Giovanna Benzoni (Milano)
Strong, weak and electromagnetic forces at work in atomic nuclei, decay properties

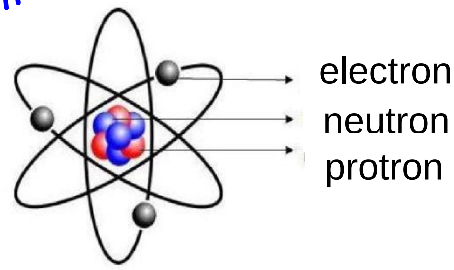
Outline of the talk:

- Introduction
- alpha decay
- beta decay
- exotic decay modes
- examples of measurements

Istituto Nazionale
di Fisica Nucleare

Introduction

- **Atom:**

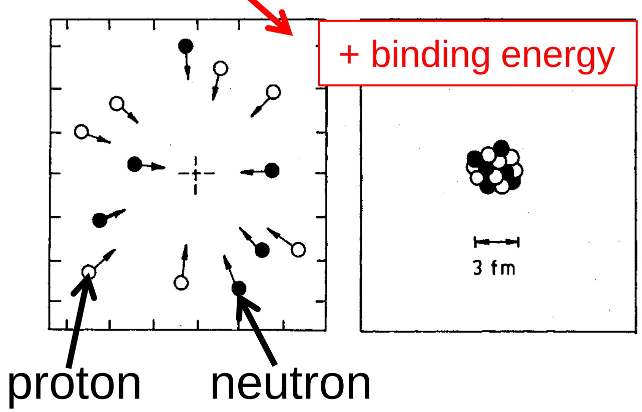


$m(n) = 0.939565\ GeV/c^2$
$m(p) = 0.938783\ GeV/c^2$

- **Fundamental interactions:**

Interaction	Strength	Reach
Strong	1	$\sim 10^{-14}$ m
Weak	10^{-4}	$\sim 10^{-15}$ m
Electromagnetic	1/137	∞
Gravitational	$\sim 10^{-38}$	∞

- **Energy:**



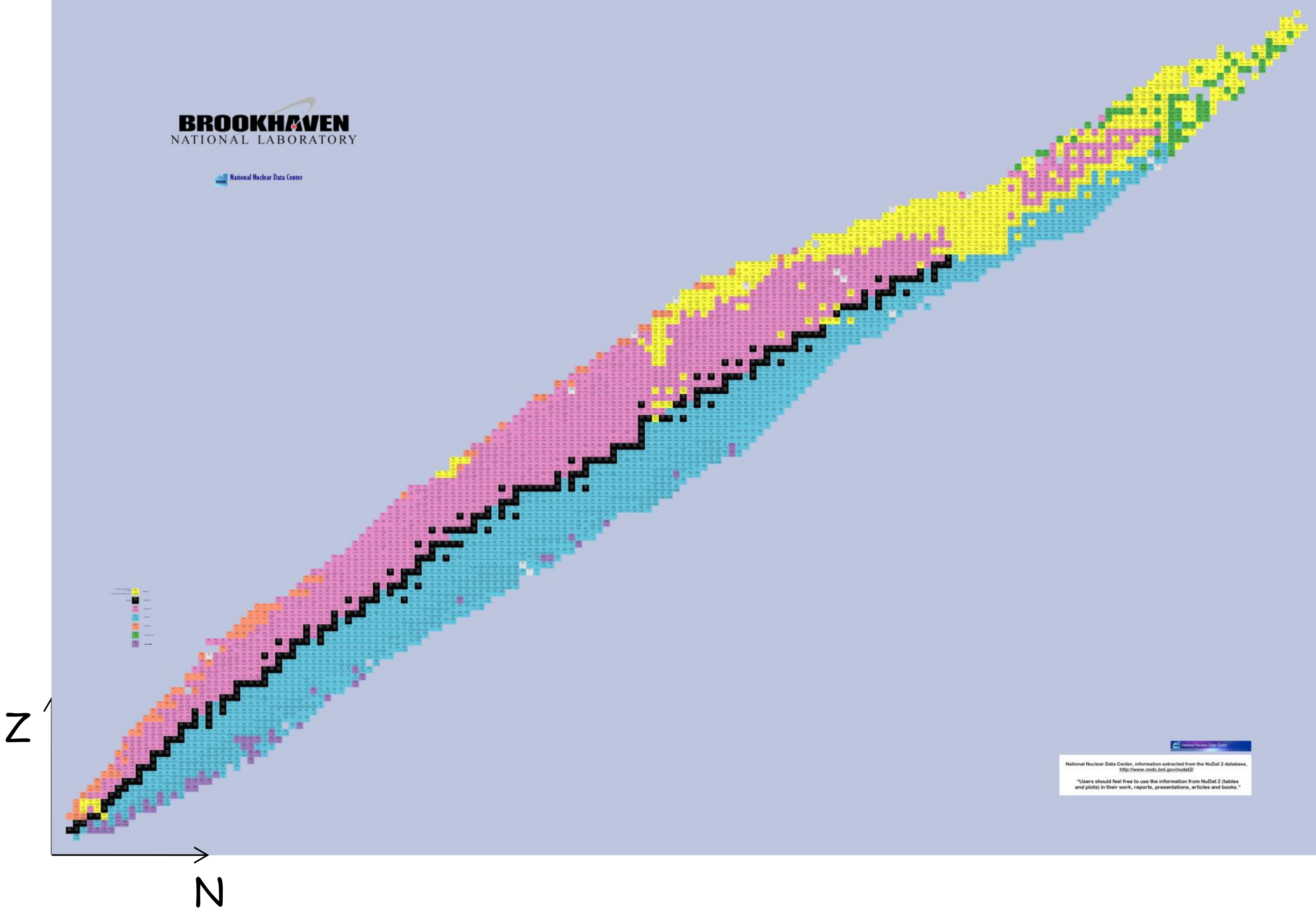
$^{56}_{26}Fe_{30}$

$26 * m(\pi) + 30 * m(\nu) = 52.595\ GeV/c^2$

~1% of total energy

$m(^{56}Fe) = 52.103\ GeV/c^2$

Introduction

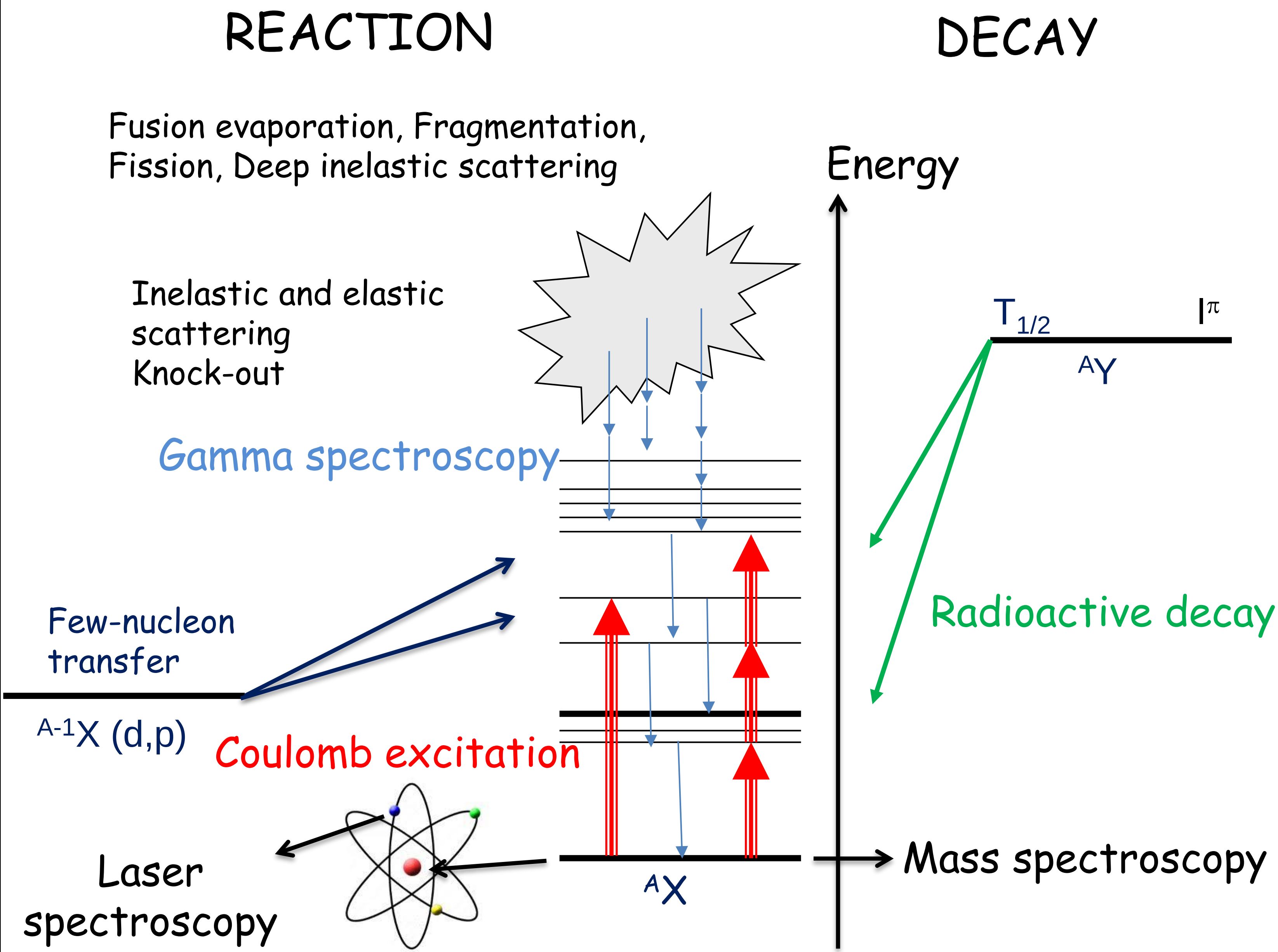


~3000 known nuclei, both natural (228) and artificial
7000+/- 500 current estimates for bound nuclei

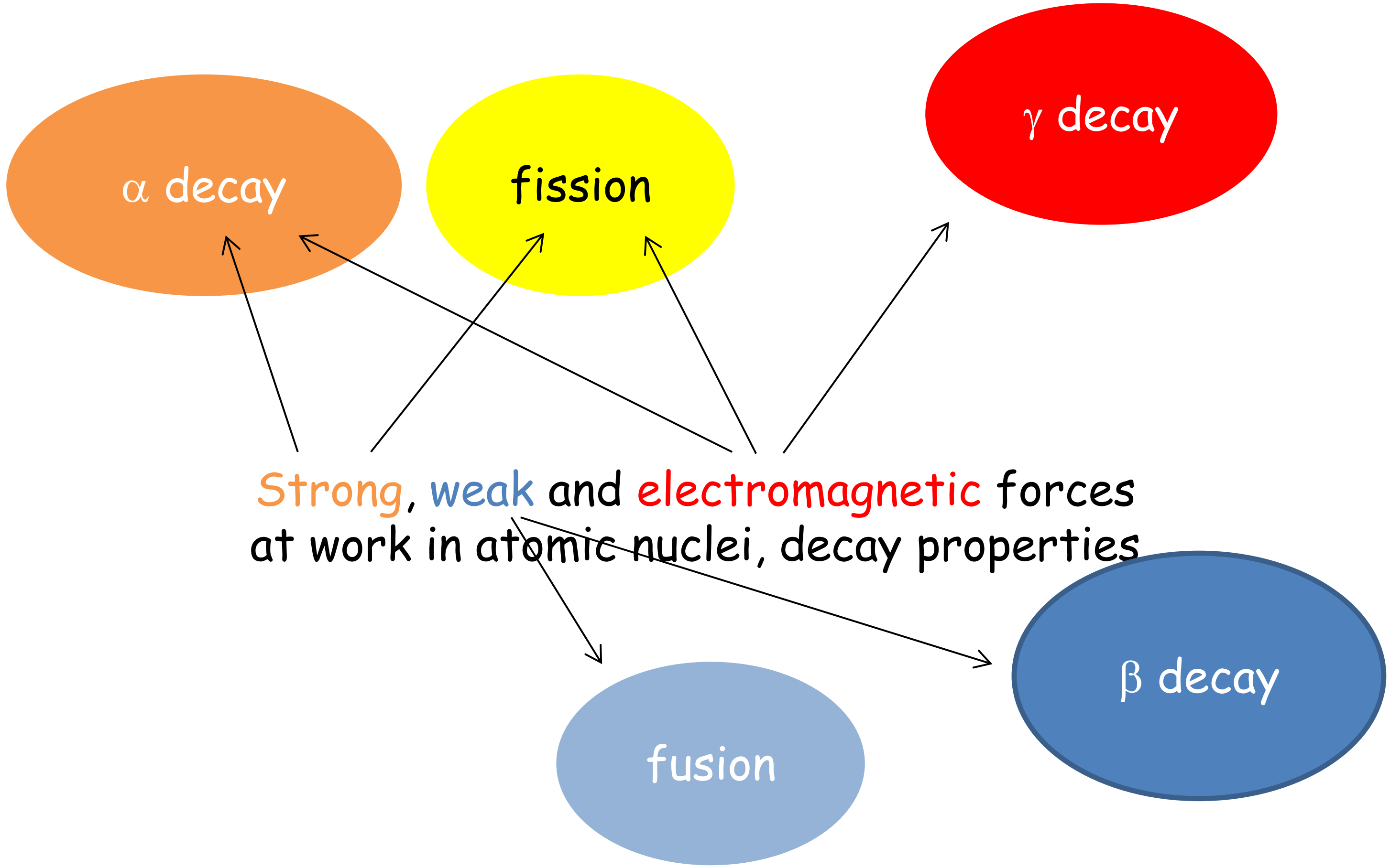
Boundaries of the bound nuclei are not defined yet

Introduction

The Experimental Probes



Introduction



4 interactions:
-strong: acting btw nucleons, keeps nucleus bound
-weak: involving presence of leptons
-electromagnetic: btw charged particles/γ rays

➔ Gravitational : usually neglected owing to small masses involved

Introduction

Decay modes

α decay: $${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha$$

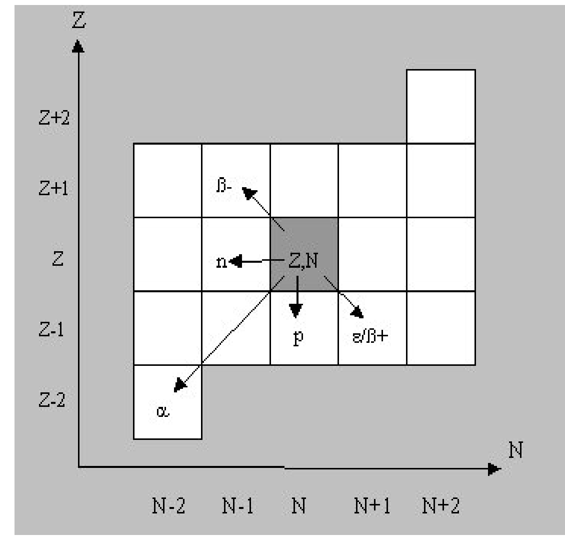
β⁻ decay: $${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \upsilon_e$$

β⁺ decay: $${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + e^{+} + \upsilon_e$$

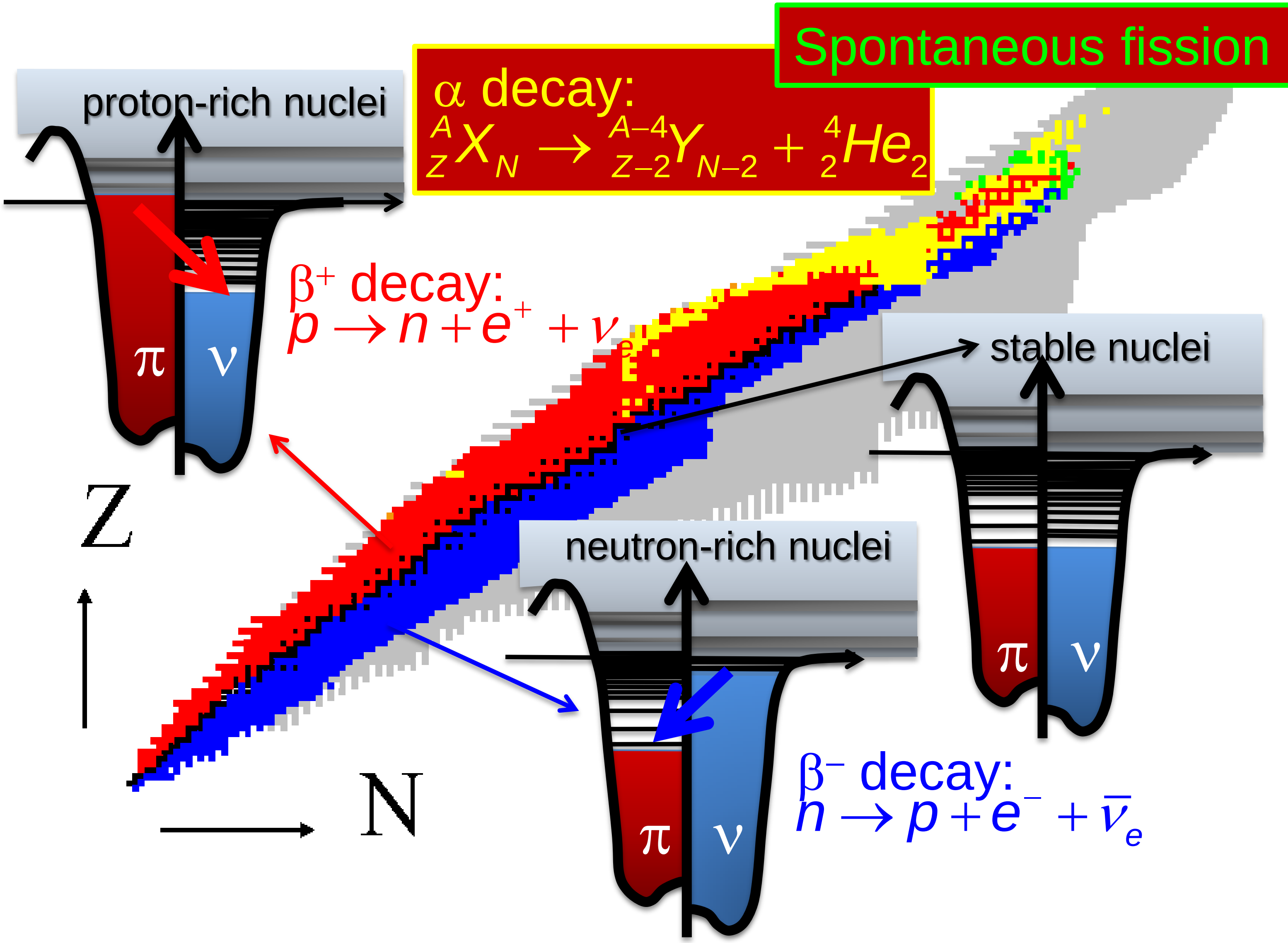
EC: $${}^{A}_{Z}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \upsilon_e$$

Spontaneous Fission

Exotic decay modes: n decay
p decay
cluster emission



The Nuclear Chart: Radioactive Decay Modes



Introduction

Introduction

Useful definitions for decay:

Law of radioactive decay:

$$N(t) = N_0 e^{-\lambda t}$$

λ	decay rate
$\tau = 2\pi/\lambda$	meanlife
$T_{1/2} = \ln 2 * \tau$	half-life

$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \approx 0.693\tau$$

Radioactive half-life

Radioactive decay constant

Mean lifetime

Qvalue = $M_{initial} - M_{final}$

Branching ratio: decay probability of two or more competing processes

Mother/Precursor == Initial/Emitting nucleus
Daughter/Successor = Final nucleus

Introduction

Bateman equations: mathematical model describing abundances and activities in a **decay chain** as a function of time, based on the **decay rates and initial abundances**.

