

Beta decay studies of the most exotic nuclei

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Outline of the lessons:

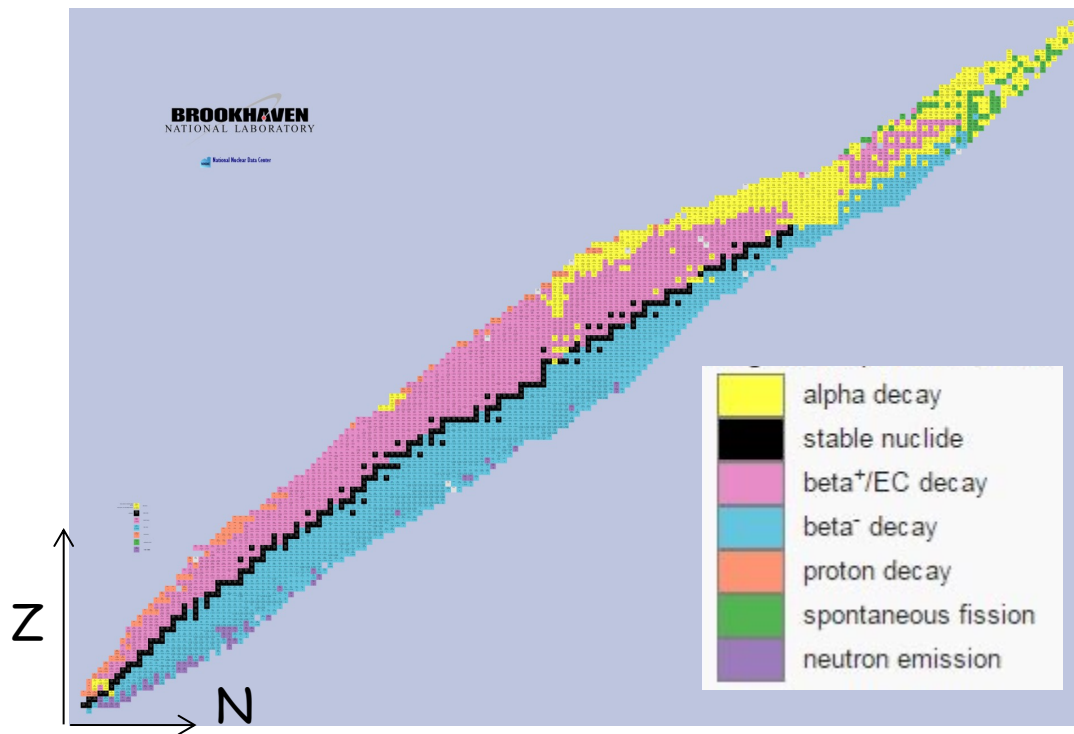
PARTI: General concepts

How to measure β decay in exotic nuclei

PARTII: β decay gross properties $T_{1/2}$ and P_n

PARTIII: High resolution vs TAS

Introduction



~3000 known nuclei,
both natural (288)
and artificial
7000 +/- 500 current
estimates for bound
nuclei
Boundaries of the
nuclei (driplines) are
not defined yet

β decay dominated by weak interaction and its properties directly relate to fundamental questions:

- Properties of the neutrinos → energy spectrum, double- β decay, sterile neutrinos
- Abundances of elements in universe → half lives and competing decay modes
- CP violation, CKM unitarity

and applications:

- PET scanners
- Radioactive sources (science and medicine)
- Homeland security
- Nuclear waste

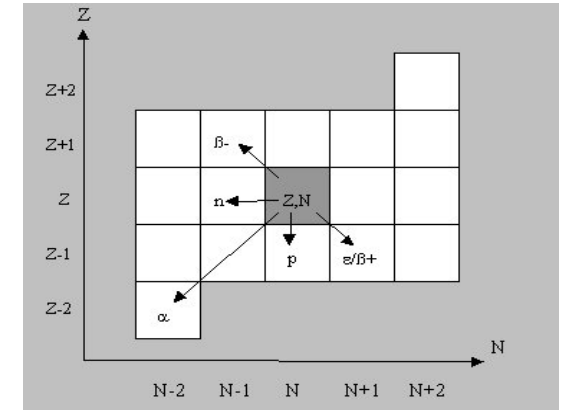
Decay modes

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

β^- decay: ${}^A_ZX \rightarrow {}^A_{Z+1}Y + e^- + \bar{\nu}_e$

β^+ decay: ${}^A_ZX \rightarrow {}^A_{Z-1}Y + e^+ + \nu_e$

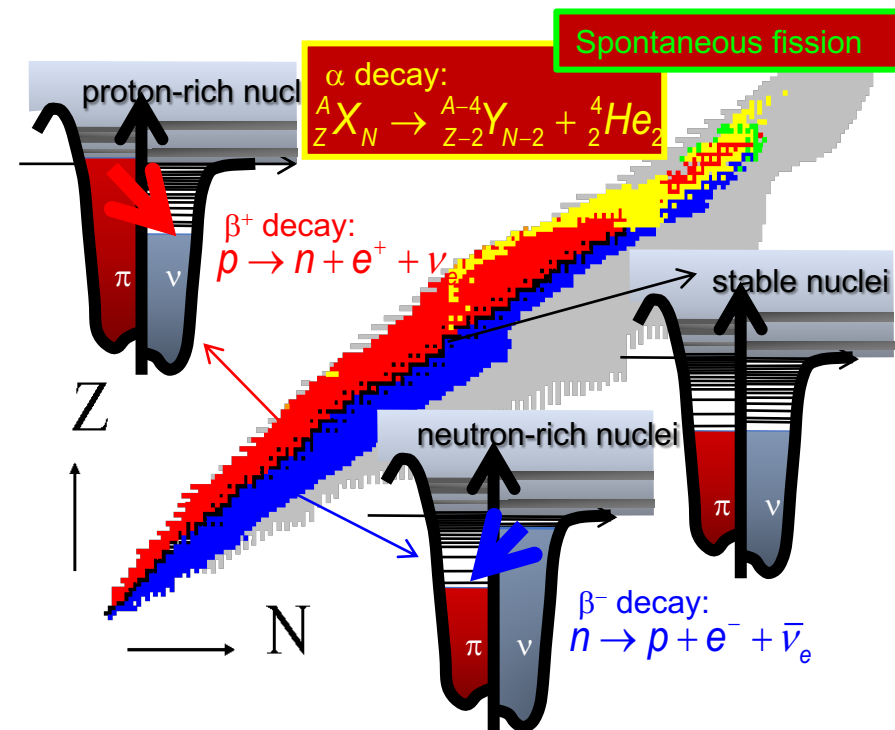
EC: ${}^A_ZX + e^- \rightarrow {}^A_{Z-1}Y + \nu_e$



Spontaneous Fission

Exotic decay modes: n decay
p decay
cluster emission

β -mediated decays:
 β -delayed n/p emission
 β -delayed fission

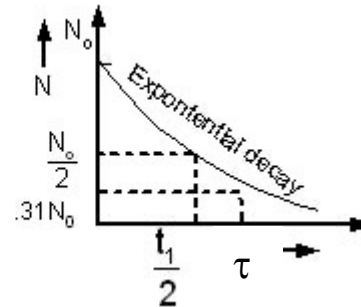


Introduction

Useful definitions for decays:

Law of radioactive decay:

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



λ decay rate

$\tau = 2\pi/\lambda$ meanlife

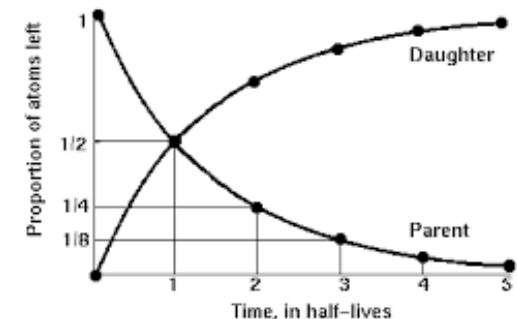
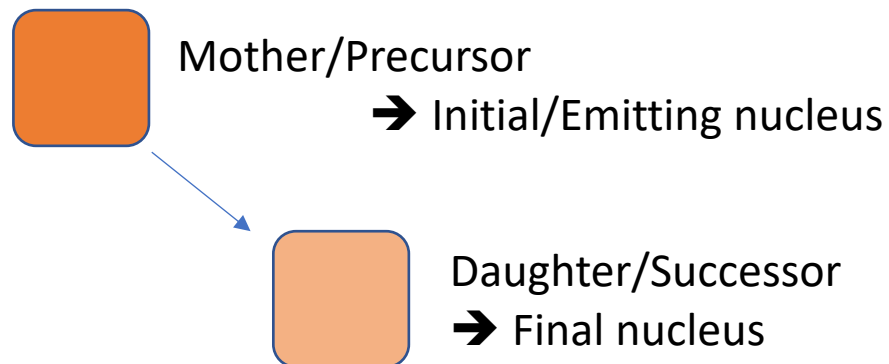
$T_{1/2} = \ln 2 * \tau$ half-life

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

Radioactive half-life Radioactive decay constant Mean lifetime

$$Q_{\text{value}} = M_{\text{initial}} - M_{\text{final}}$$

Branching ratio: decay probability of two or more competing processes



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:

$$\begin{aligned}\frac{dN_1(t)}{dt} &= -\lambda_1 N_1(t) \\ \frac{dN_i(t)}{dt} &= -\lambda_i N_i(t) + \lambda_{i-1} N_{i-1}(t) \\ \frac{dN_k(t)}{dt} &= \lambda_{k-1} N_{k-1}(t)\end{aligned}$$

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

Introduction

Detecting α β γ n particles: reminder of basic properties

α particle: massive, charged

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

β particles: light, charged

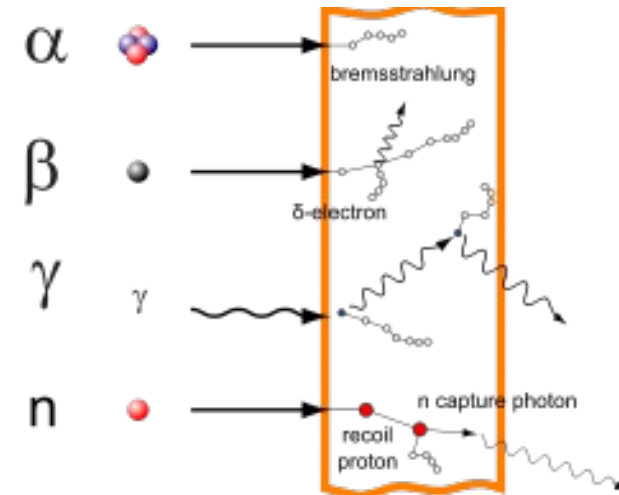
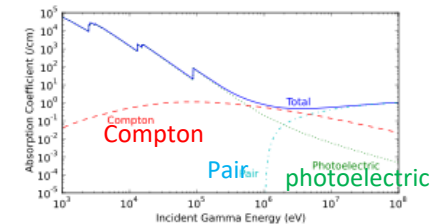
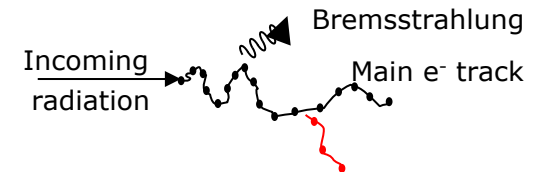
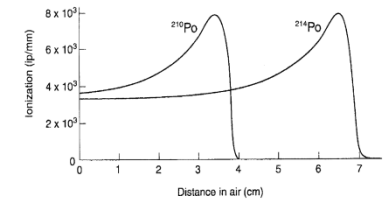
- interested in energy and correlations
- e^+ annihilates into two 511-keV γ rays
- spectrometers, Si, plastic detectors

γ particles: massless, neutral

- interested in energy and angular distributions
- HPGe detectors, inorganic scintillators

Neutrons: massive, neutral

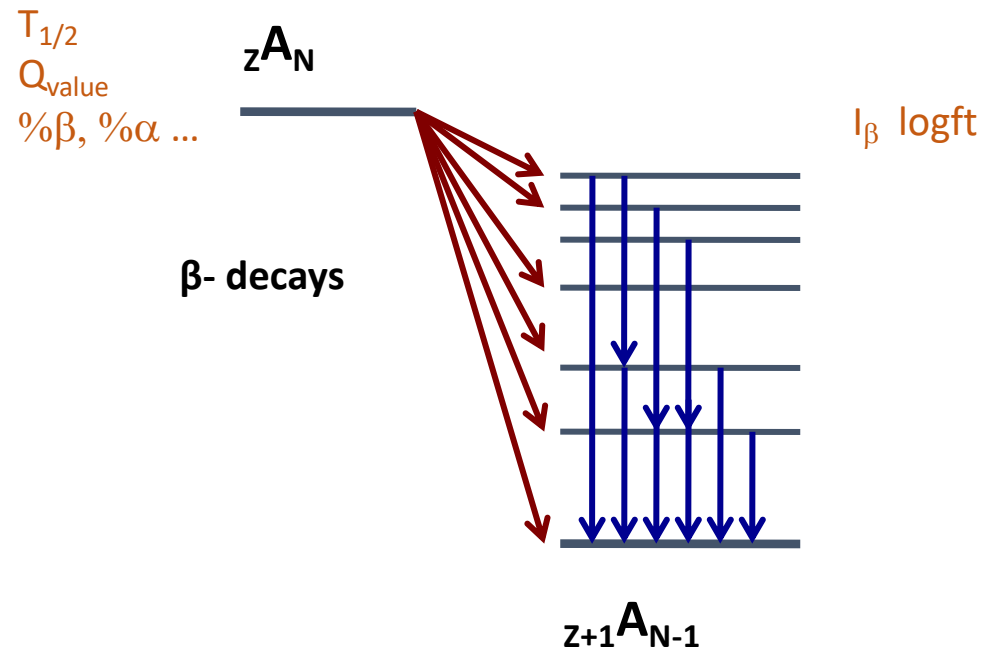
- interested in energy and correlations
- measured indirectly via capture reactions
- liquid scintillators, inorganic scintillators



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 isomeric state
 - measure half-life
- 3) Study properties of DAUGHTER nucleus:
 - which levels are populated
 - Branching Ratio btw levels
 - subsequent decays

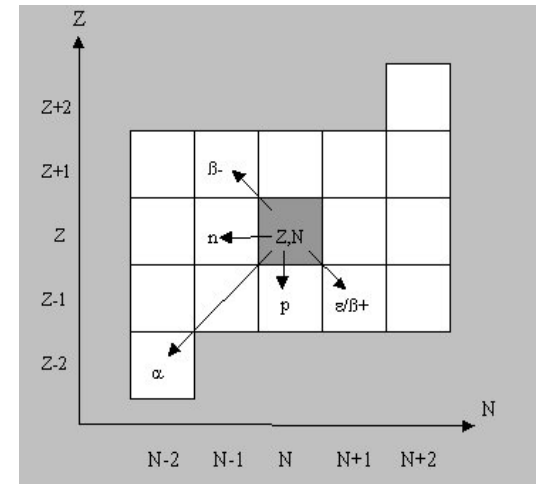


General Properties of β decay

$${}^A_ZX \rightarrow {}^A_{Z+1}Y + e^- + \bar{\nu}_e \quad \beta^- \text{ decay}$$

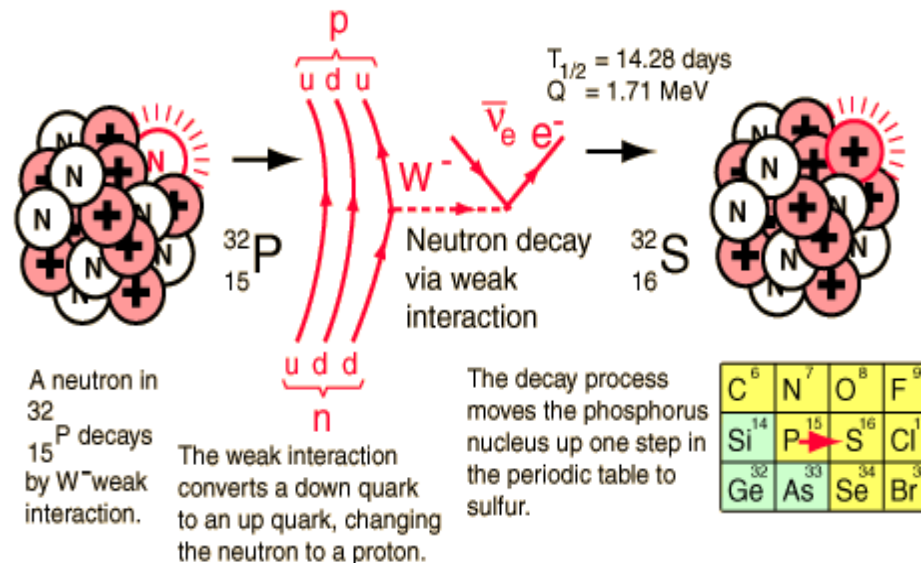
$${}^A_ZX \rightarrow {}^A_{Z-1}Y + e^+ + \nu_e \quad \beta^+ \text{ decay}$$

$${}^A_ZX + e^- \rightarrow {}^A_{Z-1}Y + \nu_e \quad \text{EC}$$



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 $gs \rightarrow gs$ decay

Q value for β^- decay is

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

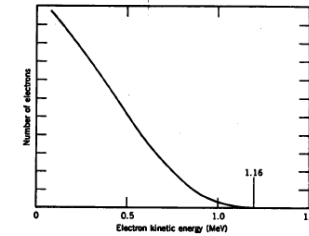


Fig. 9.1 The continuous electron distribution from the β decay of ^{210}Bi (also 1 RaE in the literature).

