

# Beta decay studies of the most exotic nuclei

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Outline of the lessons:

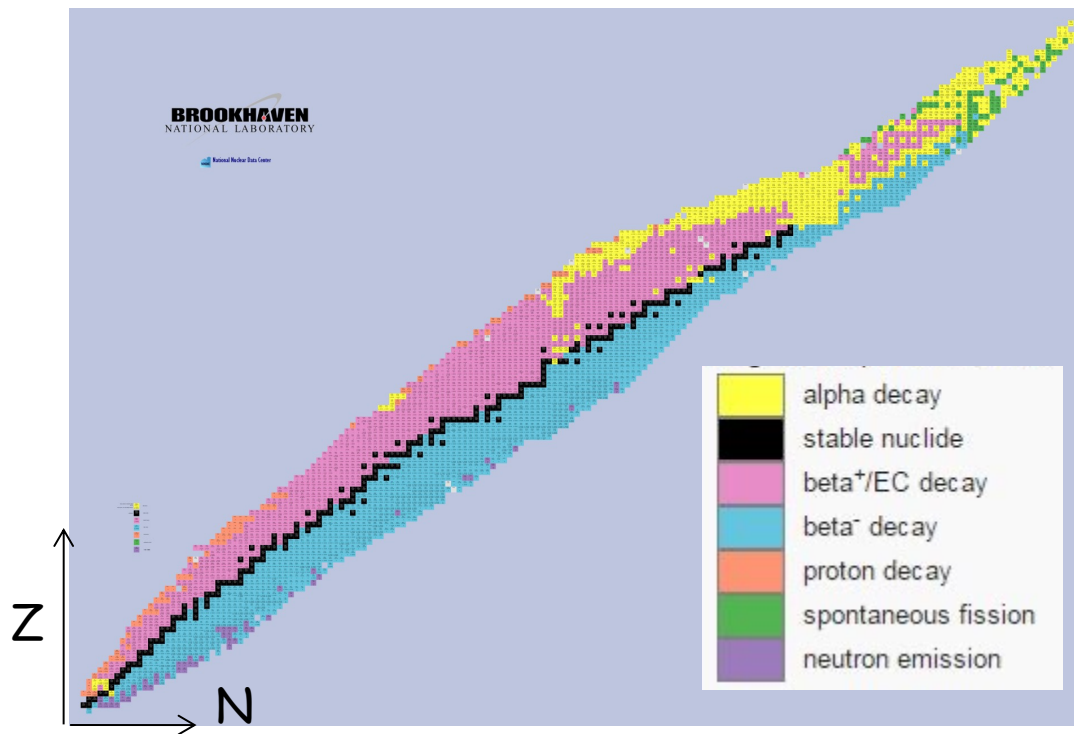
**PARTI: General concepts**

**How to measure  $\beta$  decay in exotic nuclei**

PARTII:  $\beta$  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

$\beta$  decay dominated by weak interaction and its properties directly relate to fundamental questions:

- Properties of the neutrinos → energy spectrum, double- $\beta$  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

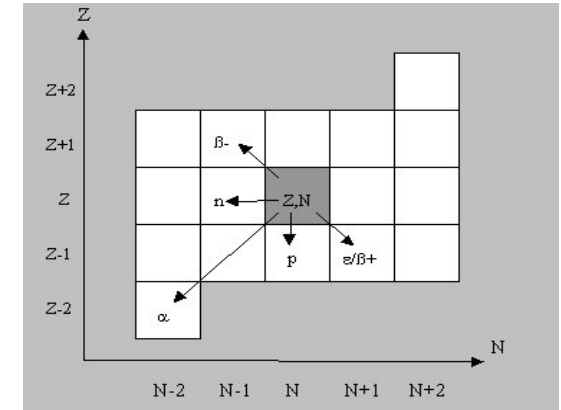
## Decay modes

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

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

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

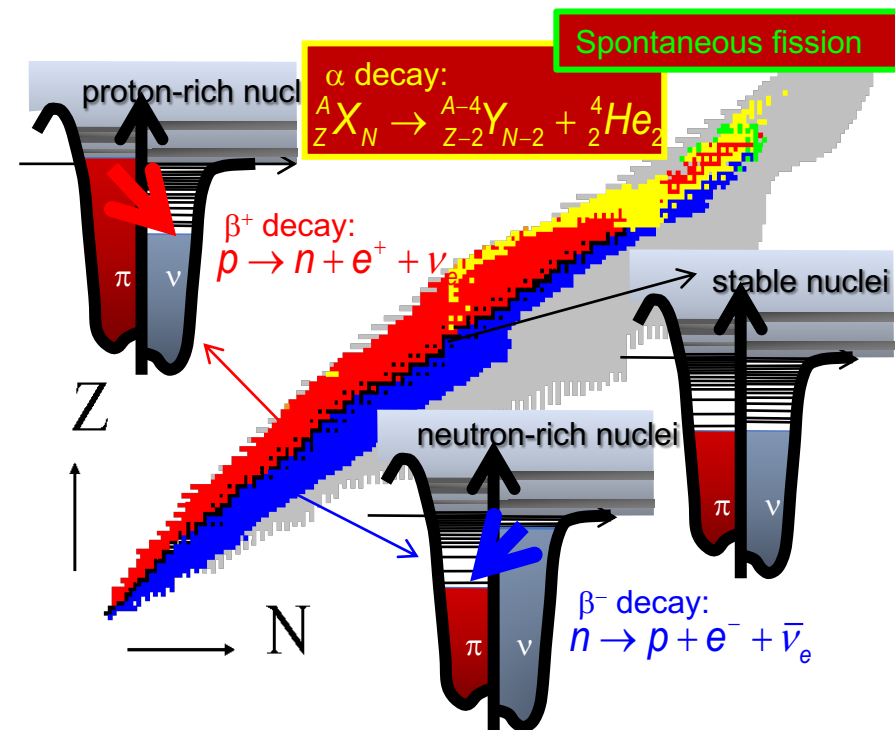
EC:  ${}^A_ZX + e^- \rightarrow {}^A_{Z-1}Y + \nu_e$



Spontaneous Fission

Exotic decay modes: n decay  
p decay  
cluster emission

$\beta$ -mediated decays:  
 $\beta$ -delayed n/p emission  
 $\beta$ -delayed fission

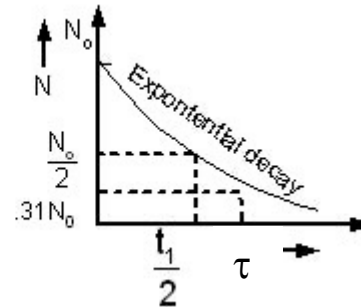


# Introduction

Useful definitions for decays:

Law of radioactive decay:

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



$\lambda$  decay rate

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

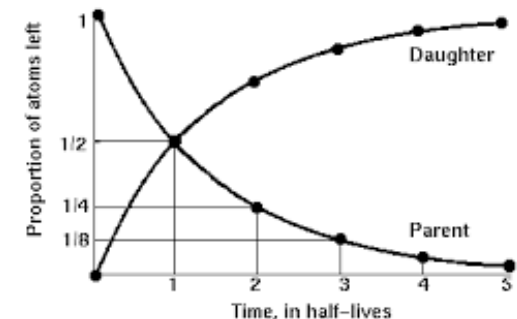
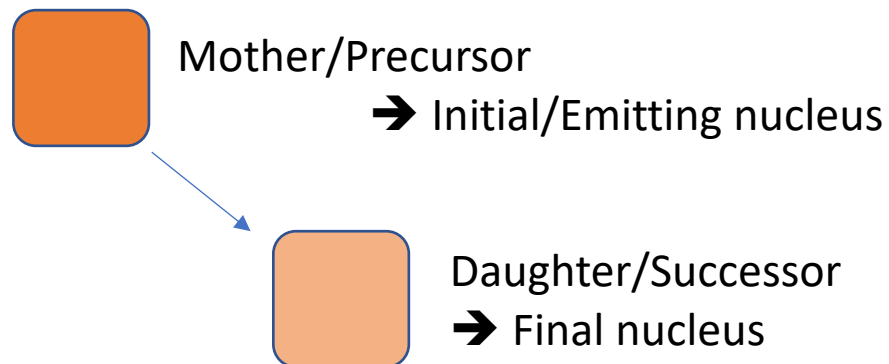
$T_{1/2} = \ln 2 * \tau$  half-life

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

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  $\lambda_i$ , 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 $\alpha$ $\beta$ $\gamma$ n particles: reminder of basic properties

$\alpha$  particle: massive, charged

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

$\beta$  particles: light, charged

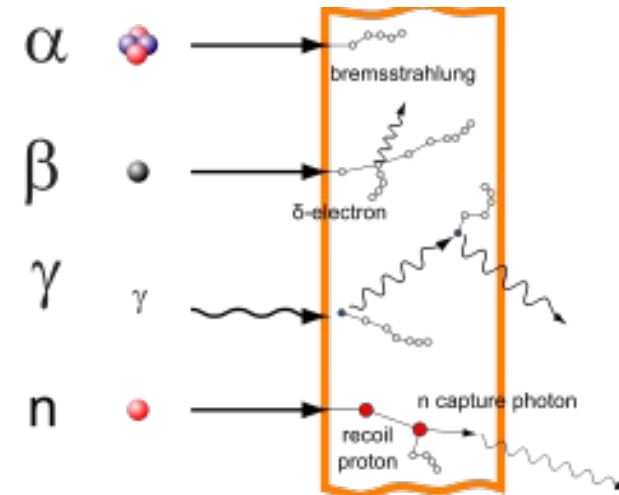
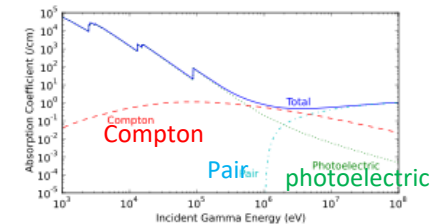
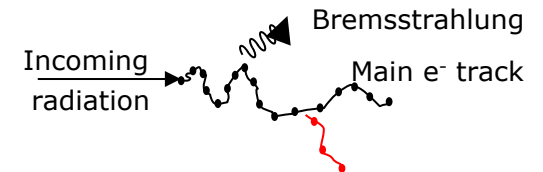
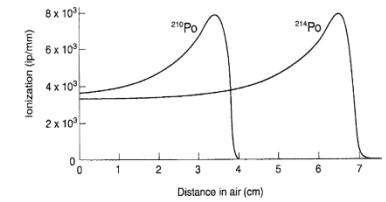
- interested in energy and correlations
- $e^+$  annihilates into two 511-keV  $\gamma$  rays
- spectrometers, Si, plastic detectors

$\gamma$  particles: massless, neutral

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

Neutrons: massive, neutral

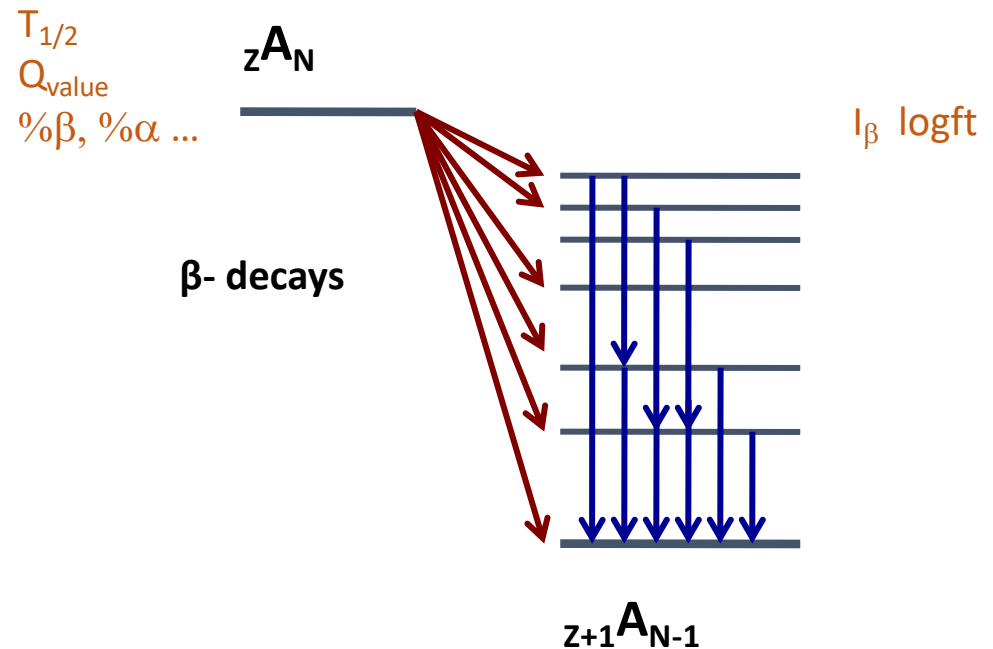
- interested in energy and correlations
- measured indirectly via capture reactions
- liquid scintillators, inorganic scintillators



# 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  $\alpha/\beta$ 
  - 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

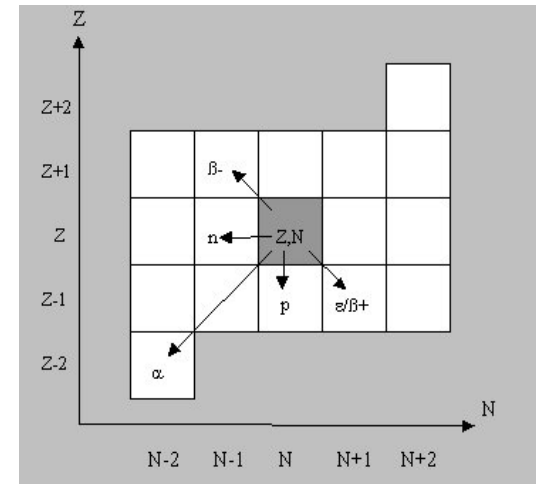


# General Properties of $\beta$ decay

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

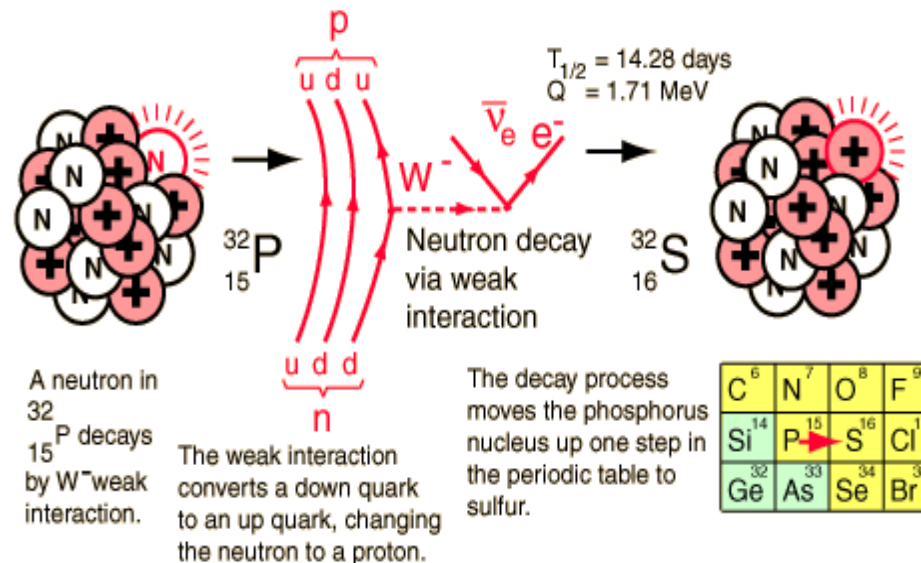
$${}^A_ZX \rightarrow {}^A_{Z-1}Y + e^+ + \nu_e \quad \beta^+ \text{ decay}$$

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



$\beta$  decay is a weak interaction “semi-leptonic” decay

The quark level Feynman diagram for  $\beta^-$  decay is shown here:



# General Properties of $\beta$ decay

- The  $Q$  value in  $\beta$  decay is effectively shared between the electron and antineutrino.
- This is the case of  $gs \rightarrow gs$  decay

$Q$  value for  $\beta^-$  decay is

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

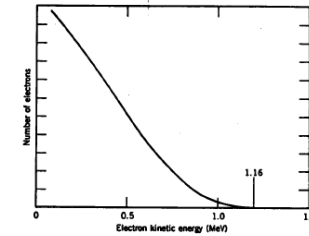


Fig. 9.1 The continuous electron distribution from the  $\beta$  decay of  $^{210}\text{Bi}$  (also 1 RaE in the literature).

$Q_{\beta^-}$  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  $\beta^+$  are not always competing:

if  $\beta^+$ , EC is possible, the contrary is not guaranteed

Note these are atomic masses

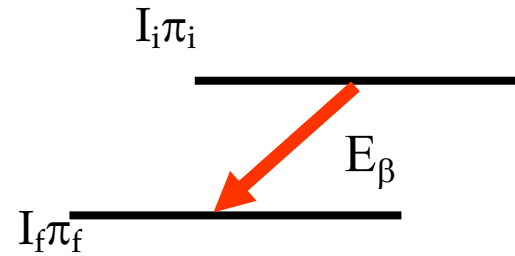
# General Properties of $\beta$ decay

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

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

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

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



$L_\beta = n$  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 $\beta$ decay

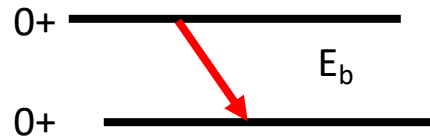
Selection rules for possible decays

| Type of transition | Order of forbiddenness | $\Delta I$ | $\pi_i \pi_f$ |
|--------------------|------------------------|------------|---------------|
| Allowed            |                        | 0, +1      | +1            |
| Forbidden unique   | 1                      | $\mp 2$    | -1            |
|                    | 2                      | $\mp 3$    | +1            |
|                    | 3                      | $\mp 4$    | -1            |
|                    | 4                      | $\mp 5$    | +1            |
|                    | .                      | .          | .             |
| Forbidden          | 1                      | 0, $\mp 1$ | -1            |
|                    | 2                      | $\mp 2$    | +1            |
|                    | 3                      | $\mp 3$    | -1            |
|                    | 4                      | $\mp 4$    | +1            |
|                    | .                      | .          | .             |

Classification of **allowed decays**

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

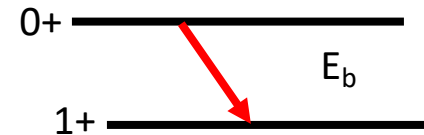
**Fermi**



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

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

**Gamow-Teller**



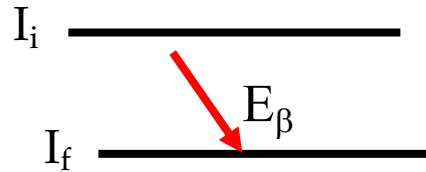
$$\Delta I = |I_i - I_f| \equiv 1$$

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

## Useful empirical rules

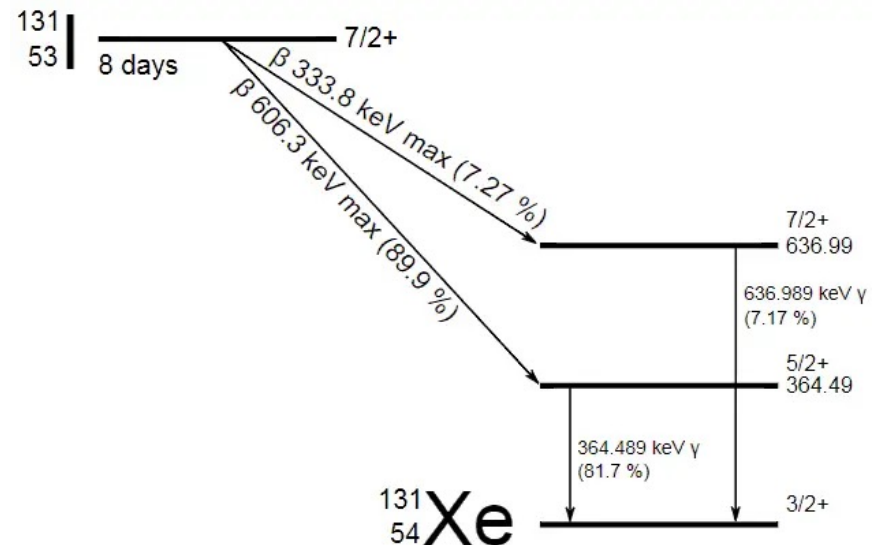
The fifth power beta decay rule:

the speed of a  $\beta$  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 $\beta$ 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  $\beta$  particle

$W_e$  – total energy of the  $\beta$  particle

$W_0$  – maximum energy of the  $\beta$  particle

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

$C_n$  – shape factor

$Z$  – atomic number

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

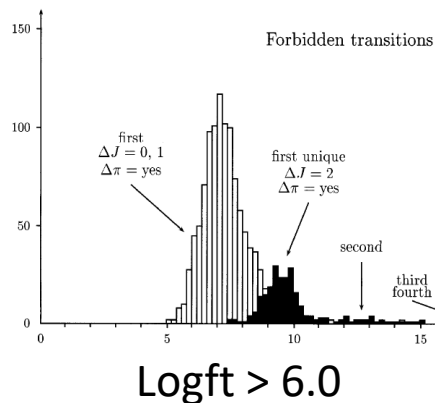
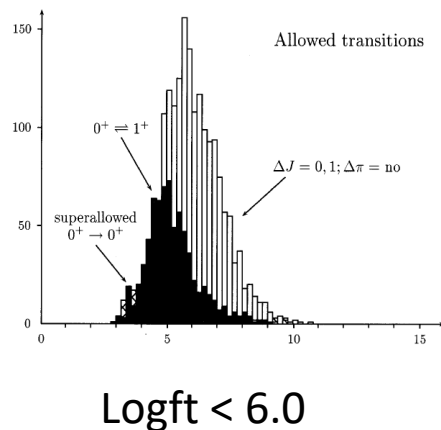
$$f_o = \int_1^{W_o} F(Z, W) W (W^2 - 1)^{1/2} (W_o - W)^2 dW$$

## 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

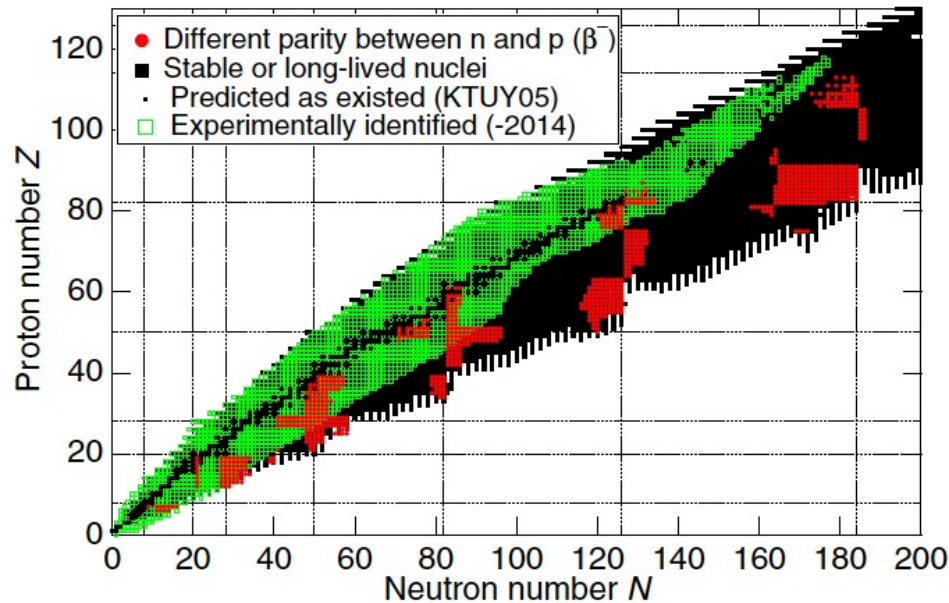


Review Of  $\text{Log}f\tau$  Values  
In  $\beta$  Decay\*

*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  $\beta$ -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

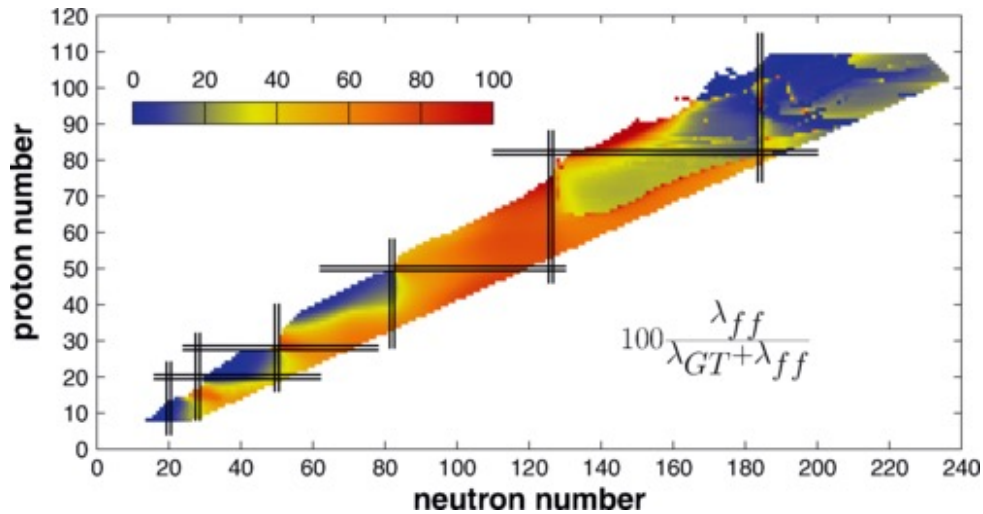
Example of  
measurements  
of  $\beta$ -decays

Perspectives

Conclusions

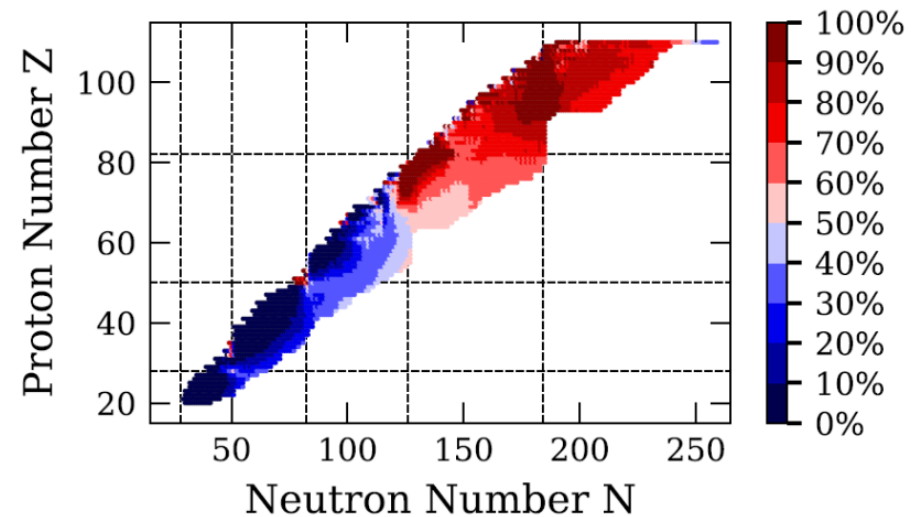
T. Marketin, L. Huther, G. Martinez-Pinedo, PRC93, 025805 (2016)

## First-forbidden beta decay



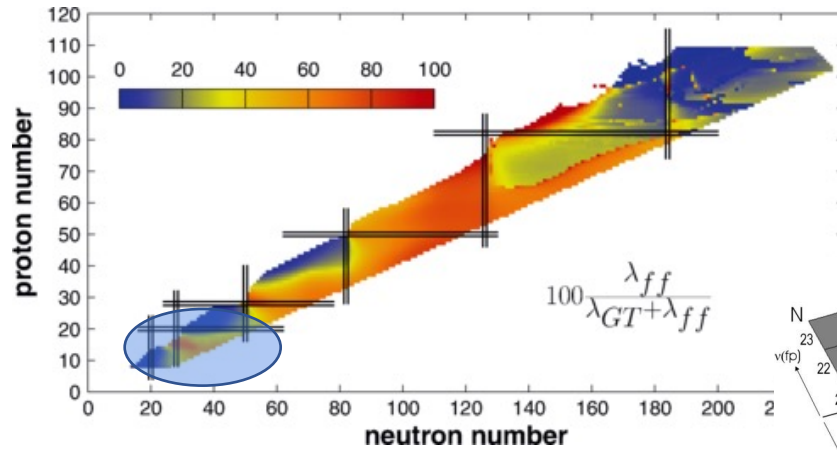
microscopic description based on Skyrme density functional, EFA applied to describe odd-A and odd-odd nuclei

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)

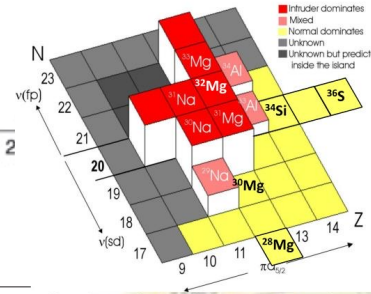
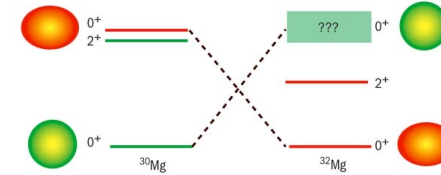
Editors' Suggestion

Featured in Physics

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

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

## First-forbidden beta decay



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

#### $\beta^-$ decay of exotic P and S isotopes with neutron number near 28

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



# First-forbidden beta decay

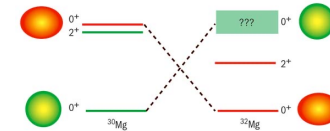
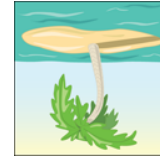
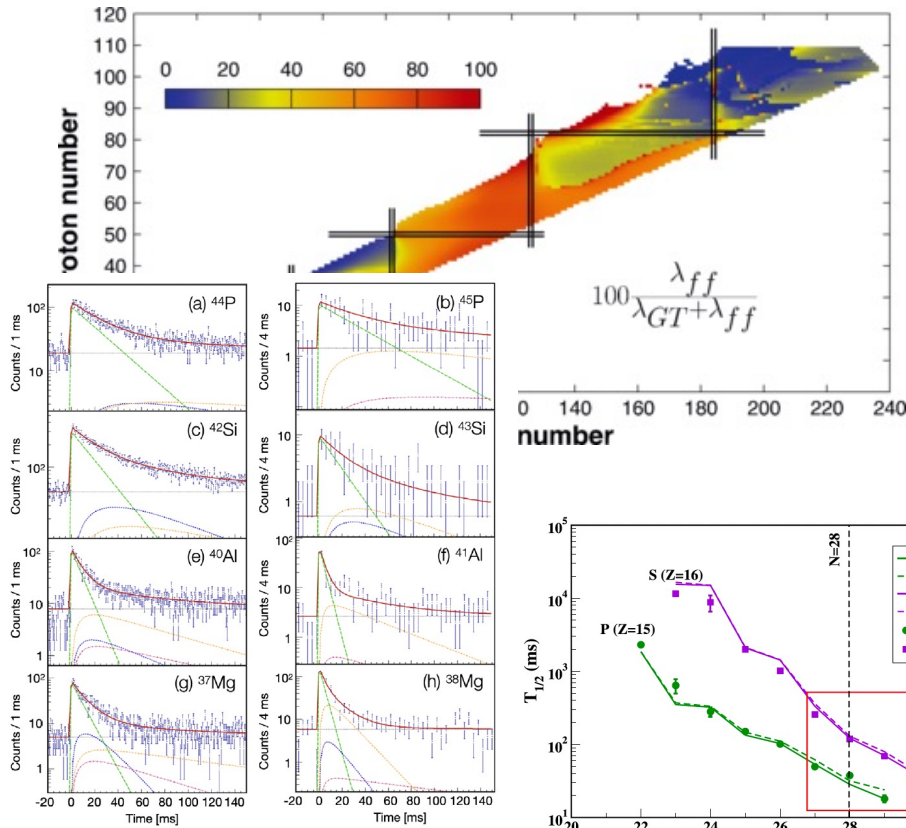
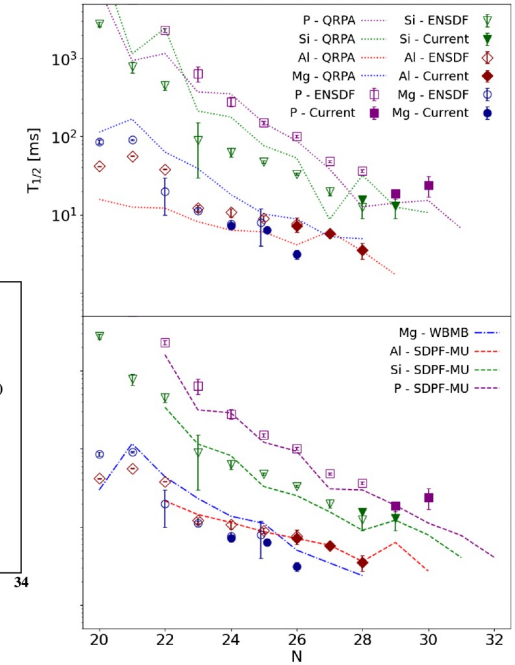
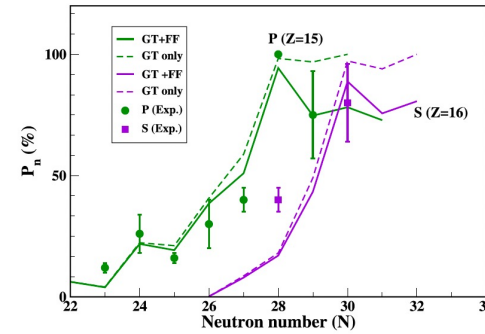
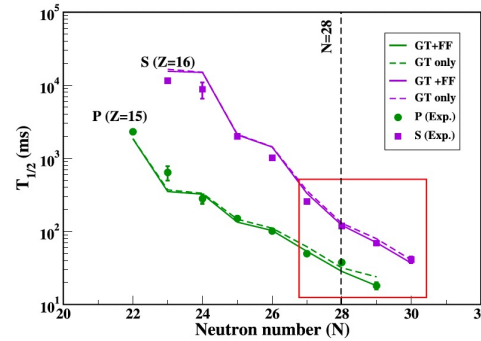
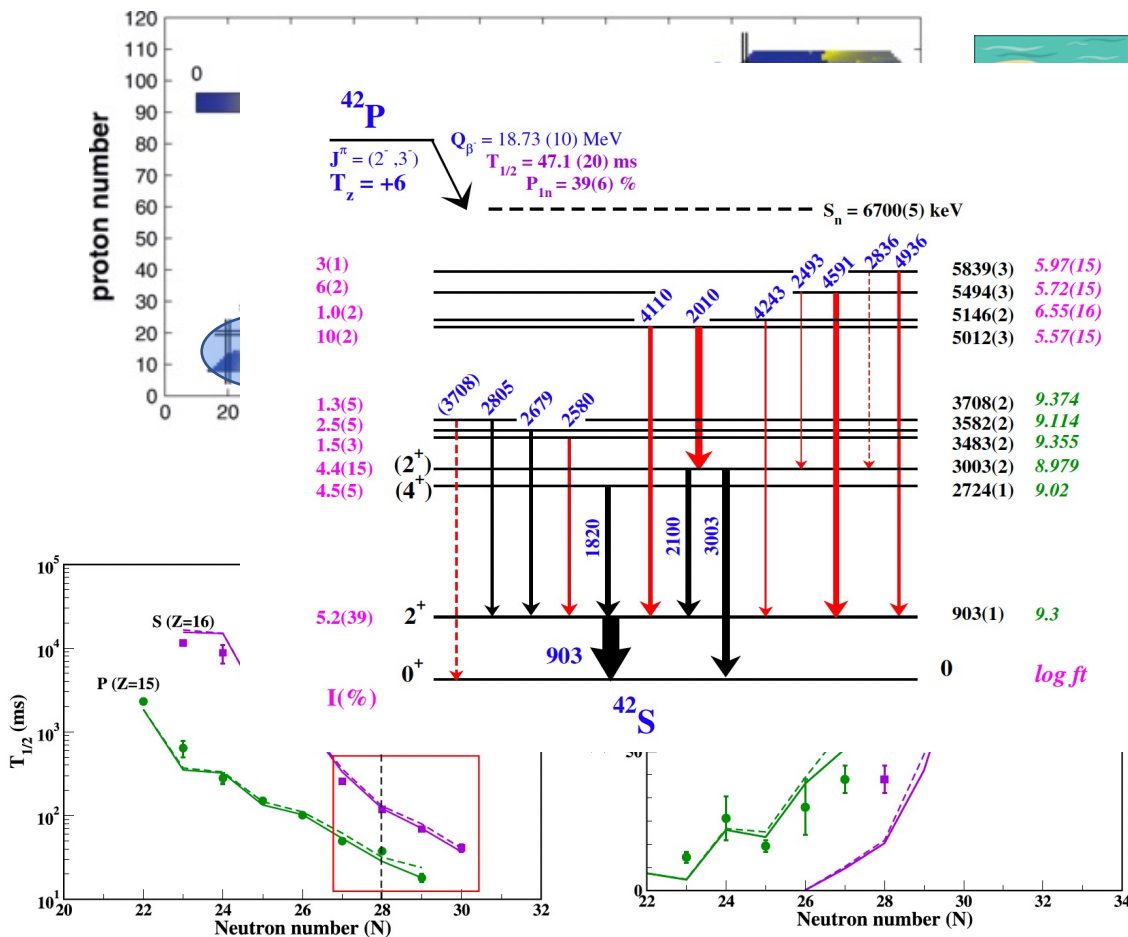


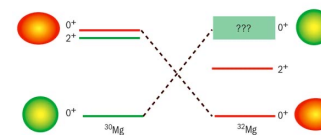
FIG. 2. Decay curves in panels (a)–(h) for  $^{44,45}\text{P}$ ,  $^{42,43}\text{Si}$ ,  $^{40,41}\text{Al}$ , and  $^{37,38}\text{Mg}$  respectively. The components of the fits are shown by the curves, where the solid red line is the total fit, the green dashed curve is the parent decay, the dot-dash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





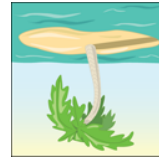
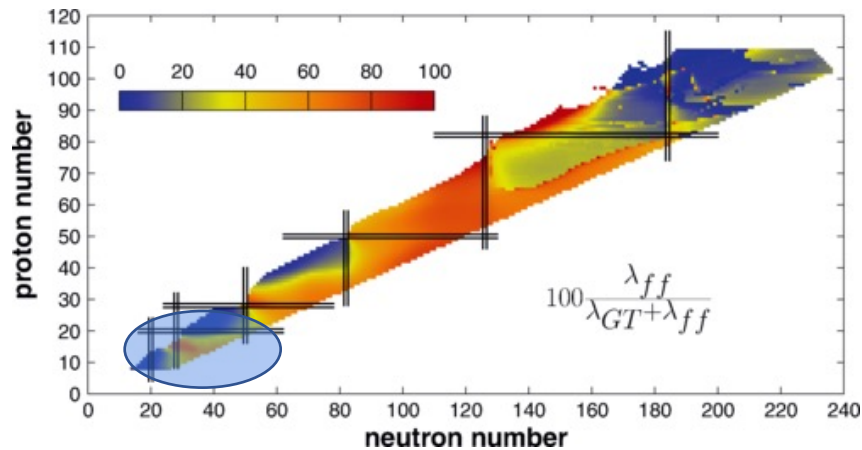


## First-forbidden beta decay

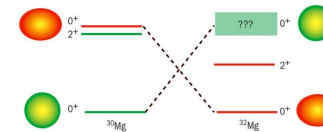


The impact of FF transitions which can be important for neutron-rich nuclei in this region with neutrons filling the  $1p_{3/2}$  orbital by comparing the measured  $T_{1/2}$  and  $P_n$  values with SM calculations with and without FF transitions included.

- P isotopes with  $N = 27, 28, 29$  displayed a larger contribution from FF transitions in their  $\beta$  decay. For the case of  $^{42}\text{P}$  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.
- Both the half-life and  $P_n$  value of  $^{44}\text{P}$  also indicate influence of FF transitions. Comparison with SM calculations of states populated in  $^{42}\text{S}$  in the decay of  $^{42}\text{P}$  both via allowed GT and FF decays suggests a  $J^\pi$  of  $2^-$  or  $3^-$  for the ground state of  $^{42}\text{P}$  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  $\beta$ -delayed neutron emission probability ( $P_n$ ).

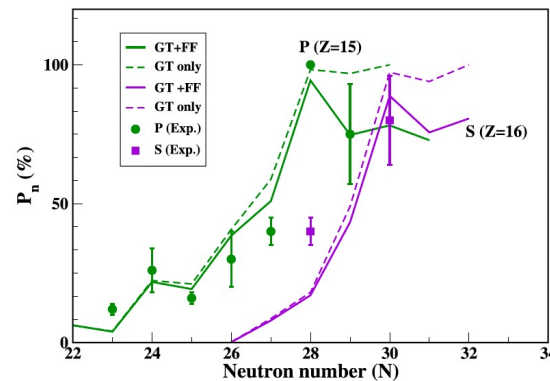
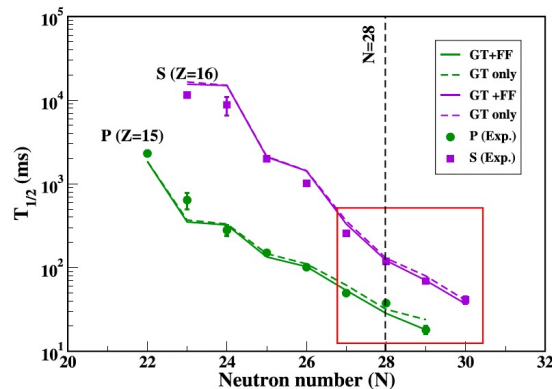


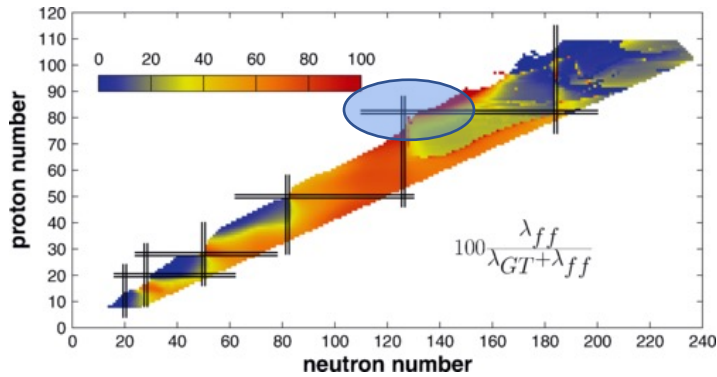
## First-forbidden beta decay



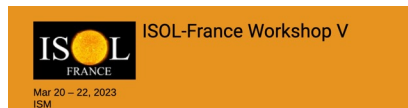
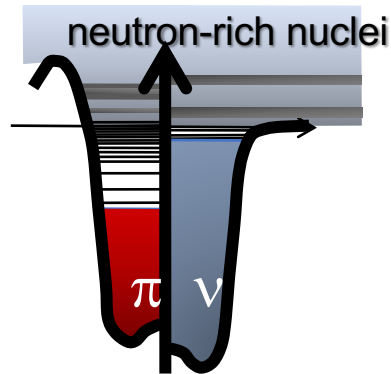
The impact of FF transitions which can be important for neutron-rich nuclei in this region with neutrons filling the  $1p_{3/2}$  orbital by comparing the measured  $T_{1/2}$  and  $P_n$  values with SM calculations with and without FF transitions included.