If at a time t, there are $N_i(t)$ atoms of the i-th isotope which decays into the i+1 one with a decay rate λ_i, the amounts of isotopes in the k-th step of the decay chain evolves as:

$$\frac{dN_1(t)}{dt} = -\lambda_1 N_1(t)$$

$$\frac{dN_i(t)}{dt} = -\lambda_i N_i(t) + \lambda_{i-1} N_{i-1}(t)$$

$$\frac{dN_k(t)}{dt} = \lambda_{k-1} N_{k-1}(t)$$

This can be written in an explicit form as:

$$N_n(t) = \prod_{j=1}^{n-1} \lambda_j \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{N_i(0) e^{-\lambda_j t}}{\prod_{p=1,p\neq j}^{n} (\lambda_p - \lambda_j)} \right)$$

This can be extended to cases in which we have many branches

H. Bateman. "Solution of a System of Differential Equations Occurring in the Theory of Radio-active Transformations," Proc. Cambridge Phil. Soc. IS, 423 (1910) https://archive.org/details/cbarchive_122715_solutionofasystemofdifferentia1843

Introduction

Secular equilibrium:

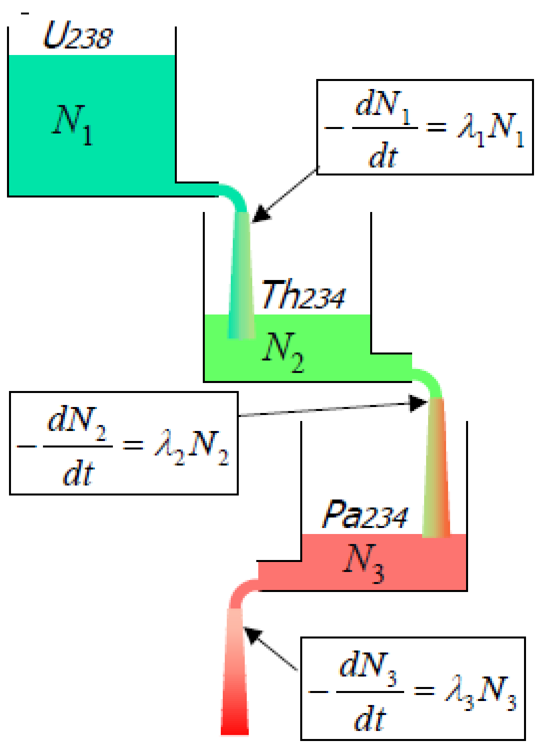
The rate of production and decay of an element is constant

It can be achieved in a decay chain if the daughter B has a much shorter half-life than the mother A

The decay rate of A, which is translated into the production rate of B is constant

The quantity of B accumulates since the number of nuclei which decay in 1s if equal to that produced in 1 s.

This depends on $N_A(t=0)$, λ_A and λ_B



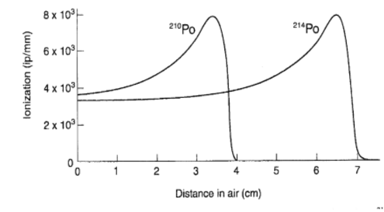
- Each member of the family is a dewar. They are connected and the fill each other in chain
- The rate of emptying (-dN/dt) are function of the level in the dewar N and the decay rate λ
- At equilibrium the rate of evacuation in each dewar is equal
- In nuclear physics rate of decay is the Activity and depend on the decay constant λ
- At equilibrium all activities are equal

Introduction

Detecting α β γ particles: reminder of basic properties

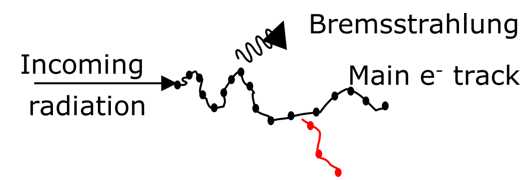
α particle: massive, charged

- ➔ interested in energy, angular distribution
- ➔ spectrometers, Si, plastic detectors



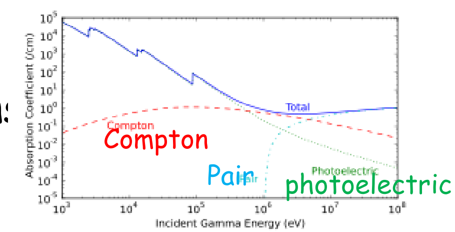
β particles: light, charged

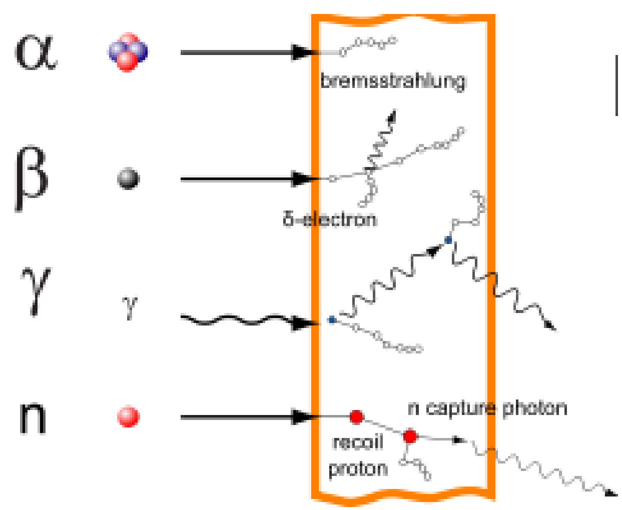
- ➔ interested in energy and correlations
- ➔ e^+ annihilates into two 511 keV γ rays
- ➔ spectrometers, Si, Plastic detectors



γ particles: massless, neutral

- ➔ interested in energy and angular distributions
- ➔ HPGe detectors, Organic scintillators





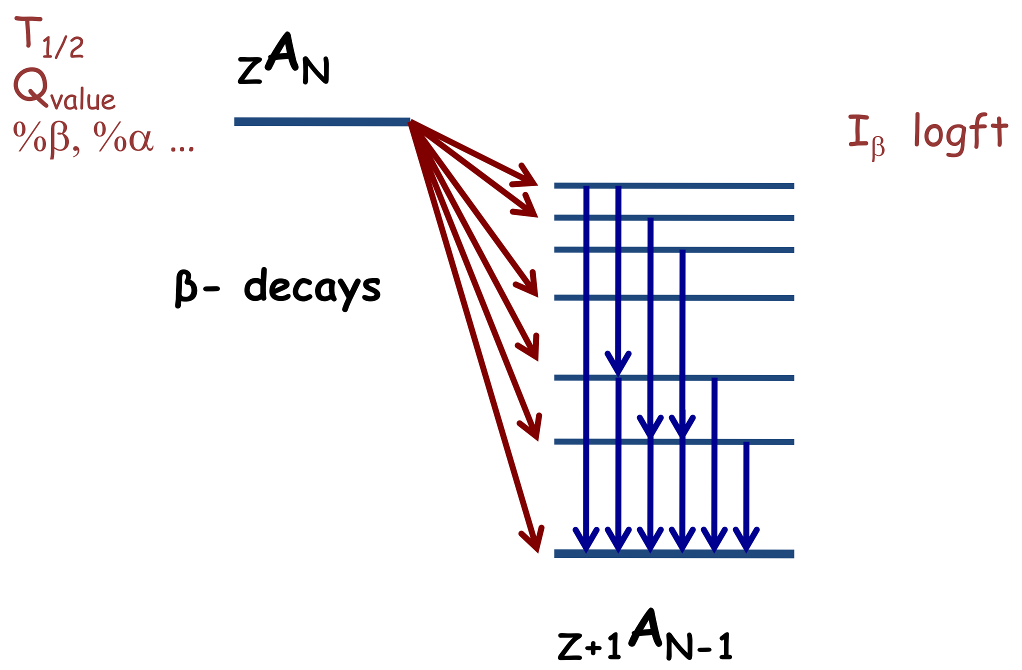
Introduction

Example of detailed study of a decay:

1) Produce and Identify PARENT nucleus: reactions/ISOL/fragmentation

2) Detect the decay: identify the emitted particle α/β
identify competing mechanisms
identify decaying state, g.s. or excited
measure half-life

3) Study properties of DAUGHTER nucleus:
which levels are populated
Branching Ratio btw levels
subsequent decays



Introduction

Producing radioactive beams

relativistic fragmentation/fission of heavy nuclei on thin targets

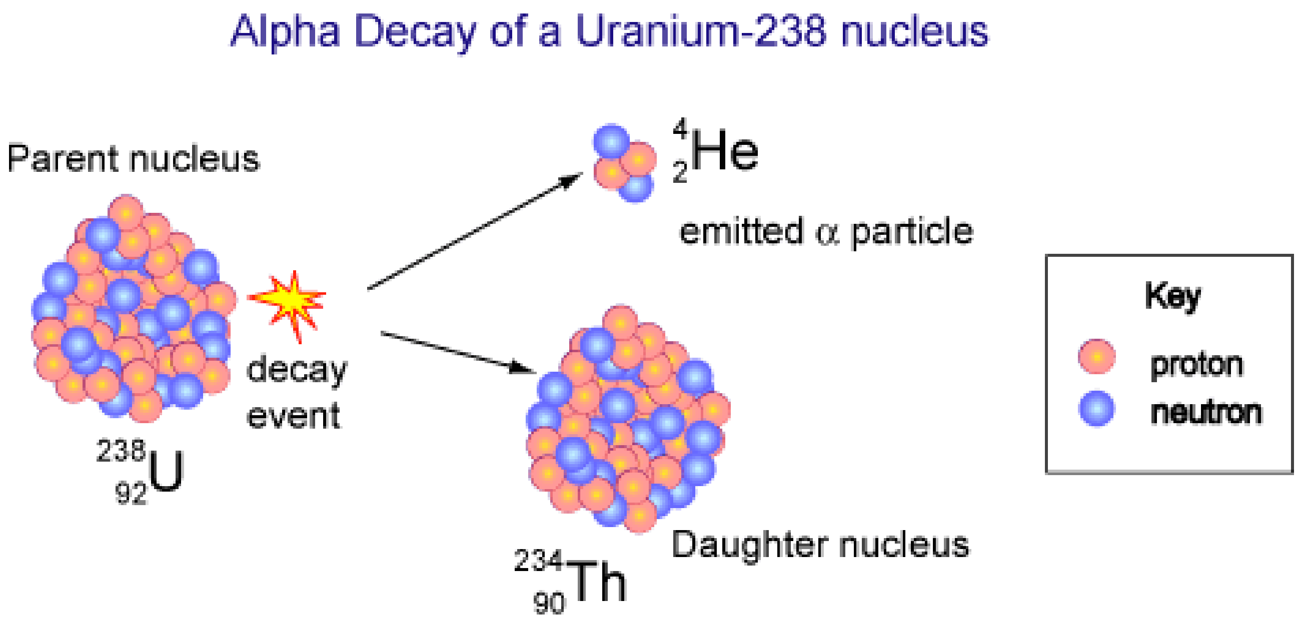
- > 50 MeV/u ➔ production of cocktail beams of many nuclei
- Use of spectrometers to transport/separate nuclei of interest
  ➔ Relatively long decay paths
  Δt > 150-300 ns
- Nuclei are brought to rest in final focal plane and let decay

+ cocktail beam: many nuclei at once
+ both short and long-living species
+ get information already with few particles
- Low cross sections
- Limitation on rate to distinguish contribution from each species

ISOL method, spallation/fission/fragmentation on thick targets, followed by chemical/physical processes to extract desired nuclei

- beams produced at very low energies (60 keV)
- Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species ➔ usually long-living though

+ high cross section
+ no need to re-accelerate beams
+ high rates accepted
- short-living species might not be accessed easily
- Refractory elements
- Presence of long-living impurities (isobaric contamination)

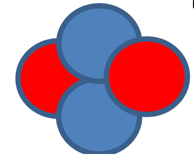

Alpha Decay of a Uranium-238 nucleus
Parent nucleus
238
92
U
decay
event
4
2
He
emitted α particle
234
90
Th
Daughter nucleus
Key
proton
neutron

General Properties of α decay

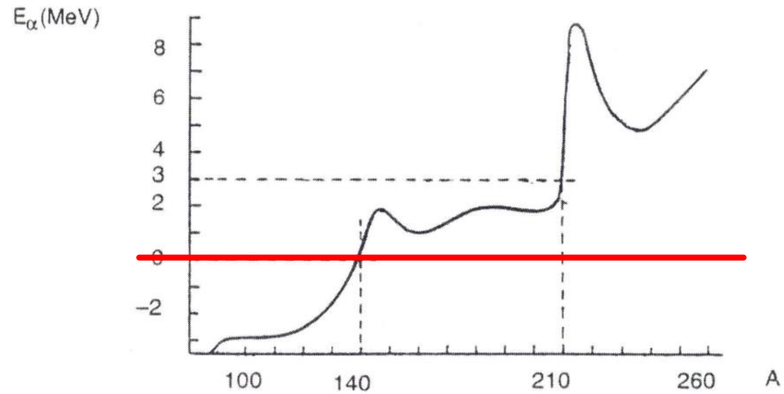
$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \alpha$$

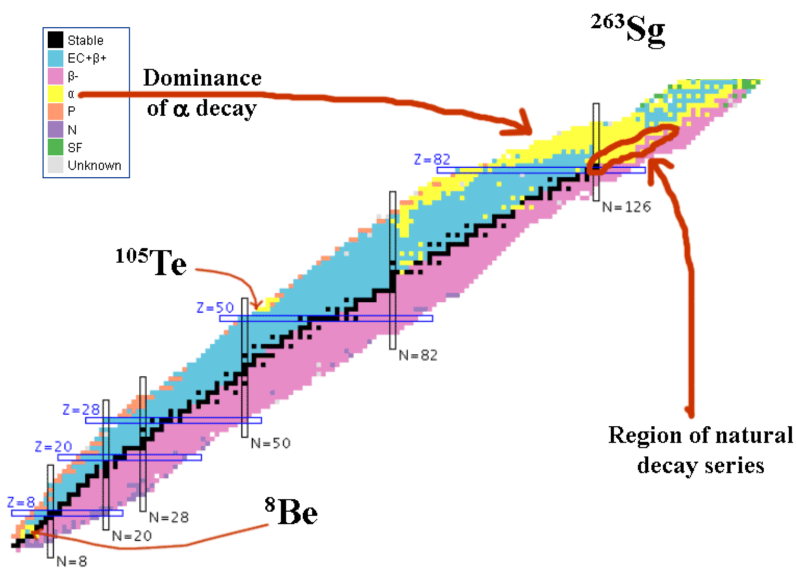
One of the first discoveries in modern physics:
1908 Rutherford shows that emission of radiation is made of nuclei of4He.
$Q=(M_X-M_Y-M_\alpha)c^2$

^4He:
2p + 2n



No α emitters with A<146:
A< 140 Eα<0 : no emission
140<A<210: Eα<3 MeV:decay possible but not probable
A>210 spontaneous decay





Artificial isotopes >Pb decay by α emission
Exceptions: ^8Be ^9Be ^{162}Gd, ^{174}Hf
N-poor with Z=60-80, very short half-lives (s-ms)

General Properties of α decay

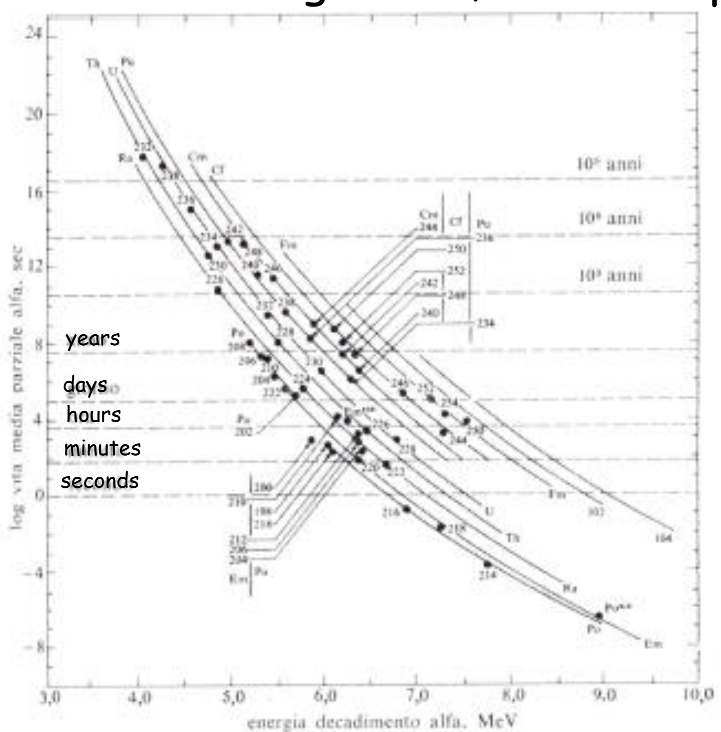
Geiger-Nuttall formula:

$\ln \lambda = A + B \ln E$ ➔ the higher the energy the lower the $T_{1/2}$
$\ln \lambda = a + b \ln R$, $R = E^n$ is the range of α particles in air

$E \div 4\text{-}9$ MeV

Egs: ^{218}Th $Q = 9.85$ MeV, $T_{1/2} = 10^{-7}$ s
^{232}Th $Q = 4.08$ MeV $T_{1/2} = 1.4\ 10^{10}$ y

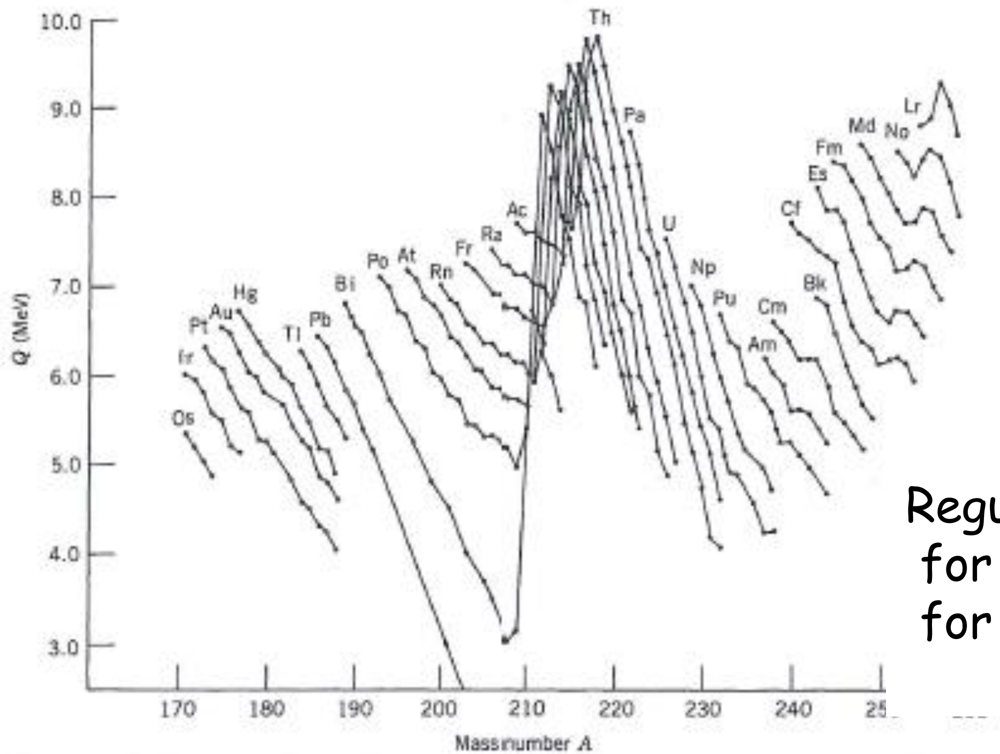
Phenomenologic rule, can be explained by quantum mechanics



