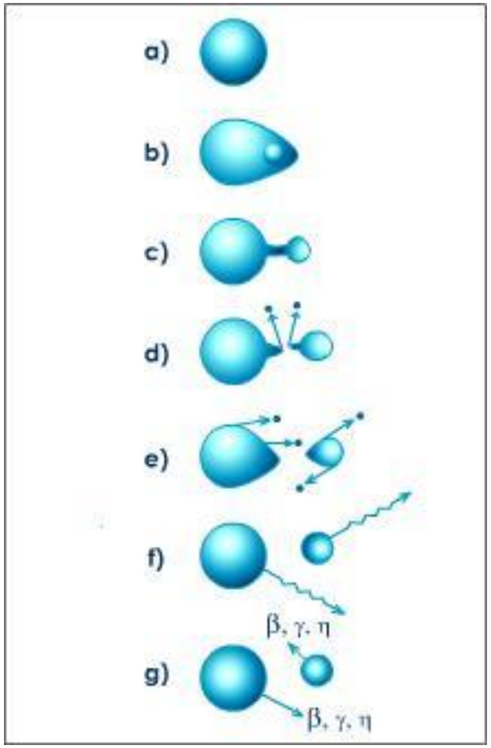
Fission resulting in stable nuclides in unlikely

Fission resulting in ground state is unlikely

Excited states of neutron-rich nuclides are populated. They discharge by sequence on gamma, beta and neutron decays

Source of delayed neutrons to enforce induced fission in nuclear reactors

Droplet model of nucleus. Bethe–Weizsäcker formula



$$E_B = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A^{1/3}} - a_C \frac{Z(Z-1)}{A^{1/3}} + \delta(A,Z)$$

Volume term, Surface term, Asymmetry term, Coulomb term, Pairing term

For pairing term:

$$\delta(A,Z) = \begin{cases} +\delta_o & \text{A, Z even} \\ 0 & \text{A odd} \\ -\delta_o & \text{A, Z odd} \end{cases}$$