- P isotopes with  $N = 27, 28, 29$  displayed a larger contribution from FF transitions in their  $\beta$  decay. For the case of  $^{42}\text{P}$  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.
- Both the half-life and  $P_n$  value of  $^{44}\text{P}$  also indicate influence of FF transitions. Comparison with SM calculations of states populated in  $^{42}\text{S}$  in the decay of  $^{42}\text{P}$  both via allowed GT and FF decays suggests a  $J\pi$  of  $2^-$  or  $3^-$  for the ground state of  $^{42}\text{P}$  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  $\beta$ -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

$^{208}\text{Pb}$

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

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

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

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

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

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

$3d_{3/2}$

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

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

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

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

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

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

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

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

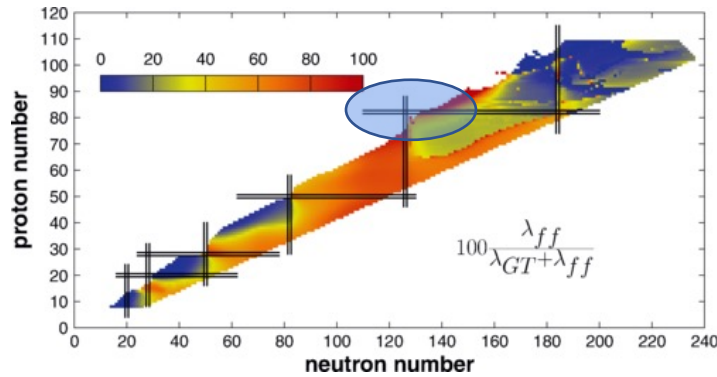
82

$\pi$

126

$\nu$

$3d_{3/2}$



## First-forbidden beta decay

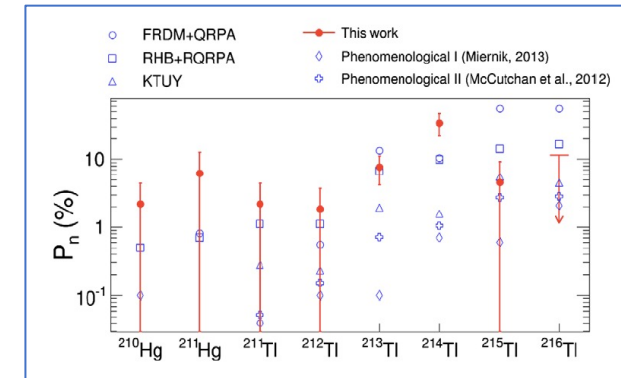
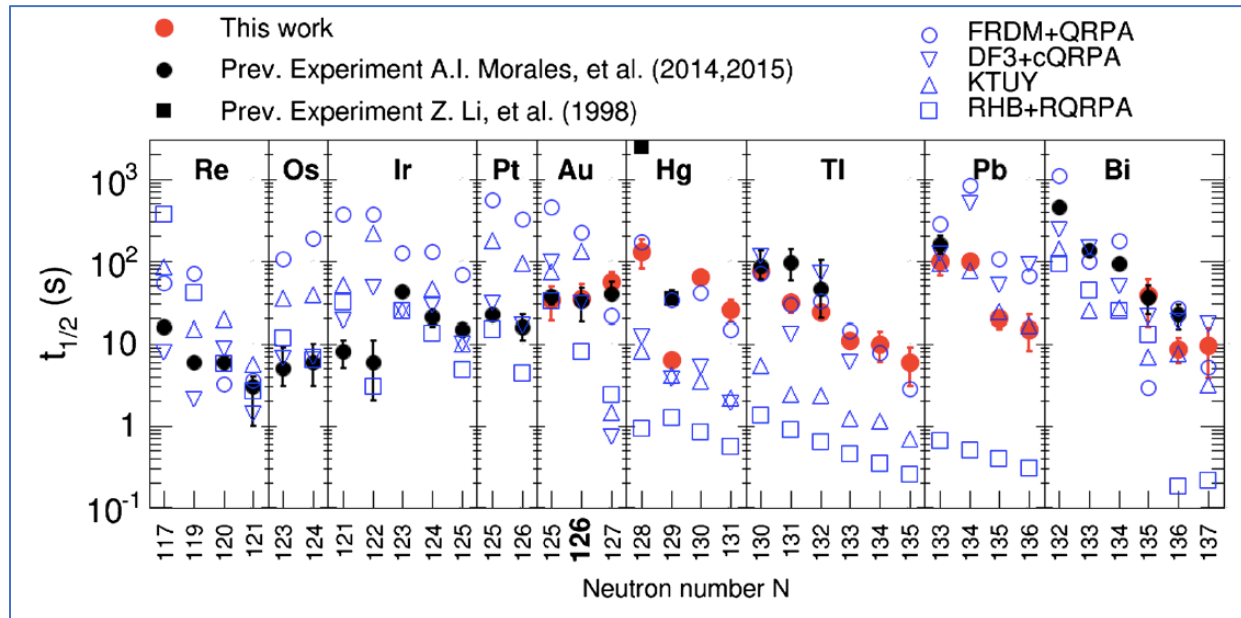
PRL 117, 012501 (2016)

PHYSICAL REVIEW LETTERS

week ending  
1 JULY 2016

### First Measurement of Several $\beta$ -Delayed Neutron Emitting Isotopes Beyond $N=126$

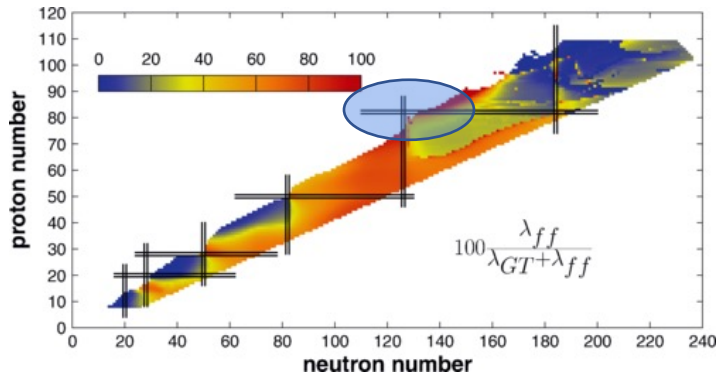
R. Caballero-Folch,<sup>1,2</sup> C. Domingo-Pardo,<sup>3,\*</sup> J. Agramunt,<sup>3</sup> A. Algora,<sup>3,4</sup> F. Ameil,<sup>5</sup> A. Arcones,<sup>5</sup> Y. Ayyad,<sup>6</sup> J. Benlliure,<sup>6</sup> I. N. Borzov,<sup>7,8</sup> M. Bowry,<sup>9</sup> F. Calviño,<sup>1</sup> D. Cano-Ott,<sup>10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



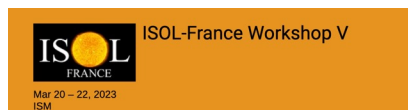
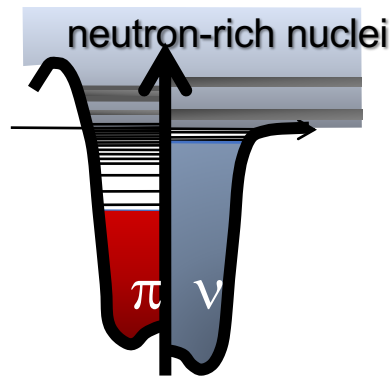
ISOL-France Workshop V

Mar 20 – 22, 2023  
ISM





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

$^{208}\text{Pb}$

$\pi=-$  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

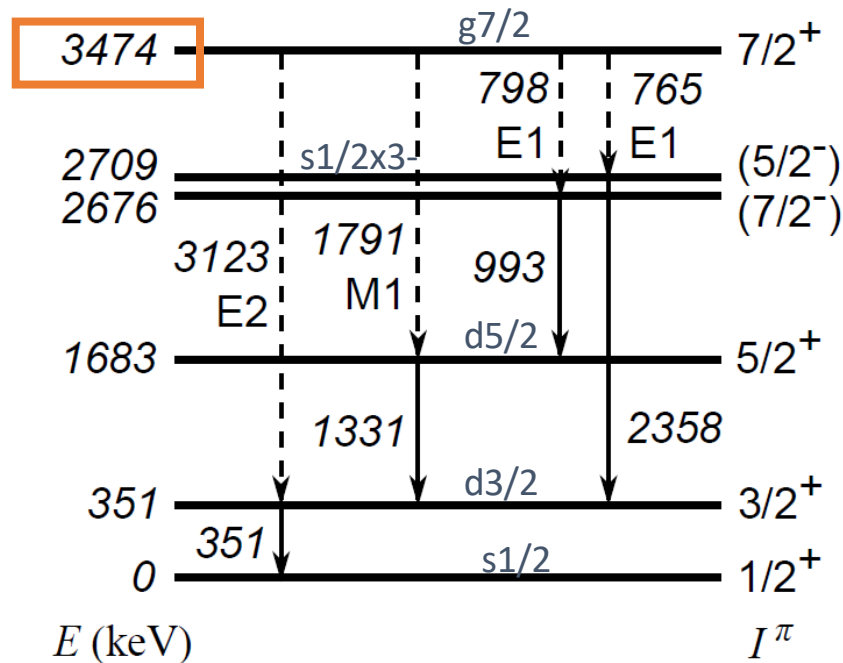
$\pi$

126

$\nu$

3d3/2

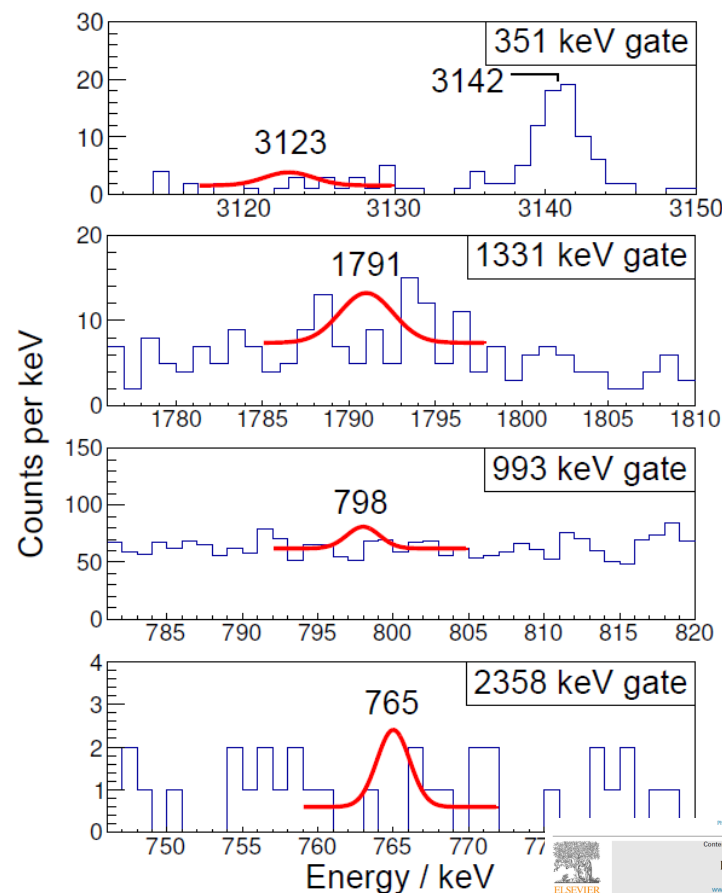
# The $2g_{9/2} \rightarrow 1g_{7/2}$ beta decay ( $^{207}\text{Hg} \rightarrow ^{207}\text{Tl}$ )



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

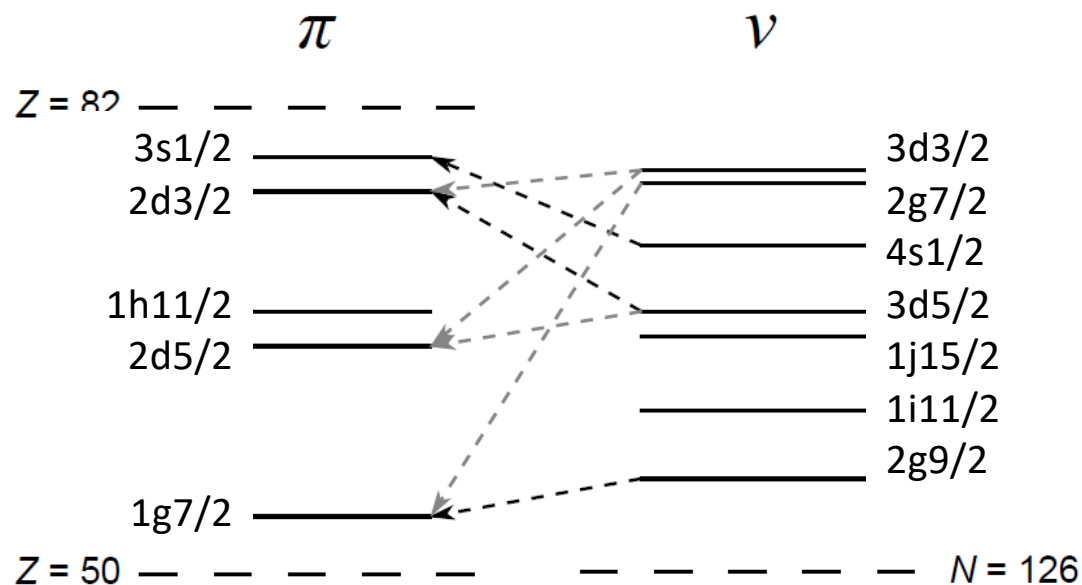
$\log ft > 8.8$  (95% confidence limit)

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



Investigation of the  $\Delta n = 0$  selection rule in Gamow-Teller transitions: The  $\beta$ -decay of  $^{207}\text{Hg}$

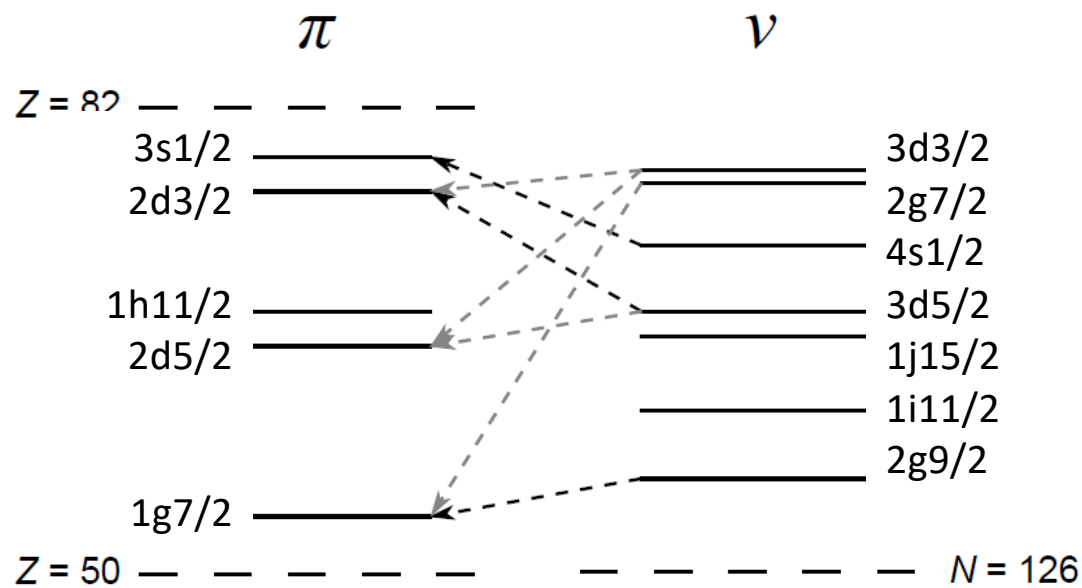
T.A. Berry<sup>a,\*</sup>, Zs. Podolyák<sup>a</sup>, R.J. Carroll<sup>a</sup>, R. Lic<sup>b,c</sup>, H. Gräwe<sup>d</sup>, N.K. Timofeyuk<sup>e</sup>, T. Alexander<sup>f</sup>, A.N. Andreyev<sup>g</sup>, S. Ansari<sup>h</sup>, M.J.G. Borge<sup>i,j</sup>, J. Creswell<sup>k</sup>, C. Fahlander<sup>l</sup>, L.M. Fraile<sup>m</sup>, H.O.U. Fyfe<sup>n</sup>, W. Gellert<sup>o</sup>, R.-B. Gerst<sup>p</sup>, M. Gorska<sup>q</sup>, A. Gredley<sup>r</sup>, P. Greenlees<sup>s</sup>, L.J. Harkness-Brennan<sup>t</sup>, M. Huyse<sup>u</sup>, S.M. Judge<sup>v</sup>, D.S. Judson<sup>w</sup>, J. Konki<sup>x,y,z</sup>, J. Kurevics<sup>aa</sup>, I. Kuti<sup>ab</sup>, S. Lashin<sup>ac</sup>, I. Lazarus<sup>ad</sup>, M. Lind<sup>ae</sup>, M. Madurga<sup>af</sup>, N. Marginean<sup>ag</sup>, R. Marginean<sup>ah</sup>, I. Marroquin<sup>ai</sup>, C. Mihai<sup>aj</sup>, R.E. Mihal<sup>ak</sup>, E. Nacher<sup>al</sup>, S. Nae<sup>am</sup>, A. Negret<sup>an</sup>, C. Nita<sup>ao</sup>, R.D. Page<sup>ap</sup>, S. Pascu<sup>aq</sup>, Z. Patel<sup>ar</sup>, A. Perez<sup>as</sup>, V. Pucknell<sup>at</sup>, P. Rahkila<sup>au</sup>, E. Rapisarda<sup>av</sup>, P.H. Regan<sup>aw</sup>, F. Rotaru<sup>ax</sup>, C.M. Shand<sup>ay</sup>, E.C. Simpson<sup>az</sup>, Ch. Sotny<sup>ba</sup>, S. Stegemann<sup>bb</sup>, T. Stora<sup>bc</sup>, O. Tengblad<sup>bd</sup>, A. Turturica<sup>be</sup>, P. Van Duppen<sup>bf</sup>, V. Veda<sup>bg</sup>, R. Wadsworth<sup>bh</sup>, P.M. Walker<sup>bi</sup>, N. Warr<sup>bj</sup>, F. Weare<sup>bk</sup>, H. De Witte<sup>bl</sup>



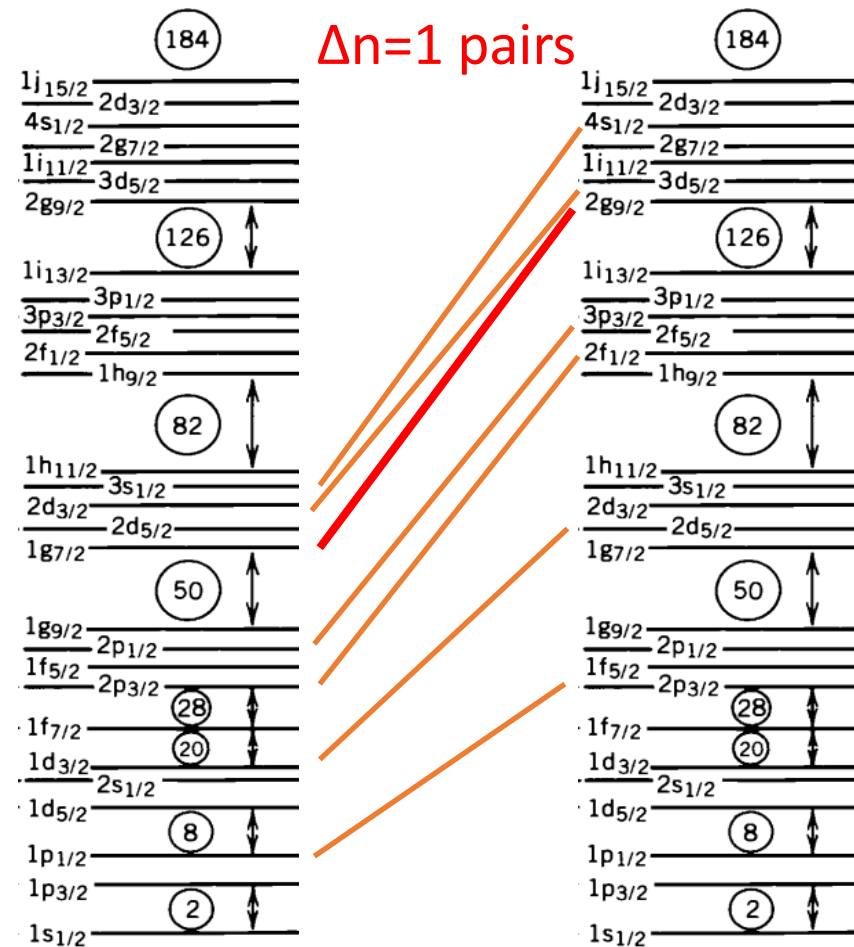
These increase dramatically for extremely neutron-rich nuclei, when either exploring deeper into the proton shell below  $Z=82$  or extending further into  $N>126$

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

The same selection rule also affects nuclei 'south-east' of  $^{132}\text{Sn}$  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  $Q_\beta$  values



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

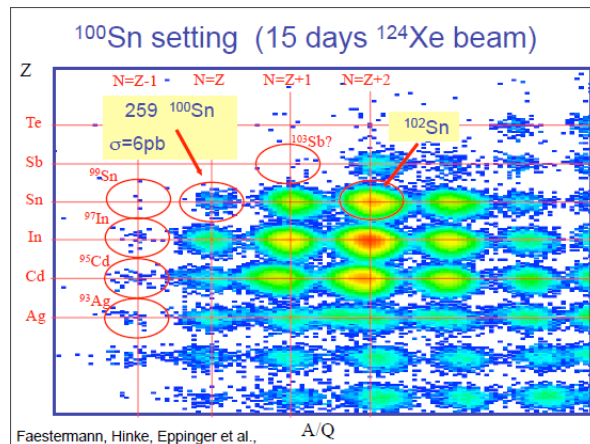




# Superaligned Gamow–Teller decay of the doubly magic nucleus $^{100}\text{Sn}$

$^{100}\text{Sn}$   $N=Z=50$   
Heaviest  $N=Z$  nucleus

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



$\sim 260$   $^{100}\text{Sn}$  nuclei produced (0.75/h)  
 $\sim 126$  fully reconstructed decay chains

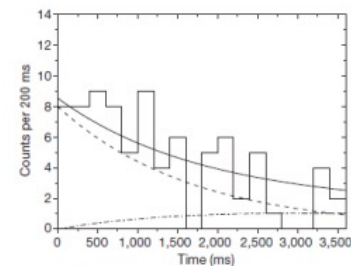
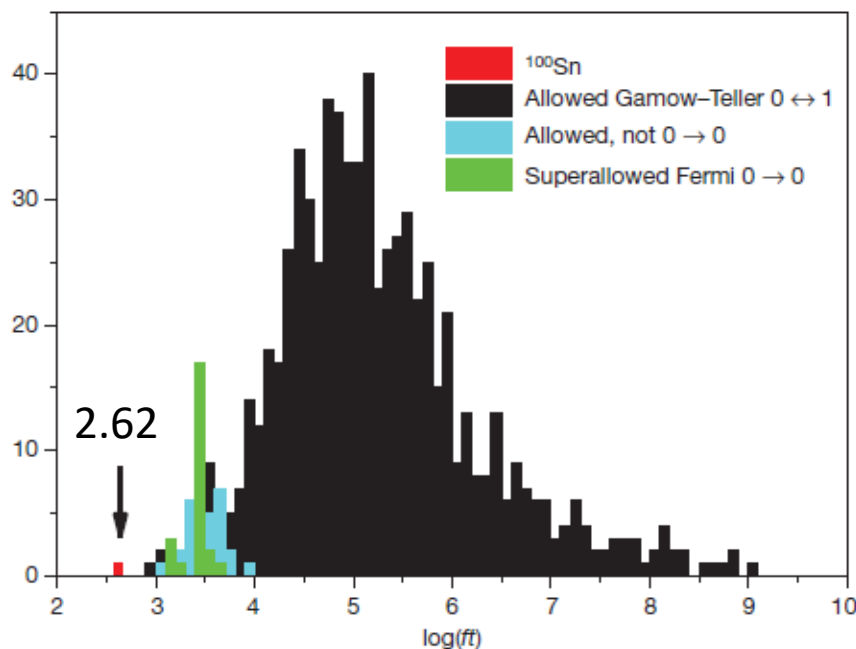


Figure 2 | Time distribution of first decay events. The histogram shows the observed time distribution of all first decay events in the nearest-neighbouring pixels after implantation of  $^{100}\text{Sn}$  nuclei. Decay curves resulting from the MLH analysis are shown individually for  $^{100}\text{Sn}$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

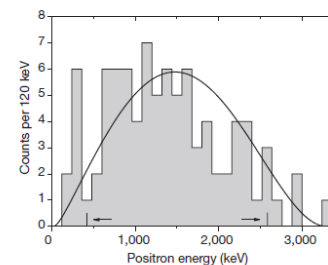


Figure 5 | Distribution of the positron energies emitted in the  $\beta$ -decay of  $^{100}\text{Sn}$ . The spectrum contains only decay events that can be assigned to  $^{100}\text{Sn}$  decays with a probability of at least 75%. The MLH fit was applied to the region between 400 and 2,600 keV, which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

# $^{100}\text{Sn}$ N=Z=50 Heaviest N=Z nucleus

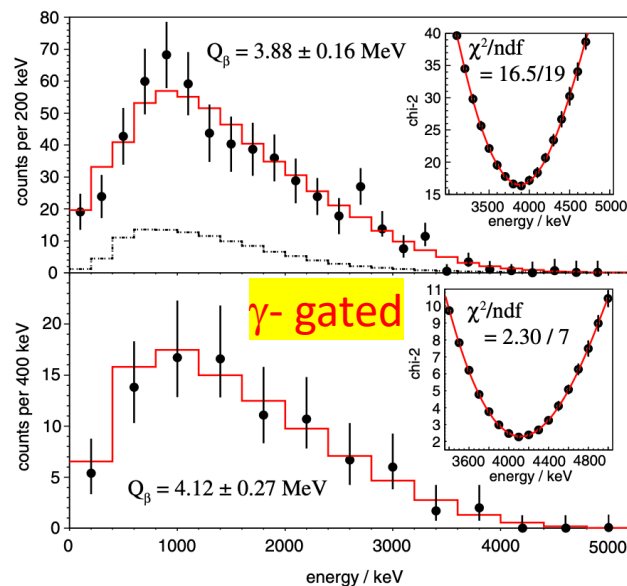
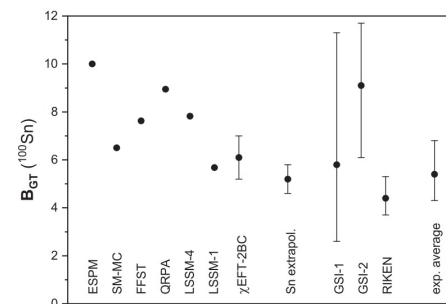
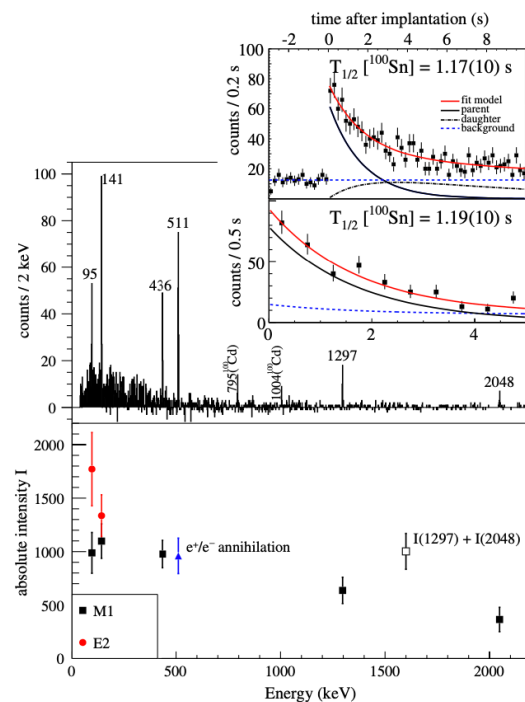


FIG. 3. Top: the energy distribution of positrons after the  $\beta$  decay of  $^{100}\text{Sn}$ . Bottom: energy distribution of the  $\gamma$ -gated event selection. The insets show the  $\chi^2$  values when comparing the measured spectrum with the simulated spectrum for a certain end point energy.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

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

## $\beta$ Decay of $^{138}\text{La}$

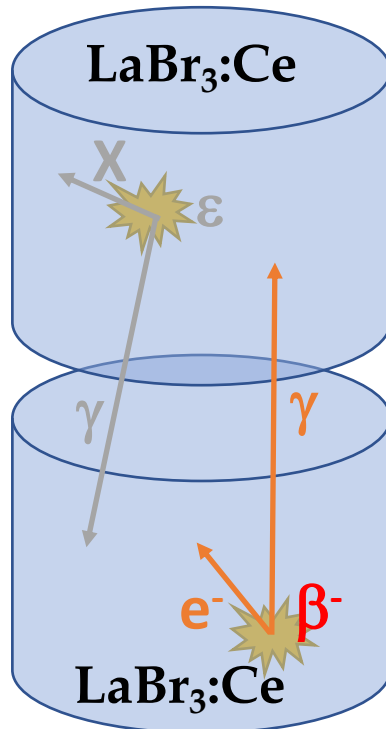
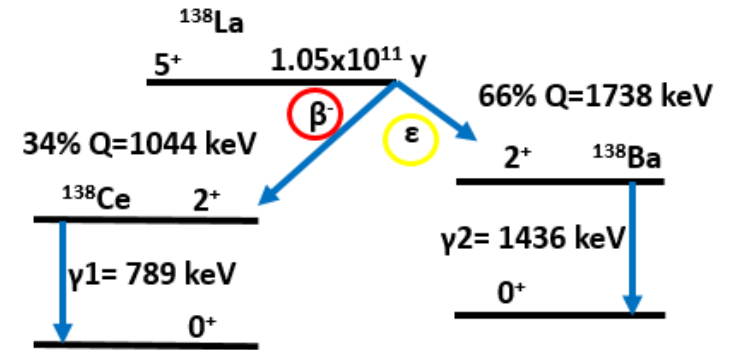
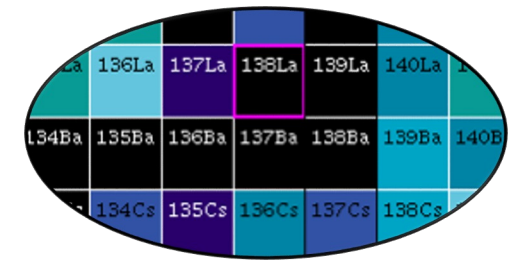
Lanthanum has two isotopes

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

$^{138}\text{La}$  has two decay branches

- $\beta^-$  towards  $^{138}\text{Ce}$ , BR= 33.6 %
- $\text{EC}$  towards  $^{138}\text{Ba}$  BR=66 %

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

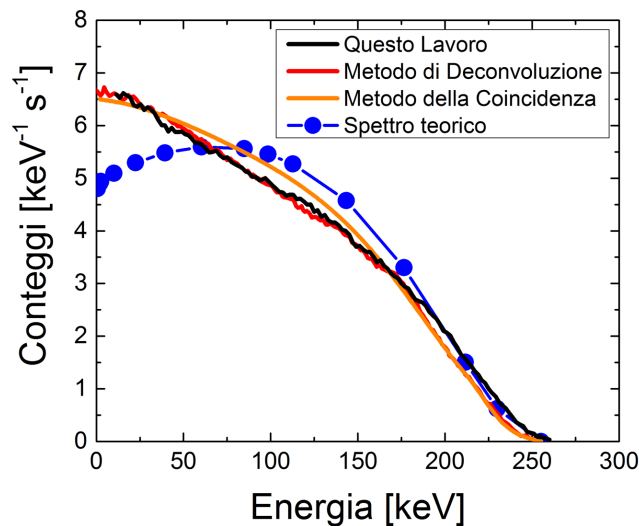
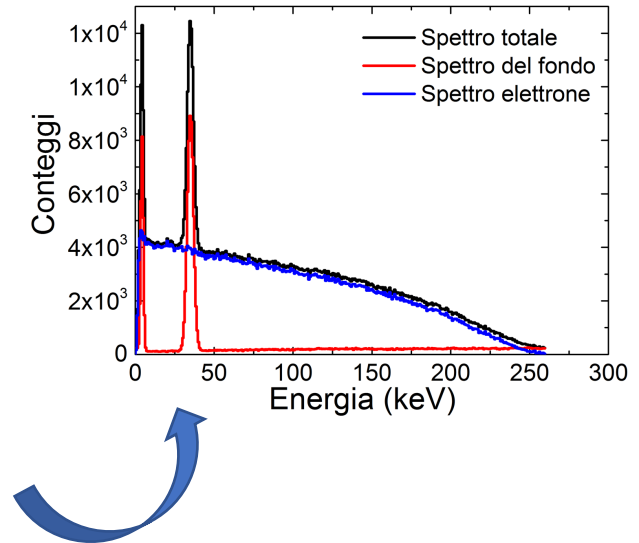
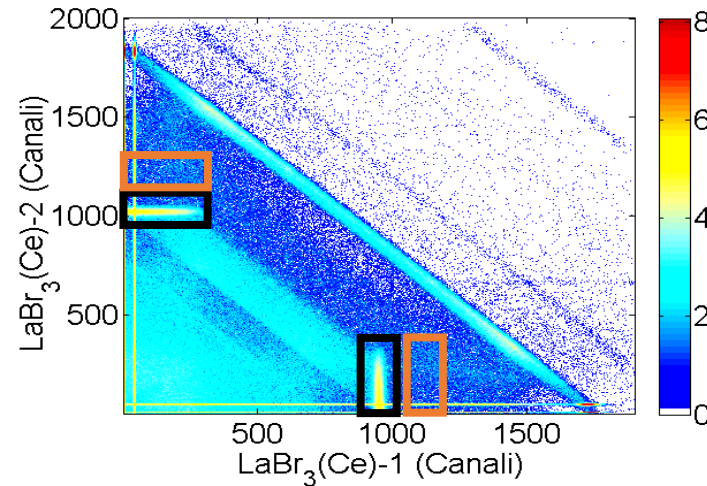


Experiment: measuring the BR and the electron spectra  
 Using  $\text{LaBr}_3(\text{Ce})$  detectors as **source AND as detectors**

- $\beta^-$  decay:  $e^-$  in the det. which  $\beta$  decays, 789 keV  $\gamma$  ray in the other;
- EC: X ray in the det. which decays, 1436 keV  $\gamma$  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.

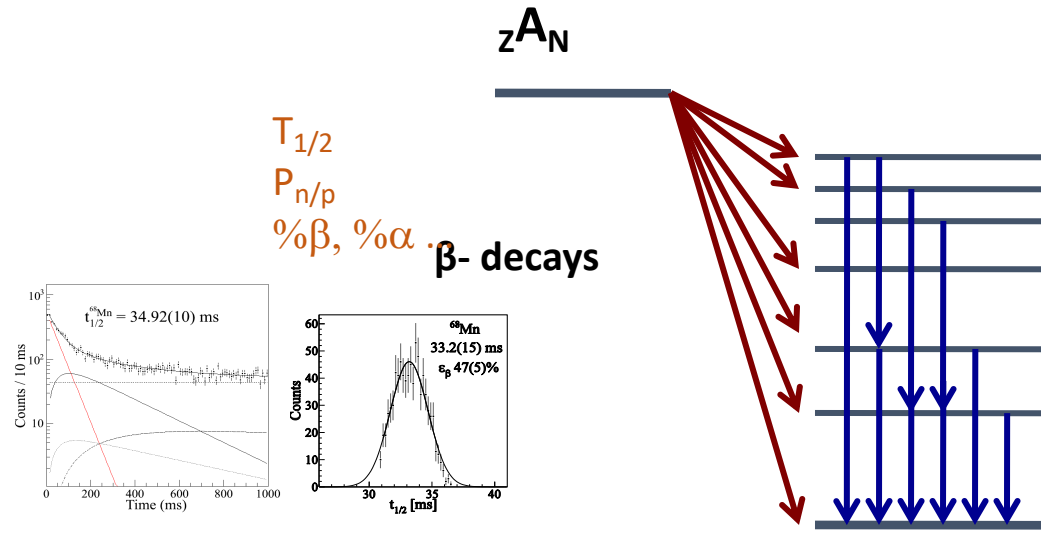


Theory has hard time reproducing low-energy shape of  $\beta$ -electron spectrum

Interaction btw Coulomb field of the nucleus and electron

# General Properties of $\beta$ decay

Quantities that can be extracted in a  $\beta$  decay experiment

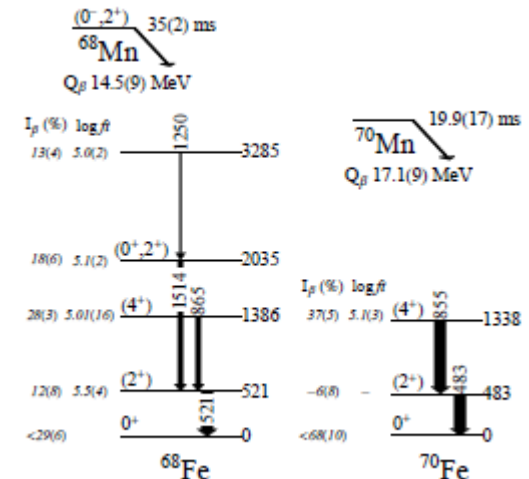
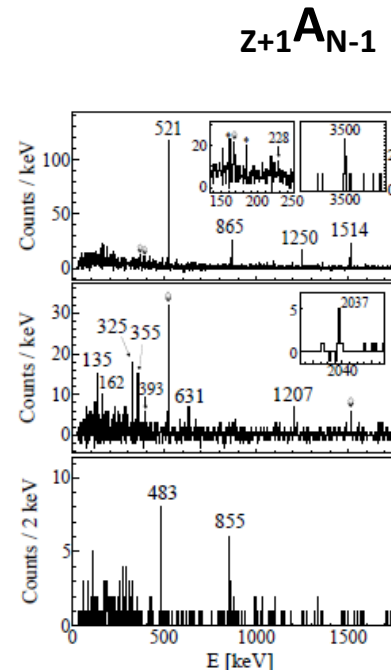
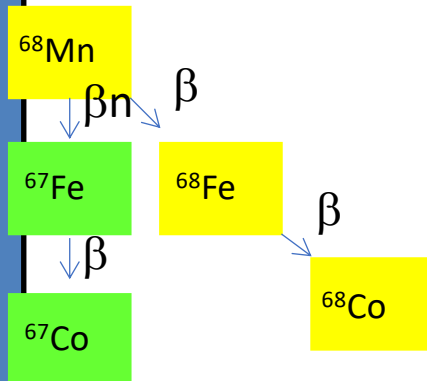


$\gamma$  transitions

Possible existence of many decaying states

$\gamma$ - $\gamma$  coincidences  $\rightarrow$  level schemes

Relative intensities  $I_\beta$   
 $\log ft$



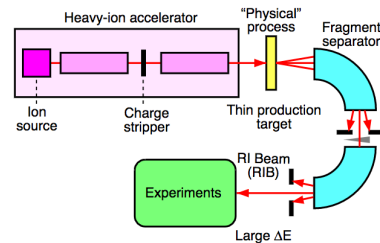
Selection rules allow to suggest/define  $I^\pi$  in both mother and daughter

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

# Introduction

## Producing radioactive beams i.e. exotic nuclei

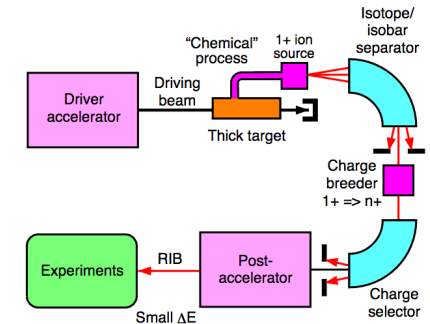
### IN-FLIGHT



**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

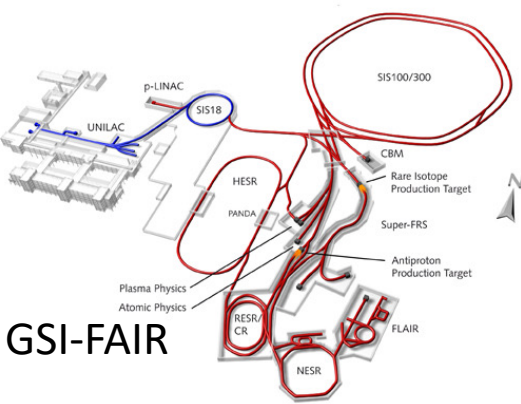


**spallation/fission/fragmentation** on thick targets, followed by chemical/physical processes to extract desired nuclei

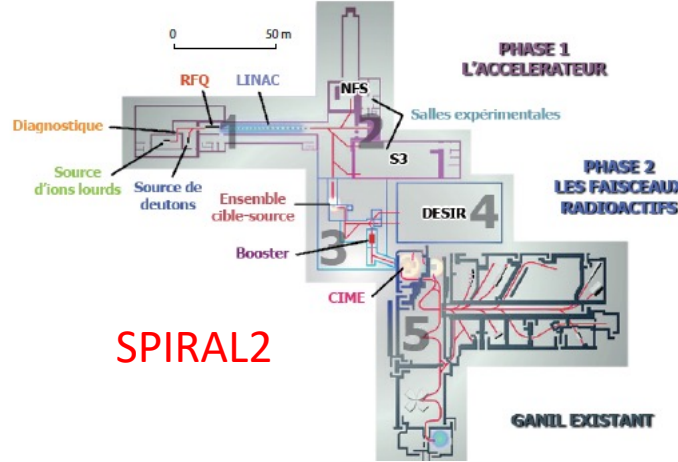
- beams produced at very low energies ( $\sim 60 \text{ keV}$ )
  - Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species  $\rightarrow$  usually long-living though
- + high cross section  
 + no need to re-accelerate beams  
 + high rates accepted
- short-living species might not be accessed easily
  - Refractory elements
  - Presence of long-living impurities (isobaric contamination)



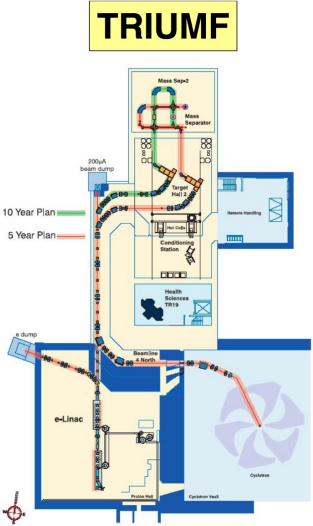
Examples of facilities all over the world...in-flight and isol



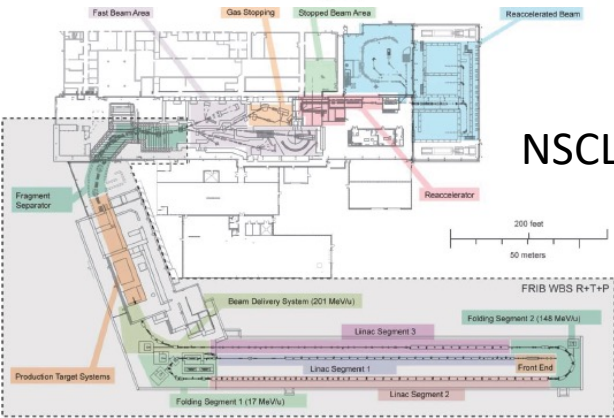
GSI-FAIR



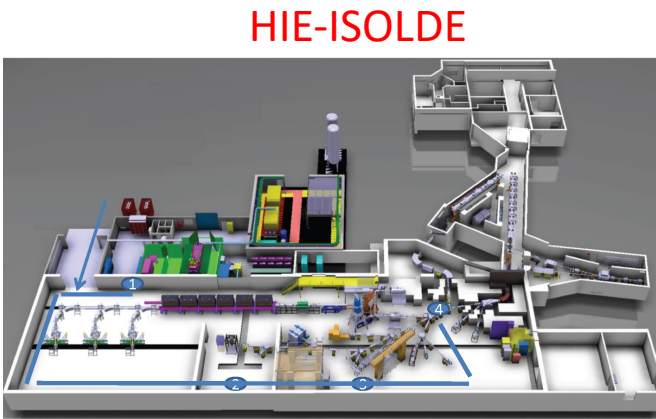
SPIRAL2



TRIUMF

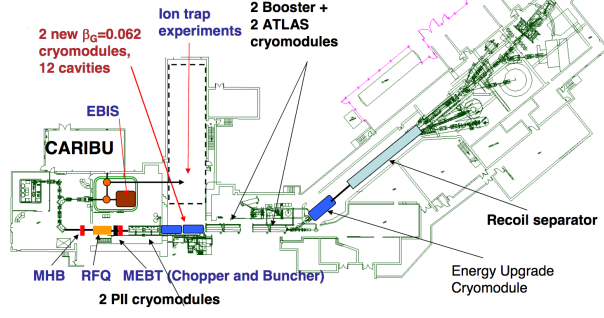


NSCL-FRIB

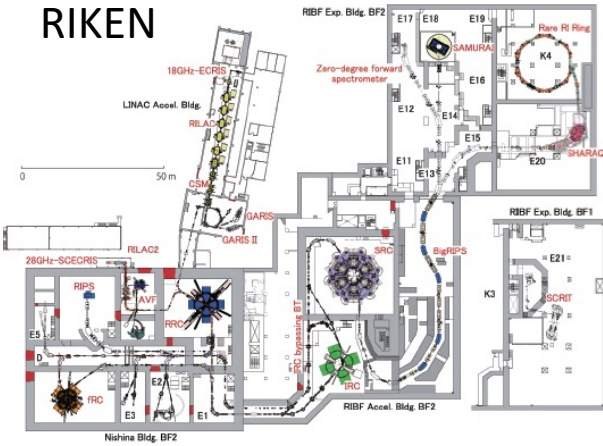


HIE-ISOLDE

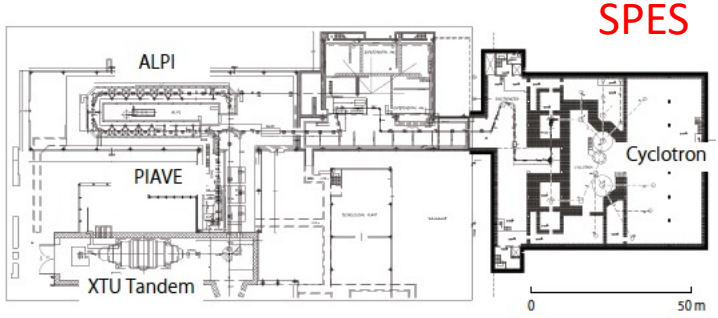
Increase intensity of stable beams from ATLAS by factor >10  
Increase intensity of CARIBU reaccelerated beams by > 5-10  
Increase intensity of in-flight radioactive beams by >100



RIKEN



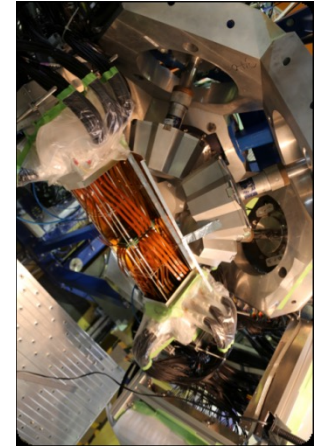
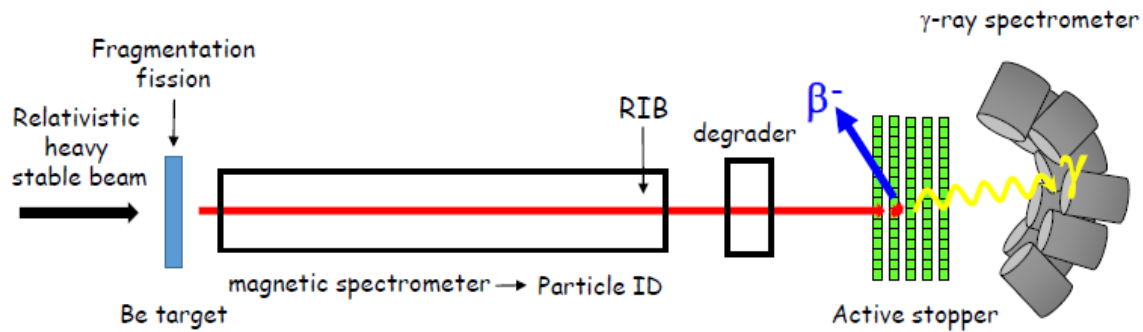
ALTO



SPES

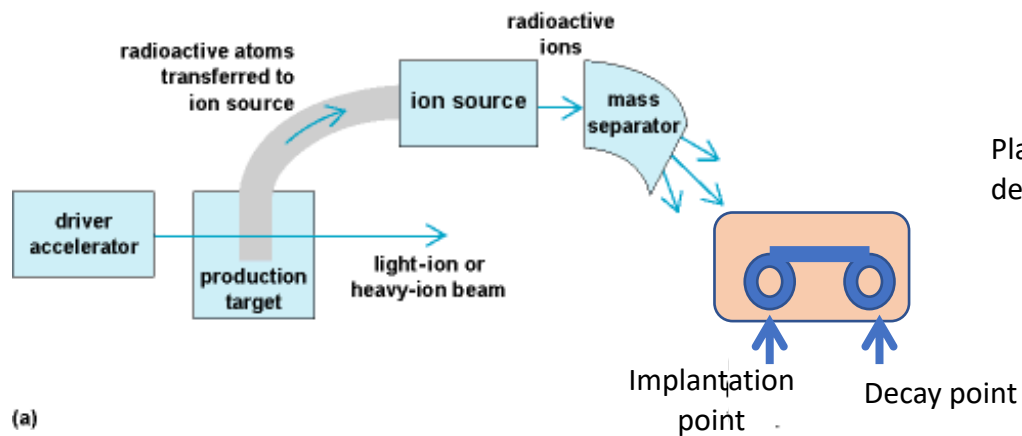
# General Properties of $\beta$ decay

## Measuring $\beta$ decay



Eurica@RIKEN

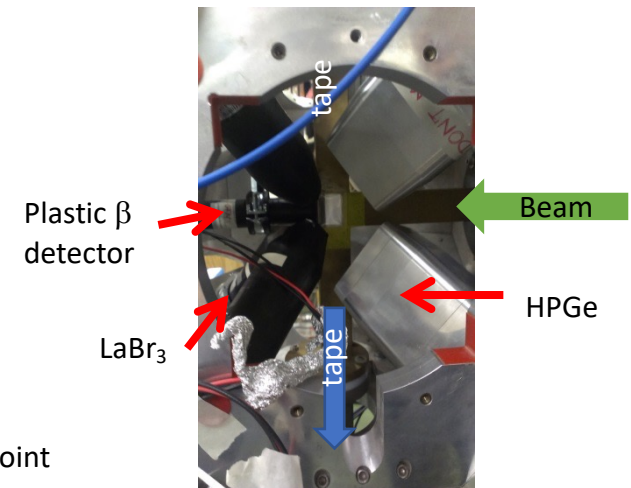
IN-Flight facility



(a)

ISOL facility

Tape decay stations

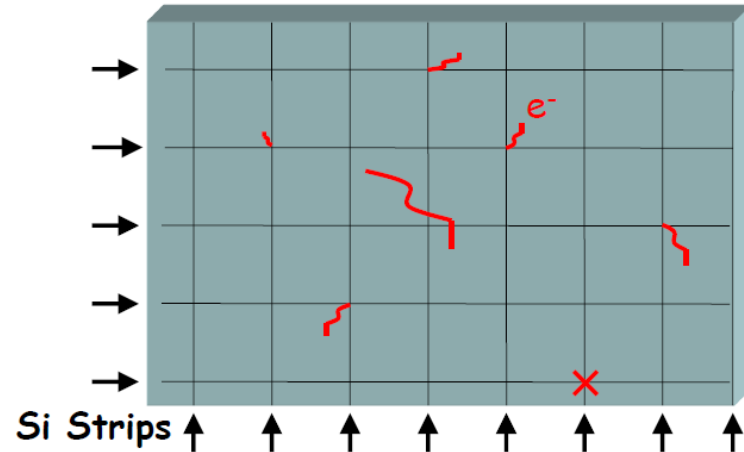


IDS @ CERN



# 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  $\beta$ -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  $\beta$