Geiger-Nuttal formula explains why α decay is not seen for Q<4 MeV

Large Q➔
large difference btw X and Y
X more unstable
X decays faster

General Properties of α decay



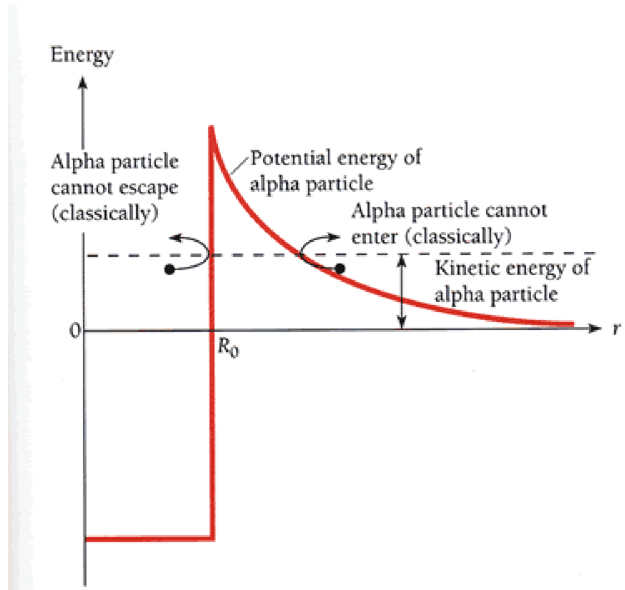
Regular trend for $Z \geq 89$
for a given Z: $E\alpha \downarrow$ $A\uparrow$
for a given A: $E\alpha \uparrow$ $Z\uparrow$

Dependence of Q(A,Z) starting from semi-empirical mass formula:

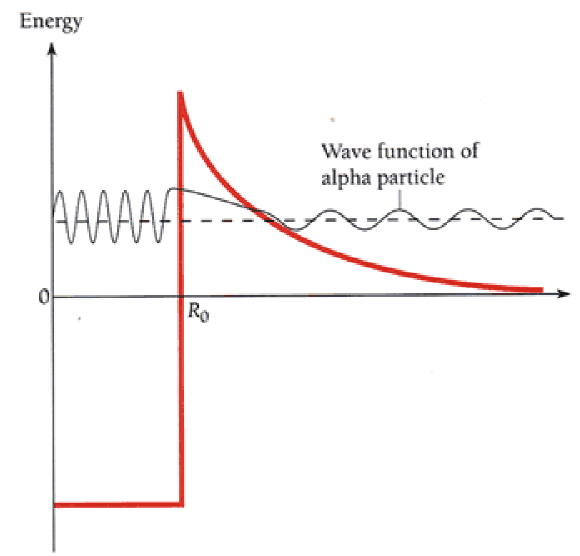
$$Q=28.3-4a_v+8/3a_s\,A^{-1/3}+4a_c\,ZA^{-1/3}(1-Z/3A)-4a_{symm}(1-2Z/A)^2+3a_p\,A^{-7/4}$$

General Properties of α decay

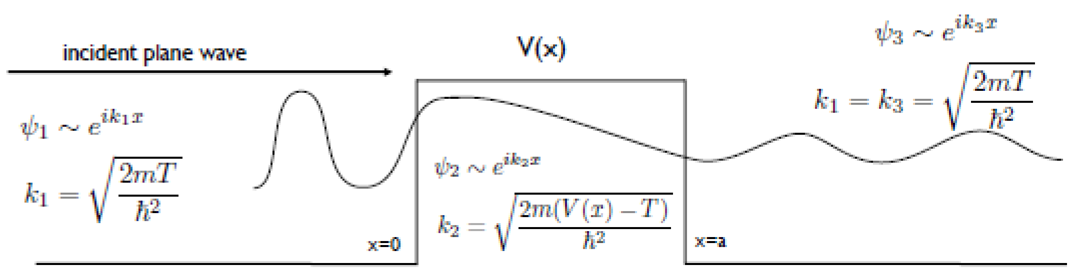
Theory of the emission of a particles: α particle pre-exists in the nucleus and has to overcome the Coulomb barrier



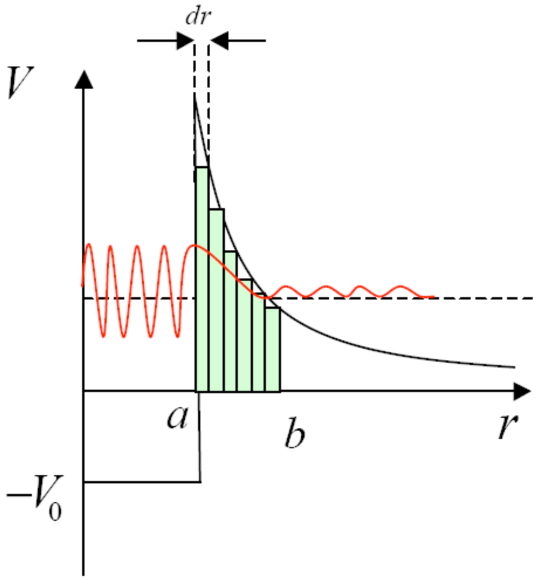
Classical description
HEIGHT of the barrier



Quantum-mechanical description
WIDTH of the barrier



General Properties of α decay



Semi-classical approach:
λ = fP f = knocking frequency
P = probability of transmission thr. barrier
F ~ v/a v= velocity of α particle in DAUGHTER nucleus (K~Q)

Egs: K=8 MeV, v~10^7m/s f=$10^7/10^{-14}$ = 10^{21}/s
if P=10^{-29} λ~10^8

We can consider the Coulomb barrier as a series of infinitesimal rectangular barriers
The probability for penetration of each infinitesimal barrier is:

$$dP = \exp(-2dr\sqrt{\frac{2m}{\hbar^2}(V(r) - Q)})$$

Or $P=e^{-2G}$ where G is the GAMOW FACTOR

$$G = \sqrt{\frac{2m}{\hbar^2}}\int_a^b \sqrt{(V(r) - Q}\,\mathrm{dr}$$

General Properties of α decay

Low momentum approximation:

$$Q = \frac{1}{2}mv^2 \ll \frac{zZe^2}{4\pi\epsilon_0 R}$$

Particle energy lower barrier

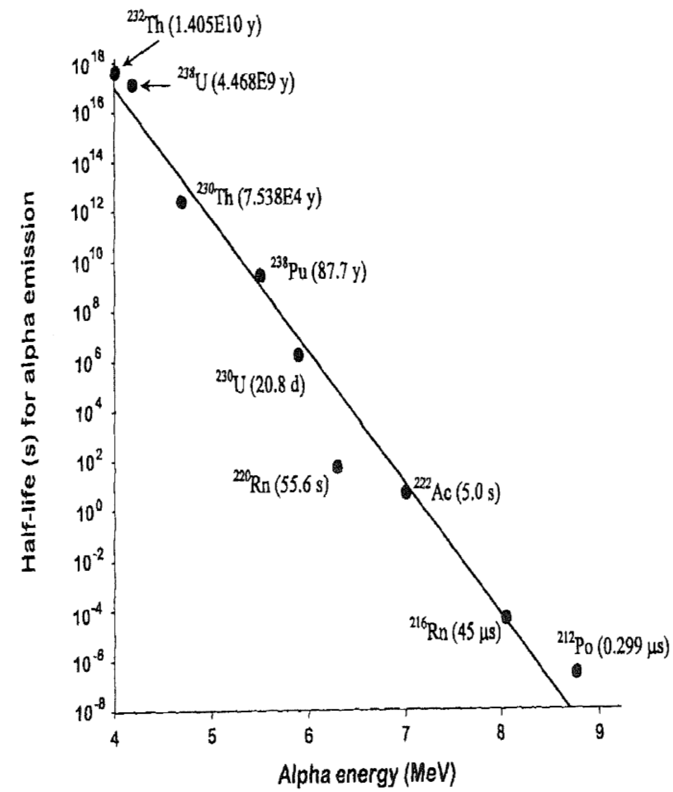
$$G \cong \sqrt{m}\frac{zZe^2}{4\pi\epsilon_0 R}$$

That is

$$G \propto Z\sqrt{\frac{m}{Q}}$$

Then $\lambda = fP$, $P=e^{-2G}$

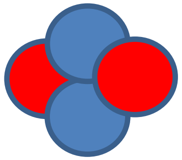
And $log\lambda = 57 - 1.7Z\sqrt{\frac{m}{Q}}$



Approximations:

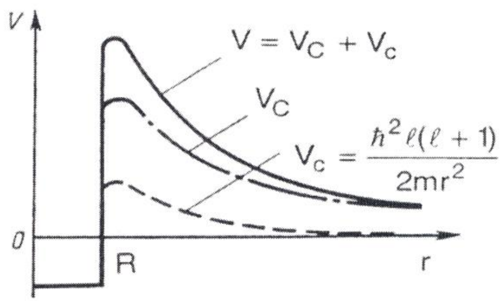
- Probability of pre-formation
- Fermi golden rule
- Only decay from and to gs
- Spherical symmetry, no deformation ➔ usually not true
- Angular momentum

General Properties of α decay



^{4}He:
2p + 2n

I=0, n and p coupled into pairs
Total ang. momentum is only given by orbital component, $l\alpha$



For l > 0 one needs to account for centrifugal barrier

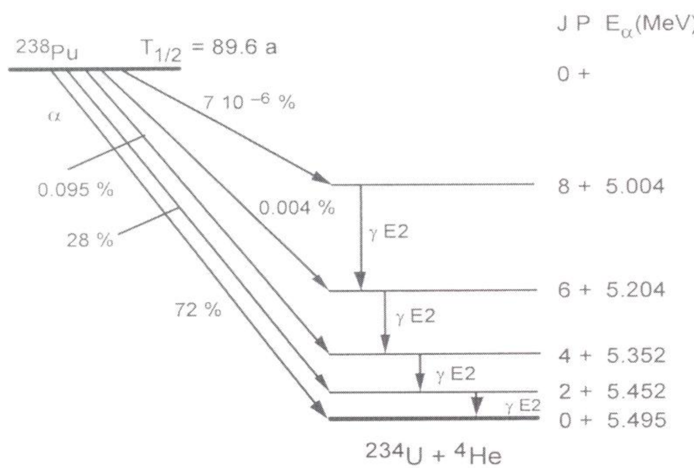
Conservation of angular momentum
$J_i = J_f + I\alpha$
Conservation of parity, depending on $l\alpha$
Conservation of isospin I

Alpha decay is sensitive to specific shell-model orbitals:
*Strong Q value dependence favours population of low-lying states
* Formation probability is sensitive to overlap of initial and final wave functions

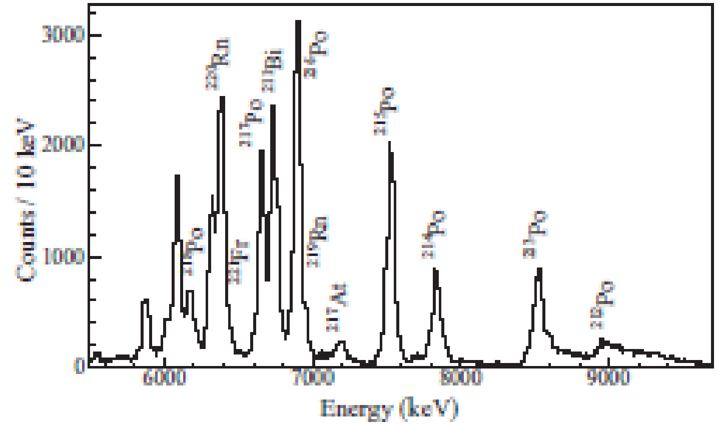
General Properties of α decay

- Observables for α decay are: $E\alpha$, $I\alpha$, $T_{1/2}$,$BR\alpha$ branching ratio
- A decay can occur either from gs or excited states and decay can be fragmented onto several excited states:

  FINE STRUCTURE of α decay
- Decay from each nucleus has specific α lines



α spectrum measured in a Si detector



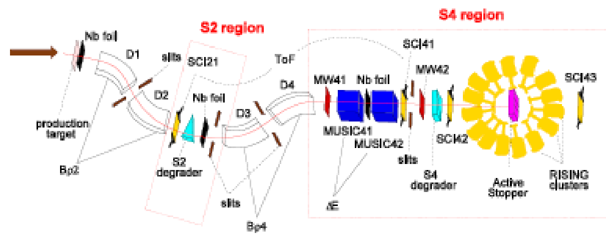
α tagging to measure new half-lives

A.I.Morales et al.

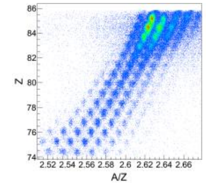
PHYSICAL REVIEW C 89, 014324 (2014)

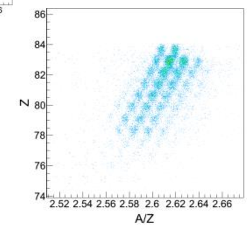
β-decay studies of neutron-rich Tl, Pb, and Bi isotopes

Fragmentation reaction of ^{238}U @1GeV/u on ^{9}Be target
Population of isotopes "north" of 208Pb

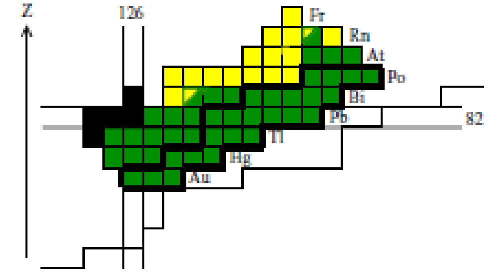


Cocktail beam



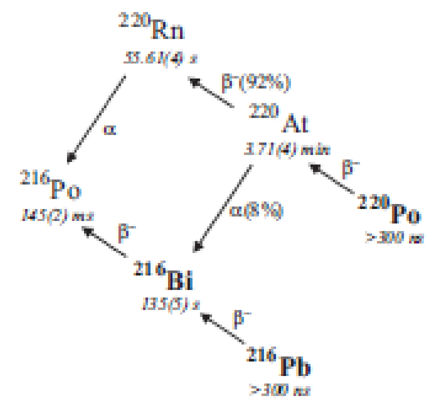


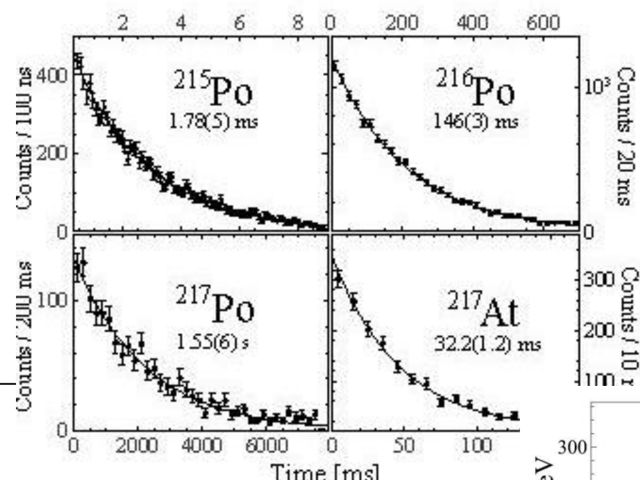
Implanted ions

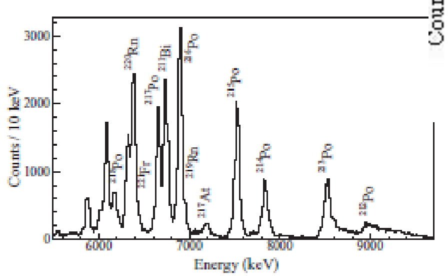


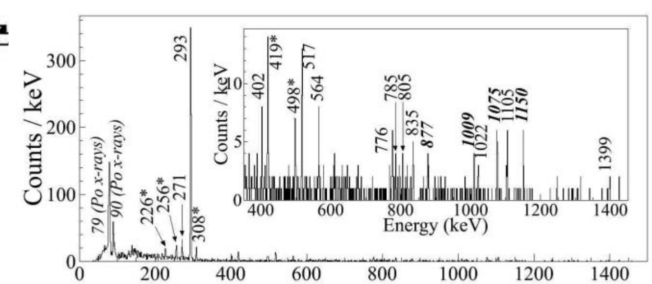
α tagging allows to follow the decay chain up to grand-mother and extract correct half-life and decay schemes

- Unique identification of α decay
- α–β–β correlation
- Batemann equations









a tagging to measure new half-lives

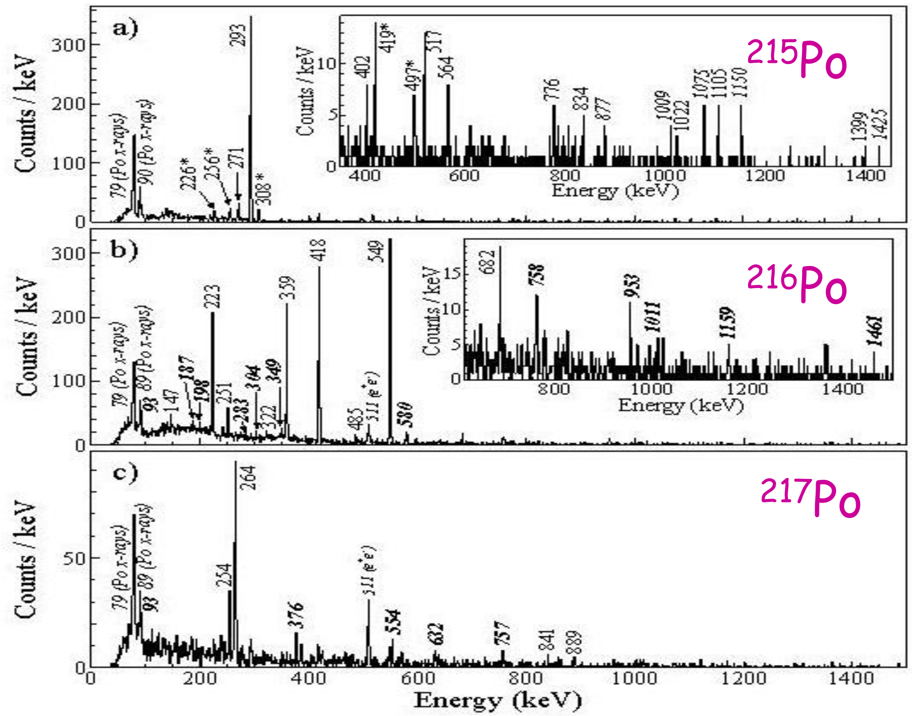
A.I.Morales et al.

