

Beta decay studies of the most exotic nuclei

Giovanna Benzoni

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Outline of the lessons:

PARTI: General concepts

How to measure β decay in exotic nuclei

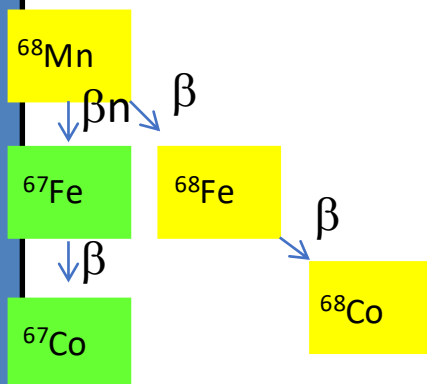
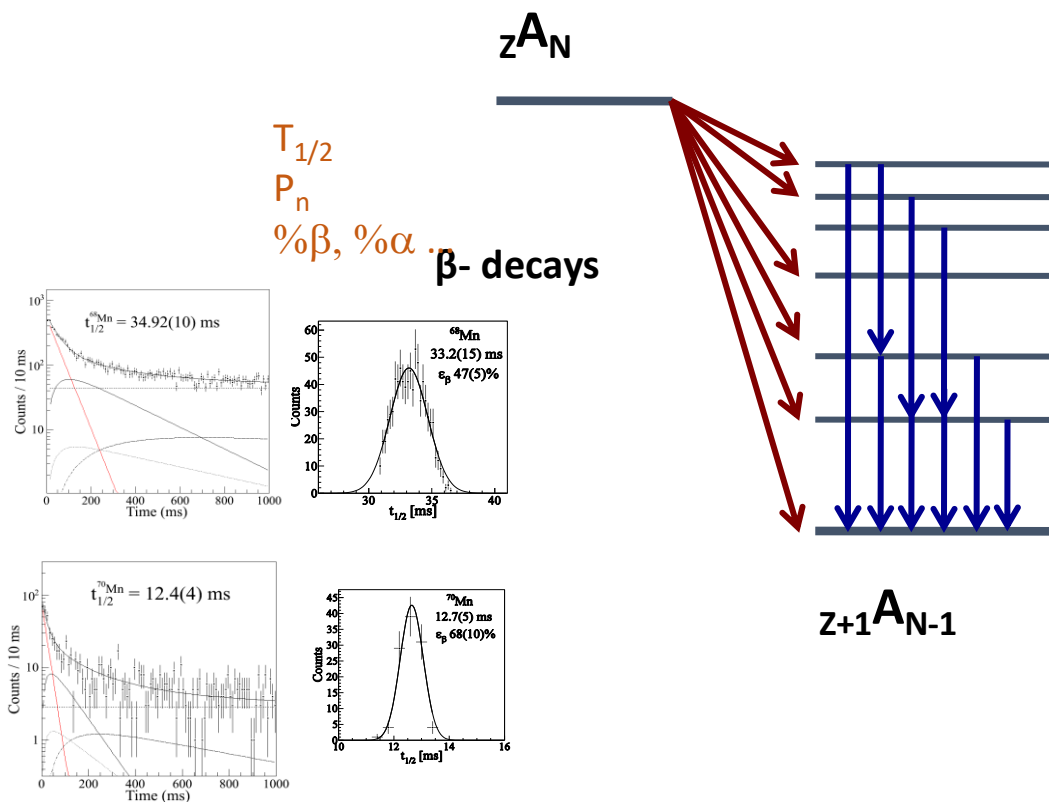
PARTII: β decay Gross properties $T_{1/2}$ and P_n

PARTIII: High resolution vs TAS



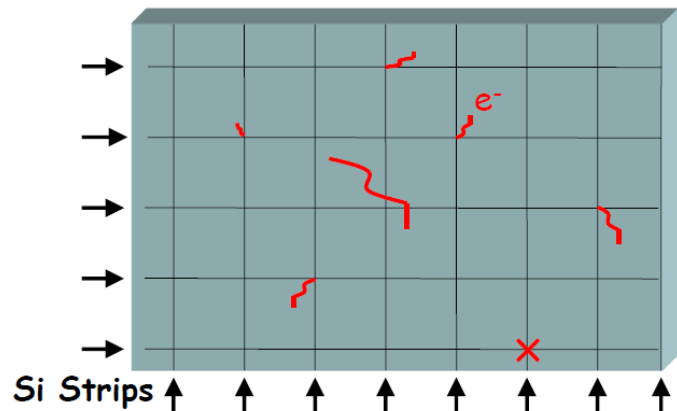
General Properties of β decay

Quantities that can be extracted in a β decay experiment



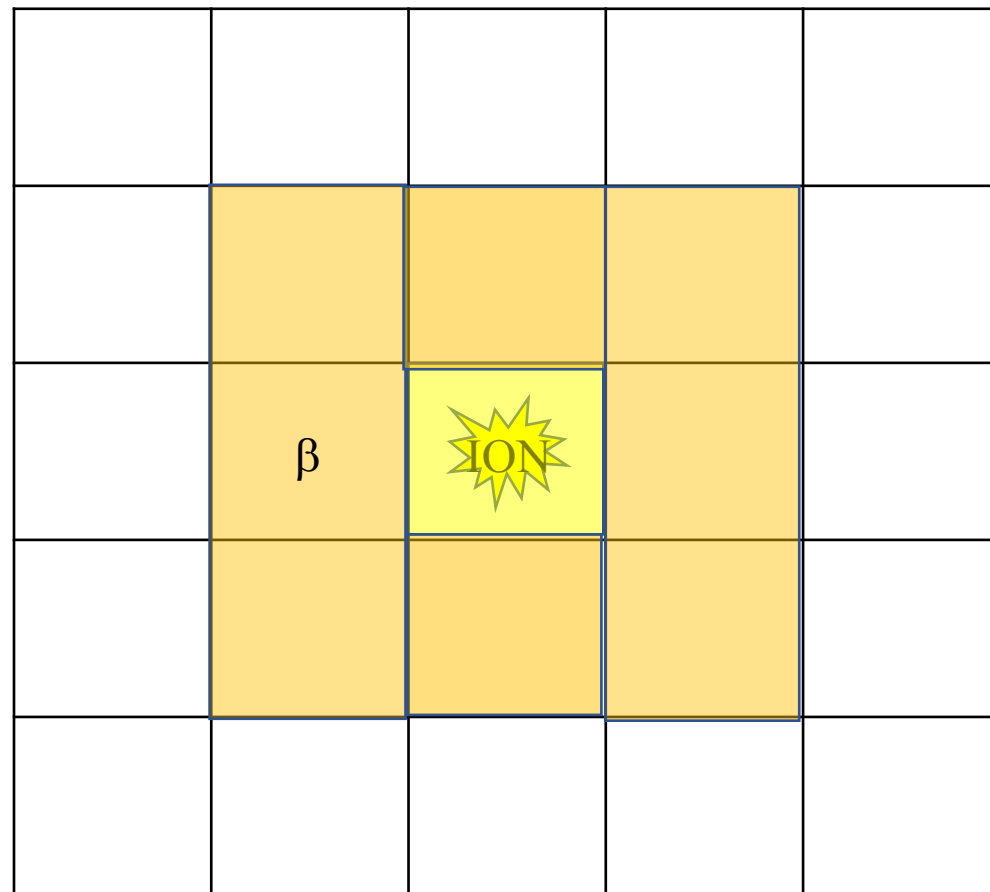
Measuring short half-lives

Focal plane implantation detector sensitive to electron emission



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

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



Measuring short half-lives

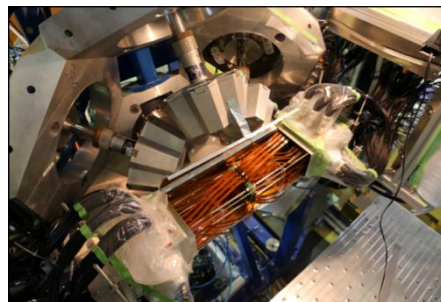
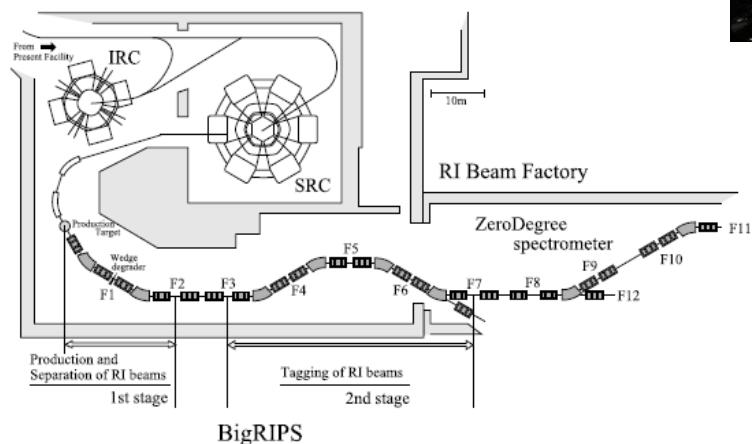


3 days of beamtime

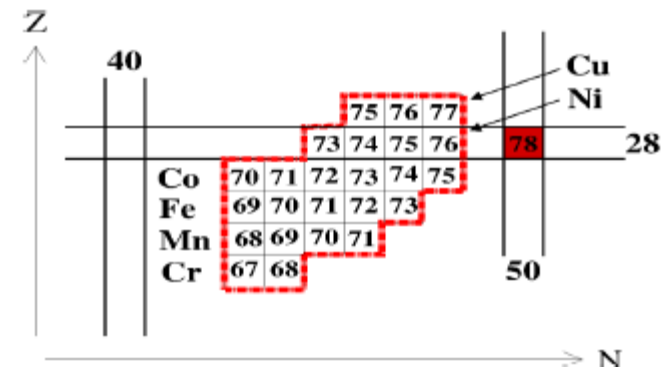
^{238}U @ 345 MeV/u

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

BigRIPS setting focused on ^{71}Fe

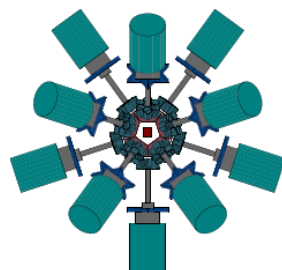


5 DSSSD - WAS3ABI
(64X40 strips)
Ion-beta correlations

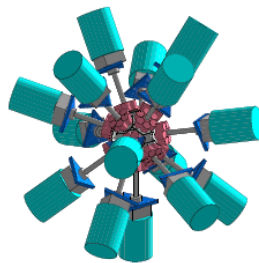


12 HPGe Clusters

β - γ correlations



(a) Upstream view



(b) View from 120 degrees

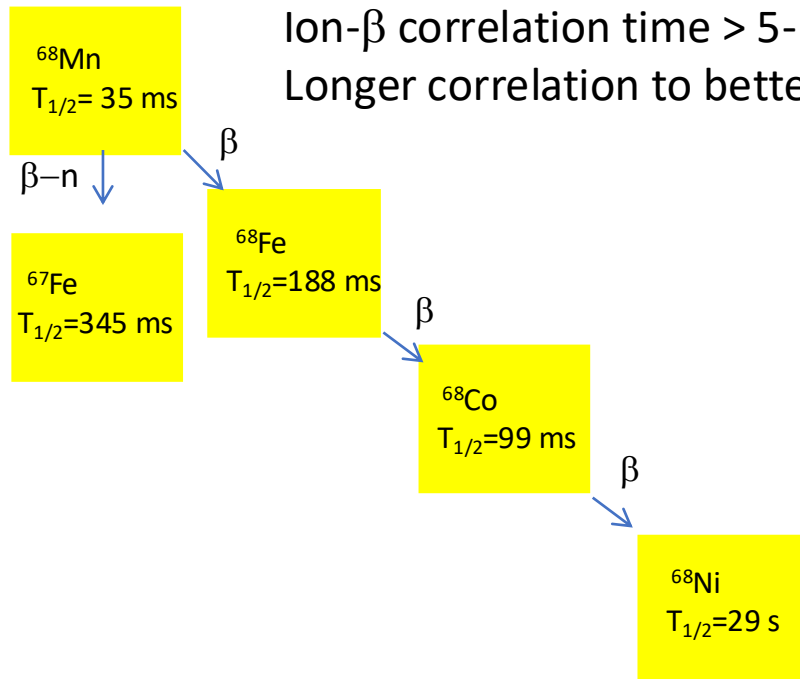


18 $\text{LaBr}_3(\text{Ce})$ (1.5" x 2")