Q_{β^-} Sum of the energy of the electron (positron) and antineutrino (neutrino)

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

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

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

For electron capture:

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

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

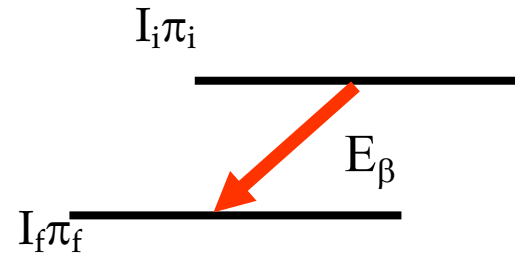
General Properties of β decay

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

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

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

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



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

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

General Properties of β decay

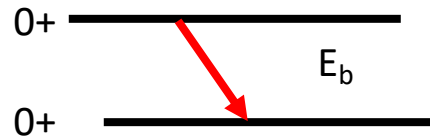
Selection rules for possible decays

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

Classification of **allowed decays**

$$(\pi_i \pi_f = +1)$$

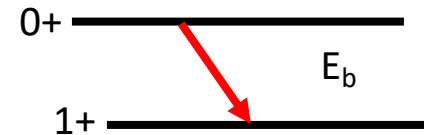
Fermi



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

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

Gamow-Teller



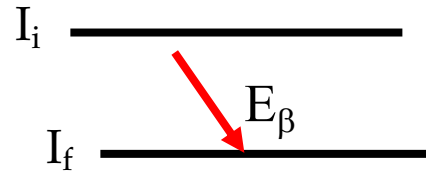
$$\Delta I = |I_i - I_f| \equiv 1$$

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

Useful empirical rules

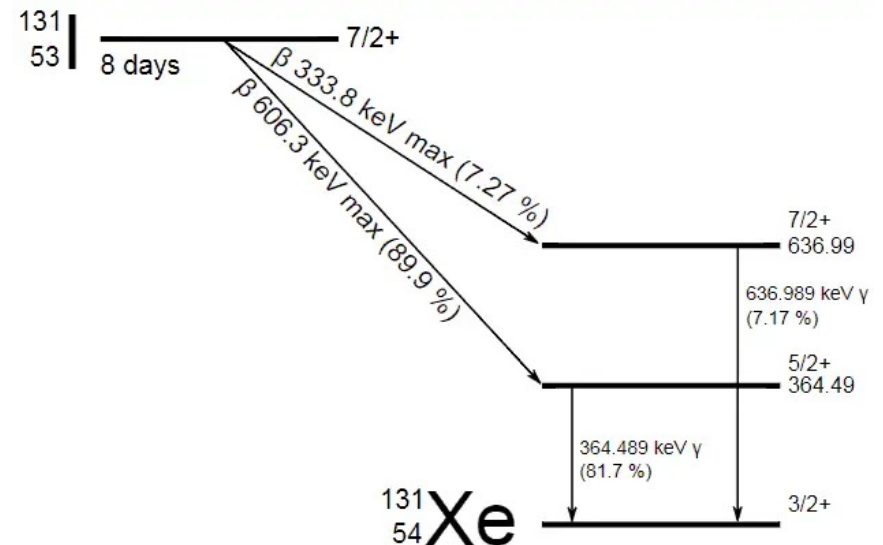
The fifth power beta decay rule:

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, “I-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

General Properties of β decay

$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\text{exp}}}{P_{\beta_i}} \quad \text{partial half-life of a given } \beta^- (\beta^+, \text{EC}) \text{ decay branch (i)}$$

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

$$\lambda = \frac{\ln 2}{t_{1/2}} = K |M_{if}|^2 f_o$$

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

$$K = 64\pi^4 m_o^5 c^4 g^2 / h^7$$

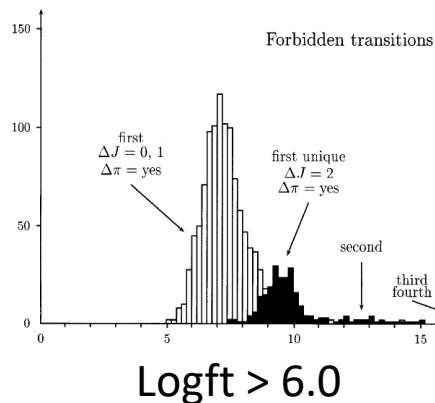
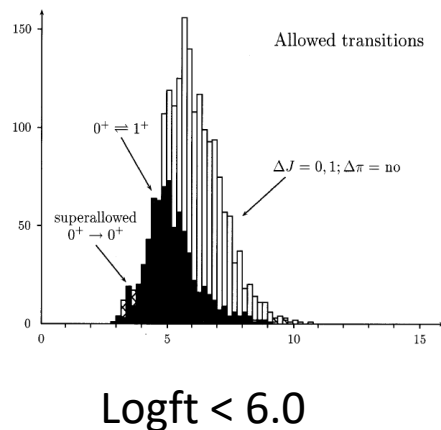
$$f_o = \int_1^{W_o} F(Z, W) W (W^2 - 1)^{1/2} (W_o - W)^2 dW$$

Comparative Half Lives

- Based on probability of electron energy emission coupled with spectrum and the Coulomb correction $f_0 t_{1/2}$ is called the comparative half life of a transition

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

- Assumes matrix element is independent of energy (true for allowed transitions)
Yields $f\tau$ (or $f_0 t_{1/2}$), 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,
- ➔ $f\tau$ has the same value for all allowed transitions
- For forbidden decays $f\tau$ increases with degree of forbiddenness

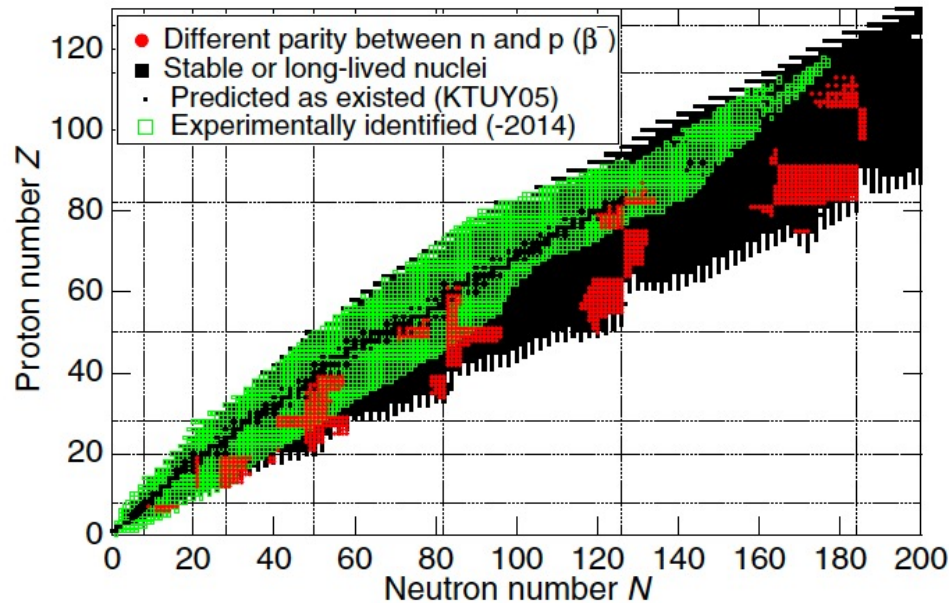


Review Of $\text{Log}f\tau$ Values
In β Decay*

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

Mismatching of parity btw ground-state neutron and proton levels

PHYSICAL REVIEW C 95, 064304 (2017)



The total β -decay rate can be written as

$$\lambda_{\beta} = \lambda_{\text{allowed}} + \lambda_{\text{first-forbidden}} \\ = \lambda_F + \lambda_{GT} + \lambda^{(0)}_1 + \lambda^{(1)}_1 + \lambda^{(2)}_1$$

the Fermi transition

Gamow-Teller transition

first forbidden transitions $L = 0, 1, \text{ and } 2$

Decay of
radioactive
nuclei

Element
formation in
stars

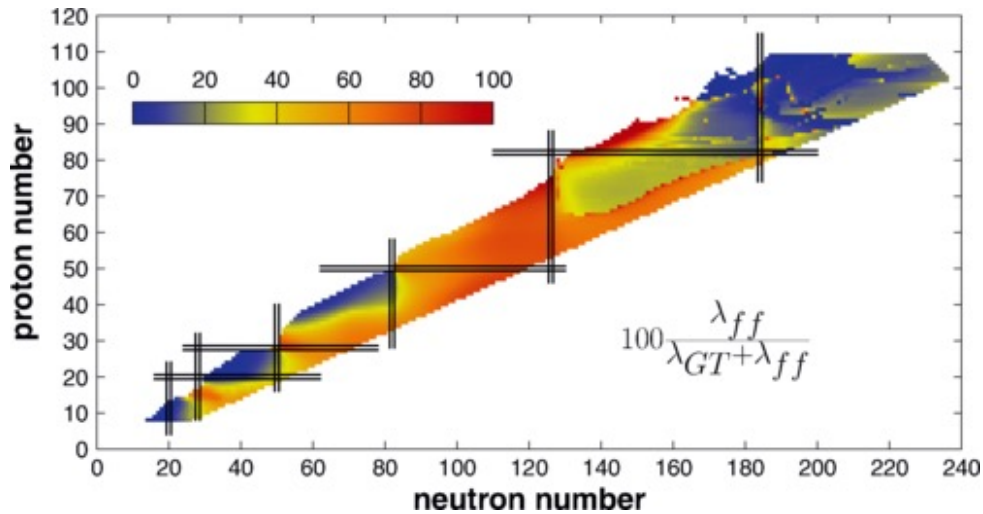
Example of
measurements
of β -decays

Perspectives

Conclusions

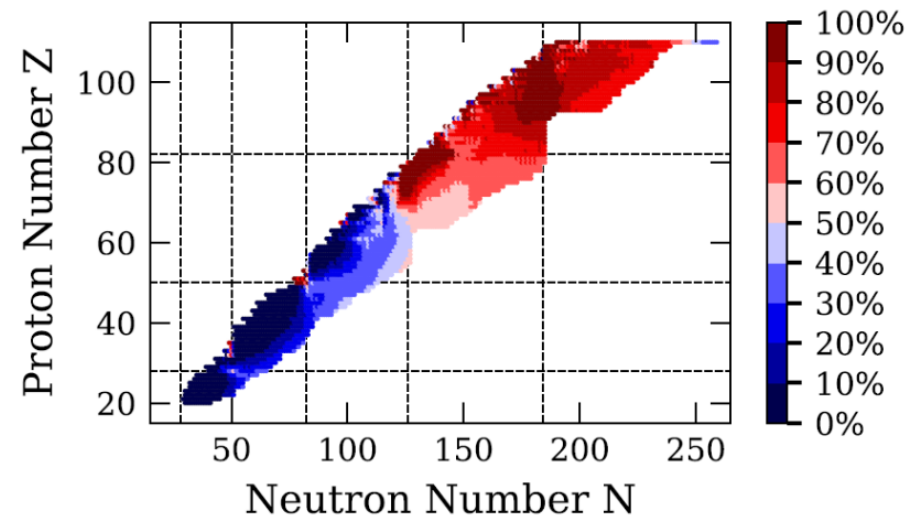
T. Marketin, L. Huther, G. Martinez-Pinedo, PRC93, 025805 (2016)

First-forbidden beta decay

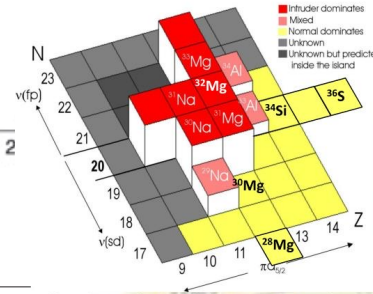
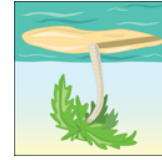
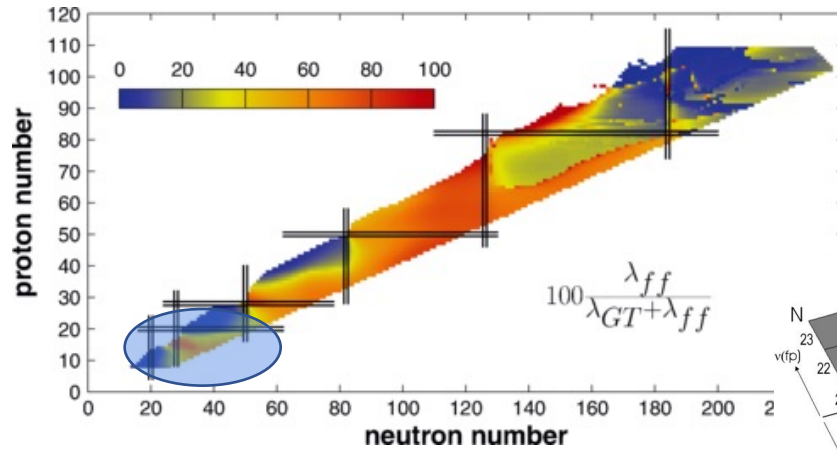


microscopic description based on Skyrme density functional,
EFA applied to describe odd-A and odd-odd nuclei

self-consistent microscopic description based on the Relativistic Hartree-Bogoliubov (RHB) model for ground state of open- and closed-shell nuclei with the proton-neutron relativistic quasiparticle random phase approximation (pn-RQRPA)



E.M. Ney, J. Engel, T.Li. N. Schunck, PRC102,034326 (2020)



PHYSICAL REVIEW LETTERS **129**, 212501 (2022)

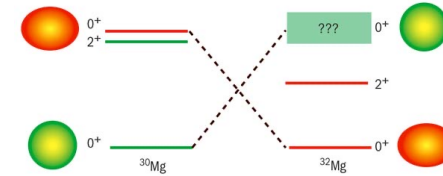
Editors' Suggestion

Featured in Physics

Crossing $N=28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford^{1,*}, V. Tripathi², J. M. Allmond³, B. P. Crider⁴, R. Grzywacz⁵, S. N. Liddick^{6,7}, A. Andalib^{6,8}, E. Argo^{6,8}, C. Benetti², S. Bhattacharya², C. M. Campbell¹, M. P. Carpenter⁹, J. Chan⁵, A. Chester⁶, J. Christie⁵, B. R. Clark⁴, I. Cox⁵, A. A. Doetsch^{6,8}, J. Dopfer^{6,8}, J. G. Duarte¹⁰, P. Fallon¹, A. Frotscher¹, T. Gaballah⁴, T. J. Gray³, J. T. Harke¹⁰, J. Heideman⁵, H. Heugens³, R. Jain^{6,8}, T. T. King³, N. Kitamura⁵, K. Kolos¹⁰, F. G. Kondev⁹, A. Laminack³, B. Longfellow¹⁰, R. S. Lubna⁶, S. Luitel⁴, M. Madurga⁵, R. Mahajan⁶, M. J. Moggannam^{6,7}, C. Morse¹¹, S. Neupane⁵, A. Nowicki⁵, T. H. Ogunbaku^{4,6}, W.-J. Ong¹⁰, C. Porzio¹, C. J. Prokop¹², B. C. Rasco³, E. K. Ronning^{6,7}, E. Rubino⁶, T. J. Ruland¹³, K. P. Rykaczewski³, L. Schaedig^{6,8}, D. Seweryniak⁹, K. Siegl⁵, M. Singh⁵, S. L. Tabor², T. L. Tang², T. Wheeler^{6,8}, J. A. Winger⁴, and Z. Xu⁵

First-forbidden beta decay



PHYSICAL REVIEW C **106**, 064314 (2022)

β^- decay of exotic P and S isotopes with neutron number near 28

Vandana Tripathi^{1,*}, Soumik Bhattacharya¹, E. Rubino¹, C. Benetti¹, J. F. Perello¹, S. L. Tabor¹, S. N. Liddick^{2,3,4}, P. C. Bender⁵, M. P. Carpenter⁶, J. J. Carroll⁷, A. Chester^{2,3}, C. J. Chiara⁷, K. Childers^{2,4}, B. R. Clark⁸, B. P. Crider⁸, J. T. Harke⁹, B. Longfellow^{2,10}, R. S. Lubna³, S. Luitel⁸, T. H. Ogunbaku⁸, A. L. Richard^{2,9}, S. Saha⁵, N. Shimizu¹¹, O. A. Shehu⁸, Y. Utsuno^{12,13}, R. Unz⁸, Y. Xiao⁸, S. Yoshida¹⁴, and Yiyi Zhu⁵