GSI

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

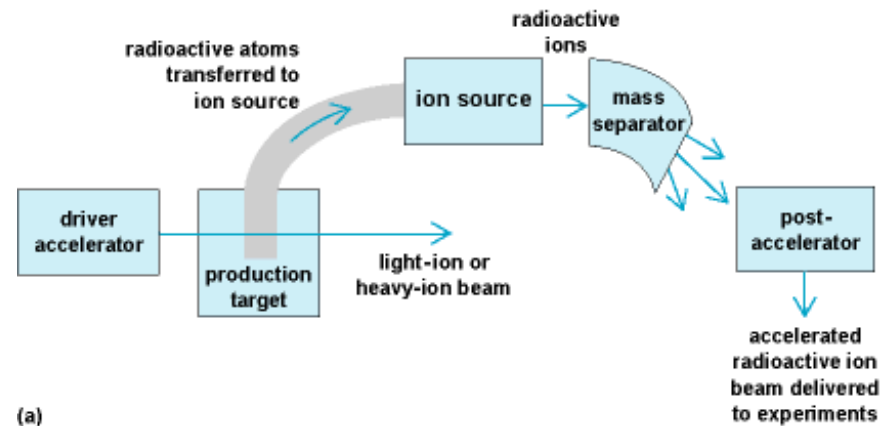
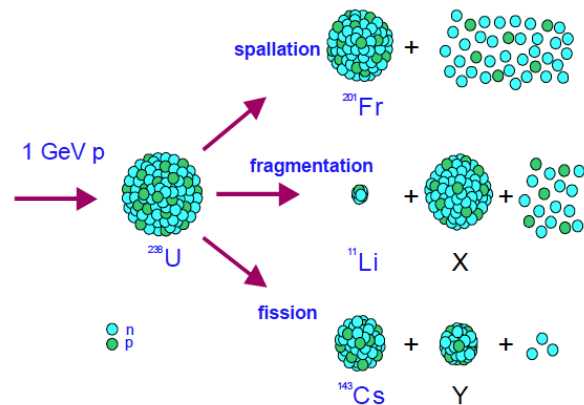
RIKEN

- \* Low gain branch for implanted ions
- \* High-gain branch for  $\beta$  and  $\alpha$  decays

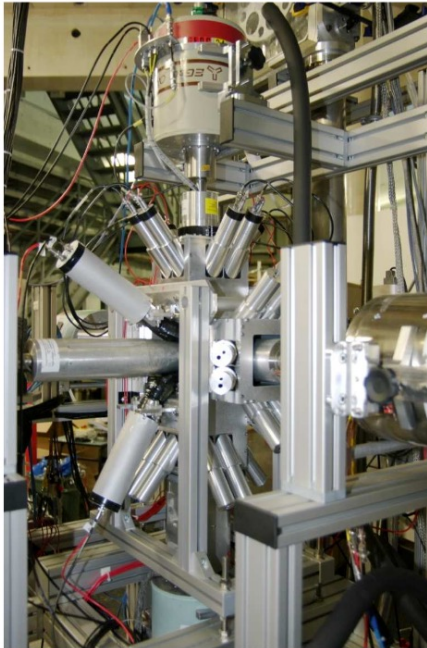
# ISOL: Isotope Separation On Line

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

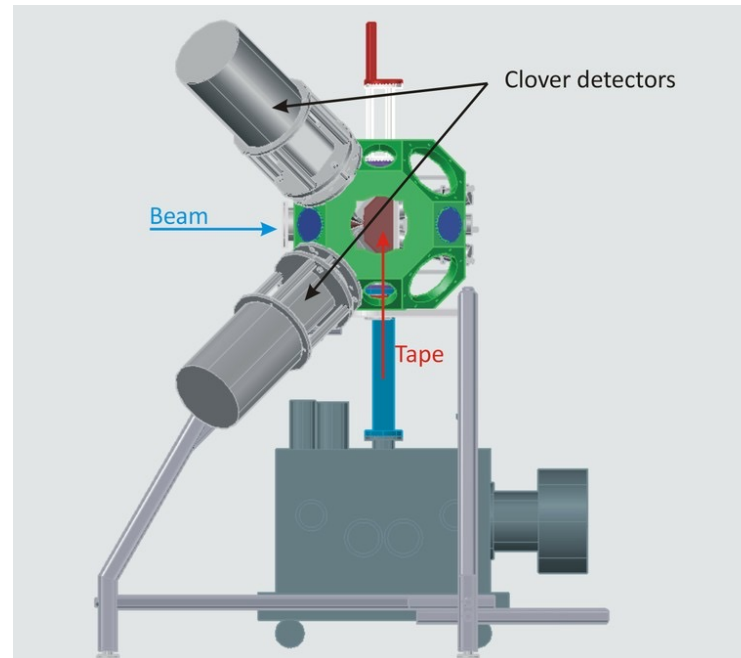


# TAPE Station systems



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  $\beta$  particles
- Trigger given by proton arrival and  $\beta$  signal
- Long-living activity is removed by moving away the tape
- NB: no direct signal of implantation

# Perspectives

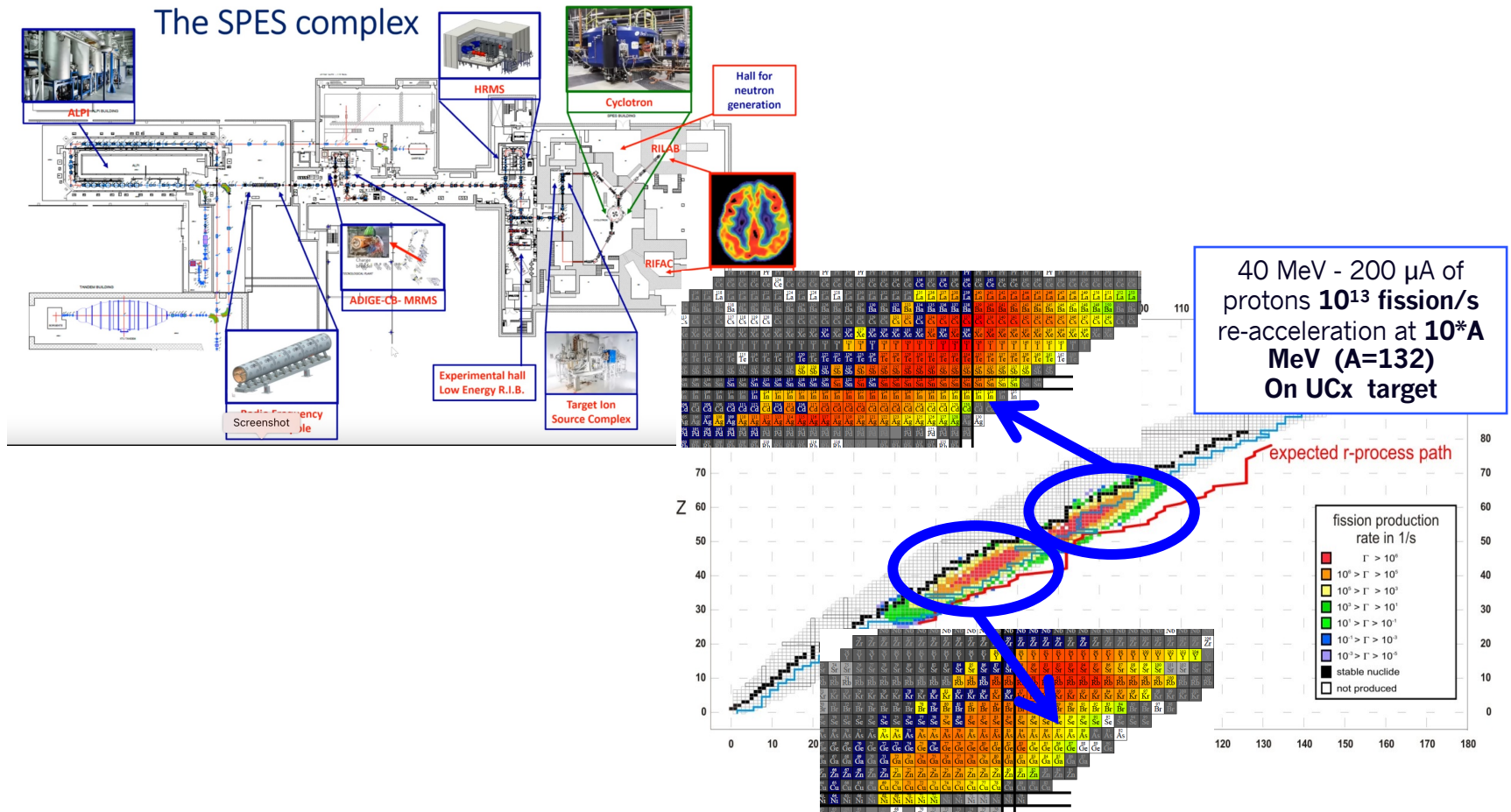
Decay of radioactive nuclei

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

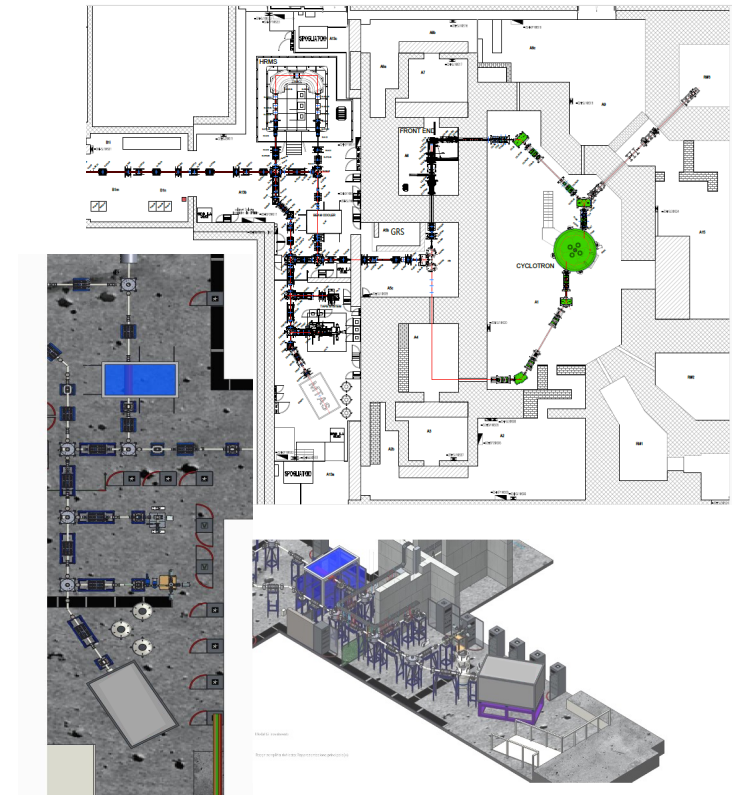
Area A13 in new SPES building dedicated to the installation of experimental set-up using low-energy beams from SPES

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

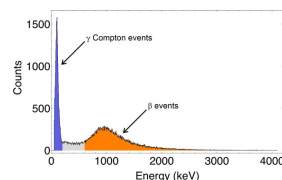
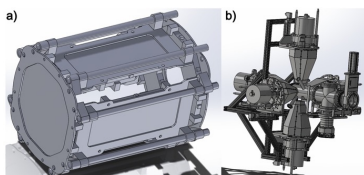
Experimental set-ups under test,  
waiting for green light for installation



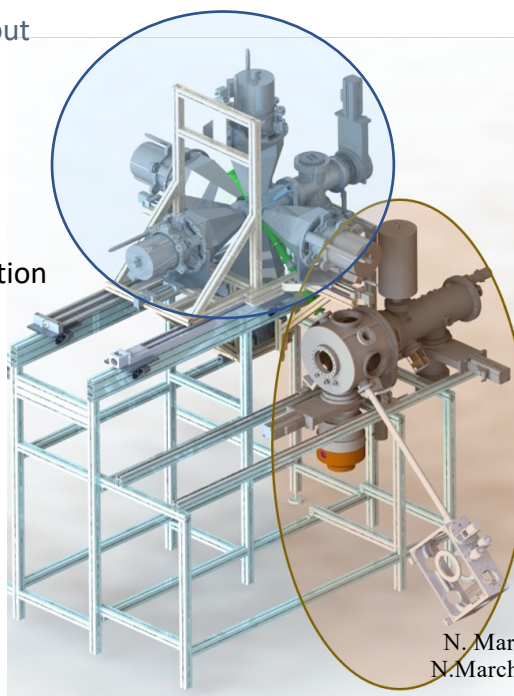
## Perspectives

### 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 (LaBr<sub>3</sub>(Ce))
- T<sub>1/2</sub>, decay scheme, Pn via  $\gamma$  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



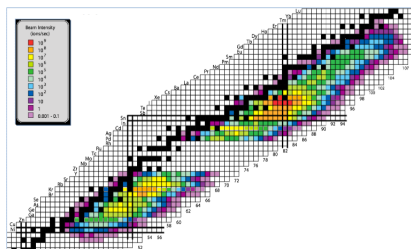
N. Marchini et al. PRC 105, 054304 (2021)  
N. Marchini et al. NIMA 1020, 165860 (2021)

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



## Perspectives

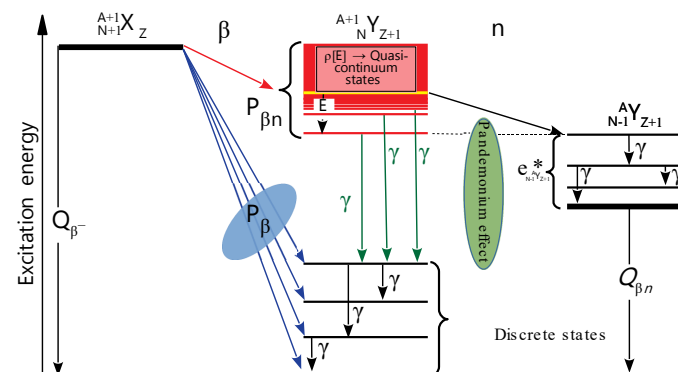
### Opportunities with existing/planned equipment



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  $\beta$  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

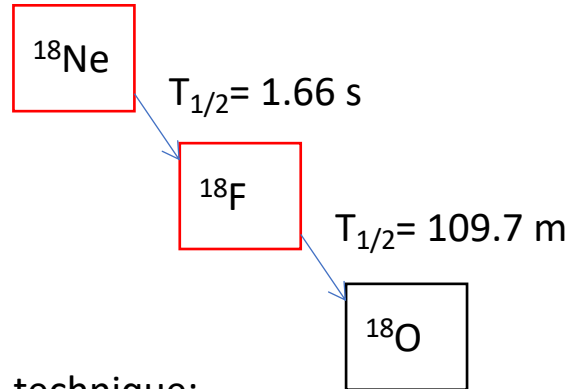


# Part III: Examples

PHYSICAL REVIEW C 87, 045502 (2013)

Improved half-life determination and  $\beta$ -delayed  $\gamma$ -ray spectroscopy for  $^{18}\text{Ne}$  decay

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



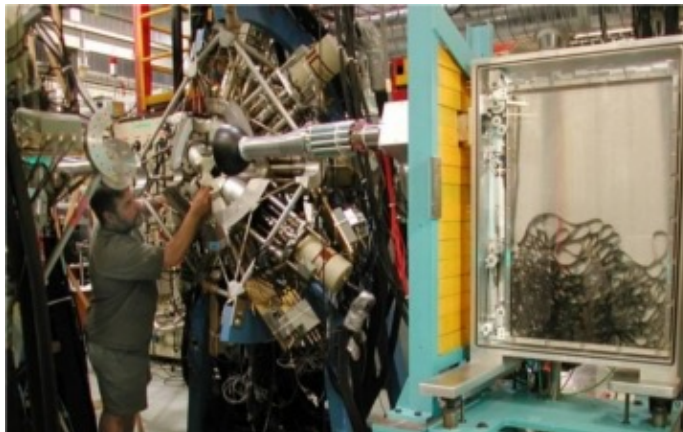
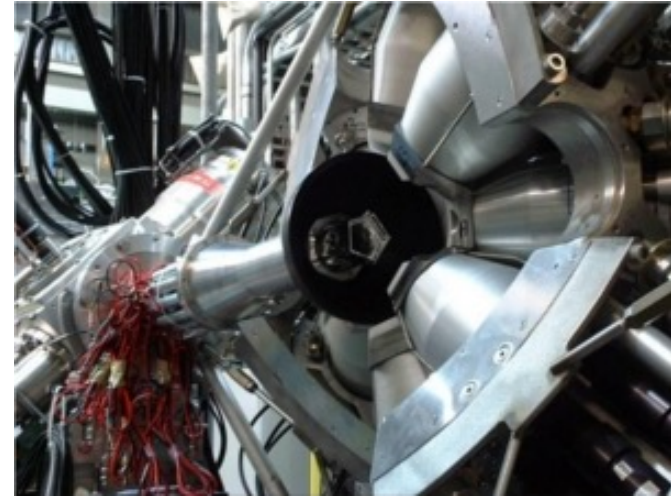
ISOL technique:

Protons @500MeV onto SiC target

$^{18}\text{Ne}$  +  $^{18}\text{F}$  contamination

$2 \times 10^6$  ions/s vs  $2.5 \times 10^7$  ions/s

Setup SCEPTAR+ $8\pi$  gamma spectr. @TRIUMF (CANADA) + Tape system



\* Scintillating Electron-Positron Tagging Array (SCEPTAR) consists of an array of 20 thin plastic scintillator beta detectors that surround the implantation point of the radioactive ion beam  
\*  $8\pi$  array of 20 high-purity germanium (HPGe) gamma-ray detectors that provides high-resolution measurements of the gamma rays emitted from excited states of the atomic nucleus.



# Part III: Examples

PHYSICAL REVIEW C 87, 045502 (2013)

Improved half-life determination and  $\beta$ -delayed  $\gamma$ -ray spectroscopy for  $^{18}\text{Ne}$  decay

Activity curve for 511 keV line:

Accumulation/decay:

Composite curve since it has contributions from  $^{18}\text{Ne} + ^{18}\text{F} + \text{constant bg}$

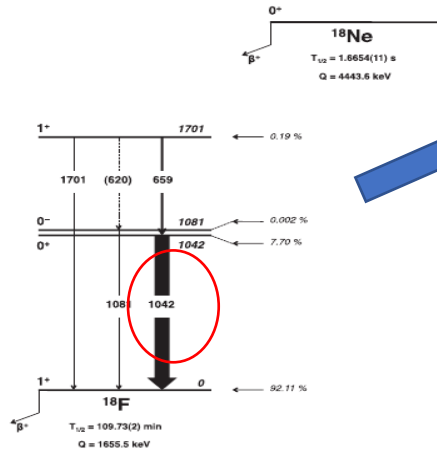
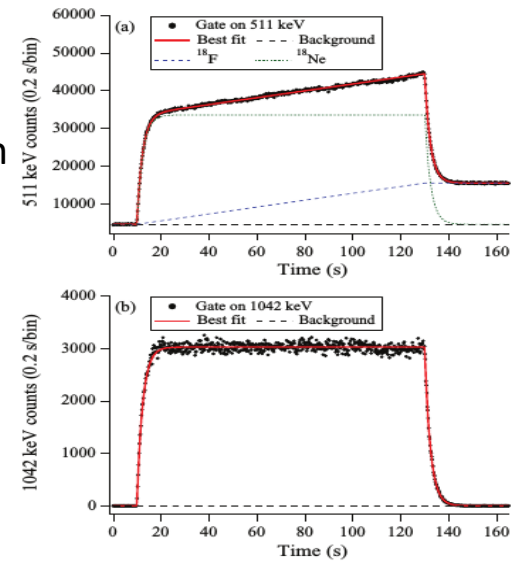
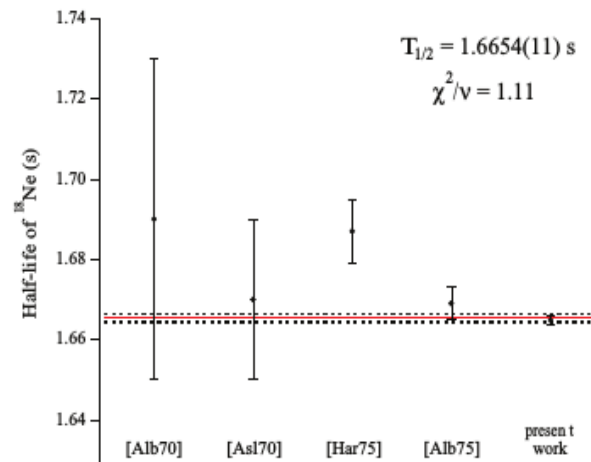


FIG. 1. Decay-level scheme of  $^{18}\text{Ne}$ .



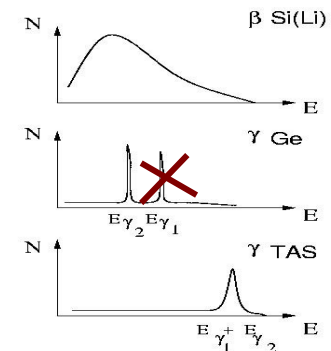
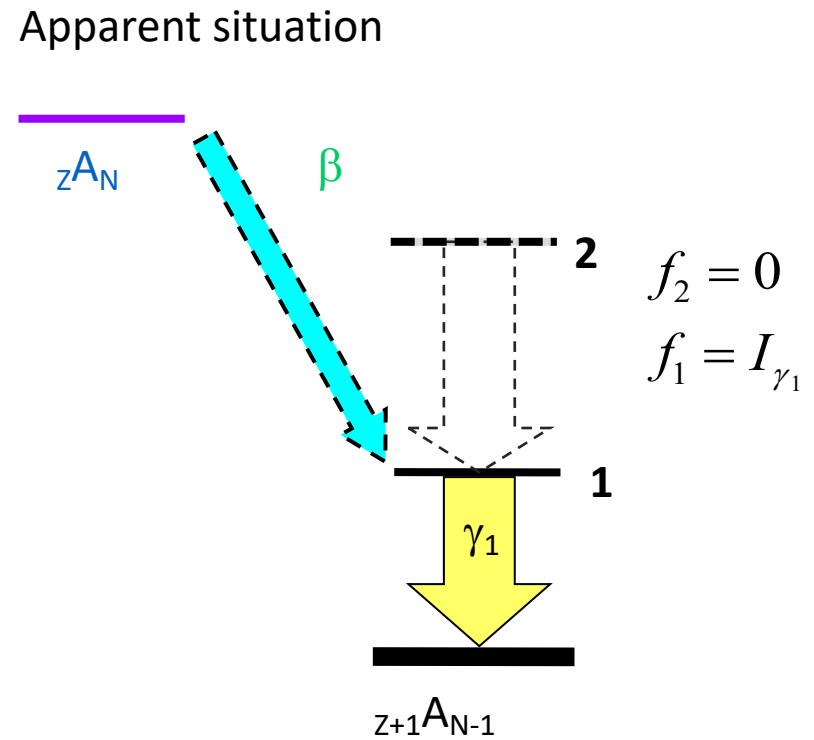
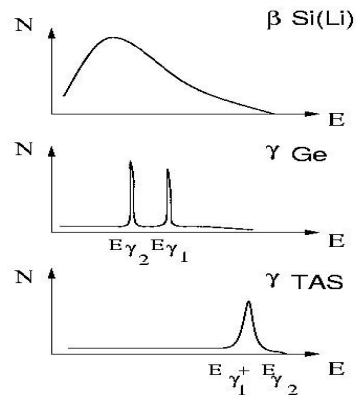
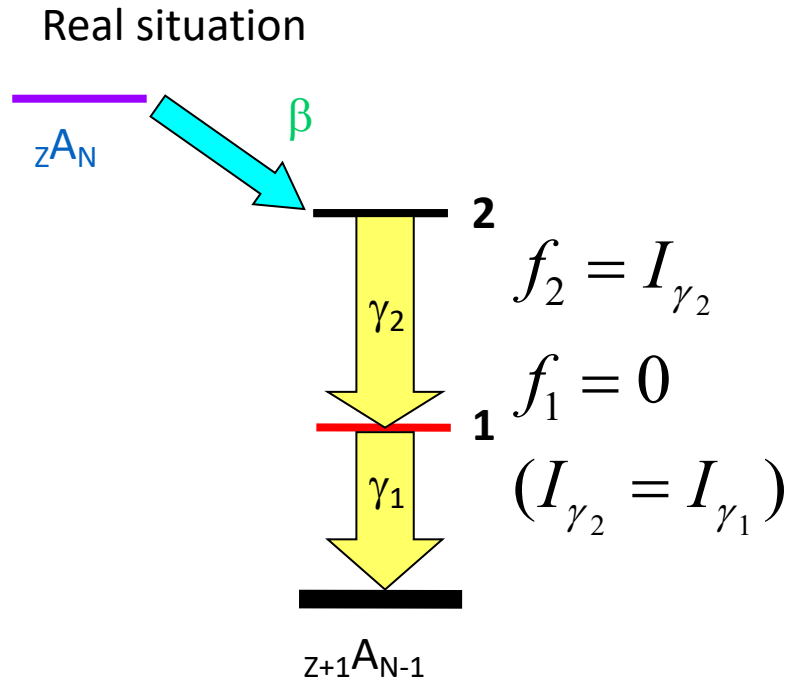
Gating on a specific  $\gamma$  line of the daughter nucleus cleans the spectrum  
 ➔ only contributions from wanted decay

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

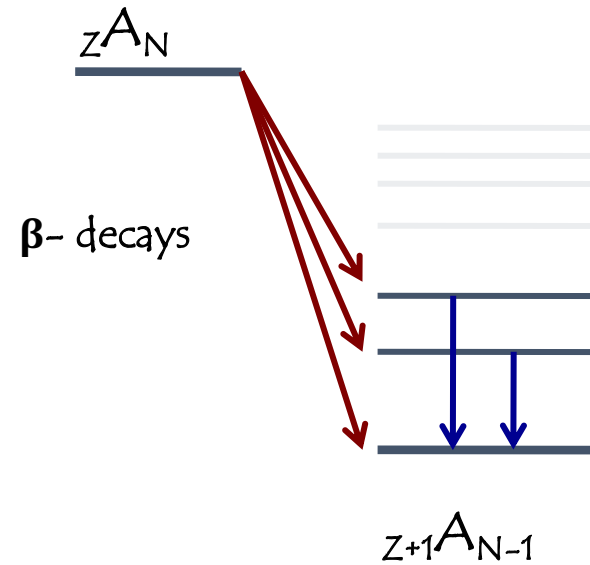
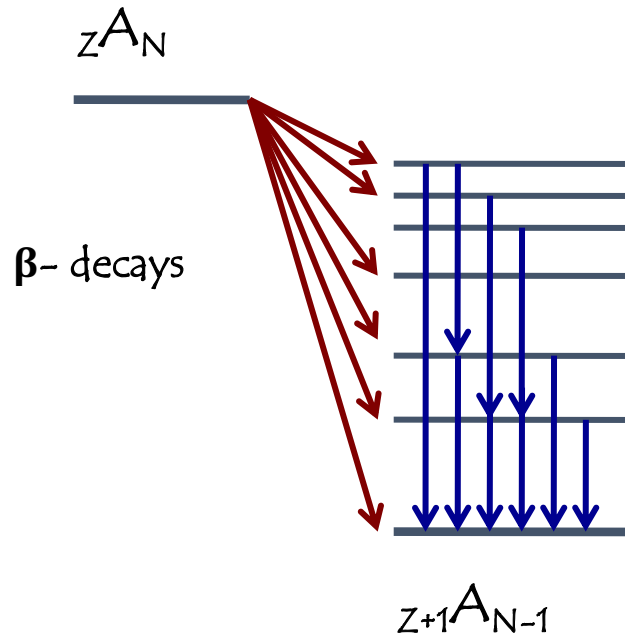
- Better reduction of contaminants
- Higher efficiency and selectivity
- Faster electronics

# General Properties of $\beta$ decay

## Pandemonium effect

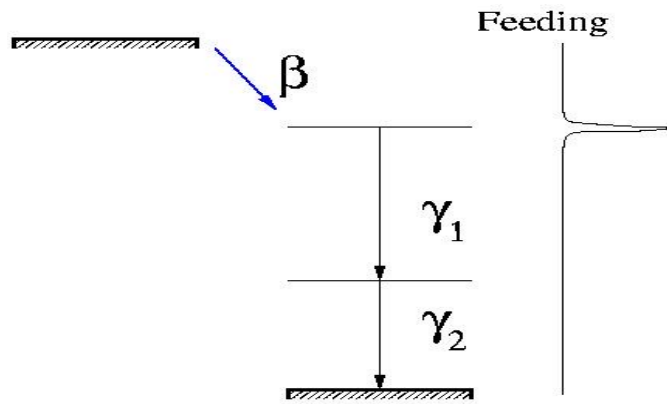


# General Properties of $\beta$ decay



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

# Total Absorption Gamma Spectrometer measurements



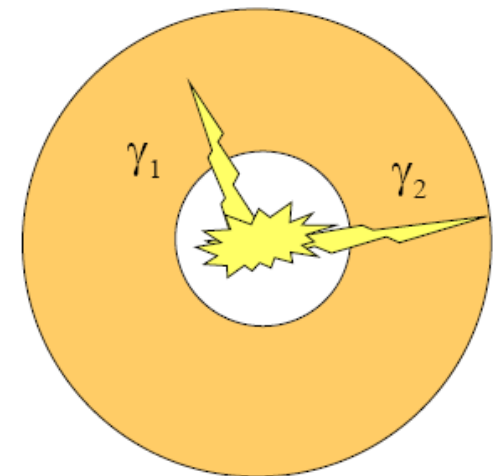
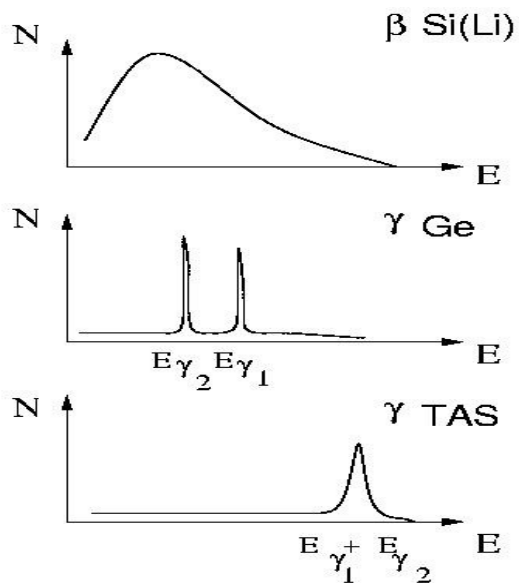
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

## A TOTAL ABSORTION SPECTROMETER

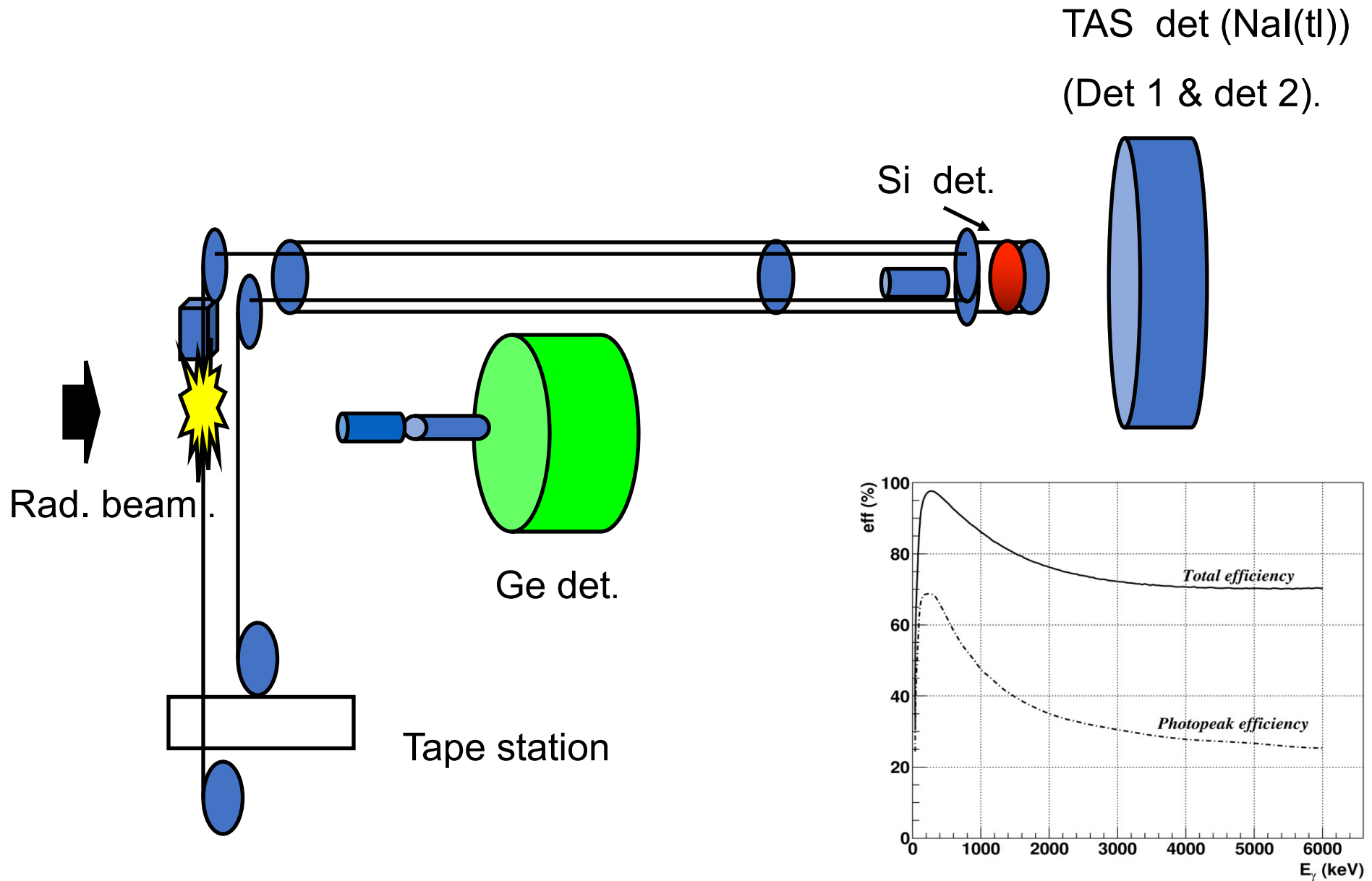
Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

A TAS is a **calorimeter**!

Big crystal,  $4\pi$  (BaF<sub>2</sub>/NaI/HPGe)

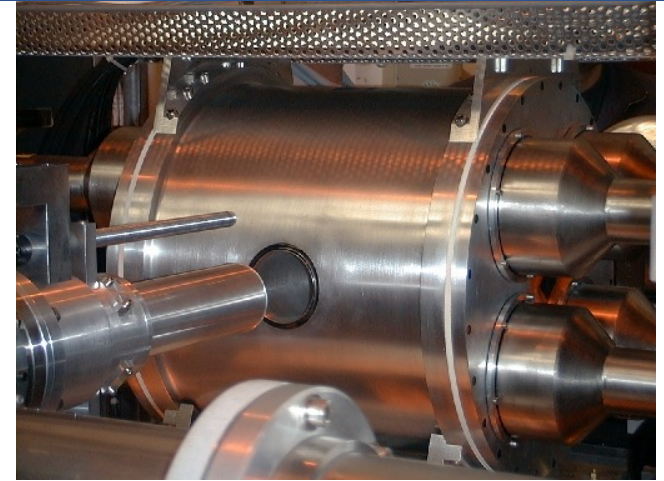
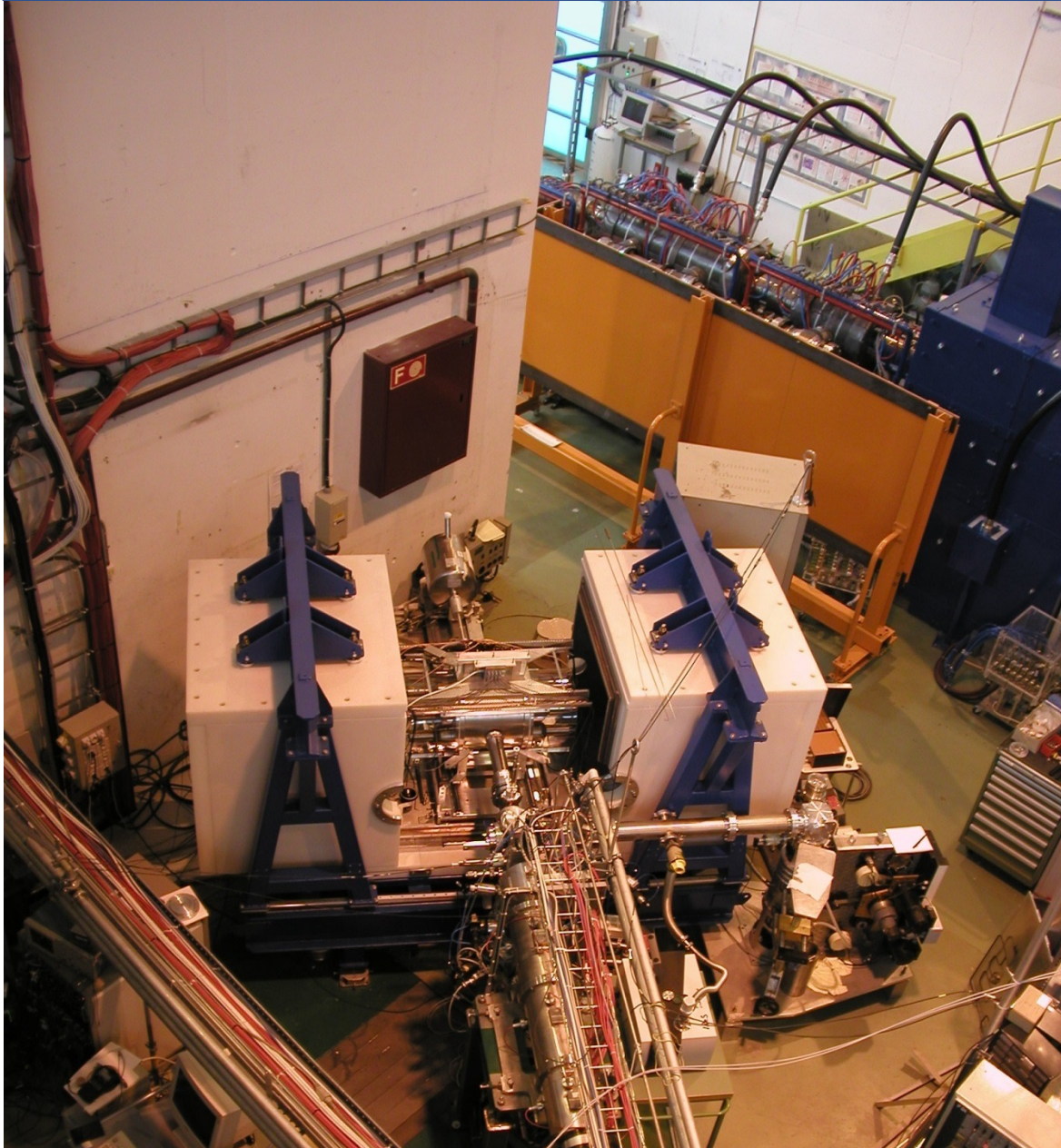


# TAS experimental setup

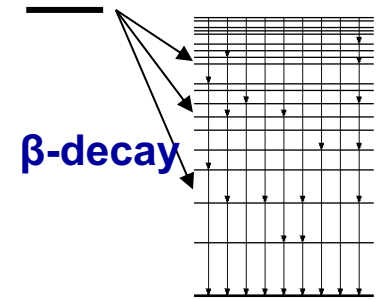




# Lucrecia: the TAS at ISOLDE (CERN) (Madrid-Strasbourg-Surrey-Valencia)



- A large NaI cylindrical crystal 38 cm Ø, 38cm length
- An X-ray detector (Ge)
- A  $\beta$  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

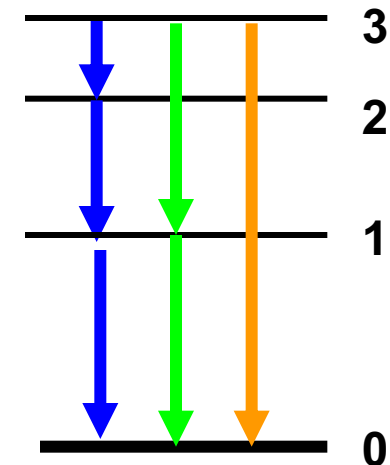
The response matrix  $\mathbf{R}$  can be constructed by recursive convolution:

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

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

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

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

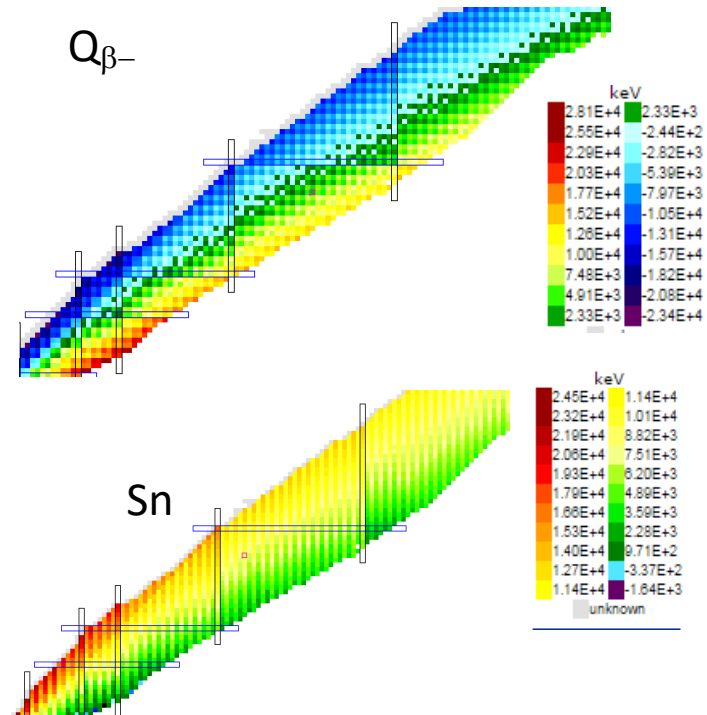
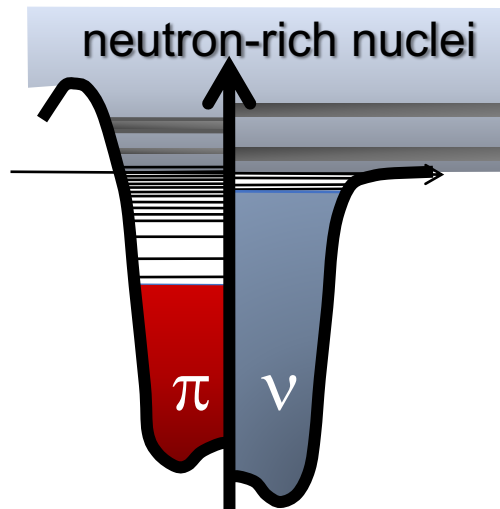




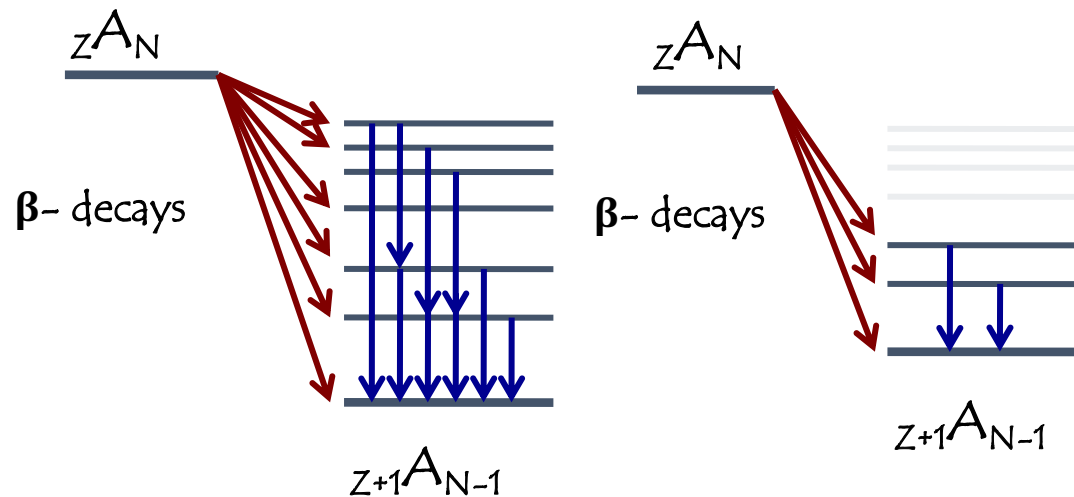
# $\beta$ Decay in Exotic Nuclei

Going away from stability

- Shortening of half-lives
- Increasing  $Q_{\text{value}}$
- 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



# Beta decay studies of the most exotic nuclei

Giovanna Benzoni

INFN sezione di Milano (Italy)

Outline of the lessons:

PARTI: General concepts

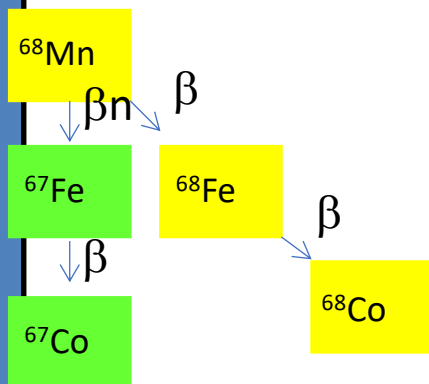
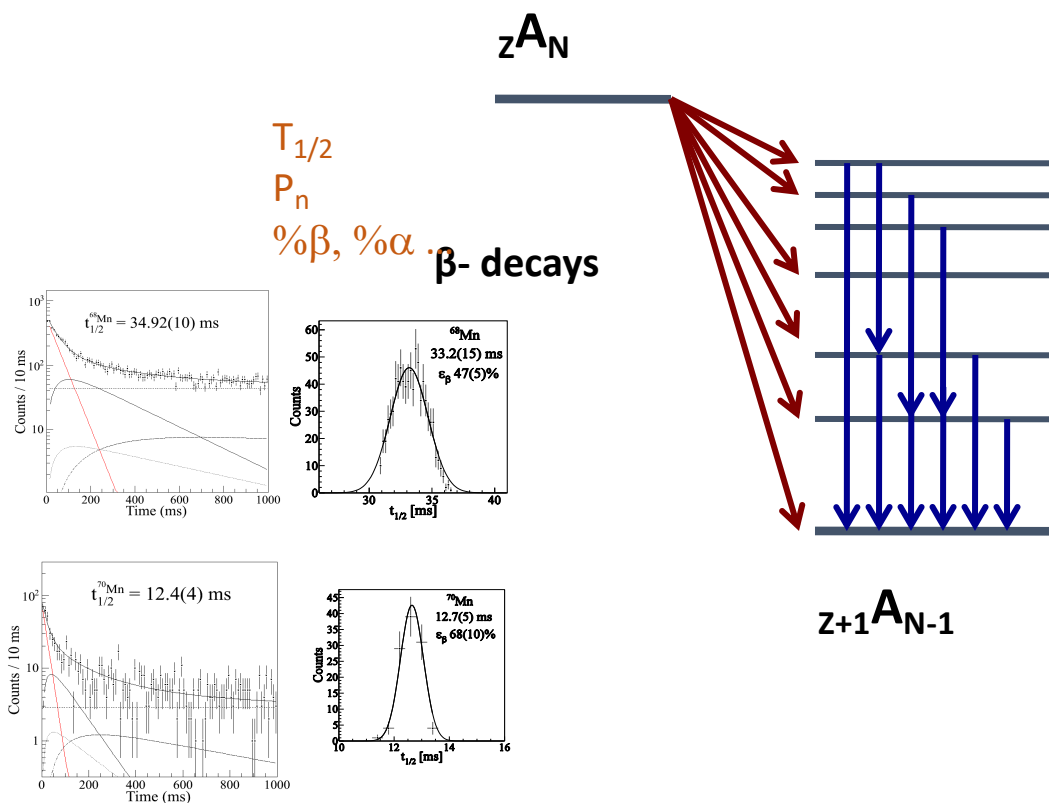
How to measure  $\beta$  decay in exotic nuclei

**PARTII:  $\beta$  decay Gross properties  $T_{1/2}$  and  $P_n$**

PARTIII: High resolution vs TAS

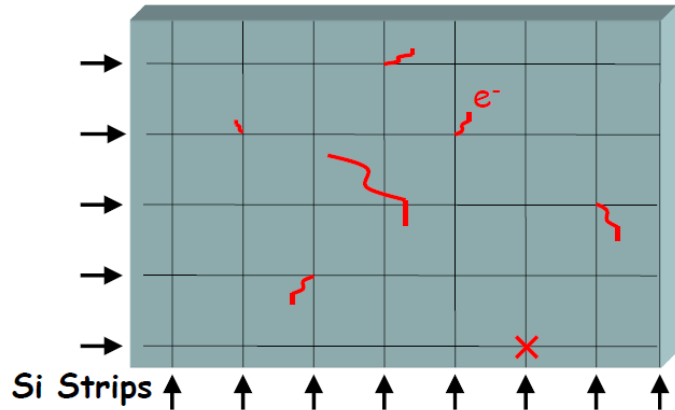
# General Properties of $\beta$ decay

Quantities that can be extracted in a  $\beta$  decay experiment

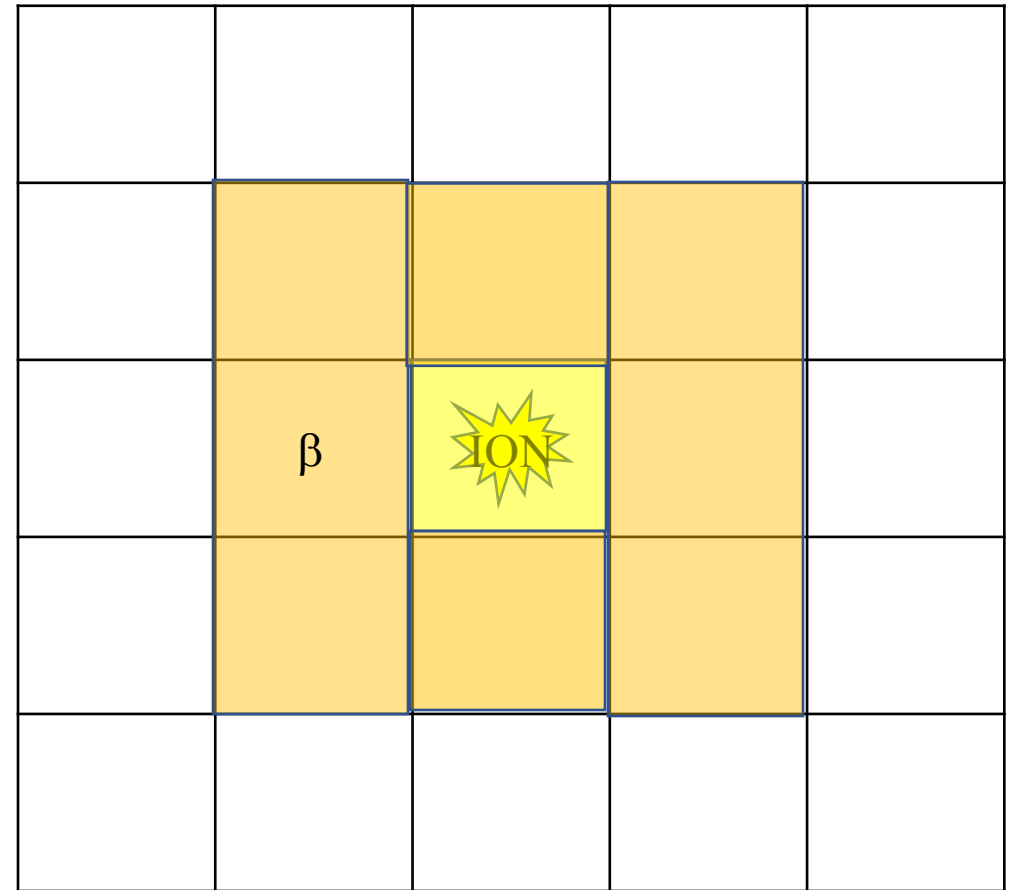


# Measuring short half-lives

Focal plane implantation detector sensitive to electron emission



The waiting time between particle implantation and  $\beta$ -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.