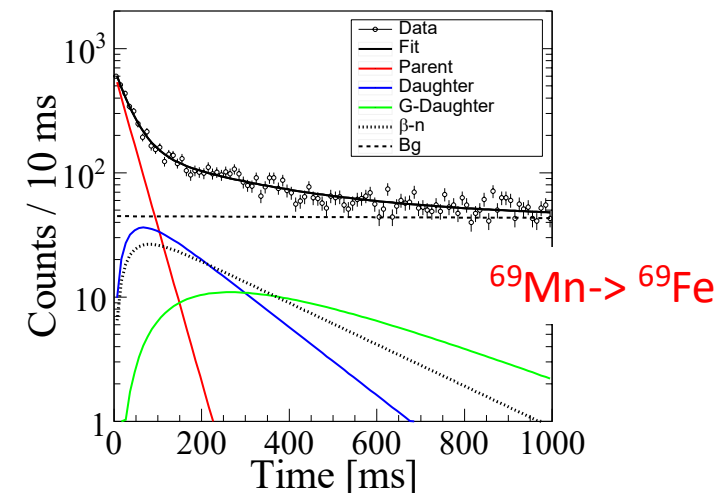
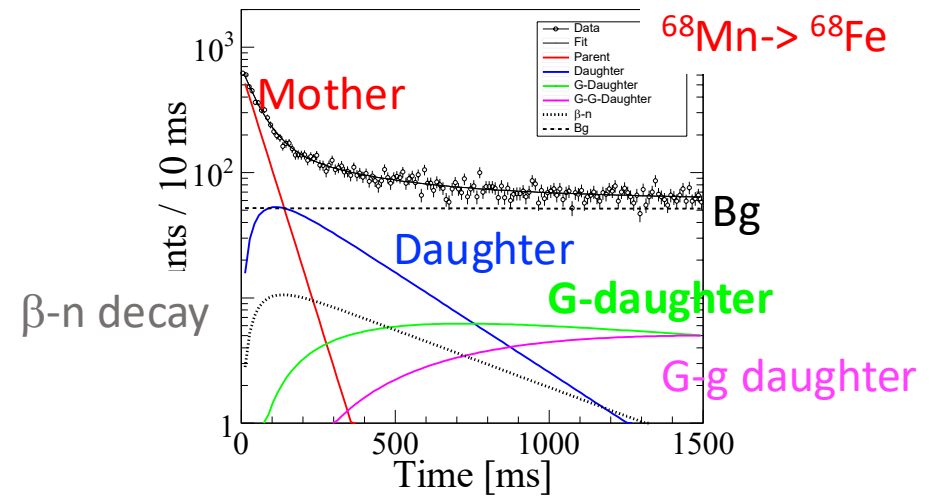
2 BC-418 Plastic 2mm thick

Fast-timing measurements

Measuring short half-lives



Ion- β 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

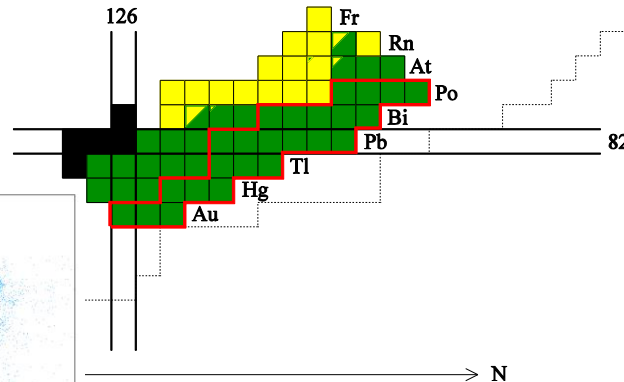
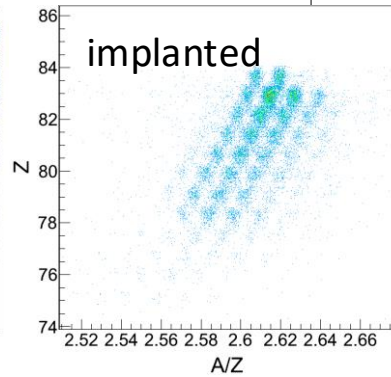
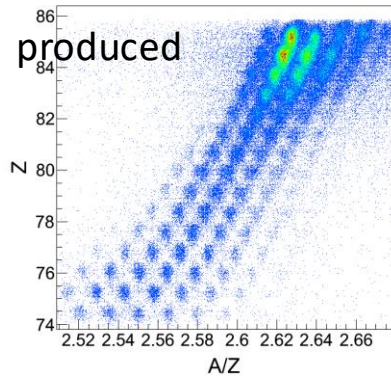
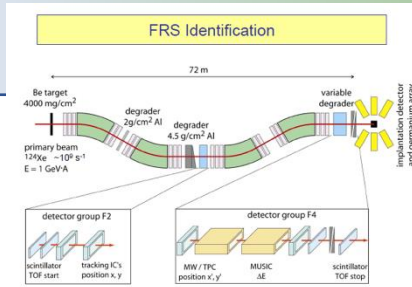


	N_{ions}	$T_{1/2}$ (ms) exp	Ref	FRDM [3]
^{68}Mn	$7.7 \cdot 10^3$	34.92(10)	40(7) [1]	12.8
^{69}Mn	$5 \cdot 10^3$	22.20(9)	18(4) [2]	12.9
^{70}Mn	500	12.4(4)		9

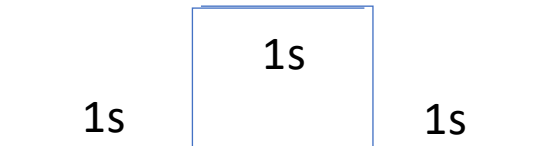
- [1] S.N.Liddick et al., PRC 87, 014325 (2013).
 [2] J.M.Daugas et al., PRC 83, 054312 (2011)
 [3] P.Moller, B.Pfeiffer and K.-L. Kratz, Phys.Rev. C 67, 055802 (2003)

Measuring long half-lives

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

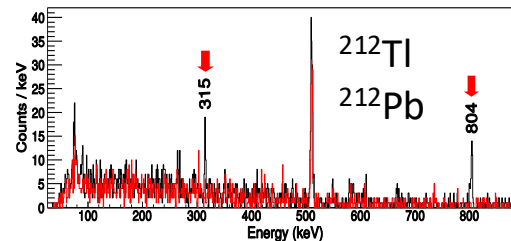
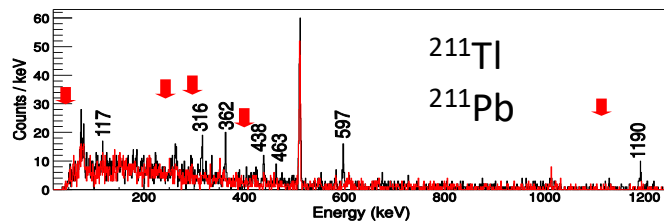
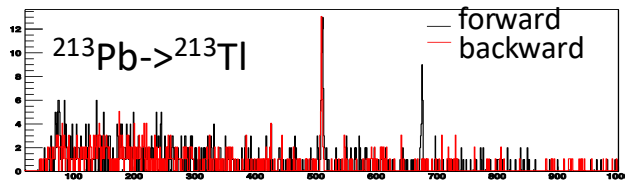


Spill structure @ GSI
extraction



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}Po $^{211-212-213}\text{Tl}$

Ad-hoc numerical procedure

- Long half-lives $\rightarrow$ cover many beam repetition cycles
 - High rate $\rightarrow$ possible double implantations
- Standard techniques are not available
- $\rightarrow$ numerical fit based on Monte Carlo simulations of the implantation-decay process including experimental implantation rates and having as free parameters the β decay half life and the β detection efficiency

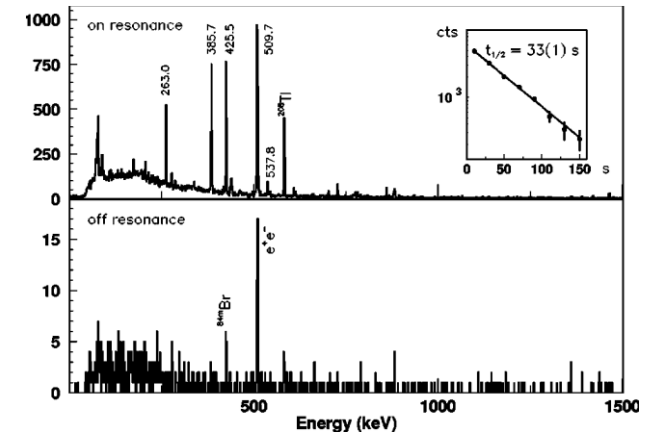
T. Kurtukián-Nieto et al., NIMA (2008)

χ^2 fits to two independent time correlations:

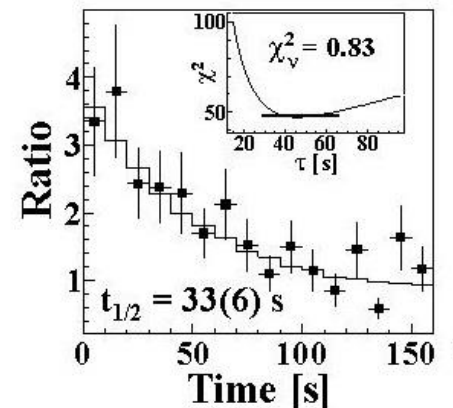
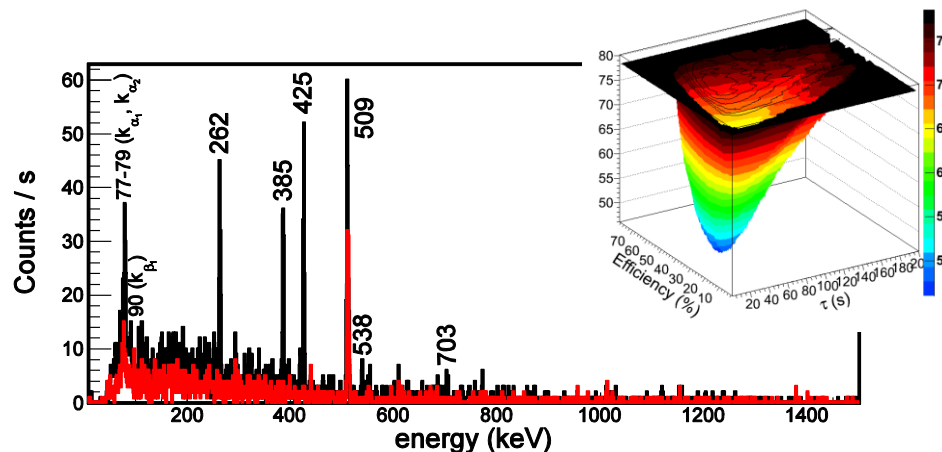
- Experimental ion- β time-correlated spectra
- Calculated time distribution obtained from Monte-Carlo simulations