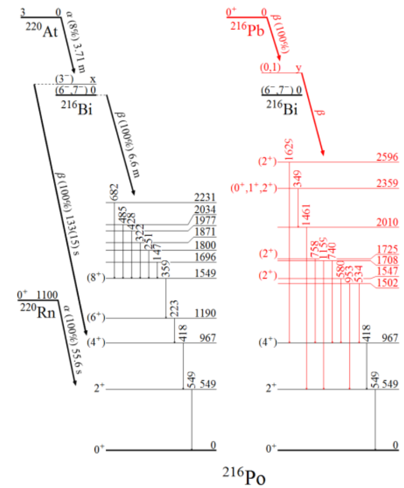
PHYSICAL REVIEW C 89, 014324 (2014)

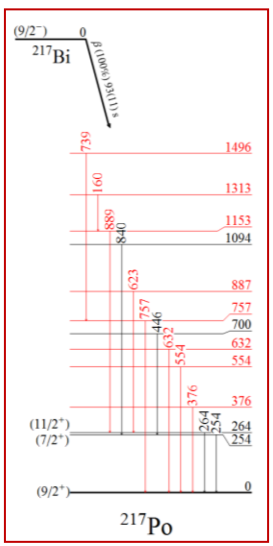
β-decay studies of neutron-rich Tl, Pb, and Bi isotopes

α–β–β–γ correlation: identification of decay schemes

γ–γ coincidences help locate transitions







General Properties of α decay

Observables for a decay are: $E\alpha$, $I\alpha$, $T_{1/2}$,$BR\alpha$ branching ratio

Formation probability, expressed as reduced α width:

$$\delta^2 = \frac{h \ln(2) b_\alpha}{T_{1/2} 100 P}$$

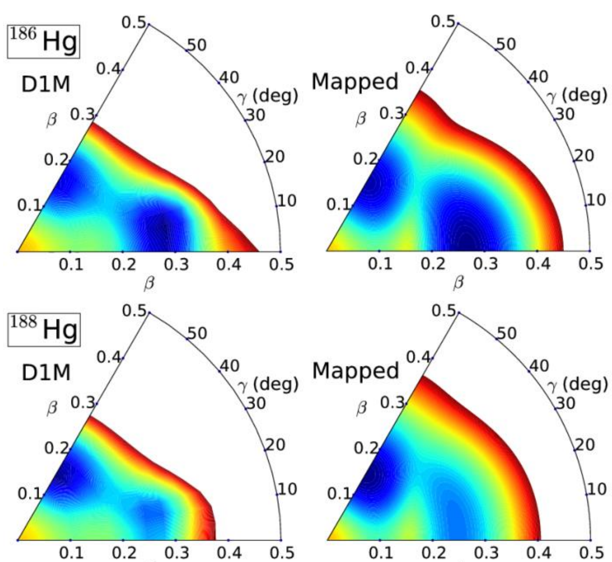
P barrier penetration probability

If the decay occurs to many levels in the daughter we can define the HF(hindrance factor) to the excited state α_2 relative to the gs α_1 as:

$$HF = \frac{I_{\alpha 1} P_{\alpha 2}}{I_{\alpha 2} P_{\alpha 1}}$$

And HF is sensitive to changes in spin and parity btw initial and final levels

In ΔI =0, 0+-> 0+ transitions HF÷0.5-85



α decay can be a complementary tool to study low-lying 0+ states in even-even nuclei

➔ Applied to the region above ^{208}Pb where shape coexistence is predicted

Potential Energy Surfaces in (β.γ) plane show presence of competing minima

a decay as a fingerprint of deformation

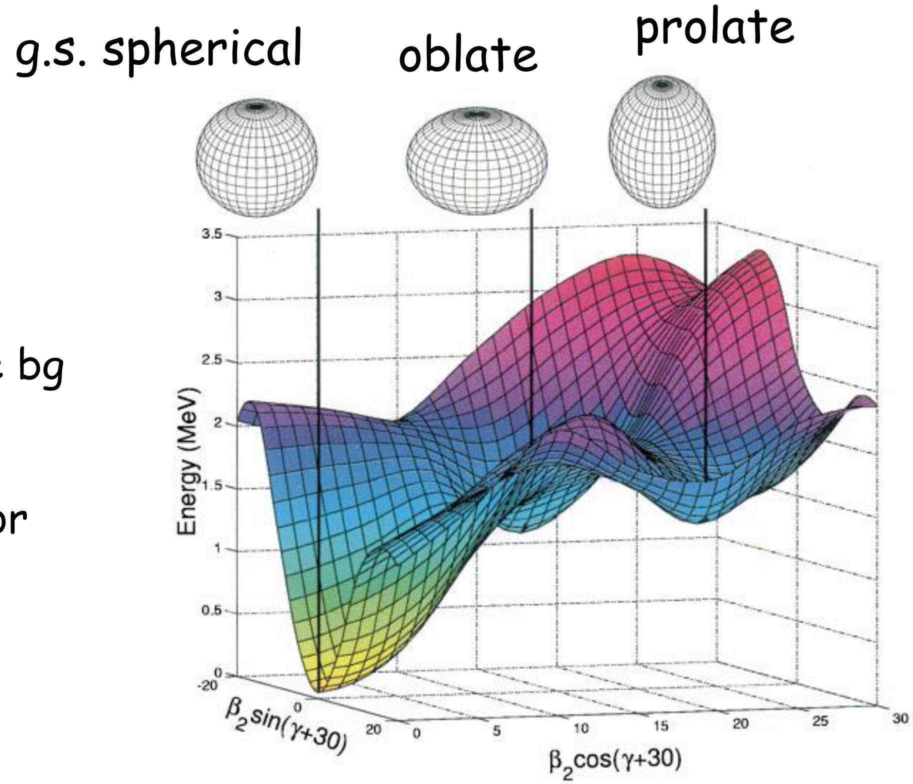
A. Andreyev et al., Nature 405 (2000) 430

letters to nature

A triplet of differently shaped spin-zero states in the atomic nucleus ^{186}Pb

PES calculated in Woods-Saxon approx.
β_2= elongation along symmetry axis
γ= degree of triaxiality

^{186}Pb
Three competing minima
Three 0+ states

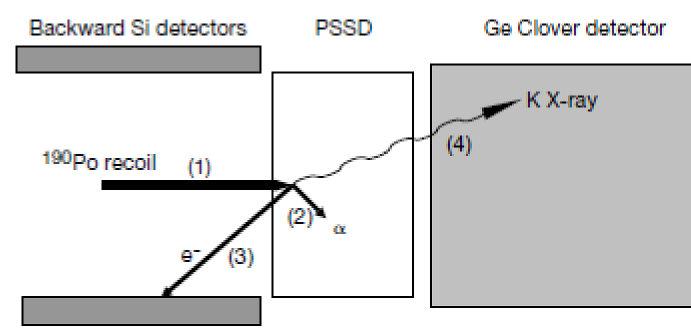


^{190}Po → ^{186}Pb+α

^{190}Pb populated in fusion-evaporation reaction → large bg owing to open reaction ch.

SHIP velocity filter separator

Detector array:
PSSD Si det. for ion-α correlations
6 Si for conversion electron
HPGe for α–γ correlations

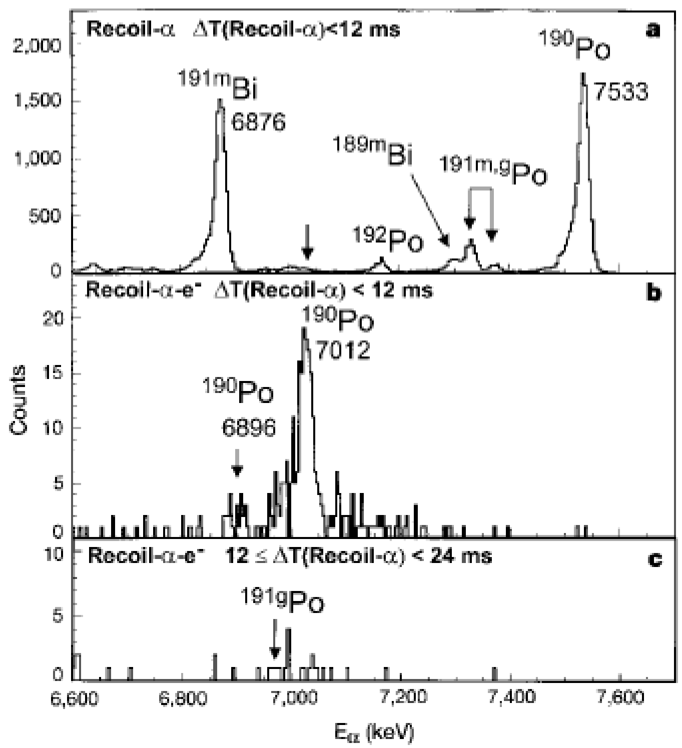


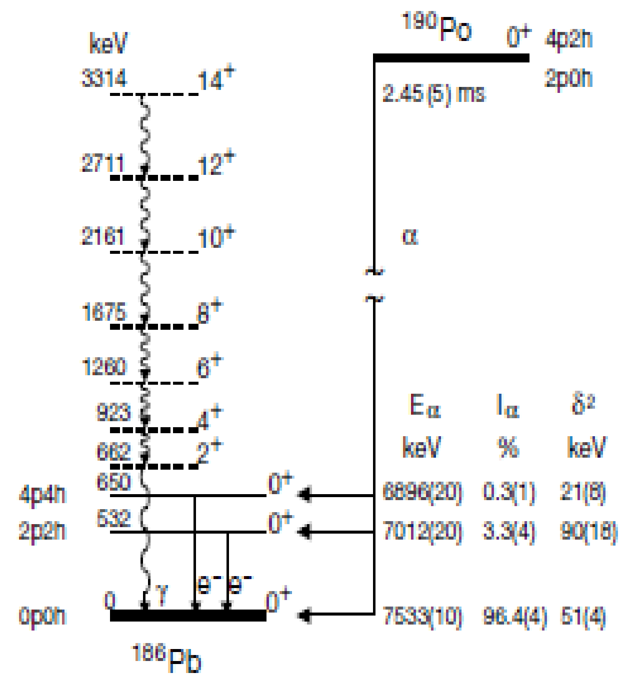
a decay as a fingerprint of deformation

A. Andreyev et al., Nature 405 (2000) 430

Measurement of α particles with energies corresponding to different low-lying 0^+ states, $T_{1/2}$ and HF

HF➔ can be related to single-particle ➔Nature of the levels

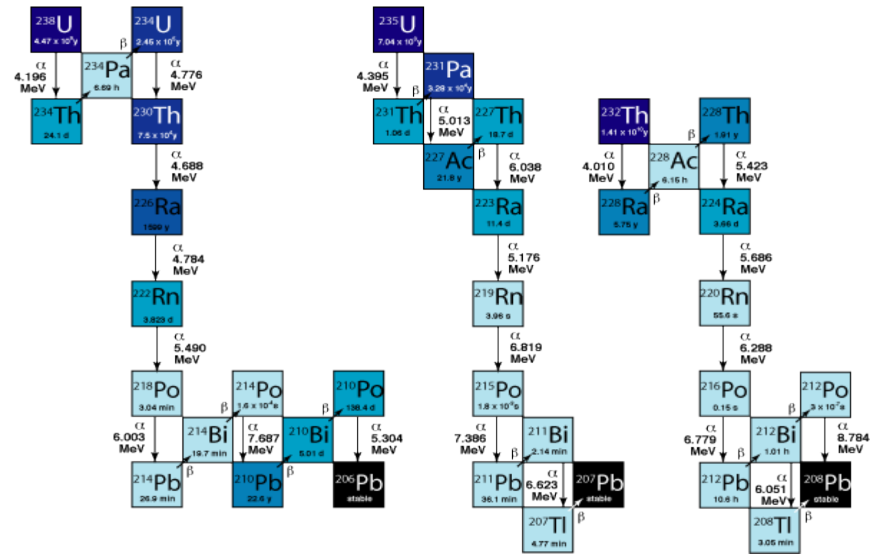


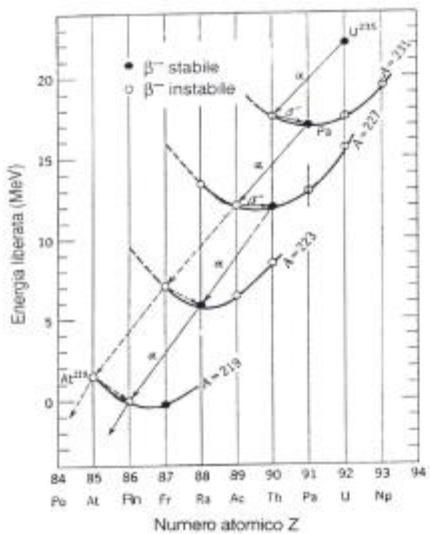


General Properties of α decay

Radioactive families: defined by specific energies of a decays

1)4n: Th series
2)4n+1: Np series
3)4n+2: U series
4) 4n+3:At series

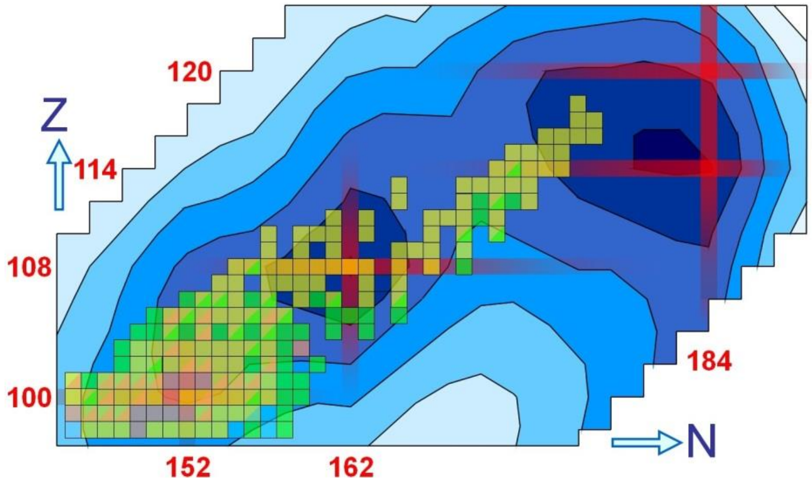




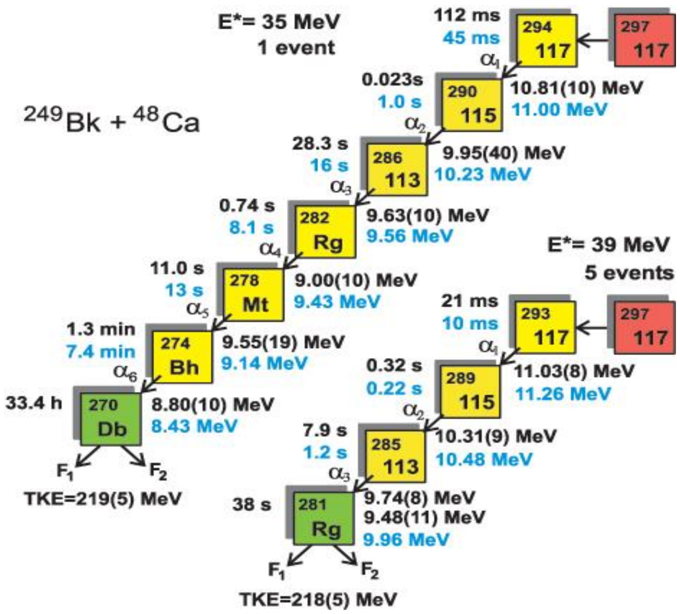
Heavy nuclei have neutron excess, but with a decay they lose in percentage more protons: daughter nuclei are beta emitters

α decay tagging: SHE

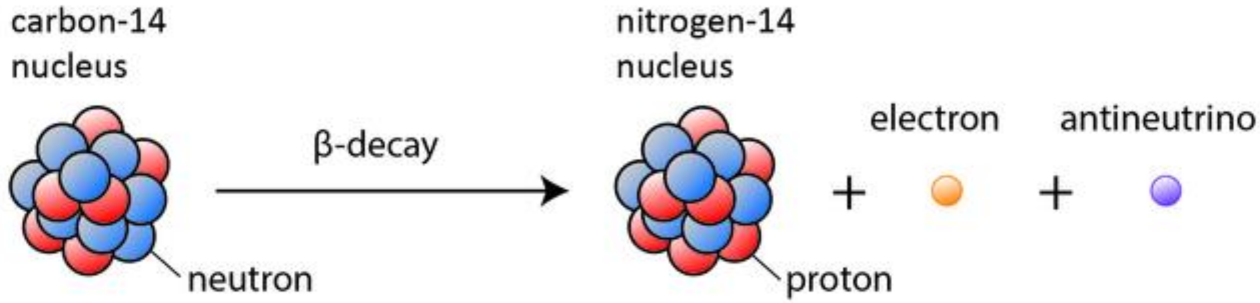
One important application is that of a decay tagging of the decay of SHE nuclei
Limits of stability of nuclear systems with very high number of proton is not well defined



To recognize the decay from an unknown nucleus one follows the decay chain down to known cases

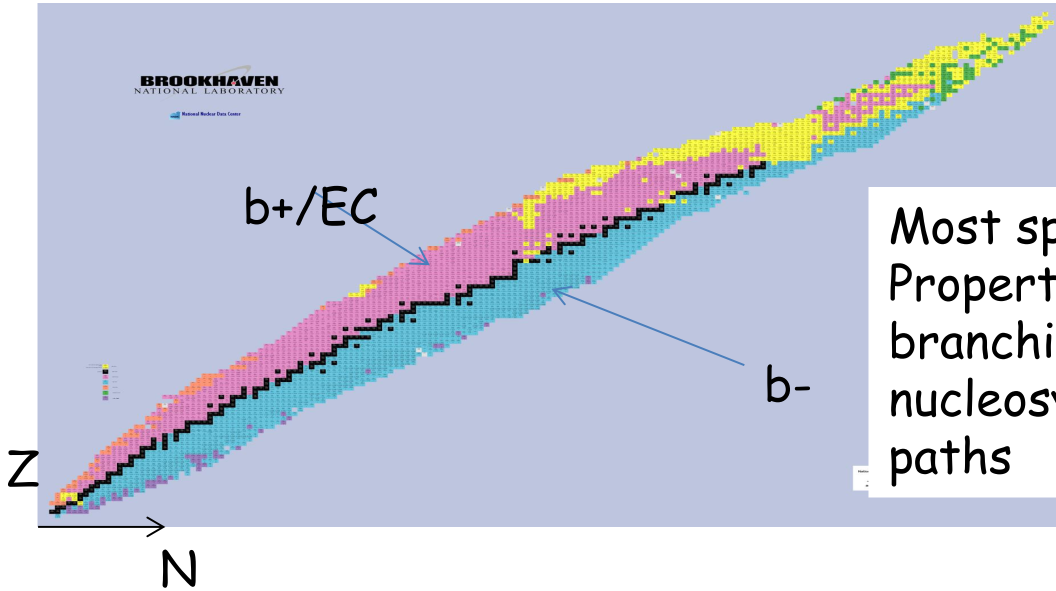


Very low production cross sections
Very low count rates
Long experiments



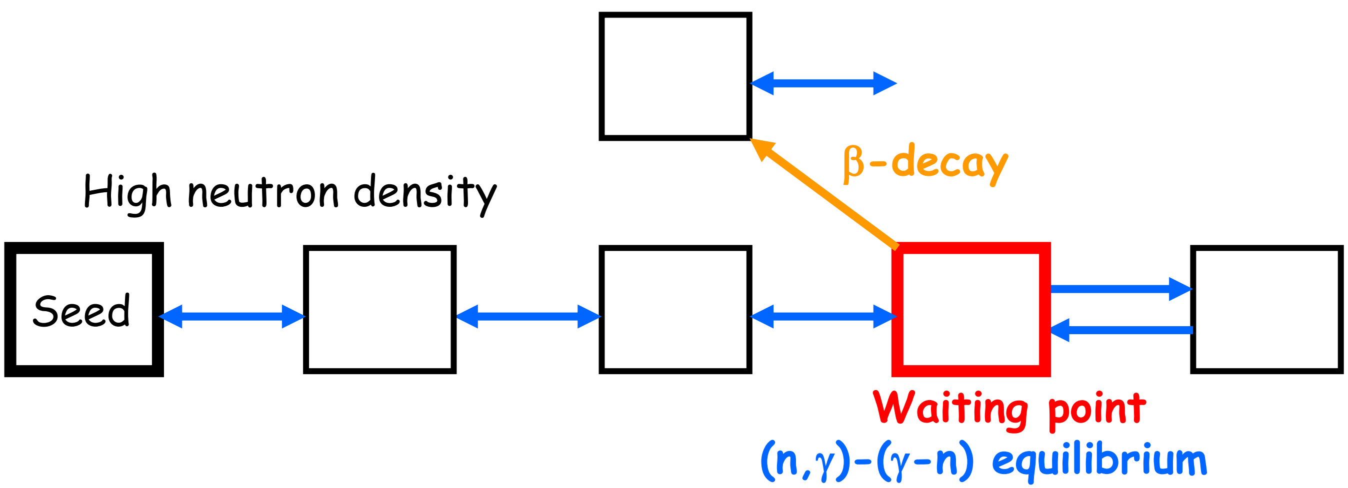
carbon-14
nucleus
β-decay
nitrogen-14
nucleus
electron
antineutrino
+
+
neutron
proton

General Properties of β decay



Most species decay via β decay
Properties (half-lives/ branching ratios) help define nucleosynthesis formation paths

R-process basics: Element formation beyond iron involving rapid neutron capture and radioactive decay

