Beta decay studies of the most exotic nuclei

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Outline of the lessons:

PARTI: General concepts

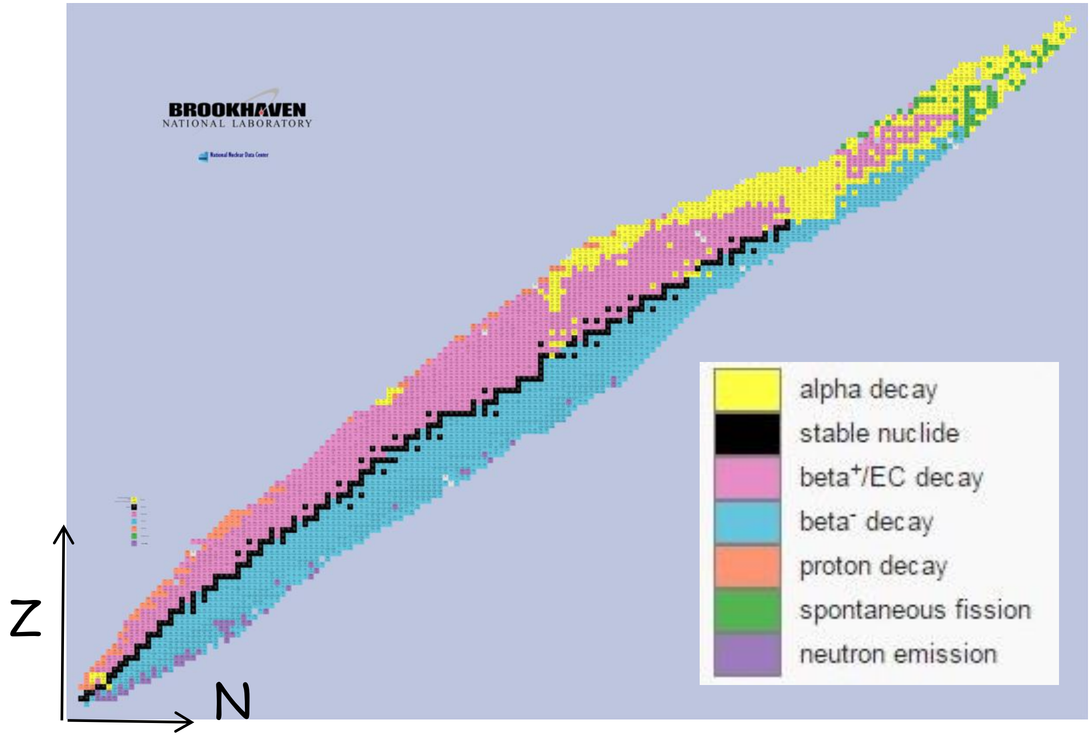
How to measure β decay in exotic nuclei

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

PARTIII: High resolution vs TAS

INFN Istituto Nazionale di Fisica Nucleare

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

Introduction

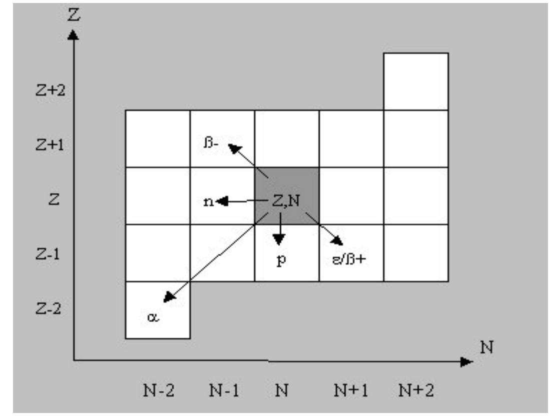
Decay modes

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

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

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

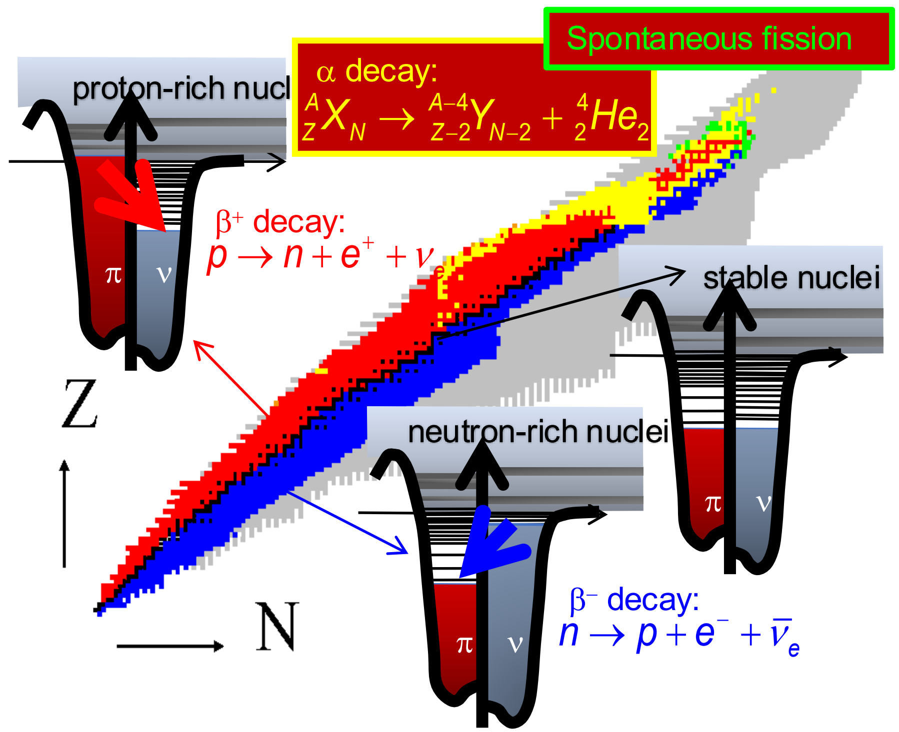
EC: $^{A}_{Z}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \upsilon_e$



Spontaneous Fission

Exotic decay modes: n decay
p decay
cluster emission

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

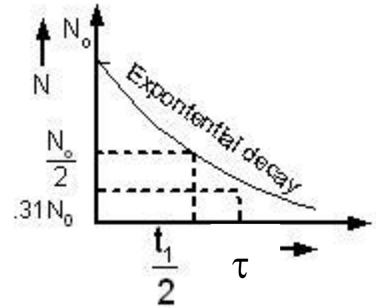


Introduction

Useful definitions for decays:

Law of radioactive decay:

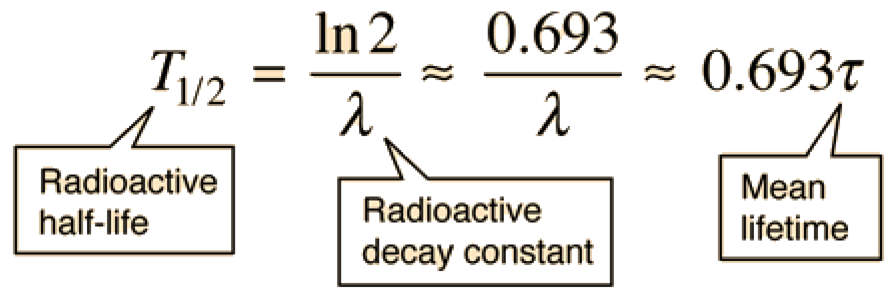
$$N(t) = N_0 e^{-\lambda t}$$



λ decay rate

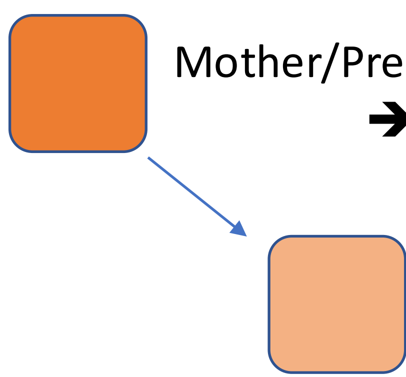
$\tau = 2\pi/\lambda$ meanlife

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



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

Branching ratio: decay probability of two or more competing processes

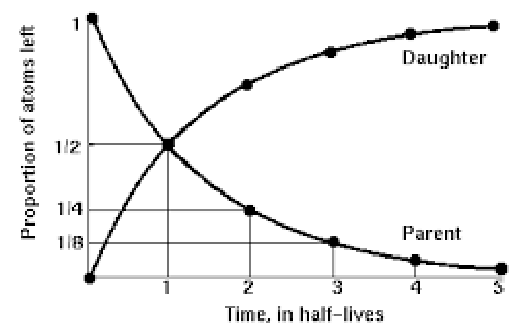


Mother/Precursor

➔ 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

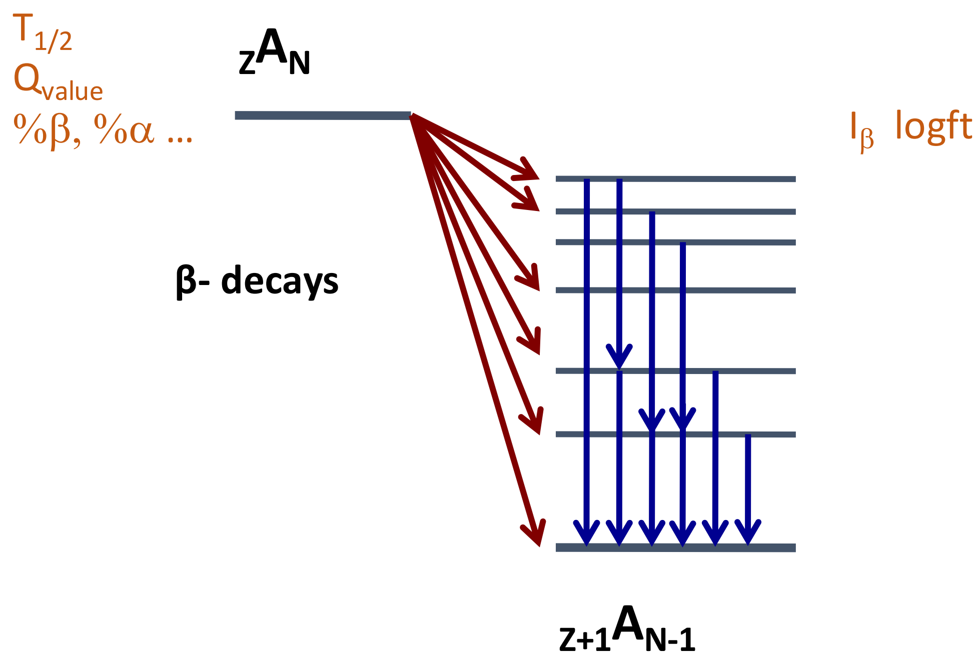
Introduction

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

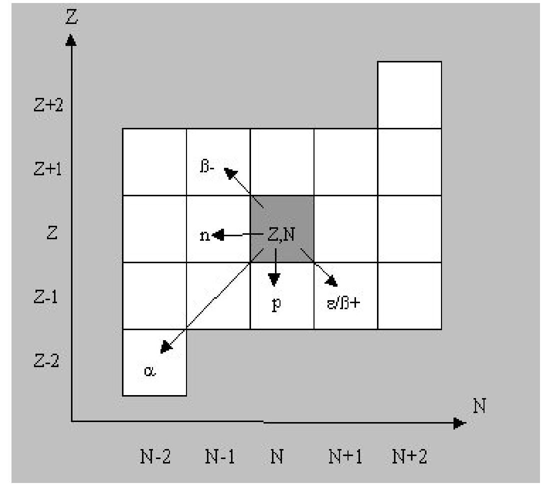


General Properties of β decay

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

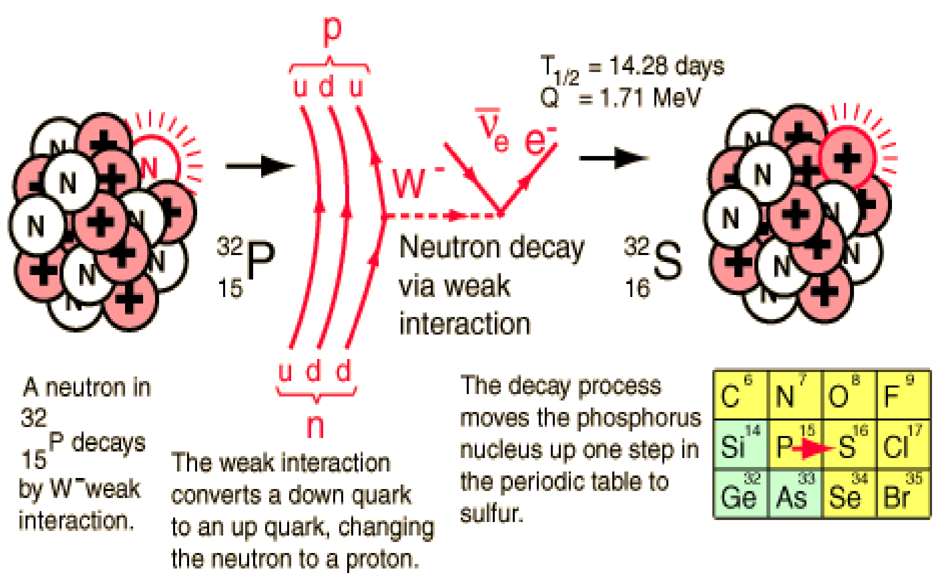
$${}^{A}_{Z}X \rightarrow {}_{Z-1}^{\;\;\;\;A}Y + e^{+} + \upsilon_e$$ β⁺ decay

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



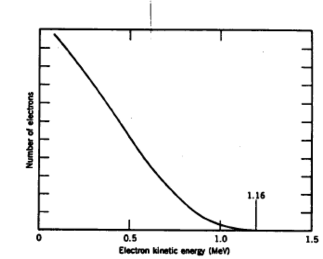
β decay is a weak interaction “semi-leptonic” decay

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



'e 9.1 The continuous electron distribution from the β decay of ^{210}Bi (also
I 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*

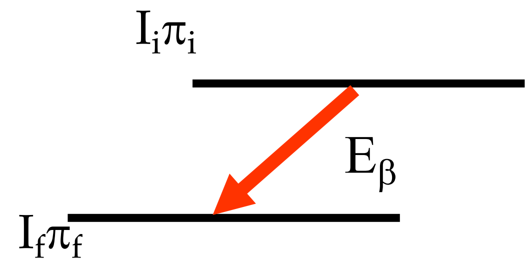
NB: EC and β+ are not always competing:

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

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

General Properties of β decay

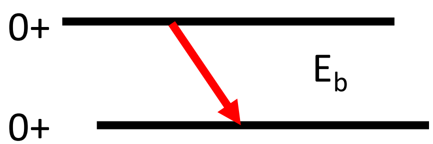
Selection rules for possible decays

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**

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

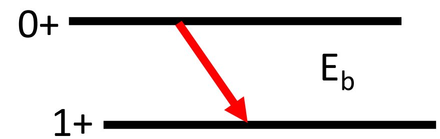
Fermi



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

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

Gamow-Teller



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

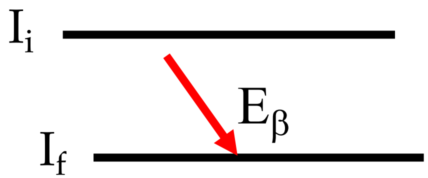
$$L_\beta = 0 \quad S_\beta = 1 \uparrow\uparrow or \downarrow\downarrow$$

General Properties of β decay

Useful empirical rules

The fifth power beta decay rule:

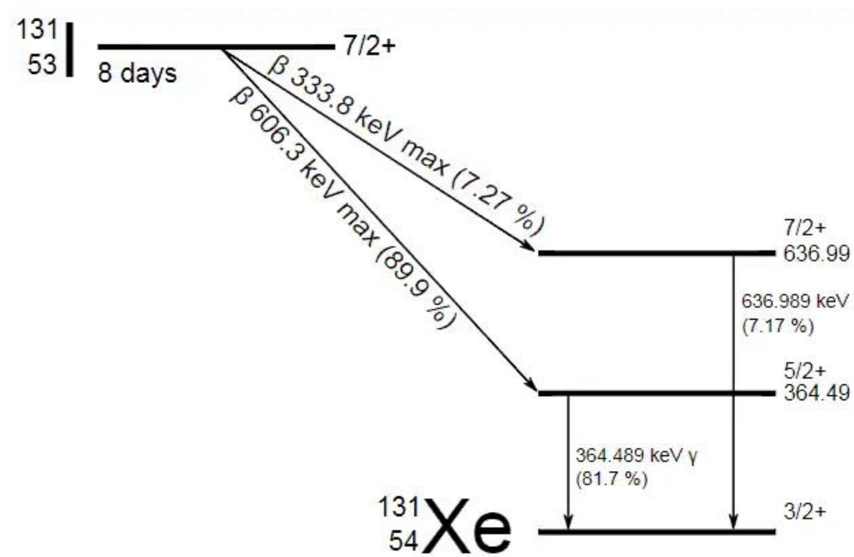
the speed of a β transition increases approximately in proportion to the fifth power of the total transition energy



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

- 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.