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

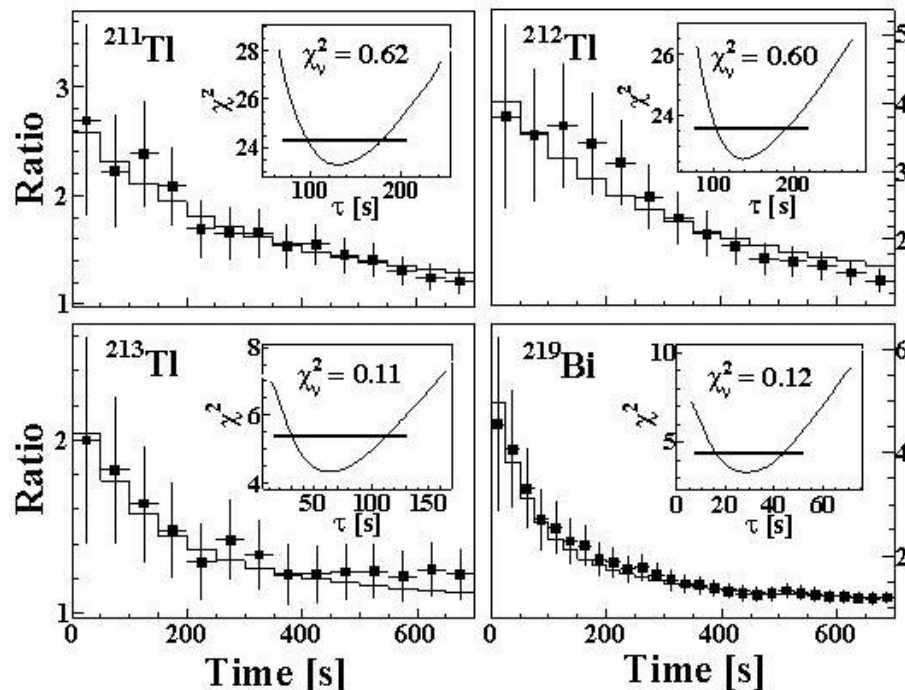
^{218}Bi : Benchmark of Analysis



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

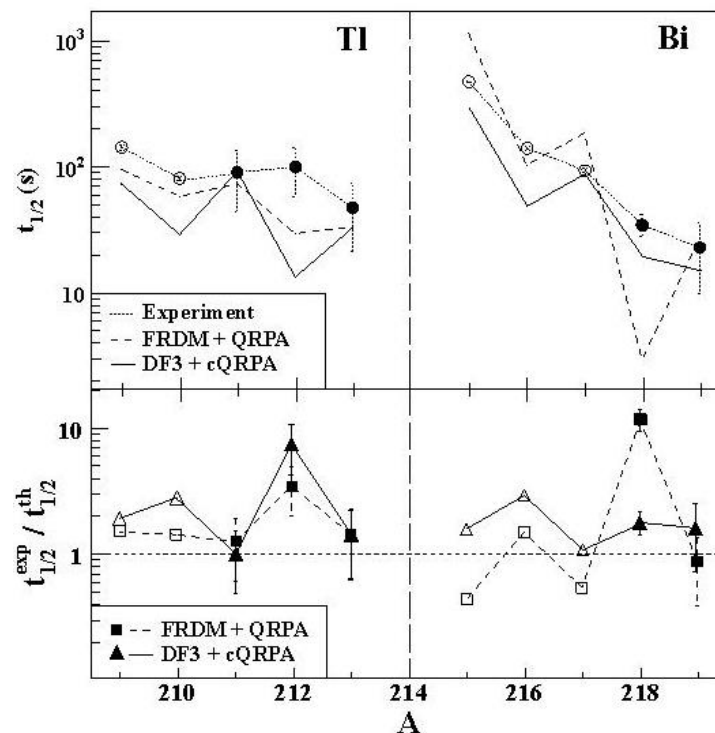


Important results in heavy mass region



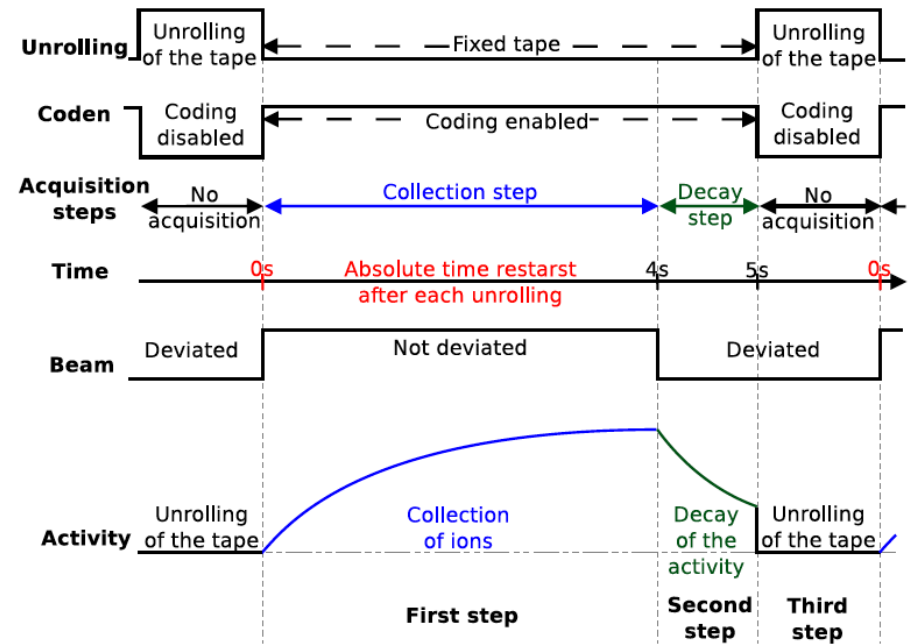
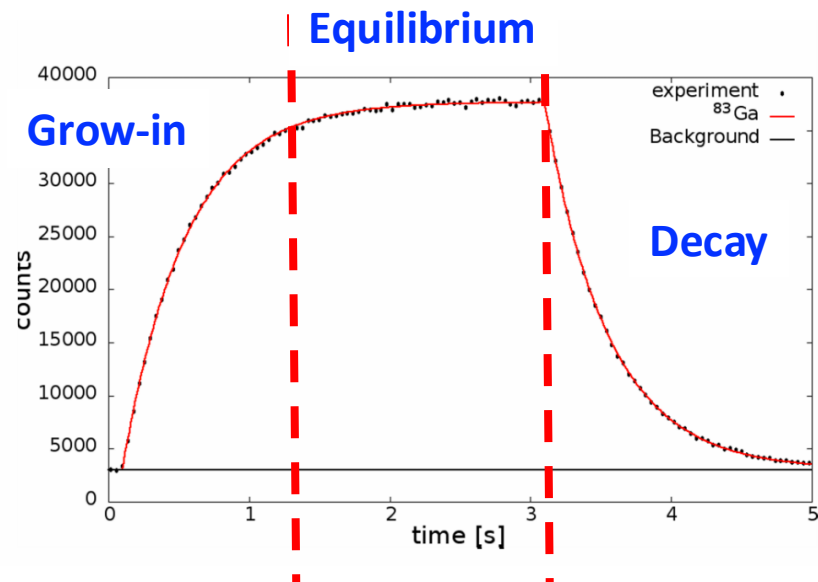
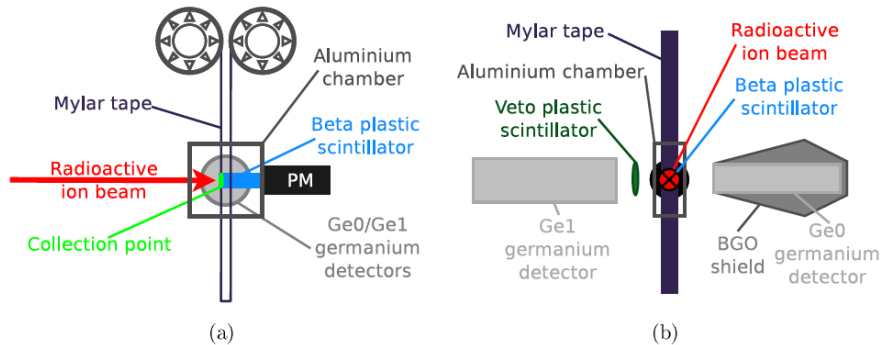
FRDM+QRPA and DF3 + QRPA models in agreement with our measurements

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

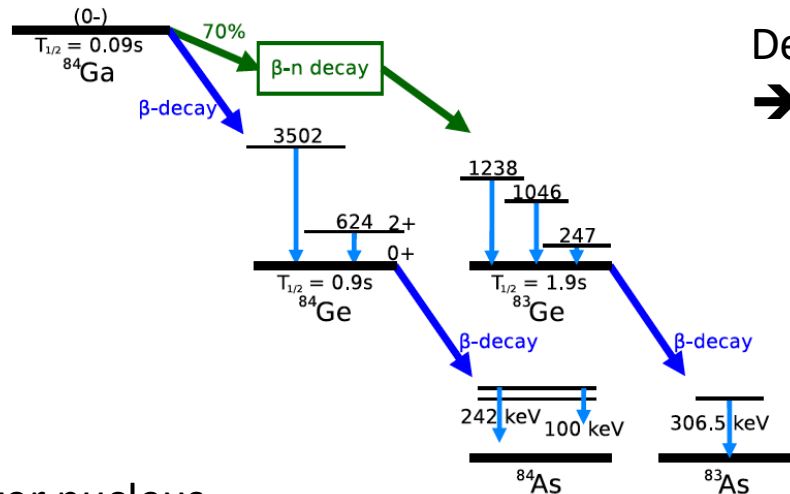


G.Benzoni et al., PLB 715 (2012) 293
 A.I.Morales et al., PRC89, 014324 (2014)
 A.I.Morales et al., PRL113, 022702 (2014)

Measuring half-lives with tape system

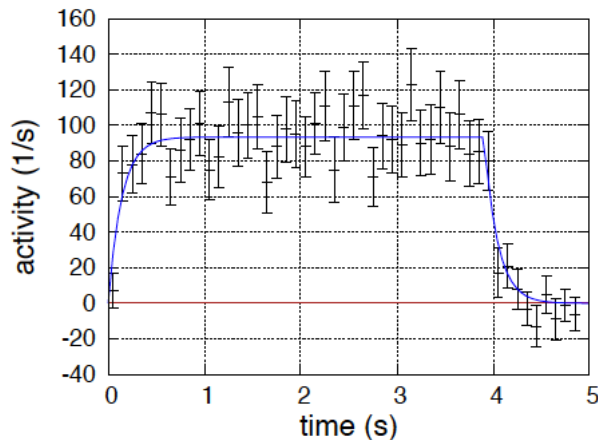


Measuring half-lives with tape system



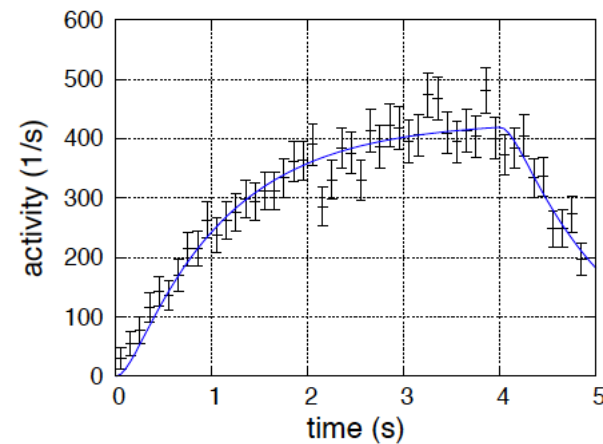
Decay curve can have many components
 → γ gating helps singling out

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



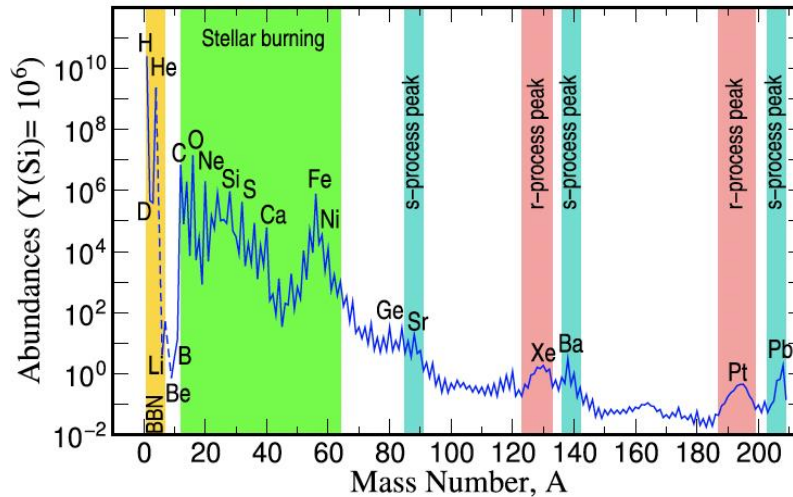
(a) 624 keV

Activity of grand-daughter nucleus



(c) 242 keV

Nucleosynthesis: Element formation in Stars

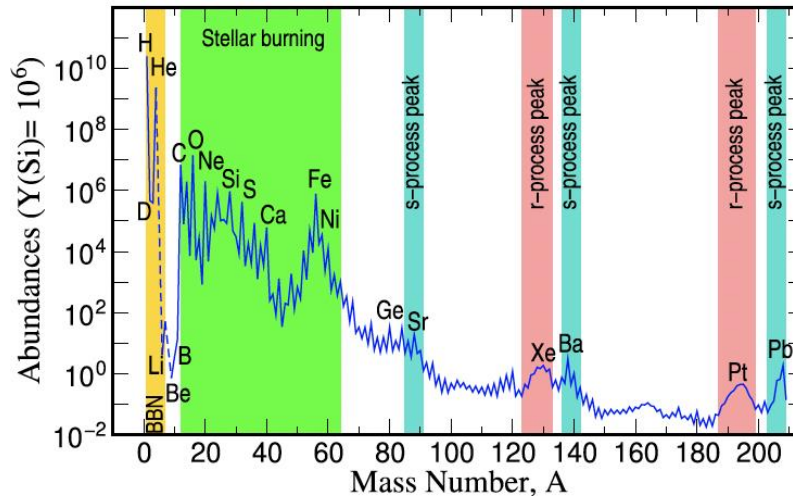


2 sets of data:

- 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



2 sets of data:

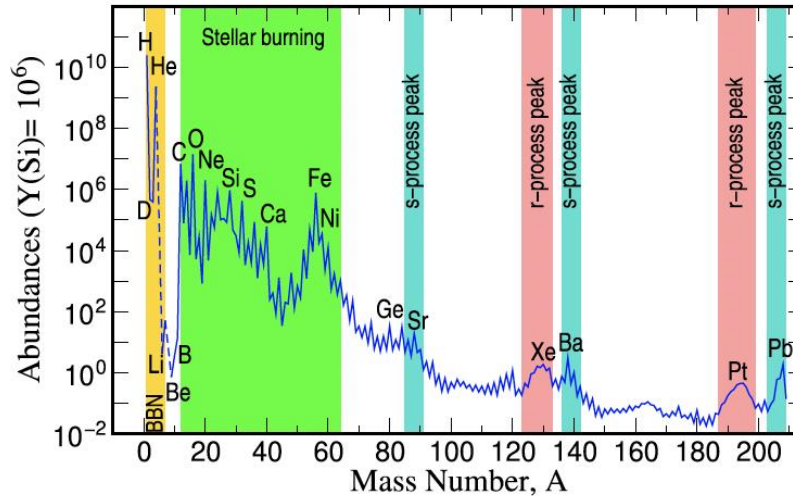
- Spectral analysis of Sun
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Spectra line analysis based on element- specific spectral emission lines following atomic de-excitation

Main Features:

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

Nucleosynthesis: Element formation in Stars



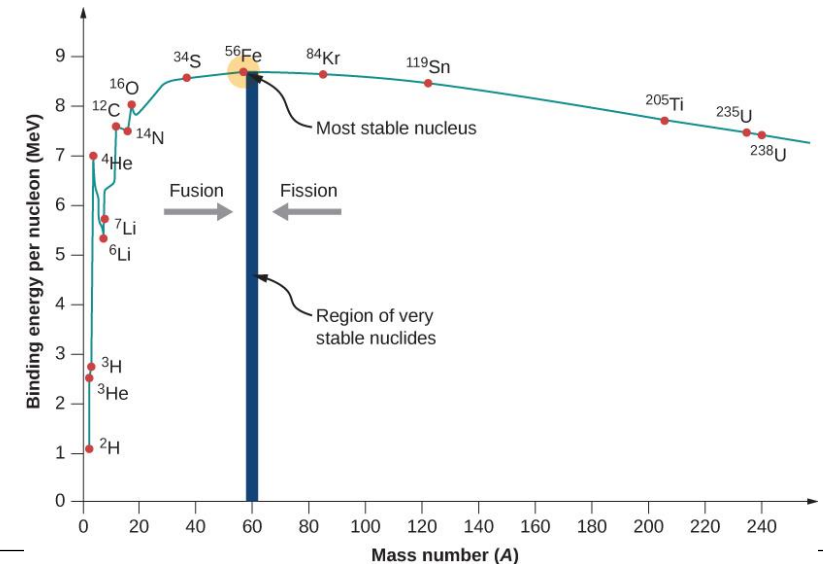
Main Features:

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

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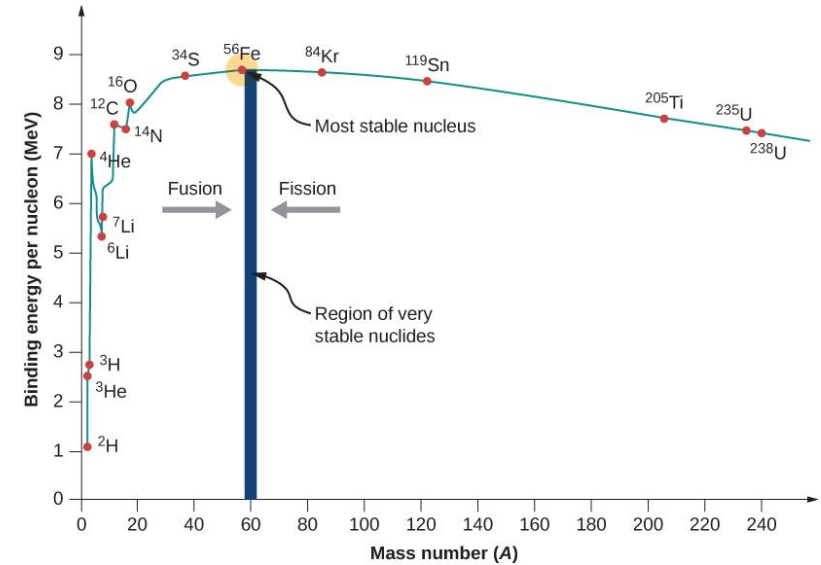
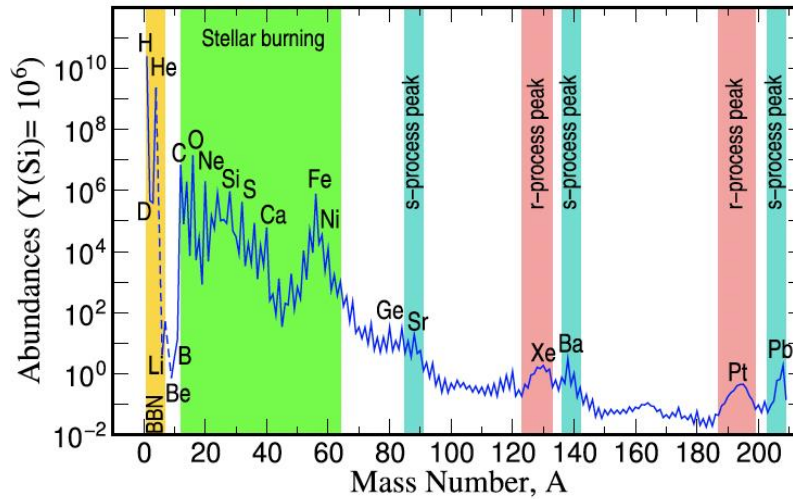
Decay of radioactive nuclei

Element formation in stars

Example of measurements of β -decays

Perspectives

Conclusions



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

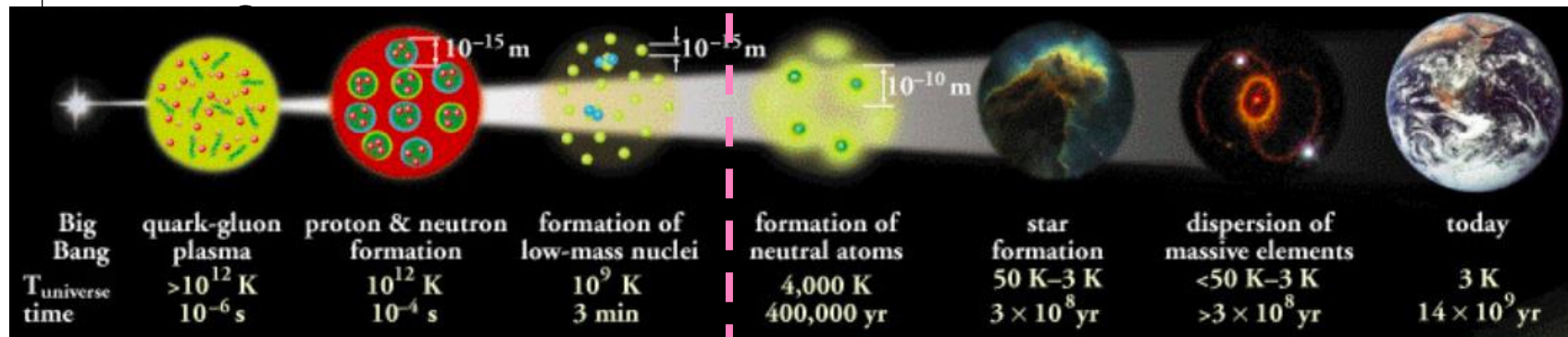
H, He $\rightarrow$ C, N,

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}Fe - - ^{238}U - s- p nucleosynthesis



Element formation in stars

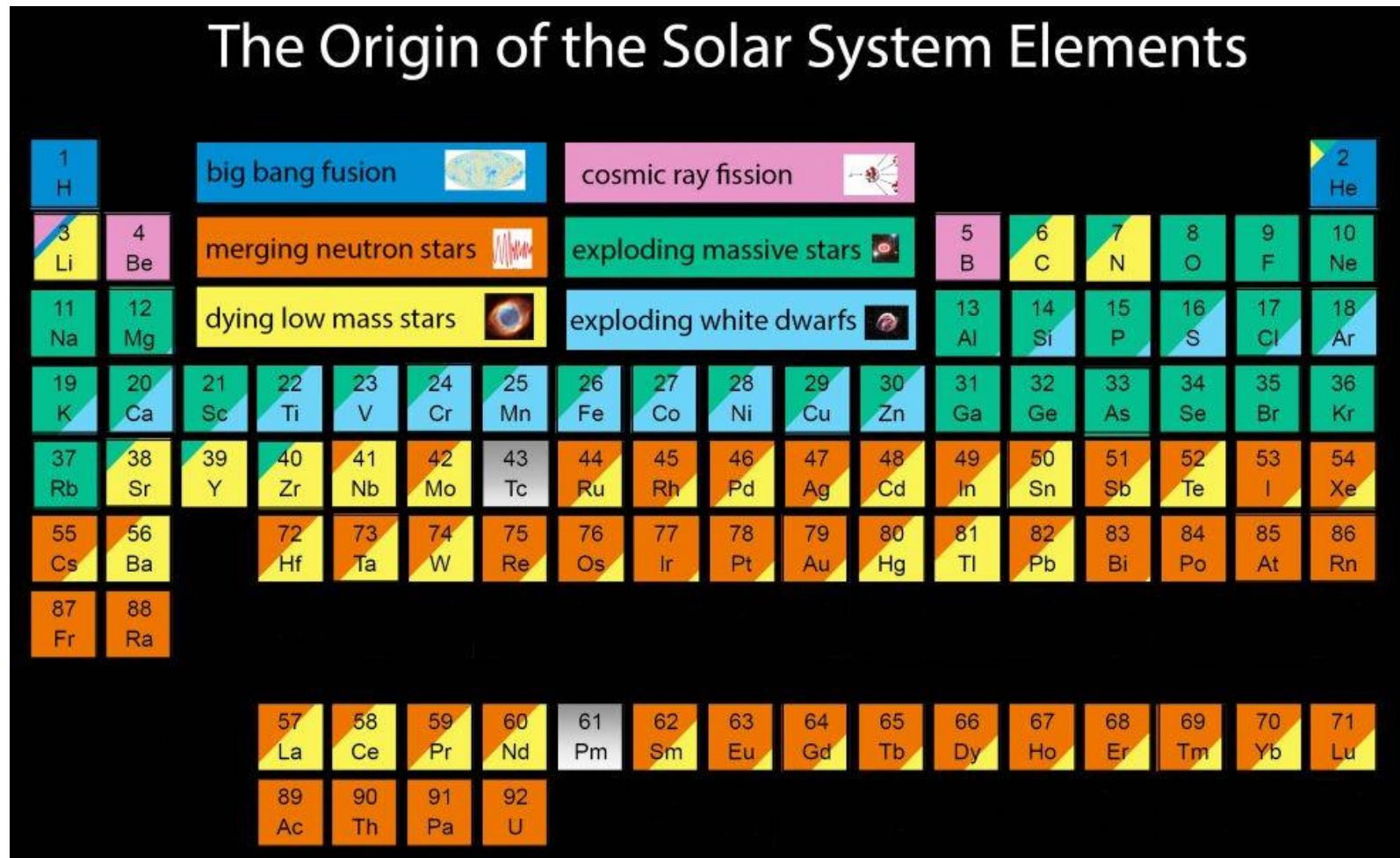
Decay of
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Nucleosynthesis: Element formation in Stars

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REVIEWS OF	
MODERN PHYSICS	
VOLUME 29, NUMBER 4	OCTOBER, 1957
Synthesis of the Elements in Stars*	
E. MARGARET BURRIDGE, G. R. BURRIDGE, WILLIAM A. FOWLER, AND F. HOYLE	
<i>Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California</i>	
"It is the stars, The stars above us, govern our conditions"; (<i>King Lear</i> , Act IV, Scene 3)	
but perhaps	
"The fault, dear Brutus, is not in our stars, But in ourselves," (<i>Julius Caesar</i> , 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