- Limit Ion rate
- Time and space ion- $\beta$  correlations
- 2 options:
  - Wait for 1<sup>st</sup>  $\beta$  particle
  - Consider all following  $\beta$  up to next implantation
- $\Delta T(\text{Ion} - \beta)$  is  $T_{1/2}$

# Measuring short half-lives

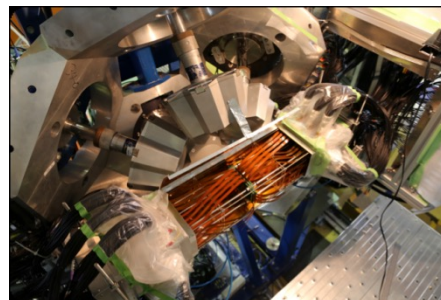
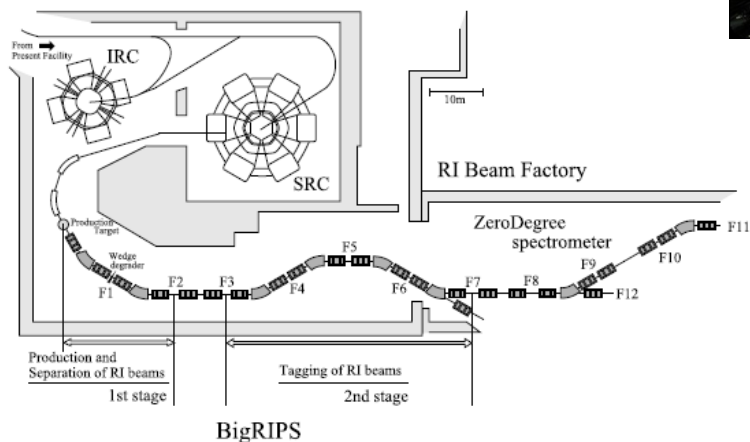


3 days of beamtime

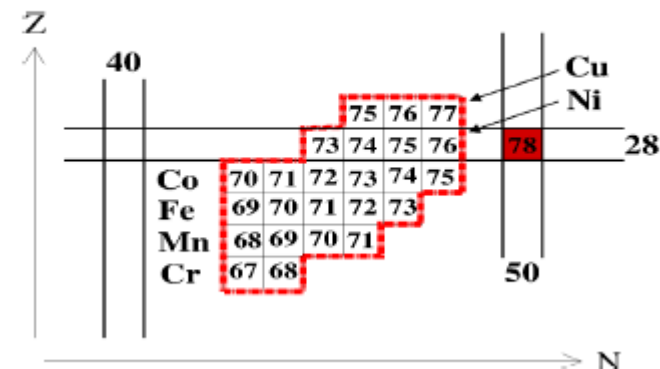
$^{238}\text{U}$  @ 345 MeV/u

$I_{\text{beam}} \sim 10$  pA

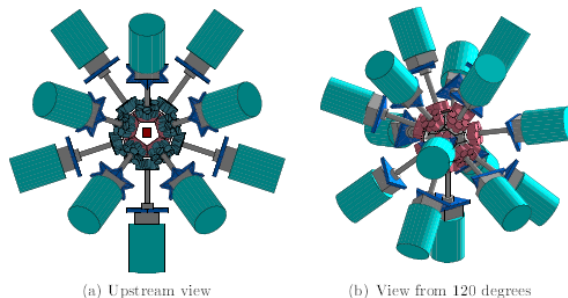
BigRIPS setting focused on  $^{71}\text{Fe}$



5 DSSSD - WAS3ABI  
(64X40 strips)  
Ion-beta correlations



12 HPGe Clusters  
 $\beta$ - $\gamma$  correlations



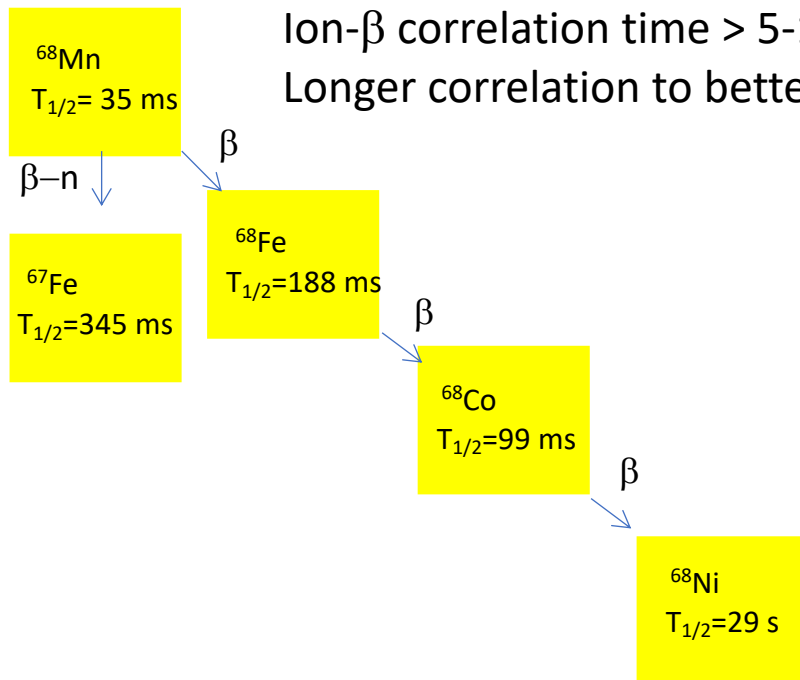
(a) Upstream view

(b) View from 120 degrees

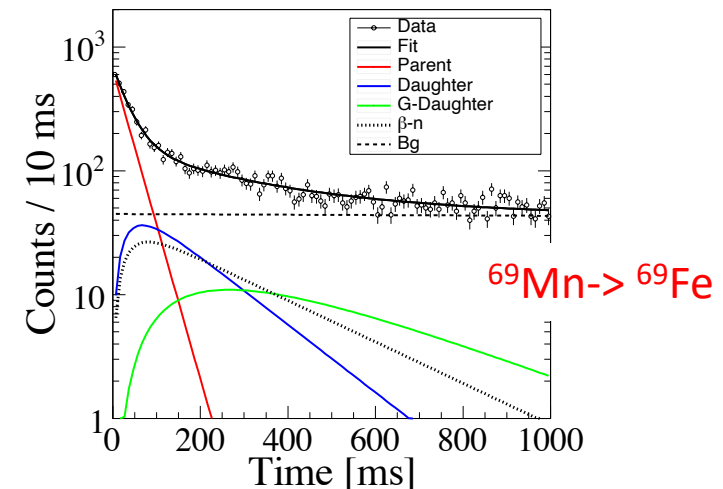
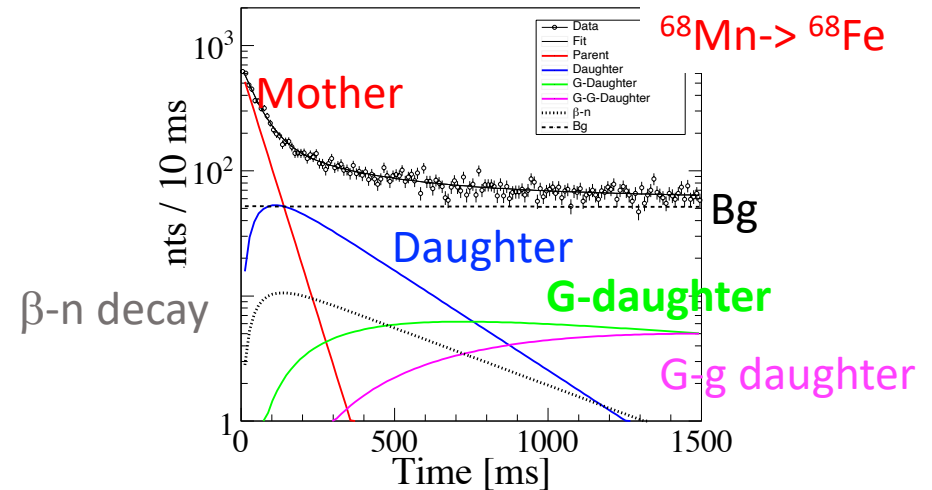


18  $\text{LaBr}_3(\text{Ce})$  (1.5" x 2")  
2 BC-418 Plastic 2mm thick  
Fast-timing measurements

# Measuring short half-lives



Ion- $\beta$  correlation time  $> 5\text{-}10 \times T_{1/2} \rightarrow$  need to include decay chain  
 Longer correlation to better estimate the bg  $\rightarrow$  include more decays

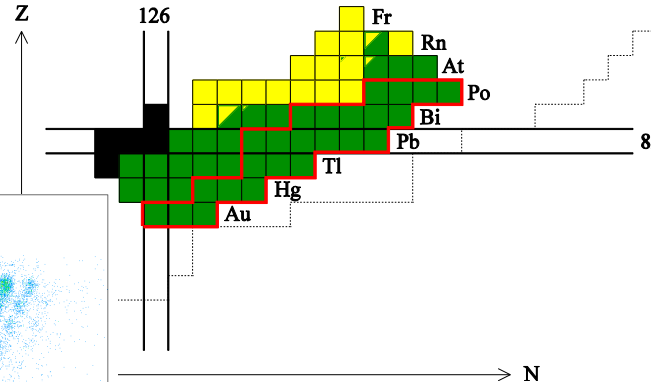
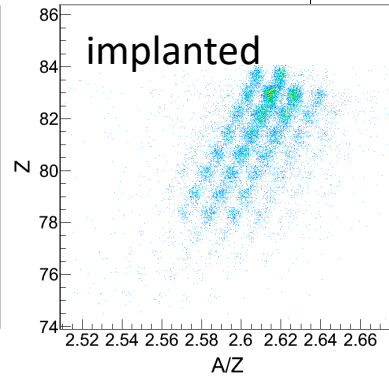
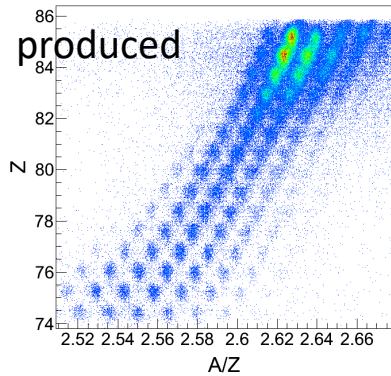
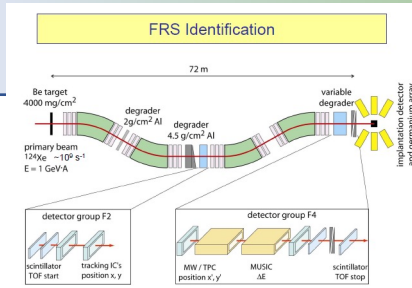


|                  | $N_{\text{ions}}$ | $T_{1/2}$ (ms) exp | Ref       | FRDM [3] |
|------------------|-------------------|--------------------|-----------|----------|
| $^{68}\text{Mn}$ | $7.7 \cdot 10^3$  | 34.92(10)          | 40(7) [1] | 12.8     |
| $^{69}\text{Mn}$ | $5 \cdot 10^3$    | 22.20(9)           | 18(4) [2] | 12.9     |
| $^{70}\text{Mn}$ | 500               | 12.4(4)            |           | 9        |

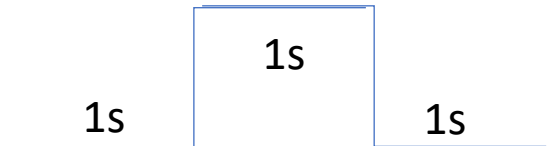
- [1] S.N.Liddick et al., PRC 87, 014325 (2013).
- [2] J.M.Daugas et al., PRC 83, 054312 (2011)
- [3] P.Moller, B.Pfeiffer and K.-L. Kratz, Phys.Rev. C 67, 055802 (2003)

# Measuring long half-lives

Fragmentation of  $^{238}\text{U}$  beam @ 1 GeV/u  
 $I_{\text{beam}} \sim 3 \cdot 10^9$  pps  
 Beam extraction 1s, beam cycle 3s

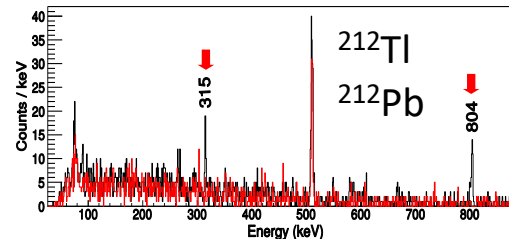
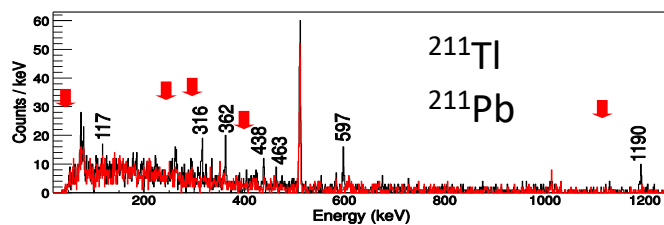
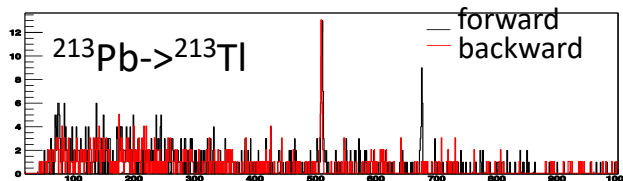


Spill structure @ GSI extraction



WARNING: long lifetimes and high rates imply a careful study of bg contributions

- ion-β correlations : out of beam + ion-β position correlations + ion-β time correlations
- uncorrelated decays determined from backward-time ion-β correlations



New spectroscopic information in  $^{219}\text{Po}$   $^{211-212-213}\text{Tl}$



# Ad-hoc numerical procedure

- Long half-lives → cover many beam repetition cycles
- High rate → possible double implantations

Standard techniques are not available

→ numerical fit based on Monte Carlo simulations of the implantation-decay process including experimental implantation rates and having as free parameters the  $\beta$  decay half life and the  $\beta$  detection efficiency

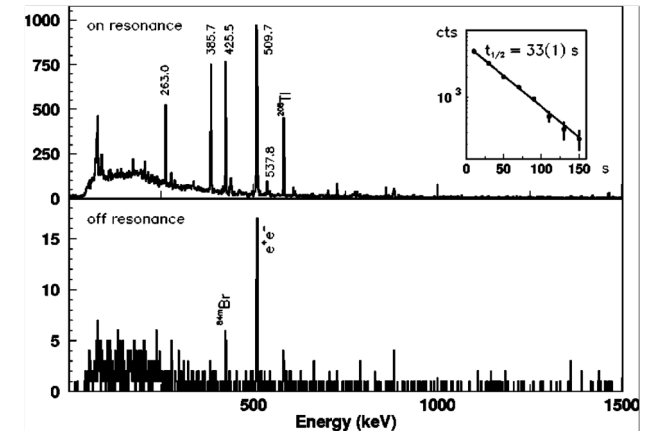
*T. Kurtukián-Nieto et al., NIMA (2008)*

$\chi^2$  fits to two independent time correlations:

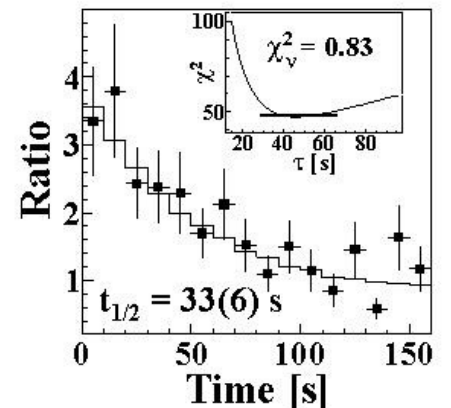
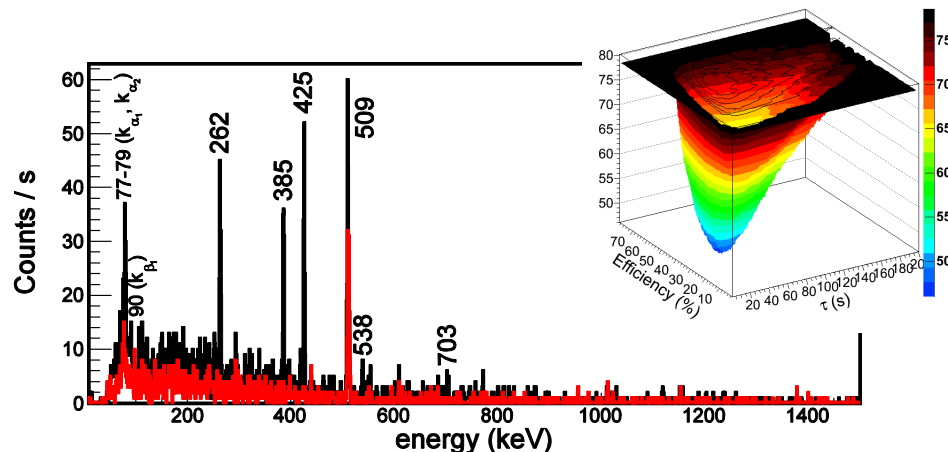
- Experimental ion- $\beta$  time-correlated spectra
- Calculated time distribution obtained from Monte-Carlo simulations

Fitting function: ratio of forward/backward time-distribution functions

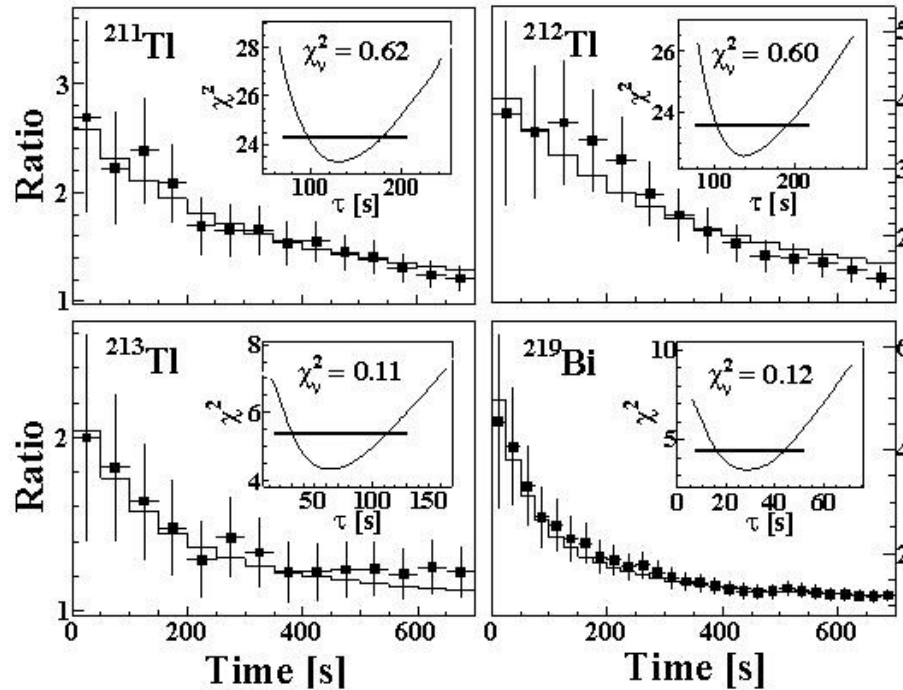
## $^{218}\text{Bi}$ : Benchmark of Analysis



H. de Witte et al., PRC (2004)

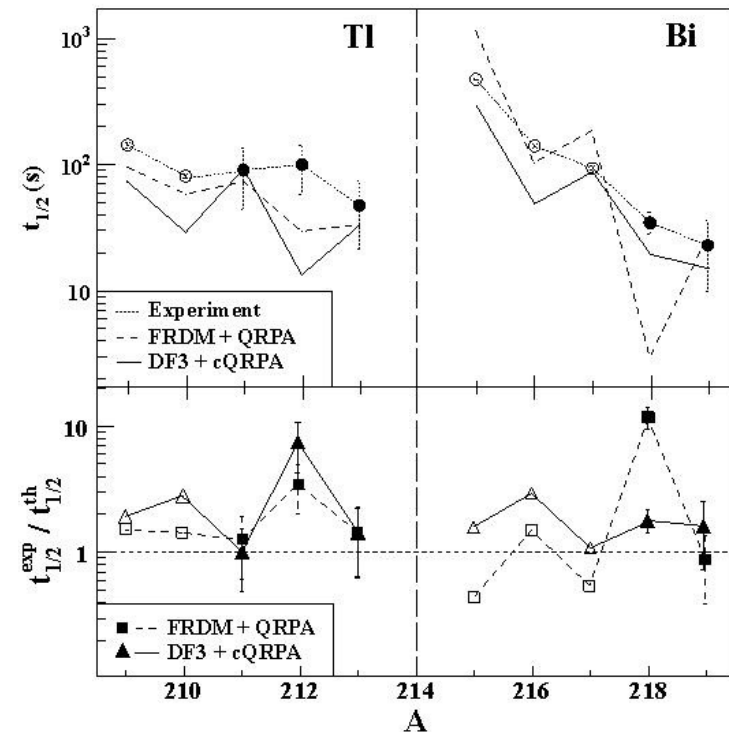


# Important results in heavy mass region



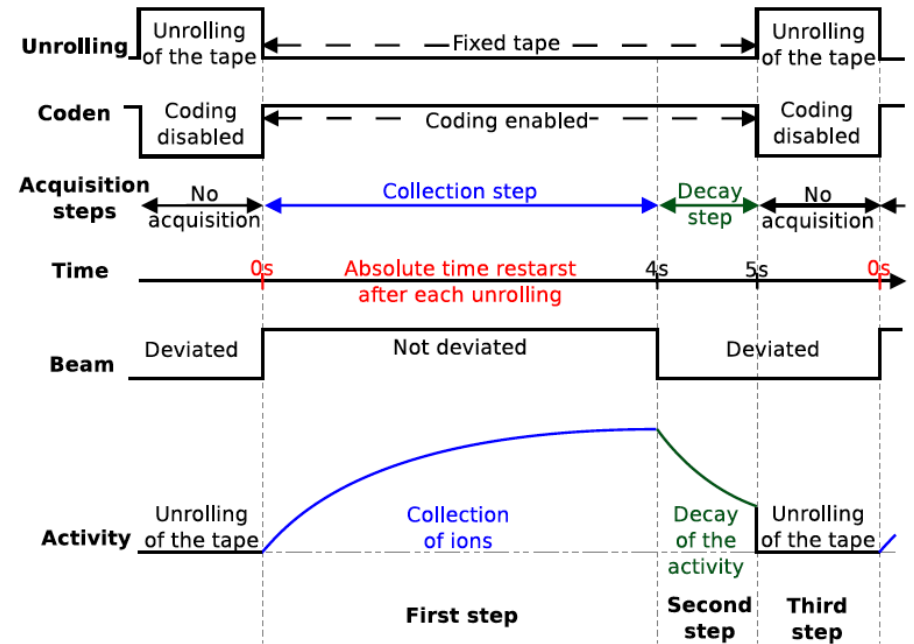
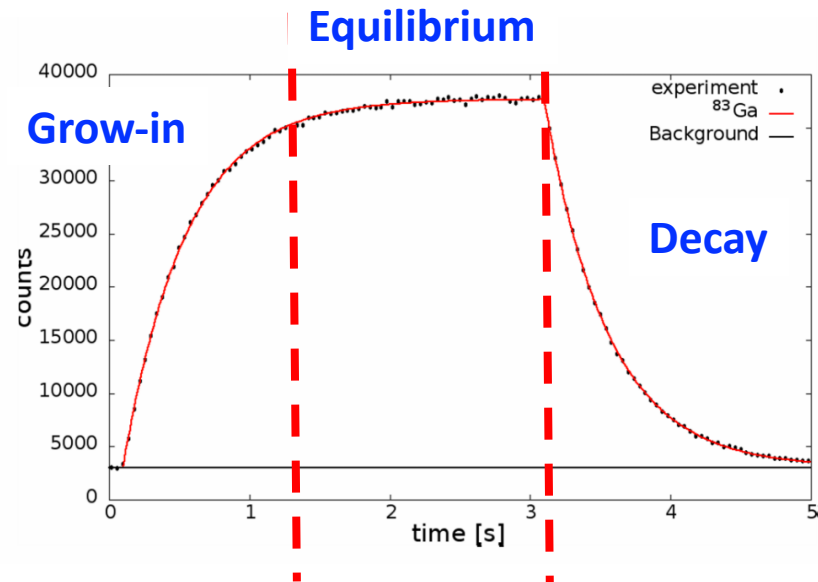
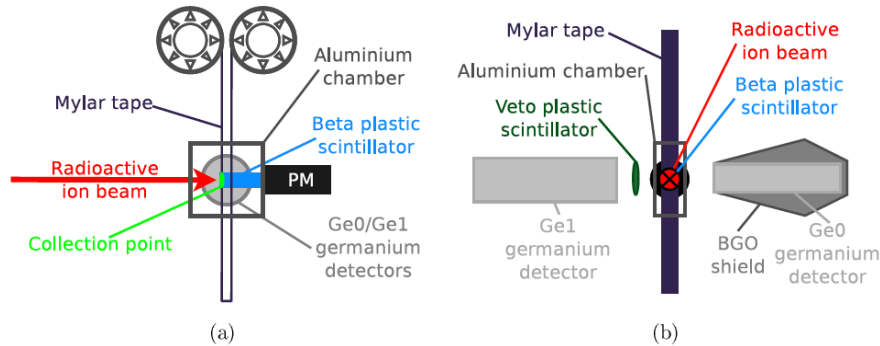
FRDM+QRPA and DF3 + QRPA models in agreement with our measurements

The description of first-forbidden (ff) transitions using macroscopic statistical models seems a good approach for these nuclei at variance from  $N < 126$  nuclei

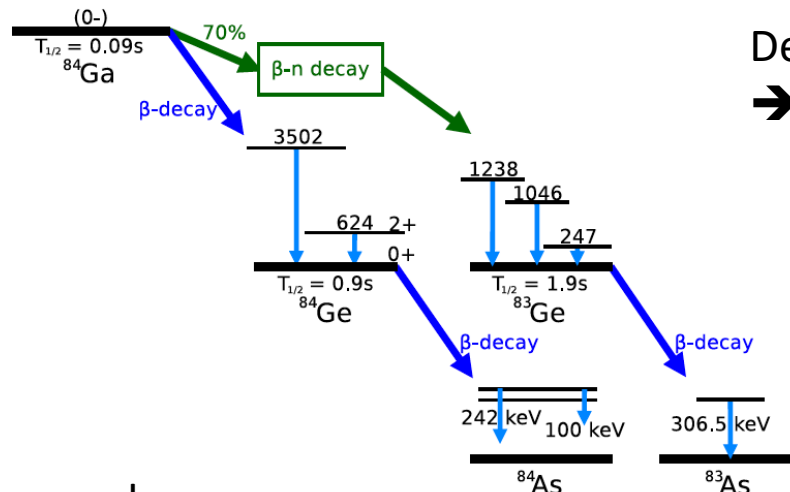


G.Benzoni et al., PLB 715 (2012) 293  
 A.I.Morales et al., PRC89, 014324 (2014)  
 A.I.Morales et al., PRL113, 022702 (2014)

# Measuring half-lives with tape system

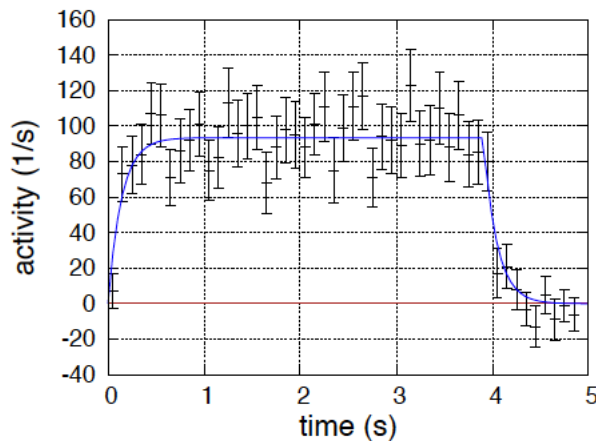


# Measuring half-lives with tape system



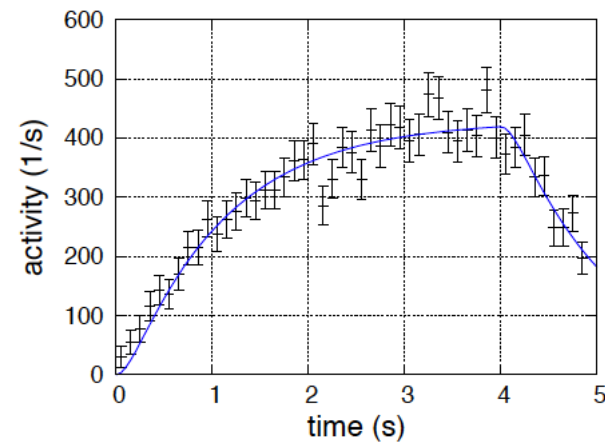
Decay curve can have many components  
 →  $\gamma$  gating helps singling out

Activity of daughter nucleus  
 → Measuring  $T_{1/2}$  of mother



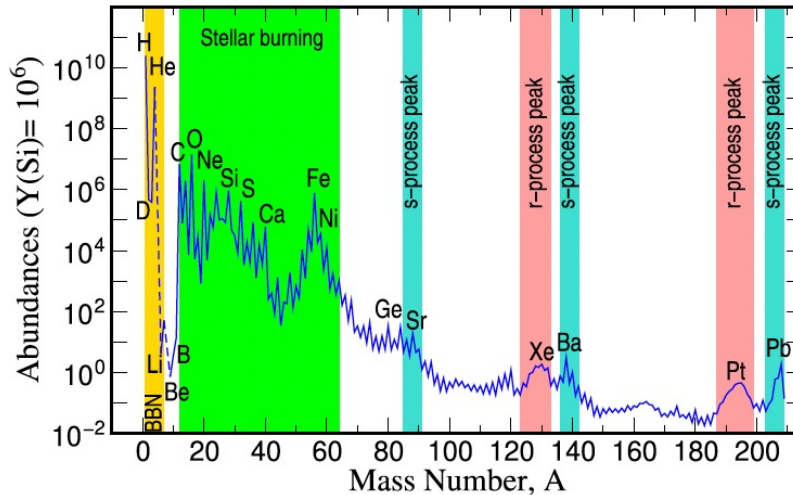
(a) 624 keV

Activity of grand-daughter nucleus



(c) 242 keV

# Nucleosynthesis: Element formation in Stars

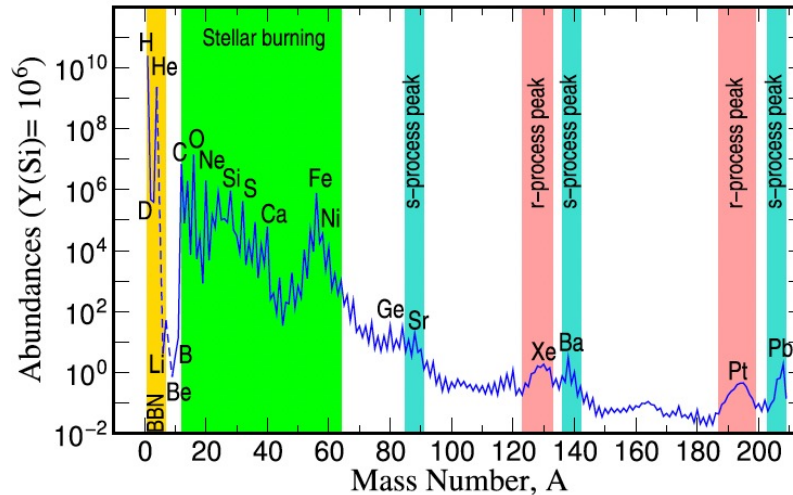


2 sets of data:

- Spectral analysis of Sun
- Direct measurement of chemical elements on Earth, Moon, asteroids, interstellar medium

Spectra line analysis based on element- specific spectral emission lines following atomic de-excitation

# Nucleosynthesis: Element formation in Stars



## Main Features:

- H/He most abundant
- Light elements up to  $A \sim 50$  ( $^{56}\text{Fe}$ )
- Lower abundance for elements  $A > 50$ , with abundance peaks appearing at specific  $A$  values

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# Nucleosynthesis: Element formation in Stars

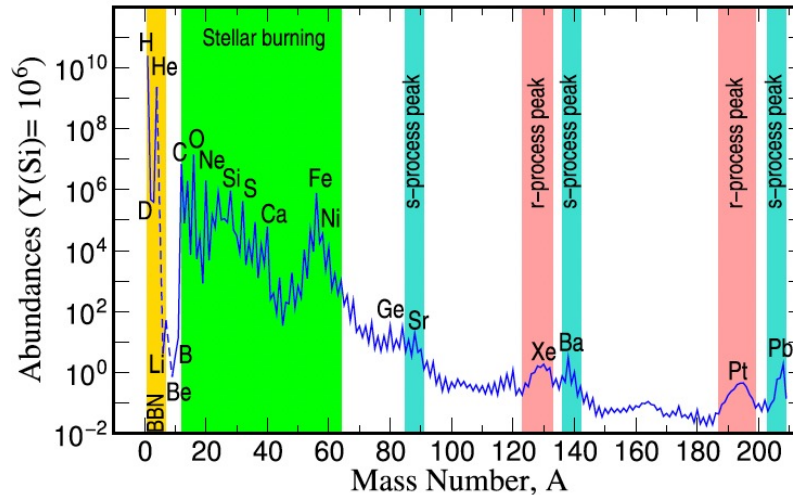
Decay of radioactive nuclei

Element formation in stars

Example of measurements of  $\beta$ -decays

Perspectives

Conclusions



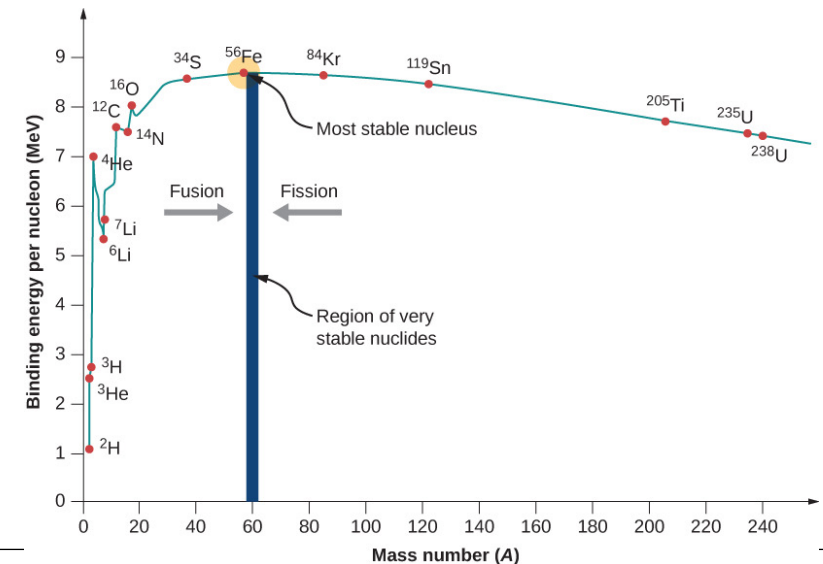
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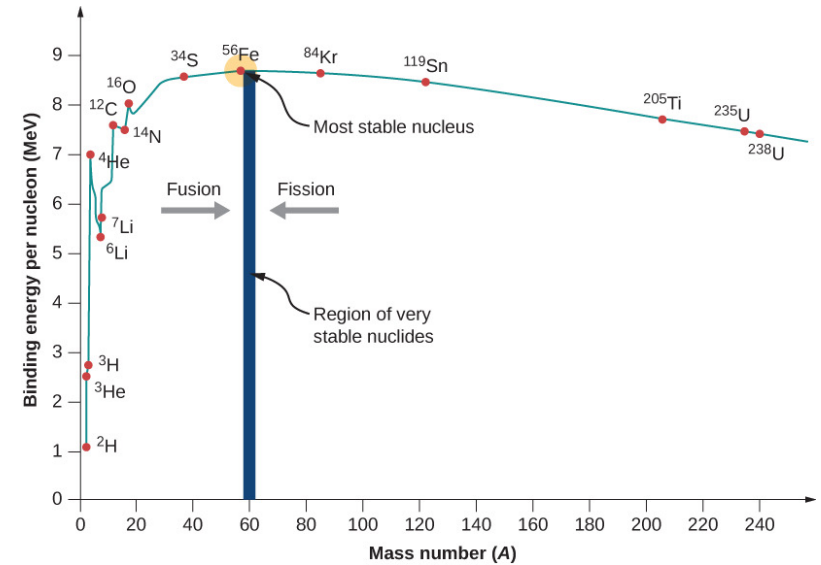
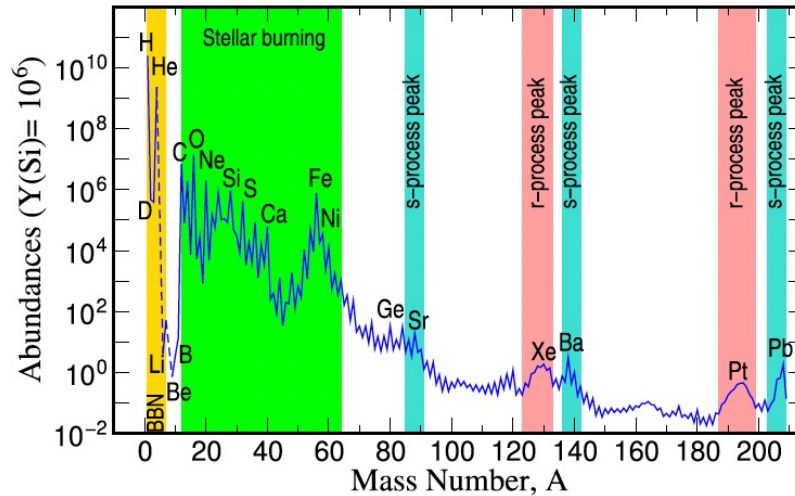
Spectra line analysis based on element-specific spectral emission lines following atomic de-excitation



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



# Nucleosynthesis: Element formation in Stars



BBN, Primordial

Fusion in stars

Capture processes

# 🤔 How are elements formed? We are all made of stars (cit.)

## The Universe Time Scale

Light elements created following the Big Bang

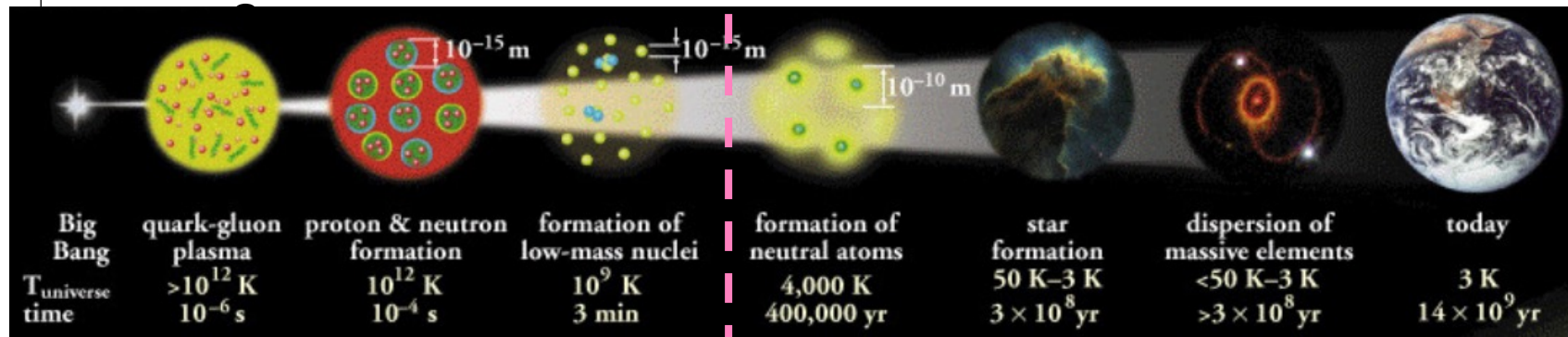
H, He  $\rightarrow$  C, N,

Heavier elements are created in the stars: **stellar nucleosynthesis**

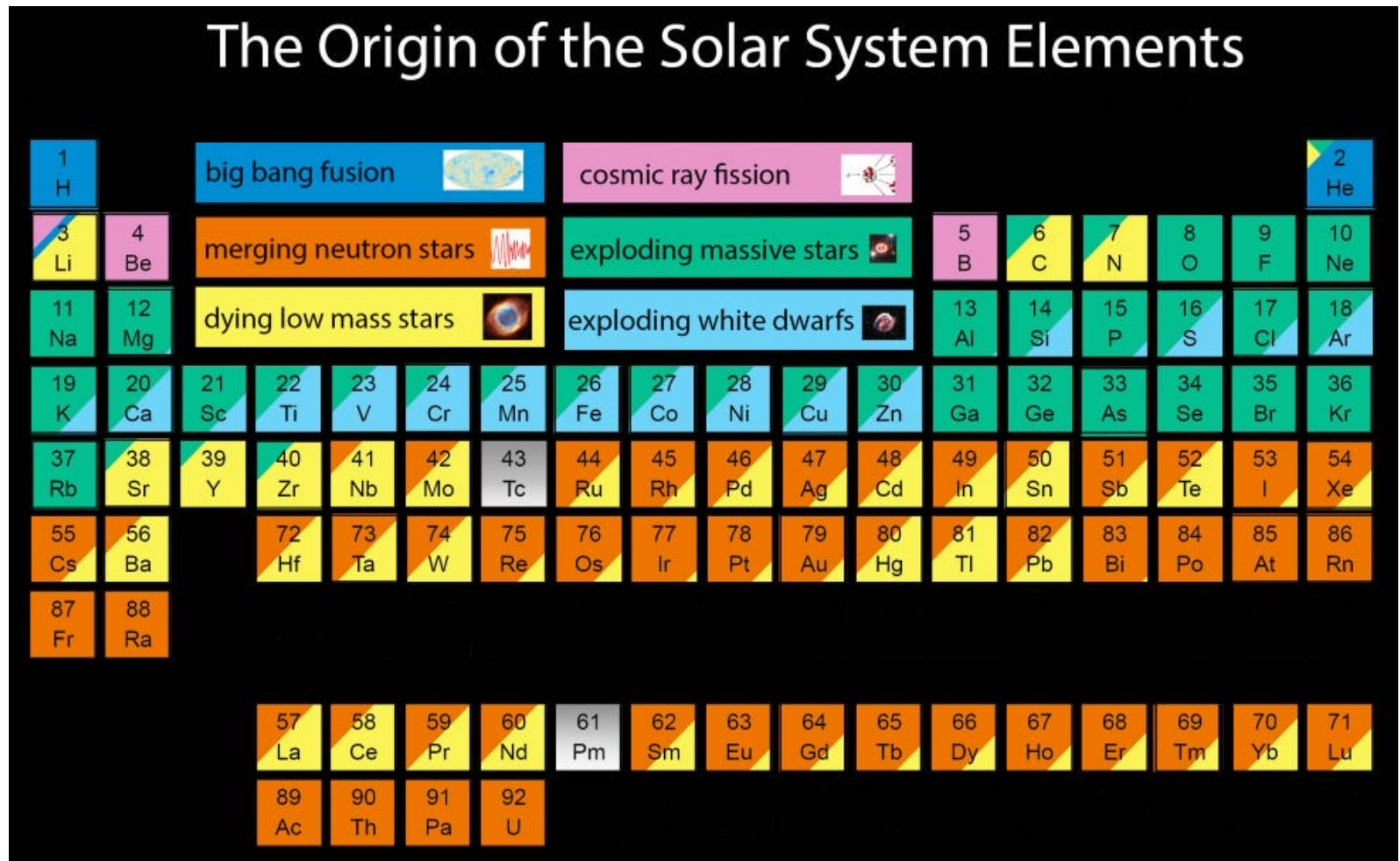
$\rightarrow$  What are the conditions? T, particles?

$\rightarrow$  What type of stars are location of «creation»?