General Properties of β decay

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

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

- ➔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

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

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

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

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

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

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

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

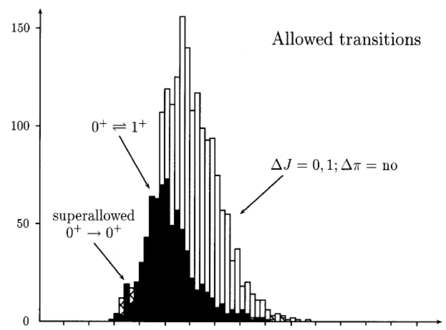
General Properties of β decay

Comparative Half Lives

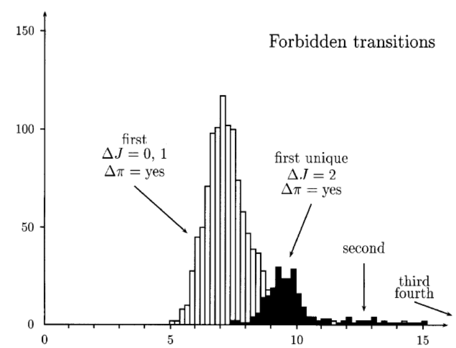
- Based on probability of electron energy emission coupled with spectrum and the Coulomb correction $f_o t_{1/2}$ is called the comparative half life of a transition

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

- Assumes matrix element is independent of energy (true for allowed transitions) Yields fτ (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



Logft < 6.0



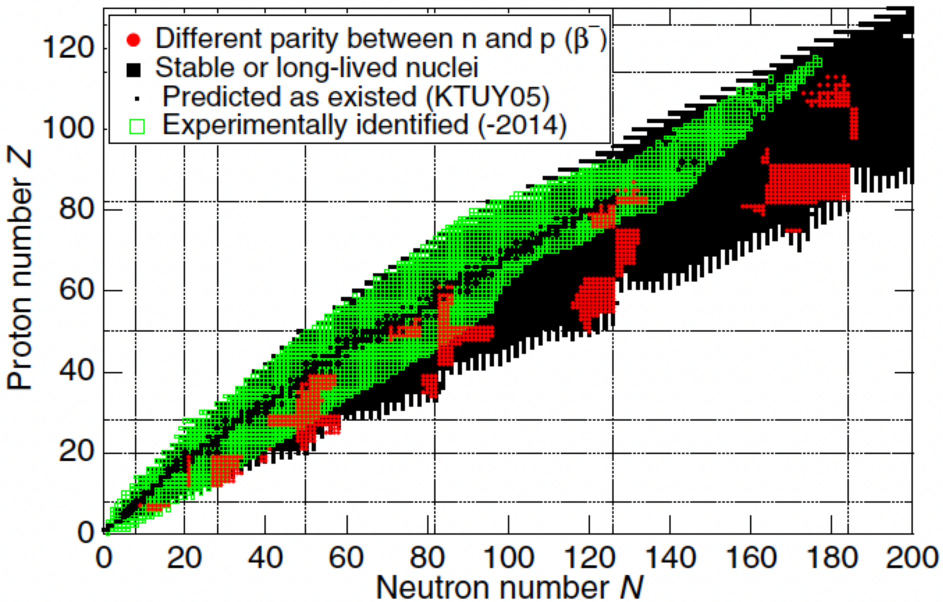
Logft > 6.0

Review Of Log*ft* 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 written as

$\lambda_\beta = \lambda_{allowed} + \lambda_{first\text{-}forbidden}$

$= \lambda_F + \lambda_{GT} + \lambda^{(0)}_1 + \lambda^{(1)}_1 + \lambda^{(2)}_1$

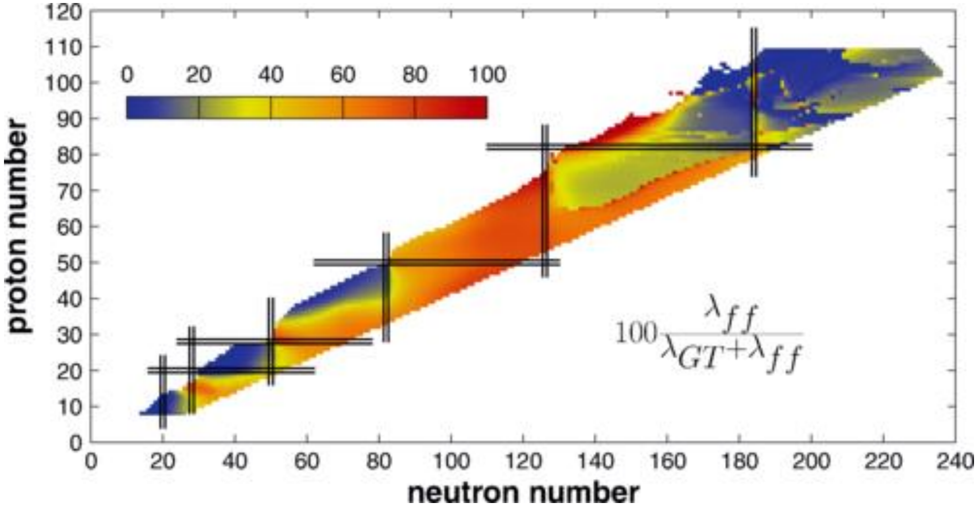
the Fermi transition

Gamow-Teller transition

first forbidden transitions L = 0, 1, and 2

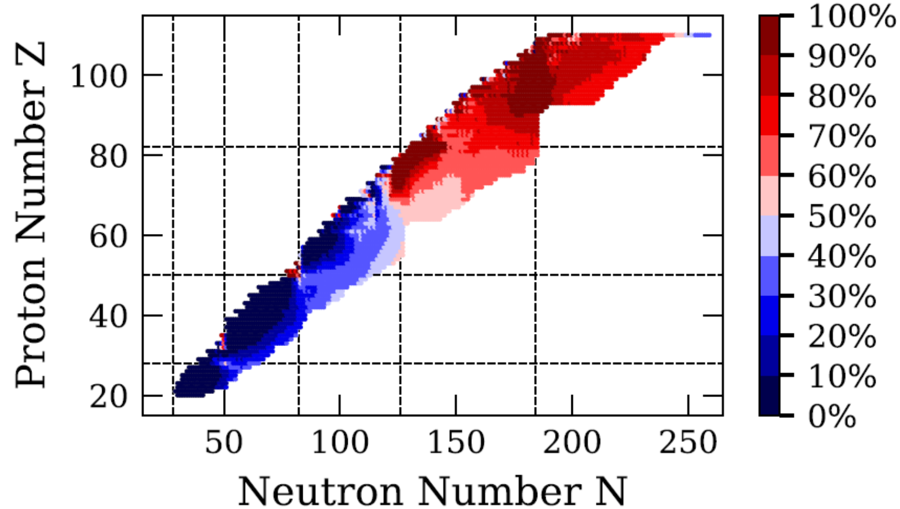
T. Marketin, L. Huther, G. Martinez-Pinedo, PRC93, 025805 (2016)

First-forbidden beta decay



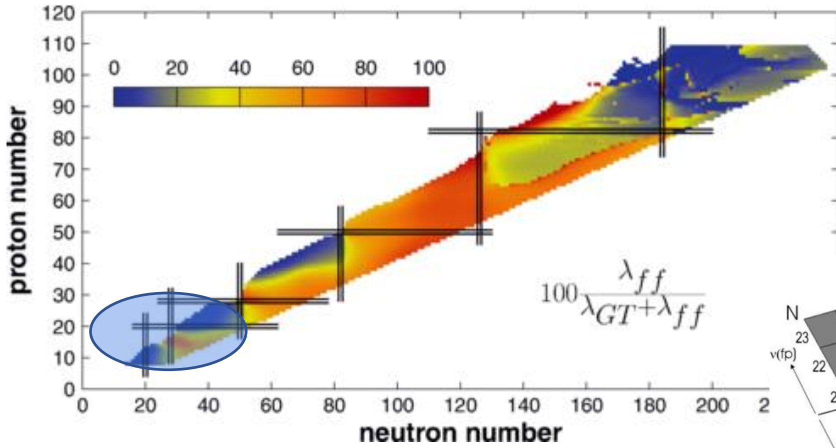
self-consistent microscopic description based on the Relativistic Hartree-Bogoliubov (RHB) model for ground state of open- and closed-shell nuclei with
the proton-neutron relativistic quasiparticle random phase approximation (pn-RQRPA)

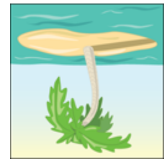
microscopic description based on Skyrme density functional, EFA applied to describe odd-A and odd-odd nuclei

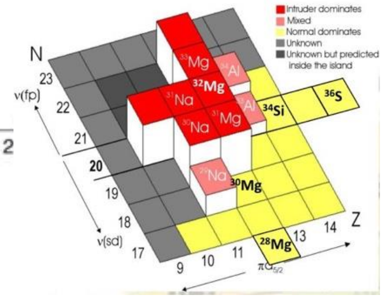


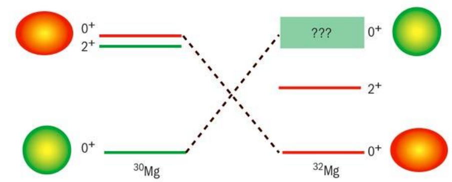
E.M. Ney, J. Engel, T.Li. N. Schunck, PRC102,034326 (2020

First-forbidden beta decay

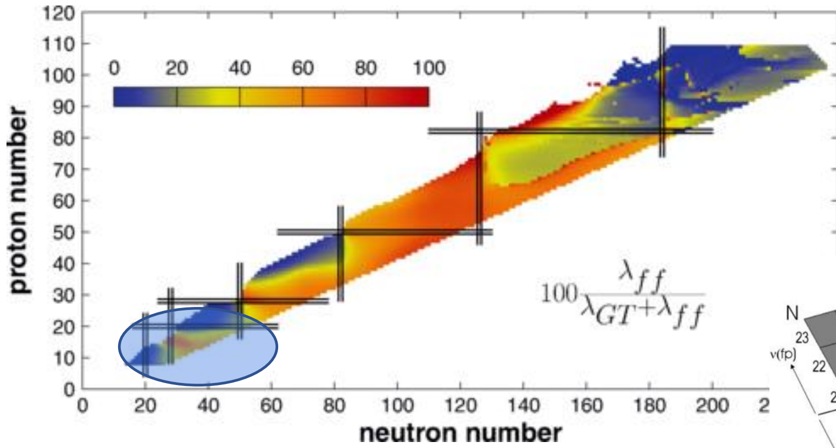


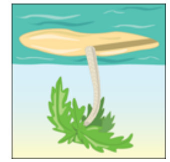


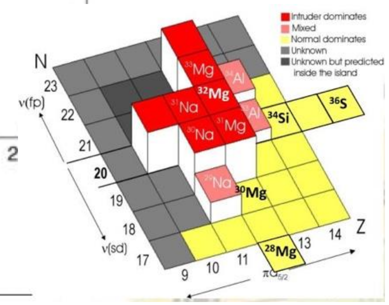


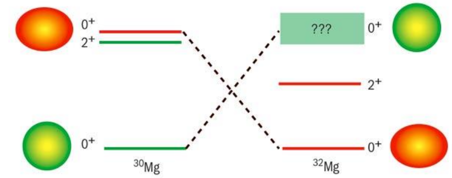


First-forbidden beta decay









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. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

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

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

Vandana Tripathi,[1,*] Soumik Bhattacharya,[1] E. Rubino,[1] C. Benetti,[1] J. F. Perello,[1] S. L. Tabor,[1] S. N. Liddick,[2,3,4] P. C. Bender,[5] M. P. Carpenter,[6] J. J. Carroll,[7] A. Chester,[2,3] C. J. Chiara,[7] K. Childers,[2,4] B. R. Clark,[8] B. P. Crider,[8] J. T. Harke,[9] B. Longfellow,[2,10] R. S. Lubna,[3] S. Luitel,[8] T. H. Ogunbeku,[8] A. L. Richard,[2,9] S. Saha,[5] N. Shimizu,[11] O. A. Shehu,[8] Y. Utsuno,[12,13] R. Unz,[8] Y. Xiao,[8] S. Yoshida,[14] and Yiyi Zhu[5]

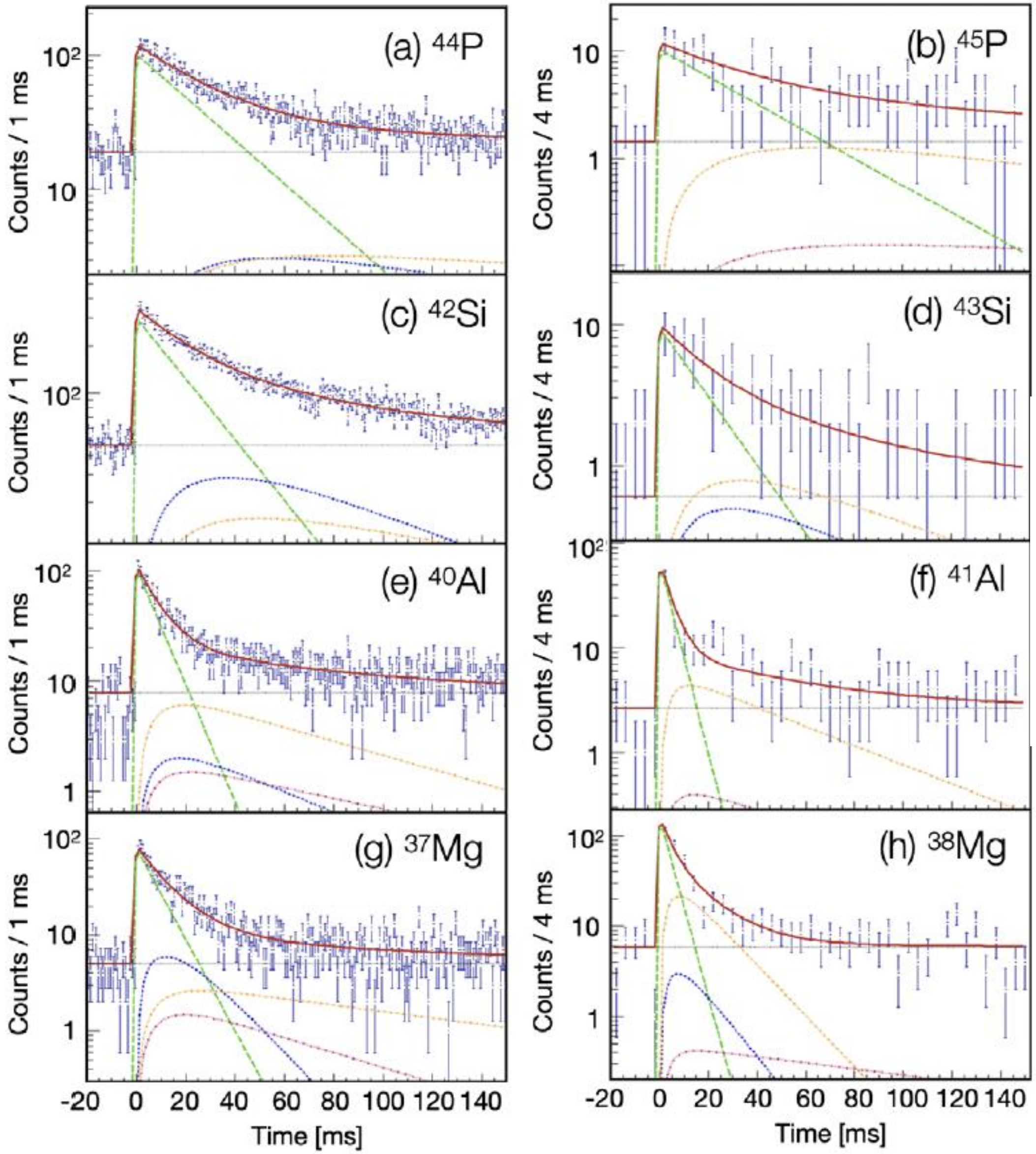
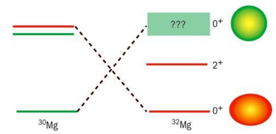
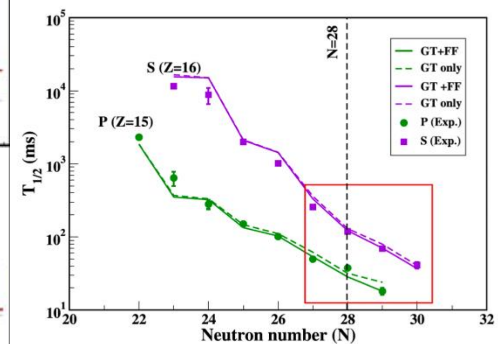
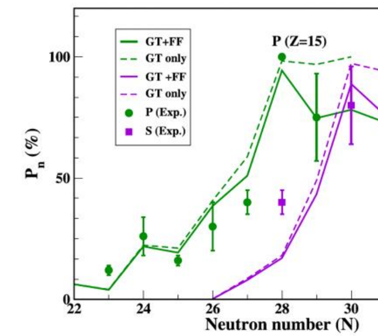


FIG. 2. Decay curves in panels (a)–(h) for ^{44,45}P, ^{42,43}Si, ^{40,41}Al, and ^{37,38}Mg respectively. The components of the fits are shown by the curves, where the solid red line is the total fit, the green dashed

First-forbidden beta decay



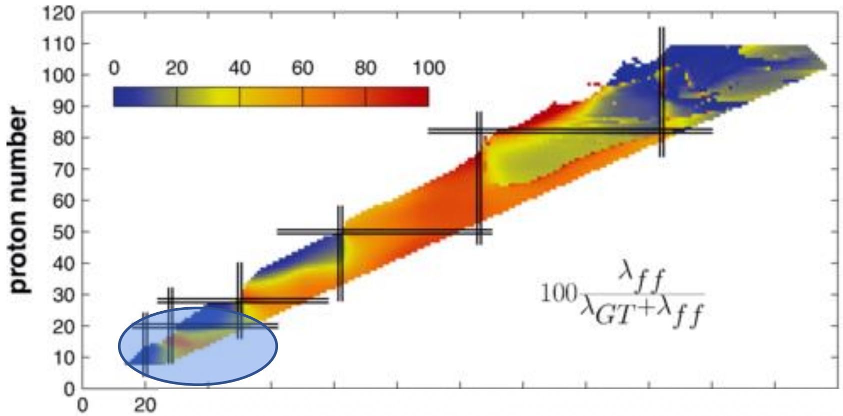


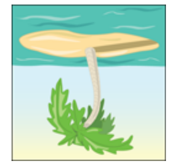


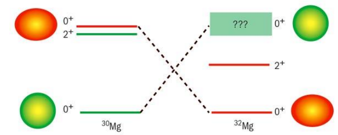
The impact of FF transitions which can b
region with neutrons filling the 1p3/2 o
Pn values with SM calculations with and