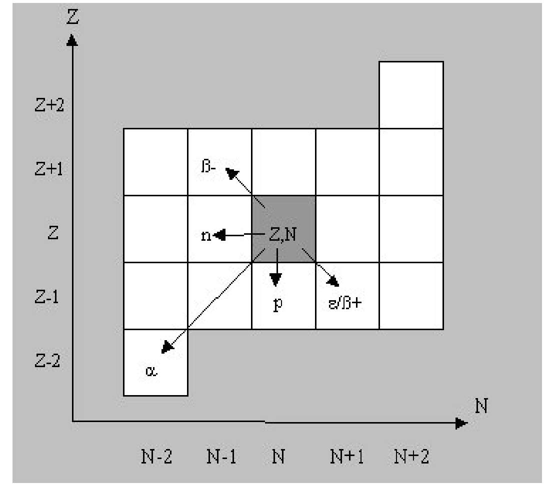


General Properties of β decay

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \nu_e$$ β⁻ decay

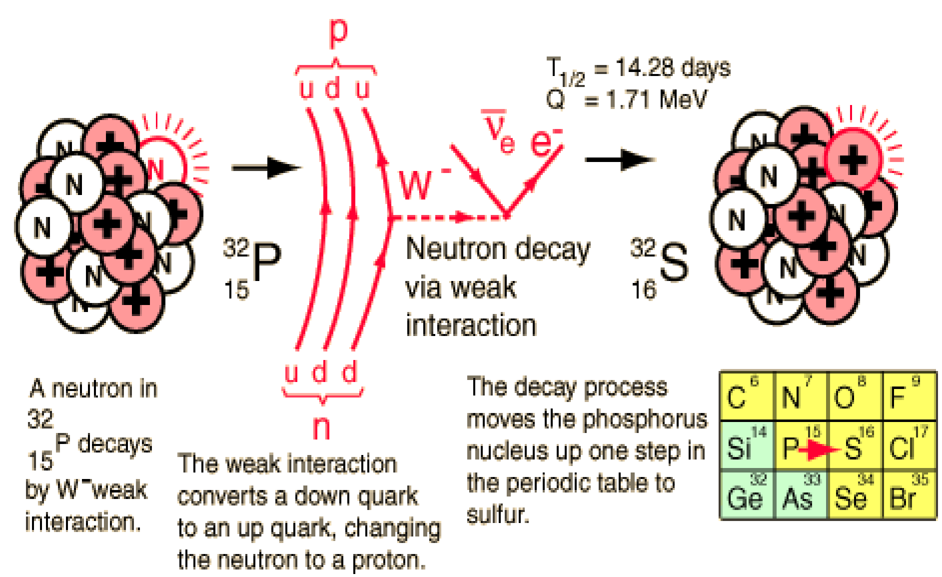
$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e$$ β⁺ decay

$$^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu_e$$ EC



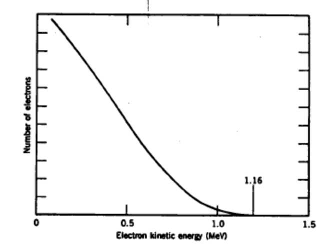
β decay is a weak interaction "semi-leptonic" decay

The quark level Feynman diagram for β⁻ decay is shown here:



General Properties of β decay

The Q value in β decay is effectively shared between the electron and antineutrino.
This is the case of *gs-> gs* decay



re 9.1 The continuous electron distribution from the β decay of ^{210}Bi (also RaE in the literature).

Q value for β^- decay is

$$Q_{\beta^-} = \left(M(A,Z) - M(A,Z+1)\right)c^2$$

Q_β Sum of the energy of the electron (positron) and antineutrino (neutrino)

$$Q_{\beta^-} = T_{M(A,Z+1)^+} + T_e + T_\nu \approx T_e + T_\nu \qquad \left(\text{since } T_{M(A,Z+1)^+} < keV\right)$$

$$Q_{\beta^-} = (T_e)_{\max} = (T_\nu)_{\max}$$ If the other term is null

$$Q_{\beta^+} = M(A,Z) - M(A,Z-1) - 2m_e c^2$$

For electron capture:

$$Q_{EC} = \left(M(A,Z) - M'(A,Z-1)\right)c^2 - B_n$$

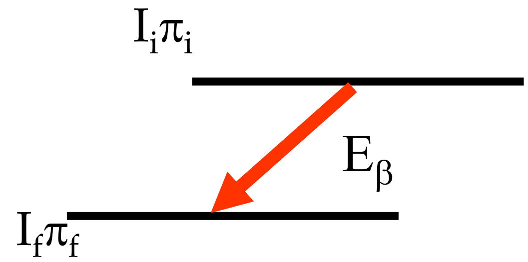
B_n *binding energy of* $n-$ *shell electron*

NB: EC and β+ are not always competing:
if β+ , EC is possible, the contrary is not guaranteed

Note these are atomic masses

General Properties of β decay

$$I_i = I_f + L_\beta + S_\beta$$



$$L_\beta = l_{\beta-(\beta+)} + l_{\tilde{\nu}(\nu)}$$

$$\pi_i \pi_f = (-1)^{L_\beta}$$

$$S_\beta = s_{\beta-(\beta+)} + s_{\tilde{\nu}(\nu\nu} = \begin{cases} 0 & \uparrow\downarrow \\ 1 & \downarrow\downarrow \text{or} \uparrow\uparrow \end{cases}$$

$L_\beta = n$ defines the degree of forbiddenness (n)

allowed

when $L_\beta = n = 0$

and $\pi_i \pi_f = +1$

Electron and neutrino do not carry angular momentum

forbidden

when the angular momentum conservation requires that $L_\beta = n > 0$ and/or $\pi_i \pi_f = -1$

$$\Delta I = \left| I_i - I_f \right| \equiv 0,1$$

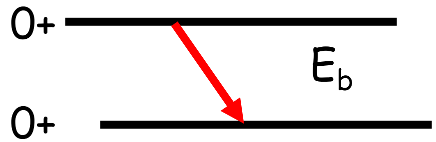
General Properties of β decay

Selection rules for possible decays

Type of transition	Order of forbiddenness	ΔI	$\pi_i \pi_f$
Allowed		0,+1	+1
Forbidden unique	1 2 3 4 .	∓ 2 ∓ 3 ∓ 4 ∓ 5 .	-1 +1 -1 +1 .
Forbidden	1 2 3 4 .	0, ∓ 1 ∓ 2 ∓ 3 ∓ 4 .	-1 +1 -1 +1 .

Classification of **allowed decays** $(\pi_i \pi_f = +1)$

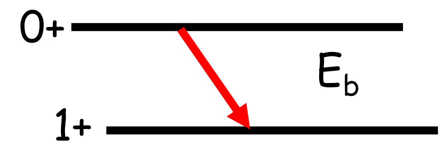
Fermi



$$\Delta I = \left| I_i - I_f \right| \equiv 0$$

$$L_\beta = 0 \qquad S_\beta = 0 \downarrow\uparrow$$

Gamow-Teller

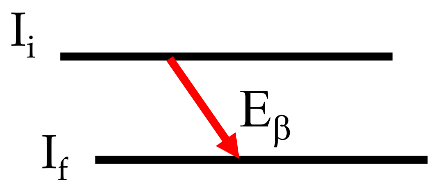


$$\Delta I = \left| I_i - I_f \right| \equiv 1$$

$$L_\beta = 0 \quad S_\beta = 1 \uparrow\uparrow or \downarrow\downarrow$$

Useful empirical rules

The fifth power beta decay rule: the speed of a β transition increases approximately in proportion to the fifth power of the total transition energy



$$\frac{1}{\tau} \propto [(M(Z) - M(Z \pm 1))c^2]^5$$

- depends on spin and parity changes between the initial and final state
- additional hindrance due to nuclear structure effects :

  isospin, “l-forbidden”, “K-forbidden”, etc.

Fermi Golden Rule

Treat beta decay as a transition that depends upon the strength of coupling between the initial and final states
Decay constant is given by Fermi's Golden Rule

$$\lambda_\beta = \frac{2\pi}{\hbar}|M|^2 \rho(E_f); M = \int \psi_f V \psi_i dv$$

➔Electron and neutrino do not pre-exist in atom but are formed at the time of decay

➔The decay is the result of the interaction btw the nucleon and the field produced by the electron-antineutrino couple ➔ weak interaction

- Perturbation theory can be applied since the interaction is "weak"
- M matrix element which couples the initial and final states

- Rate proportional to the strength of the coupling between the initial and final states factored by the density of final states available to the system electron-antineutrino

$V=g\,\delta(\mathbf{r}_e-\mathbf{r})\delta(\mathbf{r}_\nu-\mathbf{r})$ g is the "intensity" of the interaction
There are two values: g_F e g_{GT}

General Properties of β decay

$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$$

partial half-life of a given β⁻ (β⁺,EC) decay branch (*i*)

$$\frac{\ln 2}{T_{1/2}^{n}} = \frac{g^2}{2\pi^3}\int_1^W p_e W_e (W_0 - W_e)^2 F(Z, W_e) C_n dW_e$$

g – weak interaction coupling constant

p_e – momentum of the β particle

W_e – total energy of the β particle

W_0 – maximum energy of the β particle

$F(Z,W_e)$ – Fermi function – distortion of the β particle wave function by the nuclear charge

C_n – shape factor

Z – atomic number

$$K = 64\pi^4 m_o^5 c^4 g^2 / h^7 \qquad \lambda = \frac{\ln 2}{t_{1/2}} = K\left|M_{if}\right|^2 f_o$$

$$f_o = \int_1^{W_o} F(Z,W) W (W^2 - 1)^{1/2} (W_o - W)^2 dW$$

General Properties of β decay

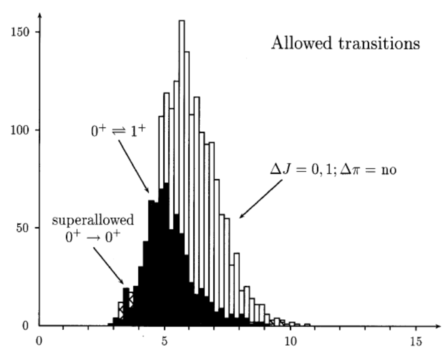
Comparative Half Lives

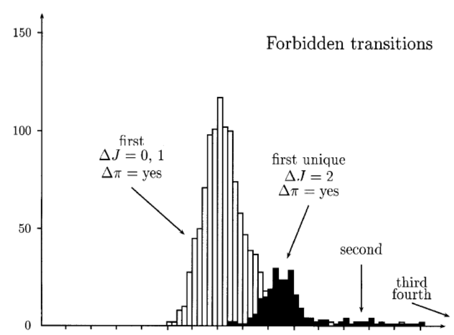
Based on probability of electron energy emission coupled with spectrum and the Coulomb correction $f_o t_{1/2}$ is called the comparative half life of a transition

$$f\tau = \frac{2\pi^3\hbar^7c^3}{g^2|M_{if}|2}$$

Assumes matrix element is independent of energy (true for allowed transitions) Yields $f\tau$ (or $f_o t_{1/2}$), comparative half-life may be thought of as the half life corrected for differences in Z and energy

ALLOWED transitions second term is independent on nucleus,
➔ ft has the same value for all allowed transitions
For forbidden decays ft increases with degree of forbiddenness





Review Of Log*ft* Values
In β Decay*

Nuclear Data Sheets 84, 487 (1998)
Article No. DS980015

Measuring logft

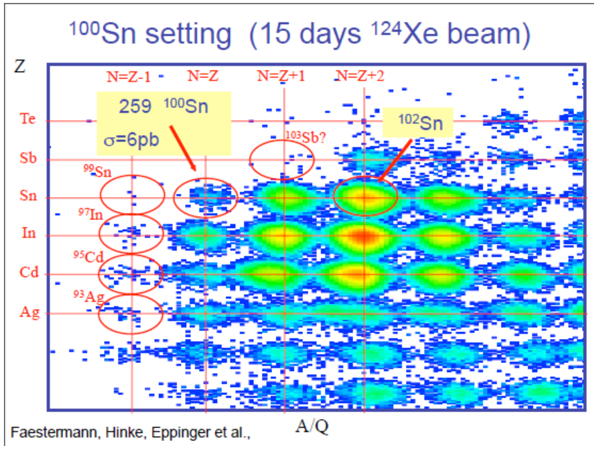
Nature 486, 341 (2012)

doi:10.1038/nature11116

Superallowed Gamow–Teller decay of the doubly magic nucleus ^{100}Sn

^{100}Sn N=Z=50
Heaviest N=Z nucleus

Relativistic Fragmentation reaction
^{124}Xe beam on ^{9}Be target



~260 ^{100}Sn nuclei produced (0.75/h)
~ 126 fully reconstructed decay chains

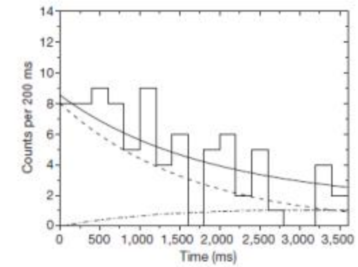
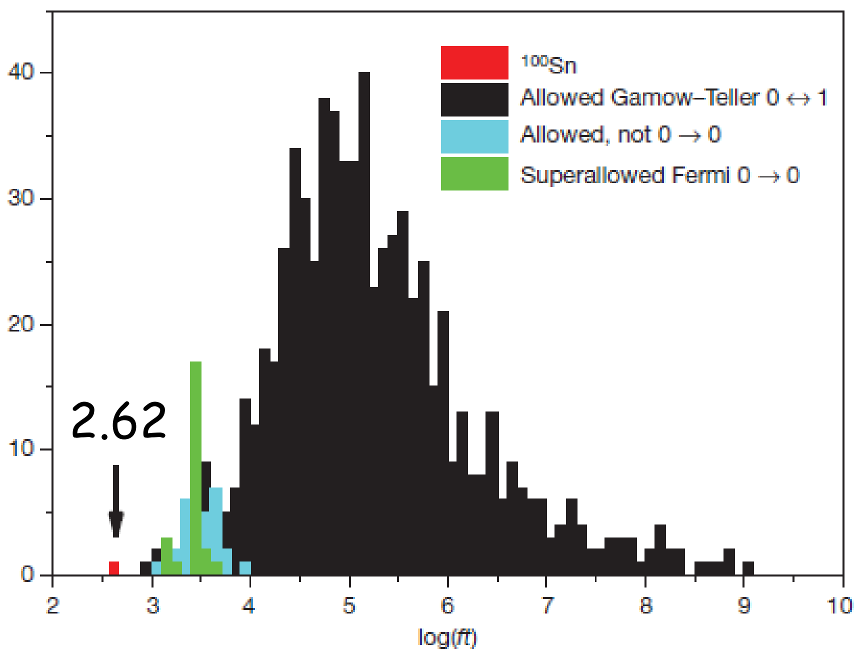


Figure 2 | Time distribution of first decay events. The histogram shows the observed time distribution of all first decay events in the nearest-neighbouring pixels after implantation of ^{100}Sn nuclei. Decay curves resulting from the MLH analysis are shown individually for ^{100}Sn (dashed) and its daughter nucleus ^{100}In (dash–dot). The solid line shows the sum of these decay curves and takes into account a small amount of random background.



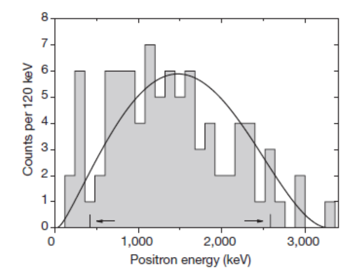


Figure 5 | Distribution of the positron energies emitted in the β-decay of ^{100}Sn. The spectrum contains only decay events that can be assigned to ^{100}Sn decays with a probability of at least 75%. The MLH fit was applied to the region between 400 and 2,600 keV, which is indicated with markers. The solid curve illustrates the shape of the best-fitting single-component β-decay phase space function determined by MLH analysis.

Superallowed decays

Standard model description of the mixing btw quark flavours: CKM (Cabibbo Kobayashi Maskawa) mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{V_{ud} \quad V_{us} \quad V_{ub}} \\ V_{cd} \quad V_{cs} \quad V_{cb} \\ V_{td} \quad V_{ts} \quad V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$

Quark Weak states

Quark Mass states

CKM is a unitary matrix. If not there is physics beyond SM
To test this we concentrate to the first line, which is known with greater precision

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

Vud from β decay
Known with highest precision
Leading term

Vus from K meson decay:
$K^+ \to \pi^0 e^+ \nu$

Vub B meson decay
small contributions

Superallowed decays

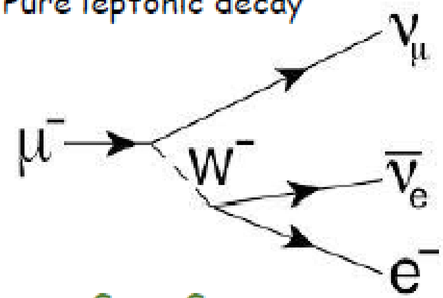
Test of fundamental symmetries of the weak interaction

1) Verify the Conserved Vector Current hypothesis:

   G_F is independent on nuclear interaction

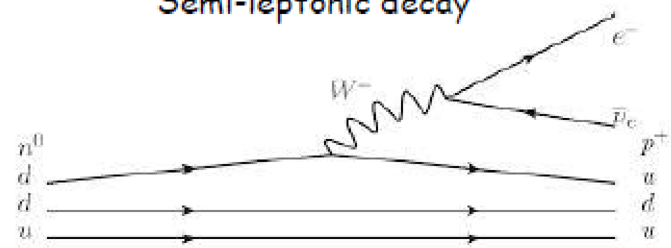
1) Determine the Vud element

Pure leptonic decay



$G_\mu = G_F$

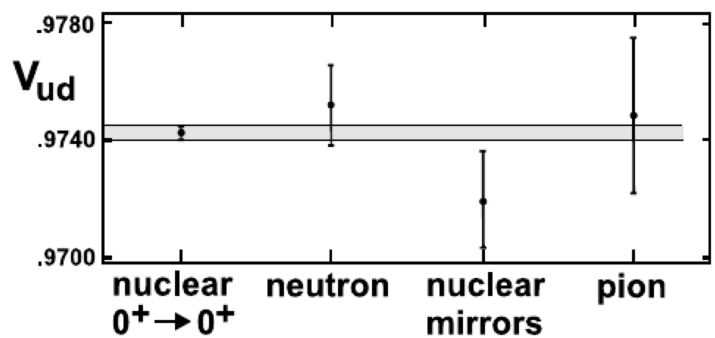
Semi-leptonic decay



$Ft \propto (G_F V_{ud})^{-2}$

Vud extracted with different decay studies:
most precise value is given by superallowed Fermi decays

Type of study	V_{ud}
$0^+ \to 0^+$ transitions	0.97425(22)
Pion decay	0.9728(30)
Neutron decay	0.9746(19)
$T = 1/2$ mirror transitions	0.9717(17)



Superallowed decays

Superallowed $0^+ \rightarrow 0^+$ decay between T=1 analog states depends uniquely on the vector part of the weak interaction and, according to the Conserved Vector Current (CVC) hypothesis, its experimental ft value should be directly related to the vector coupling constant, which is a fundamental constant, equal to all the transitions.

The expression for ft includes small correction terms, which account to 1% of its value. It is therefore convenient to define a "corrected" Ft value:

$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G^2(1+\Delta_R)}$$

Transition dependent

Transition independent in CVC hypothesis

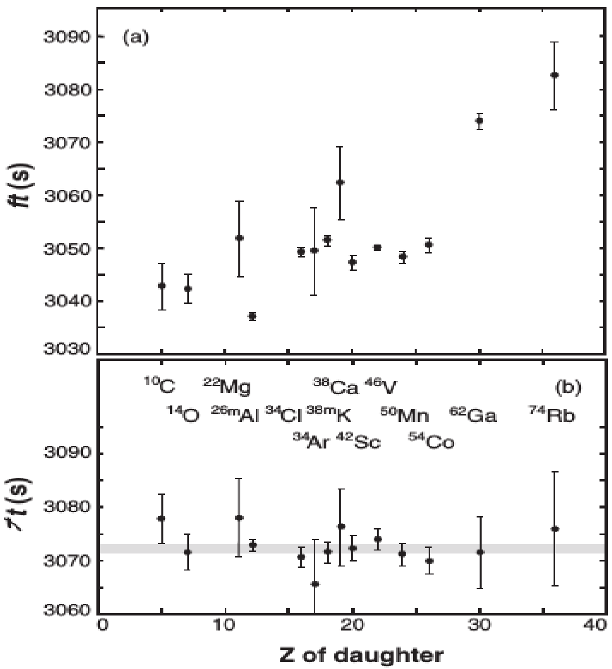
Being: f statistical rate, t half-life, $G=G_V$ vector coupling constant for semileptonic weak int.