where

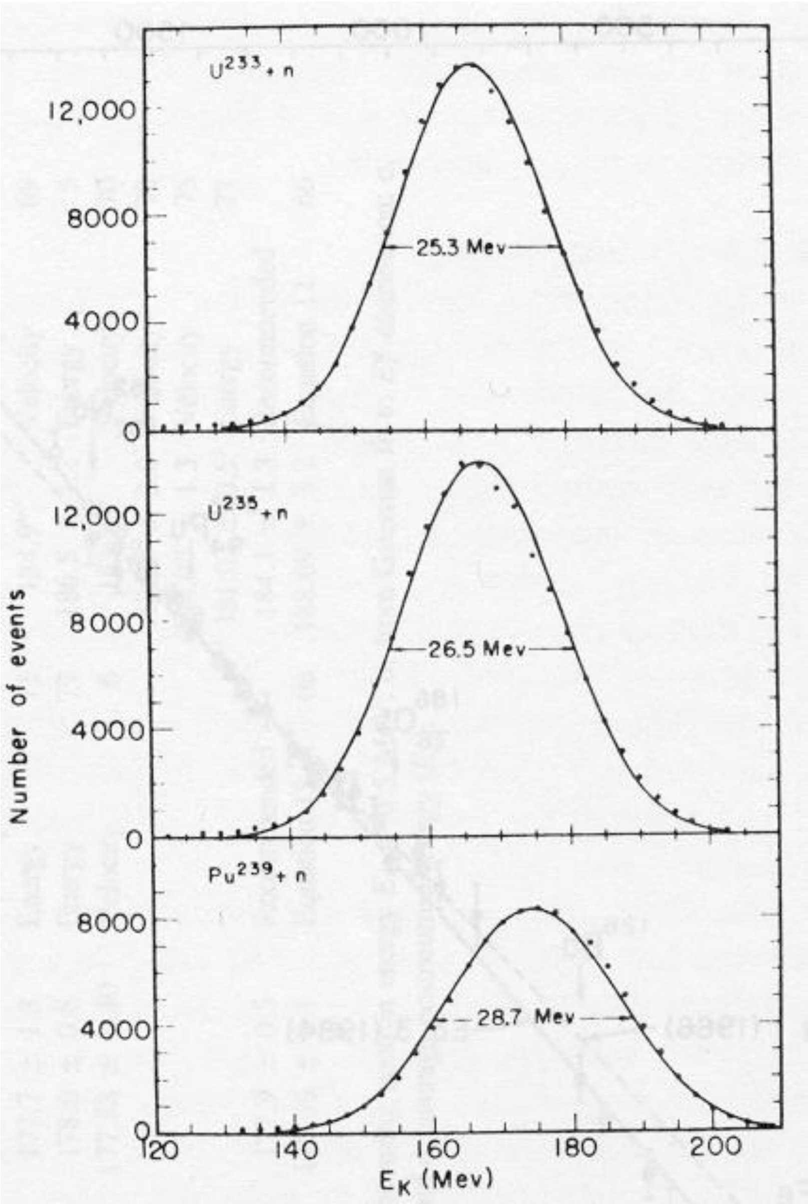
$$\delta_o = \frac{a_P}{A^{1/2}}$$

Coefficients:

$a_V = 15.85$ MeV
$a_S = 18.34$ MeV
$a_A = 23.21$ MeV
$a_C = 0.714$ MeV
$a_P = 12.00$ MeV

- Substance with saturated density - liquid
- Liquid droplet model of nucleus
- Fission physics: analogy with charged droplet instability
- Simple mass relations: Bethe-Weizaecker formula