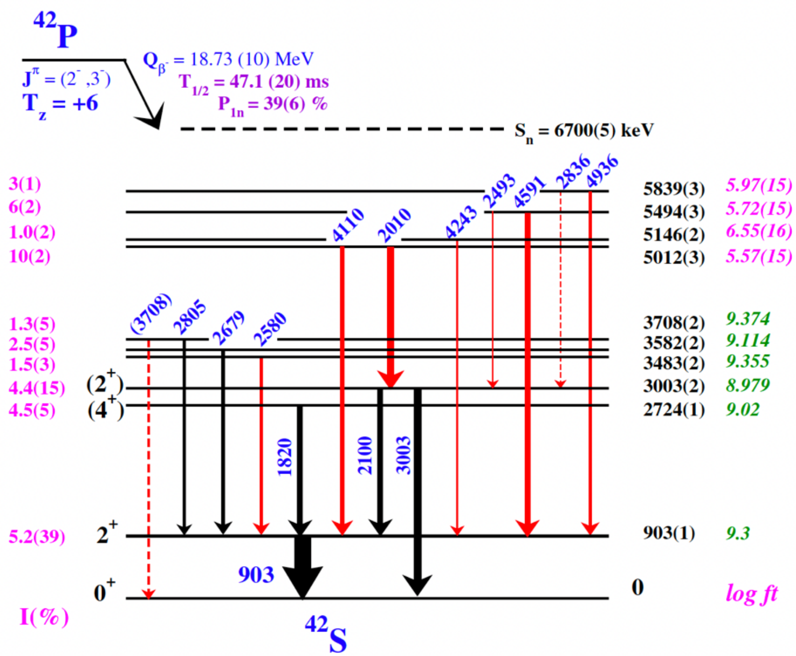
- P isotopes with N = 27, 28, 29 displa
in their β decay. For the case of 42P
which could be populated in FF deca

First-forbidden beta decay





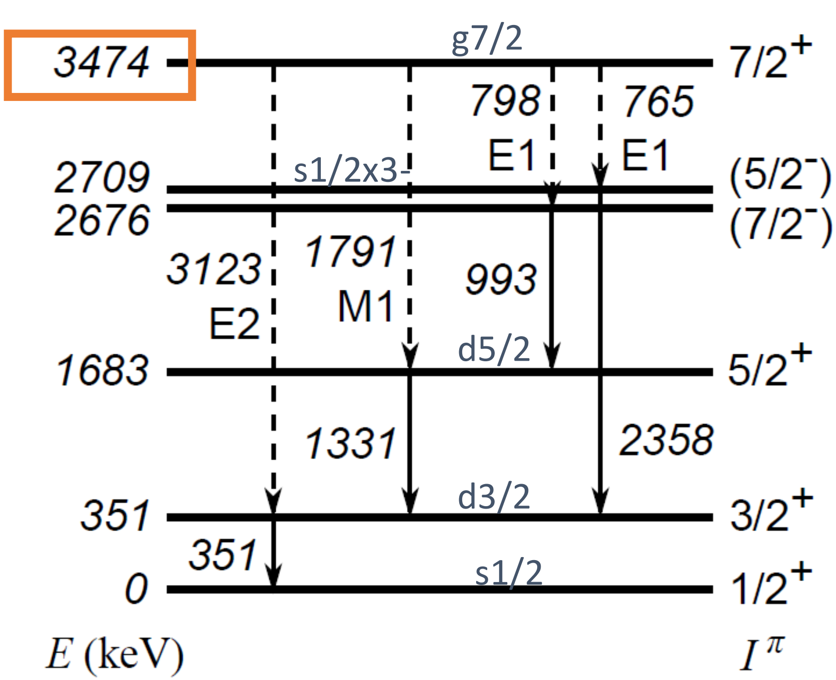


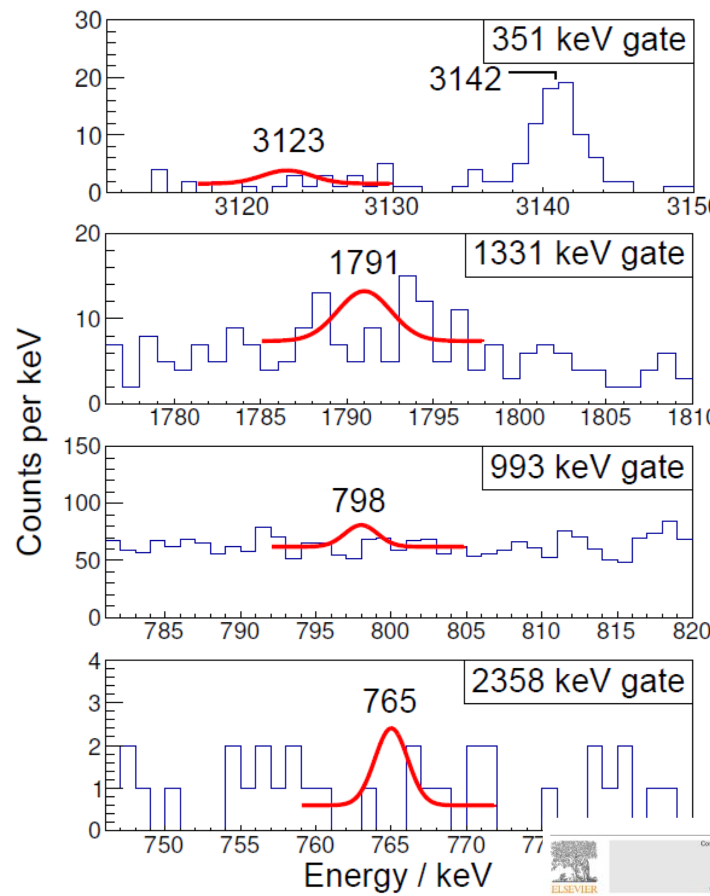


- Both the half-life and Pn value of 44P also indicate influence of FF transitions. Comparison with SM calculations of states populated in 42S in the decay of 42P both via allowed GT and FF decays suggests a Jπ of 2− or 3− for the ground state of 42P contrary to earlier suggestion of 0−.

- The Gamow-Teller (GT) strength distribution depends on the deformation and affects the half-life (T1/2) and β-delayed neutron emission probability (Pn).

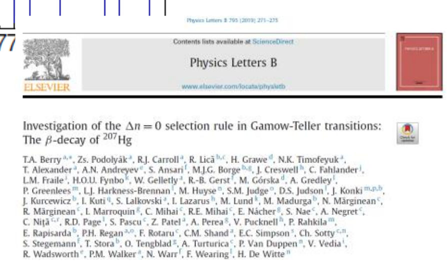
The $2g_{9/2}$ -> $1g_{7/2}$ beta decay (^{207}Hg-> ^{207}Tl)





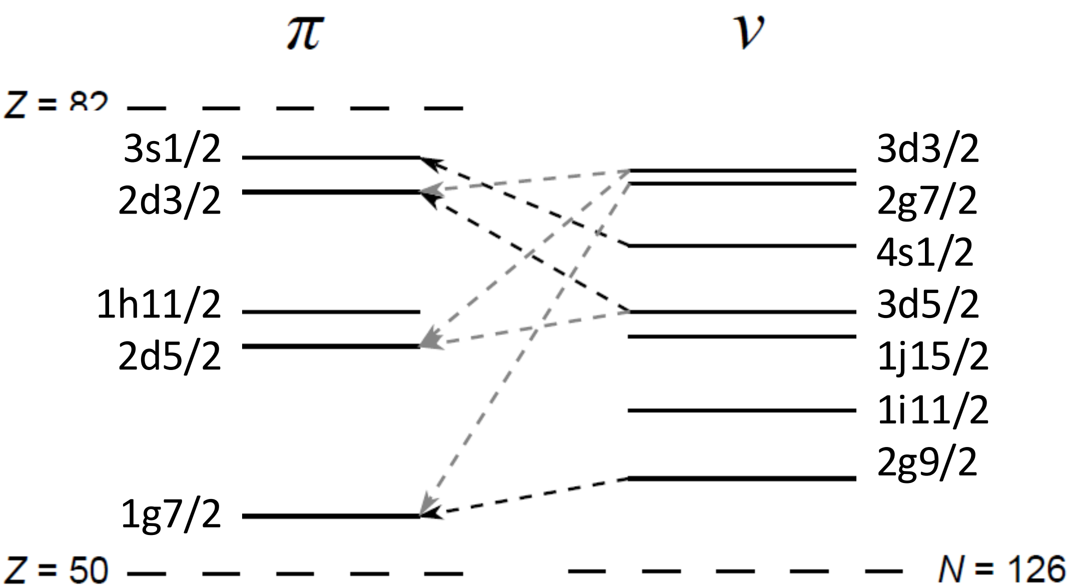
(Non-)population of the $g_{7/2}$ state <3.9x10^{-3}%

log ft > 8.8 (95% confidence limit)


Physics Letters B

Investigation of the Δn = 0 selection rule in Gamow-Teller transitions: The β-decay of ^{207}Hg

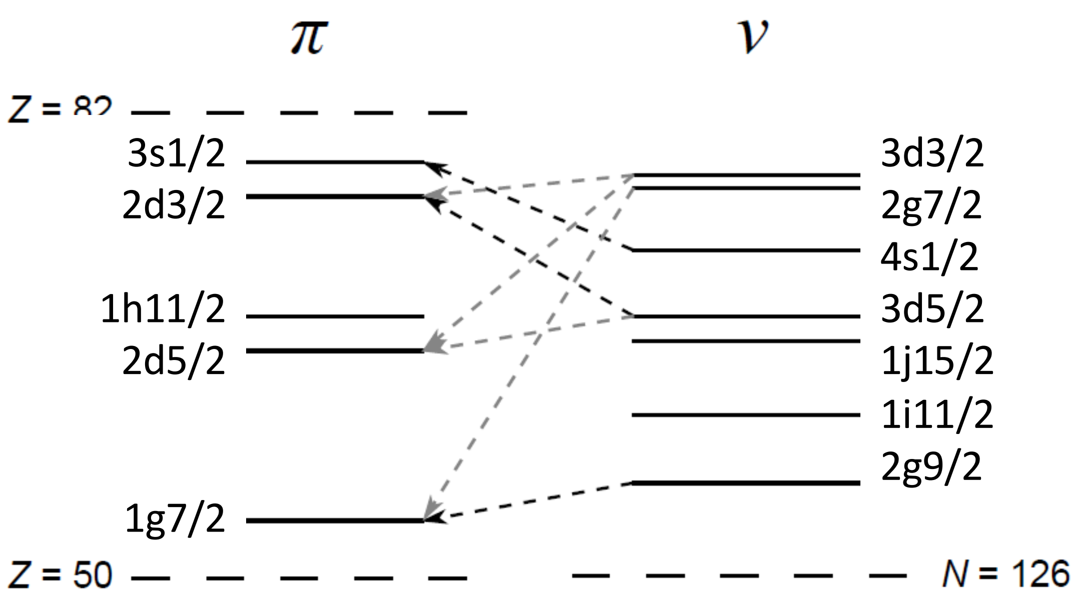
(only one other, less stringent, test of Δn=0: 209Tl->209Pb)

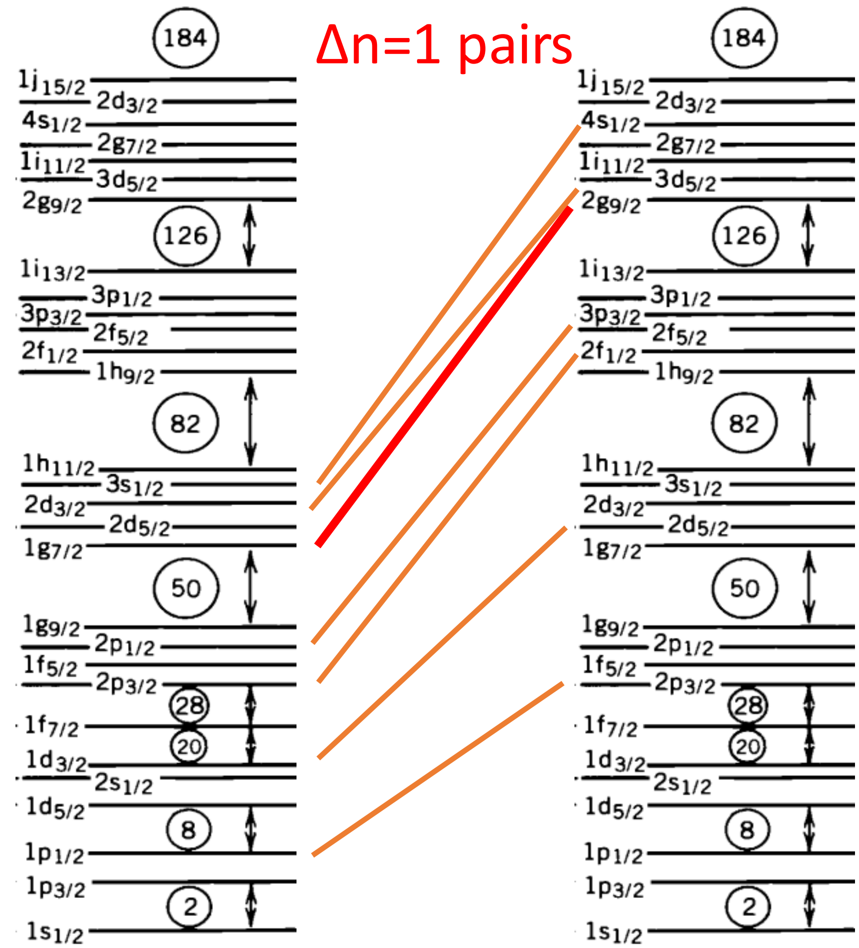


These increase dramatically for extremely neutron-rich nuclei, when either exploring deeper into the proton shell below *Z*=82 or extending further into *N*>126

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

The same selection rule also affects nuclei 'south-east' of 132Sn due to the existence of *n* =1, *l* =0 neutron-proton orbital pairs in the region of *N*>82and *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)

Measuring logft

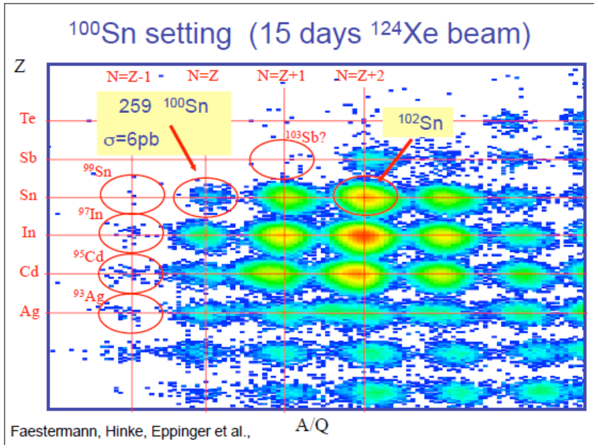
Nature 486, 341 (2012)

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

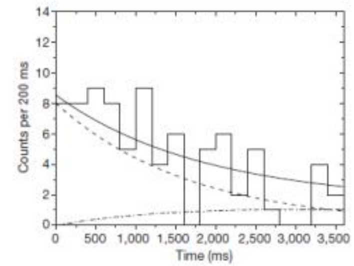
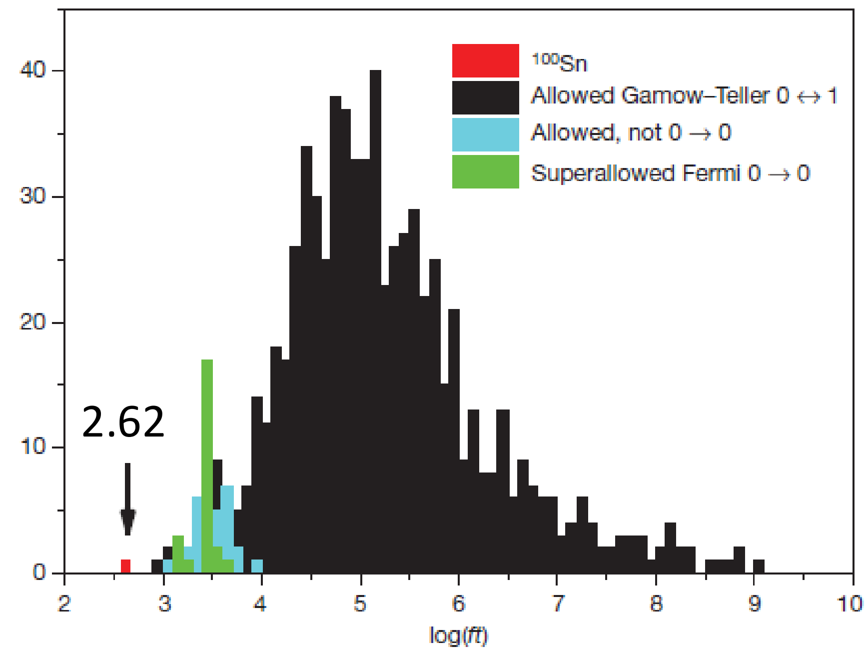


Figure 2 | Time distribution of first decay events. The histogram shows the observed time distribution of all first decay events in the nearest-neighbouring pixels after implantation of ^{100}Sn nuclei. Decay curves resulting from the MLH analysis are shown individually for ^{100}Sn (dashed) and its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



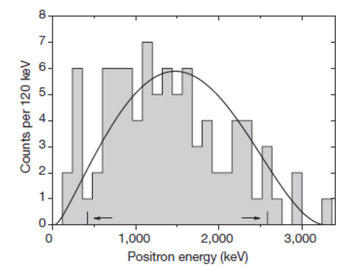


Figure 5 | Distribution of the positron energies emitted in the β-decay of ^{100}Sn. The spectrum contains only decay events that can be assigned to ^{100}Sn decays with a probability of at least 75%. The MLH fit was applied to the region between 400 and 2,600 keV, which is indicated with markers. The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