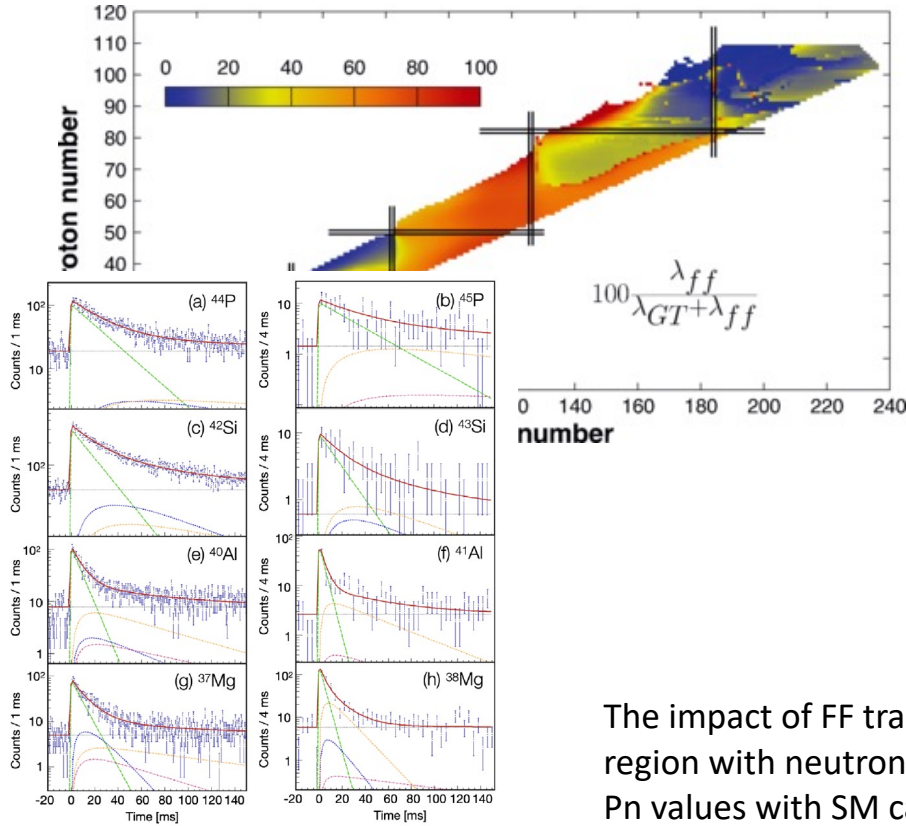
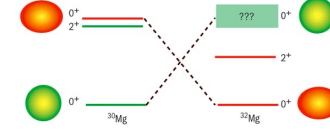
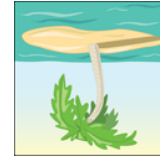
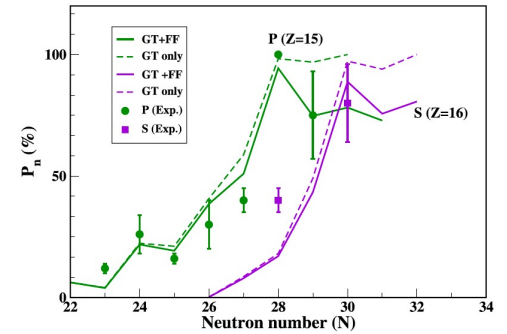
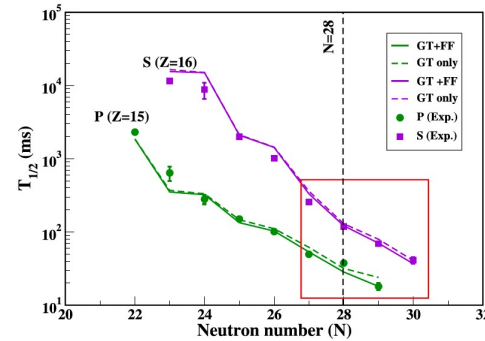


FIG. 2. Decay curves in panels (a)–(h) for $^{44,45}\text{P}$, $^{42,43}\text{Si}$, $^{40,41}\text{Al}$, and $^{37,38}\text{Mg}$ respectively. The components of the fits are shown by the curves, where the solid red line is the total fit, the green dashed curve is the parent decay, the dot-dash blue line is the $\beta 0n$ daughter contribution, the dot-dot-dash orange line is the $\beta 1n$ contribution, the dot-dot-dot-dash magenta line is the $\beta 2n$ contribution, and the dotted gray line is the constant background. The derived half-lives are included in Table I.

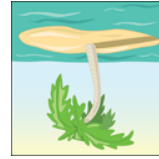
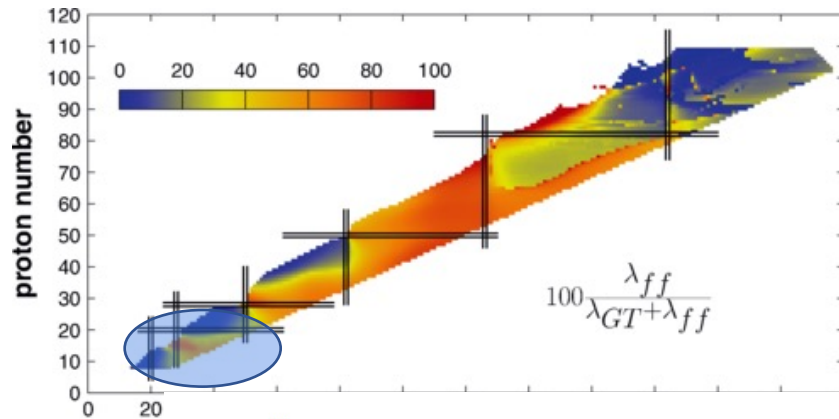


First-forbidden beta decay

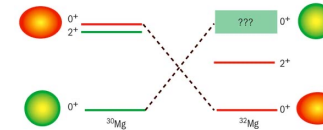


The impact of FF transitions which can be important for neutron-rich nuclei in this region with neutrons filling the $1p_{3/2}$ orbital by comparing the measured $T_{1/2}$ and P_n values with SM calculations with and without FF transitions included.

- P isotopes with $N = 27, 28, 29$ displayed a larger contribution from FF transitions in their β decay. For the case of ^{42}P decay there are clear indicators of states which could be populated in FF decay with $\log ft$ values consistent with the predictions of the SM calculations.



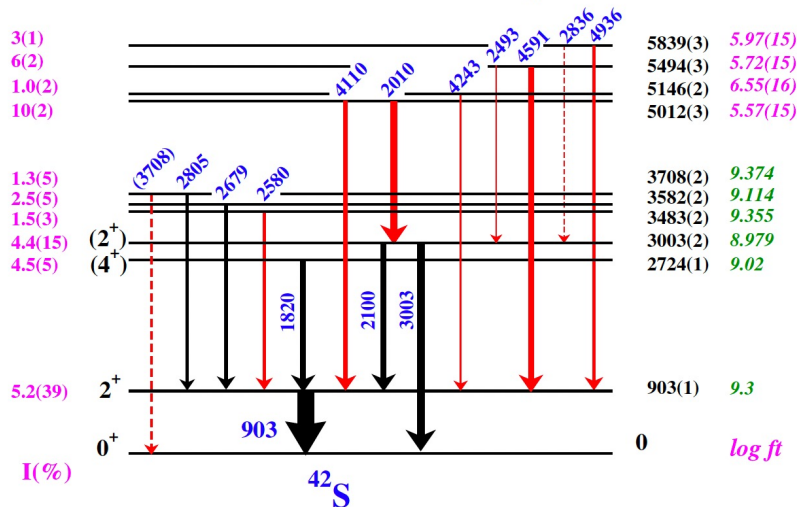
First-forbidden beta decay



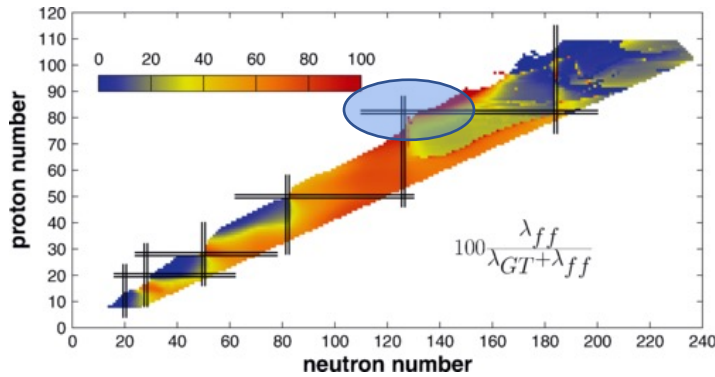
^{42}P

$J^\pi = (2^-, 3^-)$
 $T_z = +6$
 $Q_\beta = 18.73(10) \text{ MeV}$
 $T_{1/2} = 47.1(20) \text{ ms}$
 $P_{\text{In}} = 39(6) \%$

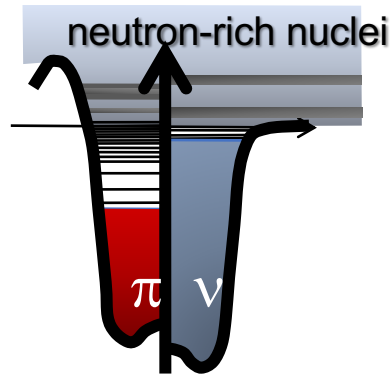
$S_n = 6700(5) \text{ keV}$



- Both the half-life and P_n value of ^{44}P also indicate influence of FF transitions. Comparison with SM calculations of states populated in ^{42}S in the decay of ^{42}P both via allowed GT and FF decays suggests a J^π of 2^- or 3^- for the ground state of ^{42}P contrary to earlier suggestion of 0^- .
- The Gamow-Teller (GT) strength distribution depends on the deformation and affects the half-life ($T_{1/2}$) and β -delayed neutron emission probability (P_n).



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 beta decay

^{208}Pb

$\pi=-$ $3p_{1/2}$

$\pi=-$ $3p_{3/2}$

$\pi=-$ $2f_{5/2}$

$\pi=+$ $1i_{13/2}$

$\pi=-$ $2f_{7/2}$

$\pi=-$ $1h_{9/2}$

$3d_{3/2}$

$2g_{7/2}$ $\pi=+$

$4s_{1/2}$ $\pi=+$

$3d_{5/2}$ $\pi=+$

$1j_{15/2}$ $\pi=-$

$1i_{11/2}$ $\pi=+$

$2g_{9/2}$ $\pi=+$

$\pi=+$ $3s_{1/2}$

$\pi=+$ $2d_{3/2}$

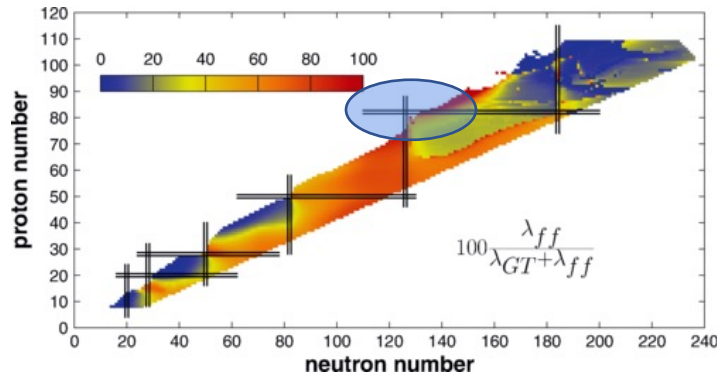
82

π

126

ν

$3d_{3/2}$



First-forbidden beta decay

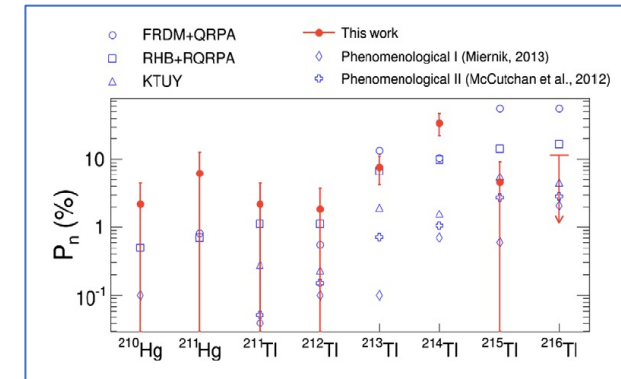
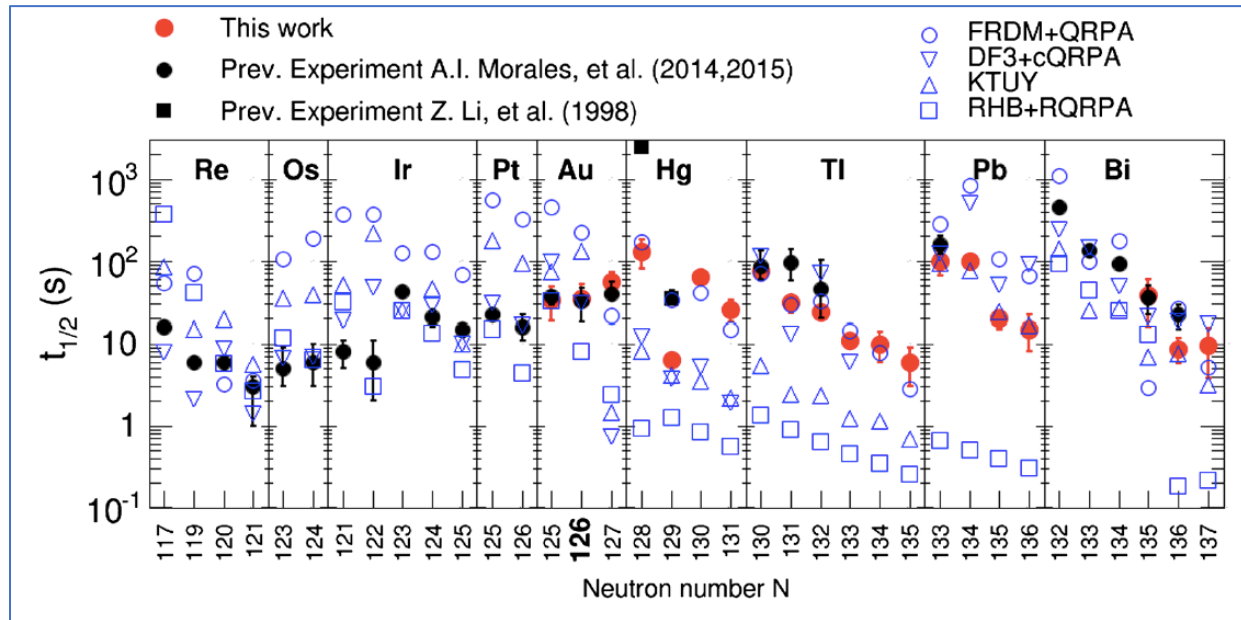
PRL 117, 012501 (2016)

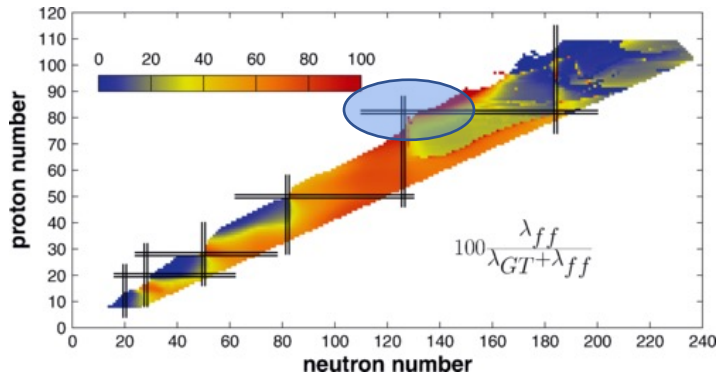
PHYSICAL REVIEW LETTERS

week ending
1 JULY 2016

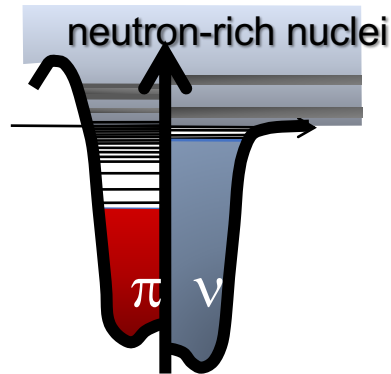
First Measurement of Several β -Delayed Neutron Emitting Isotopes Beyond $N=126$

R. Caballero-Folch,^{1,2} C. Domingo-Pardo,^{3,*} J. Agramunt,³ A. Algora,^{3,4} F. Ameil,⁵ A. Arcones,⁵ Y. Ayyad,⁶ J. Benlliure,⁶ I. N. Borzov,^{7,8} M. Bowry,⁹ F. Calviño,¹ D. Cano-Ott,¹⁰ G. Cortés,¹ T. Davinson,¹¹ I. Dillmann,^{2,5,12} A. Estrade,^{5,13} A. Evdokimov,^{5,12} T. Faestermann,¹⁴ F. Farinon,⁵ D. Galaviz,¹⁵ A. R. García,¹⁰ H. Geissel,^{5,12} W. Gelletly,⁹ R. Gernhäuser,¹⁴ M. B. Gómez-Hornillos,¹ C. Guerrero,^{16,17} M. Heil,⁵ C. Hinke,¹⁴ R. Knöbel,⁵ I. Kojouharov,⁵ J. Kurcewicz,⁵ N. Kurz,⁵