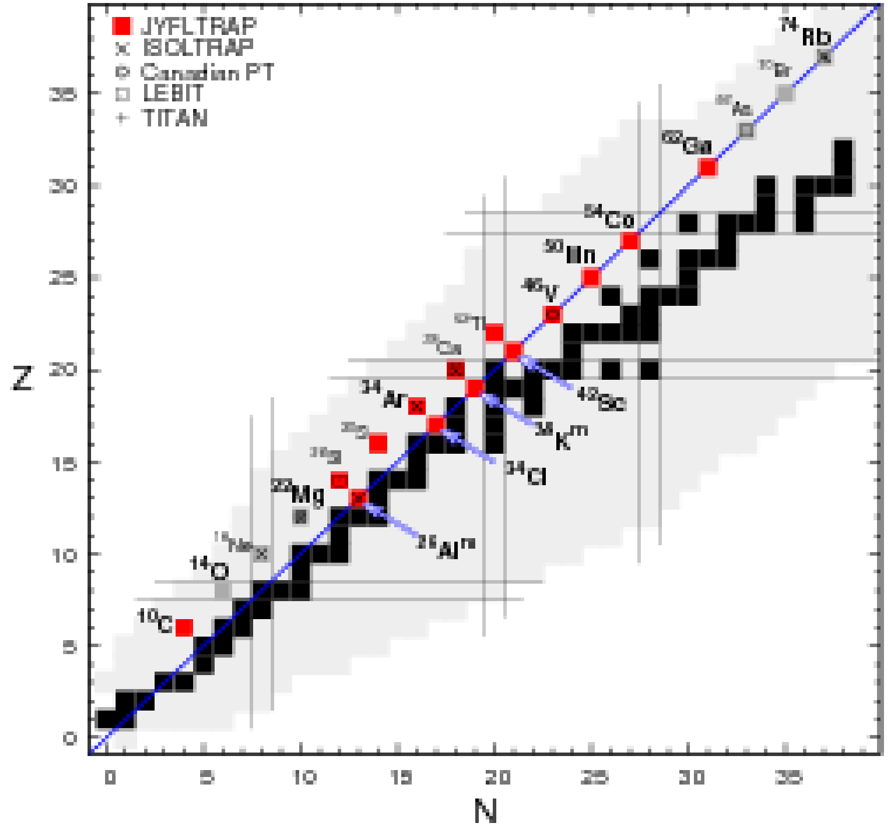
δ'_R, δ_{NS} and Δ_R are radiative corrections,

δ_C is an isospin-symmetry breaking term.

Superallowed decays

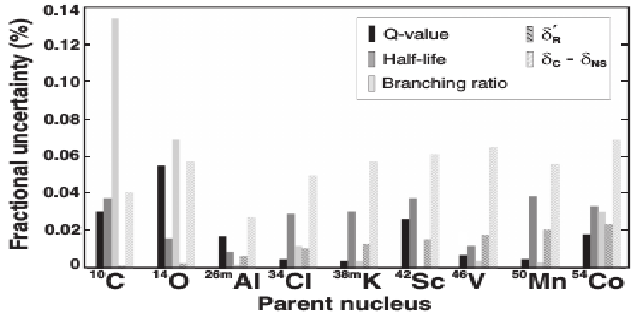
Quantities to extract experimentally are:
Half-life
Branching ratio with different transitions





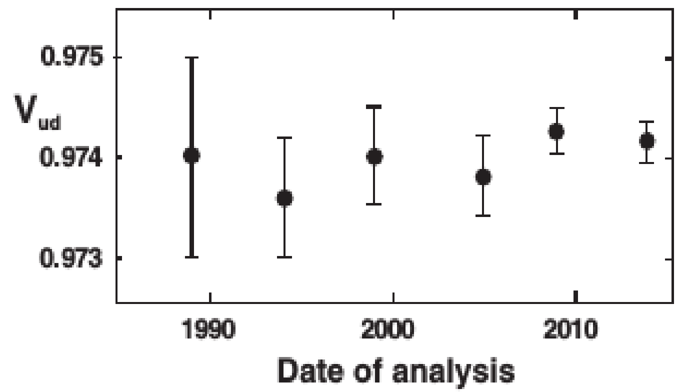
14 transitions 8 of which with uncertainties lower than 1%

Superallowed decays



Weights of the different contributions to the uncertainties in the measurements

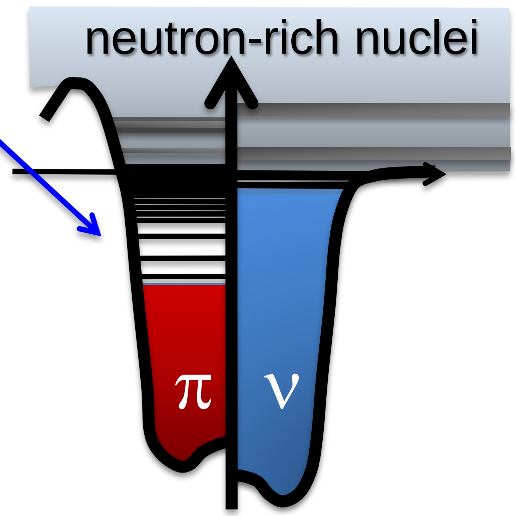
Evolution of the precision in the determination of the Vud values in past 30 years



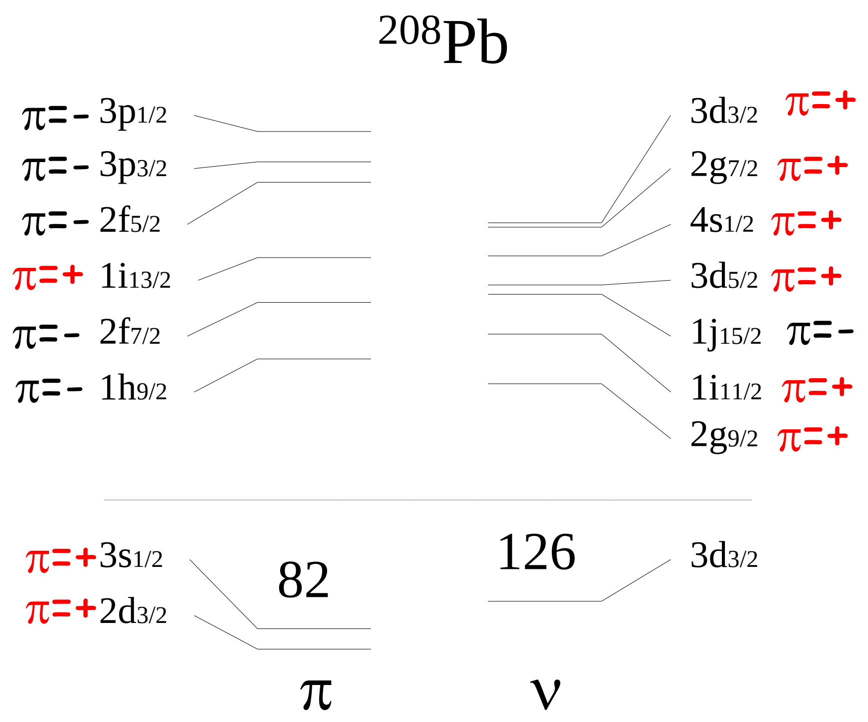
* Improved productions and separation of beams
  ➔ lower bg conditions
  ➔higher statistics allow for exclusive measurements
* Simulations help to define properties of detectors
* Definition of goal-standard in data analysis

General Properties of β decay

Exotic nuclei with excess of neutrons have different Fermi energies for n and p
Allowed decays might not be possible owing to large mismatch in wave functions



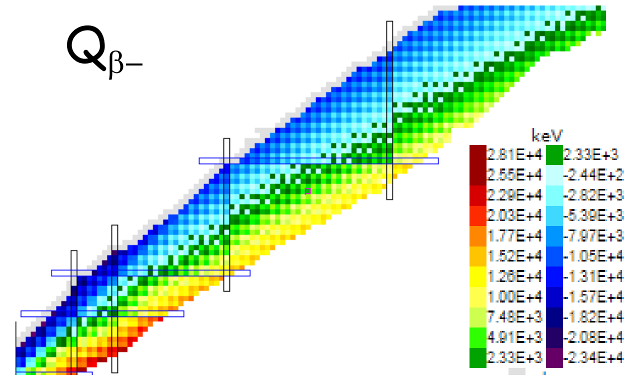
First forbidden transitions play a role



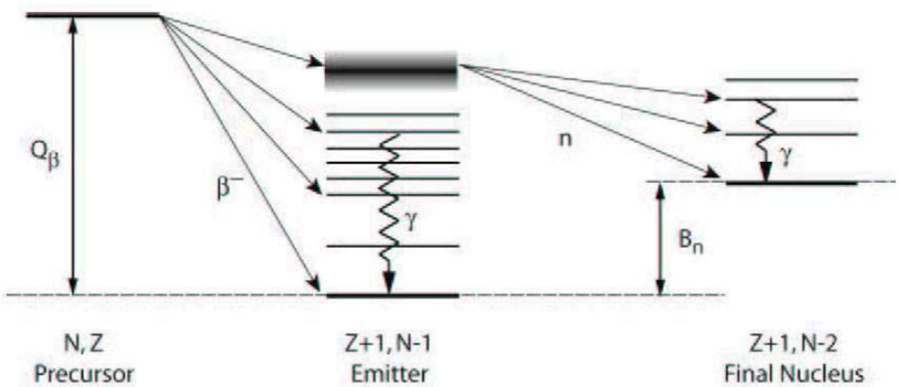
General Properties of β decay

Evolution towards the n-rich side:
$Q_{\beta-}$ generally gets larger while Sn gets smaller

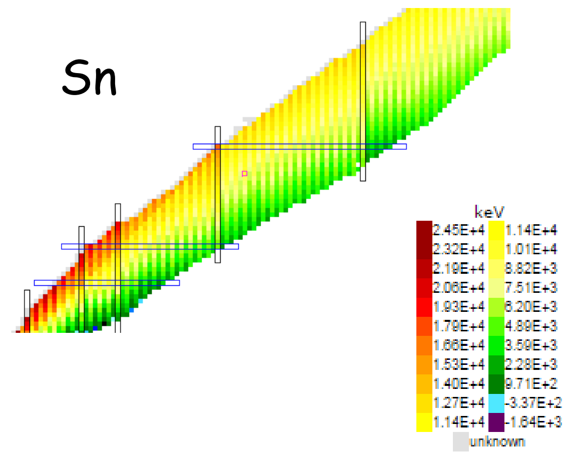
$Q_{\beta-}$



Conditions for β delayed neutron emission



Sn

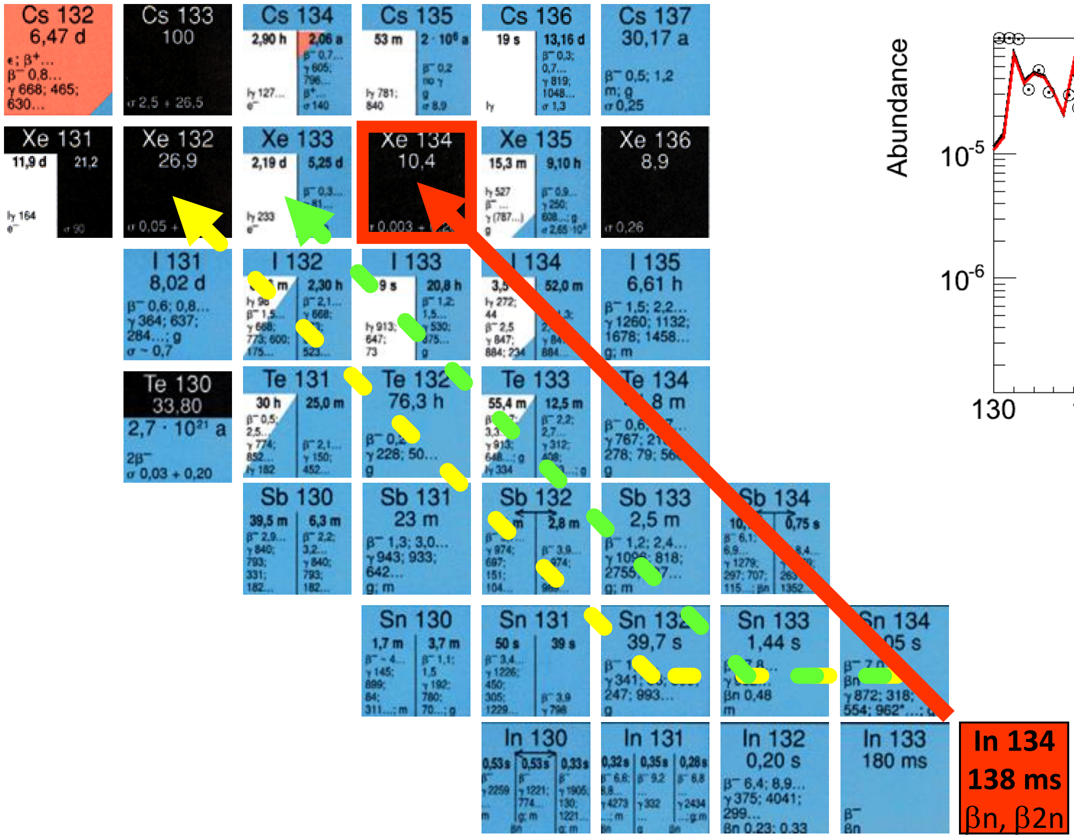


$$P_n = \frac{\sum_{S_n}^{Q_\beta} S_\beta(E_i) f(Z, R, Q_\beta - E_i)}{\sum_{0}^{Q_\beta} S_\beta(E_i) f(Z, R, Q_\beta - E_i)}$$

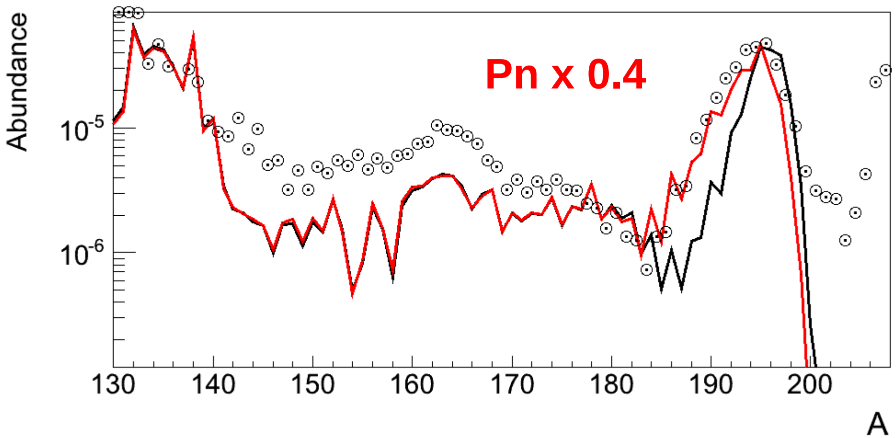
➔ neutron emission competes and can dominate over γ-ray de-excitation
The process will dominate far from stability on the n-rich side:
Q_β increases with A
Pn ➔ gives info on decay above Sn ➔ stringent test on β-strength function

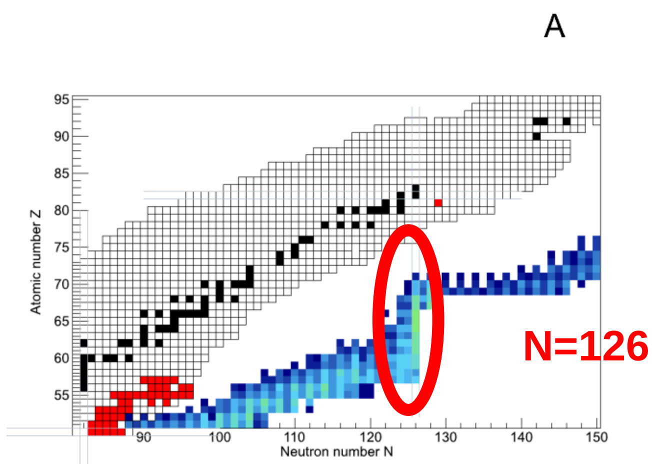
Impact on r-process abundances

During „Freeze-out“:
detour of β-decay chains
⇨ ***r-abundance changes***



During „Freeze-out“:
enhancement of neutron flux
⇨ ***r-abundance changes***



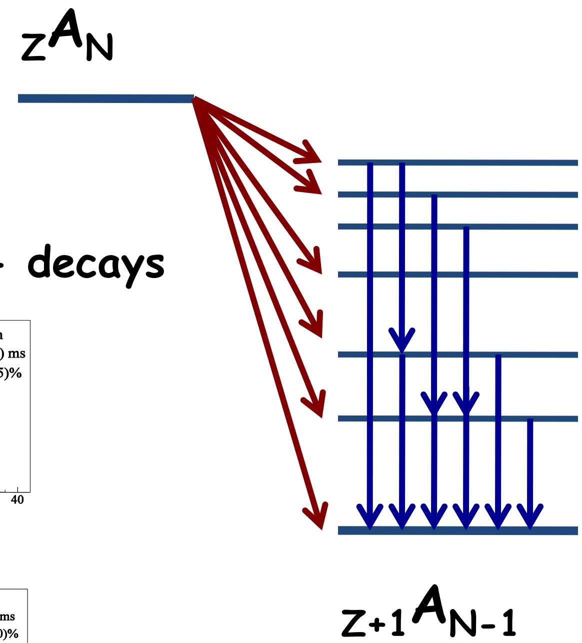


Quantities that can be extracted in a β decay experiment

General Properties of β decay

$T_{1/2}$
P_n
%β, %α …

β- decays



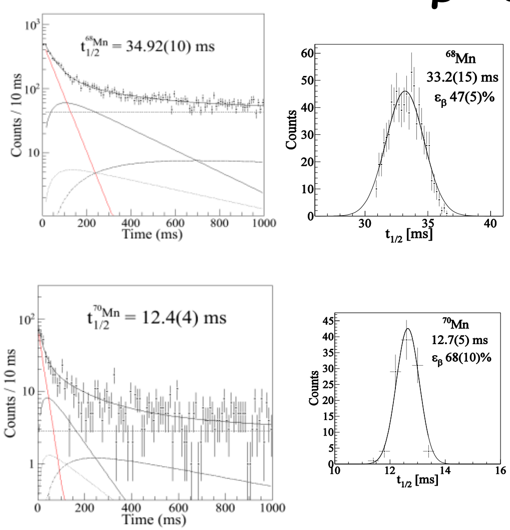
γ transitions

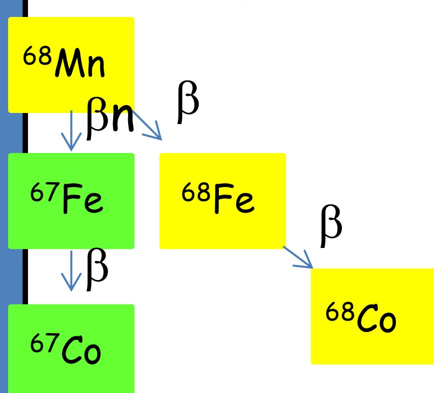
Possible existence of many decaying states