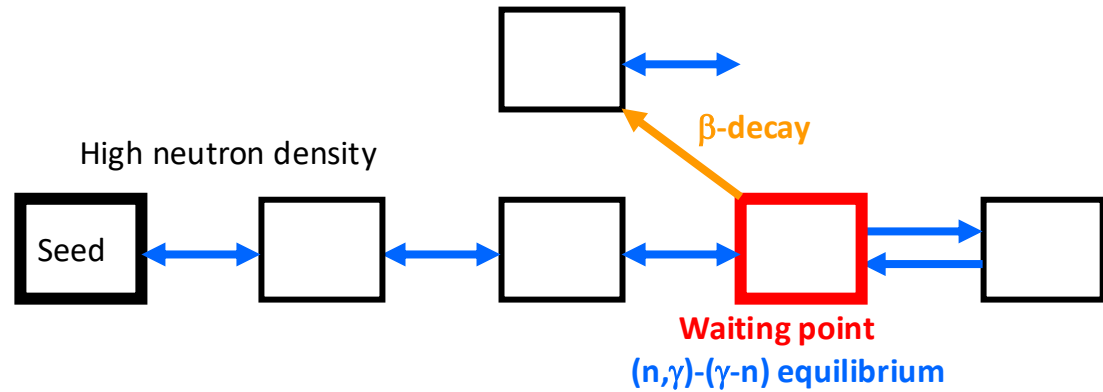
Decay of
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In r- and s- process competition between

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

β^- decay

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

Nucleosynthesis: Element formation in Stars

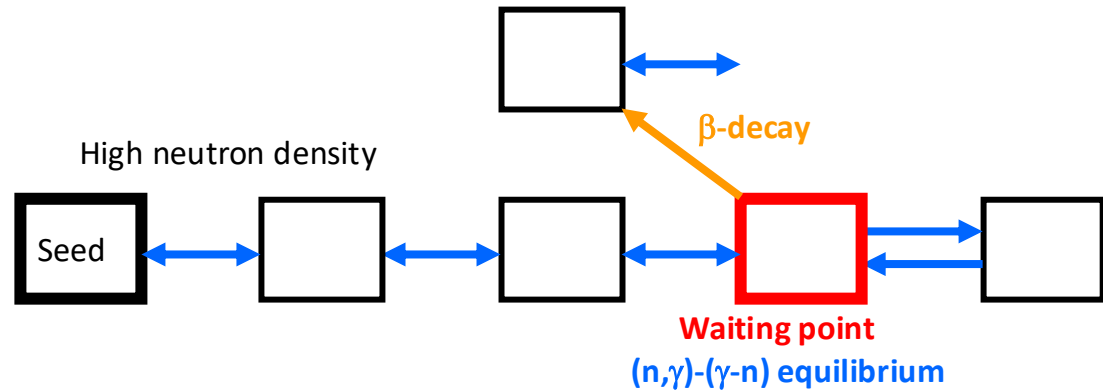
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neutron capture/photodissociation $(N, Z) + n \leftrightarrow (N + 1, Z), \gamma$

β^- 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

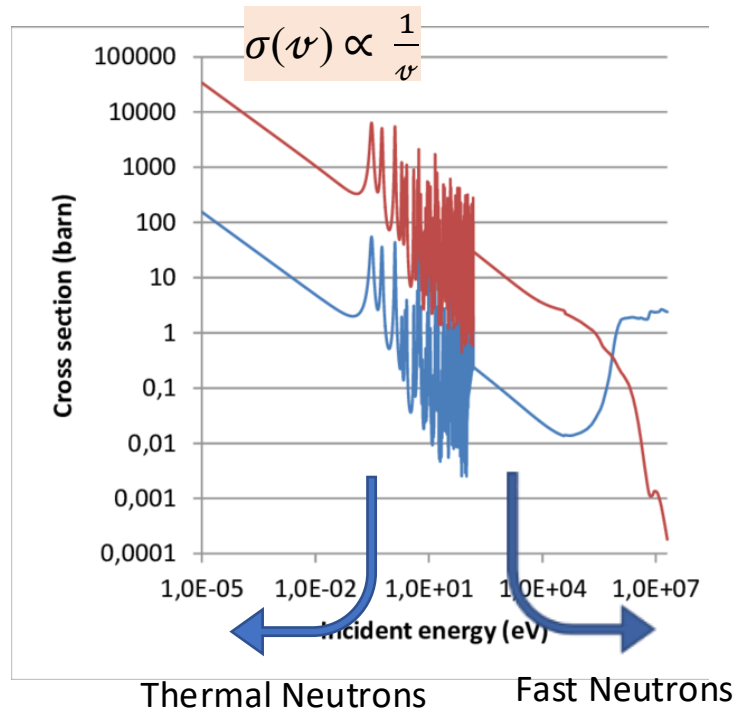
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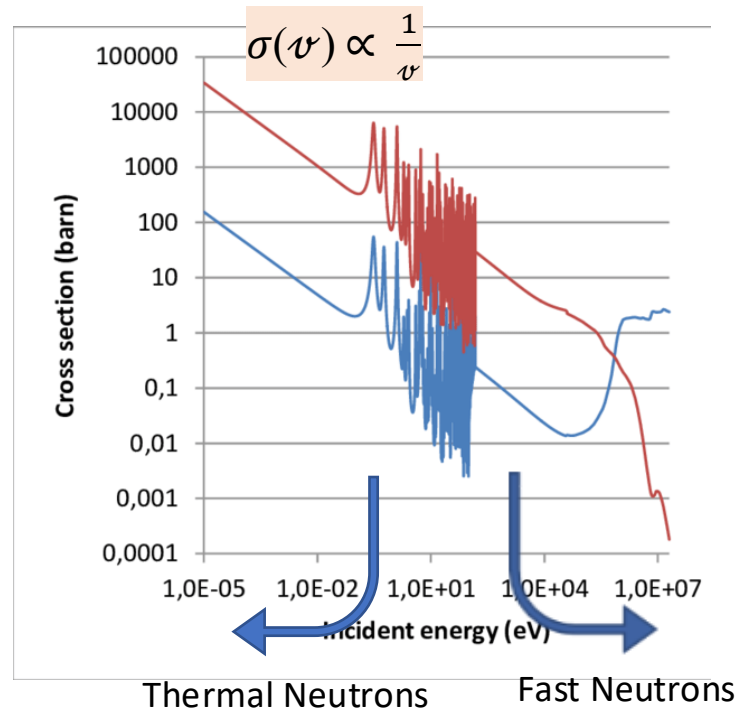
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S- process:

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

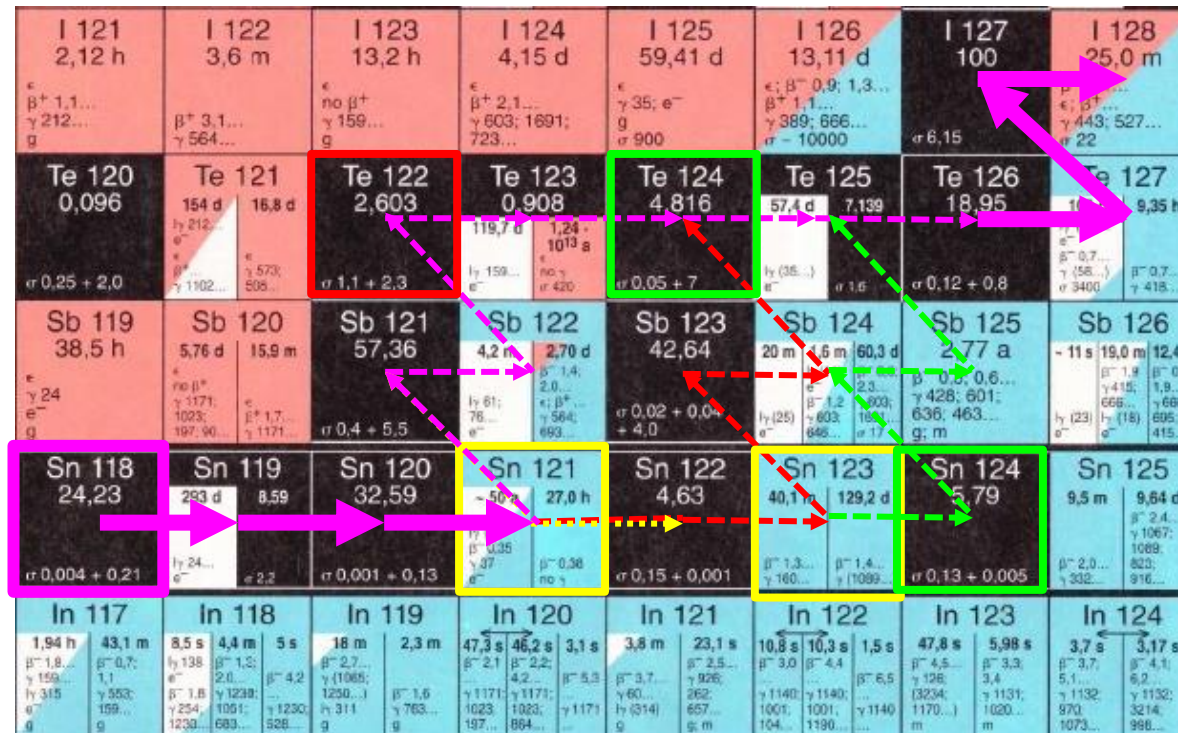
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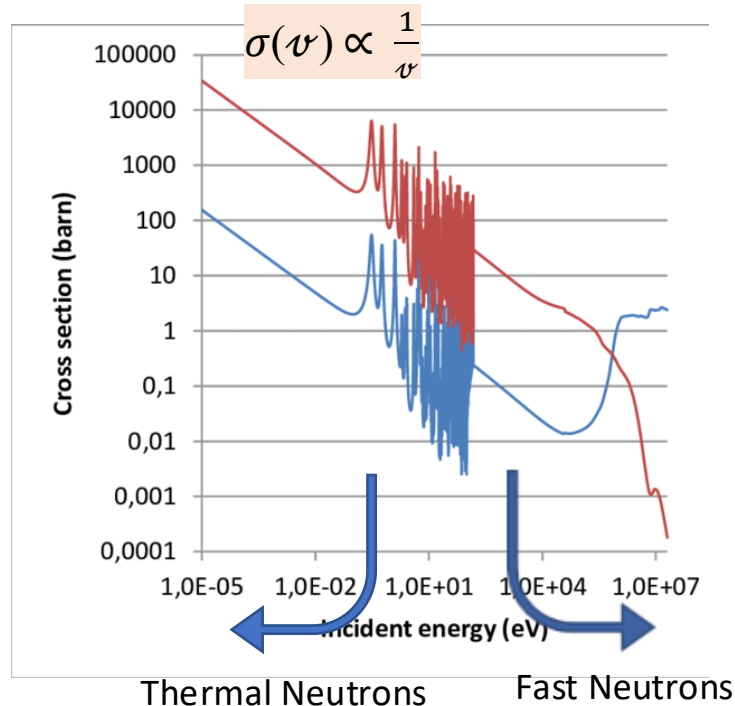
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R- process:

Explosive scenarios:

High temperatures and high n density

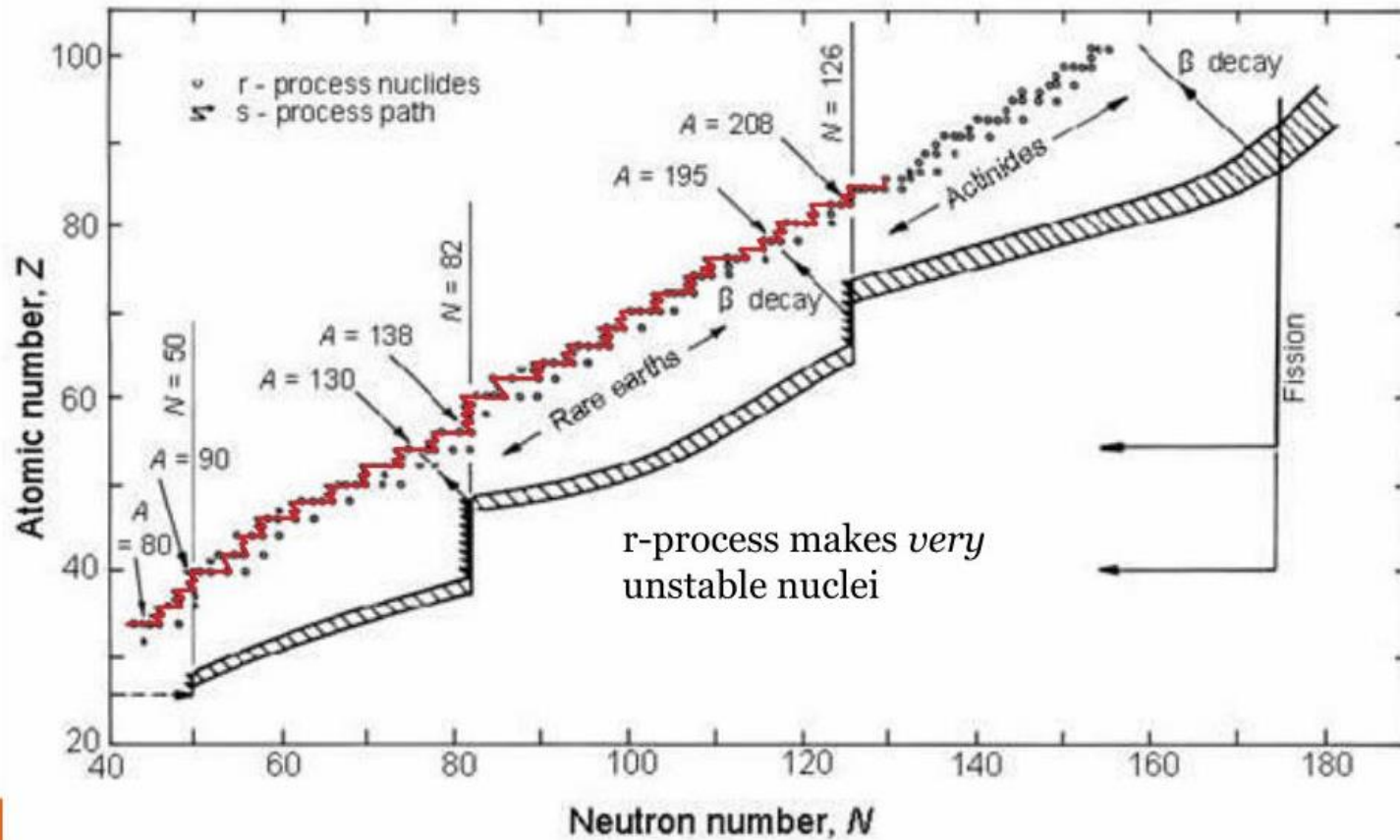
- Capture of energetic neutrons
- Many successive captures before β decay
0.01 – 10 s
- Flux is moved far away from stability line towards very short lived nuclei $[T_{1/2}] < s$

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



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

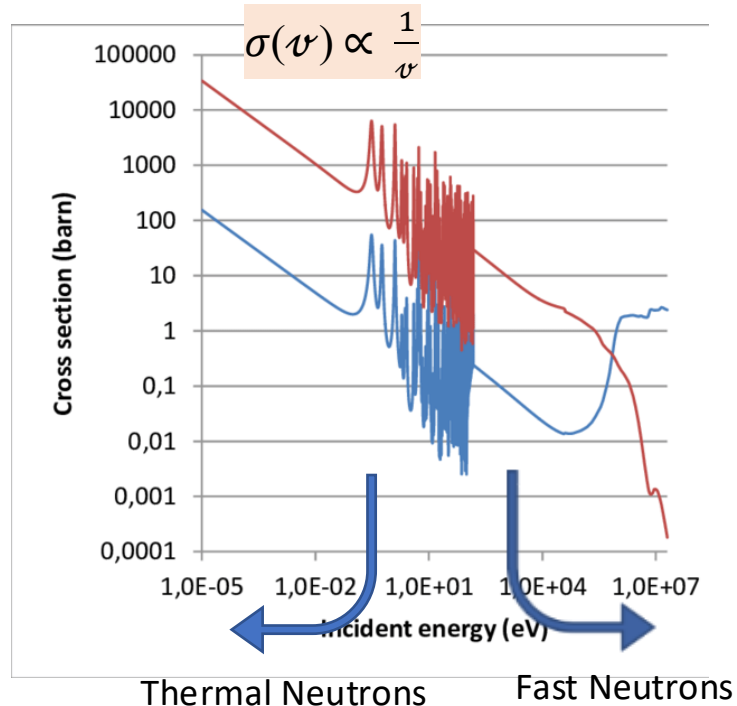
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S- process:

Lower Temperatures and lower n density

→ Astrophysical locations are Asymptotic Giant Branch of Red Giant stages

R- process:

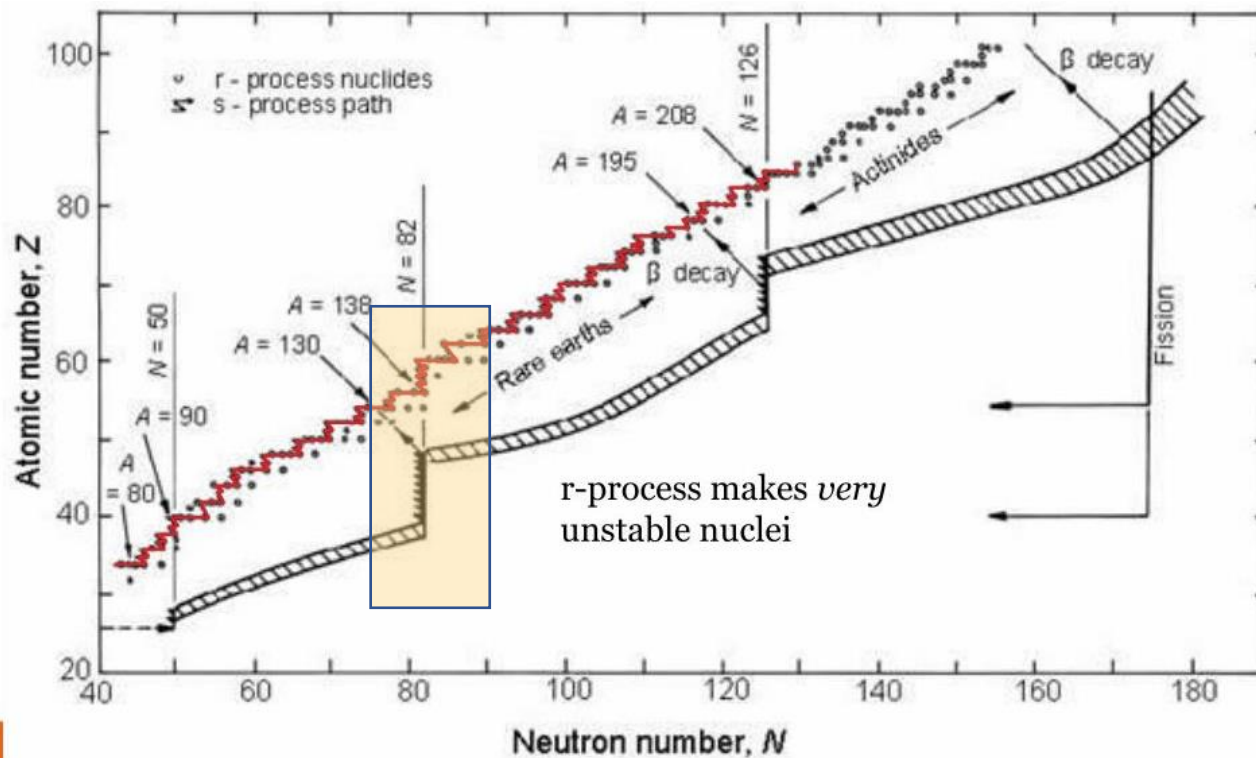
Explosive scenarios:

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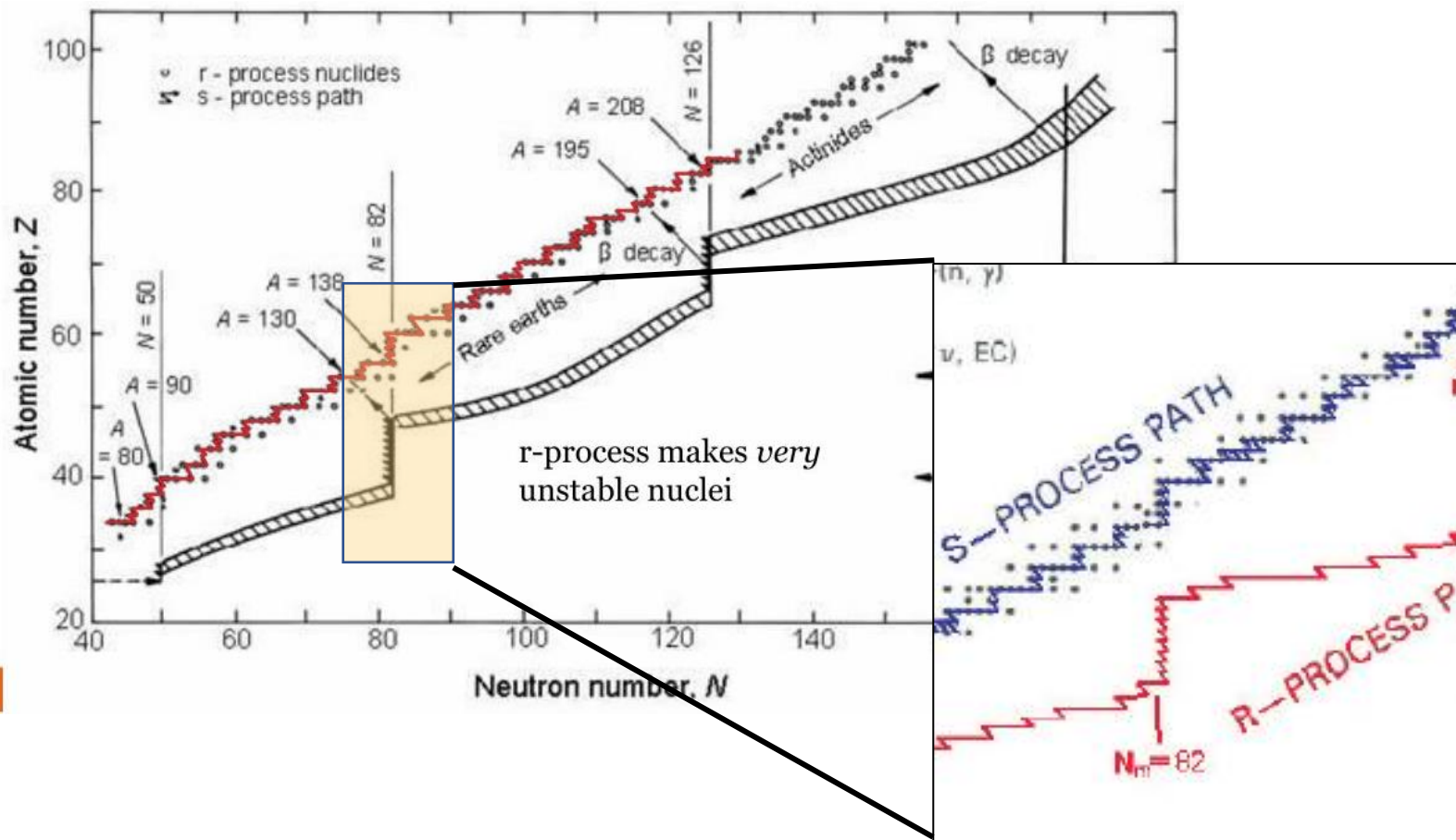
→ 3 possible sites:

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

Beta-decay spectroscopy towards the r-process path



Beta-decay spectroscopy towards the r-process path



Beta-decay spectroscopy towards the r-process path

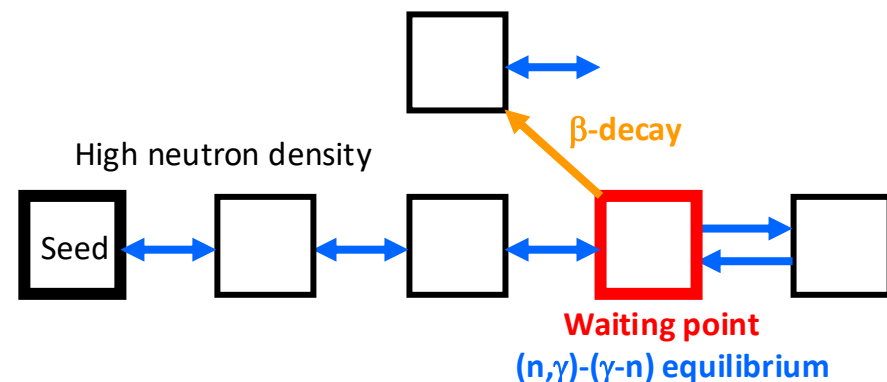
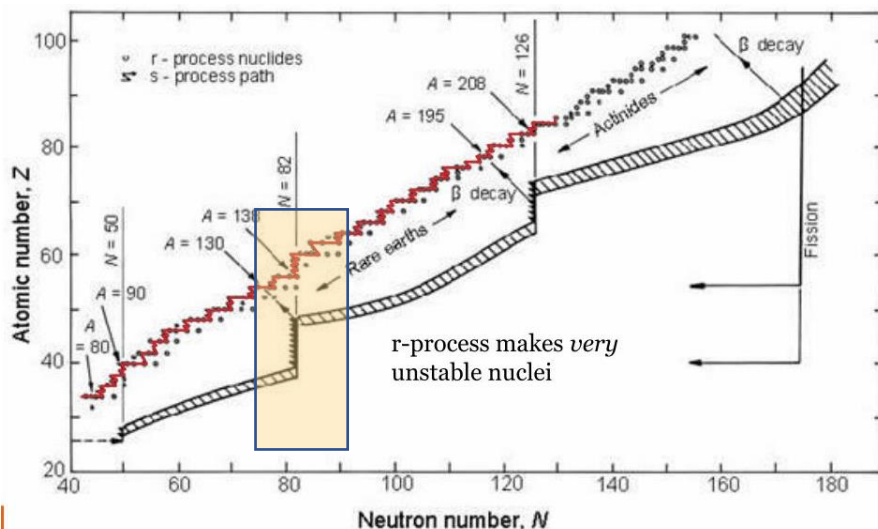
Decay of radioactive nuclei