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 beta decay

^{208}Pb

$\pi=-$ 3p1/2

$\pi=-$ 3p3/2

$\pi=-$ 2f5/2

$\pi=+$ 1i13/2

$\pi=-$ 2f7/2

$\pi=-$ 1h9/2

3d3/2

2g7/2 $\pi=+$

4s1/2 $\pi=+$

3d5/2 $\pi=+$

1j15/2 $\pi=-$

1i11/2 $\pi=+$

2g9/2 $\pi=+$

$\pi=+$ 3s1/2

$\pi=+$ 2d3/2

82

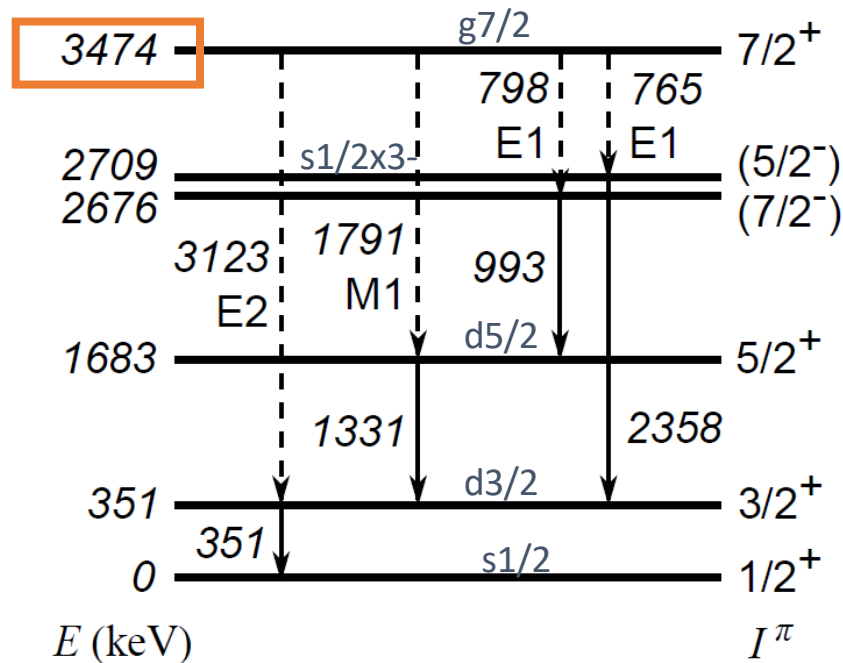
π

126

ν

3d3/2

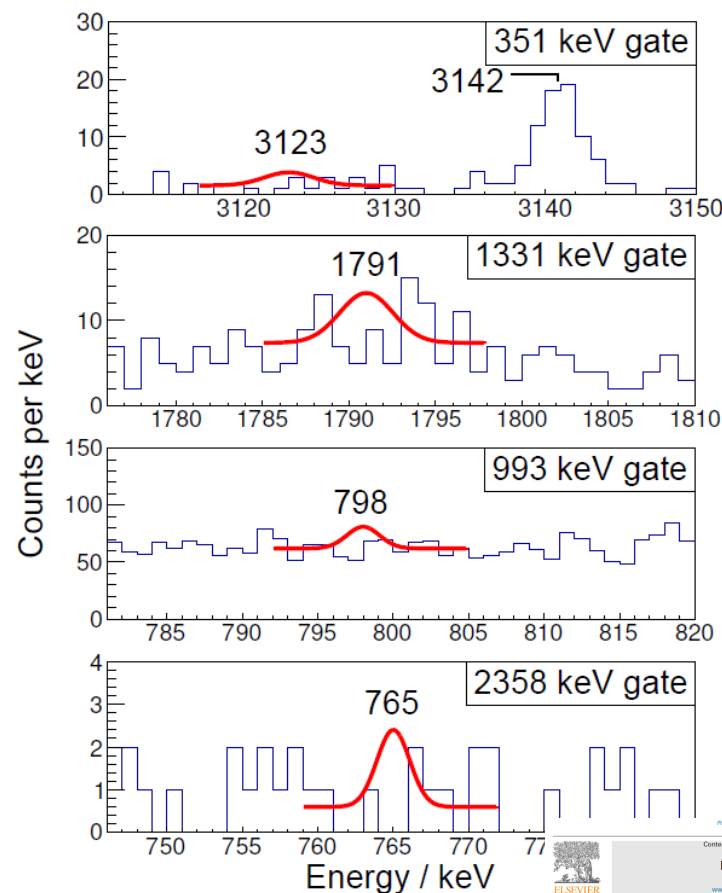
The $2g_{9/2} \rightarrow 1g_{7/2}$ beta decay ($^{207}\text{Hg} \rightarrow ^{207}\text{Tl}$)

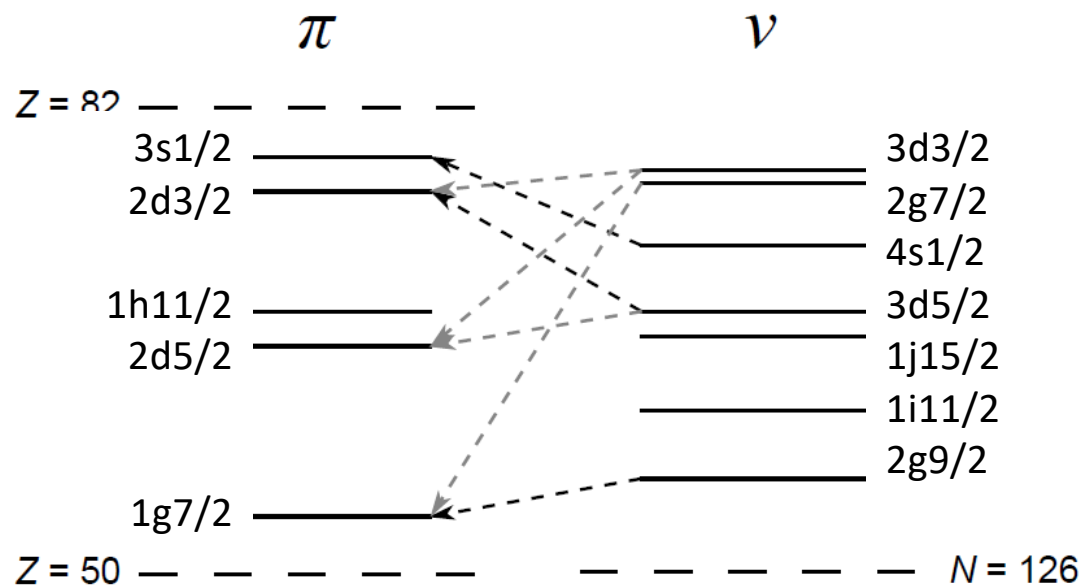


(Non-)population of the $g_{7/2}$ state $< 3.9 \times 10^{-3}\%$

$\log ft > 8.8$ (95% confidence limit)

(only one other, less stringent, test of $\Delta n=0$: $^{209}\text{Tl} \rightarrow ^{209}\text{Pb}$)

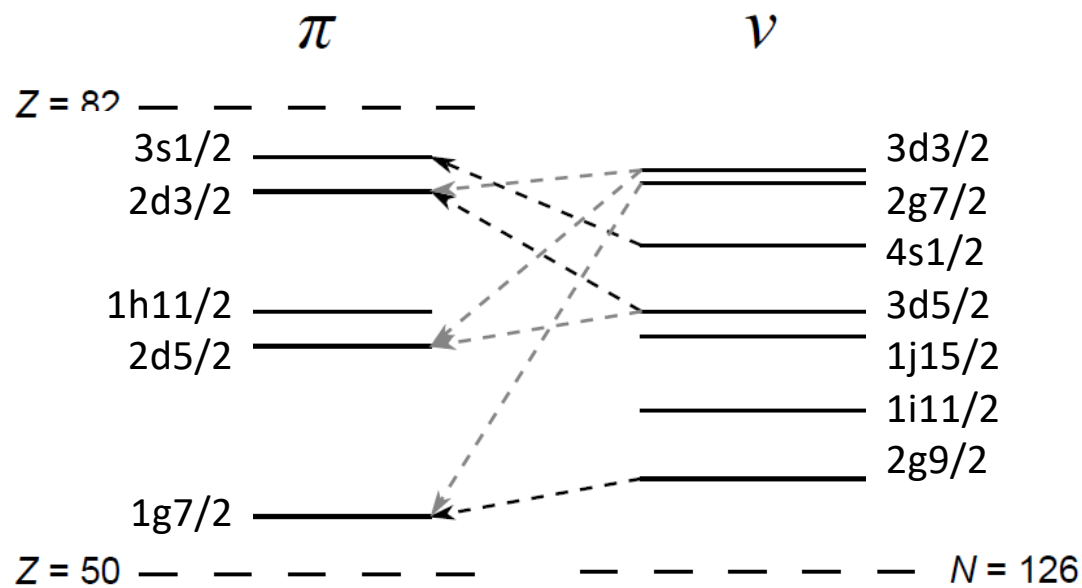




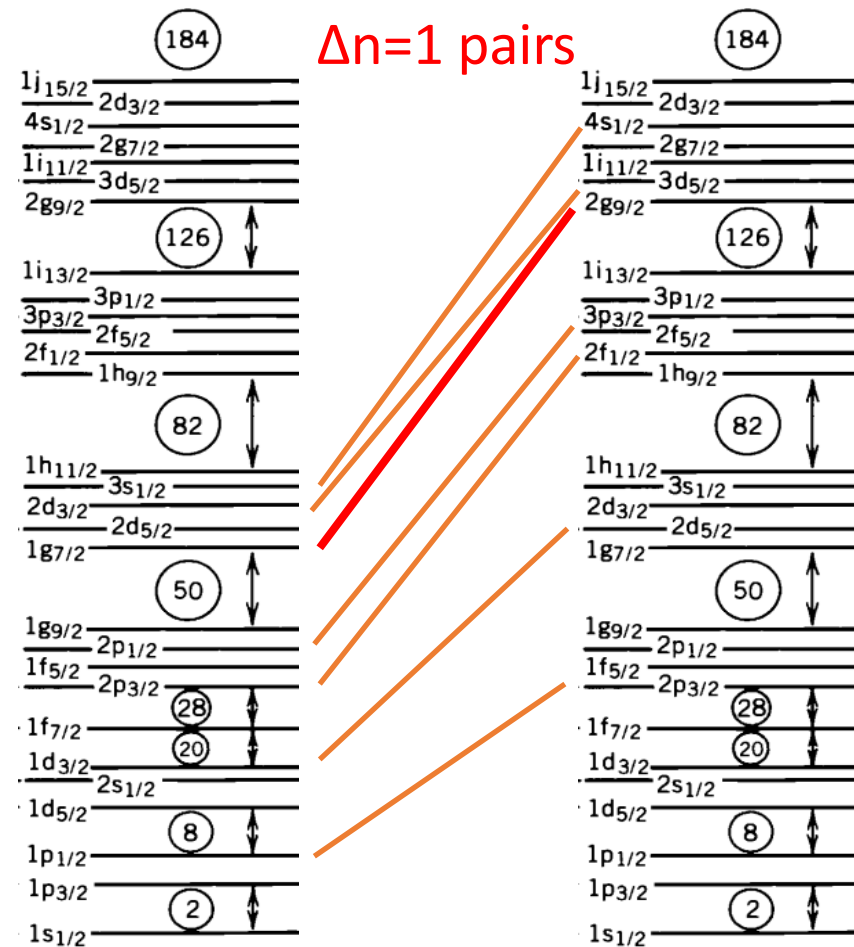
These increase dramatically for extremely neutron-rich nuclei, when either exploring deeper into the proton shell below $Z=82$ or extending further into $N>126$

lifetime of heavy neutron-rich ($Z<82$, $N>126$) nuclei strongly affected

The same selection rule also affects nuclei 'south-east' of ^{132}Sn due to the existence of $n=1$, $l=0$ neutron-proton orbital pairs in the region of $N>82$ and $Z<50$. Experimental investigation of the forbiddenness in this mass region is an interesting possibility but remains challenging due to the large Q_β values



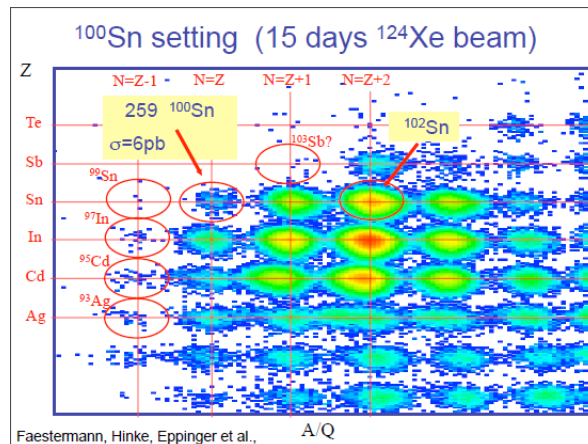
lifetime of heavy neutron-rich ($Z < 82$, $N > 126$) nuclei strongly affected
affects also the region 'south-east' of ^{132}Sn (J.Taprogge *et al.*, EPJA2016)



Superaligned 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 ^9Be target



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

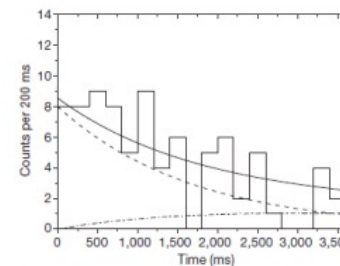


Figure 2 | Time distribution of first decay events. The histogram shows the observed time distribution of all first decay events in the nearest-neighbouring pixels after implantation of ^{100}Sn nuclei. Decay curves resulting from the MLH analysis are shown individually for ^{100}Sn (dashed) and its 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.

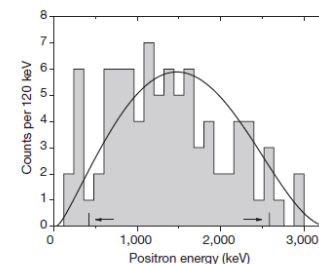
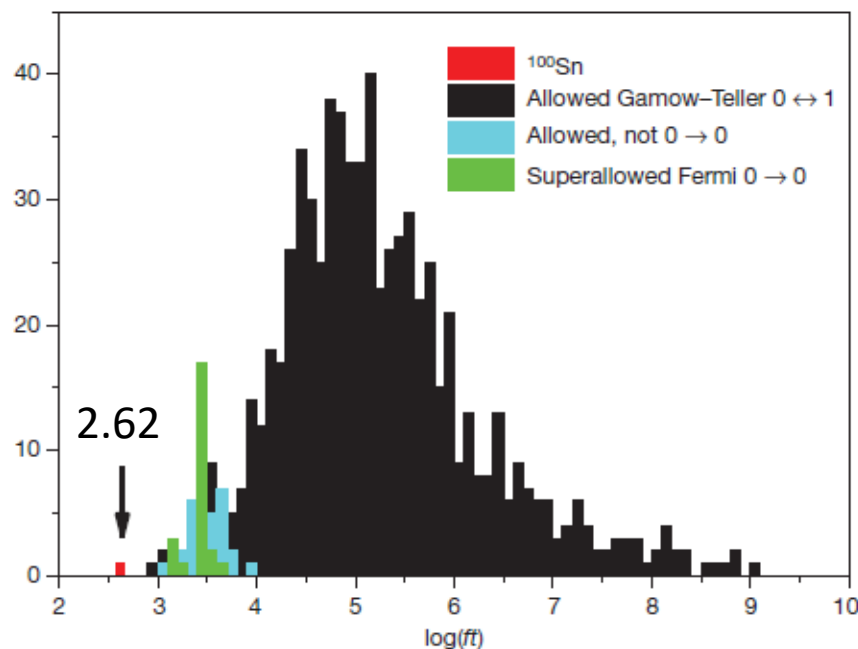


Figure 5 | Distribution of the positron energies emitted in the β -decay of ^{100}Sn . The spectrum contains only decay events that can be assigned to ^{100}Sn decays with a probability of at least 75%. The MLH fit was applied to the region between 400 and 2,600 keV, which is indicated with markers.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

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

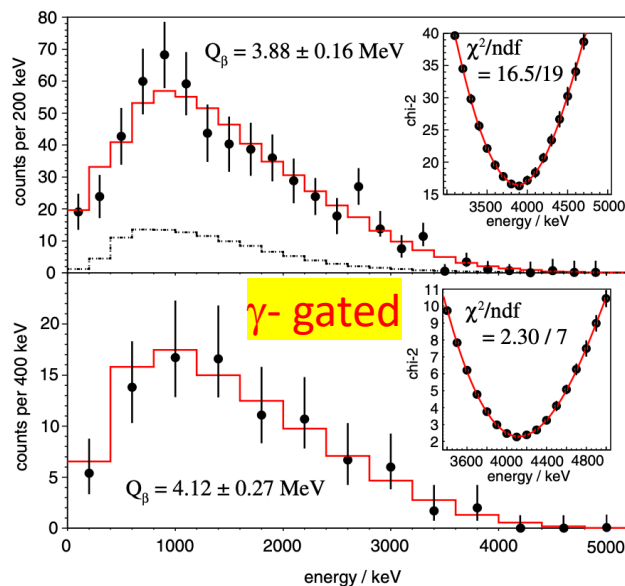
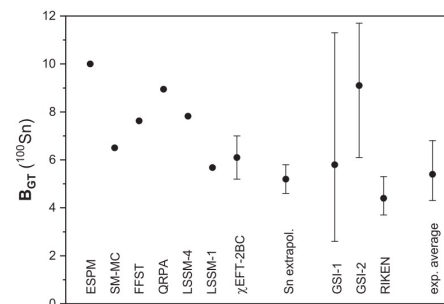
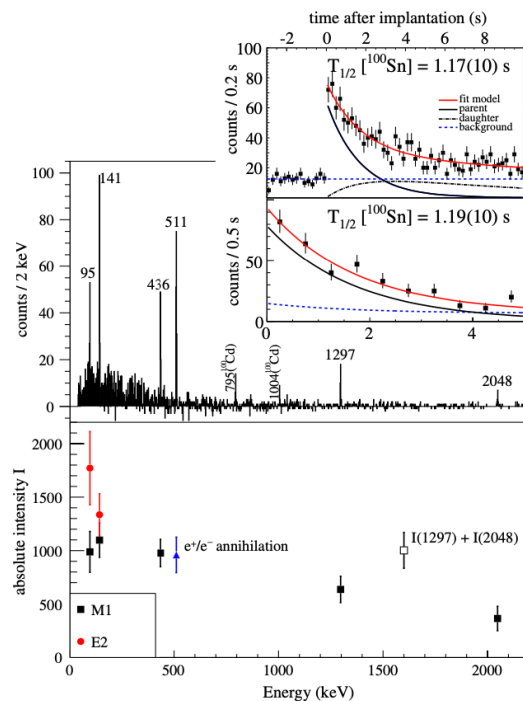


FIG. 3. Top: the energy distribution of positrons after the β decay of ^{100}Sn . Bottom: energy distribution of the γ -gated event selection. The insets show the χ^2 values when comparing the measured spectrum with the simulated spectrum for a certain end point energy. The Q values for the minimal χ^2 are given in the plot and have been used to generate the fully drawn histograms. The dashed histogram represents the contribution of the daughter decay to the spectrum.