Measuring logft

PRL 122, 222502 (2019)

Improved Value for the Gamow-Teller Strength of the ^{100}Sn Beta Decay

^{100}Sn N=Z=50

Heaviest N=Z nucleus

Relativistic Fragmentation reaction

^{124}Xe beam on ^{9}Be target

➔ RIKEN higher beam intensity (36pnA)

260 ➔ 2500 ^{100}Sn nuclei produced

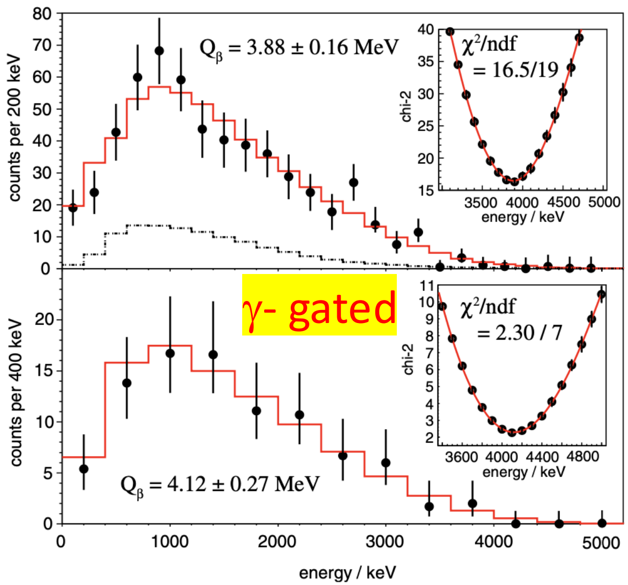
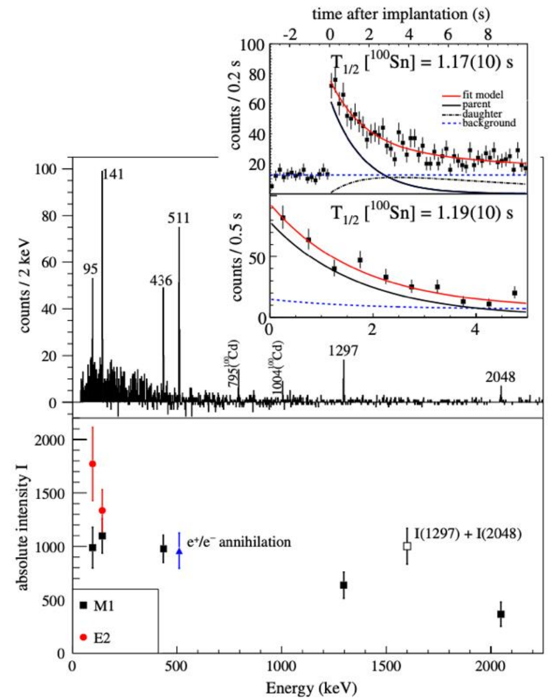
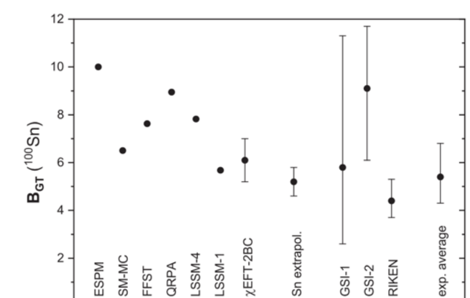


FIG. 3. Top: the energy distribution of positrons after the β decay of ^{100}Sn. Bottom: energy distribution of the γ-gated event selection. The insets show the χ^2 values when comparing the measured spectrum with the simulated spectrum for a certain end point energy. The Q values for the minimal χ^2 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





Highly forbidden decays

β Decay of ^{138}La

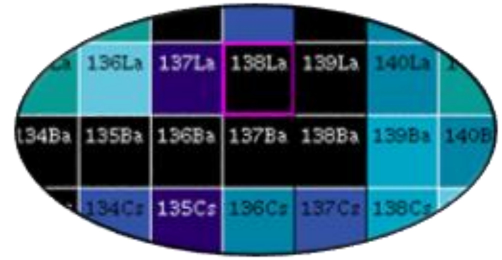
Lantanum has two isotopes

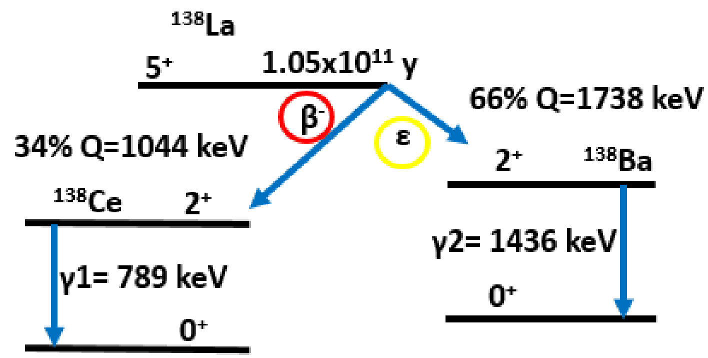
- ^{139}La, stable
- **^{138}La, radioactive**:
  - $T_{1/2}$= **1.05*10 ^{11}** years
  - abundance **0.09%**.

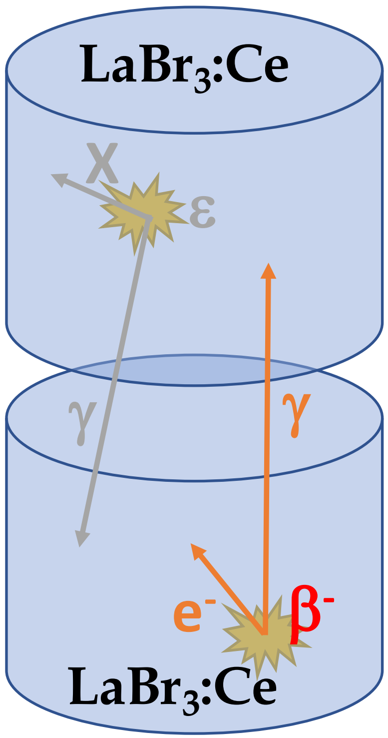
^{138}La has two decay branches

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

Both decays are **second forbidden decays**
5^+ ➔ 2^+







Experiment: measuring the BR and the electron spectra
Using LaBr3(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

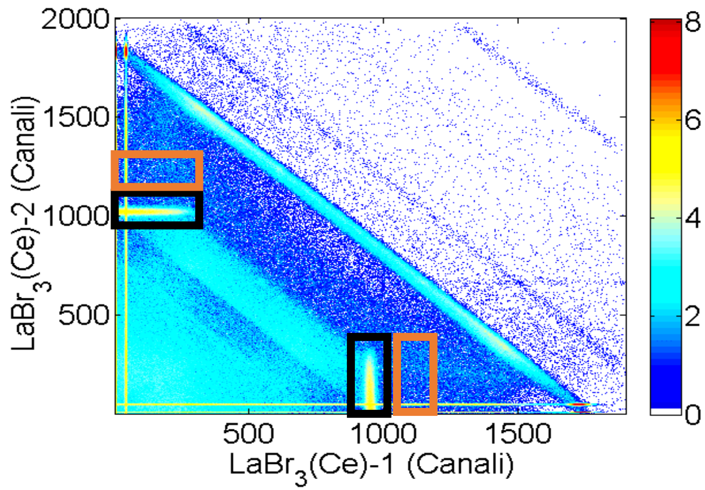
A.Giaz et al. EPL 110 (2015) 42002

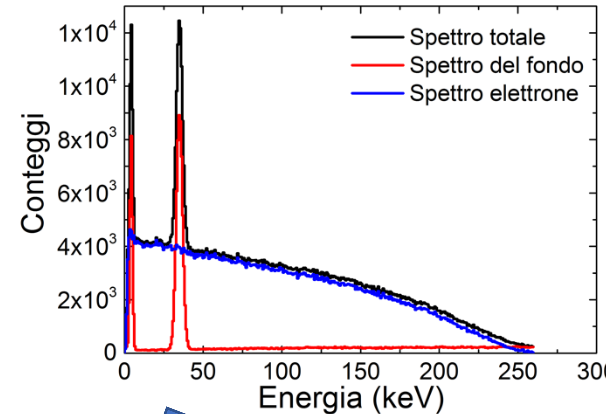
Highly forbidden decays

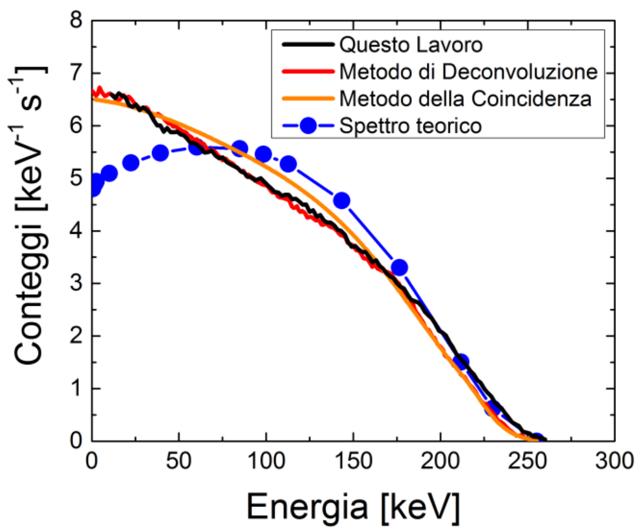
A.Giaz et al. EPL 110 (2015) 42002

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

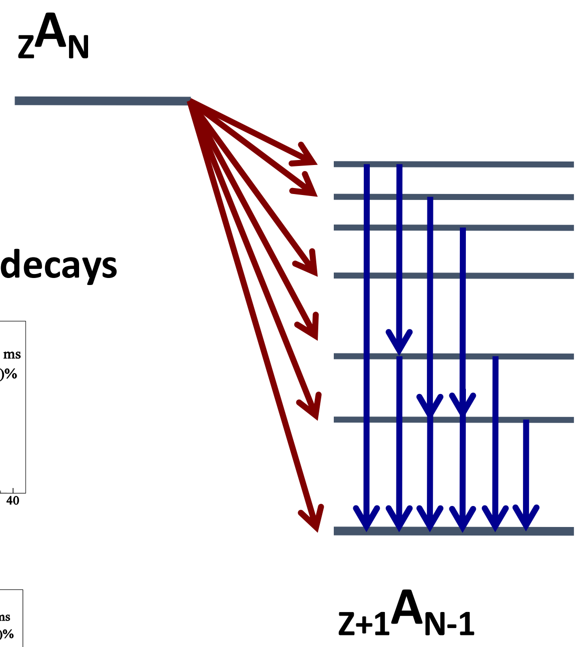
Interaction btw Coulomb field of the nucleus and electron

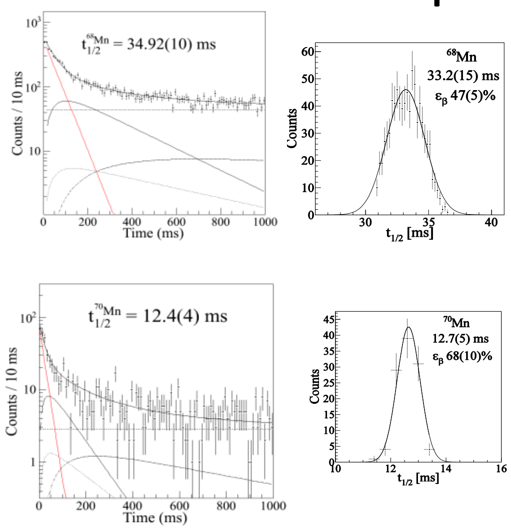
General Properties of β decay

Quantities that can be extracted in a β decay experiment

$T_{1/2}$
$P_{n/p}$
%β, %α ...

β- decays





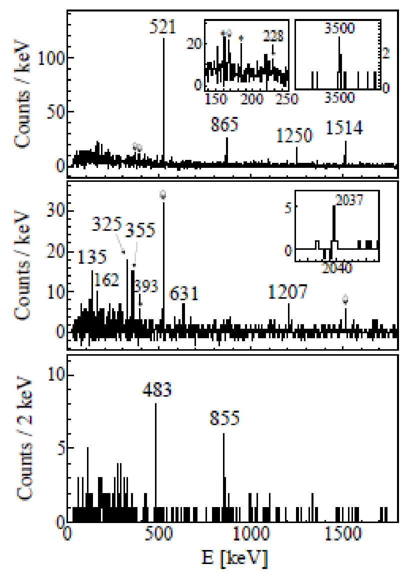
γ transitions

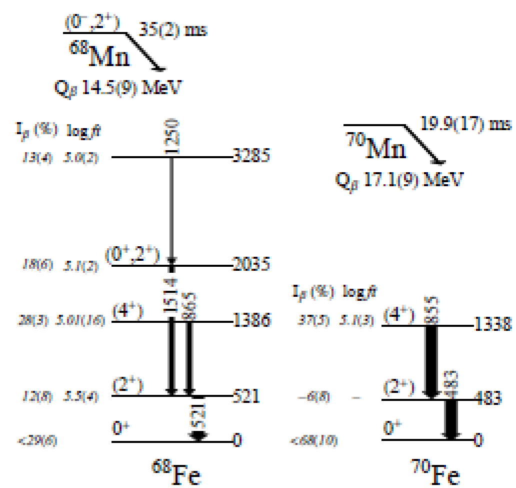
Possible existence of many decaying states

γ–γ coincidences ➔ level schemes

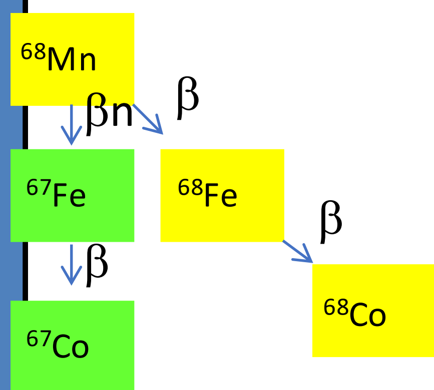
Relative intensities I_β

logft





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

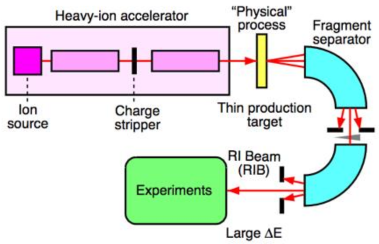


"pandemonium effect" – exotic nuclei – log *ft* is a just upper limit

Introduction

Producing radioactive beams i.e. exotic nuclei

IN-FLIGHT



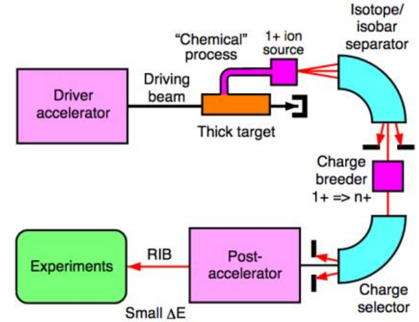
relativistic fragmentation/fission of heavy nuclei on thin targets

- > 50 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 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

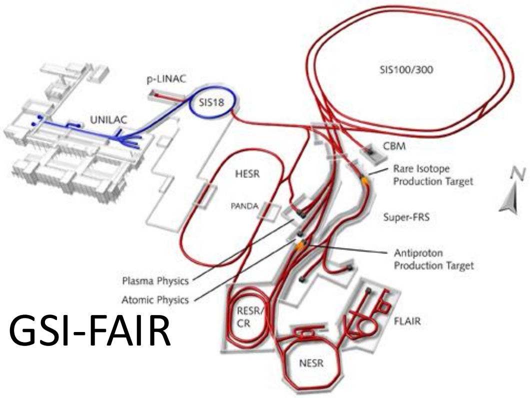
- beams produced at very low energies (~60 keV)
- Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species ➔ usually long-living though

+ high cross section
+ no need to re-accelerate beams
+ high rates accepted

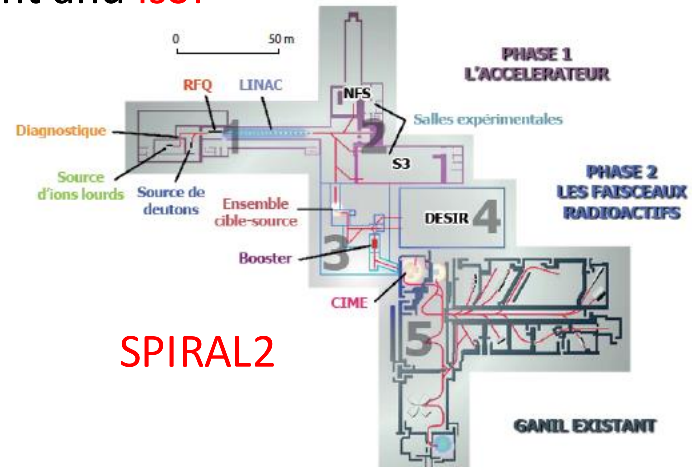
- short-living species might not be accessed easily
- Refractory elements
- Presence of long-living impurities (isobaric contamination)