Energy release in fission

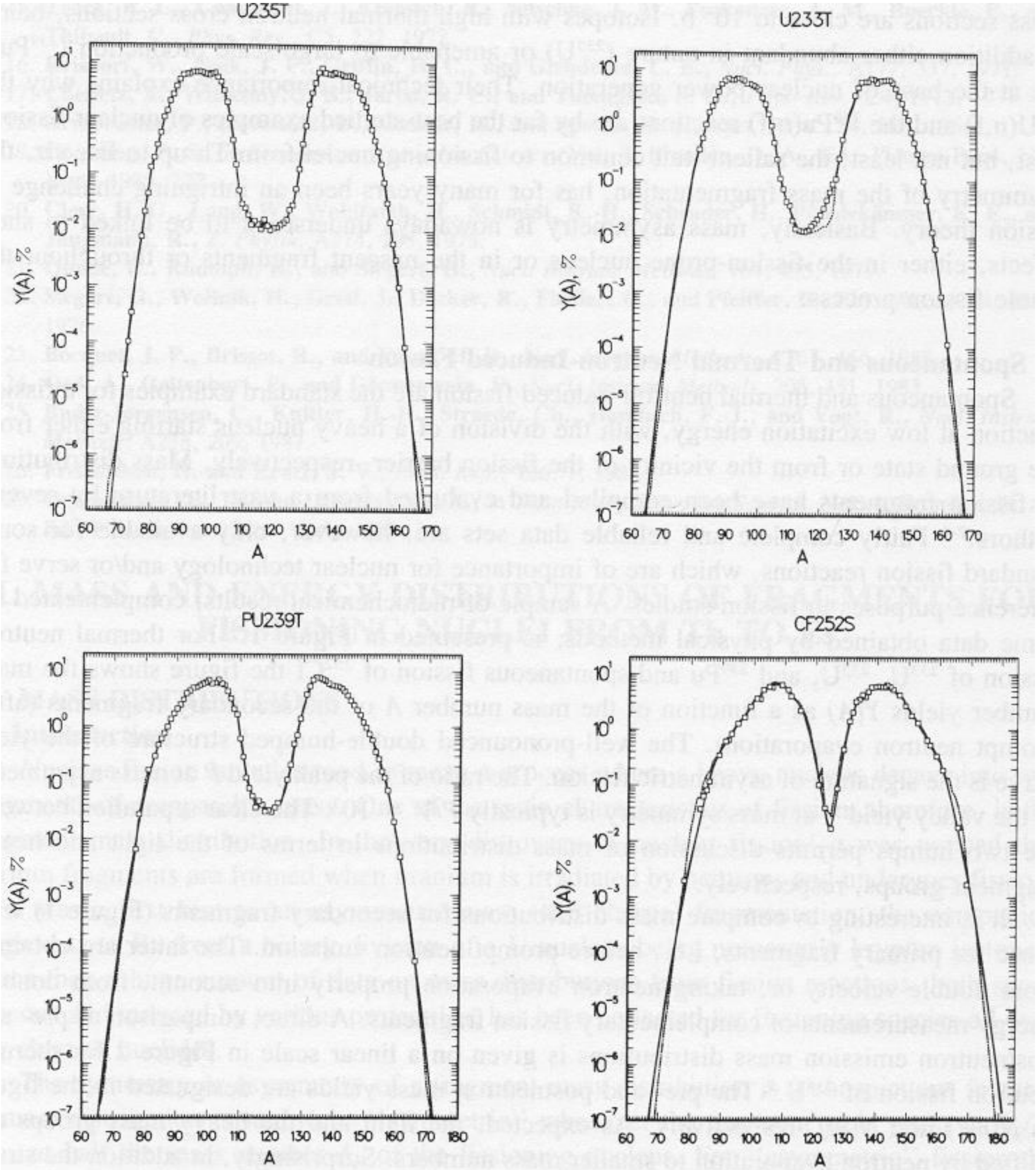


Up to 240 MeV per fission

From 150-200 MeV per fission is due to electrostatic energy released via kinetic energy of fragments