Screenshot

Relativistic Fragmentation reaction

 ^{124}Xe beam on ^9Be target $\rightarrow$ RIKEN higher beam intensity (36pA)260 $\rightarrow$ 2500 ^{100}Sn nuclei produced

β Decay of ^{138}La

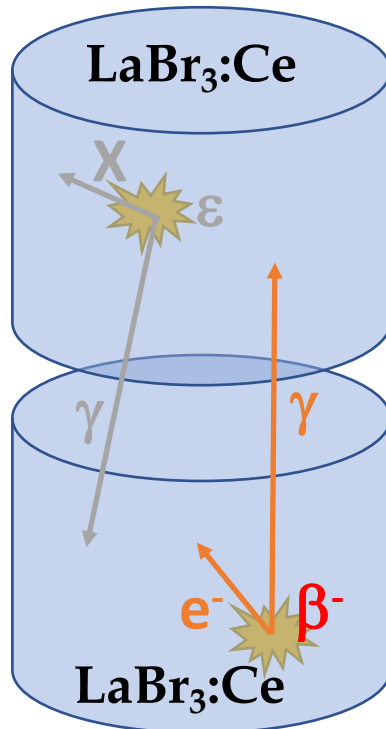
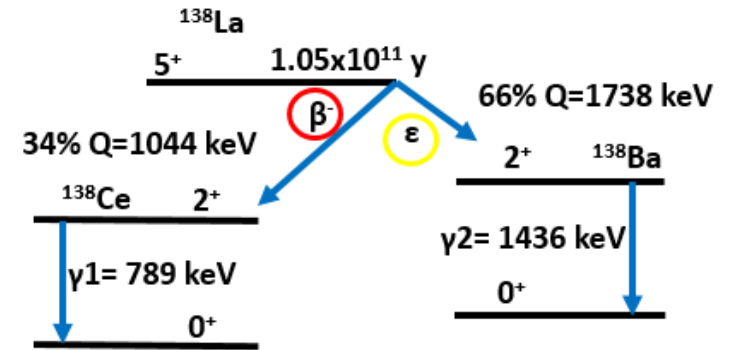
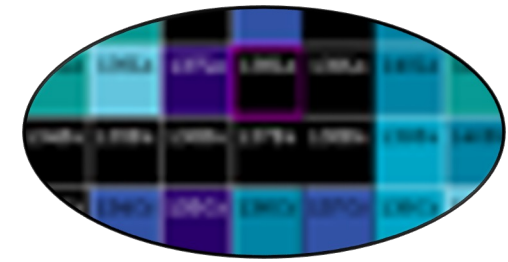
Lanthanum has two isotopes

- ^{139}La , stable
- ^{138}La , **radioactive**:
 - $T_{1/2} = 1.05 \times 10^{11}$ years
 - abundance **0.09%**.

^{138}La has two decay branches

- β^- towards ^{138}Ce , BR= 33.6%
- **EC** towards ^{138}Ba BR=66%

Both decays are **second forbidden decays**
 $5^+ \rightarrow 2^+$

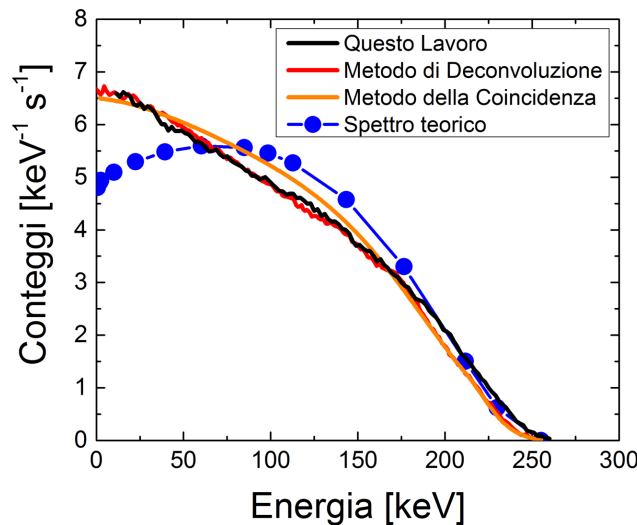
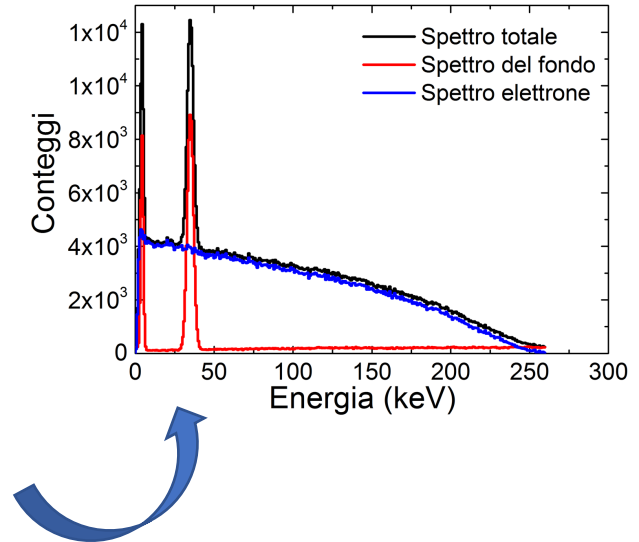
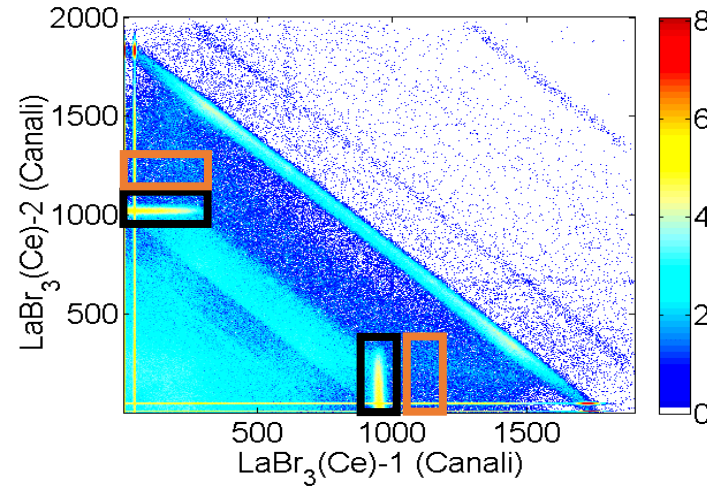


Experiment: measuring the BR and the electron spectra
 Using $\text{LaBr}_3(\text{Ce})$ detectors as **source AND as detectors**

- β^- decay: e^- in the det. which β decays, 789 keV γ ray in the other;
- EC: X ray in the det. which decays, 1436 keV γ ray in the other

Background subtraction to get e^- spectrum:

- Coincidence with 789 keV (black box) **total spectrum**
- **Compton bg** from 1436 keV (red box)
- Bg subtraction cancel peaks at **37.44** and **5.6 keV** in coincidence with 1436 keV.

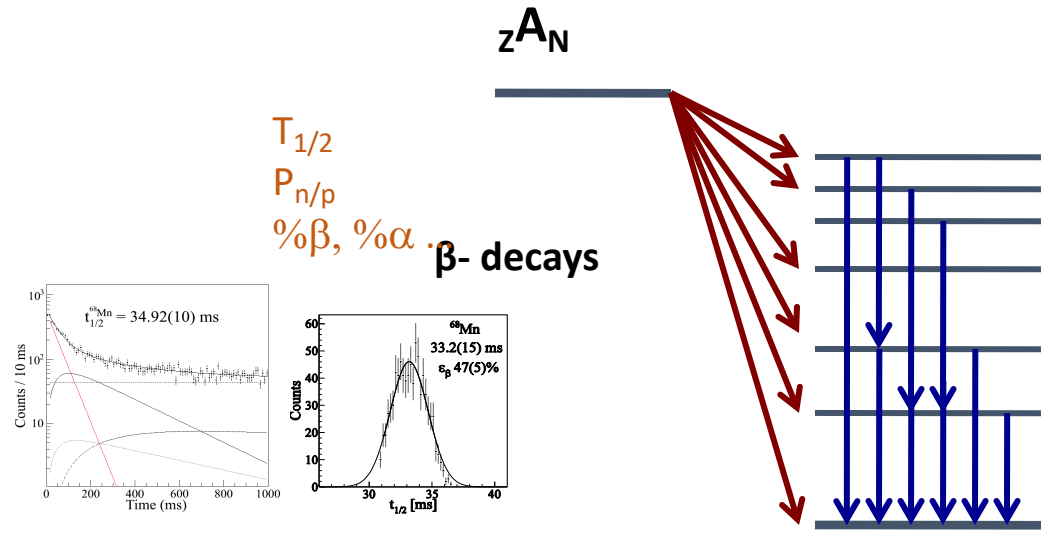


Theory has hard time reproducing low-energy shape of β -electron spectrum

Interaction btw Coulomb field of the nucleus and electron

General Properties of β decay

Quantities that can be extracted in a β decay experiment

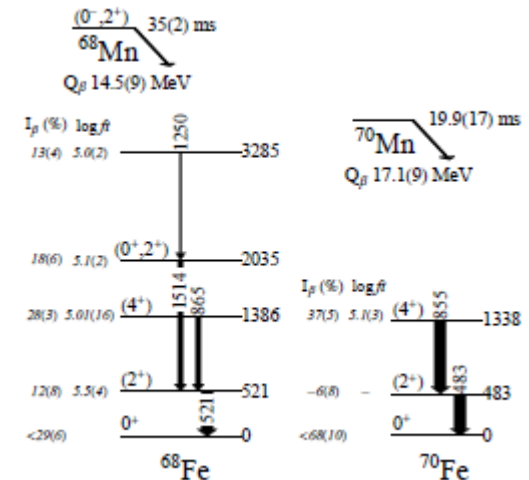
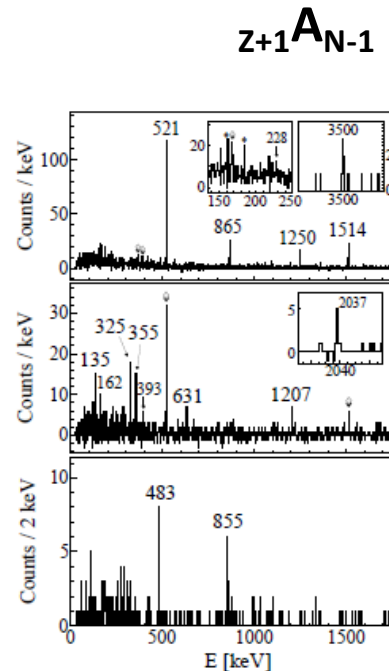
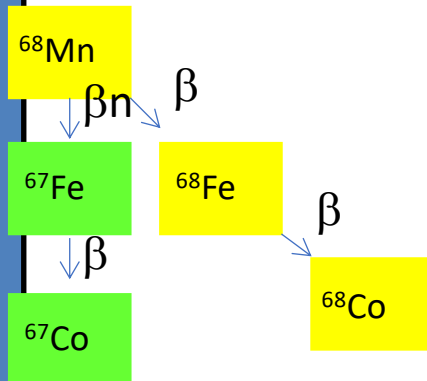


γ transitions

Possible existence of many decaying states

γ - γ coincidences $\rightarrow$ level schemes

Relative intensities I_β
 $\log ft$



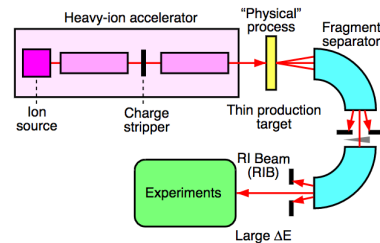
Selection rules allow to suggest/define I^π in both mother and daughter

“pandemonium effect” – exotic nuclei – $\log ft$ is a just upper limit

Introduction

Producing radioactive beams i.e. exotic nuclei

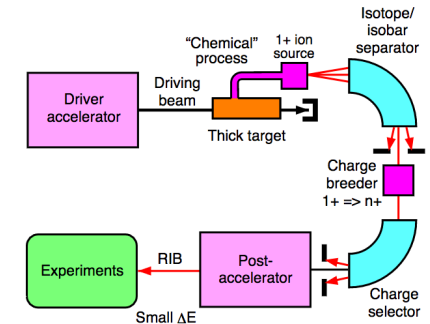
IN-FLIGHT



relativistic fragmentation/fission of heavy nuclei on thin targets

- $> 50 \text{ MeV/u} \rightarrow$ production of cocktail beams of many nuclei
 - Use of spectrometers to transport/separate nuclei of interest $\rightarrow$ Relatively long decay paths $\Delta t > 150\text{-}300 \text{ ns}$
 - 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 ions
- Low cross sections
 - Limitation on rate to distinguish contribution from each species

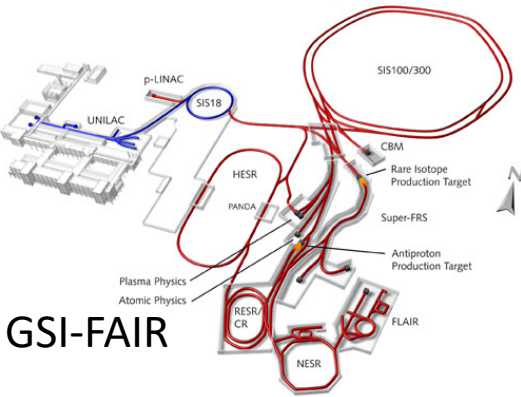
ISOL method



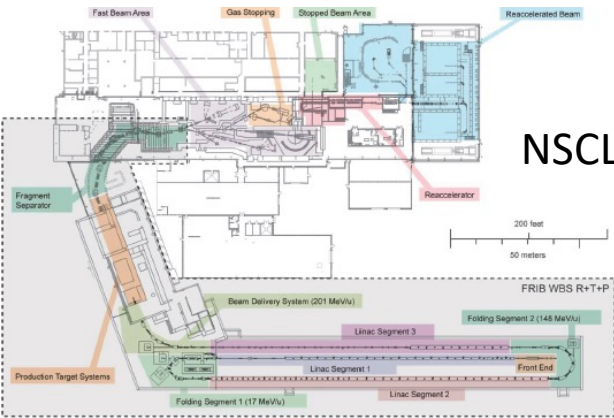
spallation/fission/fragmentation on thick targets, followed by chemical/physical processes to extract desired nuclei

- beams produced at very low energies ($\sim 60 \text{ keV}$)
 - Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species $\rightarrow$ 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)

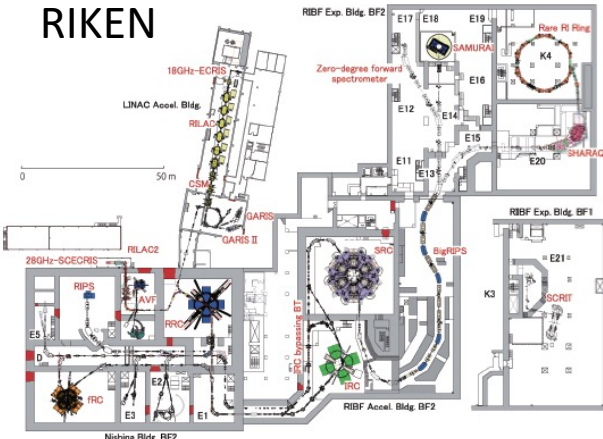
Examples of facilities all over the world...in-flight and isol