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

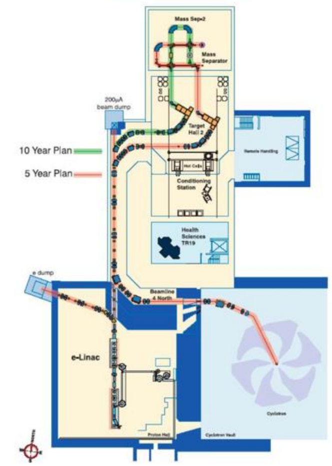
GSI-FAIR



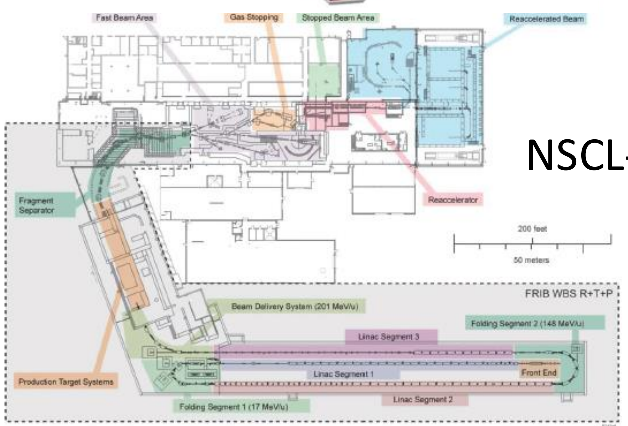
SPIRAL2



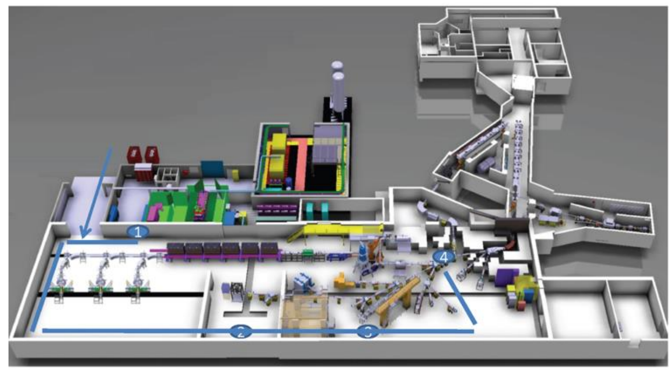
TRIUMF

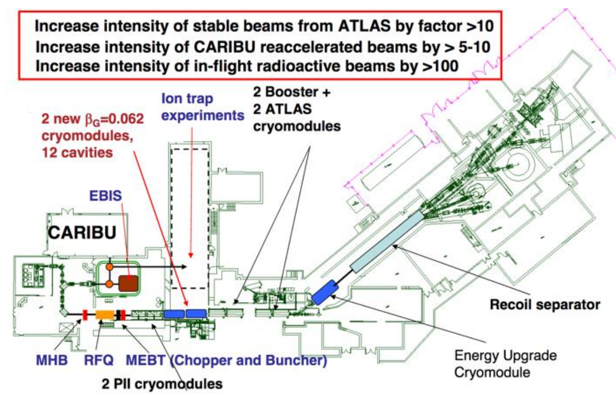


NSCL-FRIB

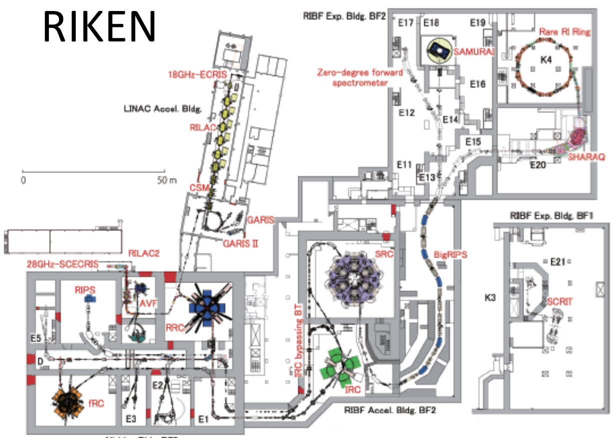


HIE-ISOLDE



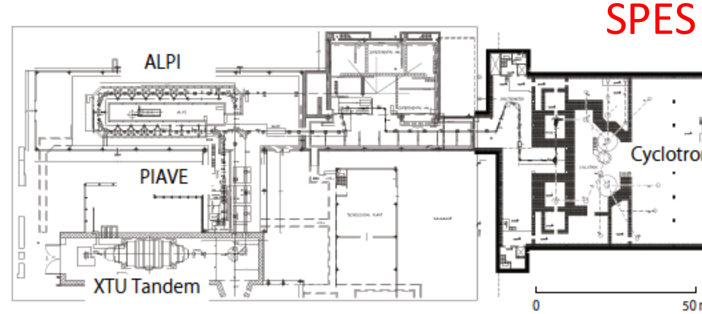


RIKEN



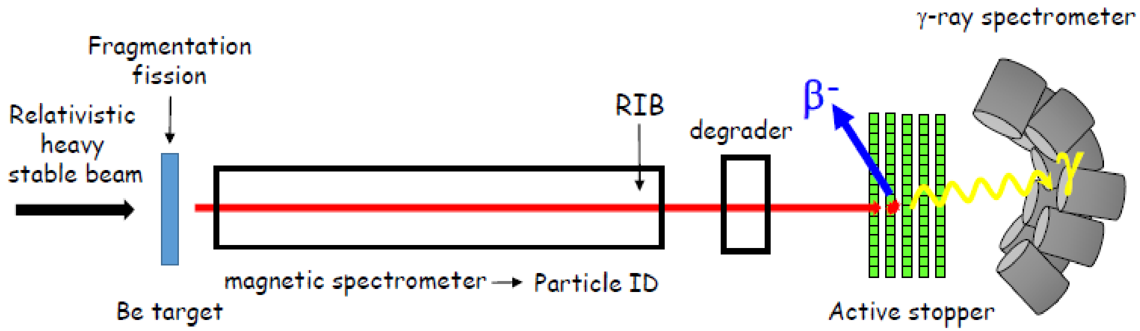
ALTO

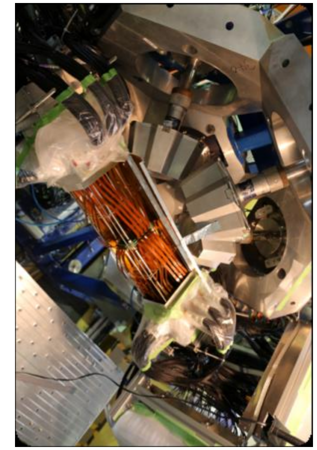
SPES



General Properties of β decay

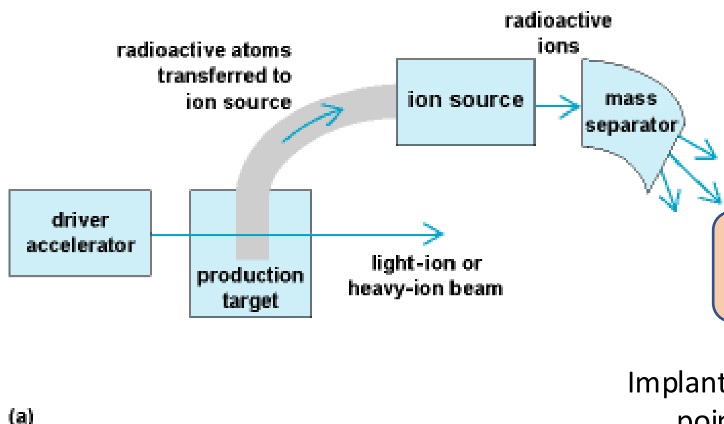
Measuring β decay

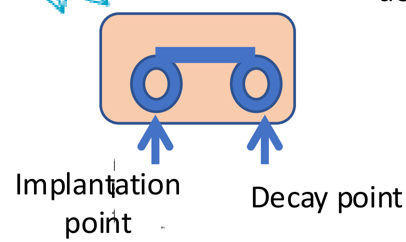


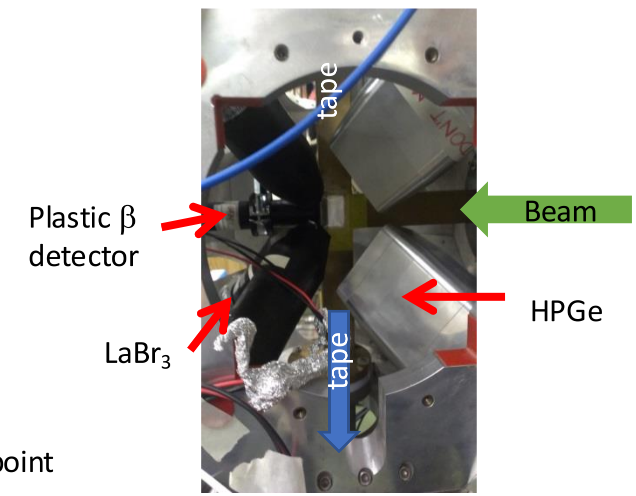


IN-Flight facility

Eurica@RIKEN







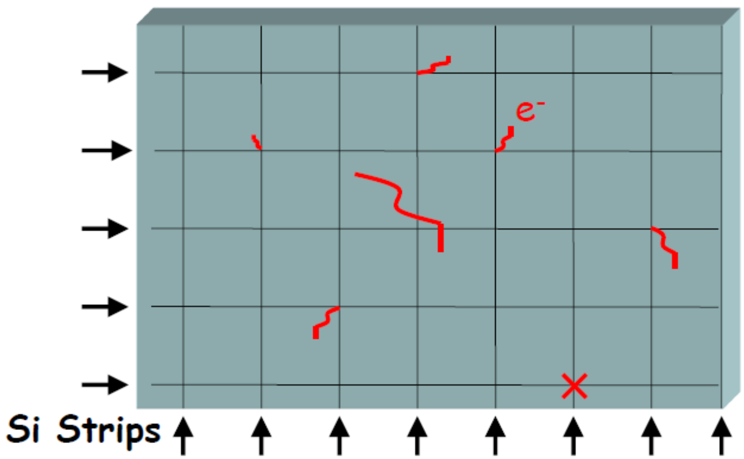
ISOL facility

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 lifes 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.

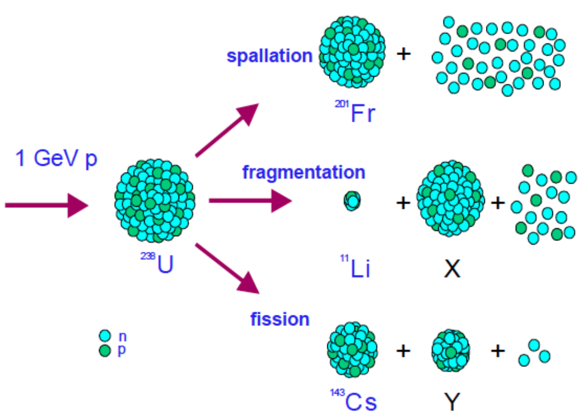
RIKEN

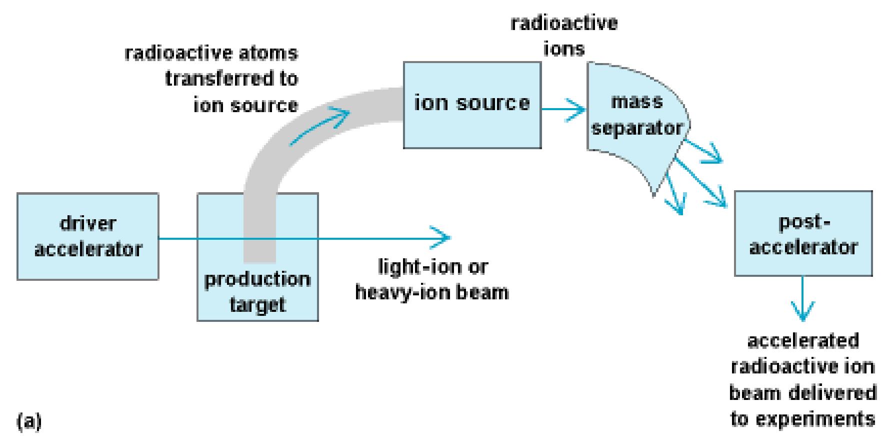
* Low gain branch for implanted ions
* High-gain branch for β and α decays

ISOL: Isotope Separation On Line

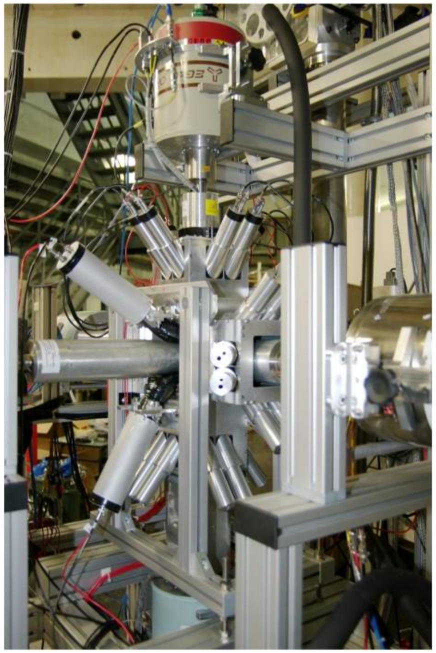
Nuclei produced by ISOL method, spallation/fission/fragmentation on thick targets, followed by chemical/physical processes to extract desired nuclei

- 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



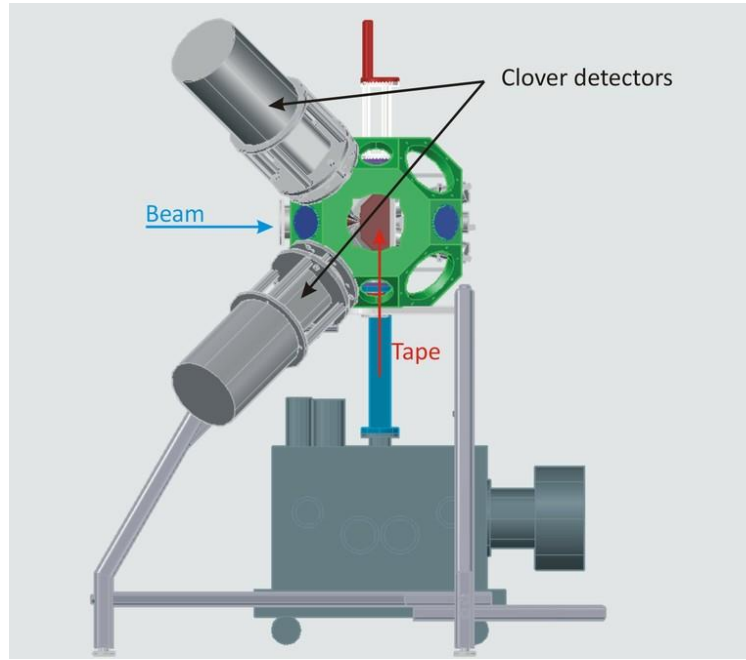


TAPE Station systems



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

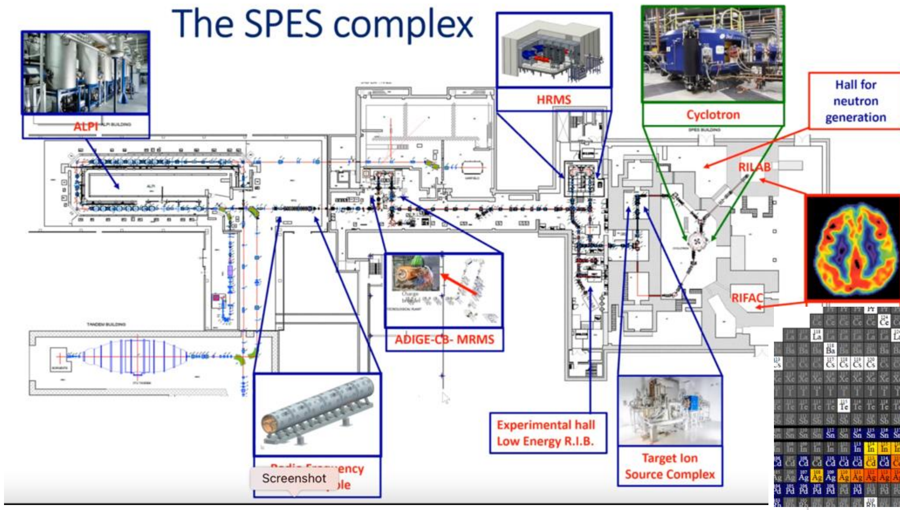
Decay of radioactive nuclei

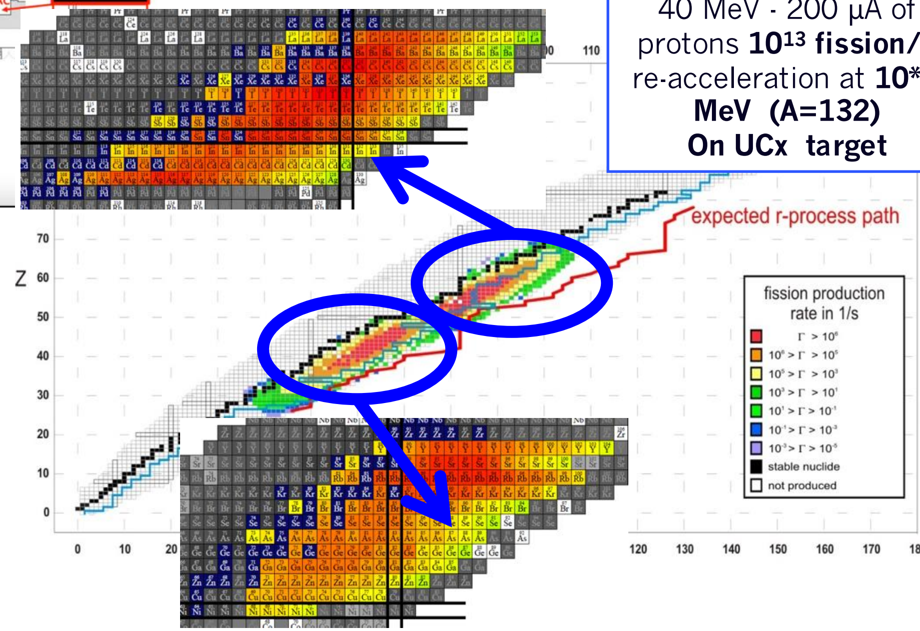
Element formation in stars

Example of measurements of b-decays

Perspectives

Conclusions





40 MeV - 200 μA of protons **10^{13} fission/s** re-acceleration at **10*A MeV (A=132)**
On UCx target

To the experimental areas

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

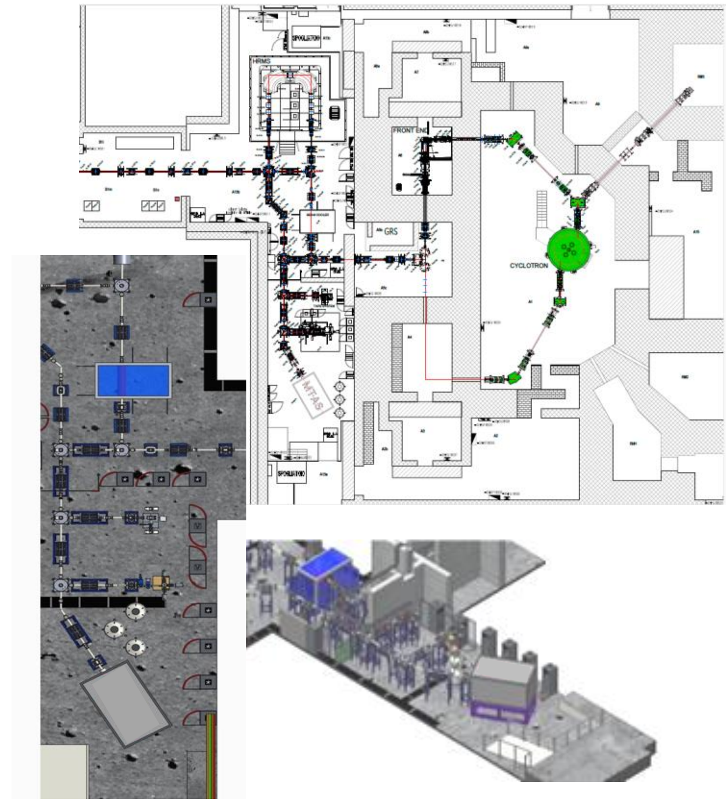
Actual – Present - Layout:

- 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)

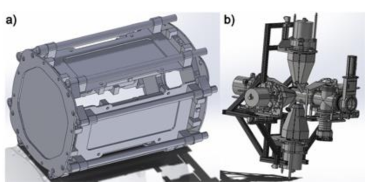
A13 area: finishing and being equipped and instrumented

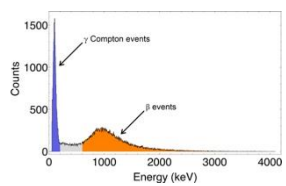
Experimental set-ups under test,
waiting for green light for installation



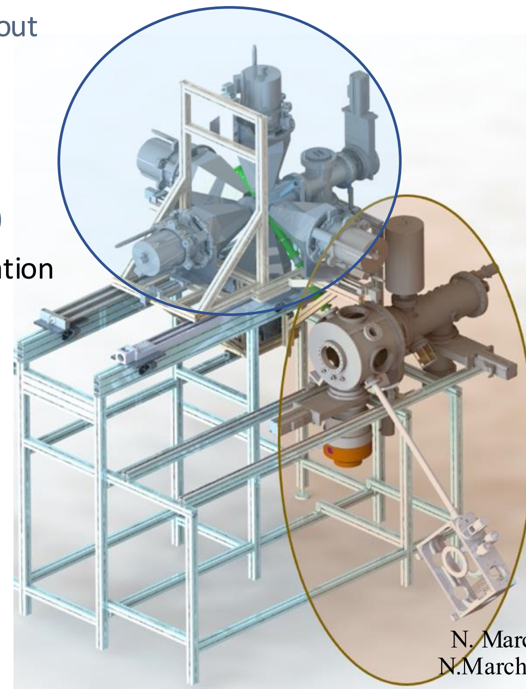
b-DS and SLICES

- 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))
- T1/2, decay scheme, Pn via γ discrimination





G.Benzoni A.Nannini, A.Saltarelli

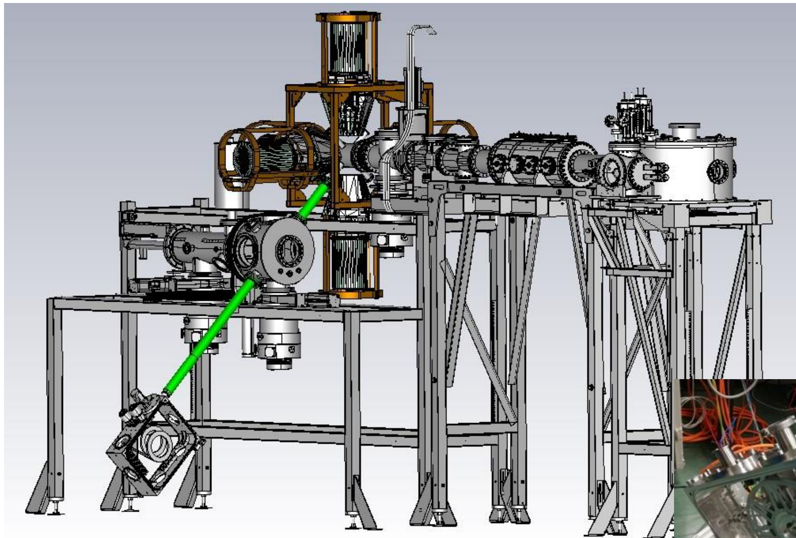


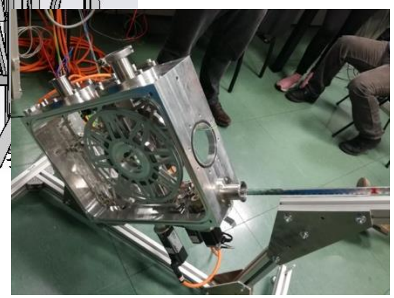
- Large area (~ 3900 mm²) Si(Li) detector 6.8 mm thick segmented in 32 sectors
- Magnetic Transport System
- Plastic Scintillator

E0 and CE spectroscopy

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

TAPE Station systems: b-DS @ SPES





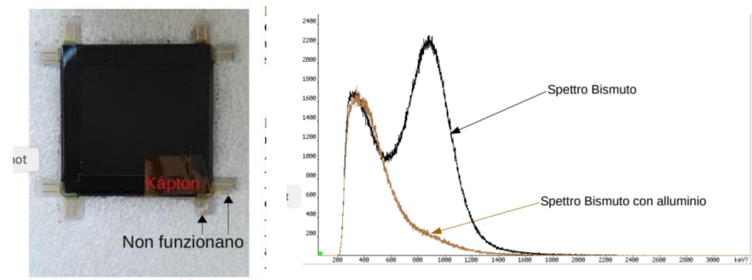


Figure 4: Left: prototype beta plastic detector. Right: reponse to electrons and gamma rays measured using a ^{207}Bi source (black line) and a ^{207}Bi source coated with Al (gold line).

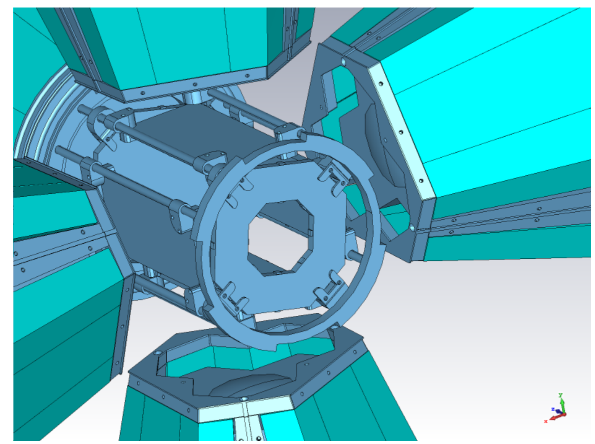
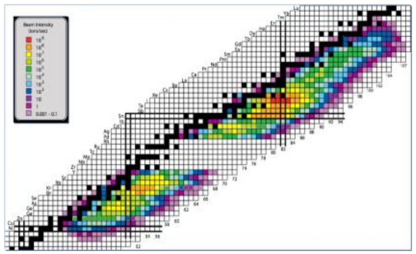


Figure 5: 3D rendering of the placemnet of the plastic detectors within the decay chamber of b-DS. The beam comes from the right sied of the figure. The scattering chamber is not shown for visualization purposes.

- 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

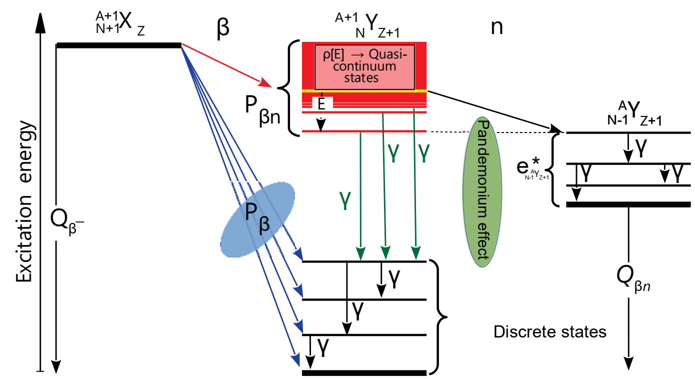
Opportunities with existing/planned equipment



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

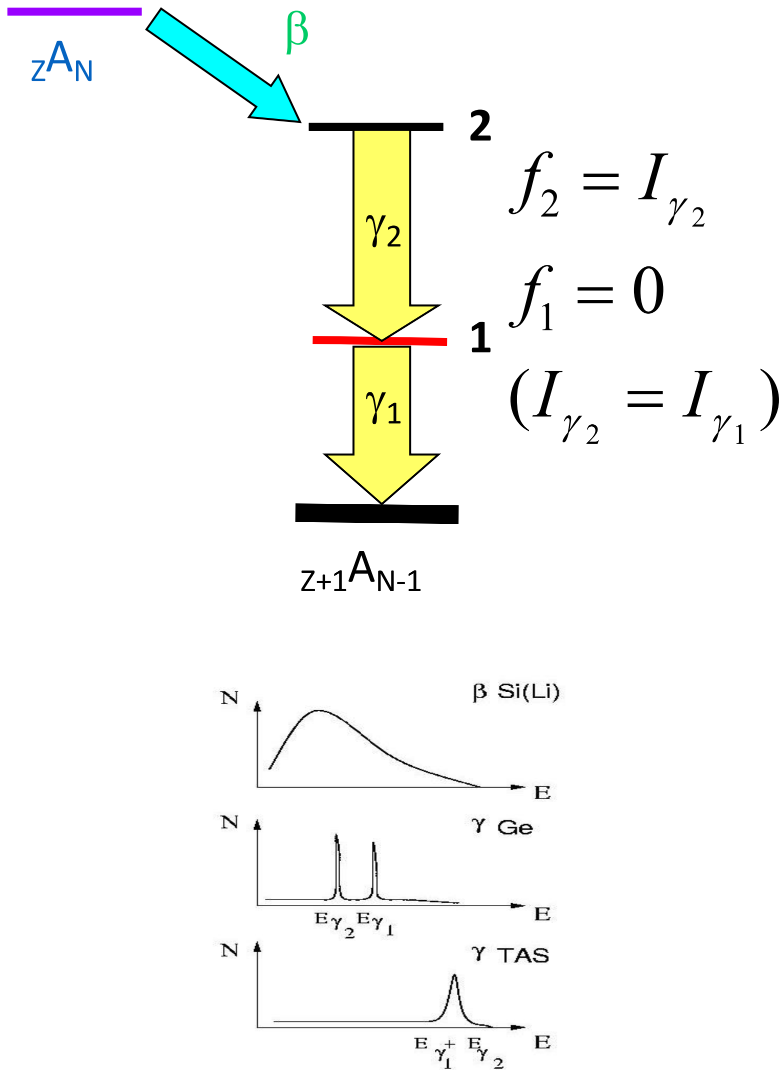
- Shell structure evolution
- Evolution of nuclear shapes
- Astrophysical r and s-process modelling
- Modelling and production of radio-isotopes



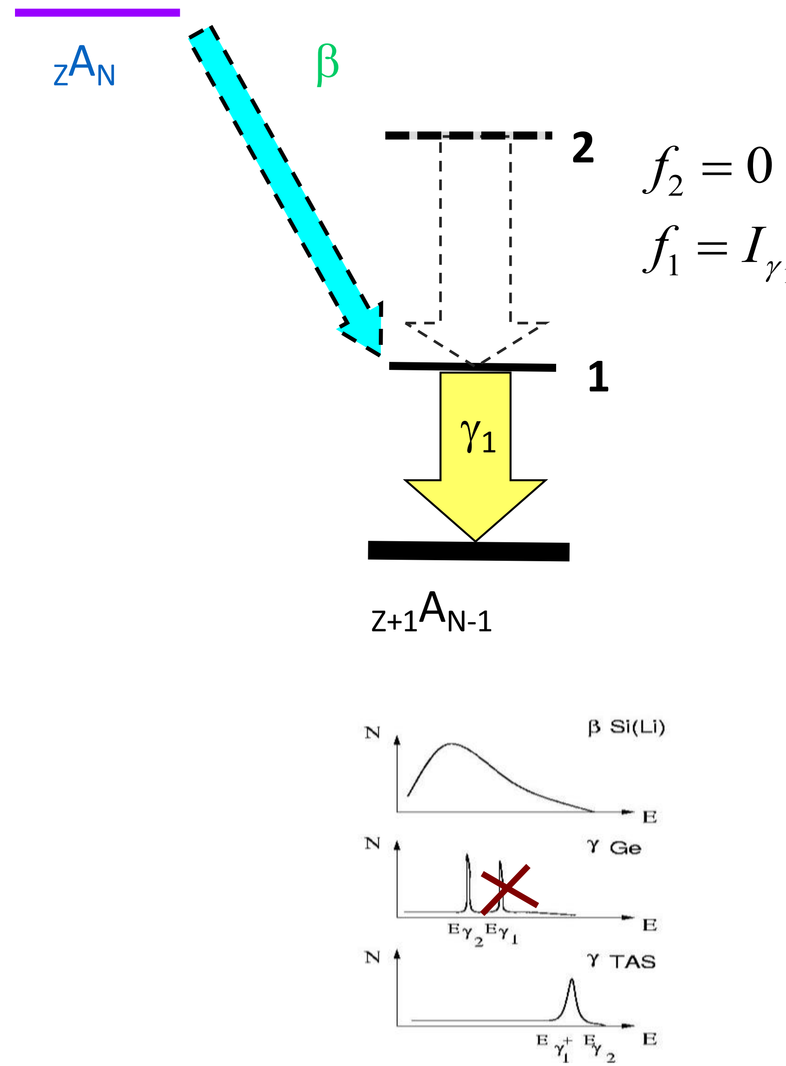
General Properties of β decay

Pandemonium effect

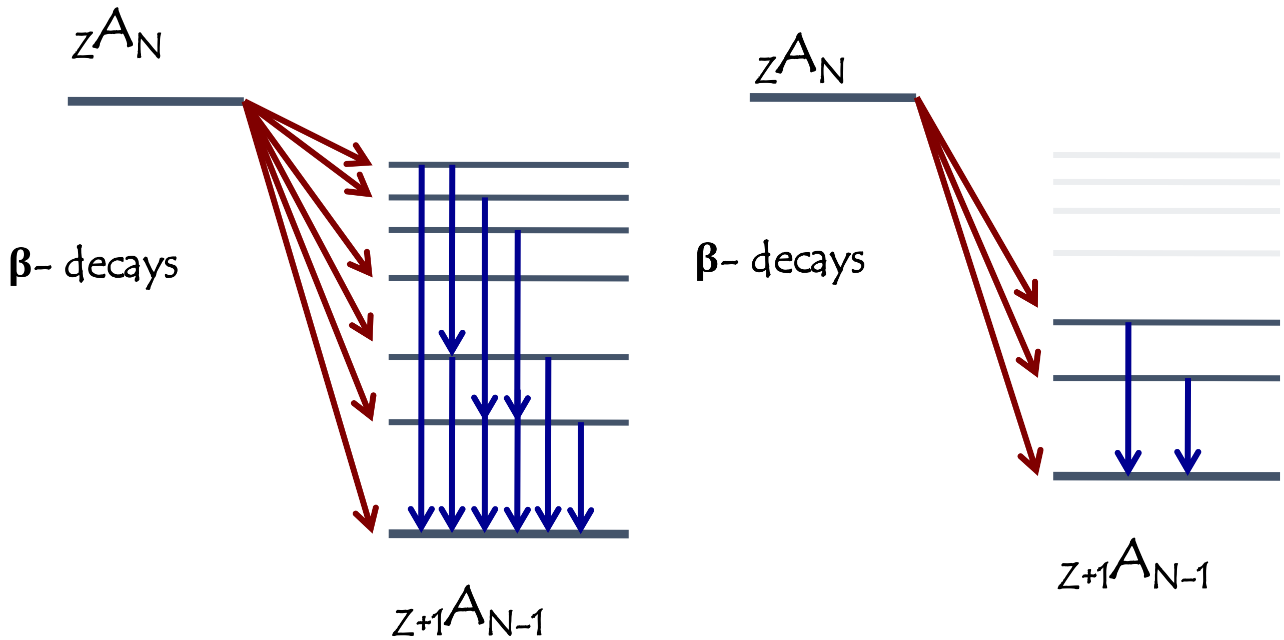
Real situation



Apparent situation



General Properties of β decay



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

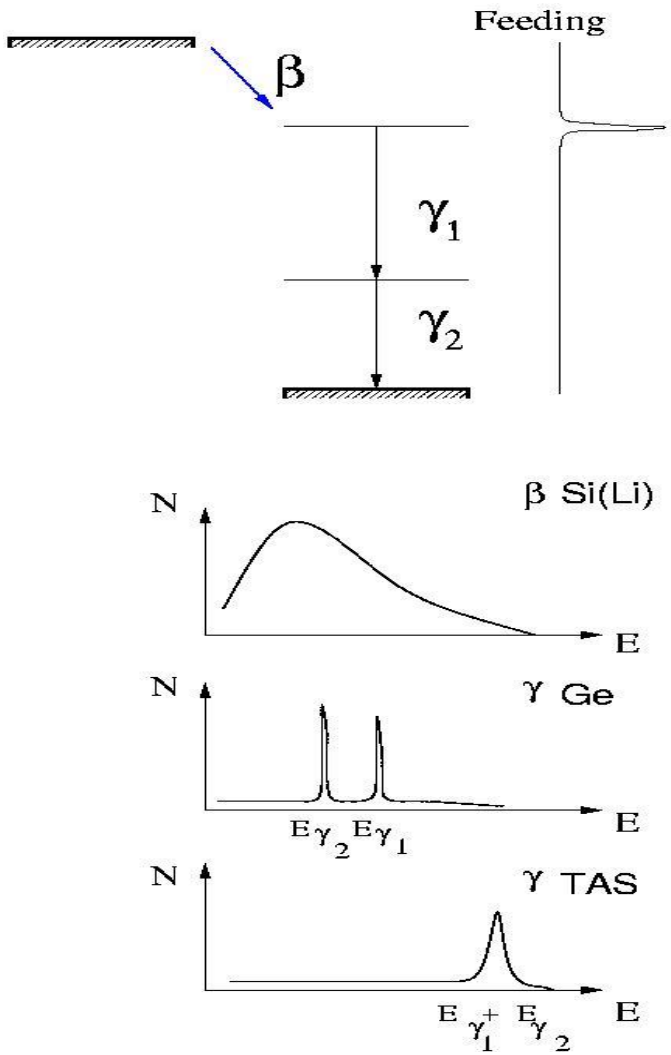
➔ Higher Q_{value} higher possibility of missing feeding owing to high-energy γ ray emission or emission of large number of γ rays