TKE distribution for fission fragments before secondary neutrons are emitted

Fragment mass distribution in fission

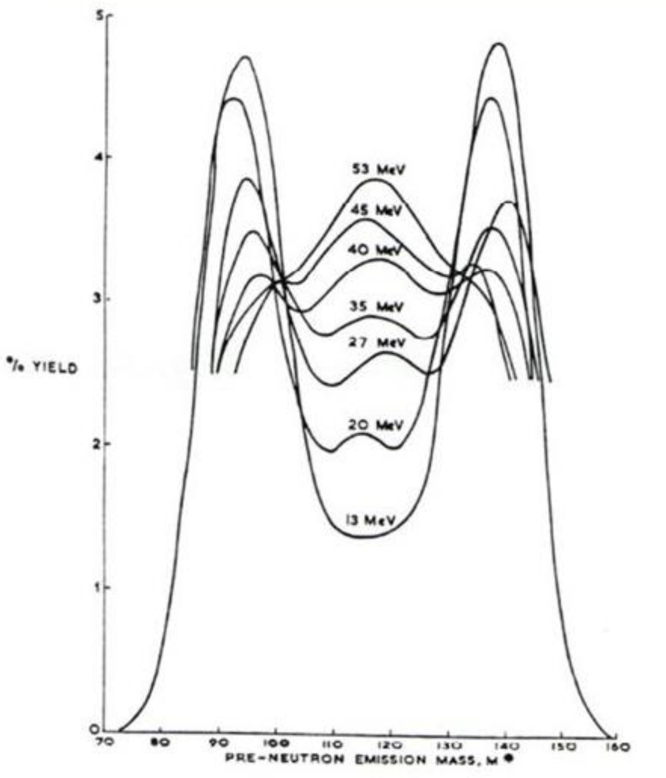


Asymmetric fission is the most typical fission mode

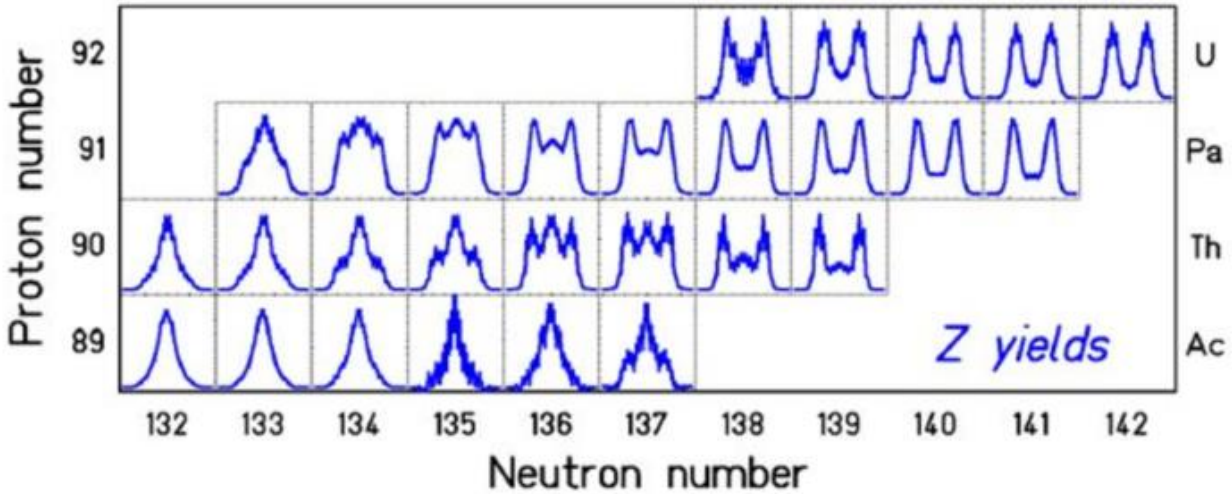
Fragment mass distribution in fission

Induced fission is increasingly symmetric with energy increase of inducing particle

Transition from asymmetric to symmetric fission takes place in exotic nuclides

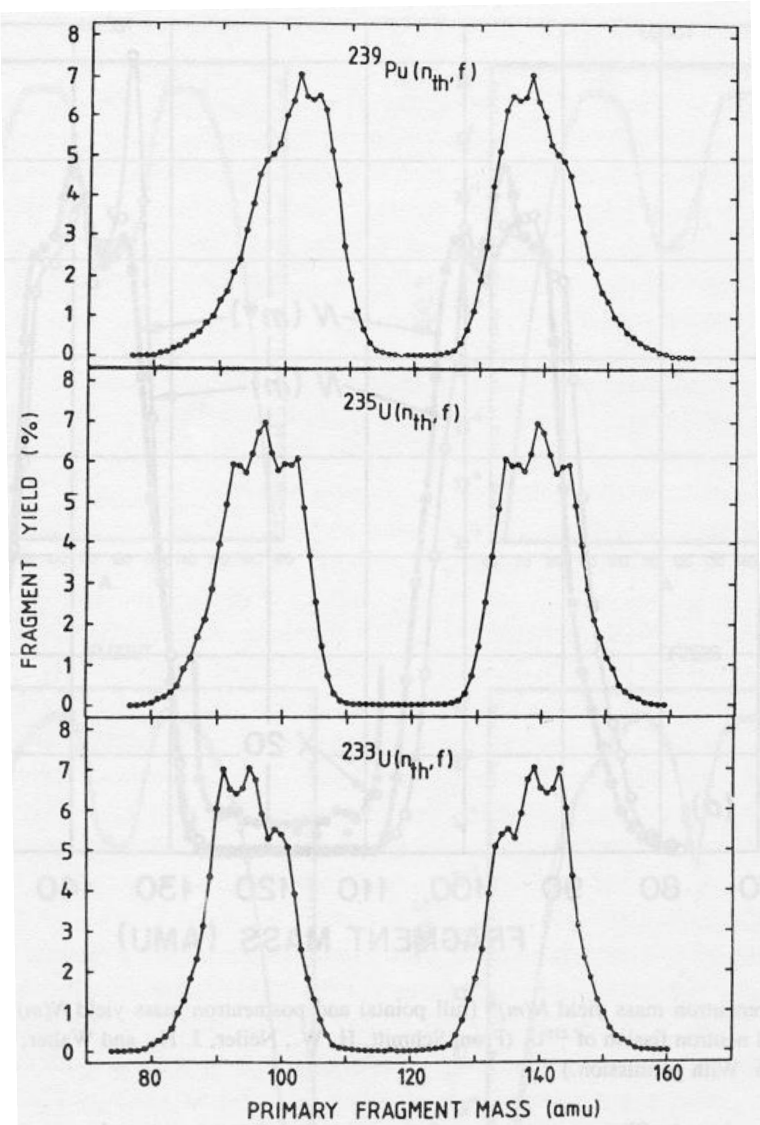


Fission mass distributions for ^{232}Th(p, f)