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Example of measurements of β -decays

Perspectives (10')

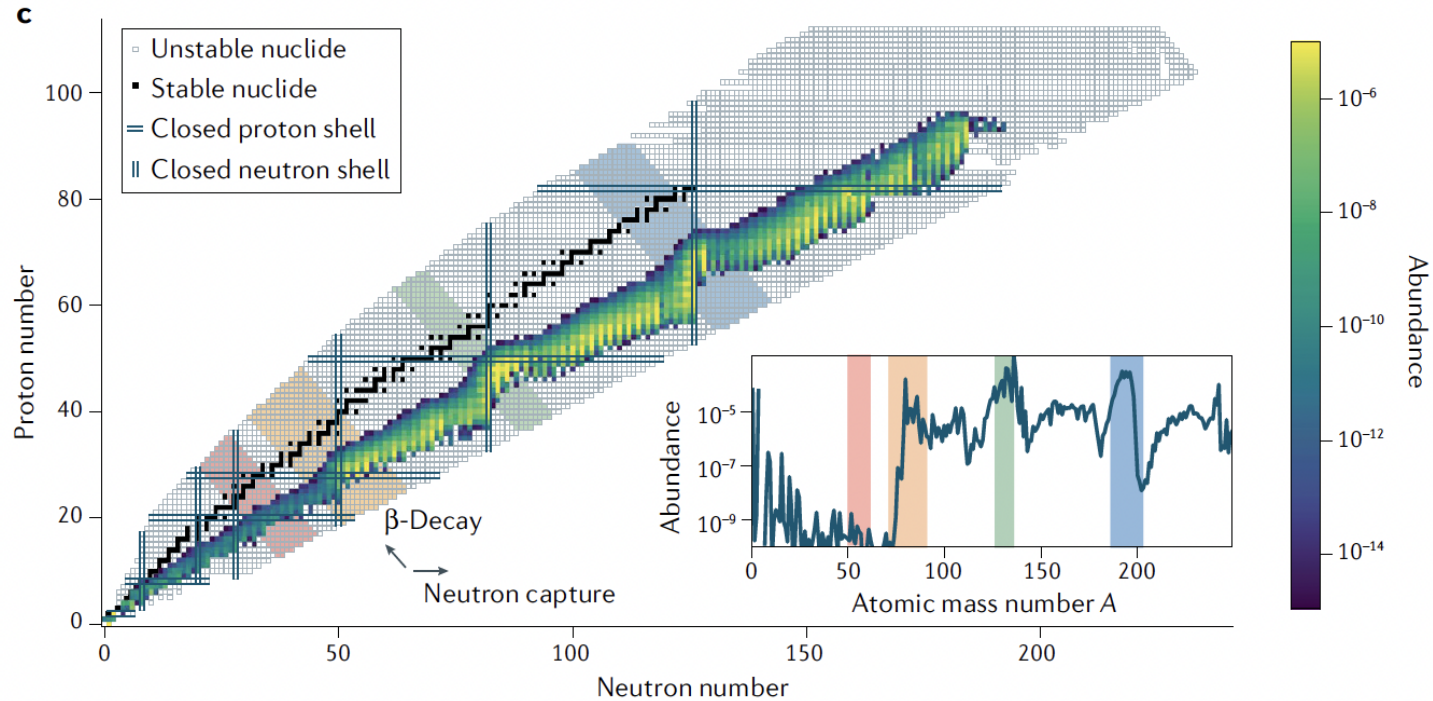
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Two different concepts

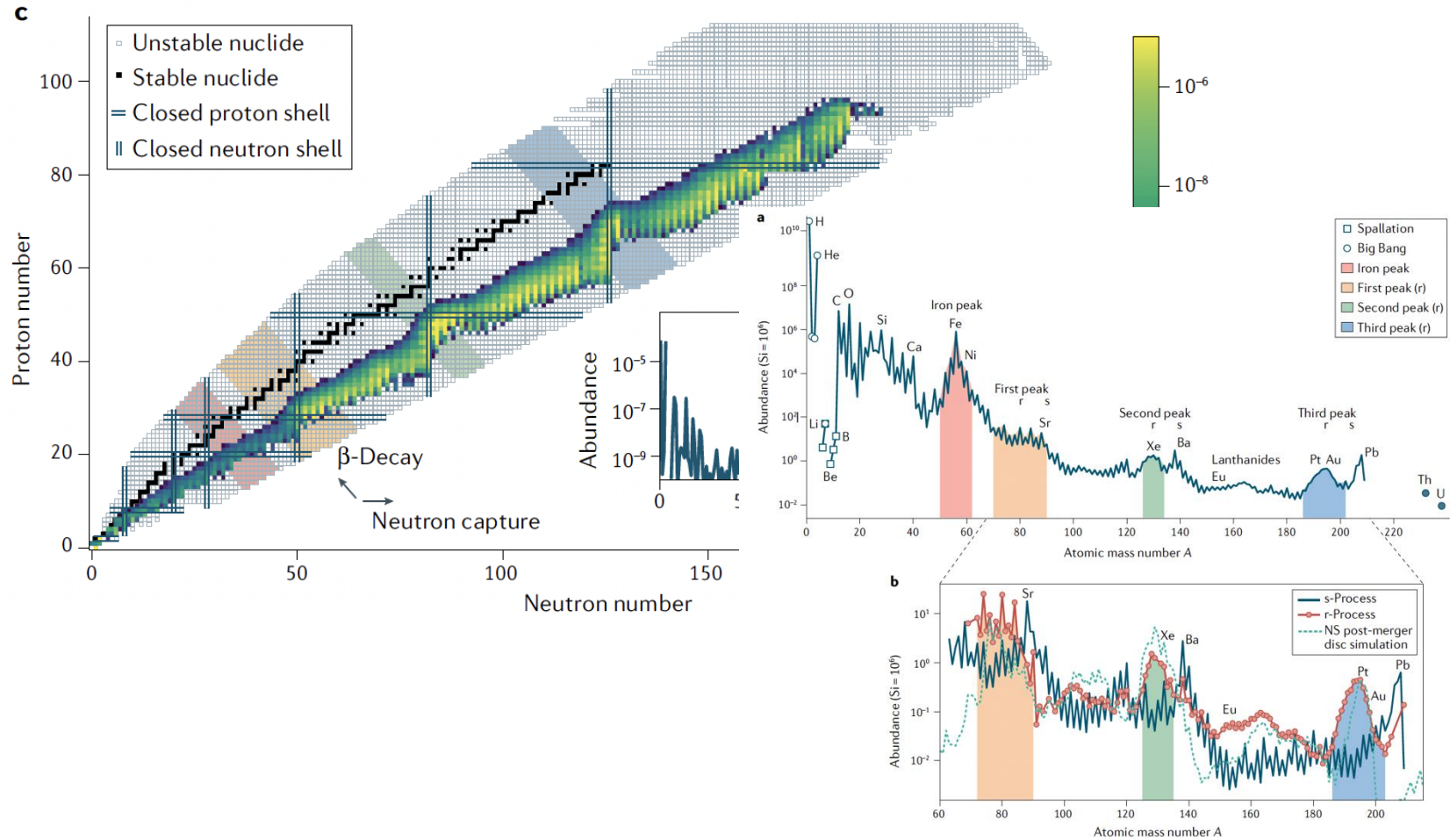
- 1- Waiting Point → the neutron capture process stops and nuclei get closer to stability line
- 2- Abundance Peak → peaks of higher abundances are created

Nucleosynthesis: Element formation in Stars

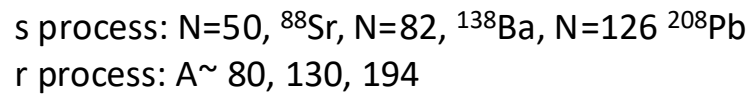


beta-decay spectroscopy towards the r-process G.Benzoni @ INFN-Milano

Nucleosynthesis: Element formation in Stars



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



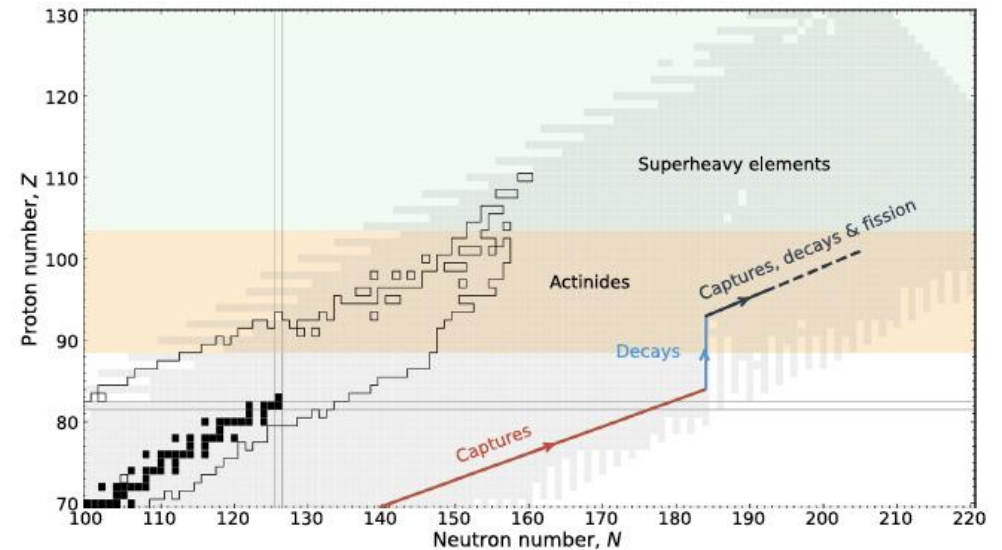
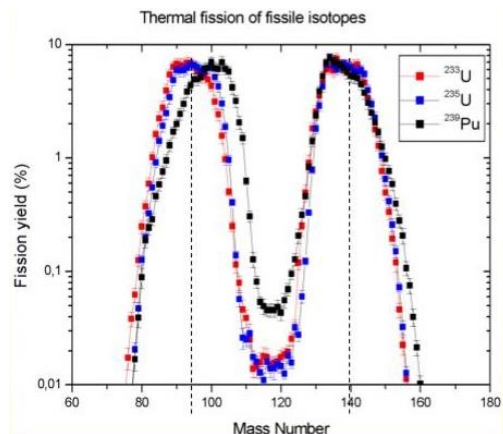
Nucleosynthesis: Element formation in Stars