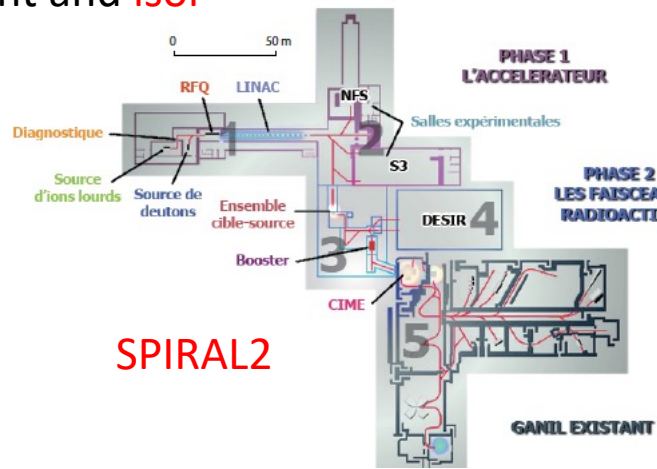
GSI-FAIR



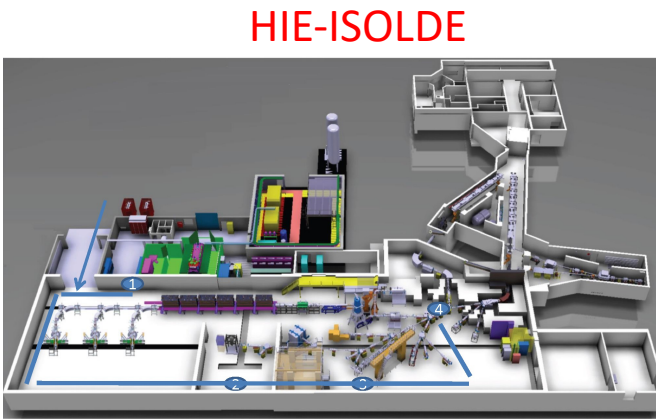
NSCL-FRIB



RIKEN

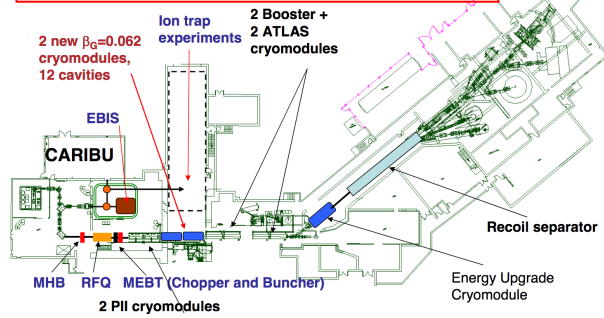


SPIRAL2

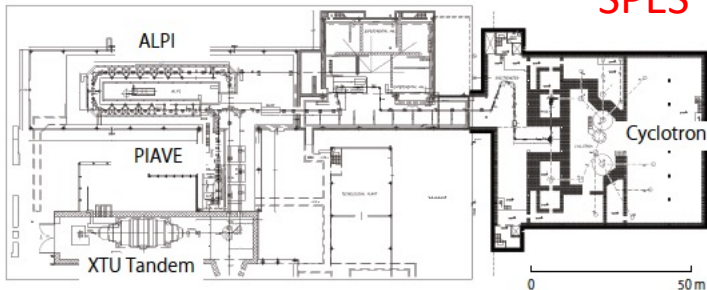


HIE-ISOLDE

Increase intensity of stable beams from ATLAS by factor >10
Increase intensity of CARIBU reaccelerated beams by > 5-10
Increase intensity of in-flight radioactive beams by >100

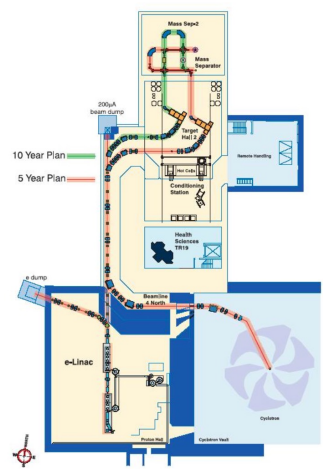


ALTO



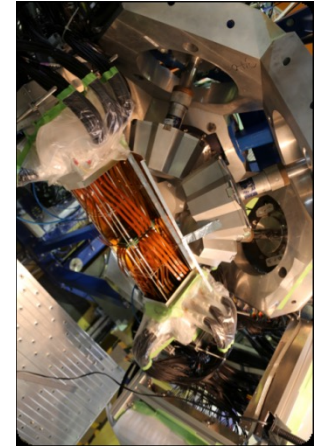
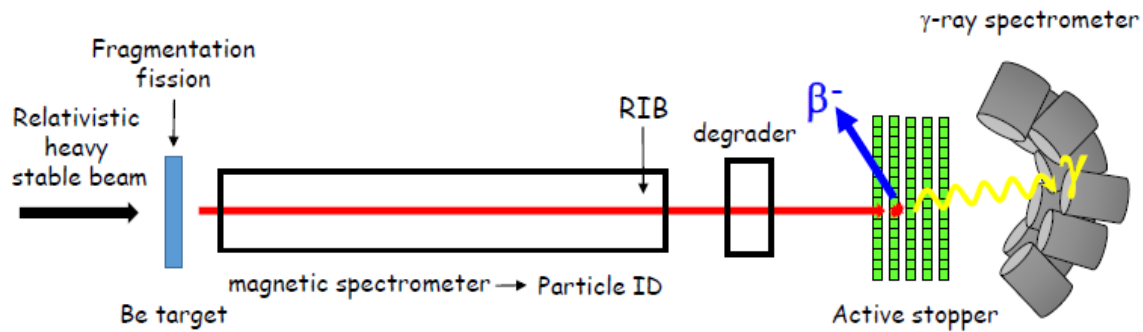
SPES

TRIUMF



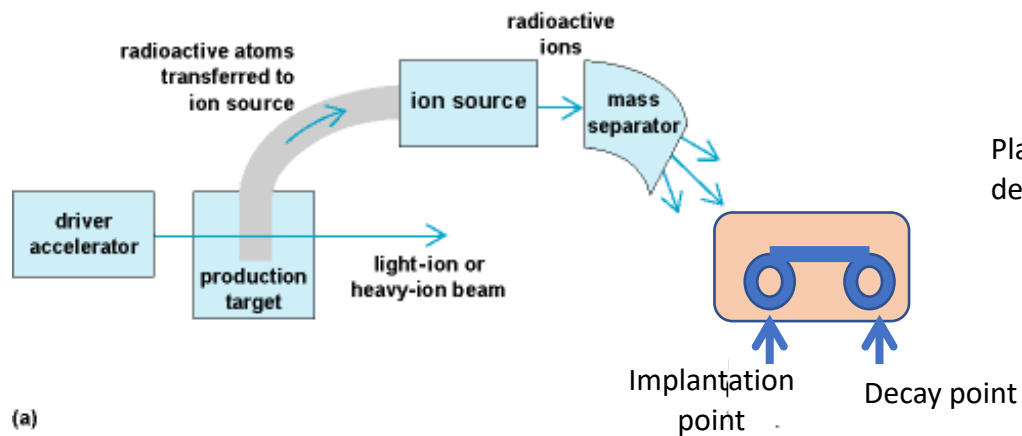
General Properties of β decay

Measuring β decay



Eurica@RIKEN

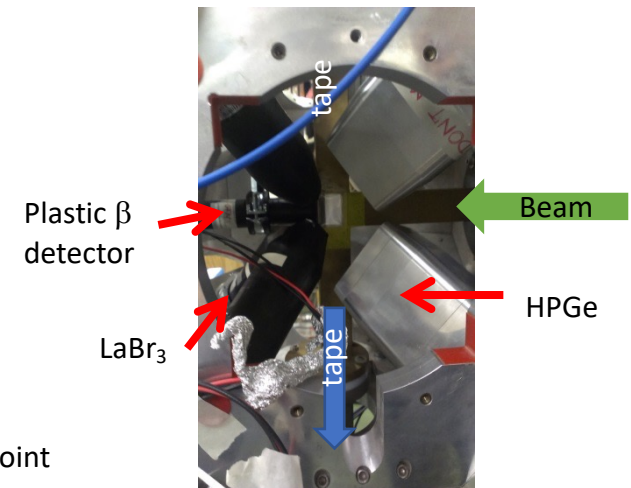
IN-Flight facility



(a)

ISOL facility

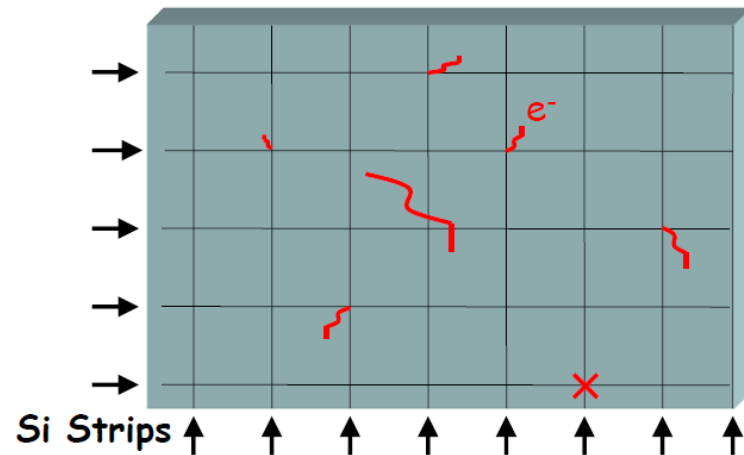
Tape decay stations



IDS @ CERN

Ion-beta correlation techniques: distinguish implantation and decay within same detector

Focal plane implantation detector sensitive to electron emission



The waiting time between particle implantation and β -particle (or i.c. electron) emission is a measure of the decay half-life. Gamma rays emitted following these decays are detected by the RISING array.

Implantation-decay correlations with large background
(half lives similar to the implantation rate):

- ✓ implant-decay time correlation: active catcher
- ✓ implant-decay position correlation: granularity
- ✓ implant of several ions: thickness and area
- ✓ energy of the implanted ion and the emitted β

GSI

- * Dual gain pre-amps on DSSSD to get energies of implanted ion and b-particle
- * All events time stamped with MHz clock.

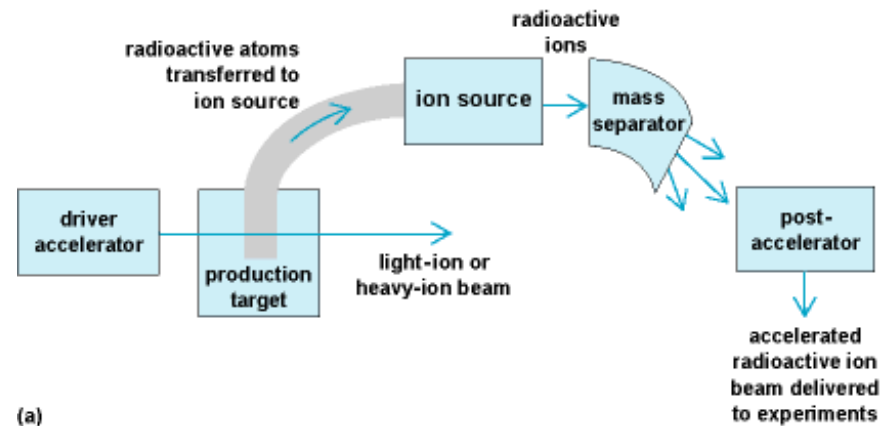
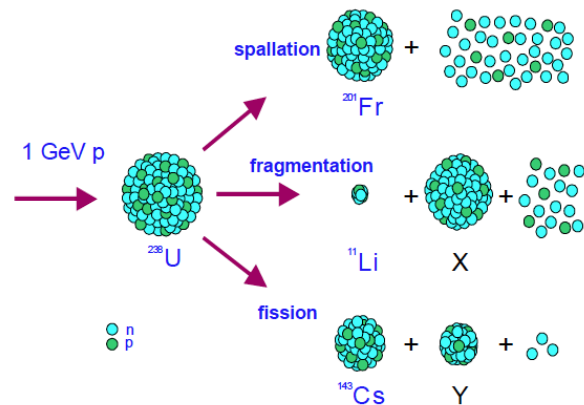
RIKEN

- * Low gain branch for implanted ions
- * High-gain branch for β and α decays

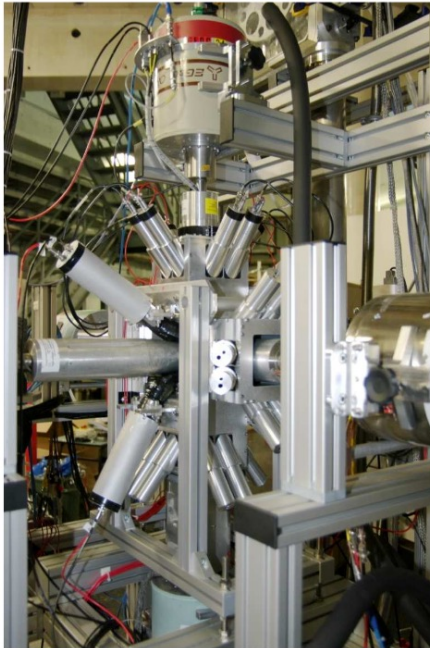
ISOL: Isotope Separation On Line

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

- High intensity proton beams and beams produced at very low energies (60 keV) [possibility for post-acceleration]
- Mono-isotopical beams sometimes achieved. Impurities due to few contaminant species → usually long-living though

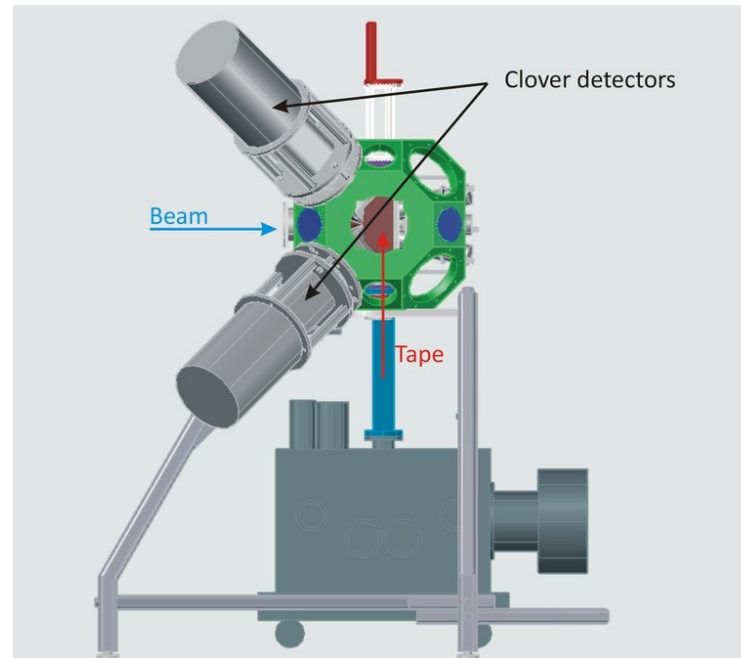


TAPE Station systems



BEDO@ALTO

Principle of operation



IDS@ISOLDE

- Implantation and decay in the same measuring point
- Equipped with egs. Ge detectors and Plastic (or Si detectors) for β particles
- Trigger given by proton arrival and β signal
- Long-living activity is removed by moving away the tape
- NB: no direct signal of implantation

Perspectives

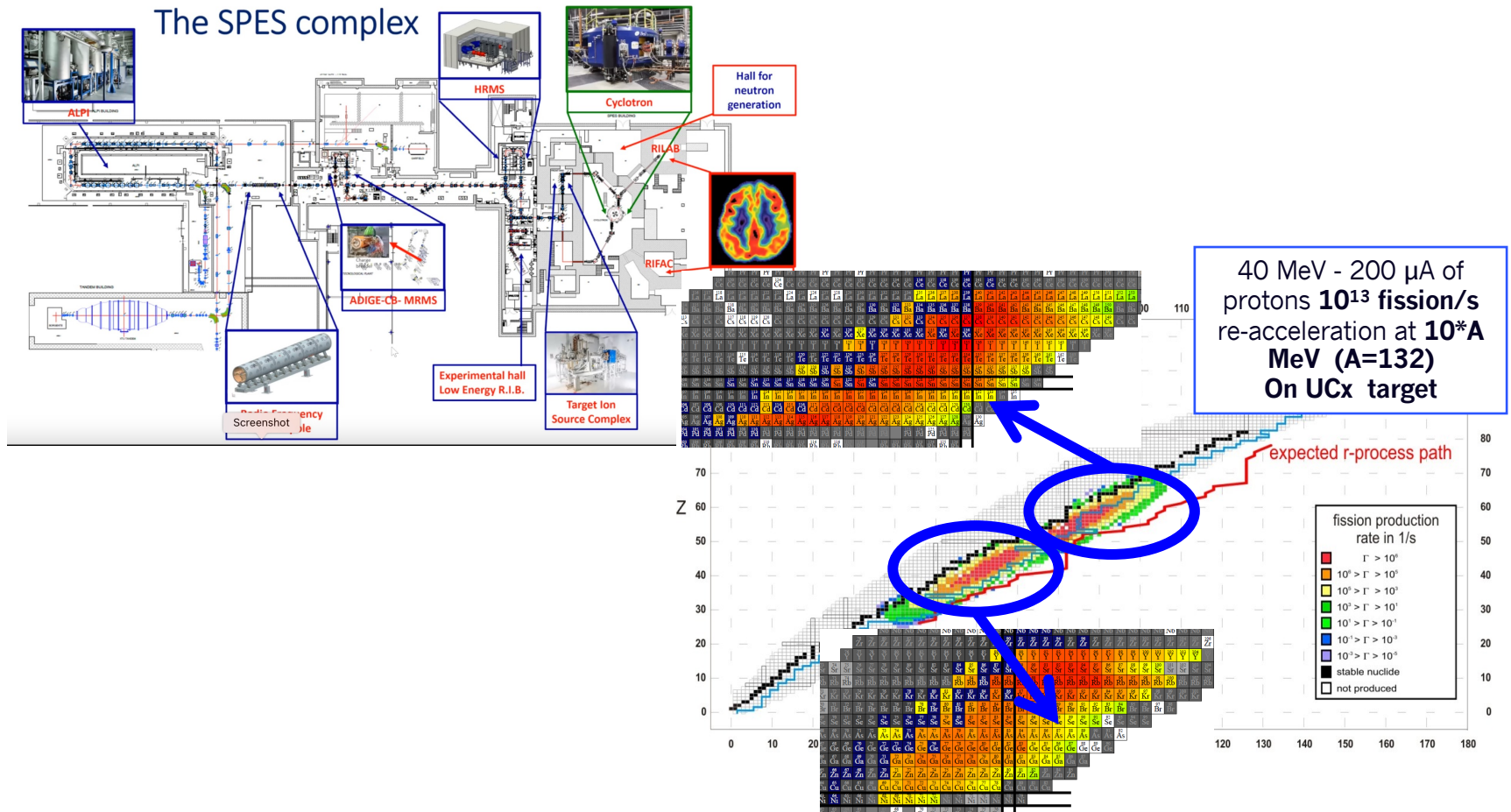
Decay of radioactive nuclei

Element formation in stars

Example of measurements of b-decays

Perspectives

Conclusions



beta-decay spectroscopy towards the r-process G.Benzoni @
INFN-Milano

Perspectives

To the experimental areas

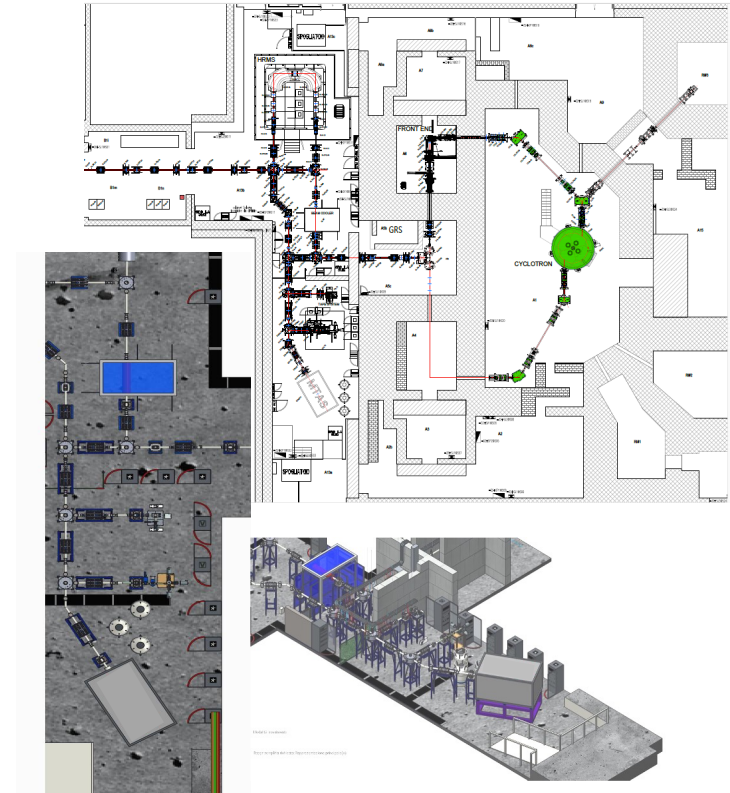
Area A13 in new SPES building dedicated to the installation of experimental set-up using low-energy beams from SPES