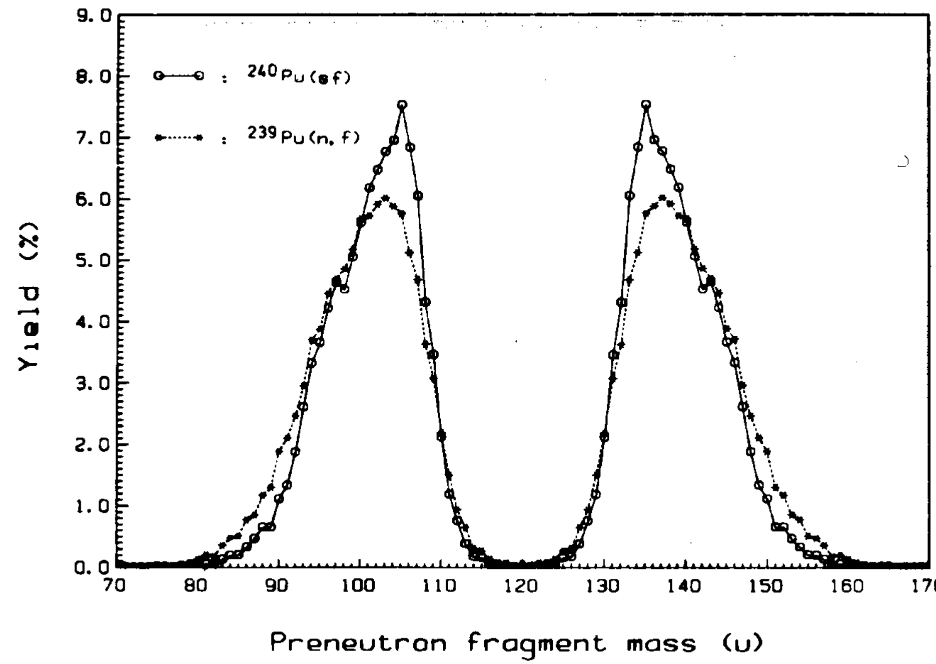


Fine structure of fission fragments mass distribution

Mass spectra of fission fragments before prompt neutron emission



Fine structure of mass spectra of fission fragments is enhanced in spontaneous fission



Proton radioactivity

Goldansky, 1960 1960, Nucl. Phys. 19, 482.

"Modern era" of radioactivity studies:
- Proton radioactivity
- Beta-delayed proton emission
- Two-proton radioactivity

Nothing special compared to alpha emission. However, shift of interest to the systems near the proton dripline and beyond

Beta-delayed proton emission discovery

^{17}Ne Karnaukhov, Ter-Akopian, Subbotin, 1963

^{25}Si Barton et al., 1963

Now proton radioactivity is well studied

~50 s=1 odd mass cases from ^{109}I to ^{185}Bi

Proton radioactivity discovery

^{53m}Co proton emission off isomeric state
Jackson et al., 1970.

^{151}Lu ground-state proton radioactivity
Hofmann et al., 1982

17 s=2 even mass cases from ^{112}Cs to ^{176}Tl

3 s>2 cases: ^{53m}Co, ^{54m}Ni, ^{94m}Ag

Types of radioactivity: cluster radioactivity

Natural generalization: p, alpha, heavier than alpha?