$^{56}\text{Fe}$  - .... -  $^{238}\text{U}$  - s- p nucleosynthesis



## Element formation in stars



Decay of  
radioactive  
nuclei

Element  
formation in  
stars

Example of  
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# Nucleosynthesis: Element formation in Stars

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REVIEWS OF  
MODERN PHYSICS

VOLUME 29, NUMBER 4OCTOBER, 1957

Synthesis of the Elements in Stars\*

E. MARGARET BURRIDGE, G. R. BURRIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and  
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,  
California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";  
(King Lear, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"  
(Julius Caesar, Act I, Scene 2)

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\* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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1957: B2FH paper sets the landscape for the synthesis of elements in Stars

- Definition of parameters for
  - Fusion in stars
  - Capture phenomena
- Definition of slow-n capture (s) process and rapid-n capture (r) process for the creation of n-rich nuclei

# Nucleosynthesis: Element formation in Stars

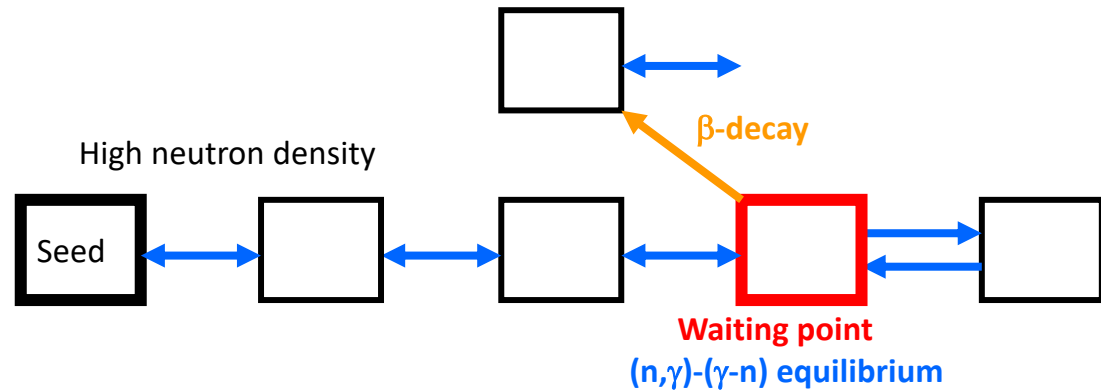
Decay of radioactive nuclei

Element formation in stars

Example of measurements of  $\beta$ -decays

Perspectives

Conclusions



In r- and s- process competition between

neutron capture/photodissociation  $(N, Z) + n \leftrightarrow (N + 1, Z), \gamma$

$\beta^-$  decay

$(N + 1, Z) \rightarrow (N, Z + 1) + e^- + \nu_e$

# Nucleosynthesis: Element formation in Stars

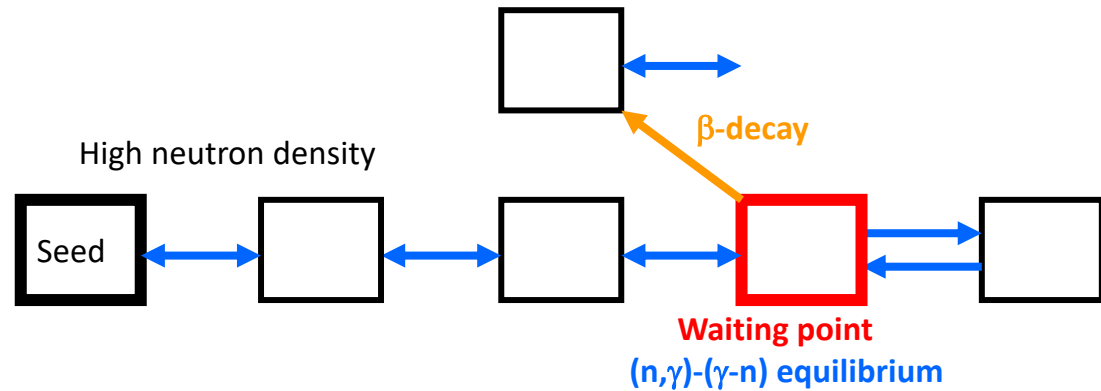
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$\beta^-$  decay  $(N + 1, Z) \rightarrow (N, Z + 1) + e^- + \nu_e$

$$\frac{dN_Z(t)}{dt} = \lambda_{Z-1}^\beta N_{Z-1}(t) - \lambda_Z^\beta N_Z(t)$$

Production

Decay

# Nucleosynthesis: Element formation in Stars

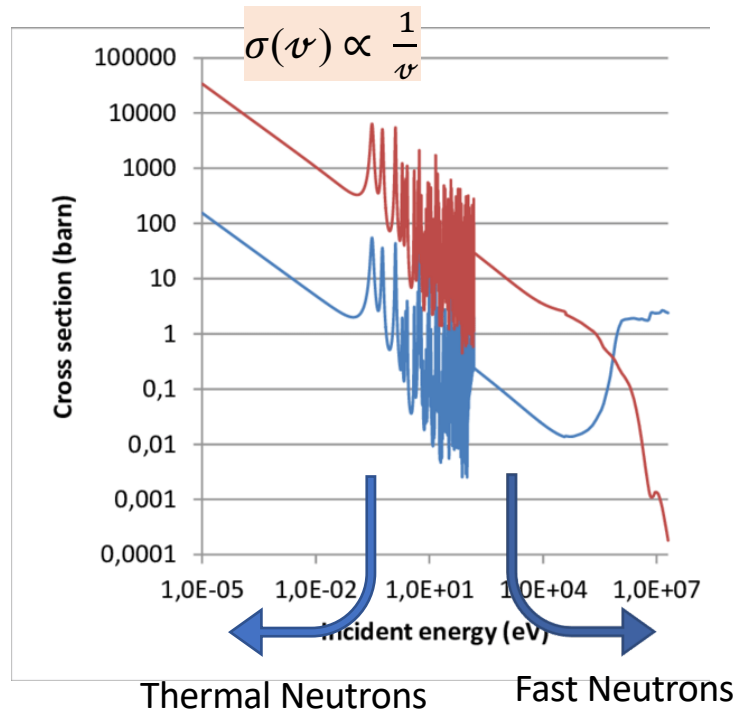
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# Nucleosynthesis: Element formation in Stars

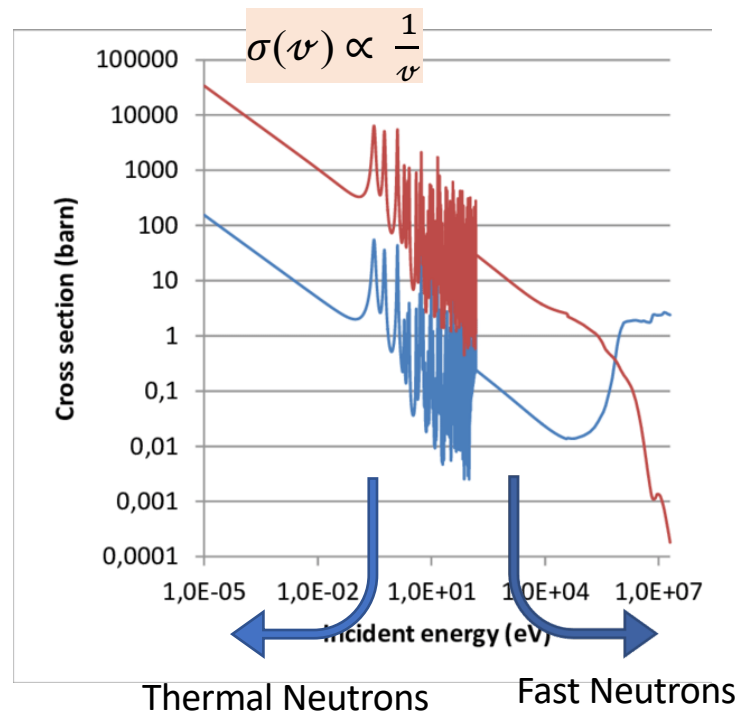
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S- process:

Lower Temperatures and lower n density

- Low neutron flux,
- BUT enough time to capture a Thermal neutron
- neutron capture over a long time-scale, from 100 years to  $10^5$  years
- Nucleus decays after neutron capture  
Moves along the stability line

$$\tau_{\beta} < \tau_{n,\gamma}$$

# The s-process fluence

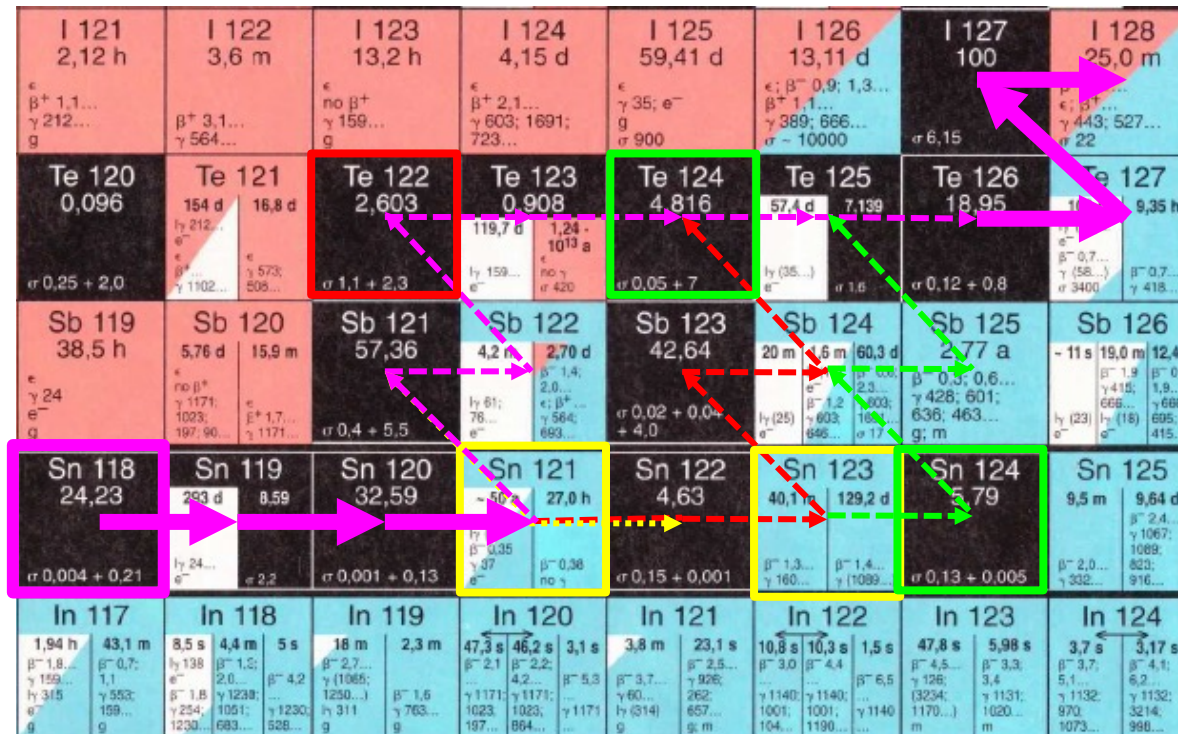
Decay of  
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beta-decay spectroscopy towards the r-process G.Benzoni @ INFN-Milano

# Nucleosynthesis: Element formation in Stars

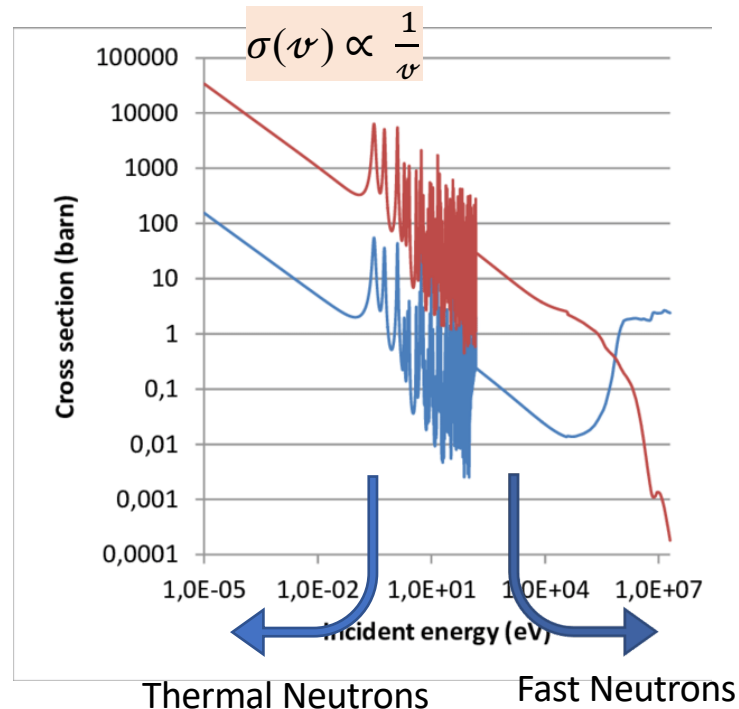
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- Nucleus decays after neutron capture  
Moves along the stability line

$$\tau_{\beta} < \tau_{n,\gamma}$$

R- process:

Explosive scenarios:

High temperatures and high  $n$  density

- Capture of energetic neutrons
- Many successive captures before  $\beta$  decay  
0.01 – 10 s
- Flux is moved far away from stability line towards very short lived nuclei  $[T_{1/2}] < s$

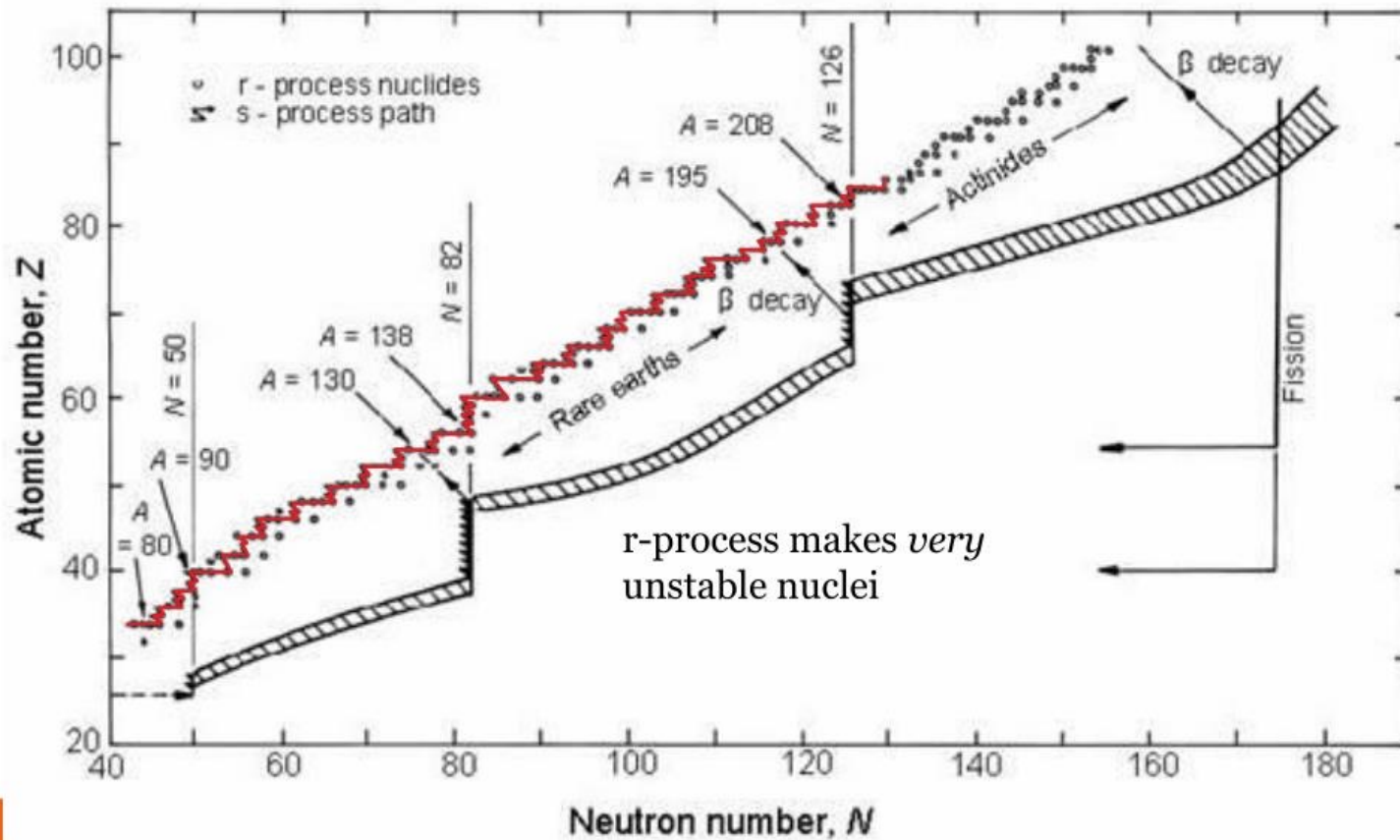
$$\tau_{(n,\gamma)} < \tau_{\beta}$$



Inizio di una nuova era: Astronomia Multimessaggera  
 Misura di onde gravitazionali e conseguente produzione di elementi pesanti



## Beta-decay spectroscopy towards the r-process path



# Nucleosynthesis: Element formation in Stars

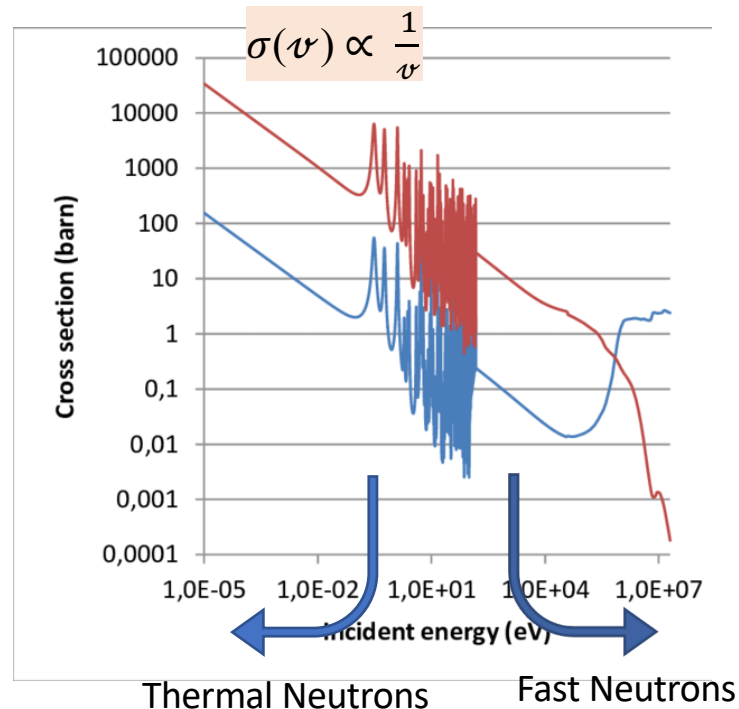
Decay of  
radioactive  
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Perspectives (

Conclusions



S- process:

Lower Temperatures and lower  $n$  density

→ Astrophysical locations are Asymptotic Giant Branch of Red Giant stages

R- process:

Explosive scenarios:

High temperatures and high  $n$  density

→ 3 possible sites:

- Neutrino driven wind of CCSNe → Only  $A < 120$
- Magneto hydrodynamic jets of CCSNe →  $A > 110$
- Neutron Star Mergers →  $A > 150$

Atomic number,  $Z$

Neutron number,  $N$

$\circ$  r - process nuclides  
 $\bullet$  s - process path

$A = 90$   
 $A = 130$   
 $A = 138$   
 $A = 195$   
 $A = 208$

$N = 50$   
 $N = 82$   
 $N = 126$

$\beta$  decay

Rare earths

Actinides

Fission

r-process makes *very* unstable nuclei

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# Beta-decay spectroscopy towards the r-process path

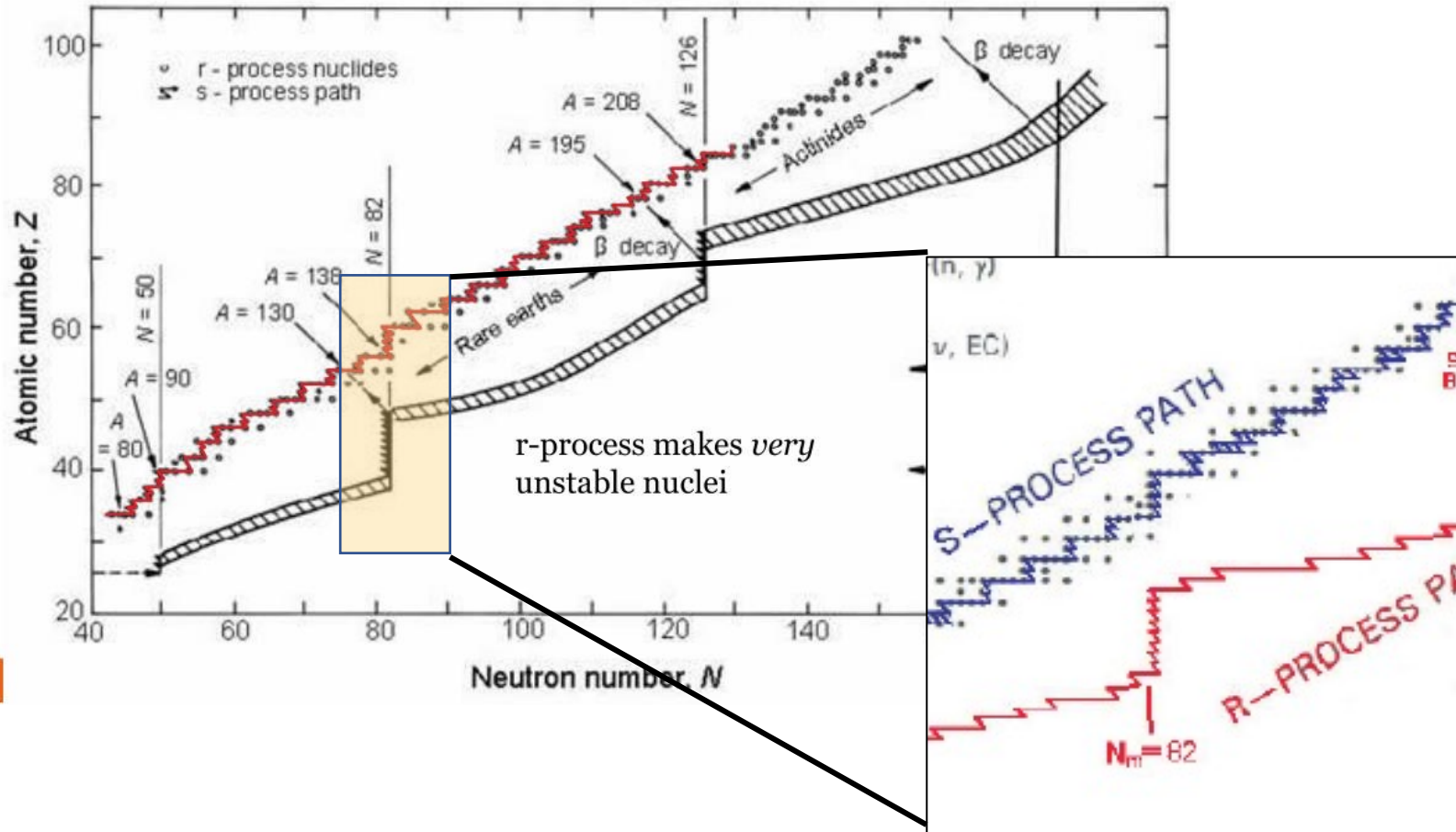
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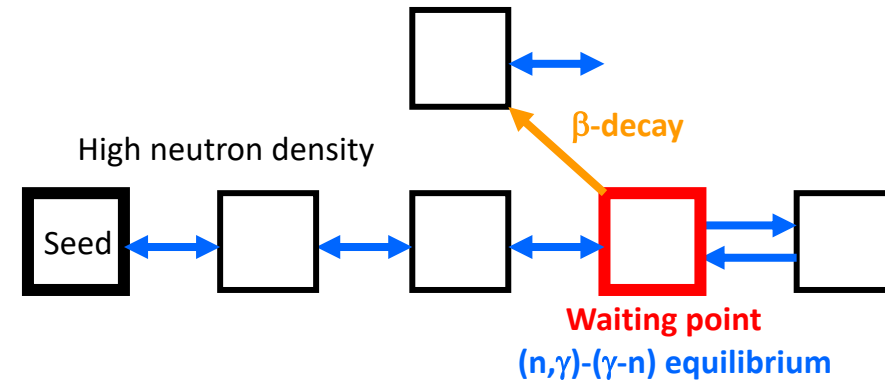
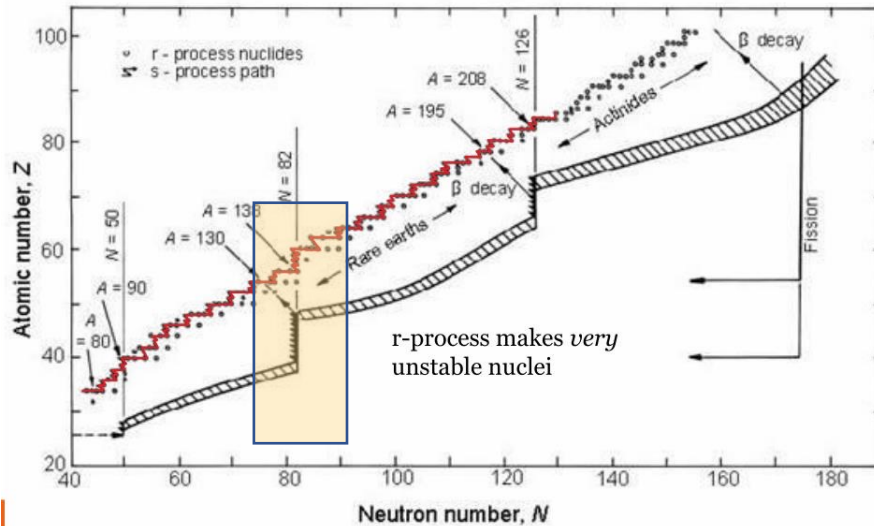
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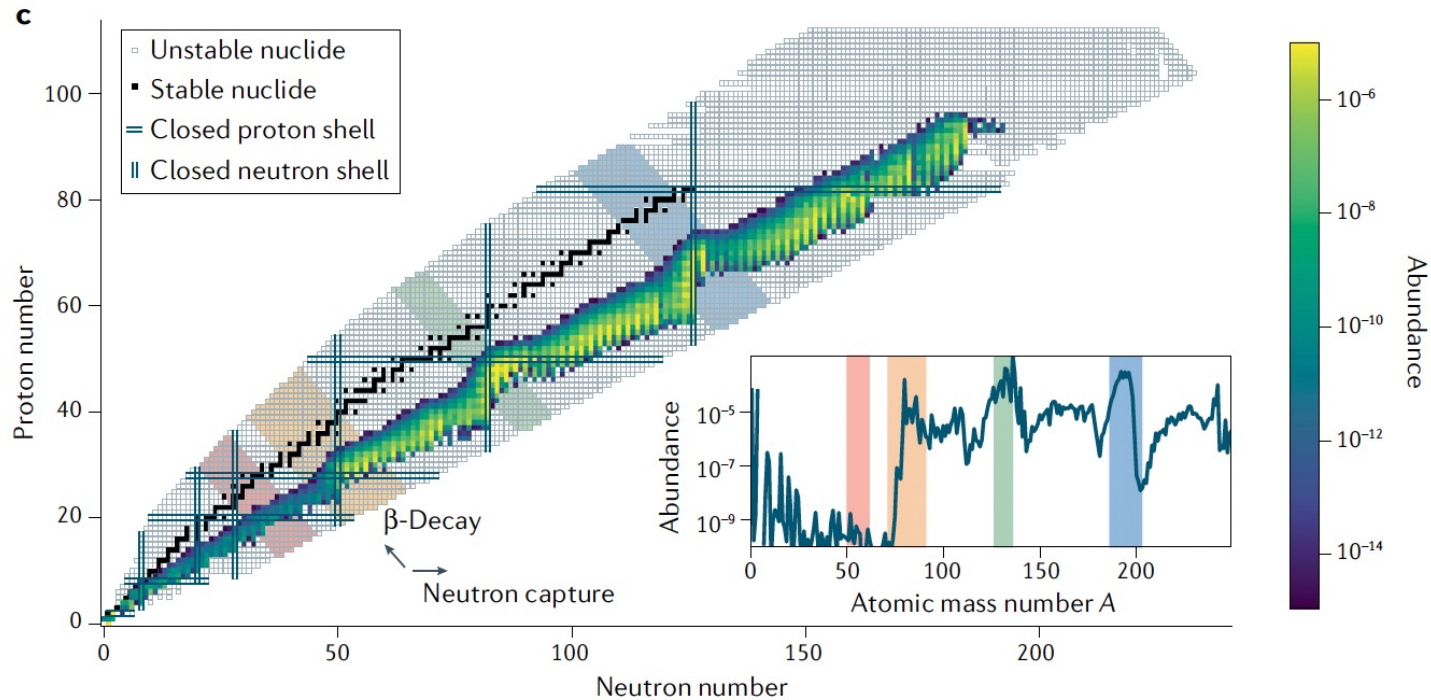
# Beta-decay spectroscopy towards the r-process path



Two different concepts

- 1- Waiting Point → the neutron capture process stops and nuclei get closer to stability line
- 2- Abundance Peak → peaks of higher abundances are created

# Nucleosynthesis: Element formation in Stars



Decay of  
radioactive  
nuclei

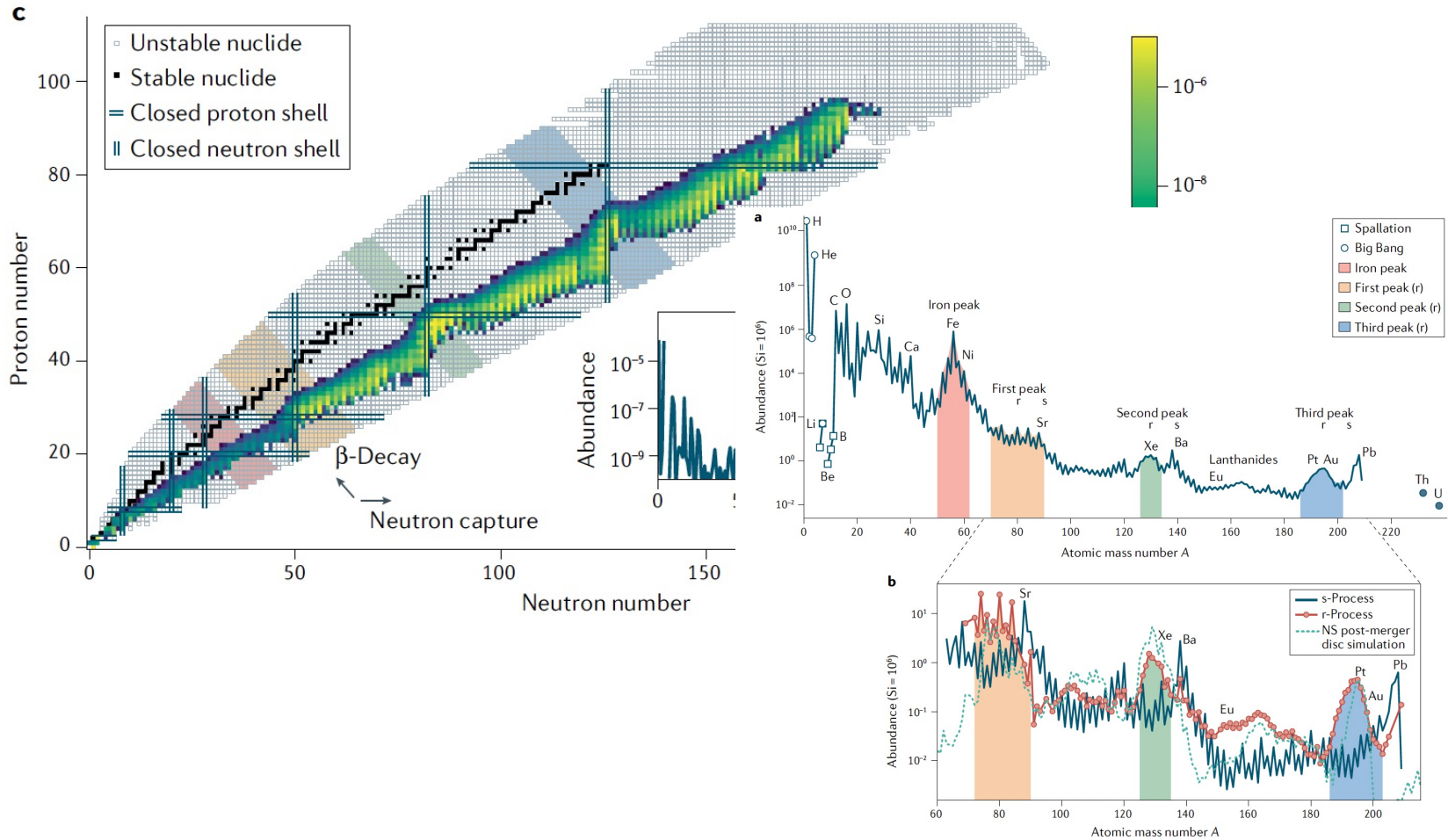
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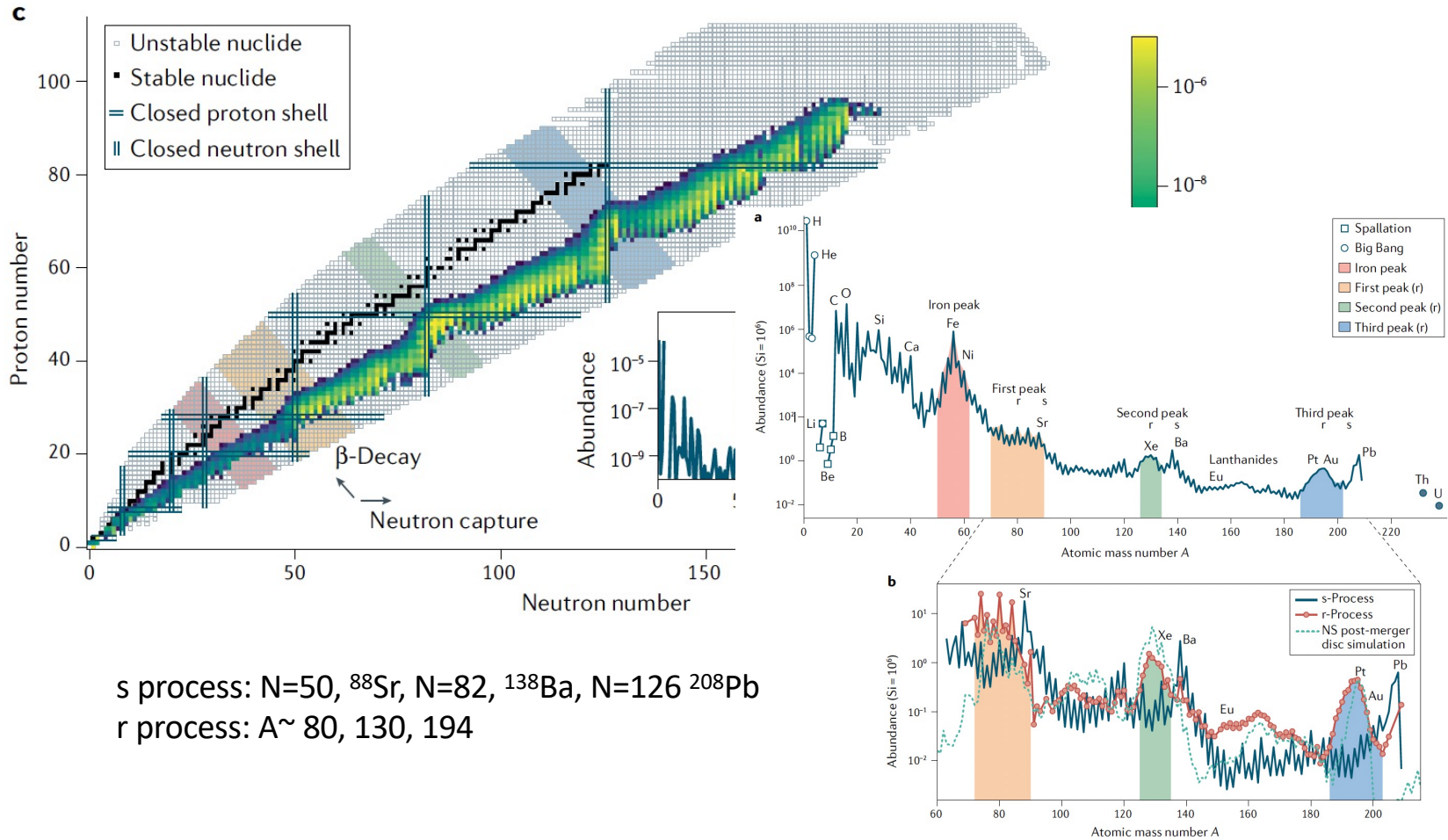
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# Nucleosynthesis: Element formation in Stars



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

# Nucleosynthesis: Element formation in Stars



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



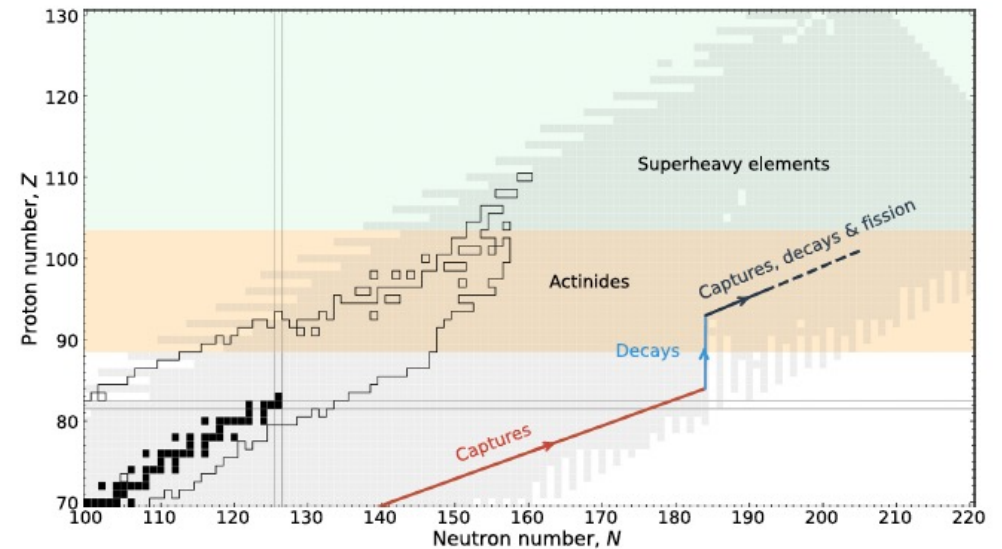
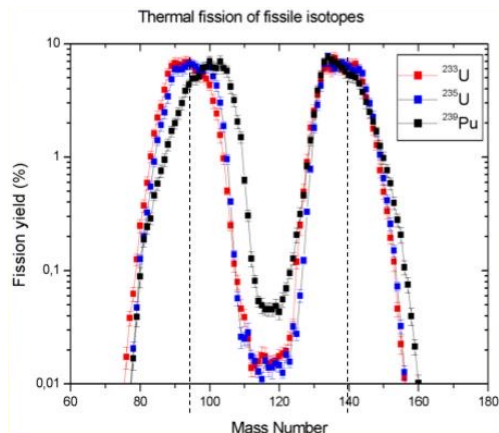
# Nucleosynthesis: Element formation in Stars

## How heavy does the r-process go?

R-process proceeds all the way above U, where competition with alpha decay and fission stop the process

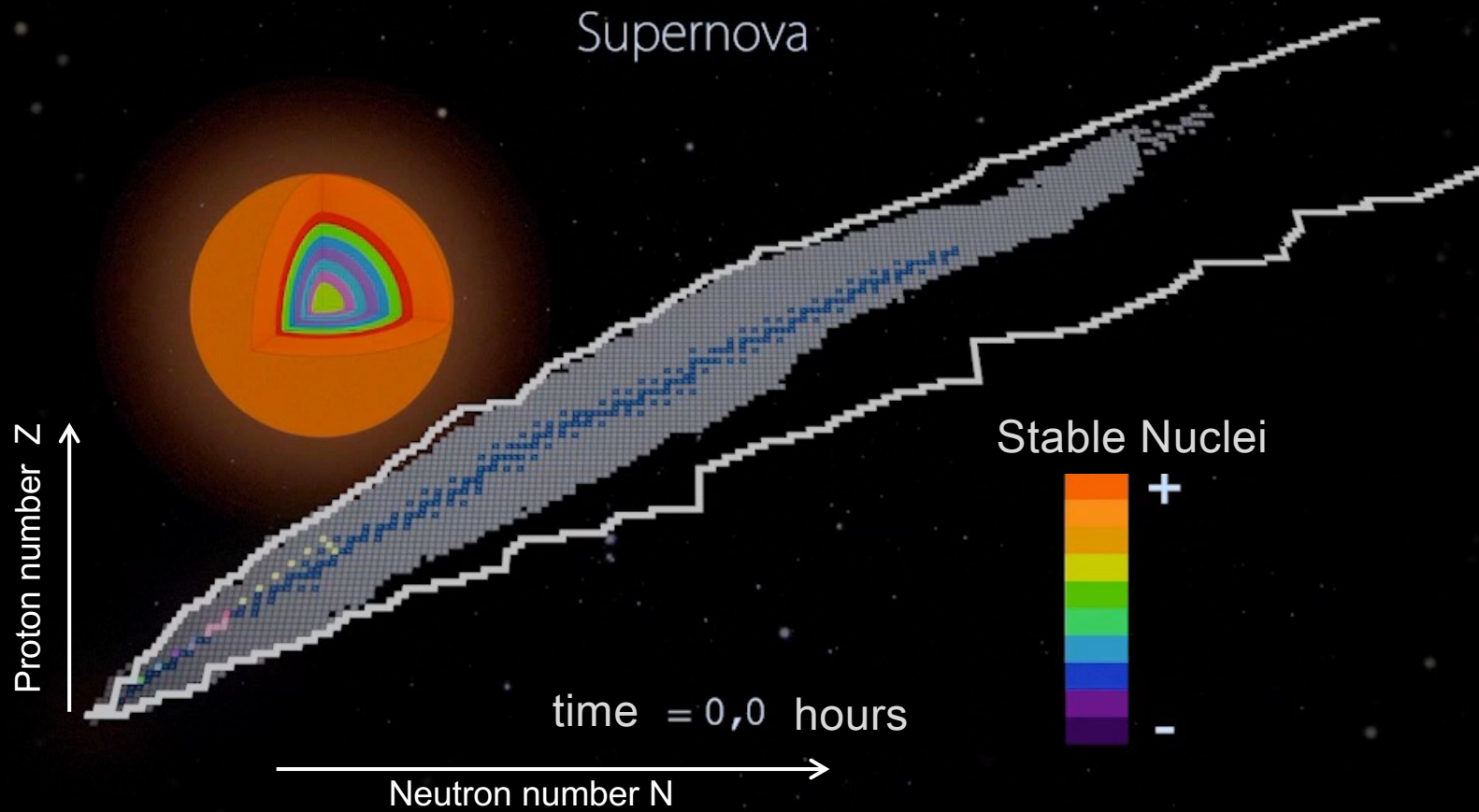
Fission has two effects

1) Formation of 2 n-rich lighter ions that enter the r-process cycle again



2) Fission emits neutrons which sustain the flux

The r-process is here towards its end, and most of neutrons are exhausted by now → Freeze-out



from CEA Sciences - "La Physique Nucléaire"



# Nucleosynthesis: Element formation in Stars

Decay of  
radioactive  
nuclei

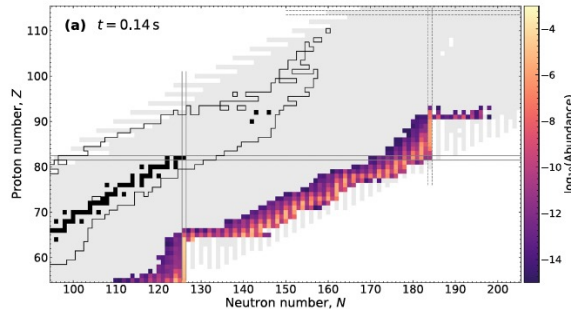
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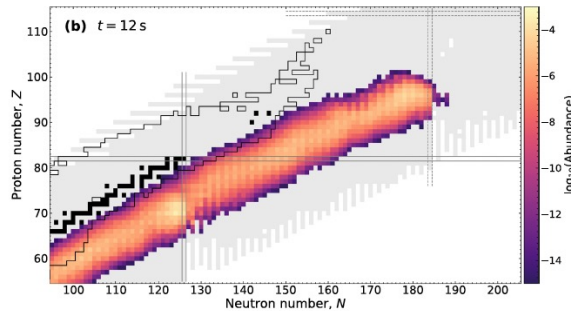
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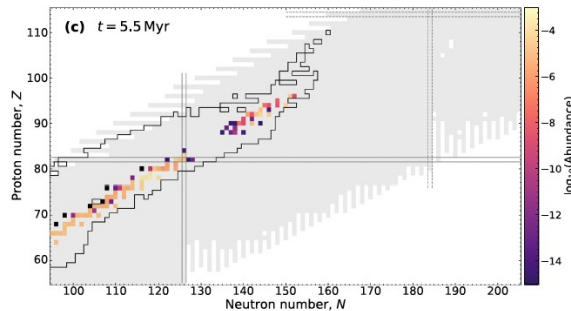
Stopping the video at different stages



Before freeze-out  
 $(n, \gamma) \rightleftharpoons (\gamma, n)$  are blocked by low  $n$  density  
 $n$  captures dominant



After freeze-out  
 $\beta$  decay becomes dominant



Well after  $r$  process is ended

Gray shaded area,  
theoretical extension of  
the process

# Nucleosynthesis: Element formation in Stars

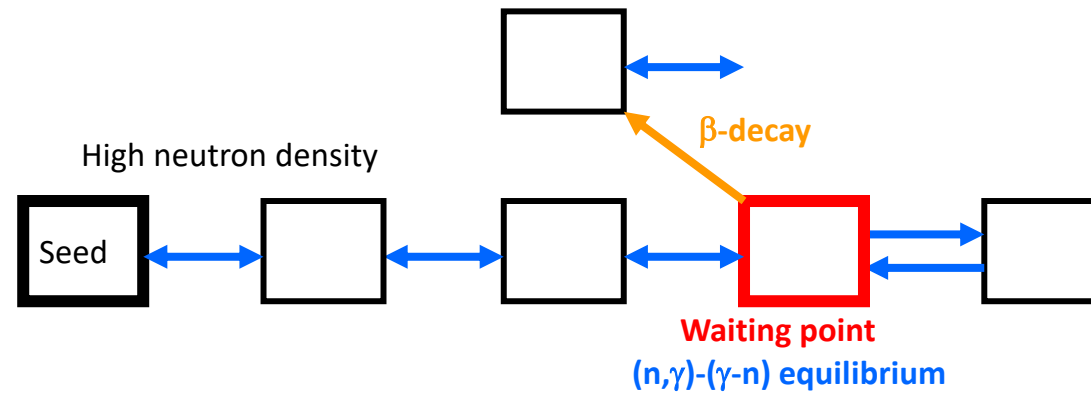
Decay of  
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Crucial inputs from experimental nuclear physics are

- Masses
- $\beta$ -decay rates
- Branching Ratios
- n-capture cross sections

**How do we produce exotic nuclei???**

# Measuring $\beta$ decay

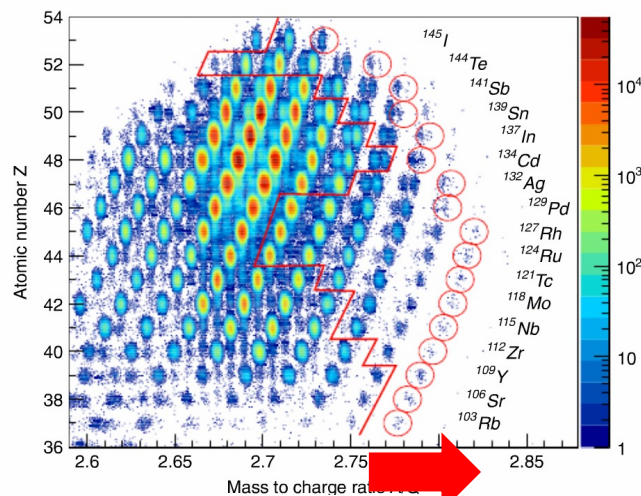
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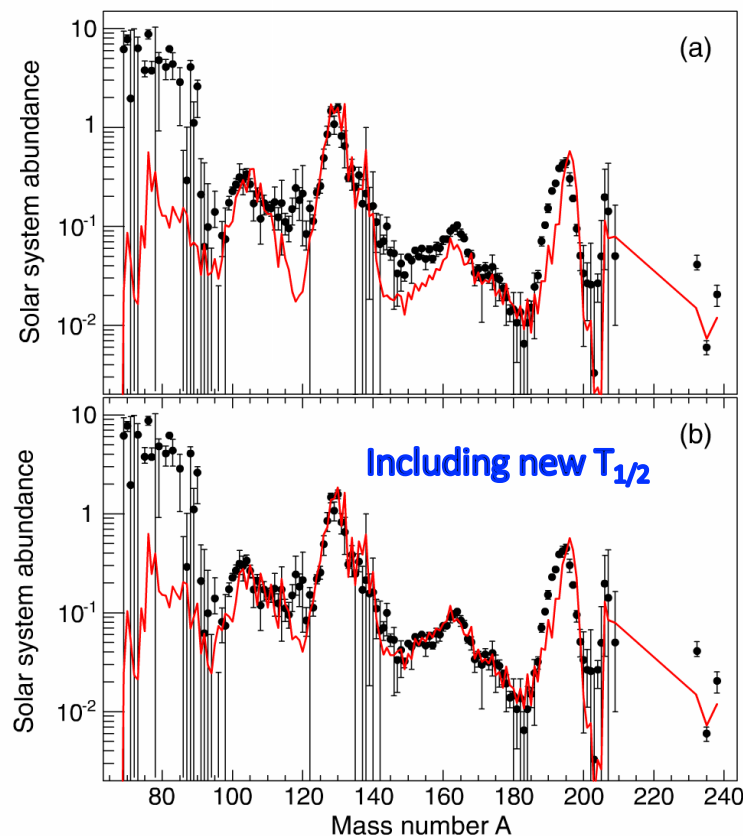
PRL 114, 192501 (2015)