Actual – Present - Layout:

- 2 measuring points,
 - one serving two combined experiments (b-DS and SLICES)
 - Big space foreseen for bulky instrumentation
- Possibility to extend the line further for small installations (ISOLFARM)

A13 area: finishing and being equipped and instrumented

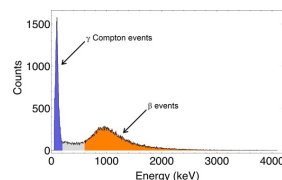
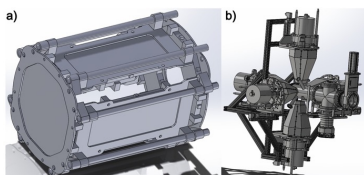
Experimental set-ups under test,
waiting for green light for installation



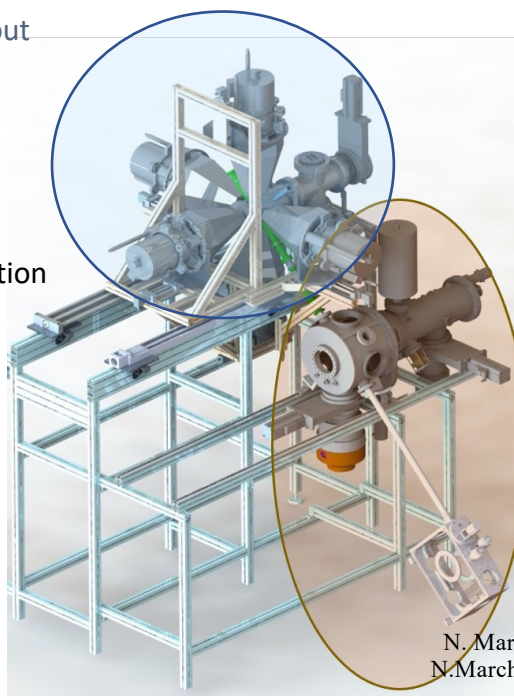
Perspectives

b-DS and SLICES

- beta tagging by EJ212 array SiPM readout
- Gamma detection using 5 GTC+AC
- Placed at implantation point
- Served by tape to remove bg.
- Can be complemented w/scintillator detectors (LaBr₃(Ce))
- T_{1/2}, decay scheme, Pn via γ discrimination



G.Benzoni A.Nannini, A.Saltarelli



- Large area ($\sim 3900 \text{ mm}^2$) Si(Li) detector 6.8 mm thick segmented in 32 sectors
- Magnetic Transport System
- Plastic Scintillator

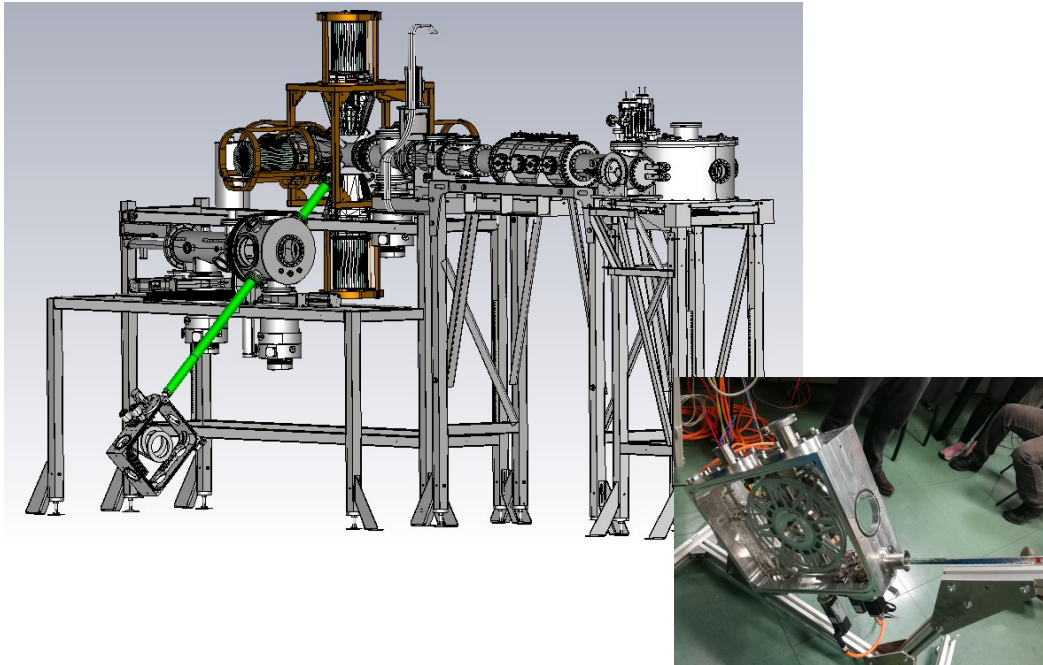
E0 and CE spectroscopy



N. Marchini et al. PRC 105, 054304 (2021)
N. Marchini et al. NIMA 1020, 165860 (2021)

beta-decay spectroscopy towards the r-process G.Benzoni @
INFN-Milano

TAPE Station systems: b-DS @ SPES



- Implantation and decay in the same measuring point
- Equipped with egs. Ge detectors and Plastic (or Si detectors) for β particles
- Trigger given by proton arrival and β signal
- Long-living activity is removed by moving away the tape
- Coupled to SLICES for E0 and conversion electron measurements
- NB: no direct signal of implantation

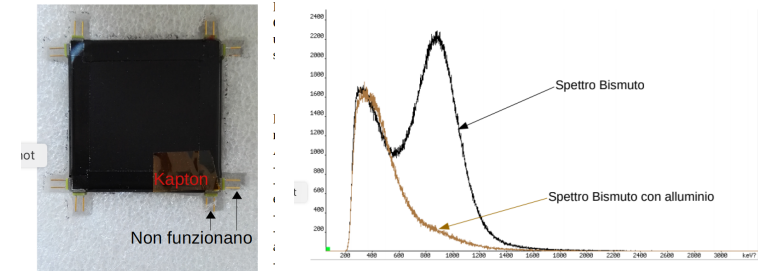


Figure 4: Left: prototype beta plastic detector. Right: response to electrons and gamma rays measured using a ^{207}Bi source (black line) and a ^{207}Bi source coated with Al (gold line).

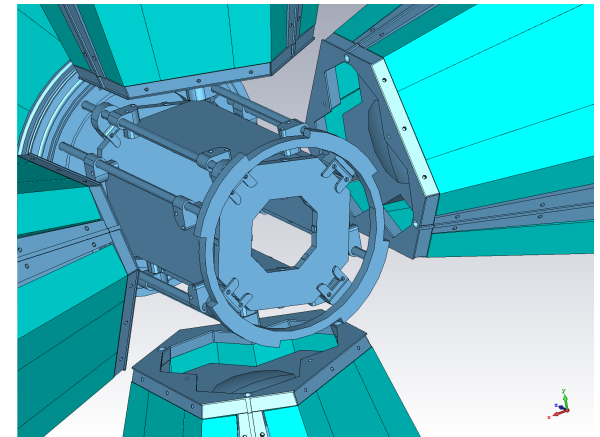
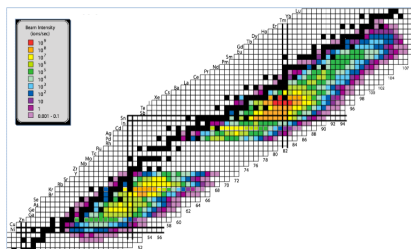


Figure 5: 3D rendering of the placement of the plastic detectors within the decay chamber of b-DS. The beam comes from the right side of the figure. The scattering chamber is not shown for visualization purposes.

Perspectives

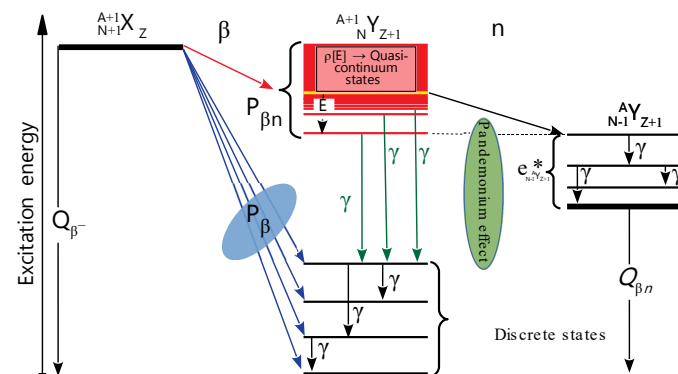
Opportunities with existing/planned equipment



n-rich nuclei → complex decay scheme
 neutron-emission channels open up
 Short lifetimes
 High-Q values, high level densities
 Access to exotic decay modes: PDR via β decay
 Fundamental questions: CKM unitarity via study of super-allowed decays

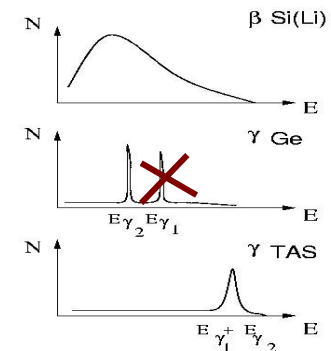
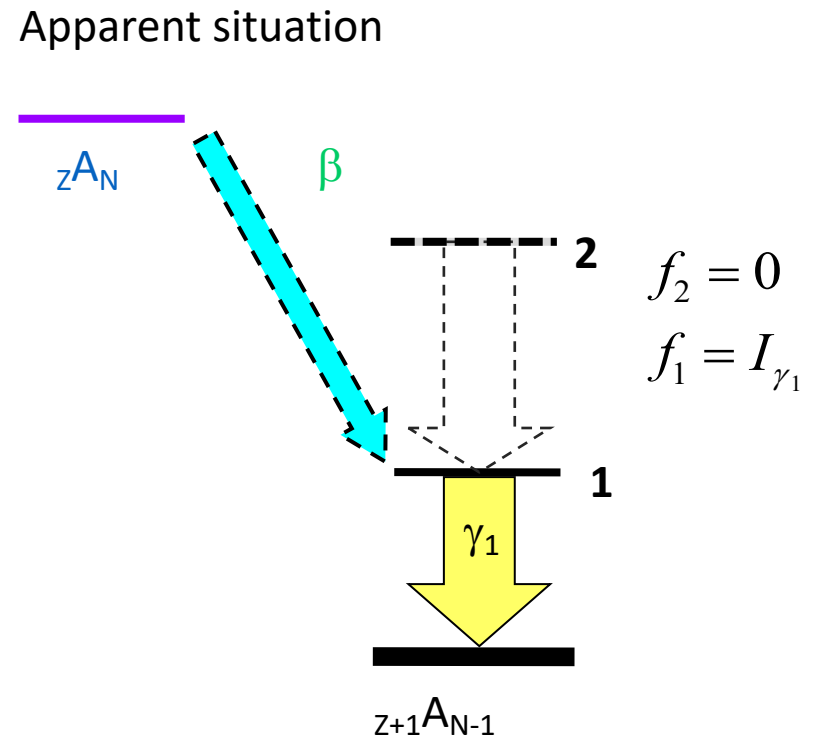
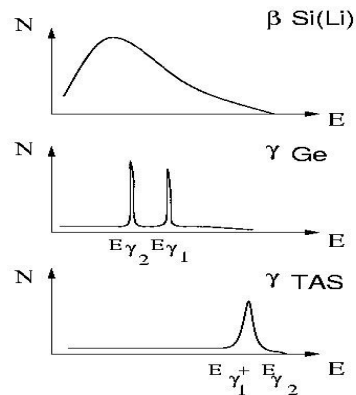
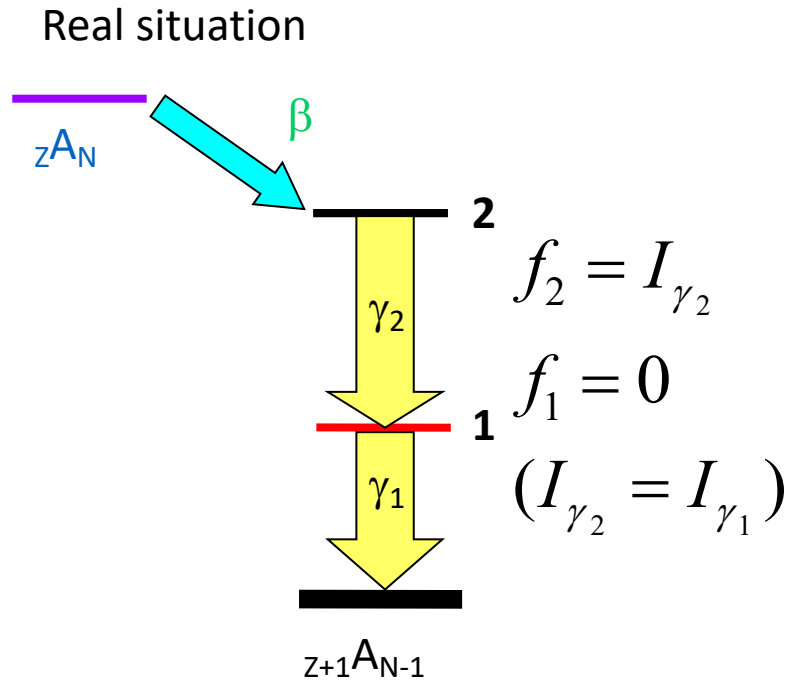
Measurements of direct impact in

- Shell structure evolution
- Evolution of nuclear shapes
- Astrophysical r and s-process modelling
- Modelling and production of radio-isotopes

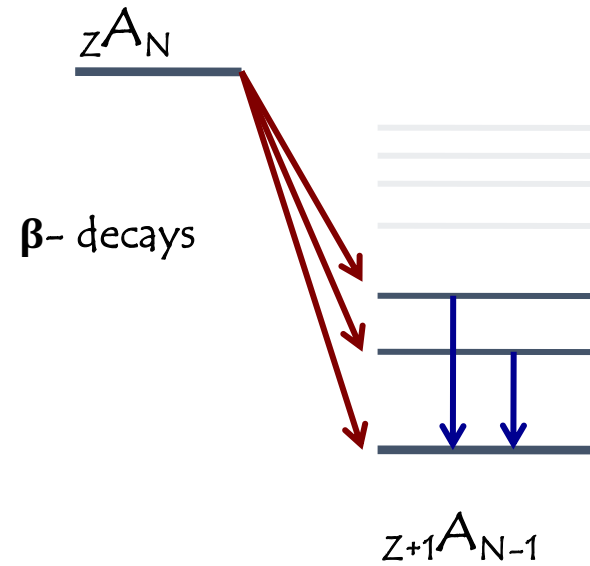
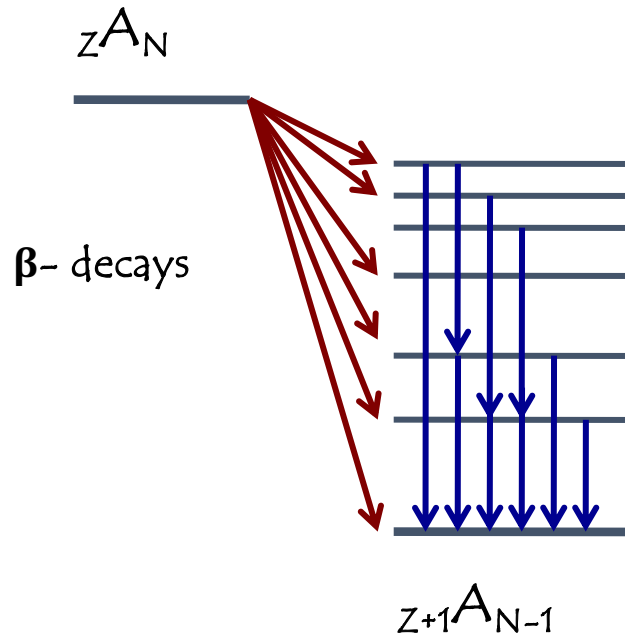