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

Pandemonium effect implies

➔ Wrong definition of gamma feeding and branching ratios I_β and logft

Total Absorption Gamma Spectrometer measurements



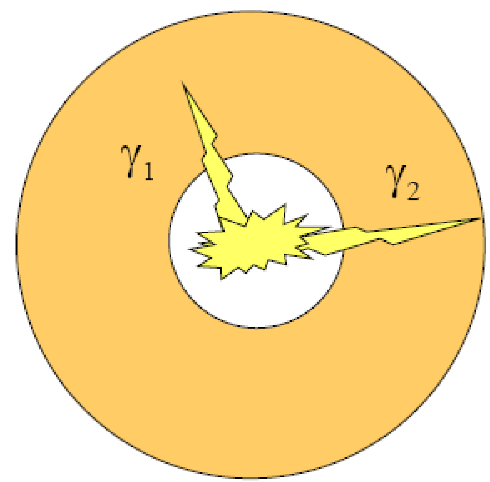
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

A TOTAL ABSORPTION SPECTROMETER

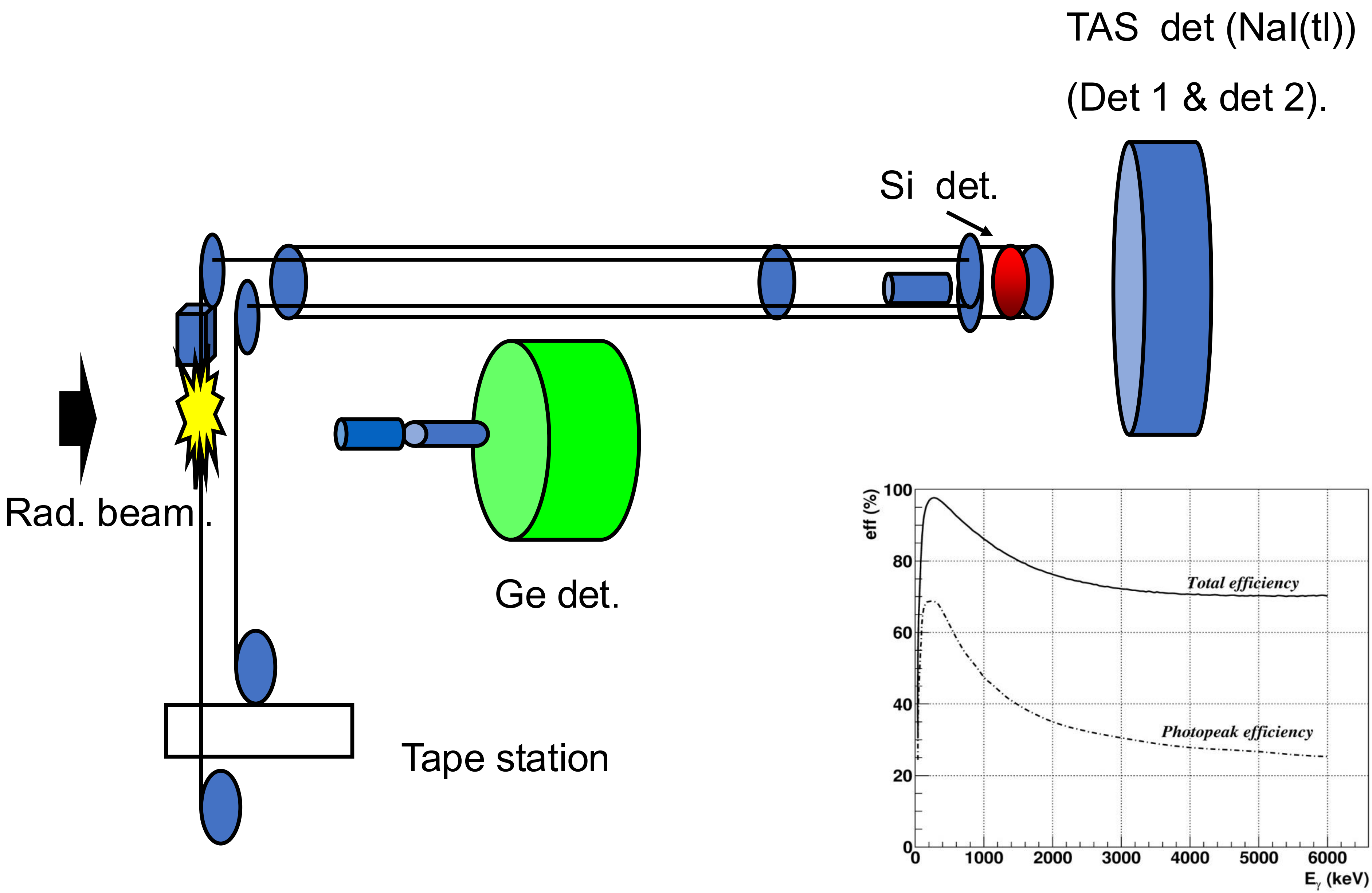
Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

A TAS is a **calorimeter**!

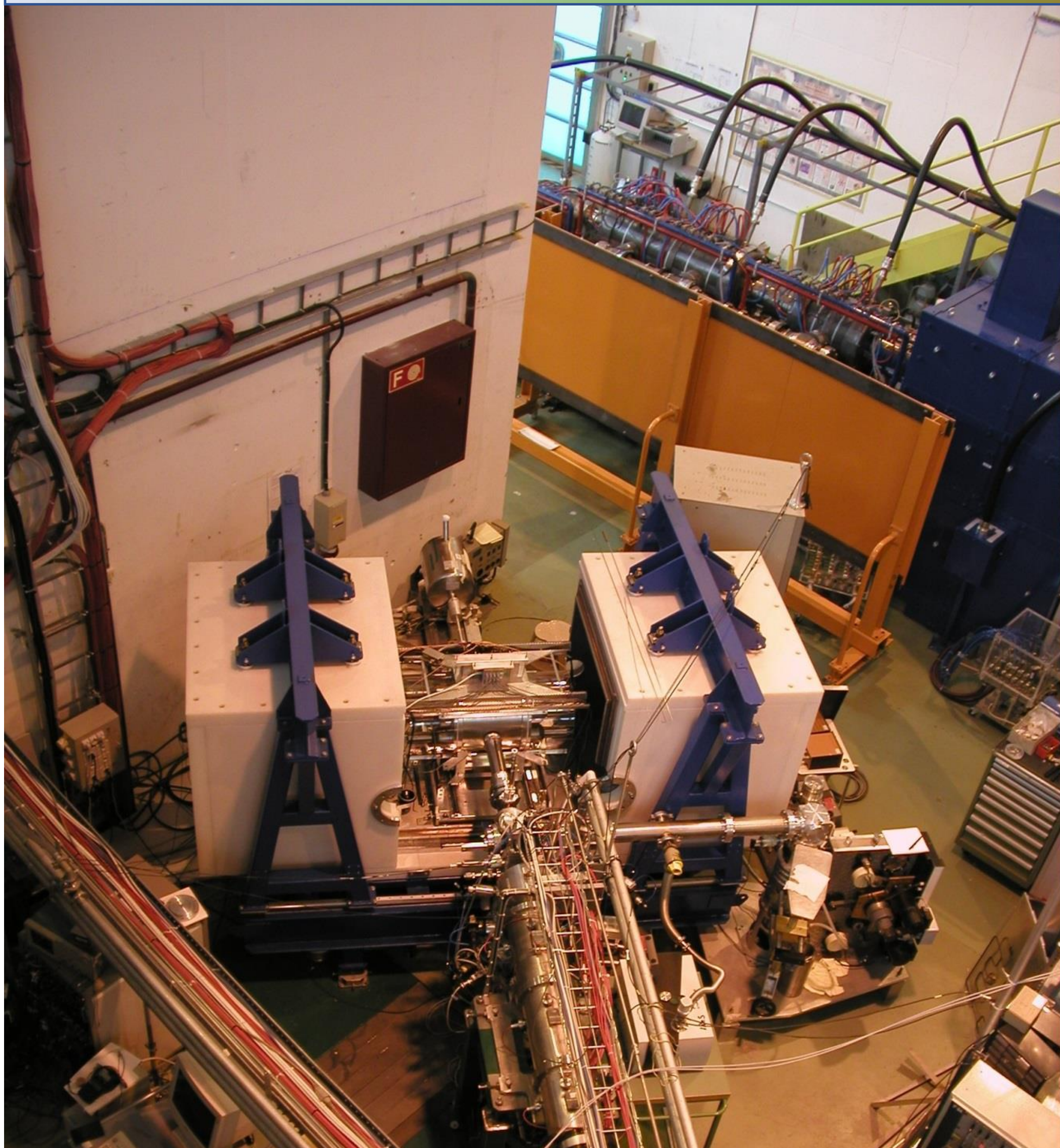
Big crystal, 4π (BaF_2/NaI/HPGe)

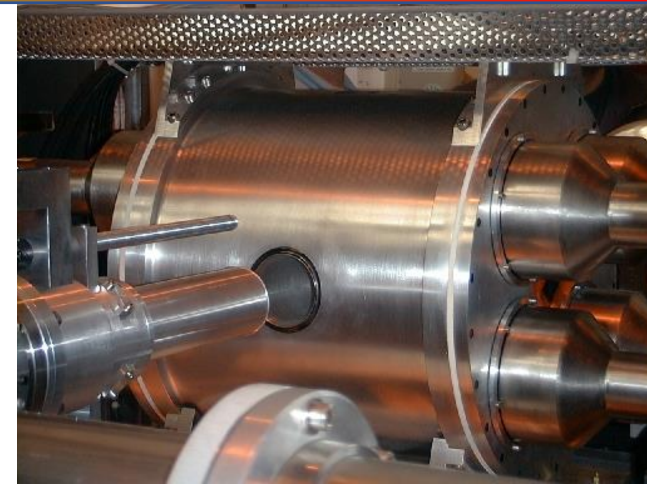


TAS experimental setup



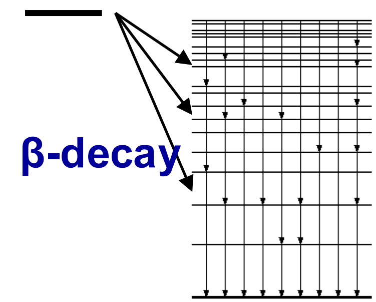
Lucrecia: the TAS at ISOLDE (CERN)
(Madrid-Strasbourg-Surrey-Valencia)





- 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

TAGS analysis

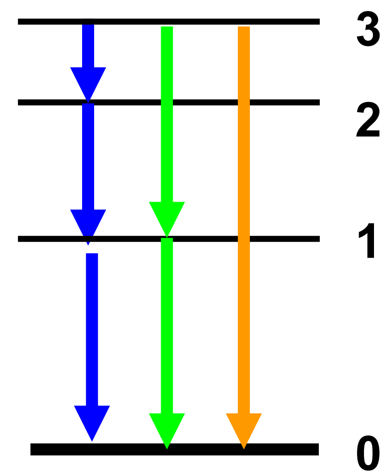


$$d_i = \sum_j R_{ij} f_j \quad or \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$

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 **R** can be constructed by recursive convolution:

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$



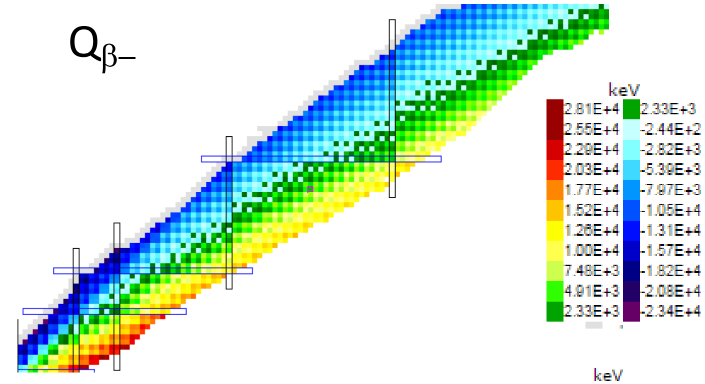
$\mathbf{g_{jk}}$: γ-response for *j* (*k* transition
$\mathbf{R_k}$: response for level *k*
b_{jk}: branching ratio for *j* (*k* transition

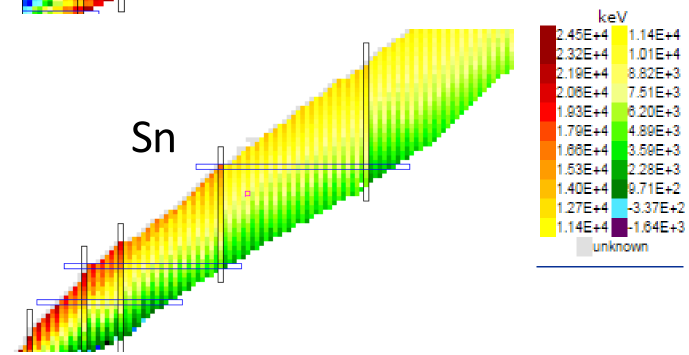
Mathematical formalization by Tain, Cano, et al.

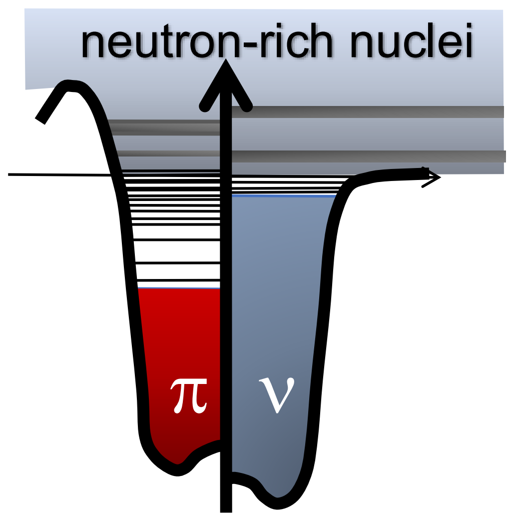
β Decay in Exotic Nuclei

Going away from stability

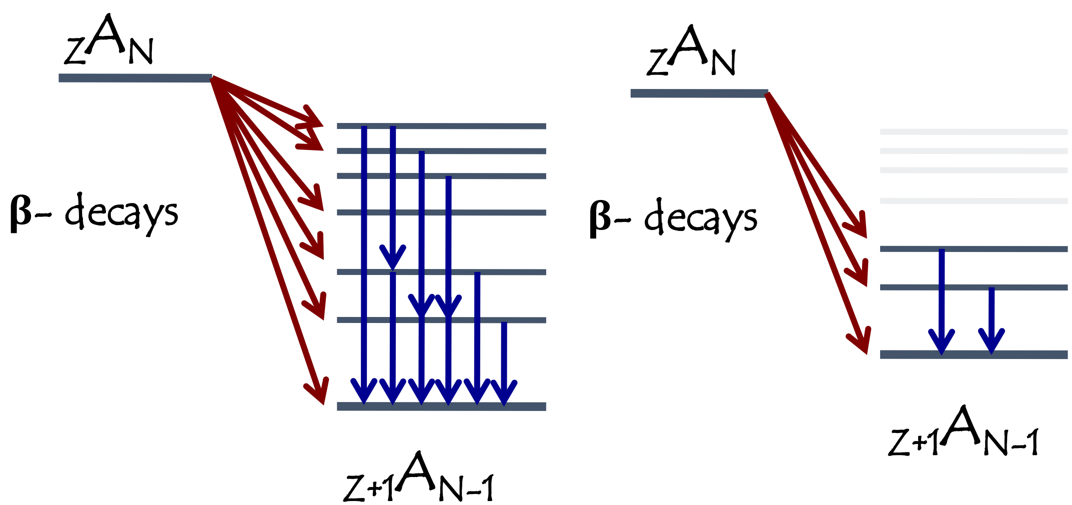
- Shortening of half-lives
- Increasing Q_{value}
- Decreasing S_n (on n-rich side)
- Higher possibilities of competing mechanisms
- GT unfavoured owing to large mismatch in wave functions btw mother/daughter
- Increasing role of forbidden decays