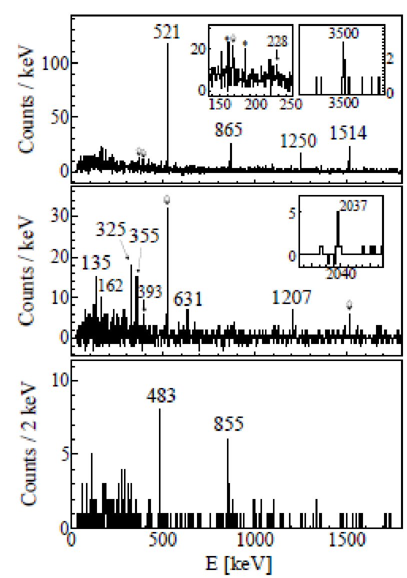
γ–γ coincidences ➔ level schemes

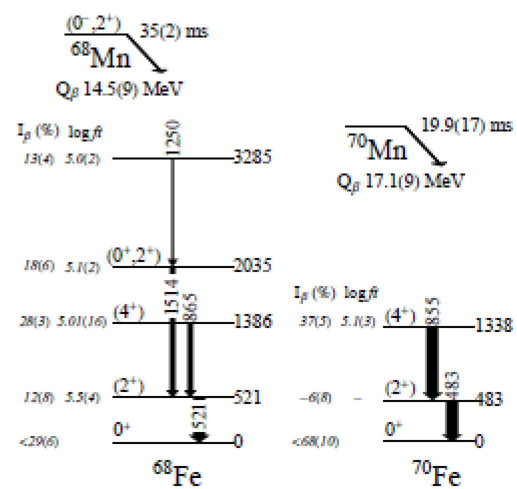
Relative intensities I_β

logft







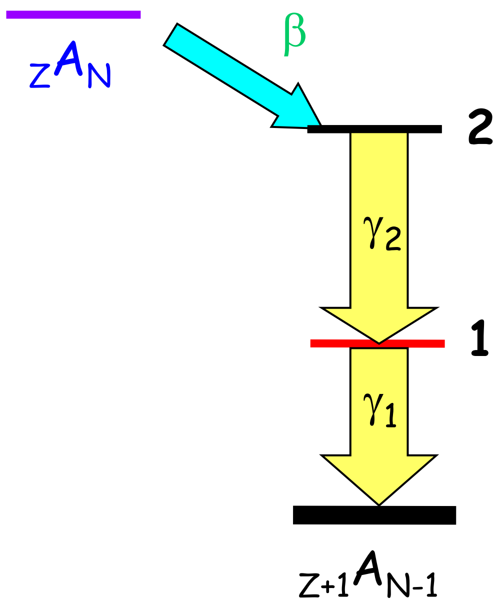


Selection rules allow to suggest/define I^π in both mother and daughter

"pandemonium effect" – neutron rich nuclei – log *ft* is a just upper limit

Pandemonium effect

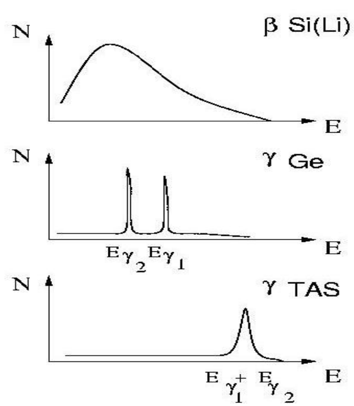
Real situation



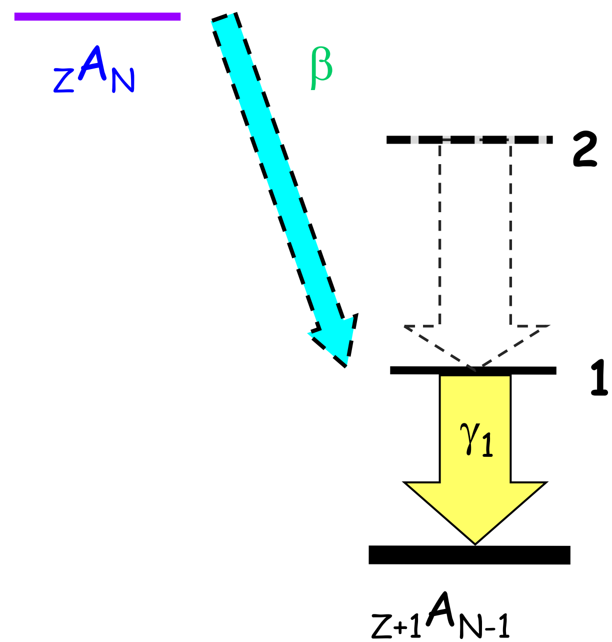
$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

$$(I_{\gamma_2} = I_{\gamma_1})$$

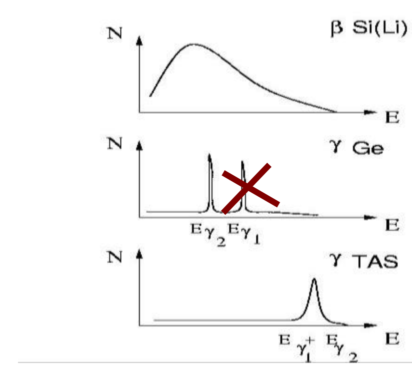


Apparent situation

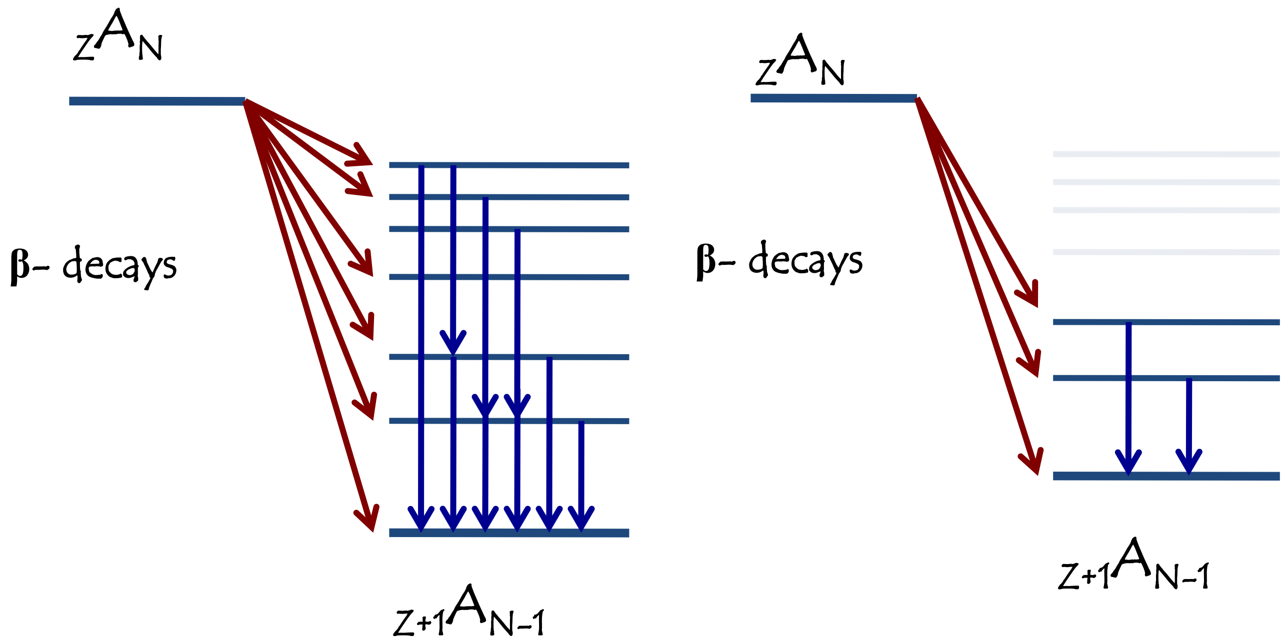


$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



General Properties of β decay



• HPGe detectors are conventionally used to construct the level scheme populated in the decay

➔ Higher Qvalue higher possibility of missing feeding

•From the γ intensity balance we deduce the β-feeding

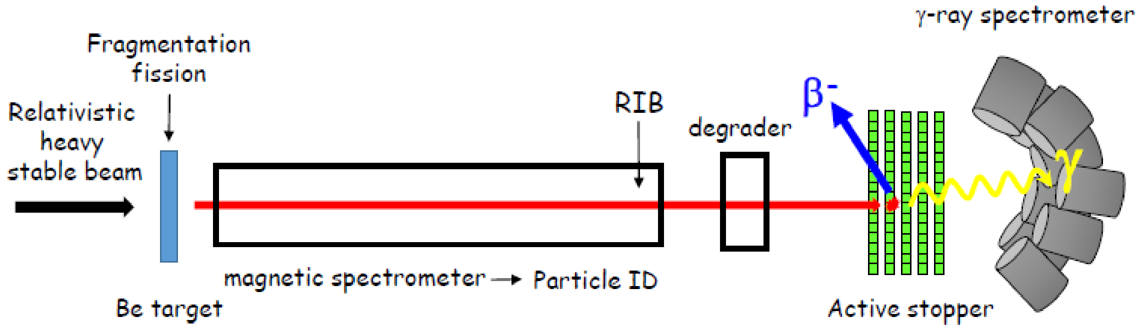
Pandemonium effect implies

➔ Wrong definition of gamma feeding and branching ratios

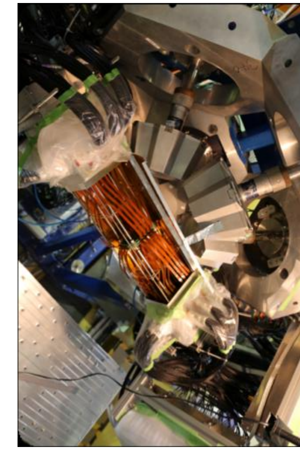
I_{β} and logft

General Properties of β decay

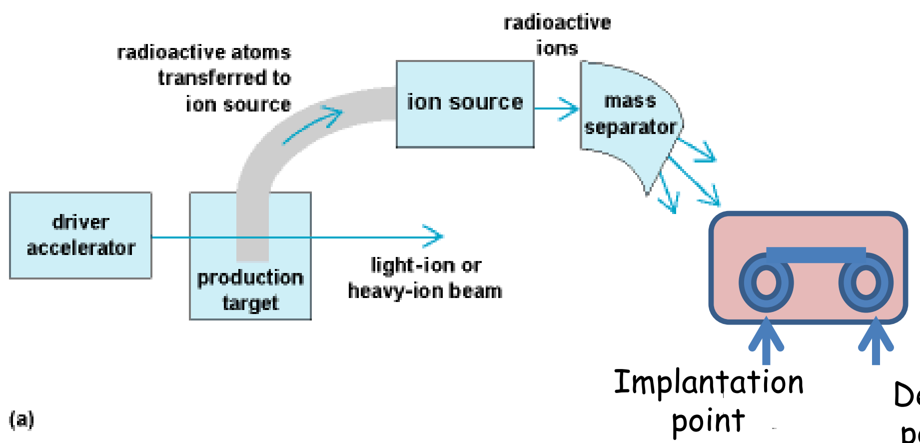
Measuring β decay



Fragmentation facility

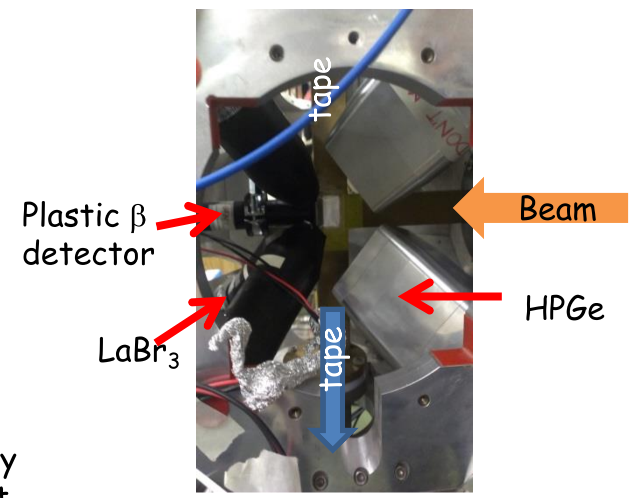


Eurica@RIKEN



ISOL facility

Tape decay stations



IDS @ CERN

Part III: Examples

Evolution in the precision of half-life measurements, example of ^{18}Ne

^{18}Ne

$T_{1/2}$= 1.66 s

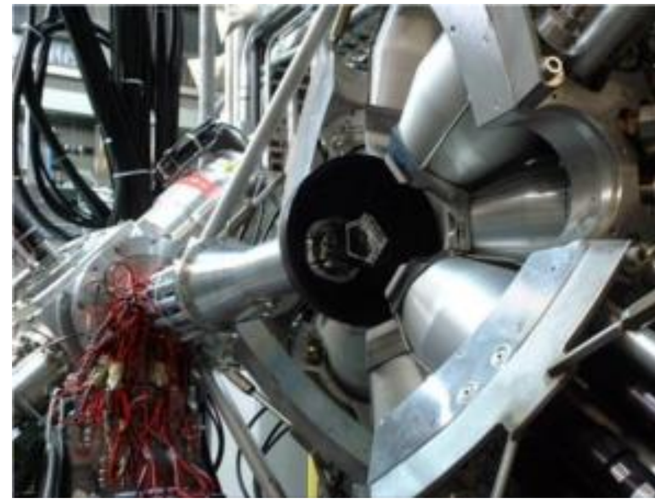
^{18}F

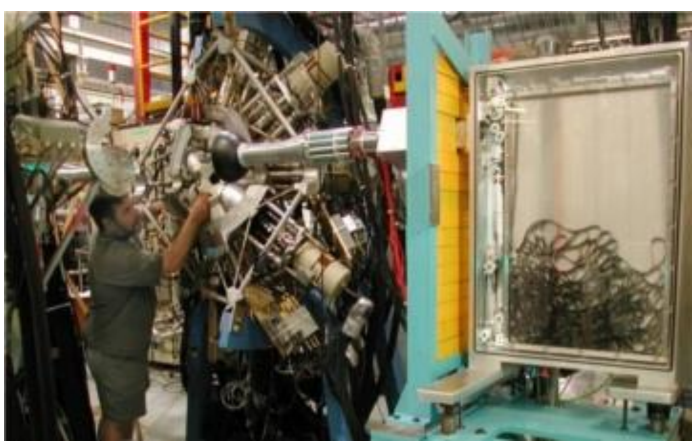
$T_{1/2}$= 109.7 m

^{18}O

ISOL technique:
Protons @500MeV onto SiC target
^{18}Ne + ^{18}F contamination
2×10^{6} ions/s vs 2.5×10^{7} ions/s

Setup SCEPTAR+8π gamma spectr.
@TRIUMF (CANADA) + Tape system





* Scintillating Electron-Positron Tagging Array (SCEPTAR) consists of an array of 20 thin plastic scintillator beta detectors that surround the implantation point of the radioactive ion beam

* 8π array of 20 high-purity germanium (HPGe) gamma-ray detectors that provides high-resolution measurements of the gamma rays emitted from excited states of the atomic nucleus.

PHYSICAL REVIEW C 87, 045502 (2013)

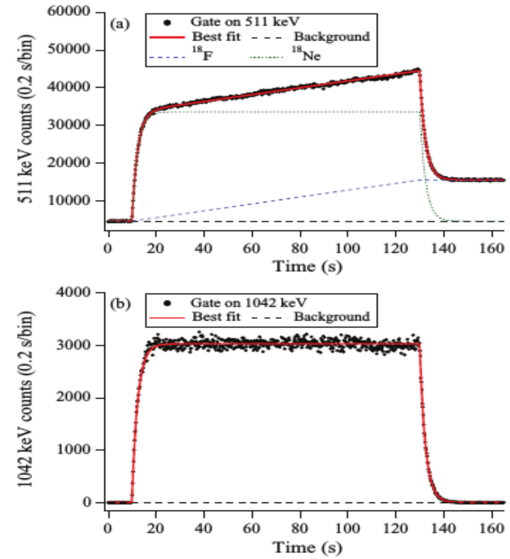
Improved half-life determination and β-delayed γ-ray spectroscopy for ^{18}Ne decay

Part III: Examples

Improved half-life determination and β-delayed γ-ray spectroscopy for ^{18}Ne decay

PHYSICAL REVIEW C 87, 045502 (2013)

Activity curve for 511 keV line:
Accumulation/decay:
Composite curve since it has contributions from
$^{18}Ne + ^{18}F$ + constant bg



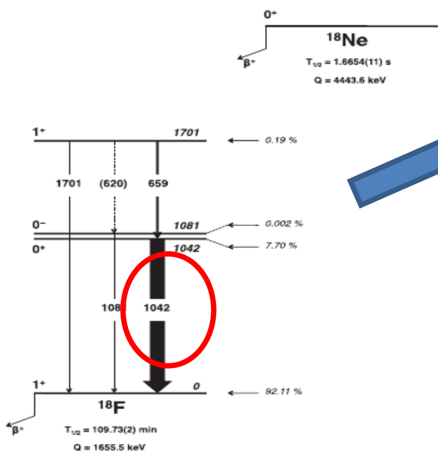
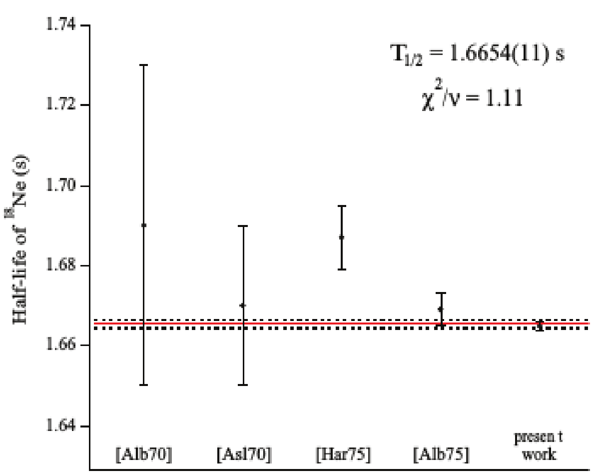


FIG. 1. Decay-level scheme of ^{18}Ne.

Gating on a specific γ line of the daughter nucleus cleans the spectrum ➔ only contributions from wanted decay



Evolution of precision of $T_{1/2}$ meas.:

- Better reduction of contaminants
- Higher efficiency and selectivity
- Faster electronics

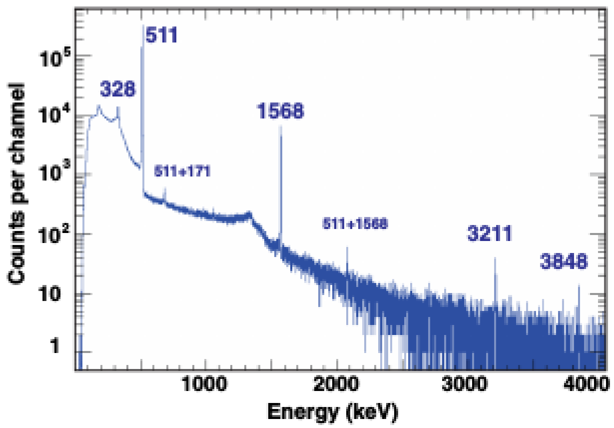
Part III: Branching ratio measurement

PRL 112, 102502 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

β Decay of ^{38}Ca: Sensitive test of Isospin Symmetry-Breaking Corrections from Mirror Superallowed $0^+ \rightarrow 0^+$ Transitions

$^{1}H(^{39}K, 2n)^{38}Ca$ reaction on a LN_2-cooled hydrogen gas target with 30A-MeV ^{39}K .
Ejectiles mass separated
Implanted on aluminized Mylar tape of a fast tape transport system.