General Properties of β decay

Pandemonium effect

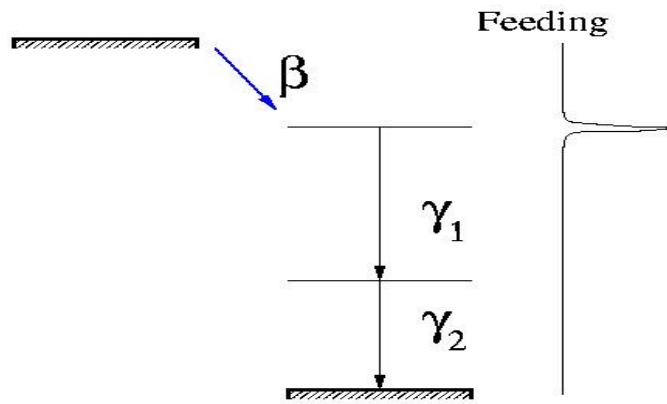


General Properties of β decay



- HPGe detectors are conventionally used to construct the level scheme populated in the decay
 - ➔ Higher Q_{value} higher possibility of missing feeding owing to high-energy γ ray emission or emission of large number of γ rays
 - From the γ intensity balance we deduce the β -feeding
- Pandemonium effect implies
- ➔ Wrong definition of gamma feeding and branching ratios I_β and $\log ft$

Total Absorption Gamma Spectrometer measurements



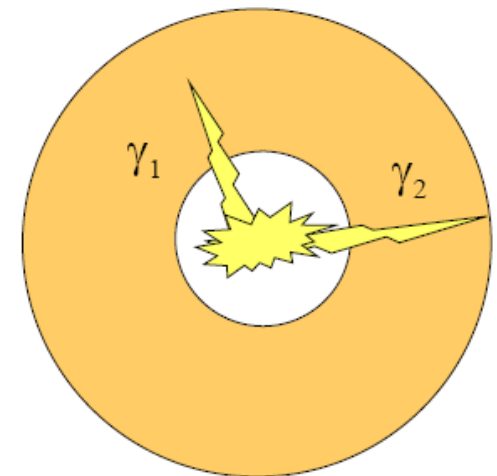
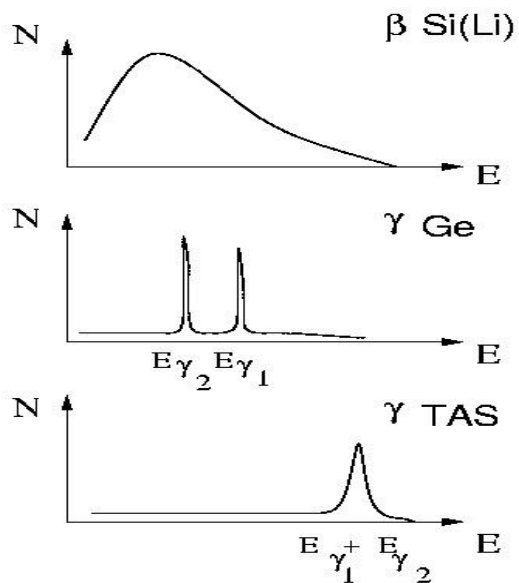
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

A TOTAL ABSORTION SPECTROMETER

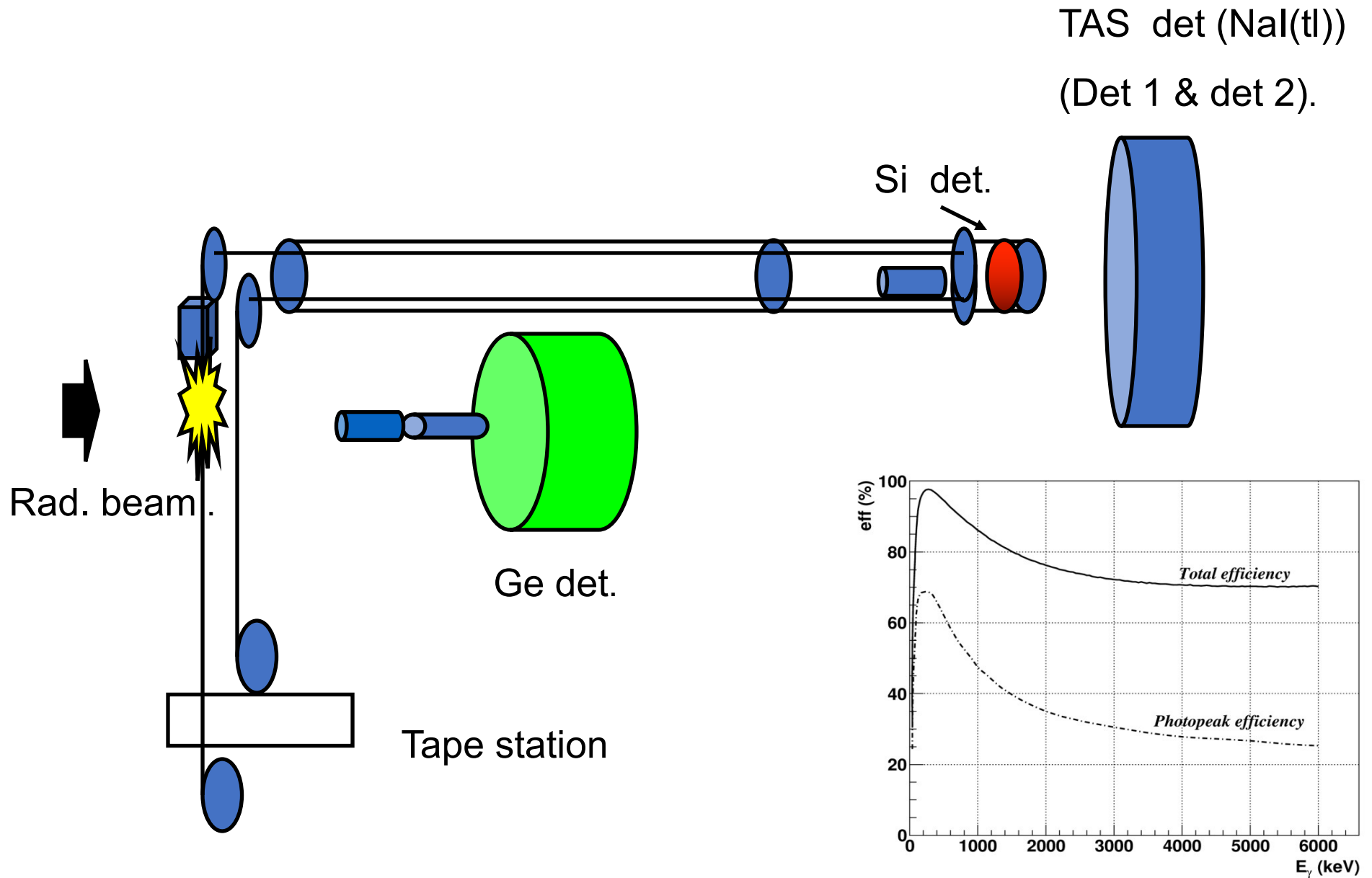
Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

A TAS is a **calorimeter**!

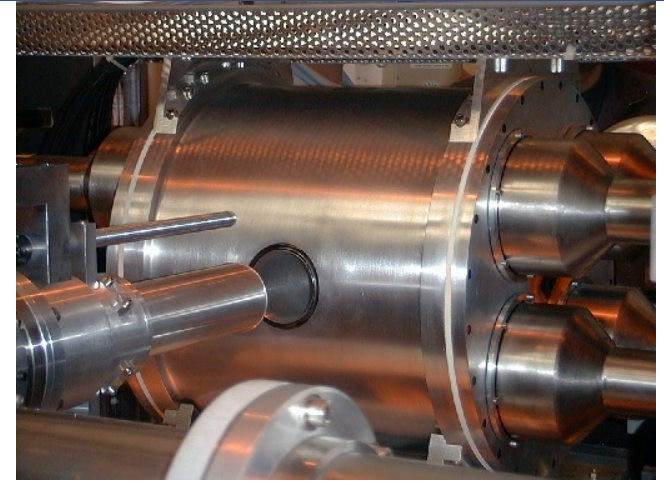
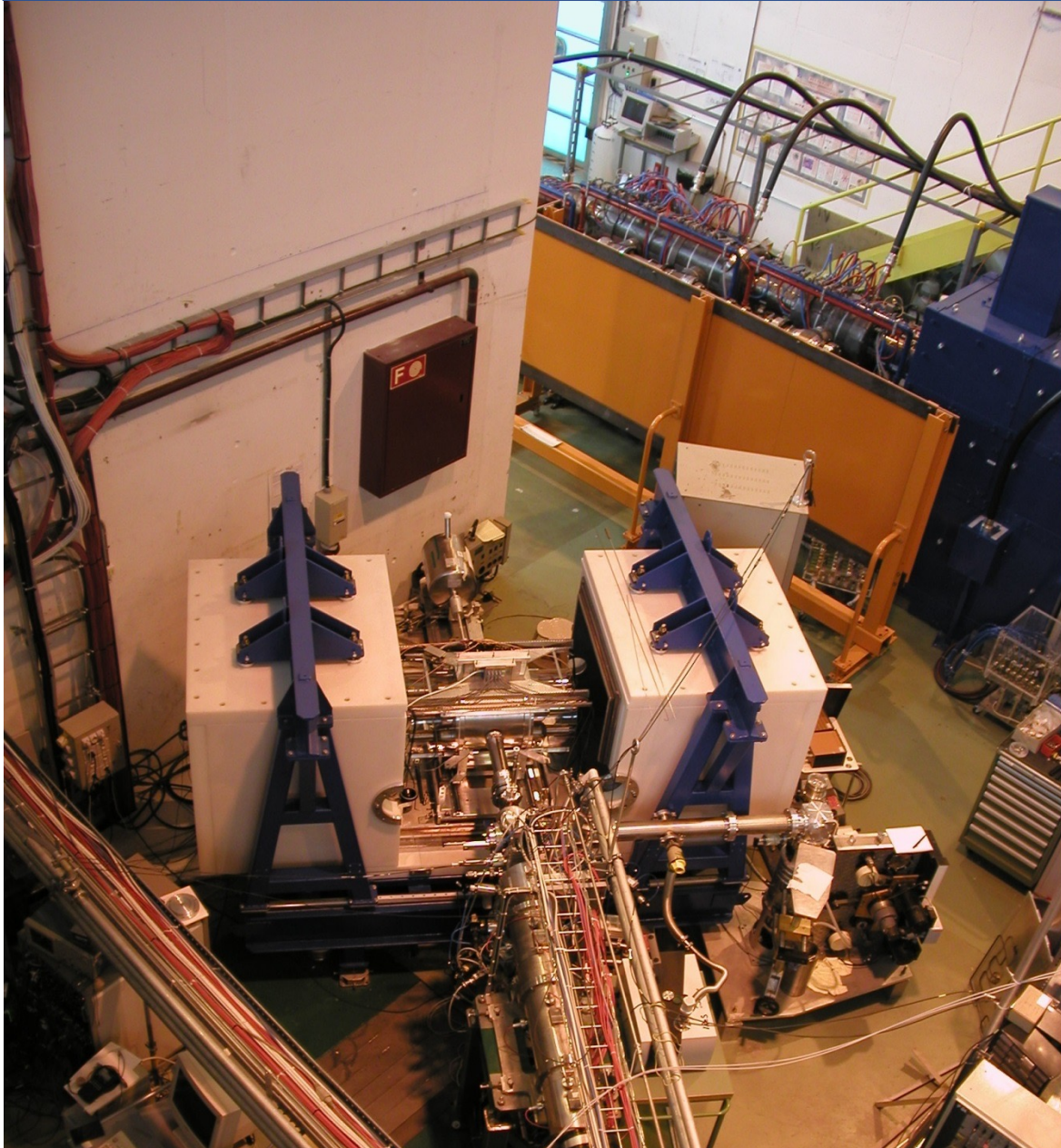
Big crystal, 4π (BaF₂/NaI/HPGe)



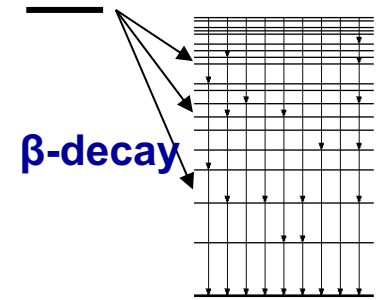
TAS experimental setup



Lucrecia: the TAS at ISOLDE (CERN) (Madrid-Strasbourg-Surrey-Valencia)



- A large NaI cylindrical crystal 38 cm Ø, 38cm length
- An X-ray detector (Ge)
- A β detector
- Possibility of collection point inside the crystal



$$d_i = \sum_j R_{ij} f_j \quad \text{or} \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$

$\mathbf{R}$ is the response function of the spectrometer, R_{ij} means the probability that feeding at a level j gives counts in data channel i of the spectrum

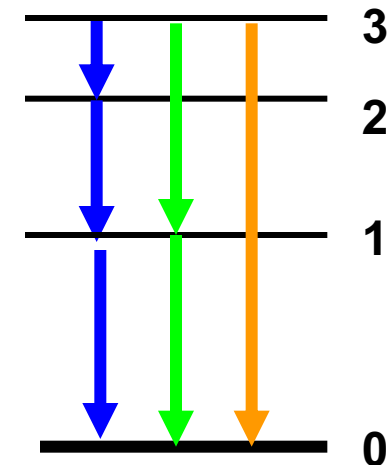
The response matrix $\mathbf{R}$ can be constructed by recursive convolution:

$$\mathbf{R}_j = \sum_{k=0}^{j-1} b_{jk} \mathbf{g}_{jk} \otimes \mathbf{R}_k$$

$\mathbf{g}_{jk}$: γ -response for $j \rightarrow k$ transition

$\mathbf{R}_k$: response for level k

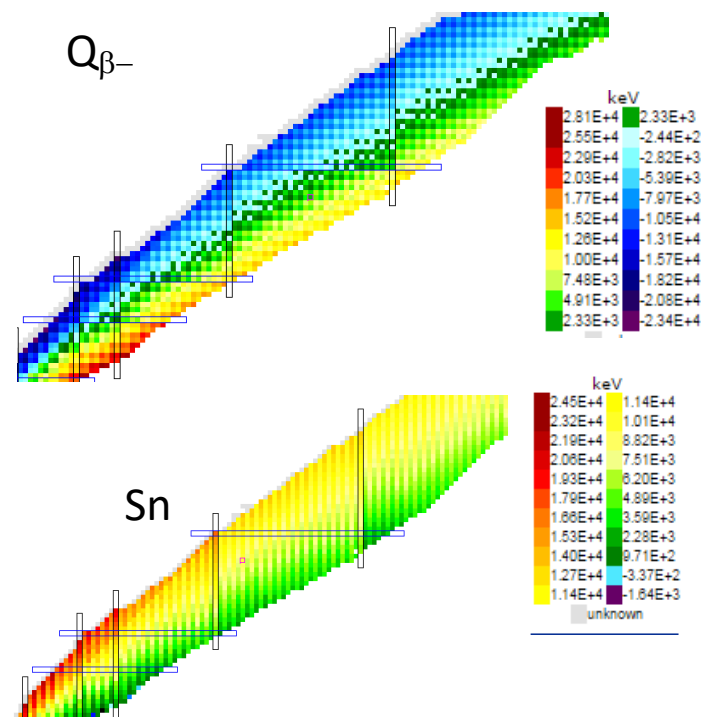
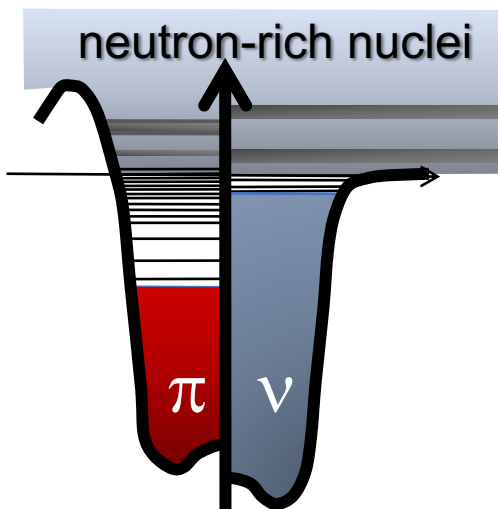
b_{jk} : branching ratio for $j \rightarrow k$ transition



β Decay in Exotic Nuclei

Going away from stability

- Shortening of half-lives
- Increasing Q_{value}
- Decreasing S_n (on n-rich side)
- Higher possibilities of competing mechanisms
- GT unfavoured owing to large mismatch in wave functions btw mother/daughter
- Increasing role of forbidden decays



- Pandemonium effect