PHYSICAL REVIEW LETTERS

week ending  
15 MAY 2015

## $\beta$ -Decay Half-Lives of 110 Neutron-Rich Nuclei across the $N = 82$ Shell Gap: Implications for the Mechanism and Universality of the Astrophysical $r$ Process

G. Lorusso,<sup>1,2,3</sup> S. Nishimura,<sup>1,4</sup> Z. Y. Xu,<sup>1,5,6</sup> A. Jungclauss,<sup>7</sup> Y. Shimizu,<sup>1</sup> G. S. Simpson,<sup>8</sup> P.-A. Söderström,<sup>1</sup> H. Watanabe,<sup>1,9</sup> F. Browne,<sup>1,10</sup> P. Doornenbal,<sup>1</sup> G. Gey,<sup>1,8</sup> H. S. Jung,<sup>11</sup> B. Meyer,<sup>12</sup> T. Sumikama,<sup>13</sup> J. Taprogge,<sup>1,7,14</sup> Zs. Vajta,<sup>1,15</sup> J. Wu,<sup>1,16</sup> H. Baba,<sup>1</sup> G. Benzoni,<sup>17</sup> K. Y. Chae,<sup>18</sup> F. C. L. Crespi,<sup>17,19</sup> N. Fukuda,<sup>1</sup> R. Gemhäuser,<sup>20</sup> N. Inabe,<sup>1</sup> T. Isobe,<sup>1</sup> T. Kajino,<sup>1,21</sup> D. Kameda,<sup>1</sup> G. D. Kim,<sup>22</sup> Y.-K. Kim,<sup>22,23</sup> I. Kojouharov,<sup>24</sup> F. G. Kondev,<sup>25</sup> T. Kubo,<sup>1</sup> N. Kurz,<sup>24</sup> Y. K. Kwon,<sup>22</sup> G. J. Lane,<sup>26</sup> Z. Li,<sup>16</sup> A. Montaner-Pizá,<sup>27</sup> K. Moschner,<sup>28</sup> F. Naqvi,<sup>29</sup> M. Niikura,<sup>5</sup> H. Nishibata,<sup>30</sup> A. Odahara,<sup>30</sup> R. Orlandi,<sup>31</sup> Z. Patel,<sup>3</sup> Zs. Podolyák,<sup>3</sup> H. Sakurai,<sup>1,5</sup> H. Schaffner,<sup>24</sup> P. Schury,<sup>1</sup> S. Shibagaki,<sup>1,4,21</sup> K. Steiger,<sup>20</sup> H. Suzuki,<sup>1</sup> H. Takeda,<sup>1</sup> A. Wendt,<sup>28</sup> A. Yagi,<sup>30</sup> and K. Yoshinaga<sup>32</sup>



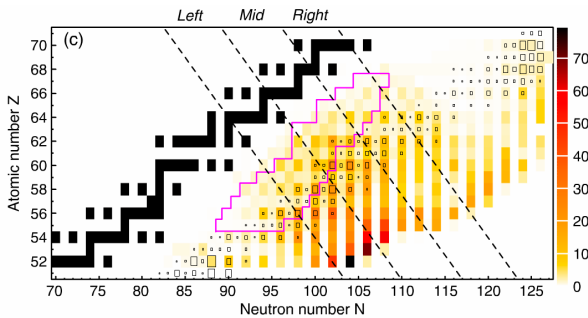
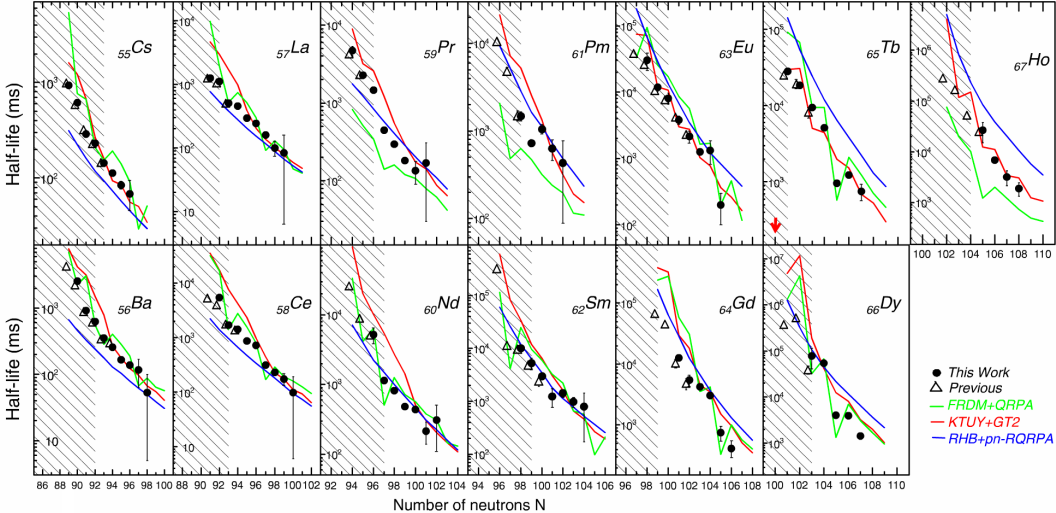
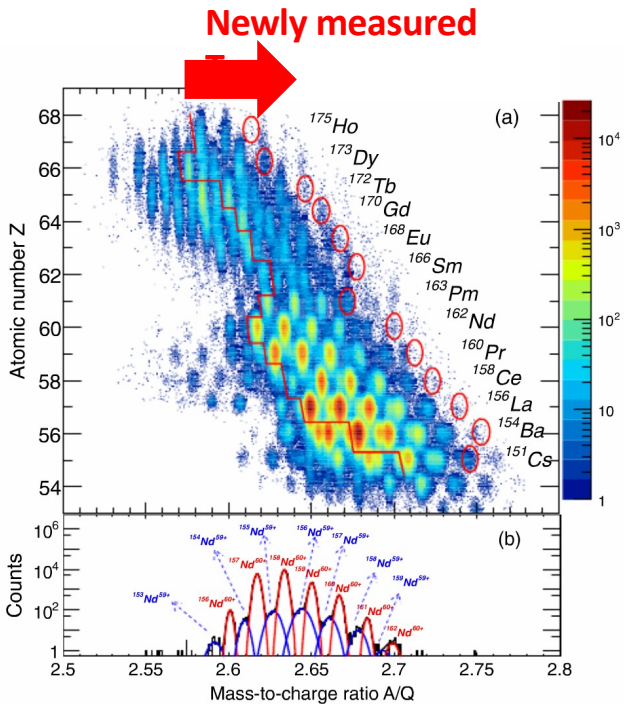
beta-decay spectroscopy towards the  $r$ -process G.Benzoni @ INFN-Milano



# Measuring $\beta$ decay

PRL 118, 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

94  $\beta$ -Decay Half-Lives of Neutron-Rich  $_{55}\text{Cs}$  to  $_{67}\text{Ho}$ : Experimental Feedback and Evaluation of the  $r$ -Process Rare-Earth Peak Formation



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

# General Properties of $\beta$ decay

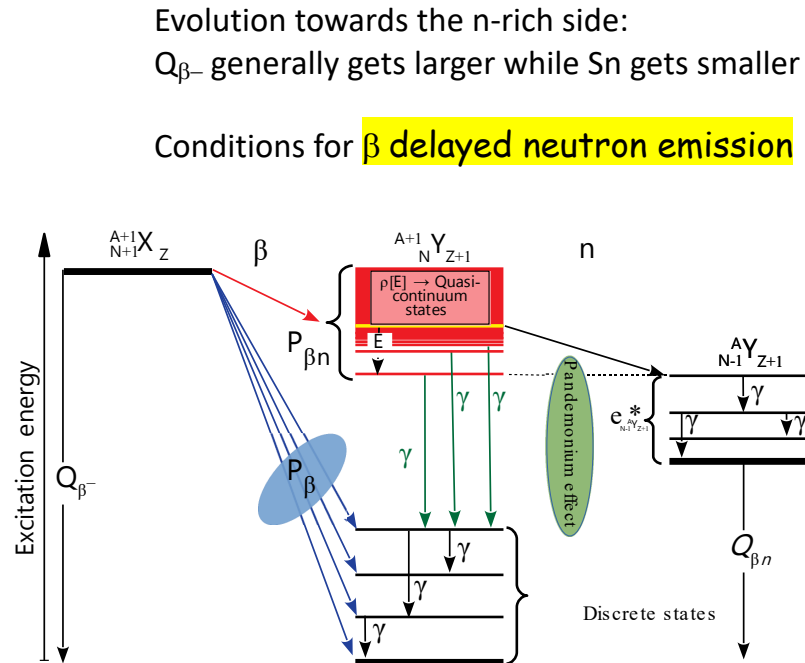
Decay of radioactive nuclei

Element formation in stars

Example of measurements of  $\beta$ -decays

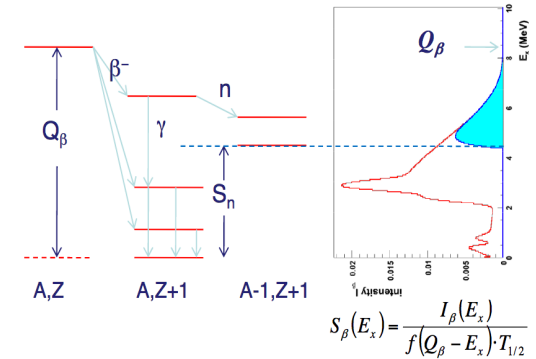
Perspectives

Conclusions



$$\frac{1}{T_{1/2}} = \sum_0^{Q_{\beta}} S_{\beta}(E_x) \cdot f(Q_{\beta} - E_x)$$

$$P_n = \frac{\sum_{S_n}^{Q_{\beta}} S_{\beta}(E_x) \cdot f(Q_{\beta} - E_x)}{\sum_0^{Q_{\beta}} S_{\beta}(E_x) \cdot f(Q_{\beta} - E_x)}$$



$\beta$ -delayed neutron emission occurs when  $Q_{\beta} > S_n$  in the daughter nucleus

$T_{1/2}$  and  $P_n$  convey information related to  $\beta$  feeding

$T_{1/2}$  yields information on the average  $\beta$  feeding

$P_n$  yields information on  $\beta$  feeding above  $S_n$

$P_n$  are difficult to predict theoretically since they reflect the “shape” of the  $\beta$  strength function and fine structure on the nucleus

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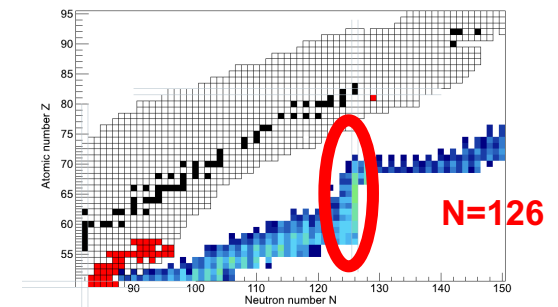
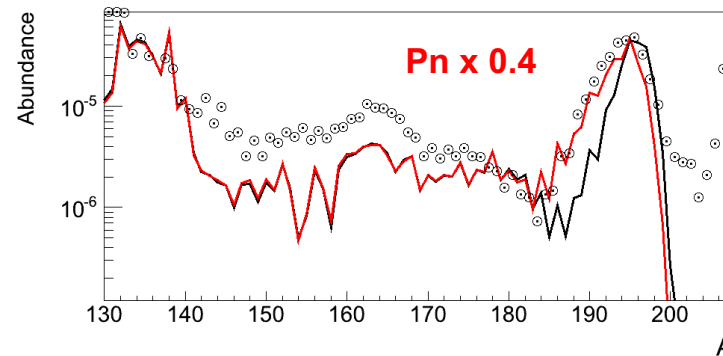
Perspectives

Conclusions

During „Freeze-out“:  
detour of  $\beta$ -decay chains  
 $\Rightarrow$  *r*-abundance changes



During „Freeze-out“:  
enhancement of neutron flux  
 $\Rightarrow$  *r*-abundance changes



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



# Sensitivity study of inputs for nucleosynthesis modeling

*M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126*

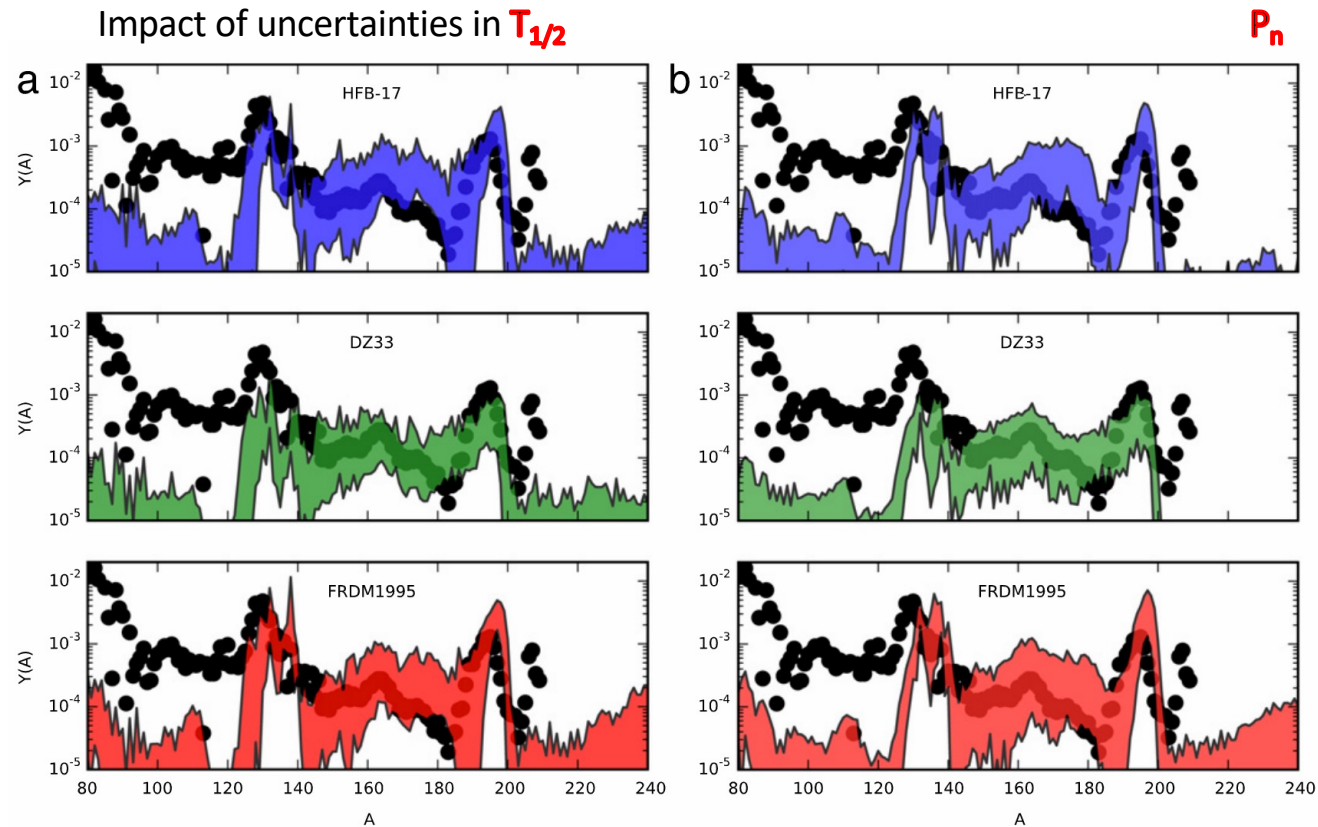
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radioactive  
nuclei

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



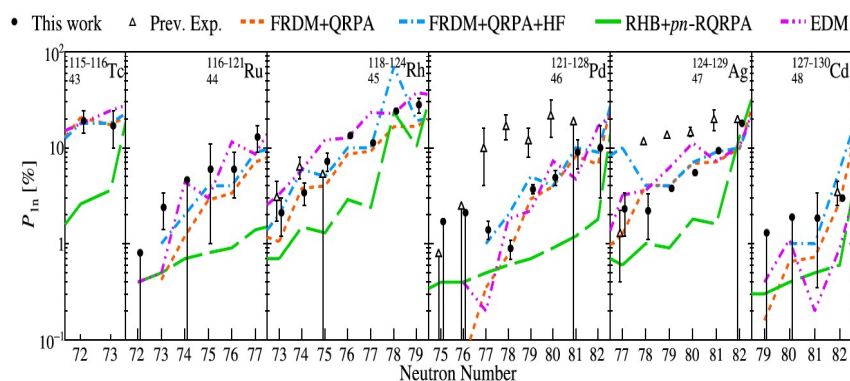
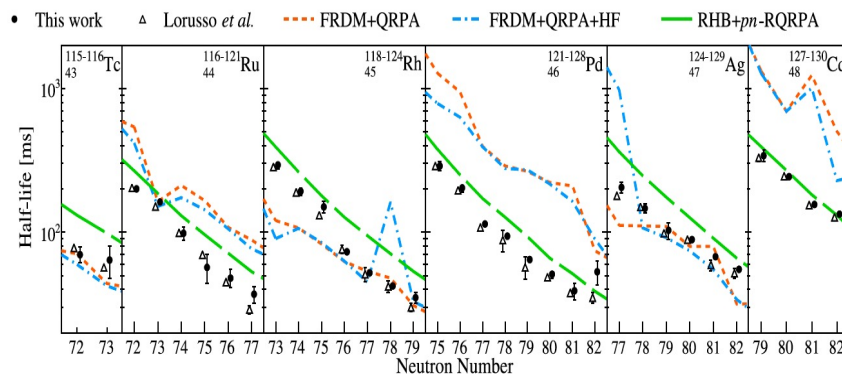
Decay of  
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*FRDM+QRPA* = cut-off approach: above  $S_n$  a neutron is emitted  
*FRDM+QRPA+HF* = statistical decay and  $\gamma$ -ray emission explicitly at every stage  
 EDM = semiempirical effective density model



# $\beta$ -delayed neutron emission of $r$ -process nuclei at the $N = 82$ shell closure

O. Hall<sup>a,\*</sup>, T. Davinson<sup>a</sup>, A. Estrade<sup>b</sup>, J. Liu<sup>c,d</sup>, G. Lorusso<sup>e,f</sup>, F. Montes<sup>g</sup>, S. Nishimura<sup>h</sup>, V.H. Phong<sup>i,j</sup>, P.J. Woods<sup>k</sup>, J. Agramunt<sup>l</sup>, D.S. Ahn<sup>m,n</sup>, A. Algora<sup>o</sup>, J.M. Allmond<sup>p</sup>, H. Baba<sup>q</sup>, S. Bae<sup>r</sup>, N.T. Brewer<sup>s</sup>, C.G. Bruno<sup>t</sup>, R. Caballero-Folch<sup>u</sup>, F. Calviño<sup>v</sup>, P.J. Coleman-Smith<sup>w</sup>, G. Cortes<sup>x</sup>, I. Dillmann<sup>y,z</sup>, C. Domingo-Fardo<sup>aa</sup>, A. Fialkowska<sup>ab</sup>, N. Fukuda<sup>ac</sup>, S. Go<sup>ad</sup>, C.J. Griffin<sup>ae</sup>, R. Grzywacz<sup>af</sup>, J. Ha<sup>ag</sup>, L.J. Harkness-Brennan<sup>ah</sup>, T. Isobe<sup>ai</sup>, D. Kahl<sup>aj</sup>, L.H. Kiem<sup>ak</sup>, G.G. Kiss<sup>al</sup>, A. Korgul<sup>am</sup>, S. Kubono<sup>an</sup>, M. Labiche<sup>ao</sup>, I. Lazarus<sup>ap</sup>, J. Liang<sup>aq</sup>, Z. Liu<sup>ar</sup>, K. Matsui<sup>as</sup>, K. Miernik<sup>at</sup>, B. Moon<sup>au</sup>, A.J. Morales<sup>av</sup>, P. Morrall<sup>aw</sup>, M.R. Mumpower<sup>ax</sup>, N. Nepal<sup>ay</sup>, R.D. Page<sup>az</sup>, M. Piersa<sup>ba</sup>, V.F.E. Pucknell<sup>bb</sup>, B.C. Rasco<sup>bc</sup>, B. Rubio<sup>bd</sup>, K.P. Rykaczewski<sup>be</sup>, H. Sakurai<sup>bf</sup>, Y. Shimizu<sup>bg</sup>, D.W. Stracener<sup>bh</sup>, T. Sumikama<sup>bi</sup>, H. Suzuki<sup>bj</sup>, J.L. Tain<sup>bk</sup>, H. Takeda<sup>bl</sup>, A. Tarifeño-Saldivia<sup>bm</sup>, A. Tolosa-Delgado<sup>bn</sup>, M. Wolinska-Cichocka<sup>bo</sup>, R. Yokoyama<sup>bp</sup>

The  $P_{1n}$  values reported in this work show a regular trend for most elements, of increasing neutron emission probability as neutron number increases. Some odd-even staggering in the  $P_{1n}$  values is observed for the lighter elements, such as Tc, Ru and Rh, though this is seen to diminish for nuclei close to  $Z=50$  where a smoother increase is observed.

The predictions of the FRDM+QRPA and FRDM+QRPA+HF calculations reproduce this trend well across all isotopic chains, matching much of the stagger-ing that is observed in the experimental values

**BUT models who work for  $T_{1/2}$  do not reproduce  $P_{1n}$**

# Measuring $\beta$ decay

Decay of radioactive nuclei

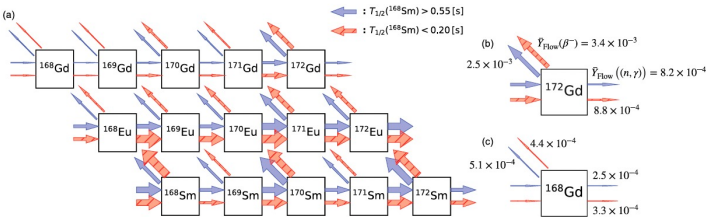
Element formation in stars

Example of measurements of  $\beta$ -decays

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The new data not only constrain the theoretical predictions of half-lives and  $\beta$ -delayed neutron-emission probabilities, but also allow for probing the mechanisms of formation of the high-mass wing of the rare-earth peak located at  $A \approx 160$  in the r-process abundance distribution through astrophysical reaction network calculations

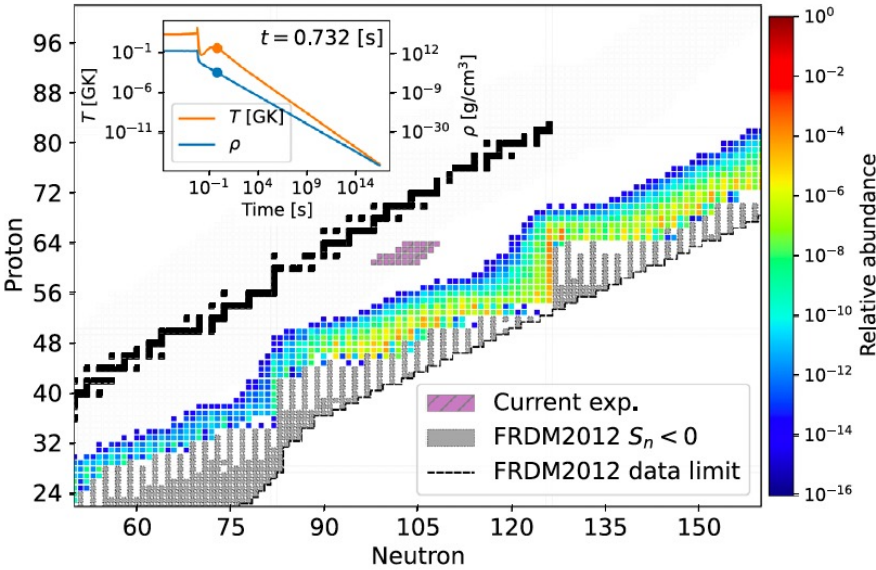


**Figure 12.** The arrows show the total abundance flow (same quantity as in panels (e)–(i) in Figure 11), averaged over the generated samples in the neutron-star merger scenario. Red corresponds to the case where the half-life of  $^{168}\text{Sm}$  is shorter than 0.20 [s], and blue shows a half-life longer than 0.55 [s]. Panels (b) and (c) focus on the flows from  $^{172}\text{Gd}$  and  $^{168}\text{Gd}$ , respectively. The propagated influence of the half-life of  $^{168}\text{Sm}$  is visible, which results in affecting the final abundances.



## Measuring the $\beta$ -decay Properties of Neutron-rich Exotic Pm, Sm, Eu, and Gd Isotopes to Constrain the Nucleosynthesis Yields in the Rare-earth Region

G. G. Kiss<sup>1</sup>, A. Vitéz-Sveicz<sup>1,2</sup>, Y. Saito<sup>3,4</sup>, A. Tarifeño-Saldivia<sup>5,6</sup>, M. Pallas<sup>3</sup>, J. L. Tain<sup>6</sup>, I. Dillmann<sup>3,7</sup>, J. Agramunt<sup>6</sup>, A. Algora<sup>1,6</sup>, C. Domingo-Pardo<sup>6</sup>, A. Estrade<sup>8</sup>, C. Appleton<sup>9</sup>, J. M. Allmond<sup>10</sup>, P. Aguilera<sup>11,12</sup>, H. Baba<sup>13</sup>, N. T. Brewer<sup>10,14</sup>, C. Bruno<sup>9</sup>, R. Caballero-Folch<sup>3</sup>, F. Calvino<sup>3</sup>, P. J. Coleman-Smith<sup>15</sup>, G. Cortes<sup>3</sup>, T. Davinson<sup>9</sup>, N. Fukuda<sup>13</sup>, Z. Ge<sup>13</sup>, S. Go<sup>13,16</sup>, C. J. Griffin<sup>3</sup>, R. K. Grzywacz<sup>10,14</sup>, O. Hall<sup>9</sup>, A. Horváth<sup>17</sup>, J. Ha<sup>13,18</sup>, L. J. Harkness-Brennan<sup>19</sup>, T. Isobe<sup>13</sup>, D. Kahl<sup>9</sup>, T. T. King<sup>14</sup>, A. Korgul<sup>20</sup>, S. Kovács<sup>3</sup>, R. Krücken<sup>3,4</sup>, S. Kubono<sup>13</sup>, M. Labiche<sup>15</sup>, J. Liu<sup>21</sup>, J. Liang<sup>3</sup>, M. Madurga<sup>14</sup>, K. Mierlik<sup>20</sup>, F. Molina<sup>11</sup>, A. I. Morales<sup>3</sup>, M. R. Mumpower<sup>22,23</sup>, E. Nacher<sup>6</sup>, A. Navarro<sup>3</sup>, N. Nepal<sup>8</sup>, S. Nishimura<sup>3</sup>, M. Piersa-Silkowska<sup>20</sup>, V. Phong<sup>3</sup>, B. C. Rasco<sup>10,14</sup>, B. Rubio<sup>3</sup>, K. P. Rykaczewski<sup>10</sup>, J. Romero-Barrientos<sup>3</sup>, H. Sakurai<sup>13</sup>, L. Sexton<sup>3,9</sup>, Y. Shimizu<sup>13</sup>, M. Singh<sup>14</sup>, T. Sprouse<sup>22,23</sup>, T. Sumikama<sup>13</sup>, R. Surman<sup>24</sup>, H. Suzuki<sup>13</sup>, T. N. Szegedi<sup>3</sup>, H. Takeda<sup>3</sup>, A. Tolosa<sup>6</sup>, K. Wang<sup>3</sup>, M. Wolinska-Cichocka<sup>25</sup>, P. Woods<sup>3</sup>, R. Yokoyama<sup>26</sup>, and Z. Xu<sup>14</sup>



# General Properties of $\beta$ decay

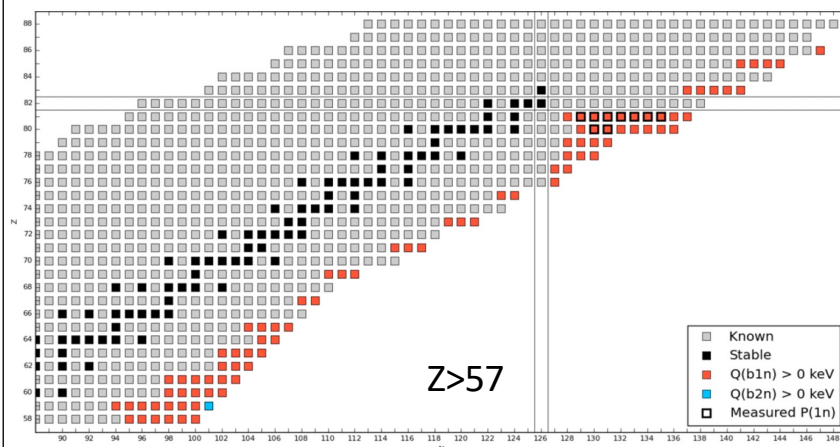
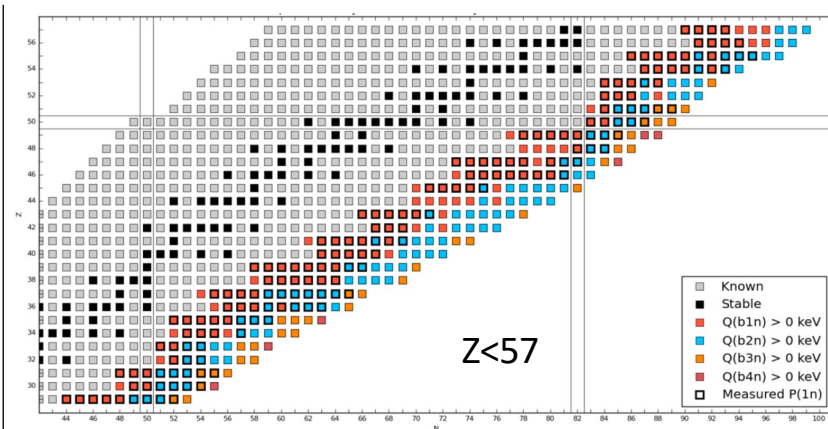
Decay of  
radioactive  
nuclei

Element  
formation in  
stars

Example of  
measurements  
of b-decays

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## Compilation and Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for $Z > 28$ Precursors

J. Liang,<sup>1</sup> B. Singh,<sup>1,\*</sup> E.A. McCutchan,<sup>2</sup> I. Dillmann,<sup>3,4</sup> M. Birch,<sup>1</sup> A.A. Sonzogni,<sup>2</sup> X. Huang,<sup>5</sup> M. Kang,<sup>6</sup> J. Wang,<sup>5</sup> G. Mukherjee,<sup>6</sup> K. Banerjee,<sup>6</sup> D. Abriola,<sup>7</sup> A. Algora,<sup>8,9</sup> A.A. Chen,<sup>1</sup> T.D. Johnson,<sup>2</sup> and K. Miernik<sup>10</sup>

Little data for heavy nuclei:

- Difficult access to nuclei
- Difficulty in measuring neutrons

# General Properties of $\beta$ decay

## How to evaluate $P_n = \frac{N_{n-decays}}{N_{decays}}$

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1-  $n/\beta$ : coincidences btw  $n$ - $\beta$   $P_n = \frac{1}{\varepsilon_n} \frac{N_{\beta n}}{N_{\beta}}$

- best method. Only one absolute efficiency is needed, for the neutron detector
- the true signal has to be separated from contaminants using the decay curves, for which the proper knowledge of the different half-lives ( $T_{1/2}$ ) is needed.

2-  $n/\beta$  separate but simultaneous  $P_n = \frac{\varepsilon_{\beta}}{\varepsilon_n} \frac{N_{\beta n}}{N_{\beta}}$

- needs two efficiencies
- this method could be advantageous in cases where the detectors cover a solid angle close to  $4\pi$

3- Ion counting  $P_n = \frac{N_{n-decays}}{N_{ions}}$

- The "ion" method relies on direct ion-counting. Difficult at low-energy ISOL facilities

4-  $\gamma$ - $\gamma$ : Total counting of all  $\gamma$ -rays emitted by daughter and/or  $\beta n$ -daughter, but no counting of neutrons is carried out.

$$P_n = \frac{\varepsilon_{\gamma,daughter} \cdot I_{abs,daughter,\gamma}}{N_{daughter,\gamma}} \bigg/ \frac{\varepsilon_{\gamma,final} \cdot I_{abs,final,\gamma}}{N_{final,\gamma}}$$

# Detecting $\alpha$ $\beta$ $\gamma$ $n$ particles: reminder of basic properties

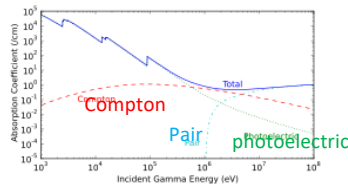
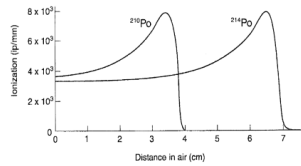
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$\alpha$  particle: massive, charged

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

$\beta$  particles: light, charged

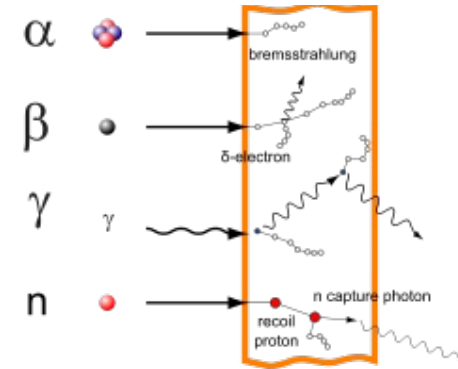
- interested in energy and correlations
- $e^+$  annihilates into two 511-keV  $\gamma$  rays
- spectrometers, Si, plastic detectors

$\gamma$  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

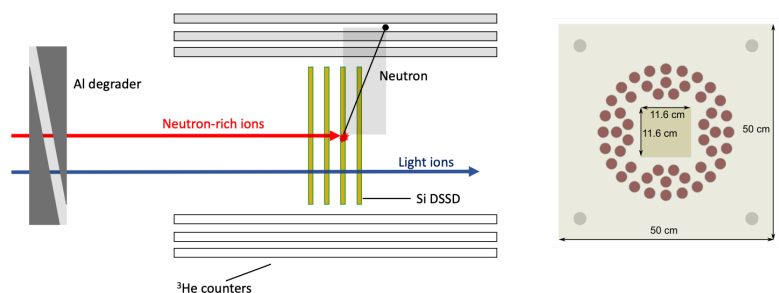


2 ways:

- TOF
- $^3\text{He}$  counters

# General Properties of $\beta$ decay

BEta-deLAYed Neutron detector (BELEN):  
48  $^3\text{He}$  cylindrical counters in Polyethylene moderator



- Successful 5-years BRIKEN campaign to measure  $\beta 1n$  and  $\beta 2n$  emission

VANDLE array : plastic scintillator bars, coupled to  $\beta$ - $\gamma$  det.  
neutron multiplicity and energy via TOF

Commissioning of the BRIKEN detector for the measurement of very exotic  $\beta$ -delayed neutron emitters

A. Tolosa-Delgado<sup>a</sup>, J. Agramunt<sup>a</sup>, J. L. Tain<sup>a,\*</sup>, A. Algorta<sup>a,b</sup>, C. Domingo-Pardo<sup>a</sup>, A. I. Morales<sup>a</sup>, B. Rubio<sup>a</sup>, A.

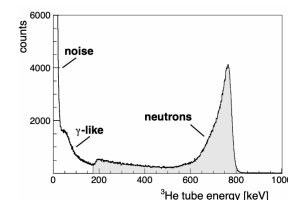
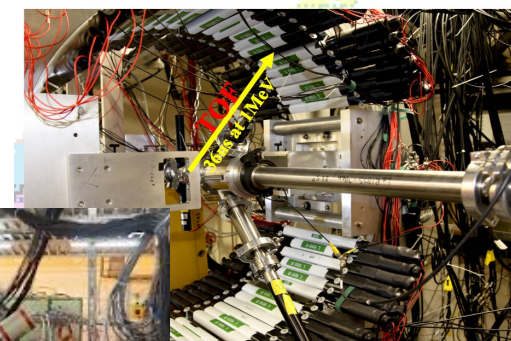


Figure 7: Distribution of energies registered in the  $^3\text{He}$  tubes of the BRIKEN neutron counter. The spectrum contains the sum of all  $^3\text{He}$  tube signals in one run. The shaded area represents the range of signals accepted as valid neutron signals. See text for details.

NIMA [925](#), 1 May 2019, Pages 133-147





### Existing arrays

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- $^3\text{He}$  counters

- B-Riken (Japan)
- Tetra (Dubna-Orsay)
- $^3\text{He}$ n (Oak Ridge)
- BELEN (GSI-FAIR)

- ✓ High angular coverage
- ✓ High efficiency ( $\sim 65\%$ )
- $\sim$  Flat efficiency in large range of energies
- X No energy information
- X Difficult to disentangle  $1n, 2n$

- TOF counters

- VANDLE (Oak Ridge)
- MONSTER (GSI-FAIR)
- TONNERE (GANIL)
- DESCANT (TRIUMF)

- ✓ High angular coverage
- ✓  $1n - 2n$  discrimination
- $\sim$  Good Resolution
- $\sim$  Position independent eff.
- X low detection threshold
- X high background



Nucleosynthesis is a gradual, still ongoing process:

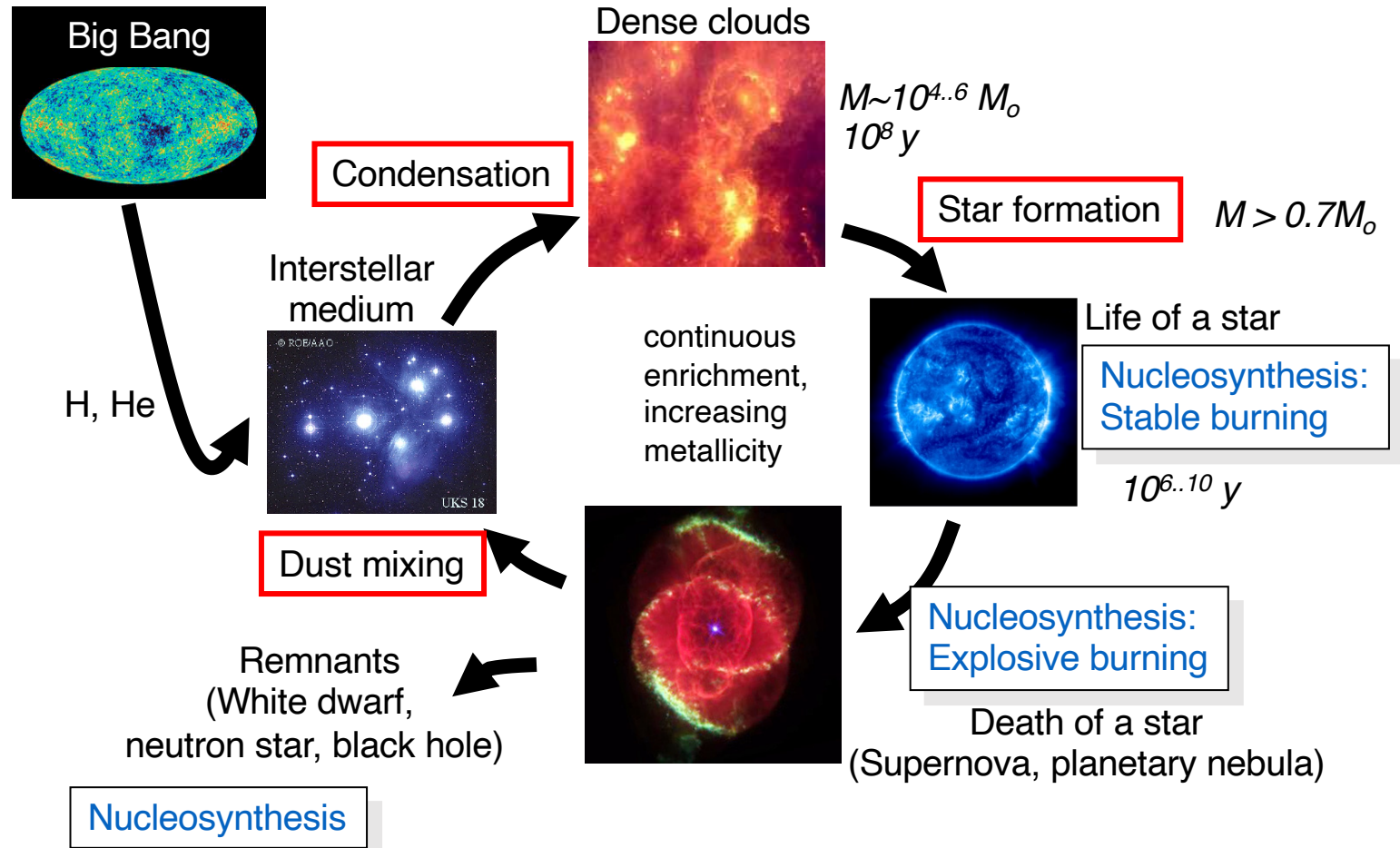
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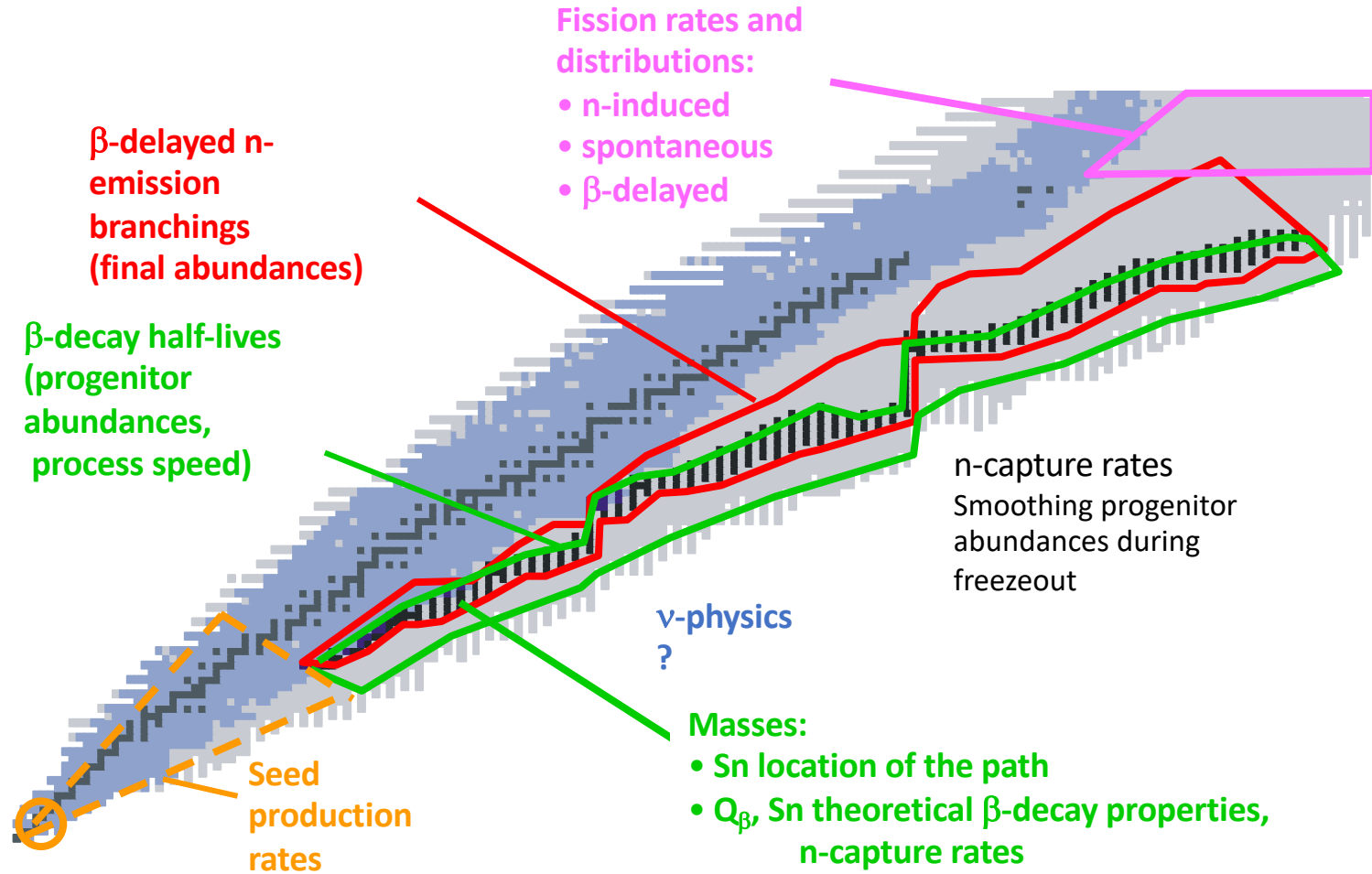
Conclusions



# Conclusions

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Element formation in stars  
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beta-decay spectroscopy towards the r-process G.Benzoni @ INFN-Milano

## Conclusions

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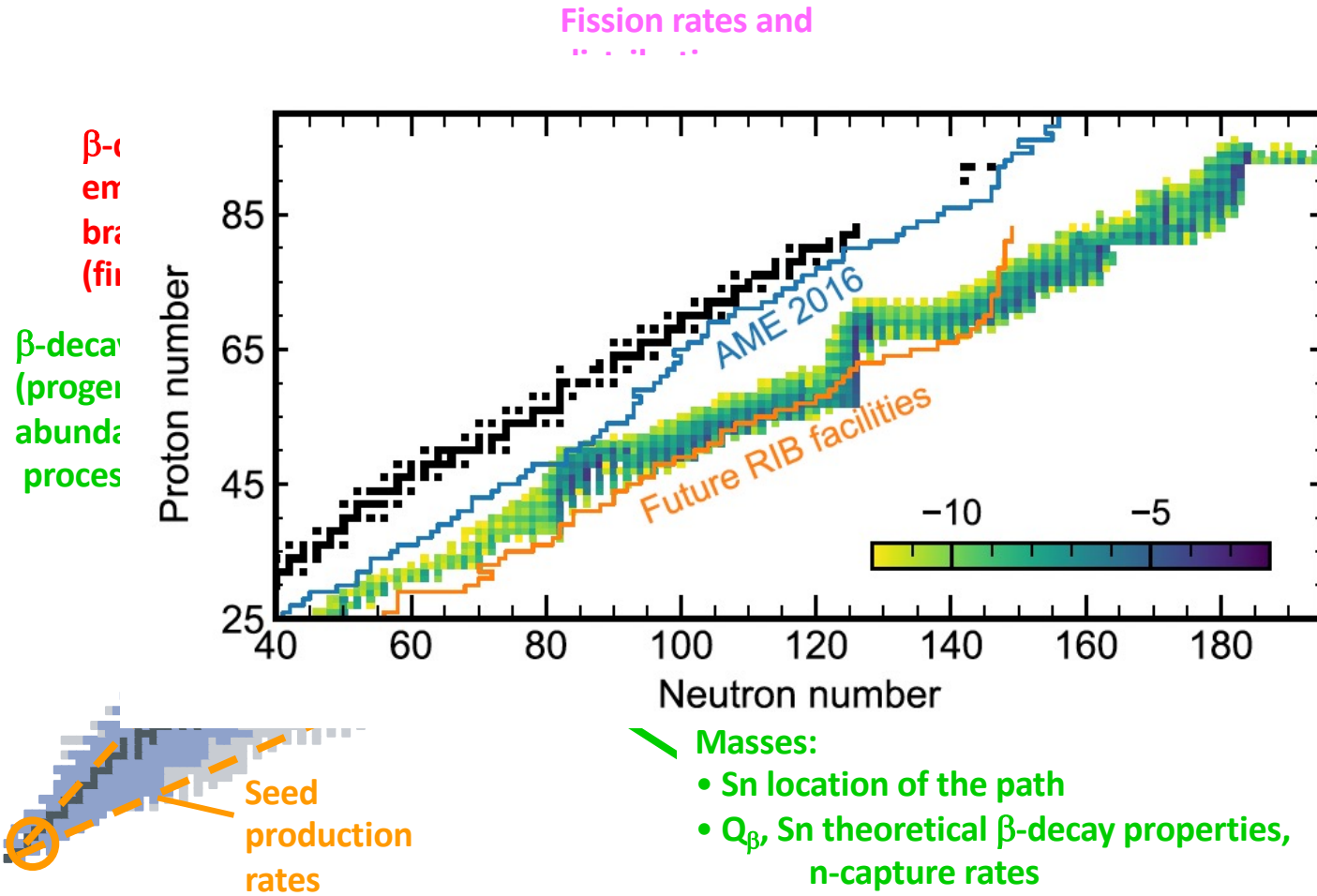
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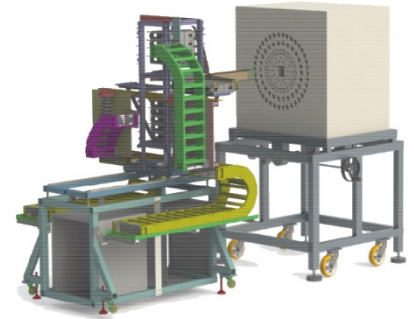
# Measuring neutrons after $\beta$ decay