1-mm-thick BC-404 scintillator to detect β particles, and an expecially calibrated 70% HPGe

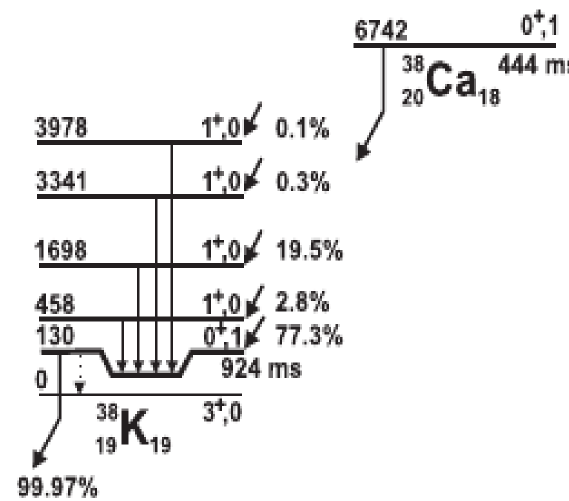


Careful determination of β and γ efficences

Branching ratio is defined as:

$$R_i = \frac{N_{\beta\gamma_i}}{N_\beta \varepsilon_{\gamma_i}} \frac{\varepsilon_\beta}{\varepsilon_{\beta_i}}, \qquad (3)$$

where $N_{\beta\gamma_i}$ is the total number of β-γ coincidences in the γ_i peak; N_β is the total number of beta singles corresponding



Exotic decay modes: Rare decay modes

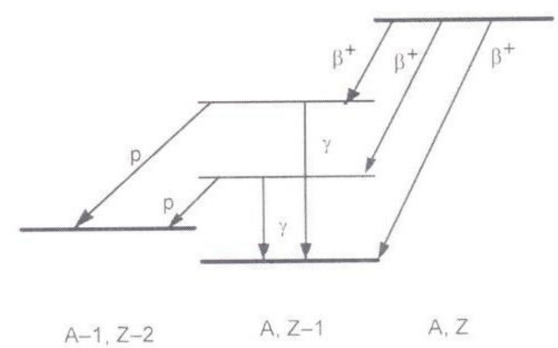
Proton emission: * emission from both gs ➔ direct emission
* emission from excited states
➔β delayed proton emission

Direct emission * usually in competition with β decay *:
Ep small: nucleus decays via β decay
Ep big: $T_{1/2}(p)$ very short and p cannot be detected

Typically seen in Z~50, Z~80, con 10^{-12} s<$T_{1/2}(p)$ < 0.1 s

Is again described as a decay as a tunneling through barrier
Here centrifugal barrier is very important

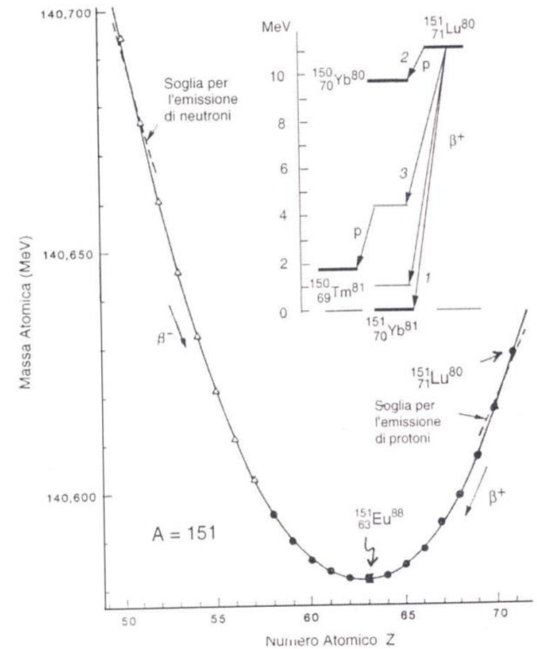
Delayed emission if p is emitted after β decay ➔ competition with γ decay

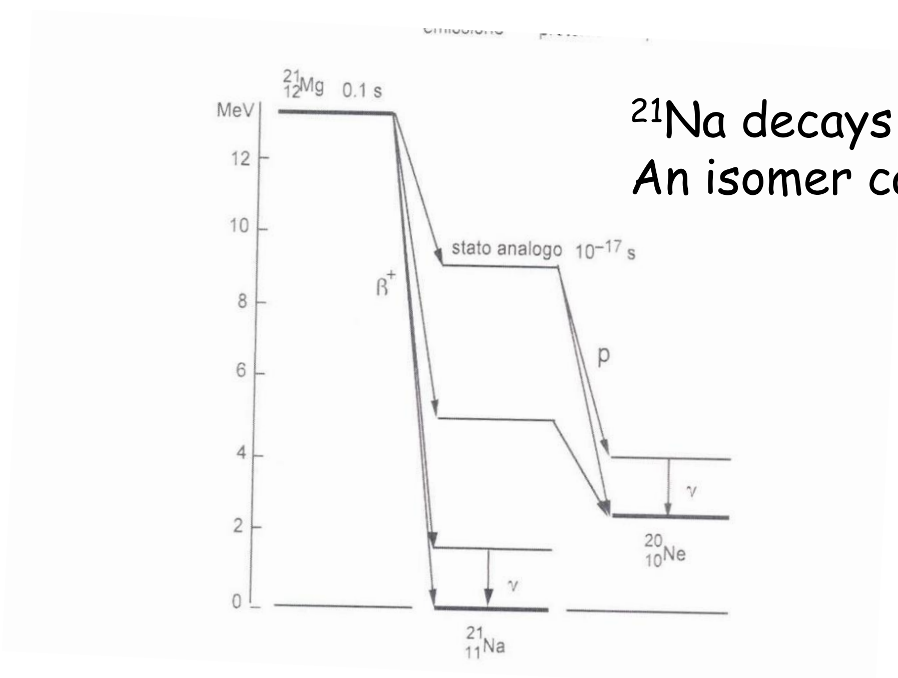


Exotic decay modes

^{151}Lu can decay via

- Beta decay
- Proton decay
- β-delayed proton emission





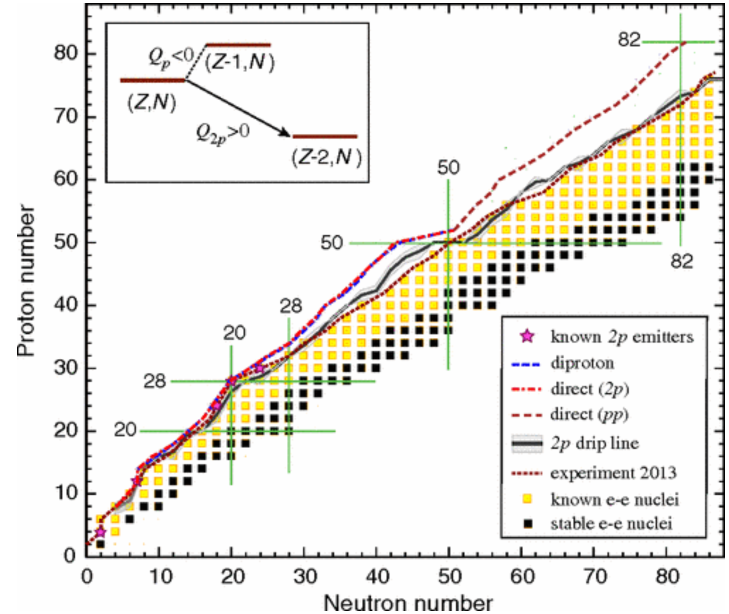
^{21}Na decays β from gs

An isomer can proton decay into ^{20}Ne

Exotic decay modes

2 proton emission

Unbound even-Z nuclei
Described by eg. Di-proton model:
The 2p leave the nucleus correlated in a s wave
Recent predictions show that there are numerous examples but soon start deviating and become not accessible exp.



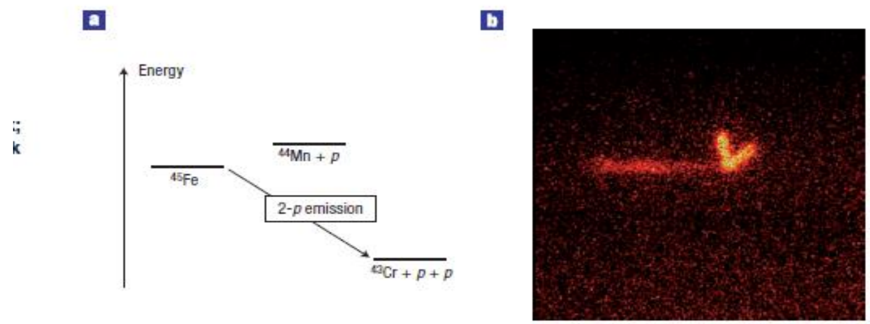


Figure 1 Two-proton decay from ^{45}Fe. **a**, One-proton decay to ^{44}Mn requires energy input and is not a possible outcome. In two-proton decay to ^{43}Cr, two protons share a kinetic energy of about 1 MeV. **b**, A ^{45}Fe ion enters the sensitive region of the chamber from the left, stops in the gas and emits two protons — seen as a V shape.

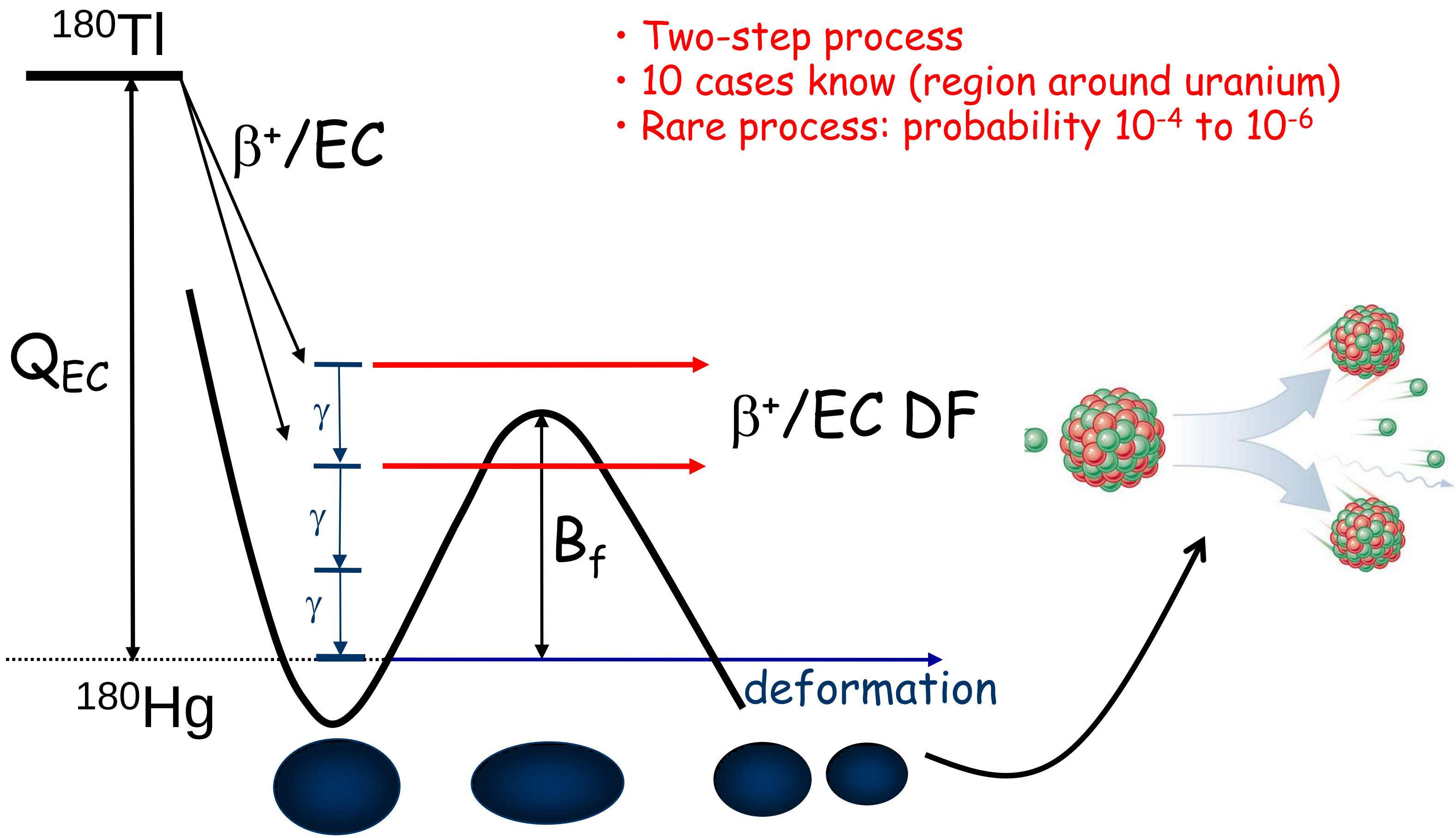
PRL **110**, 222501 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

Landscape of Two-Proton Radioactivity

E. Olsen,[1,2] M. Pfützner,[3,4] N. Birge,[1,2] M. Brown,[1,5] W. Nazarewicz,[1,2,3] and A. Perhac[1,2]

β delayed fission

- Two-step process
- 10 cases know (region around uranium)
- Rare process: probability 10^{-4} to 10^{-6}



- ^{180}Tl: $T_{1/2}$ = 1.1 s, 150 atoms/second, β-delayed fission probability is 10^{-6}
- ^{180}Hg (Z=80, N=100): expected to split into two ^{90}Zr(Z=40, N=50):
  → symmetric mass split

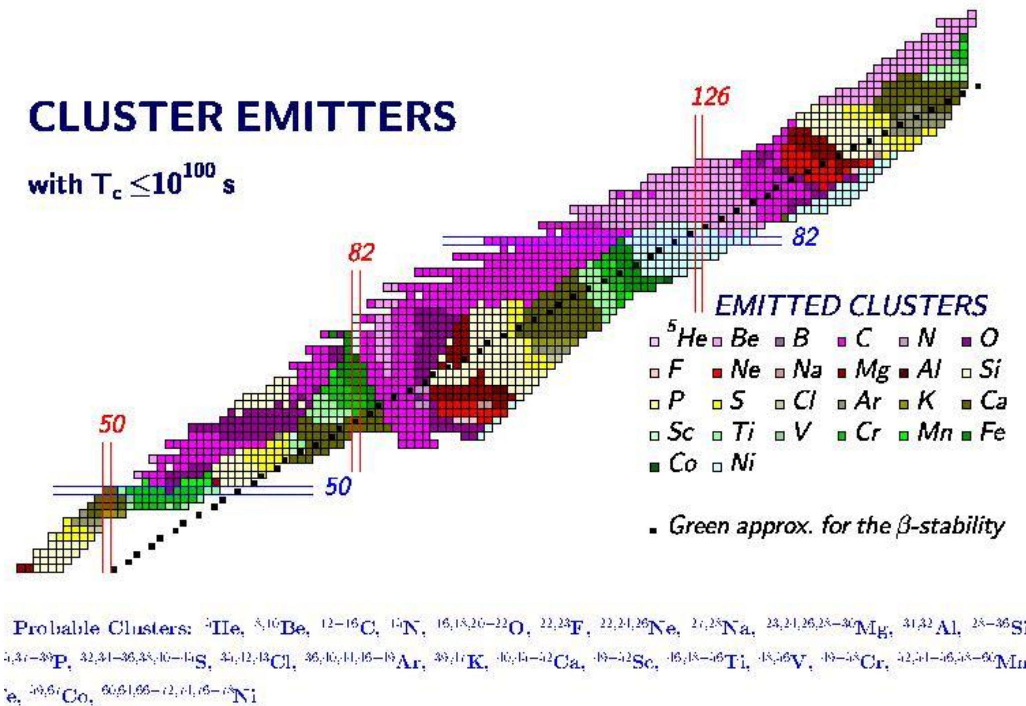
A. Andreyev et al., PRL 105 (2010) 252502

Exotic decay modes

Cluster decay→ very Asymmetric fission

Spontaneous emission of particles heavier than a:
^{14}C, ^{20}O,^{24}Ne,^{24}Mg,^{28}Si…^{34}Si
Cluster are in general n-rich and 14<A<34

Can be described either as a generalized a decay or as a very asymmetric fission



Conclusion

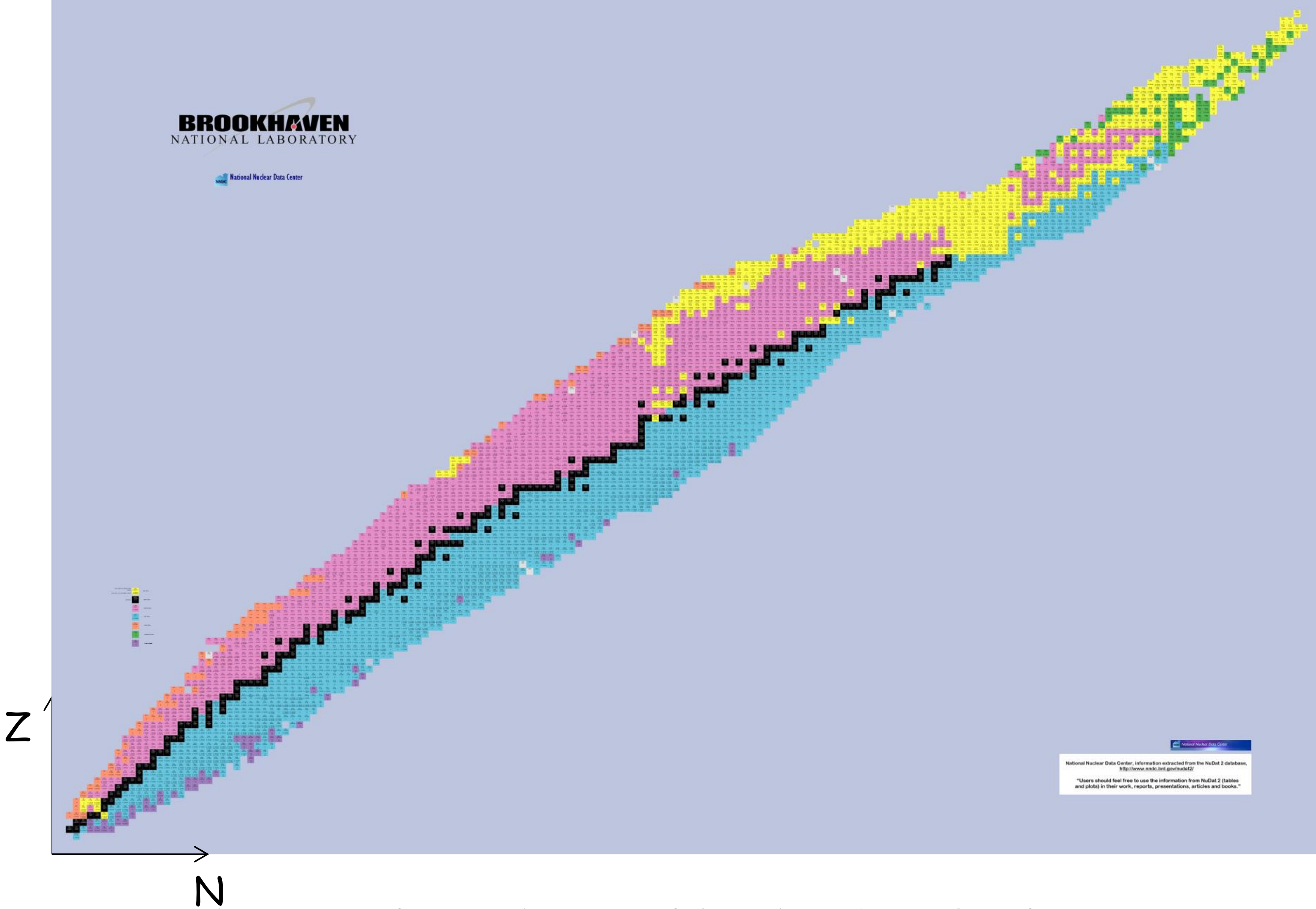
3 out of 4 fundamental interactions are at play in the nucleus:
strong/em/weak
They determine the stability/instability of the system
They define the means for a nucleus to decay

More frequent decays are:
α decay ➔ tunneling through barrier
➔ heavy systems, 2 body process, well defined a energies
β decay ➔ most frequent
➔ weak interaction "semi-leptonic" decay
➔ 3 body system, continuous emission spectrum
➔ governed by selection rules
Spontaneuos fission ➔ heavy systems, tunneling thr. barrier

Going further away of stability line more exotic decays are registered:

- β delayed emission of n, β delayed fission
- Proton decay and 2p decay
- Cluster decays.....

Conclusion



~3000 known nuclei, both natural (228) and artificial
7000+/- 500 current estimates for bound nuclei

Boundaries of the bound nuclei are not defined yet