Predictions
A. Sandulescu, D.N. Poenaru, and W. Greiner, 1980

Cluster radioactivity discovery
^{17}Ne from ^{223}Ra, Rose and Jones, 1984

Unprobable process: branching ratio to alpha emission <10^{-5}, typical: 10^{-12}-10^{-15}

~ 36 cases

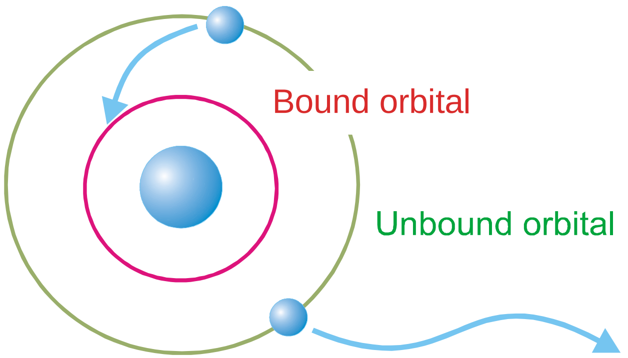
^{12}C from ^{114}Ba ⟺ **^{34}Si from ^{242}Cm**

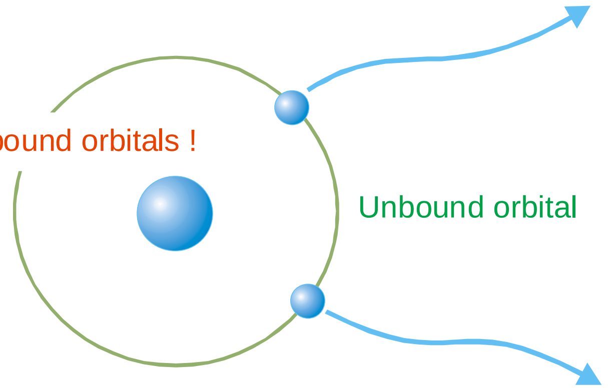
^{12,14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg, ^{32,34}Si
Mainly even mass closed-shell clusters are emitted

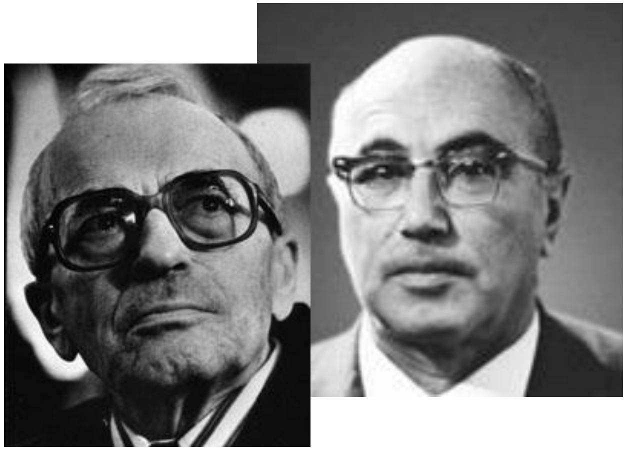
Where is borderline between cluster radioactivity and fission?

The decay via ground or lowest excited states of daughter systems

Two-proton radioactivity: a qualitative view







Goldansky and Zeldovich, 1960

Pfutzner et al and Giovinazzo et al, 2002

Classical case:
one particle emission is always possible

Quantum mechanical case:
it could be that both particles should be emitted simultaneously

Exclusive Quantum-Mechanical phenomenon

- **No deeper bound orbitals.**
- **The common orbital for two protons exists only when both are “inside”.**
- **When one of them goes out, their common orbital do not exist any more and the second HAS to go out instantaneously**

Radioactivity

strong

- 2p
- alpha
- Ternary fission
- p
- cluster
- spontaneous fission
- 2n?
- 4n?
- 2alpha?

weak

- Double electron capture
- Beta-
- Double beta
- Beta+
- Double beta neutrinoless?
- Electron capture

electromagnetic

- gamma
- Internal conversion
- isomerism

Beta-delayed

- Beta-p
- Beta-n
- Beta-2p
- Beta-d
- Beta-3p
- Beta-^{3}He
- Beta-alpha
- Beta-2n
- Beta-alpha-p