The BEta deLAYed Neutron detector (BELEN) array of  $^3\text{He}$  tubes arranged in crowns around the beam hole embedded in a polyethylene matrix. Coupled to  $\beta$ - $\gamma$  detectors

Currently measuring at B-Riken

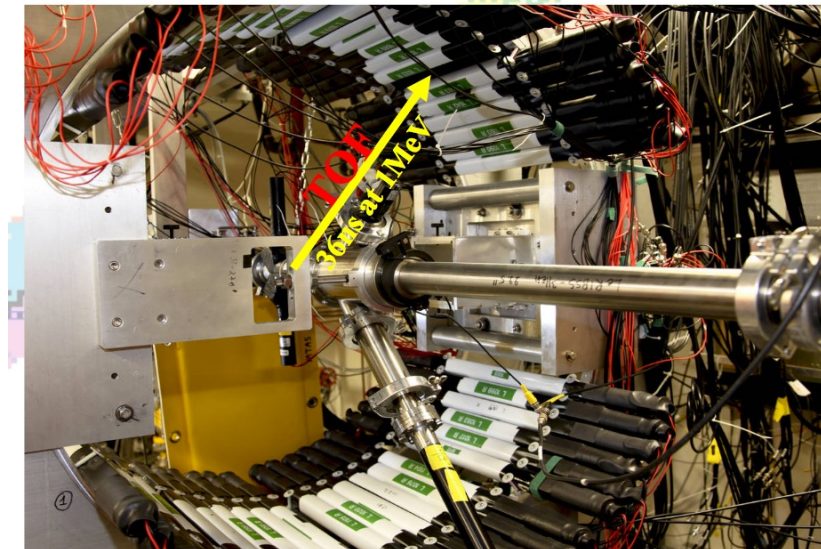
Competition with 3Hen / Tetra



VANDLE array : plastic scintillator bars, coupled to  $\beta$ - $\gamma$  det.  
neutron multiplicity and energy via TOF



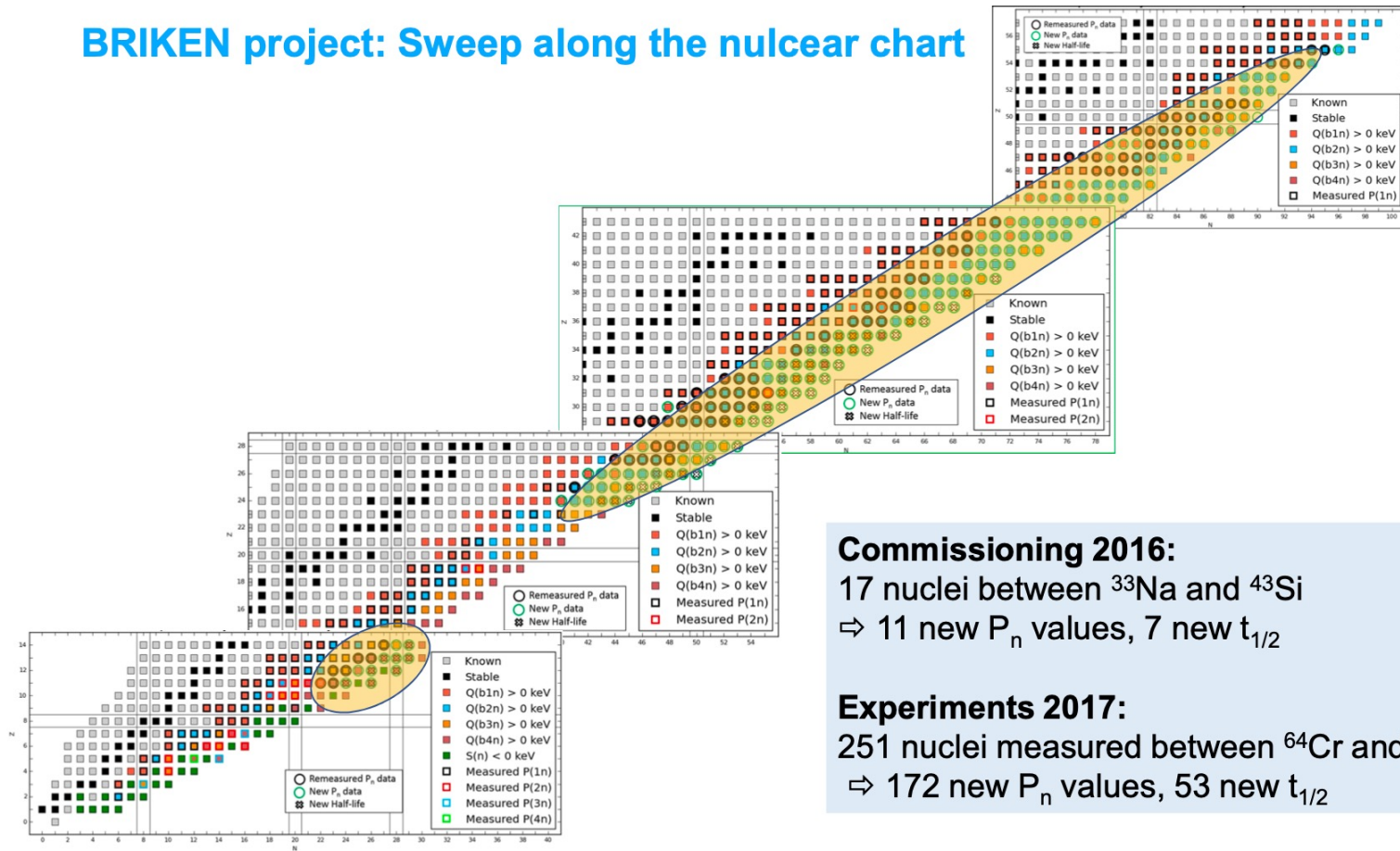
Currently measuring at IDS ISOLDE





# BRIKEN campaign: measurement of $P_n$ values at RIKEN

## BRIKEN project: Sweep along the nuclear chart



### Commissioning 2016:

17 nuclei between  $^{33}\text{Na}$  and  $^{43}\text{Si}$

⇒ 11 new  $P_n$  values, 7 new  $t_{1/2}$

### Experiments 2017:

251 nuclei measured between  $^{64}\text{Cr}$  and  $^{170}\text{Gd}$

⇒ 172 new  $P_n$  values, 53 new  $t_{1/2}$

# BRIKEN campaign

- Collection of all available He3 tubes in the world
- Coupling to Clover det. for ID and decay checks
- AIDA layers as active implantation det.
- Strong intensity from RIKEN acc. Complex

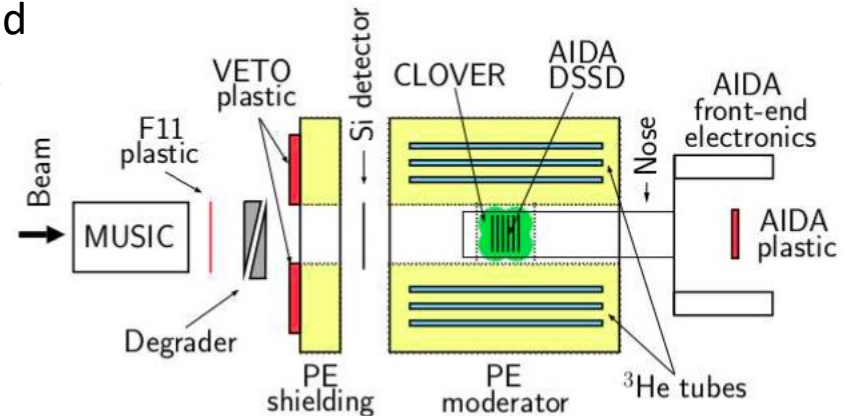


Figure 1: Arrangement of elements in the experimental setup mentioned in the text. The drawing is not to scale.

Commissioning of the BRIKEN detector for the measurement of very exotic  $\beta$ -delayed neutron emitters

A. Tolosa-Delgado<sup>a</sup>, J. Agramunt<sup>a</sup>, J. L. Tain<sup>a,\*</sup>, A. Algorta<sup>a,q</sup>, C. Domingo-Pardo<sup>a</sup>, A. I. Morales<sup>a</sup>, B. Rubio<sup>a</sup>, A.

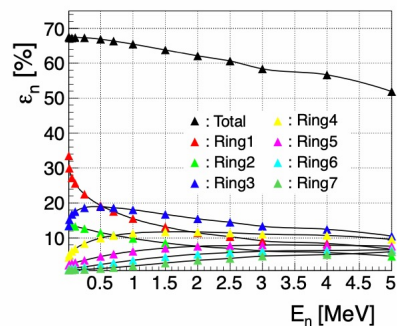


Figure 4: Efficiency of the BRIKEN neutron counter as a function of neutron energy. The total efficiency (black symbols) and the contribution of each ring (colored symbols) is shown. See Fig. 3 for the definition of rings.

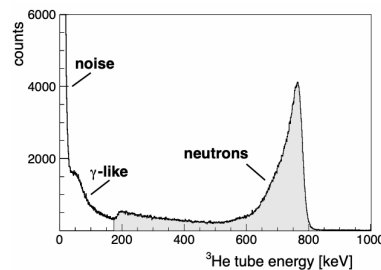


Figure 7: Distribution of energies registered in the  $^3\text{He}$  tubes of the BRIKEN neutron counter. The spectrum contains the sum of all  $^3\text{He}$  tube signals in run. The shaded area represents the range of signals accepted as valid net signals. See text for details.

**Nuclear Instruments and Methods in Physics Research**  
**Section A: Accelerators, Spectrometers, Detectors and**  
**Associated Equipment**

Volume 925, 1 May 2019, Pages 133-147

# Beta decay studies of the most exotic nuclei

Giovanna Benzoni

INFN sezione di Milano (Italy)

Outline of the lessons:

PARTI: General concepts

How to measure  $\beta$  decay in exotic nuclei

PARTII:  $\beta$  decay Gross properties  $T_{1/2}$  and  $P_n$

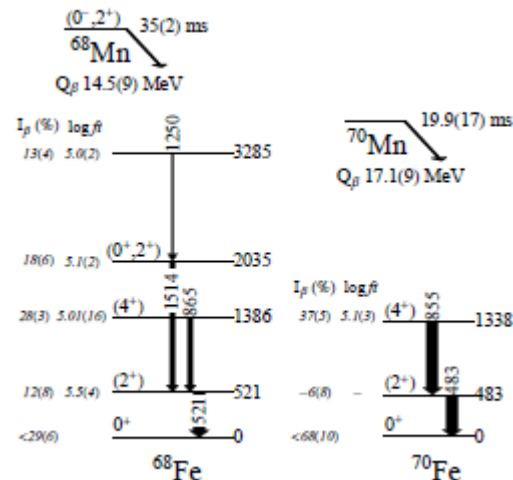
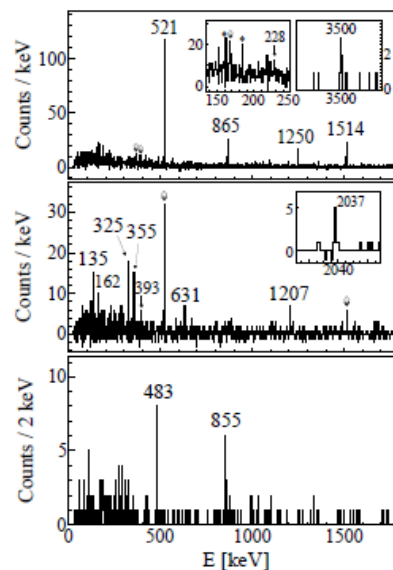
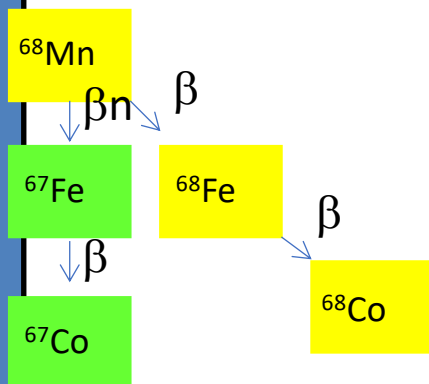
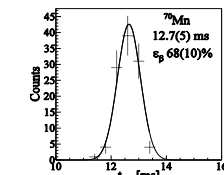
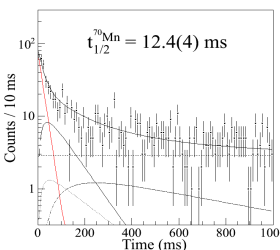
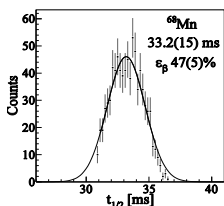
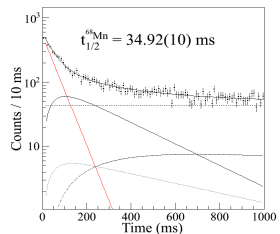
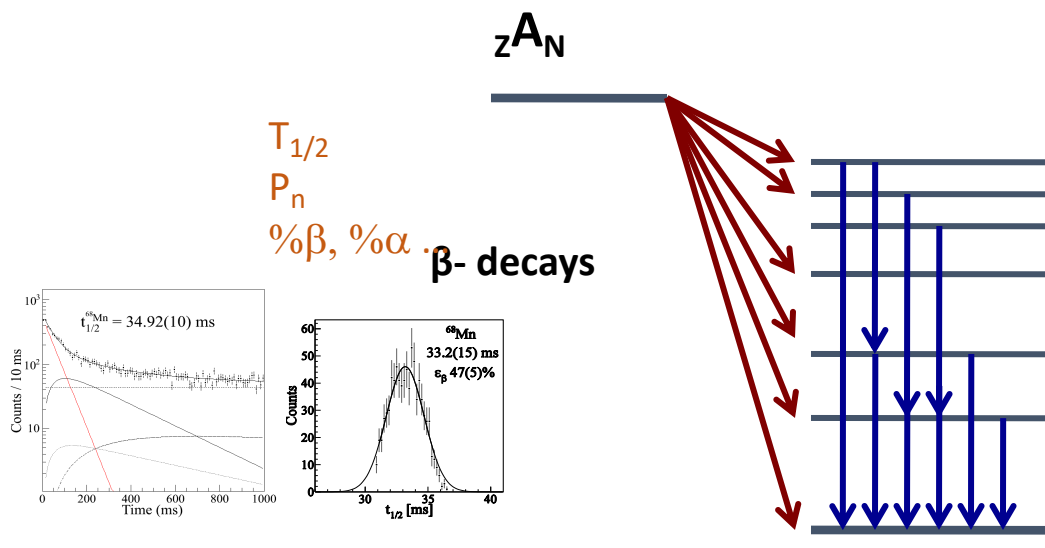
PARTIII: High resolution vs TAS





# General Properties of $\beta$ decay

Quantities that can be extracted in a  $\beta$  decay experiment



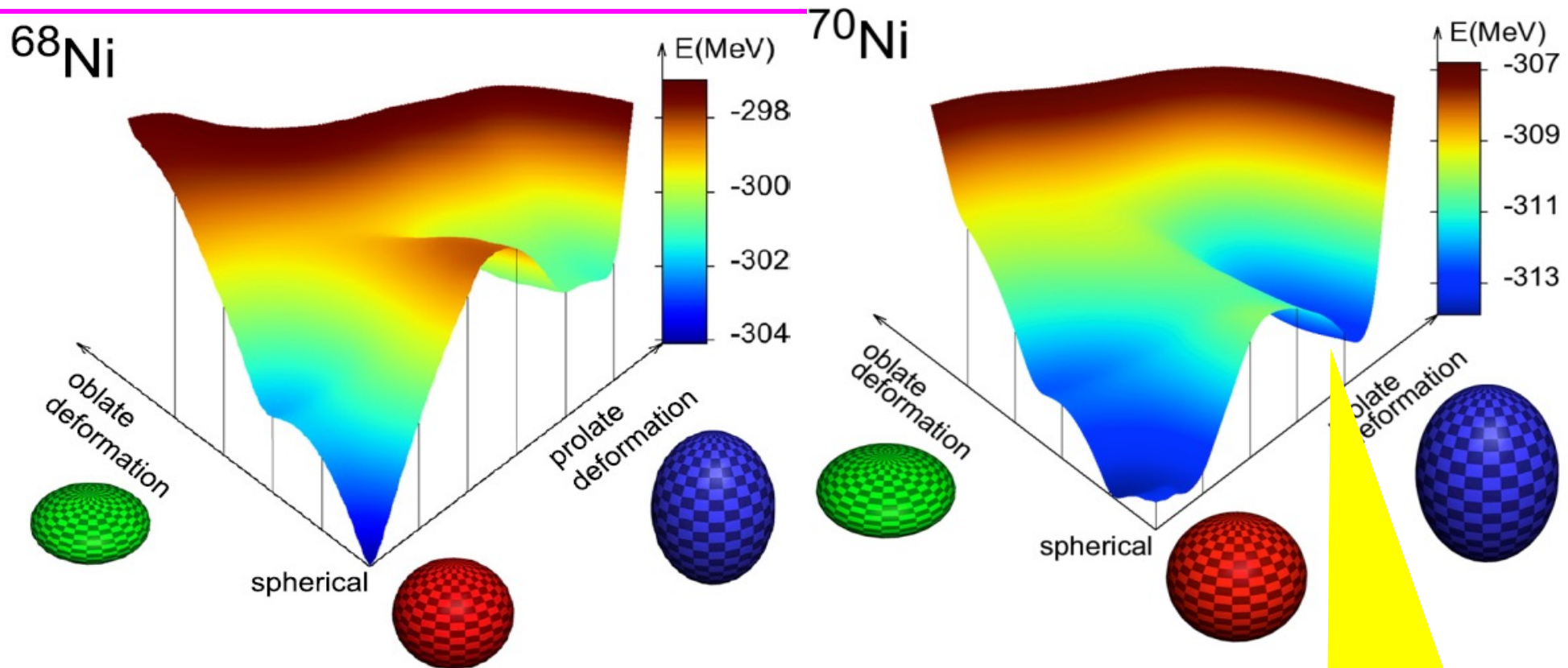
Selection rules allow to suggest/define  $I^\pi$  in both mother and daughter

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

# Triple shape coexistence in $^{68-70}\text{Ni}$

Shape transition and shell evolution also take place within the same nucleus

Three  $0^+$  states below 3 MeV in  $^{68}\text{Ni}$ , corresponding to local minima at spherical, oblate, and prolate shapes

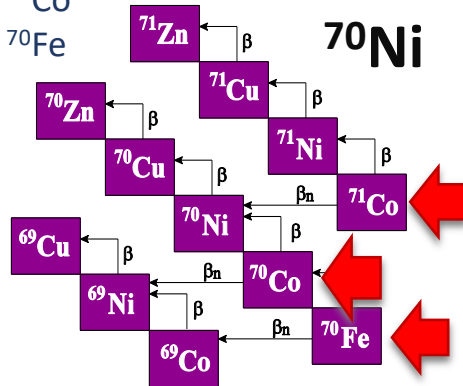


Shape coexistence

Deeper local minimum at prolate deformation

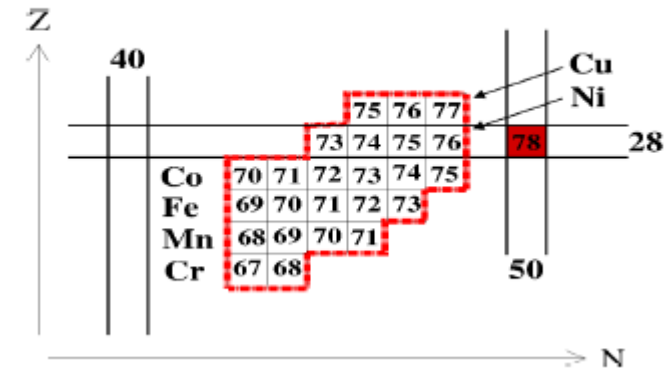
# Development of shape coexistence in $^{70}\text{Ni}$ : experiment

- $1.4 \times 10^5$   $^{70}\text{Co}$
- $1.6 \times 10^6$   $^{71}\text{Co}$
- $1.8 \times 10^5$   $^{70}\text{Fe}$

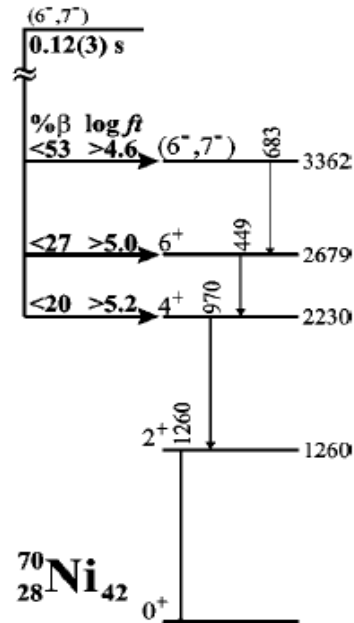


## • $^{70}\text{Ni}$ : shape coexistence

- $^{70}\text{Co} \rightarrow ^{70}\text{Ni}$  decay
- $^{71}\text{Co} \rightarrow ^{70}\text{Ni}$
- $^{70}\text{Fe} \rightarrow ^{70}\text{Co} \rightarrow ^{70}\text{Ni}$



$^{70}_{27}\text{Co}_{43}$

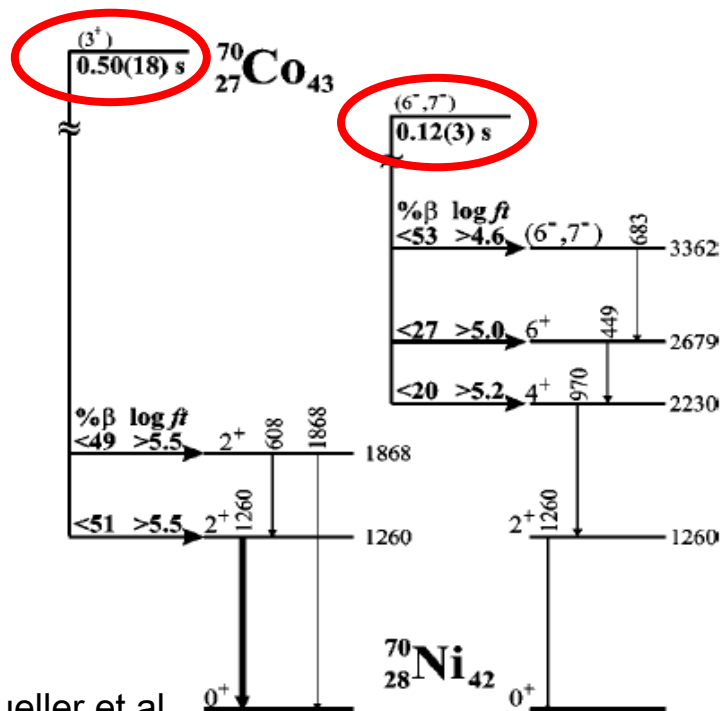
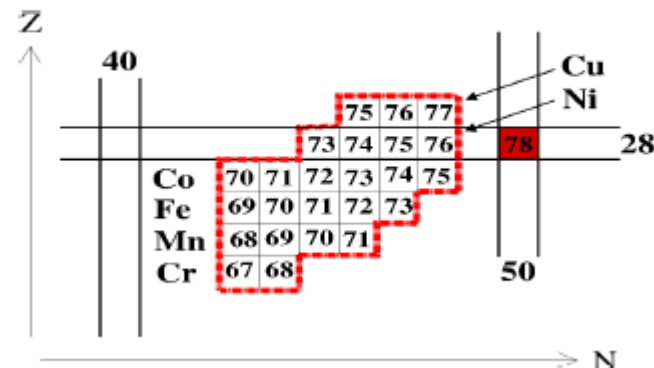


- Selection rules? Can we populate  $2^+/0^+$  states?

# Development of shape coexistence in $^{70}\text{Ni}$ : experiment

- $^{70}\text{Ni}$ : shape coexistence

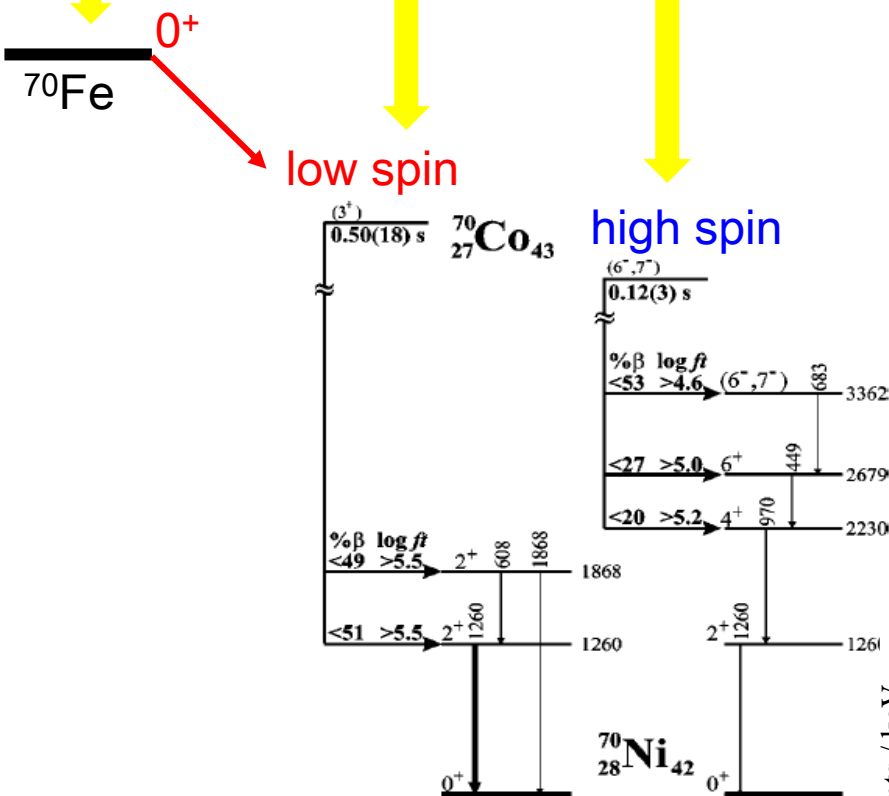
- $^{70}\text{Co} \rightarrow ^{70}\text{Ni}$  decay ➤  $1.4 \times 10^5$   $^{70}\text{Co}$
- $^{71}\text{Co} \rightarrow ^{70}\text{Ni}$  ➤  $1.6 \times 10^6$   $^{71}\text{Co}$
- $^{70}\text{Fe} \rightarrow ^{70}\text{Co} \rightarrow ^{70}\text{Ni}$  ➤  $1.8 \times 10^5$   $^{70}\text{Fe}$



- Selection rules? Can we populate  $2^+/0^+$  states?
- ∃ of Isomeric state  $J^p = 3^+$  allows population**
- Isomeric ratio: probability of populating this state in fragmentation/fission reaction is limited (dependence on spin) (45% in this case)
- $T_{1/2}$  are similar ➔ difficult to disentangle the two decays**
- Help by g-g coincidences BUT high statistics mandatory

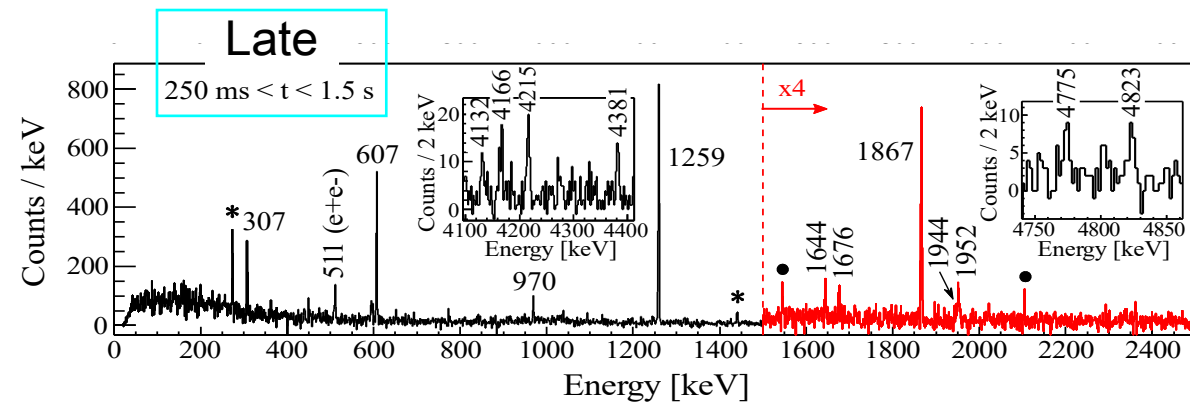
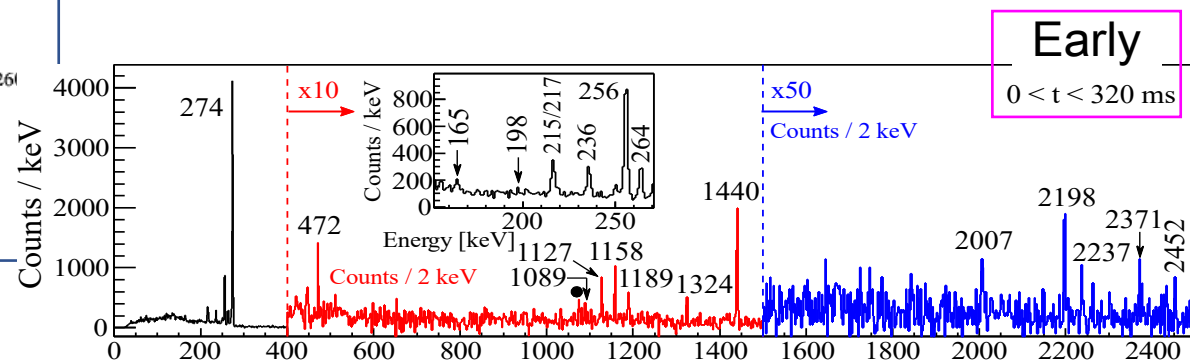
➔ use a different decay chain  $^{70}\text{Fe} \rightarrow ^{70}\text{Co} \rightarrow ^{70}\text{Ni}$

## $^{238}\text{U}$ in-flight fission



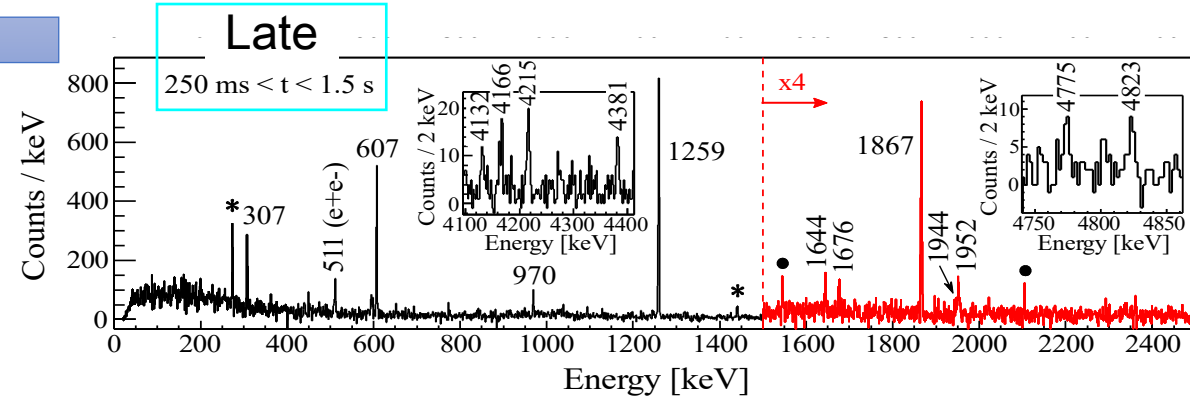
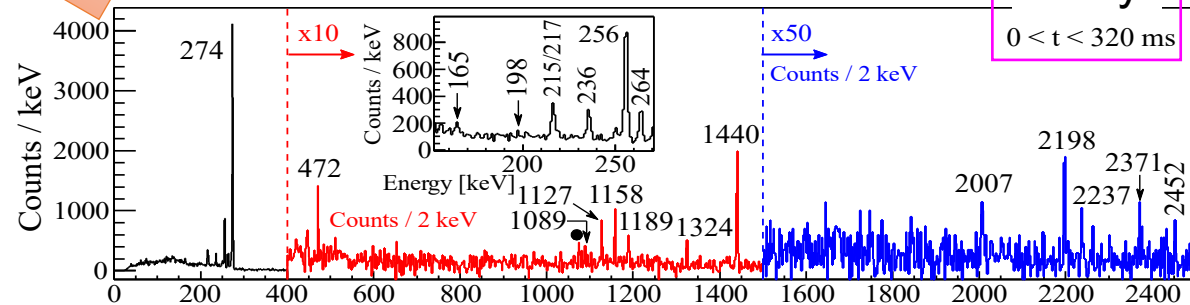
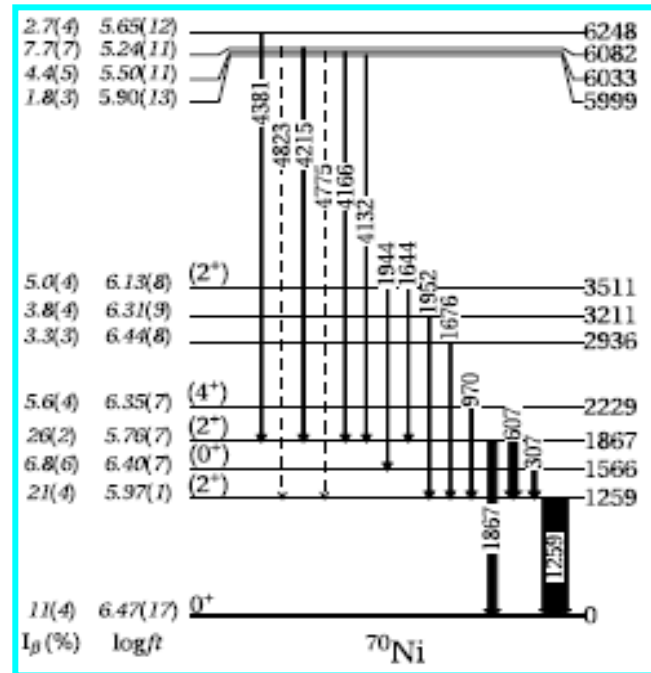
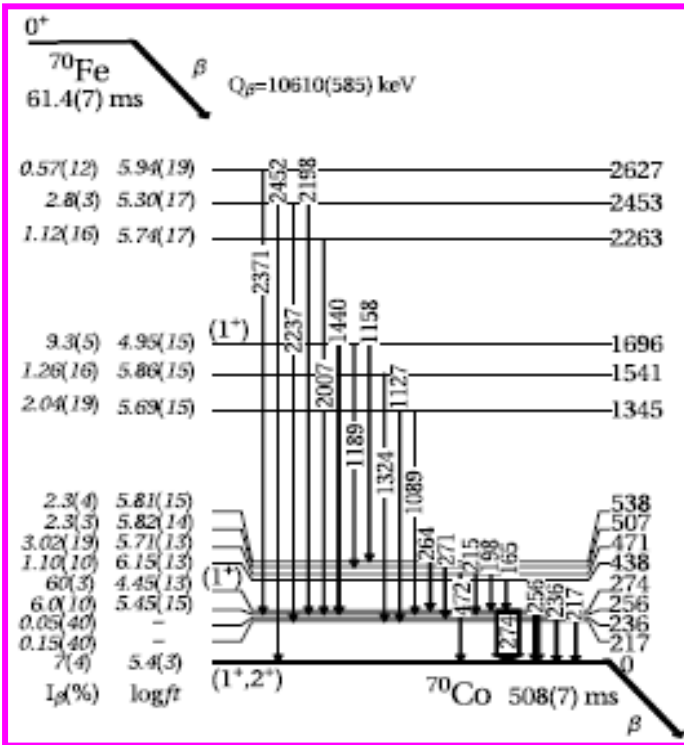
## $\beta$ decay in the $A = 70$ isobaric chain

- Two long-lived  $\beta$ -decaying states at high and low spins in  $^{70}\text{Co}$
- Low-spin  $\beta$ -decaying state in  $^{70}\text{Co}$  isolated via the  $\beta$  decay of  $^{70}\text{Fe}$
- Selectively populate low-spin states in  $^{70}\text{Ni}$



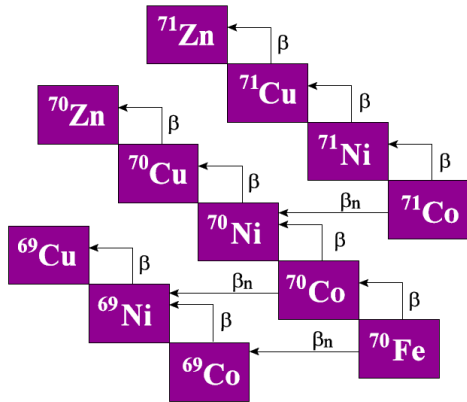
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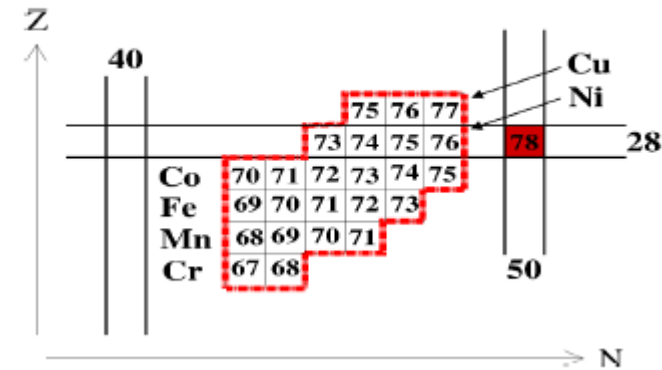
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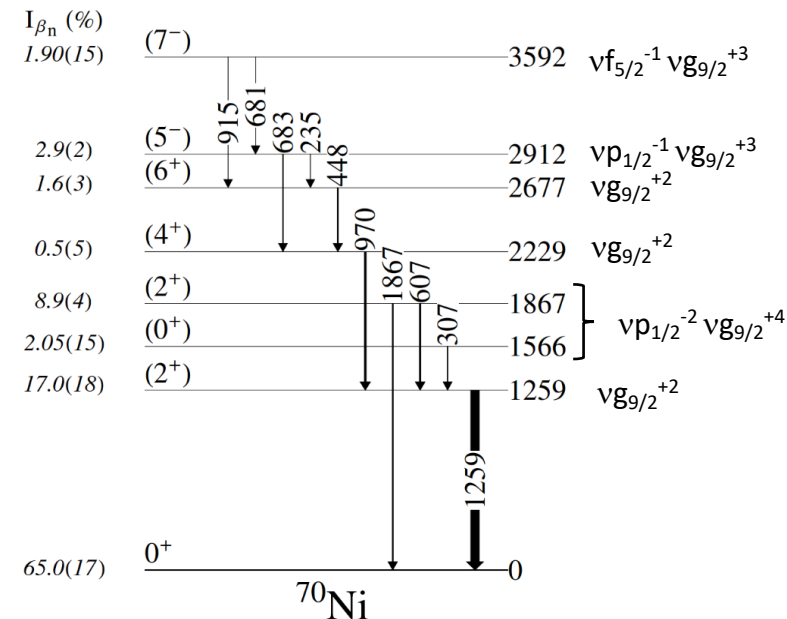
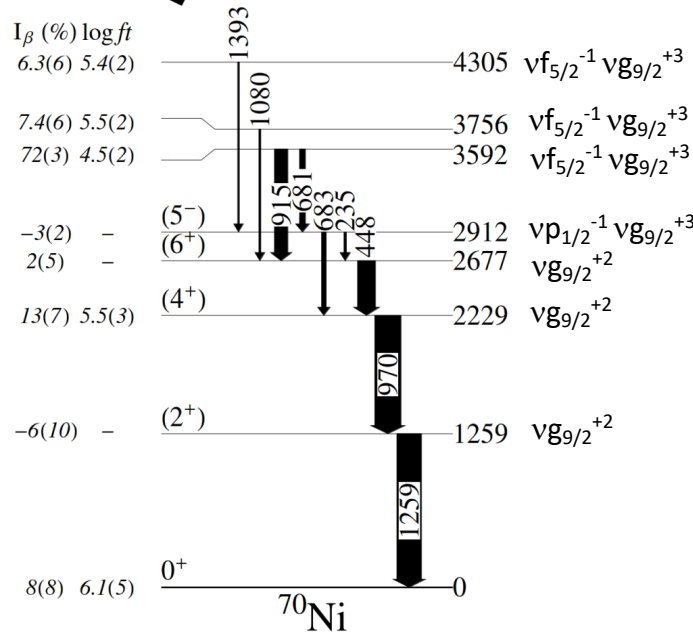
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- $^{71}\text{Co} \rightarrow ^{70}\text{Ni}$
- $^{70}\text{Fe} \rightarrow ^{70}\text{Co} \rightarrow ^{70}\text{Ni}$



$(6^-, 7^-)$   $^{70}\text{Co}$  104(2) ms  $\pi f_{7/2}^{-1} v g_{9/2}^{+3}$   
 $\beta$  93.9(8)%  
 $Q_\beta$  13500 keV

$(7/2^-)$   $^{71}\text{Co}$  89.1(8) ms  
 $(5/2^-, 7/2^-, 9/2^-)$   
 $\beta_n$  16(2)%  
 $Q_\beta$  11300 keV  
 $S_n$  4264 keV





Use different decay paths to effectively populate wanted nuclei  
 ➔ Access to refractory elements at ISOL facility via decay chains

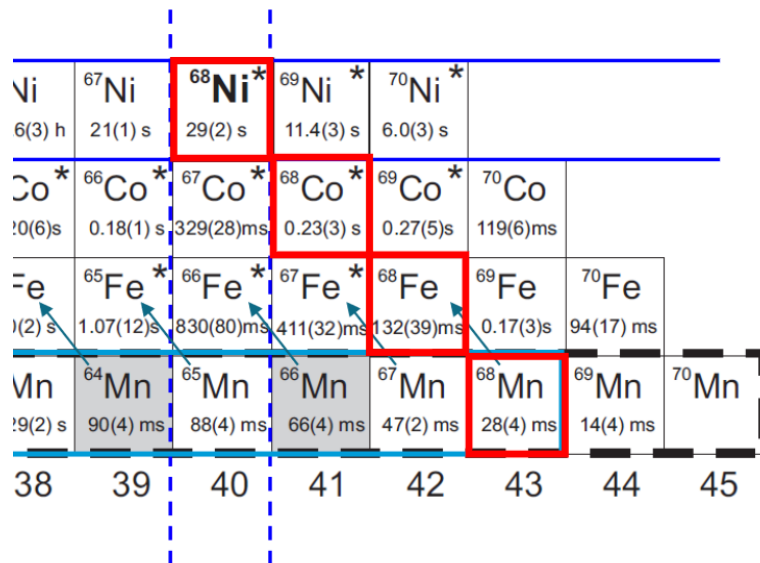
- **A=68**

- Previous exp. : 2 isomers in  $^{68}\text{Co}$

- (7-)  $T_{1/2} = 0,23(3) \text{ s}$

- **(1<sup>+</sup>,3<sup>+</sup>)  $T_{1/2} = 1,6(3) \text{ s}$**

- ISOLDE: **Selectivity of  $^{68}\text{Fe}_{\text{gs}}$  (0<sup>+</sup>) decay**



|                   |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
|-------------------|----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|----|----|----|
| ION SOURCE        |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| + SURFACE -       |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| hot PLASMA cooled |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| LASER             |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| H                 |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    | He |
| Li                | Be |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| Na                | Mg |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
| K                 | Ca | Sc | Ti | V  | Cr | Mn | Fe | Co | Ni | Cu | Zn  | Ga  | Ge  | As  | Se | Br | Kr |
| Rb                | Sr | Y  | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd  | In  | Sn  | Sb  | Te | I  | Xe |
| Cs                | Ba | La | Hf | Ta | W  | Re | Os | Ir | Pt | Au | Hg  | Tl  | Pb  | Bi  | Po | At | Rn |
| Fr                | Ra | Ac | Rf | Db | Sg | Bh | Hs | Mt | Ds | Rg | 112 | 113 | 114 | 115 |    |    |    |
|                   |    |    |    |    |    |    |    |    |    |    |     |     |     |     |    |    |    |
|                   |    |    | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy  | Ho  | Er  | Tm  | Yb | Lu |    |
|                   |    |    | Th | Pa | U  | Np | Pu | Am | Cm | Bk | Cf  | Es  | Fm  | Md  | No | Lr |    |

PHYSICAL REVIEW C 91, 034310 (2015)

Characterization of the low-lying 0<sup>+</sup> and 2<sup>+</sup> states in  $^{68}\text{Ni}$  via  $\beta$  decay of the low-spin  $^{68}\text{Co}$  isomer

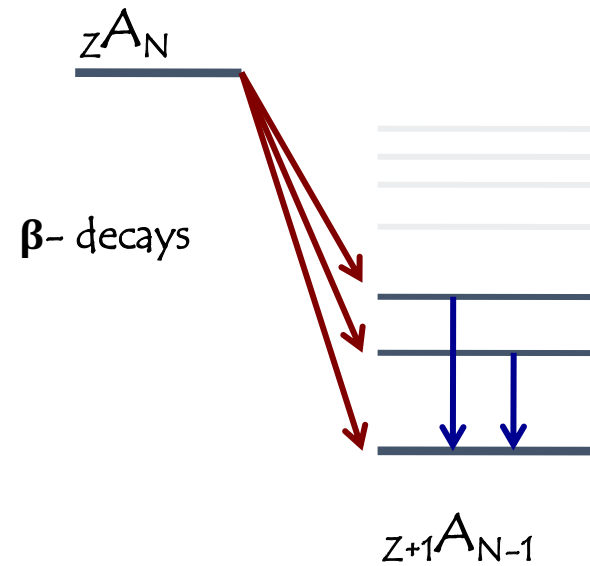
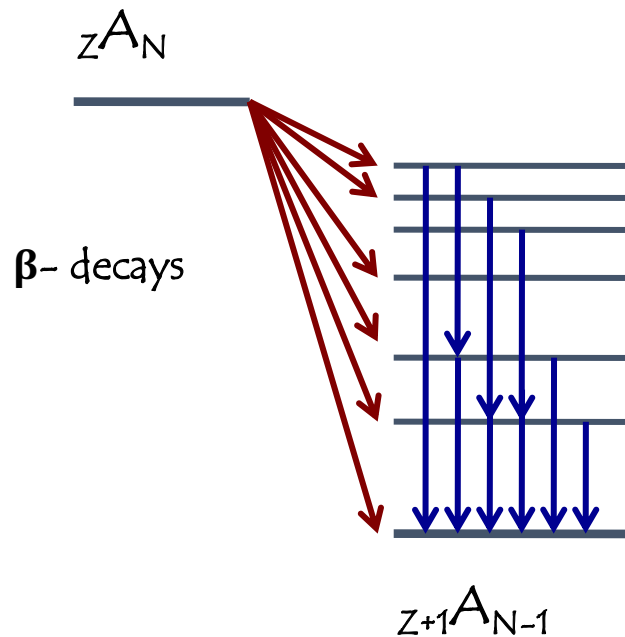
F. Flavigny,<sup>1,\*</sup> D. Pauwels,<sup>1</sup> D. Radulov,<sup>1</sup> I. J. Darby,<sup>1</sup> H. De Witte,<sup>1</sup> J. Diriken,<sup>1,2</sup> D. V. Fedorov,<sup>3</sup> V. N. Fedosseev,<sup>4</sup>  
 L. M. Fraile,<sup>5</sup> M. Huyse,<sup>1</sup> V. S. Ivanov,<sup>3</sup> U. Köster,<sup>6</sup> B. A. Marsh,<sup>4</sup> T. Otsuka,<sup>7,8</sup> L. Popescu,<sup>2</sup> R. Raabe,<sup>1</sup> M. D. Seliverstov,<sup>1,3,9</sup>  
 N. Shimizu,<sup>7</sup> A. M. Sjödin,<sup>4</sup> Y. Tsunoda,<sup>8</sup> P. Van den Bergh,<sup>1</sup> P. Van Duppen,<sup>1</sup> J. Van de Walle,<sup>10</sup> M. Venhart,<sup>1,11</sup>  
 W. B. Walters,<sup>12</sup> and K. Wimmer<sup>8,13</sup>

<sup>1</sup>KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium

<sup>2</sup>Radiation Nuclear Research Centre SCK-CEN, Boeretan 200, B-7400 Mol, Belgium

➔ Help of high Pn to reach wanted species with low contaminants

# General Properties of $\beta$ decay



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

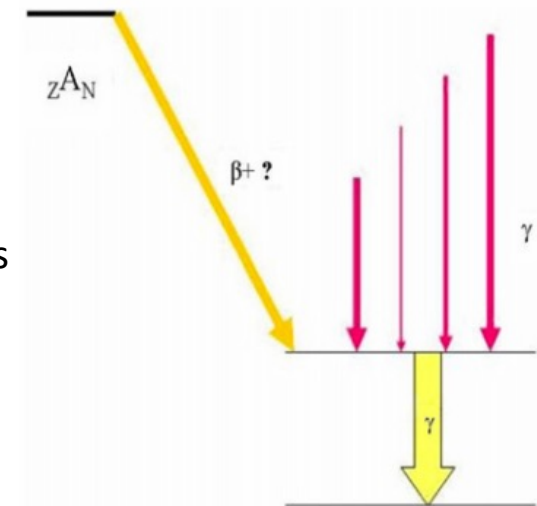
➔ Higher Qvalue higher possibility of missing feeding

- From the  $\gamma$  intensity balance we deduce the  $\beta$ -feeding

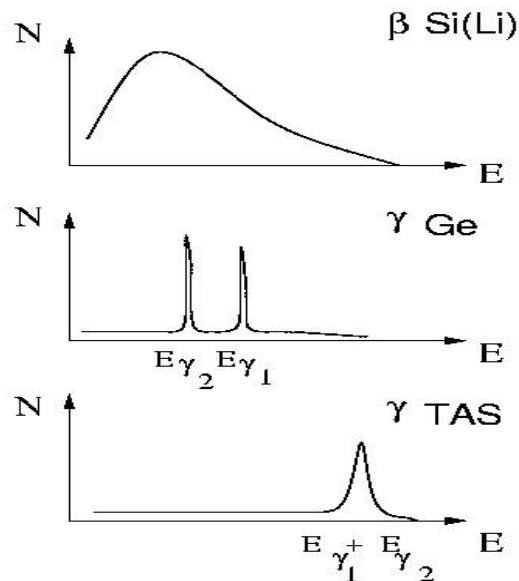
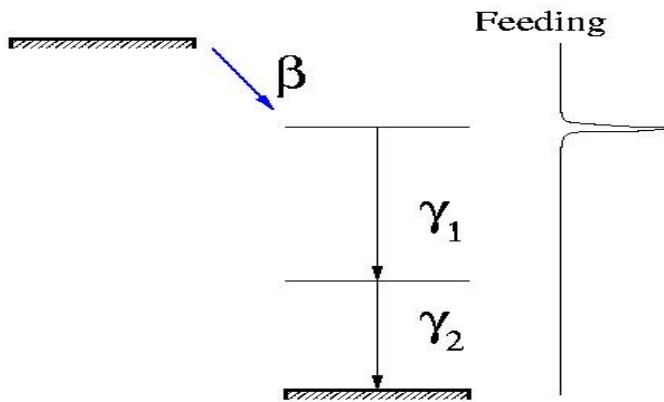
Pandemonium effect implies

➔ Wrong definition of gamma feeding and branching ratios

$I_b$  and  $\log ft$



# TAGS measurements



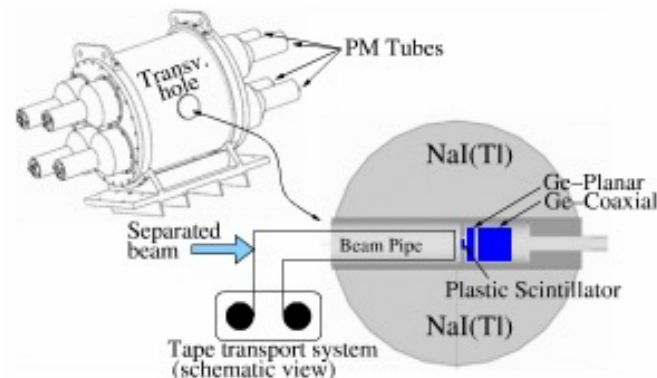
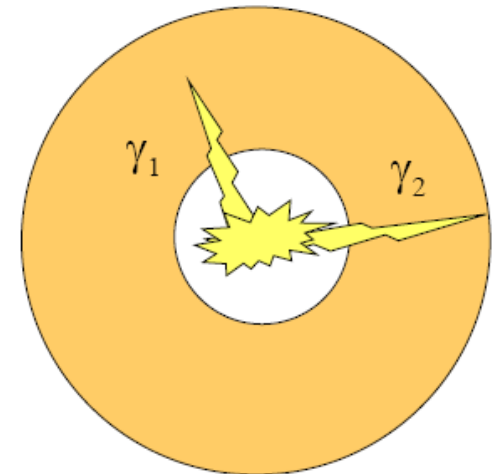
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

## A TOTAL ABSORTION SPECTROMETER

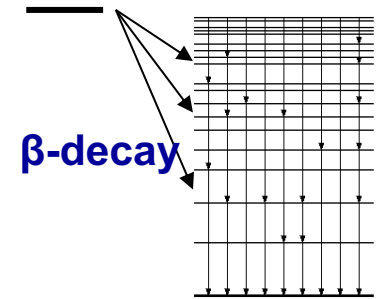
But there is a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

A TAS is like a calorimeter!