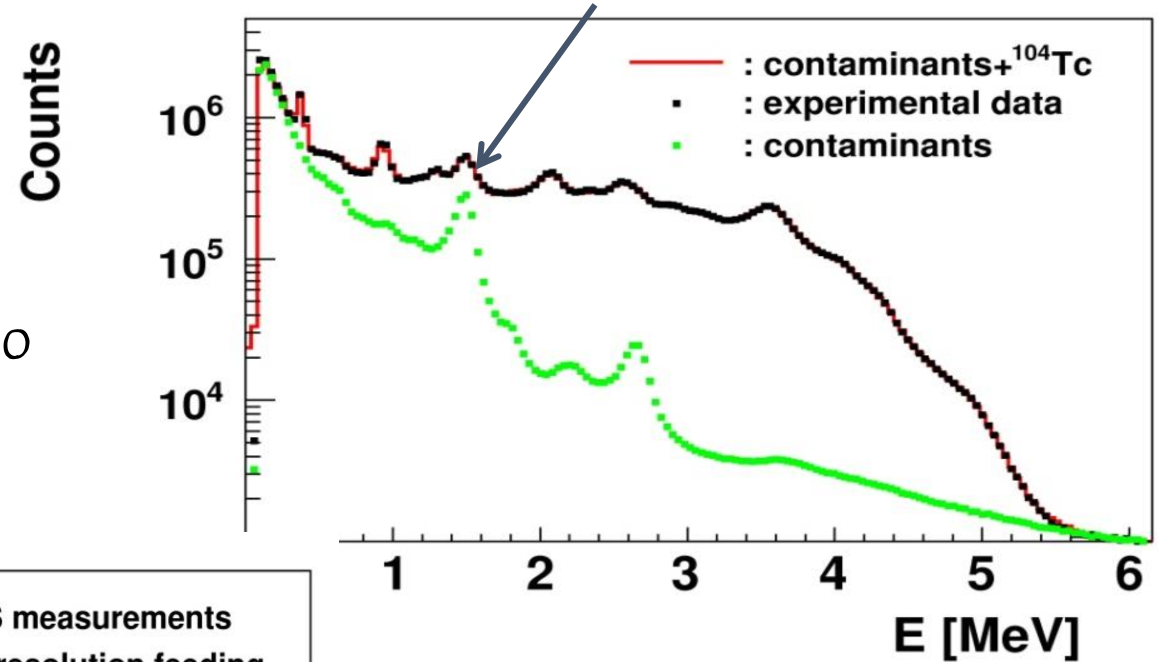




- Pandemonium effect

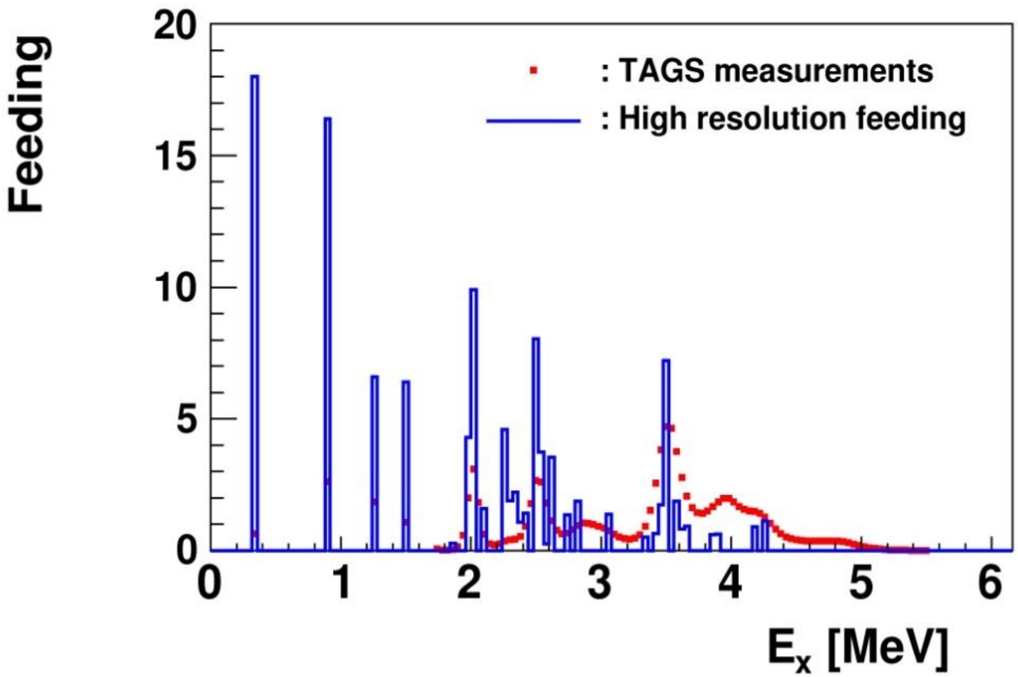


Results of the analysis for ^{104}Tc



D. Jordan, PhD Thesis, Valencia, 2010

D. Jordan, PRC 87, 044318 (2013)



$T_{1/2}$ = 1098(18) s; Q_β= 5516(6) keV

E_β(TAGS) = 931 (10) keV
E_β(JEFF-3.1) = 1595 (75) keV } ΔE_β = -664 keV

E_γ(TAGS) = 3229 (24) keV
E_γ(JEFF-3.1) = 1890 (31) keV } ΔE_γ = 1339 keV

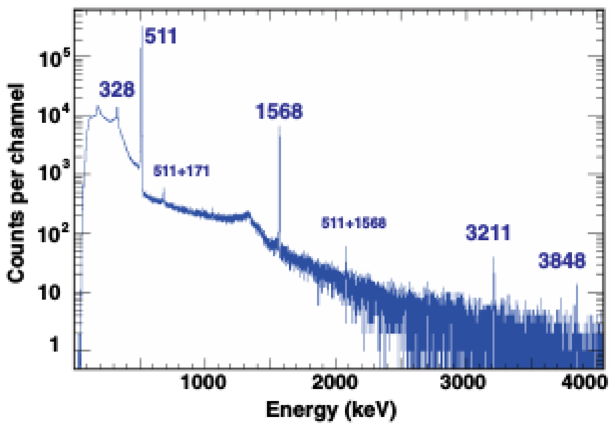
Part III: Branching ratio measurement

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 $0^+ \to 0^+$ 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

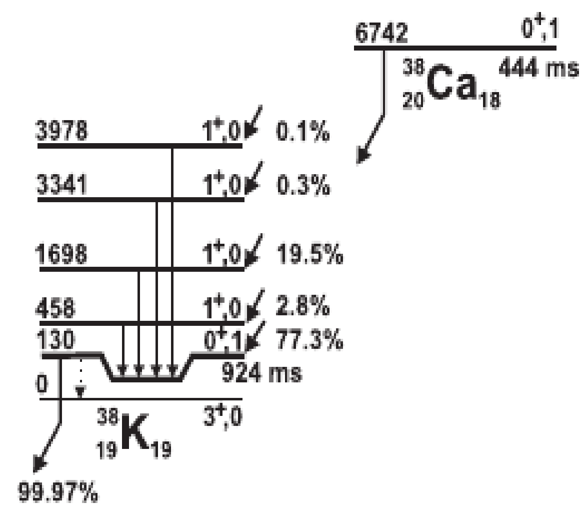


Careful determination of β and γ efficences

Branching ratio is defined as:

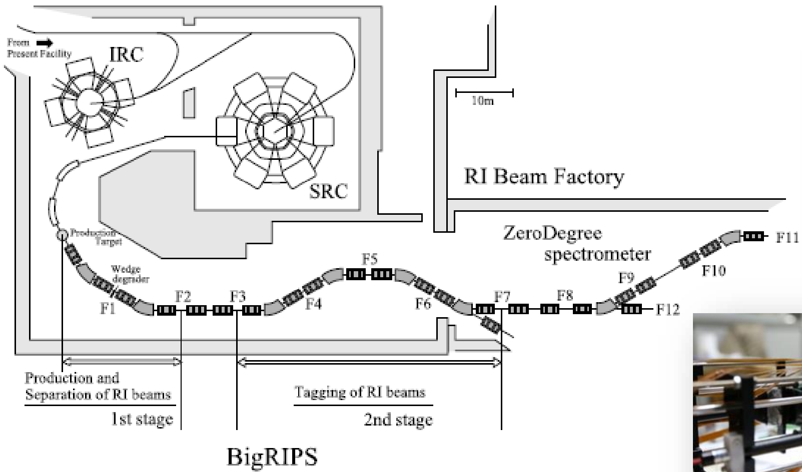
$$R_i = \frac{N_{\beta\gamma_i}}{N_\beta \epsilon_{\gamma_i}} \frac{\epsilon_\beta}{\epsilon_{\beta_i}}, \qquad (3)$$

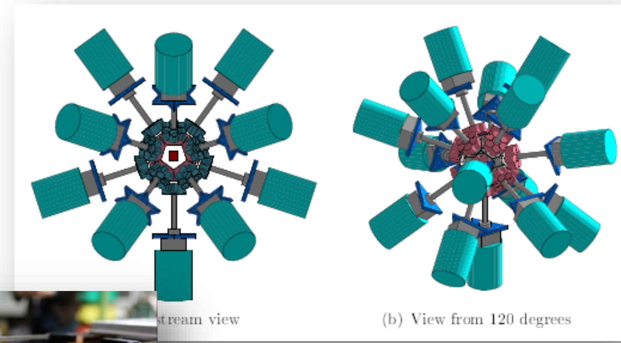
where $N_{\beta\gamma_i}$ is the total number of β-γ coincidences in the γ_i peak; N_β is the total number of beta singles corresponding

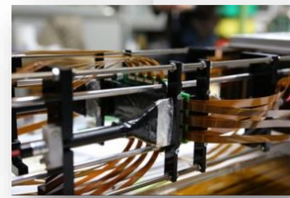


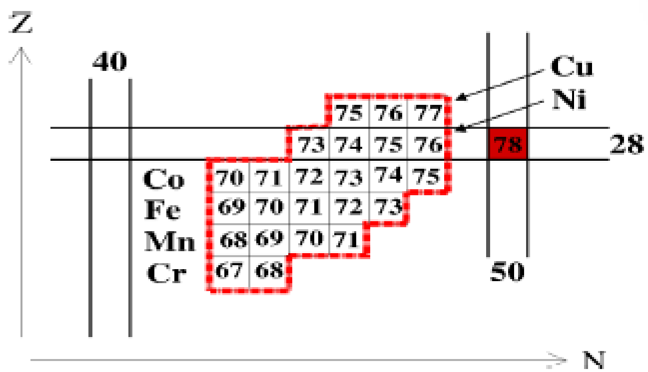
Part III: Examples

G.Benzoni et al. Riken 2013









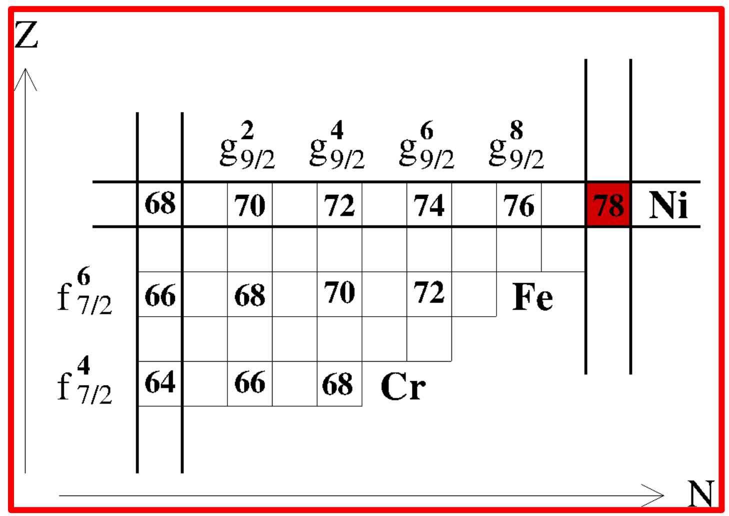
Relativistic Fission reaction

3 days of beamtime

^{238}U @ 345MeV/u

I_{beam} ~ 10 pnA

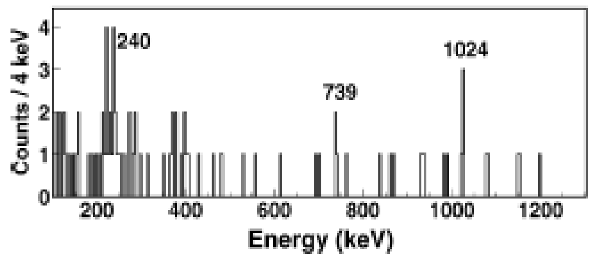
Region around ^{78}Ni: Possible change in magic numbers from 50 to 40

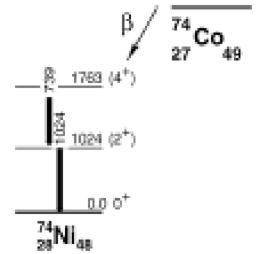


Part III: Examples

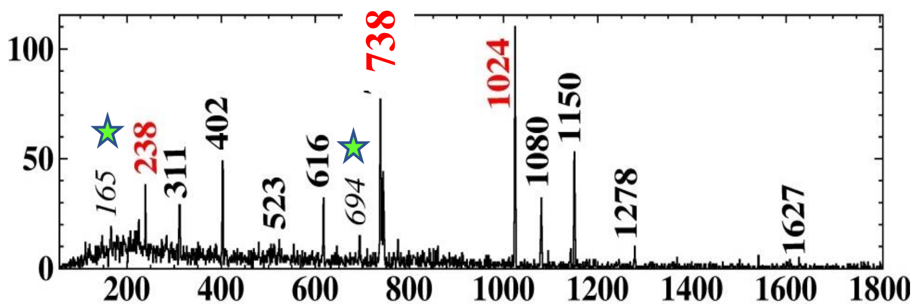
^{74}Co->^{74}Ni previous information

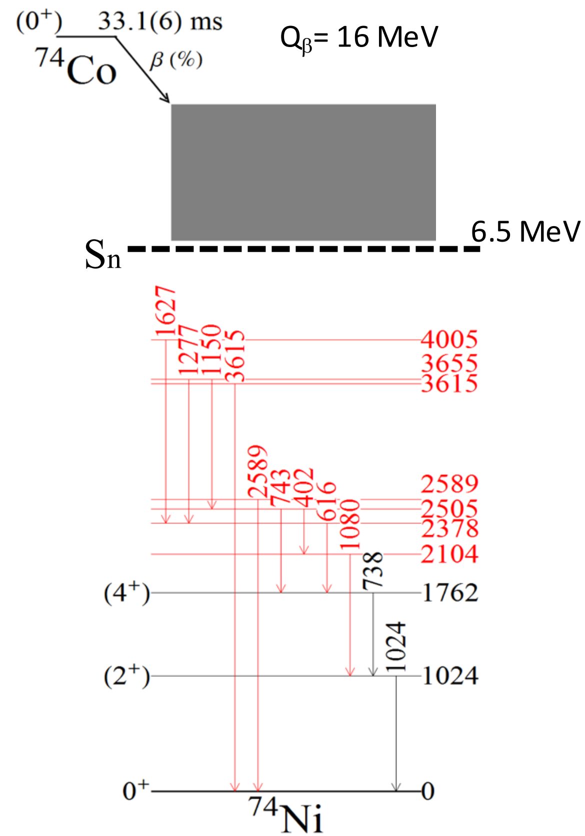
C.Mazzocchi et al. PLB622 (2005)





Much richer statistics ~10^4 nuclei
Population of states approaching the Sn ➔ better definition of beta-feeding





★ β-delayed n emission: γ rays in ^{73}Ni
Pn ~ 10%

G.Benzoni et al. Riken 2013

Conclusions

reasons to study beta decay:

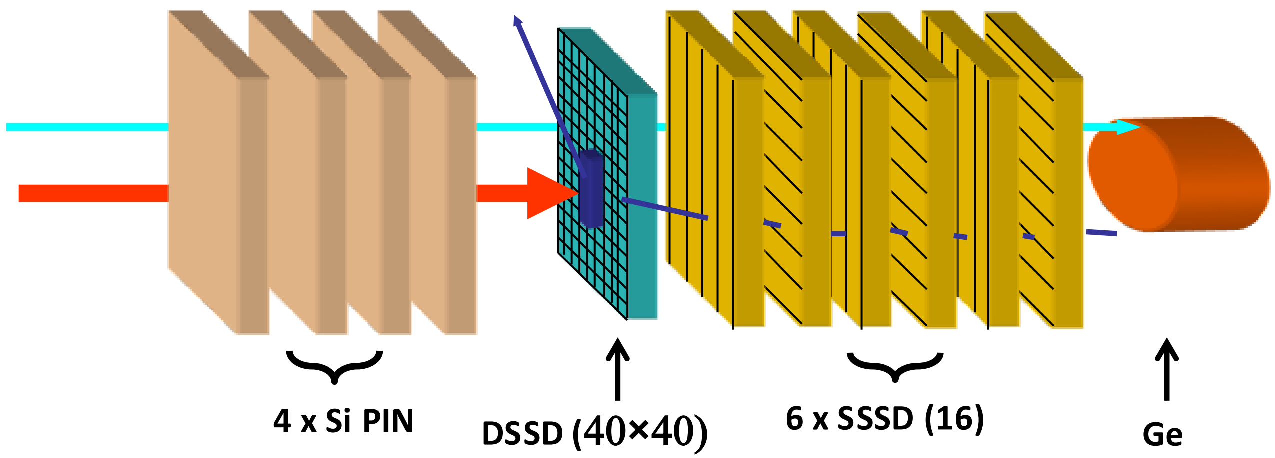
- Access to gross informations on the decay, Half-life, Pn etc.
- First information on excited states far from stability
- Spin assignments owing to selection rules
- Access to non-yrast states
- Definition of shapes of daughter nuclei
- Connection to mass measurements
- Input for astrophysics and reactor heat calculation….

……many more…

Beta Counting System (BCS) [MSU/SIMBA@GSI]

- **Implantation DSSD:**
  x-y position (pixel), time
- **Decay DSSD:**
  x-y position (pixel), time

Veto light particles



Beta calorimetry

Full reconstruction of all quantities: time/gamma/Qvalue