Big crystal,  $4\pi$  (BaF<sub>2</sub>/NaI/HPGe)



# TAGS analysis



$$d_i = \sum_{j=1}^{j_{max}} R_{ij} I(E_j)$$

$d_j$  = exp. data in channel  $i$   
 $I(E_j)$  = beta feeding of  $j$  state

**$R$**  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

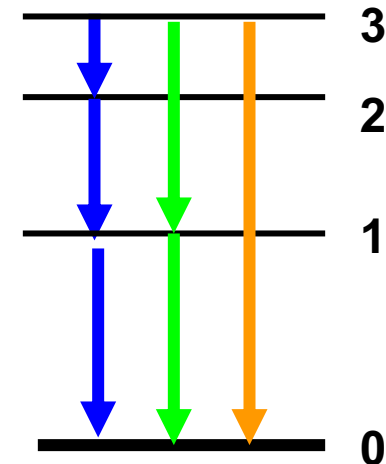
The response matrix  **$R$**  can be constructed by recursive convolution:

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

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

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

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



# TAS measurement $^{70}\text{Co} \rightarrow ^{70}\text{Ni}$

NSCL  $^{86}\text{Kr}$  @140MeV/u on  $^9\text{Be}$

Summing NaI (SuN)

$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$

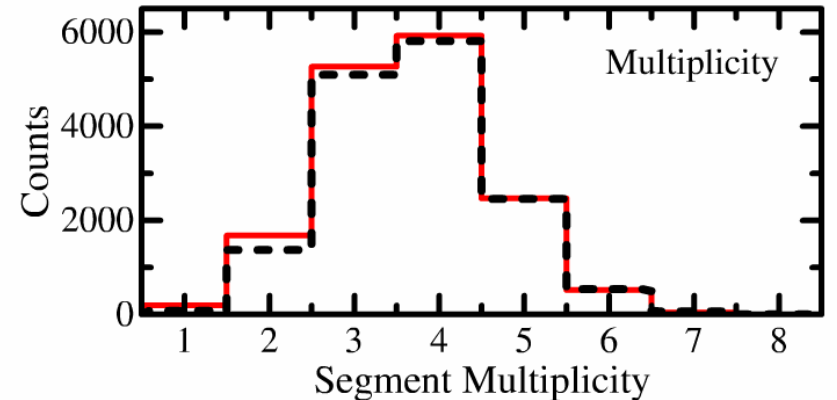
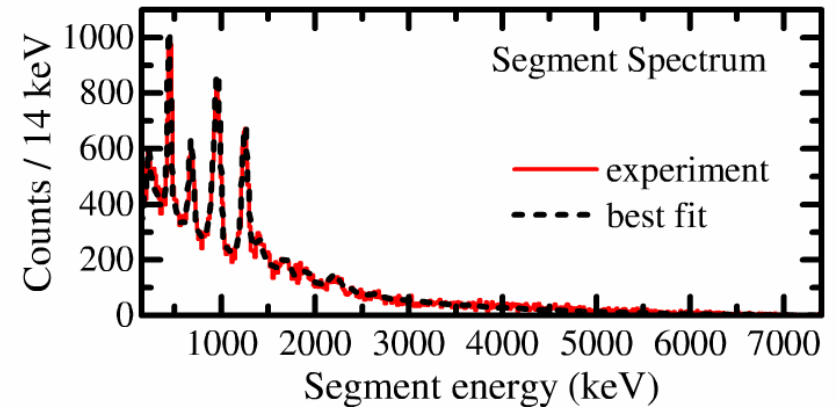
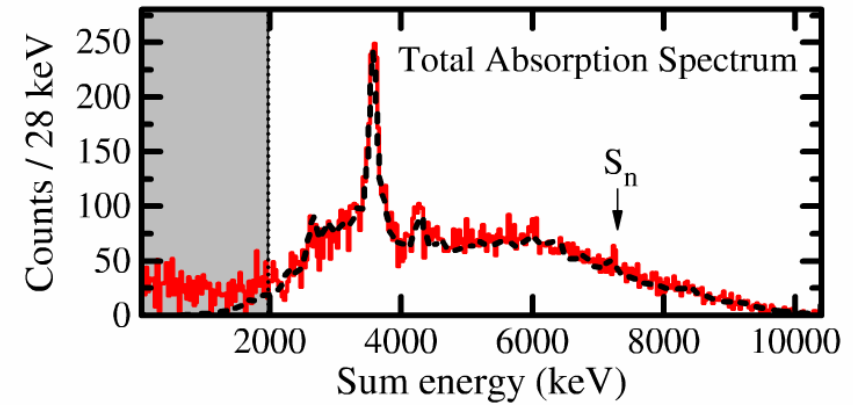
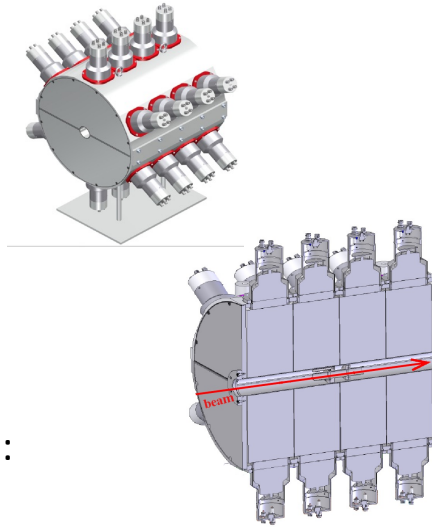
Only visible decay from g.s. ( $6^-/7^-$ )

To extract  $S_\beta$  one uses 3 information:

- Energy sum of each segment
- Energy spectrum of individual segments  $\rightarrow$  individual  $\gamma$ s
- Multiplicity

Compared to GEANT4 simulation of response:

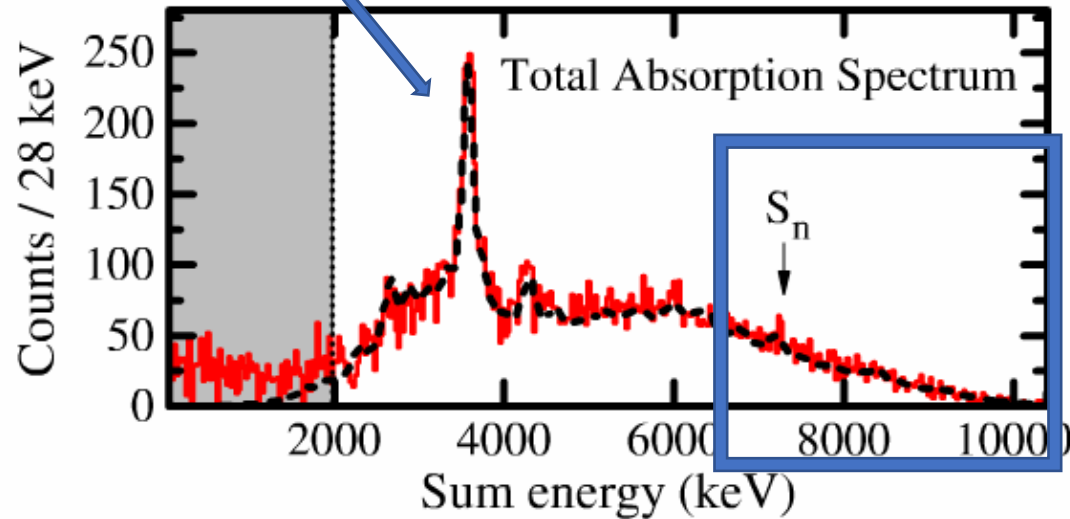
- Known level scheme up to 4 MeV
- Statistical decay above (up to  $Q_\beta = 13.5$  MeV)



## Strong Neutron- $\gamma$ Competition above the Neutron Threshold in the Decay of $^{70}\text{Co}$

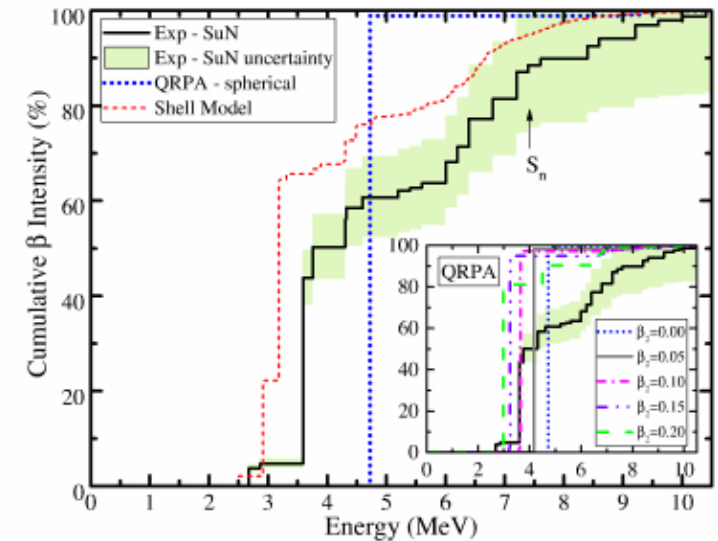
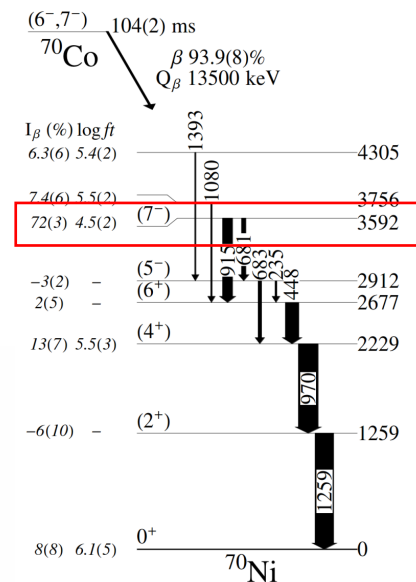
A. Spyrou,<sup>1,2,3,\*</sup> S. N. Liddick,<sup>1,4,3</sup> F. Naqvi,<sup>1,3</sup> B. P. Crider,<sup>1</sup> A. C. Dombos,<sup>1,2,3</sup> D. L. Bleuel,<sup>5</sup> B. A. Brown,<sup>1,2,3</sup> A. Couture,<sup>6</sup> L. Crespo Campo,<sup>7</sup> M. Guttormsen,<sup>7</sup> A. C. Larsen,<sup>7</sup> R. Lewis,<sup>1,4</sup> P. Möller,<sup>6</sup> S. Mosby,<sup>6</sup> M. R. Mumpower,<sup>6</sup> G. Perdikakis,<sup>8,1,3</sup> C. J. Prokop,<sup>1,4</sup> T. Renstrøm,<sup>7</sup> S. Siem,<sup>7</sup> S. J. Quinn,<sup>1,2,3</sup> and S. Valenta<sup>9</sup>

Strong population of 3.592 MeV state



continuous distribution and strong  $\gamma$ -ray emission above the neutron-separation energy at 7.3 MeV

WARNING: no  $\beta$ -delayed n emission seen  
 → 10% error owing to this missing information



$S_n < Q_\beta$  is not sufficient to guarantee sizable contribution of  $\beta$ -n channel

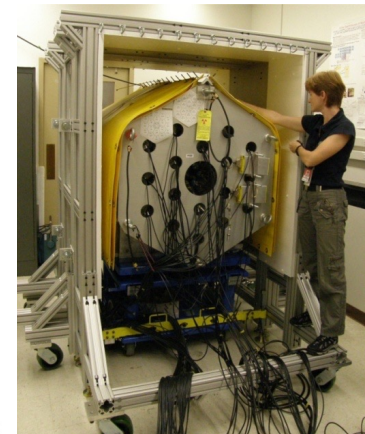
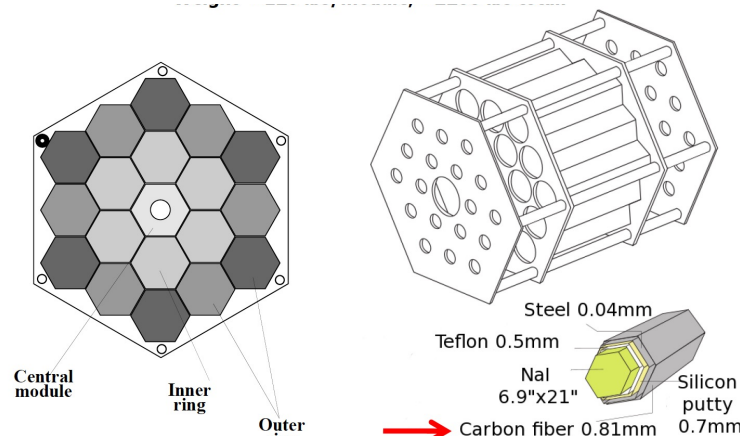
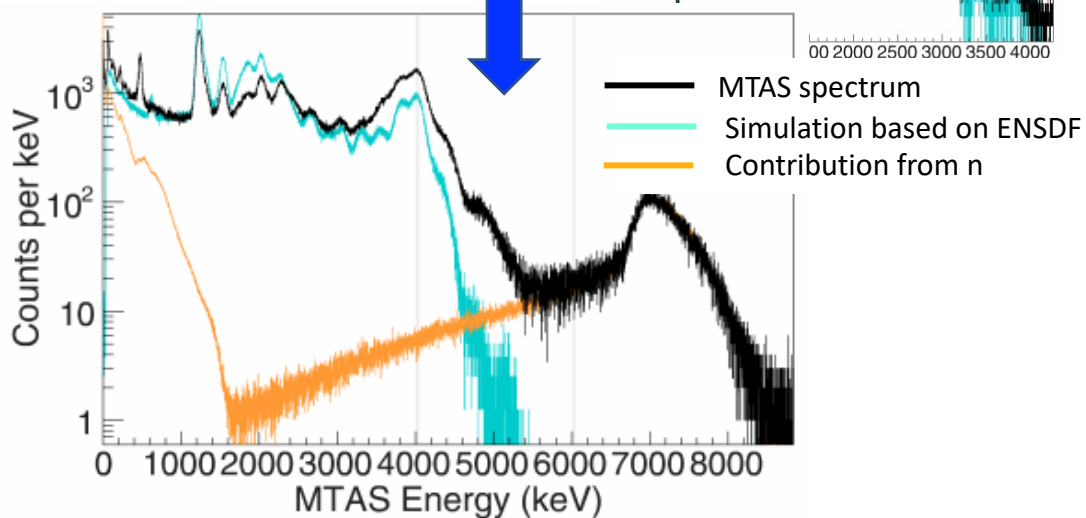
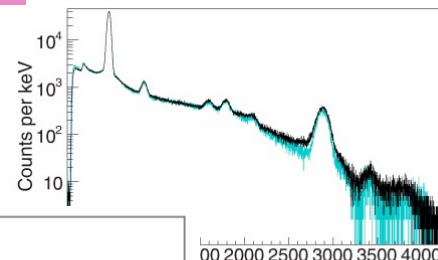


# TAS measurement for decay heat evaluation

|                                             |                                                   |                                             |                                                         |                                            |
|---------------------------------------------|---------------------------------------------------|---------------------------------------------|---------------------------------------------------------|--------------------------------------------|
| <sup>137</sup> Ba<br>STABLE<br>11.232%      | <sup>138</sup> Ba<br>STABLE<br>71.698%            | <sup>139</sup> Ba<br>83.06 M<br>β-: 100.00% | <sup>140</sup> Ba<br>12.7527 D<br>β-: 100.00%           | <sup>141</sup> Ba<br>2.27 D<br>β-: 100.00% |
| <sup>136</sup> Cs<br>13.04 D<br>β-: 100.00% | <sup>137</sup> Cs<br>30.08 Y<br>β-: 100.00%       | <sup>138</sup> Cs<br>33.41 M<br>β-: 100.00% | <sup>139</sup> Cs<br>9.27 M<br>β-: 100.00%              | <sup>140</sup> Cs<br>63.8 D<br>β-: 100.00% |
| <sup>135</sup> Xe<br>9.14 H<br>β-: 100.00%  | <sup>136</sup> Xe<br>>2.4E+21 Y<br>8.8573%<br>2β- | <sup>137</sup> Xe<br>3.818 M<br>β-: 100.00% | <sup>138</sup> Xe<br>1.25 E<br>β-: 100.00%              | <sup>139</sup> Xe<br>1.47 D<br>β-: 100.00% |
| <sup>134</sup> I<br>20.6 M<br>β-: 100.00%   | <sup>135</sup> I<br>6.6 H<br>β-: 100.00%          | <sup>136</sup> I<br>8.1 D<br>β-: 100.00%    | <sup>137</sup> I<br>24.5 S<br>β-: 100.00%<br>β-n: 7.14% | <sup>138</sup> I<br>1.07 M<br>β-: 100.00%  |

$Q_{\beta}=4162(3)$  keV

$Q_{\beta}=6027(8)$  keV



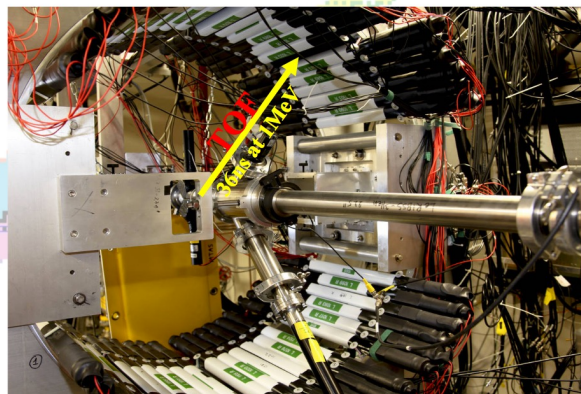
2200 pounds of NaI(Tl) - **Modular** Total Absorption Spectrometer (MTAS) and its 12,000 pound shielding

Compared to the ENSDF  $\beta$ -feeding data there are many more  $\gamma$  rays measured by MTAS in the continuously binned region above Sn energy than previously reported

The average  $\gamma$  energy for <sup>137</sup>I decay measured with MTAS increases by 19% compared to the ENSDF data

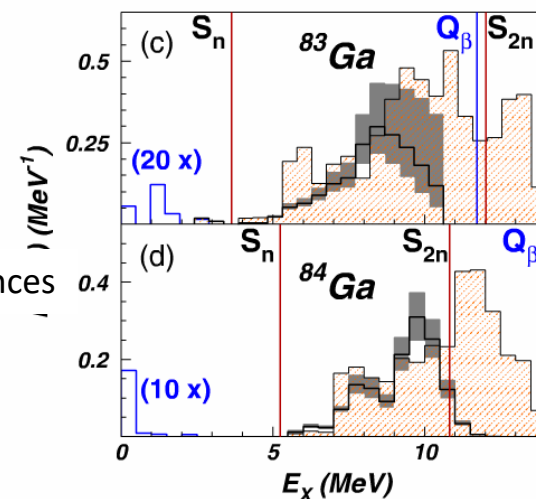
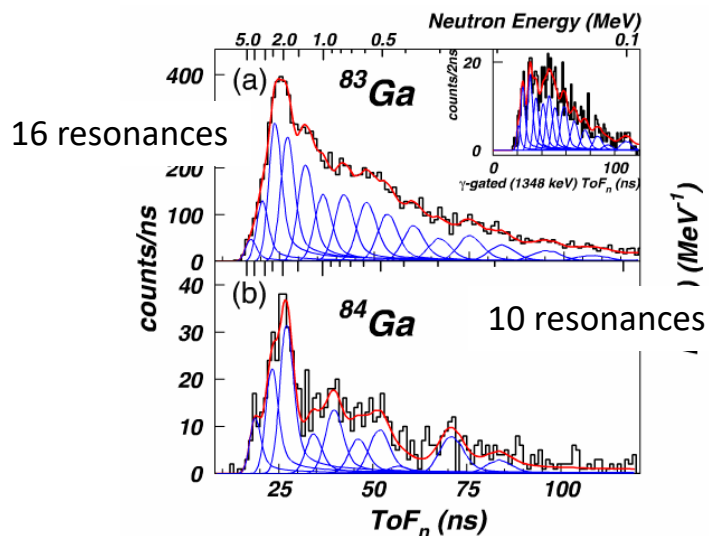
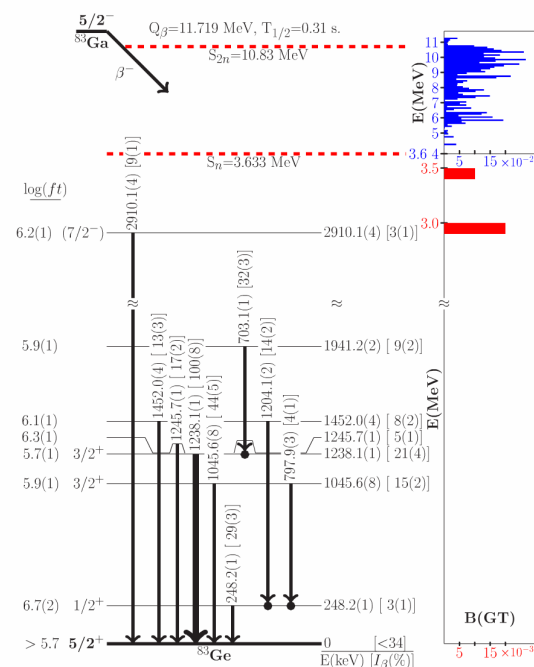
G.s. feeding increases from  $45.2 \pm 0.7\%$  to  $49 \pm 1\%$ .





## VANDLE array at HRIBF (USA): measuring n via TOF

- 48 bars 3x3 x 60 cm<sup>3</sup>
- $\Omega = 10\%$  (23%) of  $4\pi$
- $\sim 3\%$  (6%) total efficiency @ 1 MeV
- 50 cm TOF radius
- 40-60% efficiency beta "START" detector
- + 2 HPGe detectors (3% eff at 1.3 MeV)

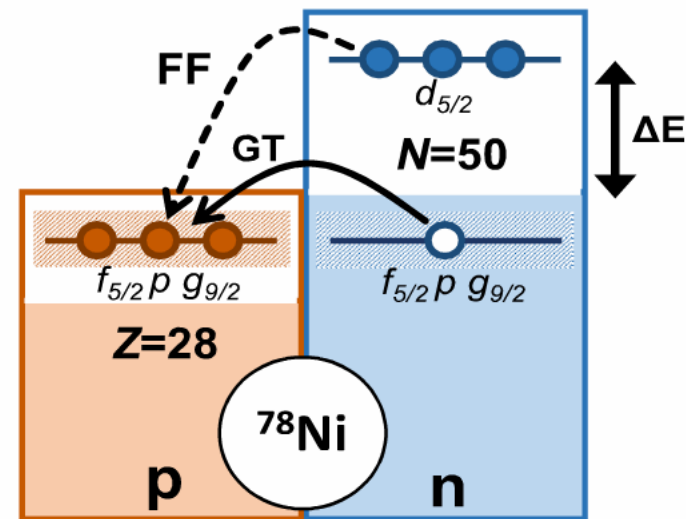
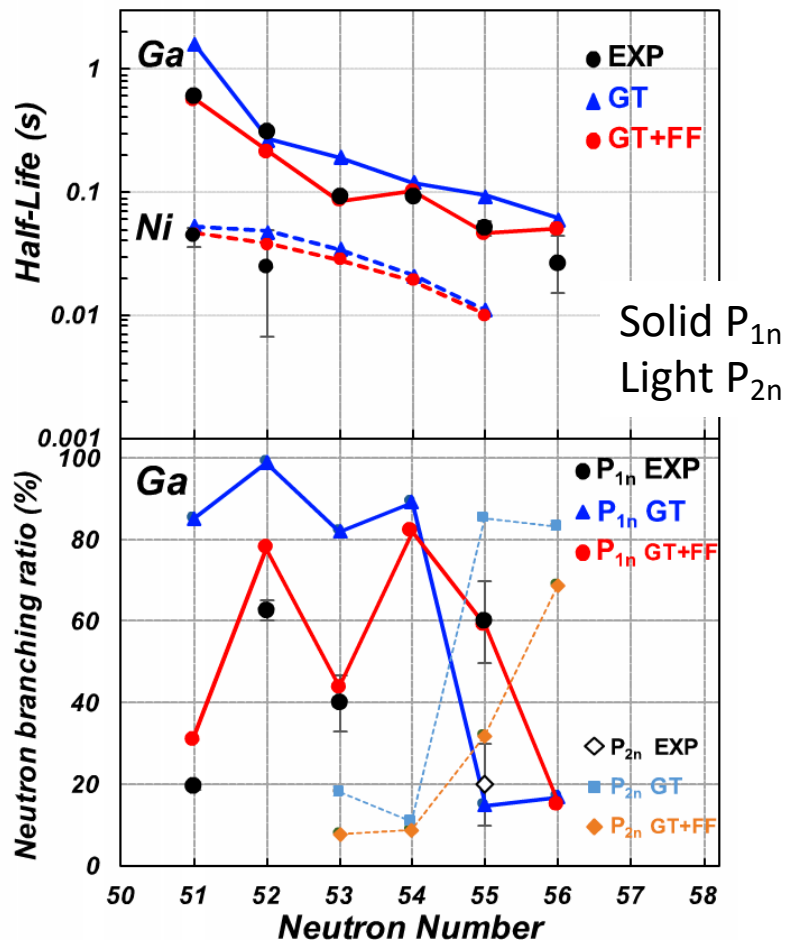


the decay above the neutron separation energy is dominated by allowed Gamow-Teller transitions.

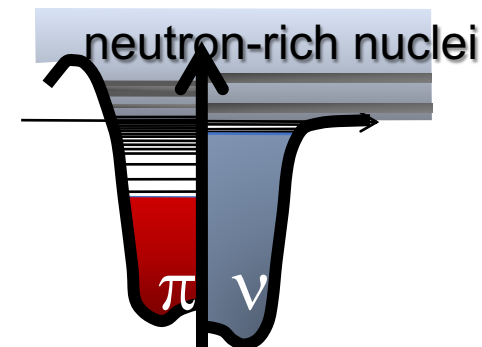
# Measuring GT with neutrons

Madurga et al. PRL 117 (2016) 092502

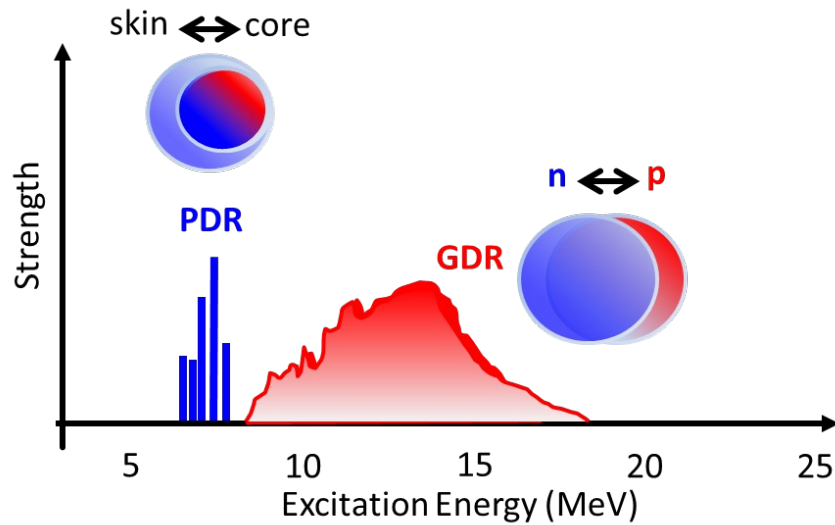
Alshudifat et al. PRC93 (2016) 044325



The GT decay transforms ns in the  $^{78}\text{Ni}$  core orbitals ( $f_{5/2}$ ,  $p_{3/2}$ ,  $p_{1/2}$ , and  $g_{9/2}$ ) into p occupying their spin-orbit partners outside the Z=28 core. These transitions are coupled with very strong matrix elements. The alternative decay mode, through the first forbidden (FF)  $d_{5/2} \rightarrow f_{5/2}$  transformation, populates neutron bound states in  $^{84}\text{Ge}$ .

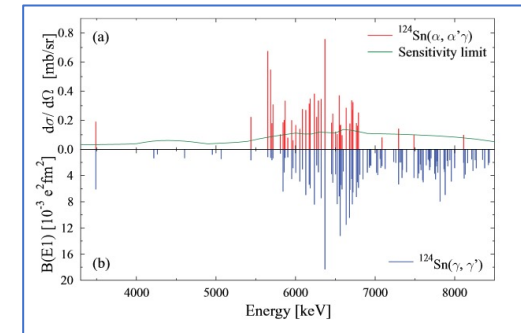
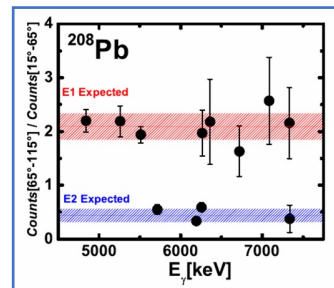
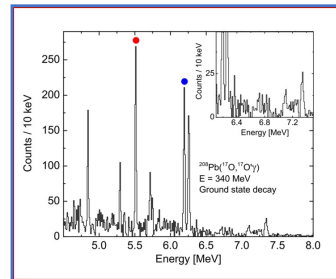
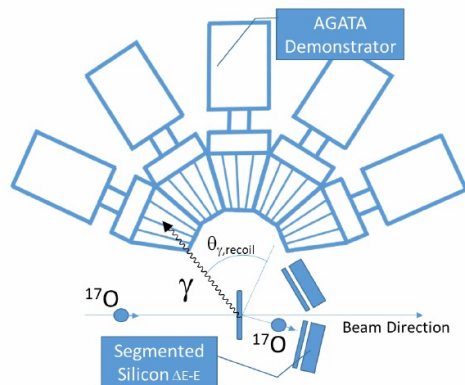


# Nuclear Structure information from the E1 response in Nuclei



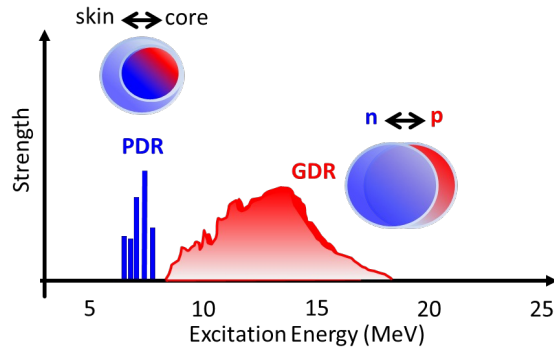
Commonly studied via:  
 $(\gamma, \gamma')$ ,  $(\alpha, \alpha')$ , Inelastic scattering of  $^{17}\text{O}$ ,  
 virtual phonon scattering

(\*) figure from J. Endres et al., Phys. Rev. Lett. 105, 212503 (2010)



- ❑ low energy part → **isoscalar character**  
*(neutron-skin oscillations)*
- ❑ high-energy states → **isovector nature**  
*(transition towards the GDR)*

# Resonances populated via $\beta$ decay in n-rich nuclei



- The large  $Q_\beta$ -value window ( $> 12$  MeV) allows populating at least the PDR

## Proof of principle in a recently published paper

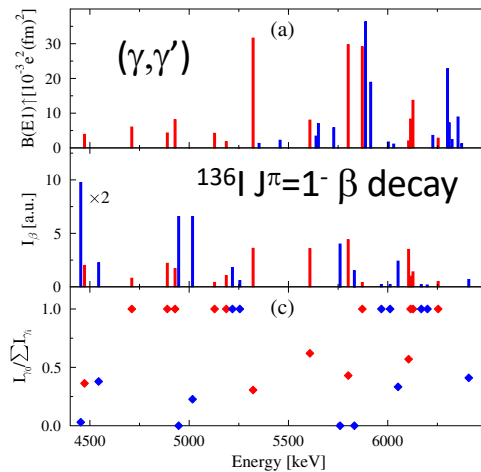
PRL **116**, 132501 (2016)

PHYSICAL REVIEW LETTERS

week ending  
1 APRIL 2016

### Investigating the Pygmy Dipole Resonance Using $\beta$ Decay

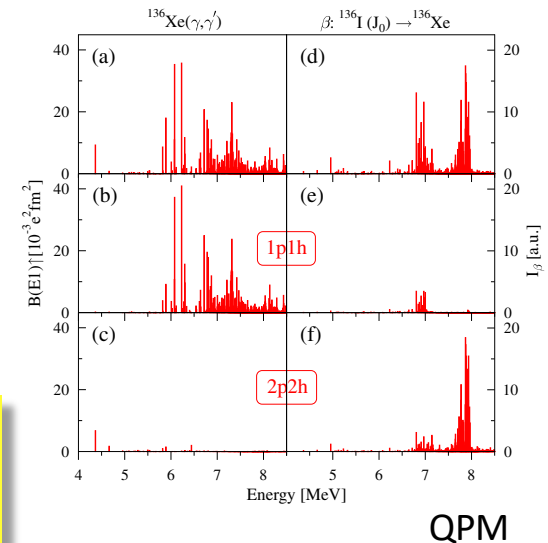
M. Scheck,<sup>1,2,\*</sup> S. Mishev,<sup>3,4</sup> V. Yu. Ponomarev,<sup>5</sup> R. Chapman,<sup>1,2</sup> L. P. Gaffney,<sup>1,2</sup> E. T. Gregor,<sup>1,2</sup> N. Pietralla,<sup>5</sup>  
P. Spagnoletti,<sup>1,2</sup> D. Savran,<sup>6</sup> and G. S. Simpson<sup>1,2</sup>



States seen in NRF are seen in  $\beta$  decay  
 $\beta$  decays shows greater number of states  $\rightarrow$  access to 2p2h excitations

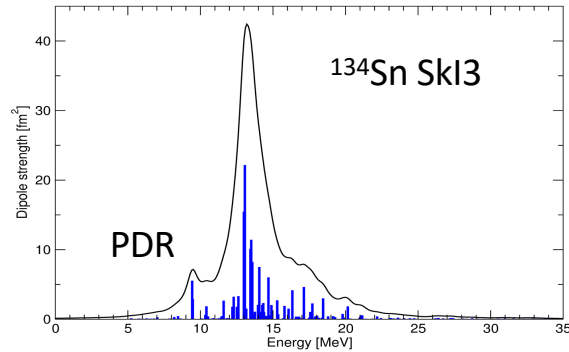


Useful tool to complement the studies  
**BUT** relies heavily on theory for the  
interpretation of nature of states



QPM

# Resonances populated via $\beta$ decay:

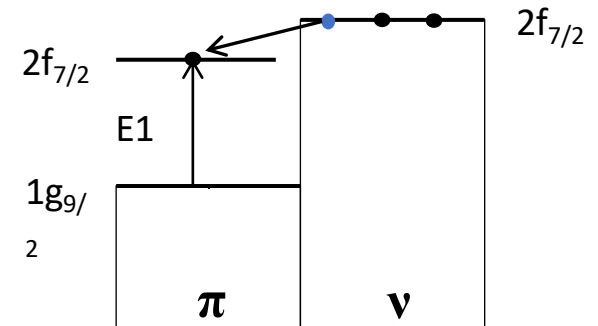


Example:  $^{134}\text{In} \rightarrow ^{134}\text{Sn}$  ( $Q_\beta = 14.7$  MeV)

$\nu f_{7/2} \rightarrow \pi g_{9/2}$

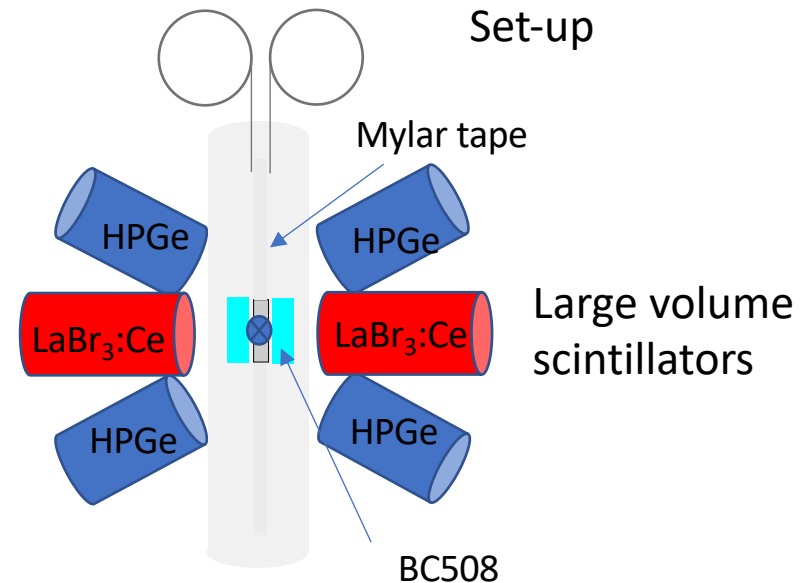
$\beta$  decay:  $\nu 2f_{7/2} \rightarrow \pi 2f_{7/2}, \pi 2f_{5/2}$ ;

QRPA calculations with the SkI3  
interaction: PDR at 10 MeV

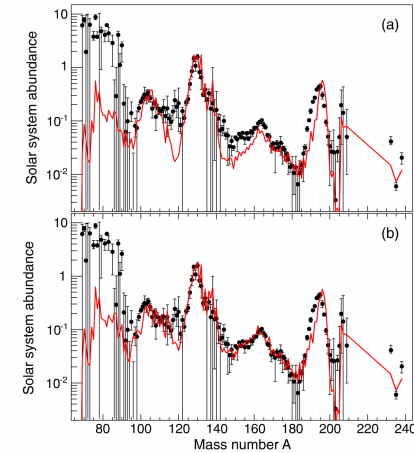
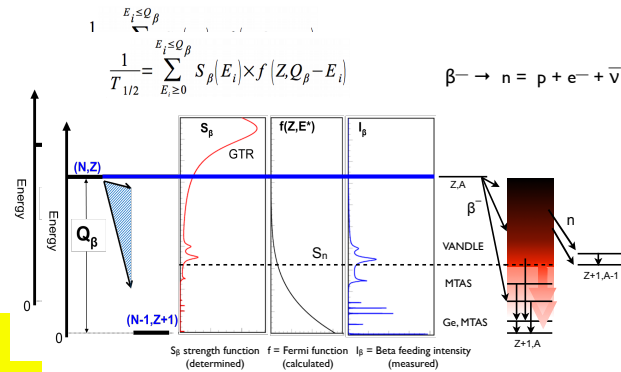


| Mother            | $J^\pi$   | Daughter          | $S_n$ [keV] | $Q_\beta$ [keV] | I [pps] @5 $\mu$ A | I [pps] @200 $\mu$ A  |
|-------------------|-----------|-------------------|-------------|-----------------|--------------------|-----------------------|
| $^{84}\text{Ga}$  | (0 $^-$ ) | $^{84}\text{Ge}$  | 5243        | 12900           | $1.01 \times 10^3$ | $4.02 \times 10^4$    |
| $^{86}\text{Br}$  | (1 $^-$ ) | $^{86}\text{Kr}$  | 9857        | 7626            | $1.93 \times 10^7$ | $7.73 \times 10^8$    |
| $^{96}\text{Y}$   | 0 $^-$    | $^{96}\text{Zr}$  | 7856        | 7096            | $1.12 \times 10^7$ | $4.47 \times 10^8$    |
| $^{98}\text{Y}$   | (0 $^-$ ) | $^{98}\text{Zr}$  | 6415        | 8824            | $5.30 \times 10^5$ | $2.12 \times 10^7$    |
| $^{130}\text{In}$ | 1 $^-$    | $^{130}\text{Sn}$ | 7596        | 10249           | $1.93 \times 10^4$ | $7.72 \times 10^5$    |
| $^{136}\text{I}$  | (1 $^-$ ) | $^{136}\text{Xe}$ | 8084        | 6930            | $2.6 \times 10^8$  | $1.04 \times 10^{10}$ |
| $^{140}\text{Cs}$ | 1 $^-$    | $^{140}\text{Ba}$ | 6428        | 6220            | $8.53 \times 10^8$ | $3.4 \times 10^{10}$  |
| $^{142}\text{Cs}$ | 0 $^-$    | $^{142}\text{Ba}$ | 6181        | 7325            | $3.35 \times 10^7$ | $1.34 \times 10^9$    |
| $^{144}\text{Cs}$ | 1 $^-$    | $^{144}\text{Ba}$ | 5901        | 8500            | $4.35 \times 10^6$ | $1.74 \times 10^8$    |
| $^{146}\text{Cs}$ | 1 $^-$    | $^{146}\text{Ba}$ | 5495        | 9370            | $1.12 \times 10^5$ | $4.46 \times 10^6$    |

Easy to produce  
(Surface Ionization)



# Conclusions



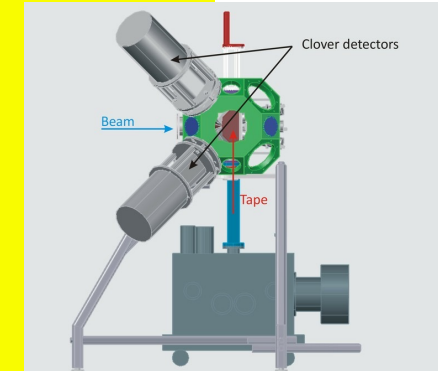
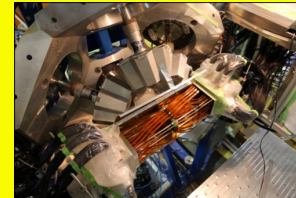
## ➤ Broad field of application:

- Inputs for stellar nucleosynthesis
- Nuclear structure studies
- Inputs for Nuclear Energy

## ➤ Simple equipment

## ➤ Versatile flexible and modular:

- Minimal setup to extract  $T_{1/2}$ ,  $P_n$ ,  $\beta$ - $\gamma$  coincidences
- $\gamma$  detectors to construct level schemes
- Fast-timing setup: lifetimes  $\sim$  ns range
- E0 measurements and long-living activity
- Complete spectroscopy using TAS



## ➤ Strong complementarity with in-beam spectroscopy

## ➤ Access to structure information already with few pps beams

## ➤ No need for post-acceleration

## ➤ Need for purified beams, even though known contribution from strong contaminants can be removed by off-line analysis

➔ **HRMS & RILIS & TRAPS**

Thank you for attention