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

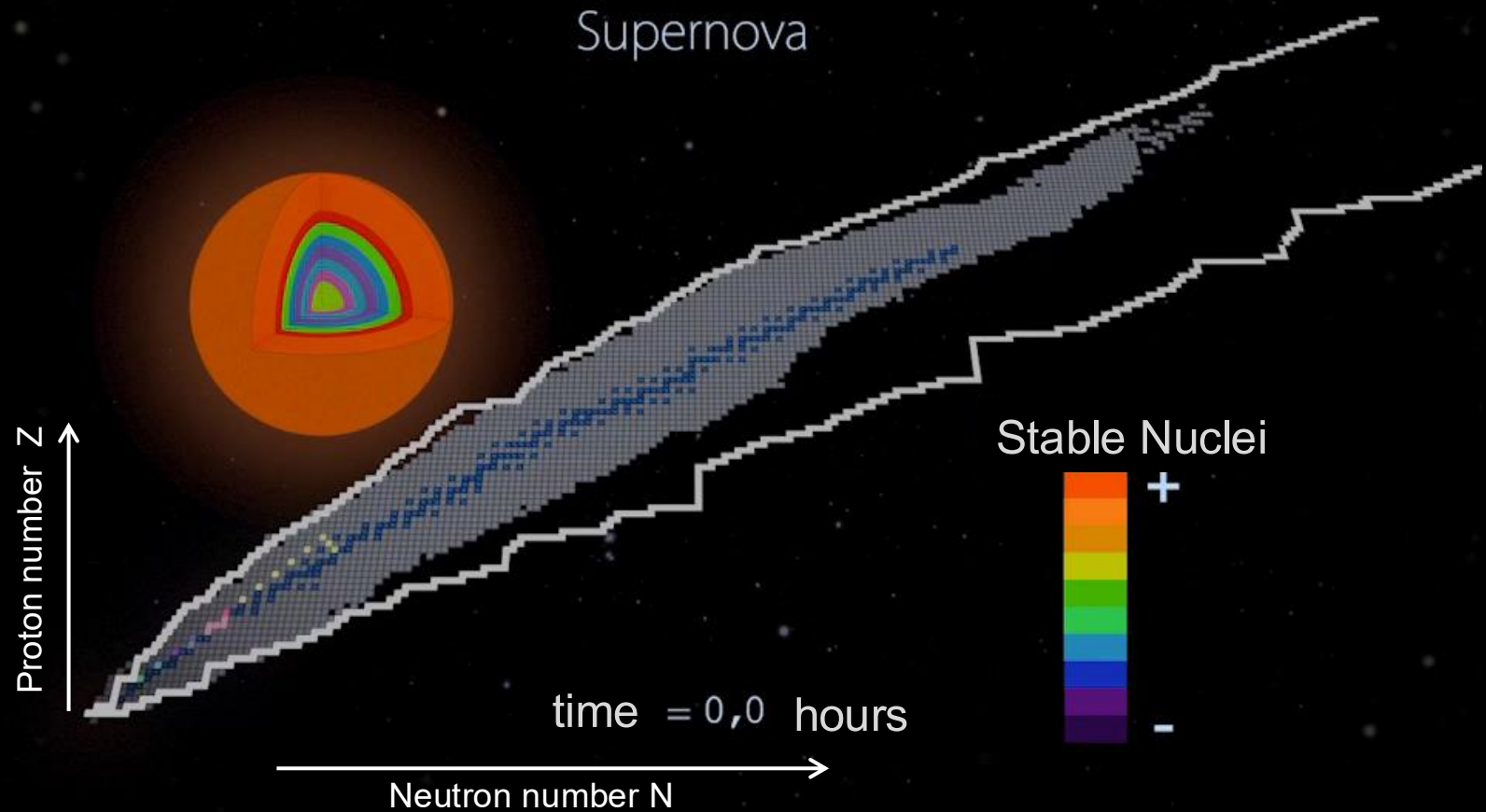
Fission has two effects

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

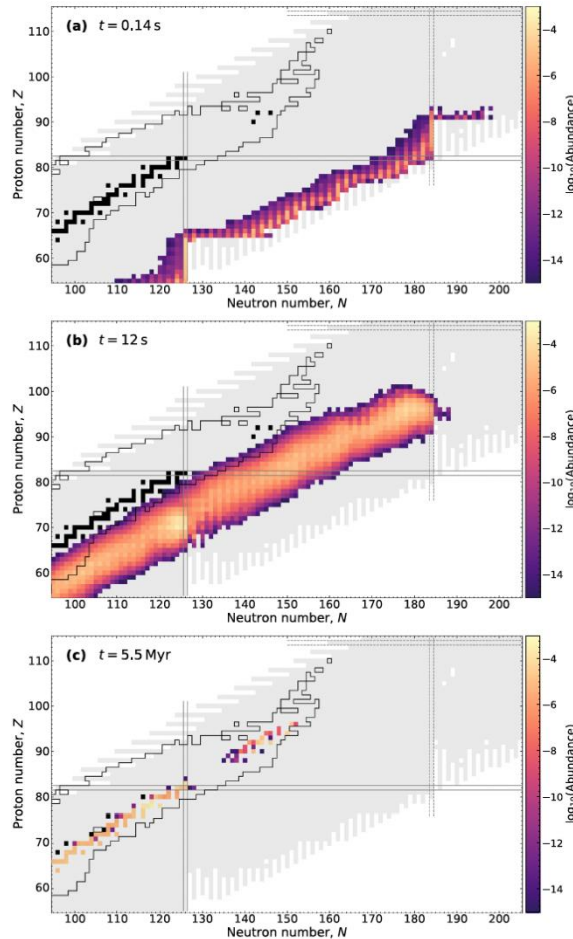
Element
formation in
stars

Example of
measurements
of β -decays

Perspectives

Conclusions

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
 β decay becomes dominant

Well after r process is ended

Gray shaded area,
theoretical extension of
the process

Nucleosynthesis: Element formation in Stars

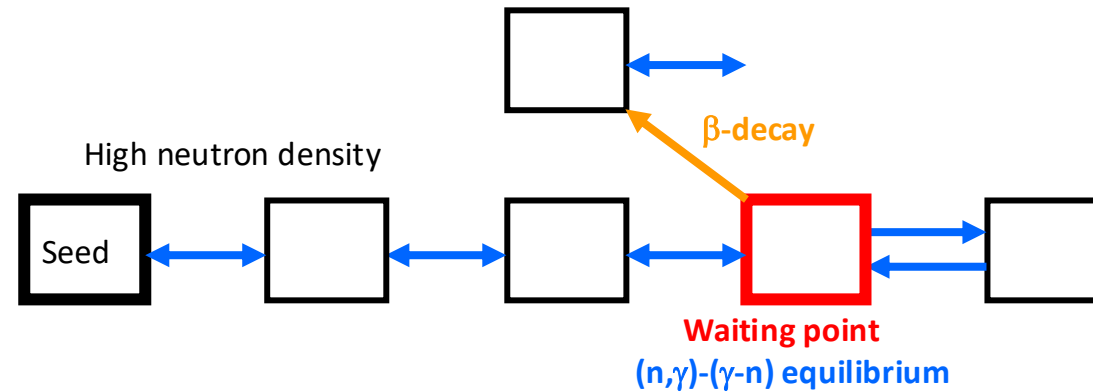
Decay of
radioactive
nuclei

Element
formation in
stars

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measurements
of β -decays

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Conclusions



Crucial inputs from experimental nuclear physics are

- Masses
- β -decay rates
- Branching Ratios
- n-capture cross sections

How do we produce exotic nuclei???

Measuring β decay

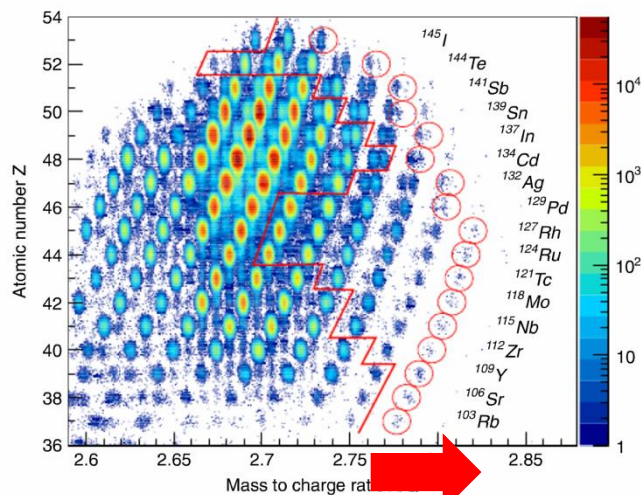
Decay of
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Element
formation in
stars

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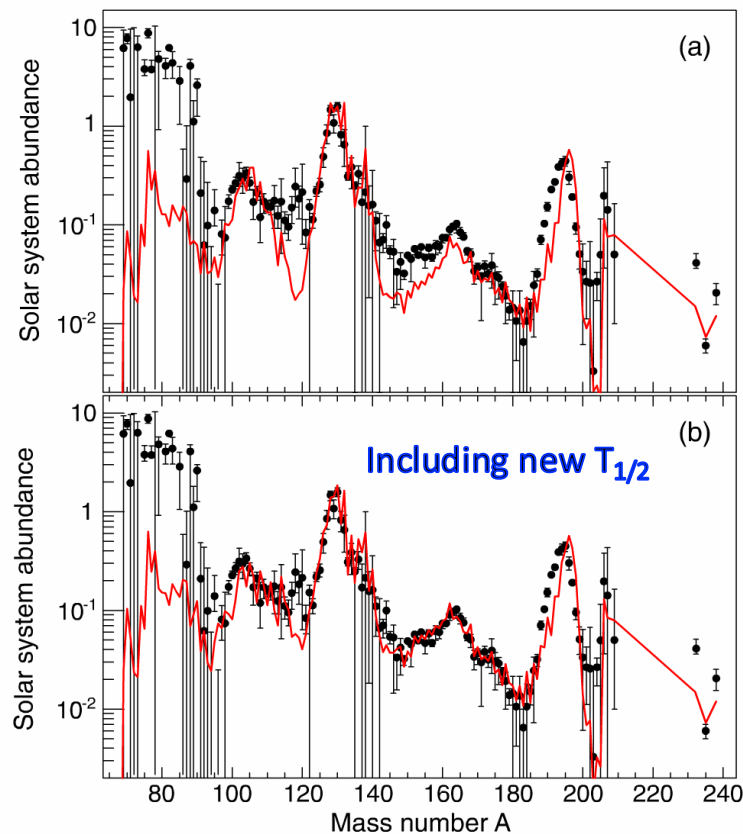


**Newly measured
 $T_{1/2}$**

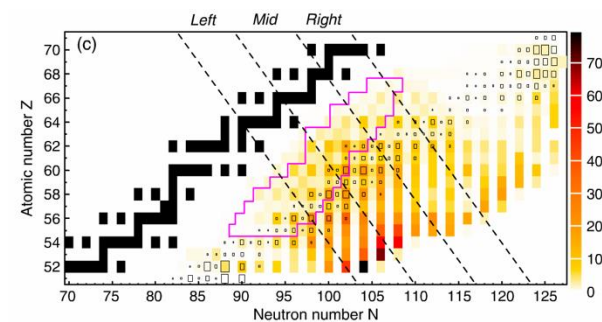
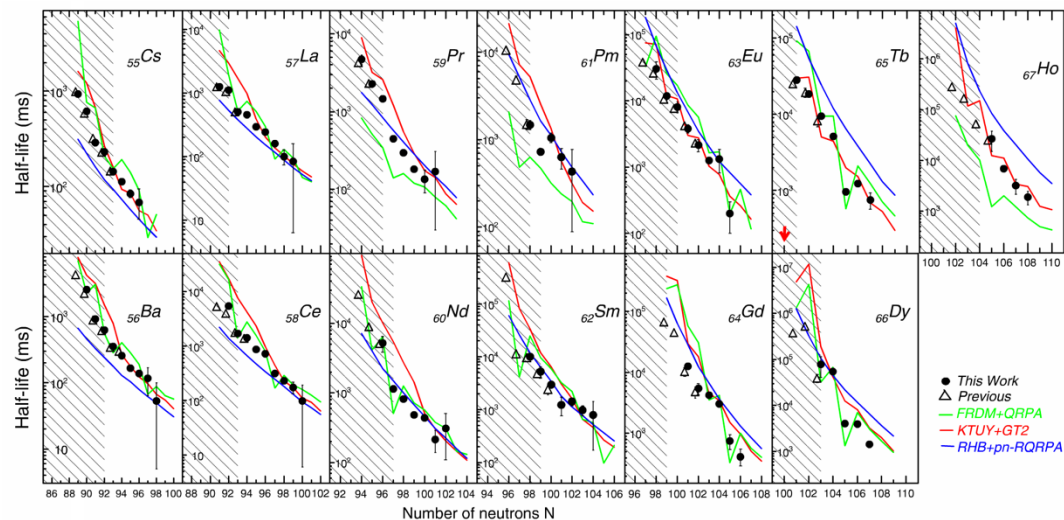
PRL 114, 192501 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

β -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,^{1,2,3} S. Nishimura,^{1,4} Z. Y. Xu,^{1,5,6} A. Jungclaus,⁷ Y. Shimizu,¹ G. S. Simpson,⁸ P.-A. Söderström,¹ H. Watanabe,^{1,9} F. Browne,^{1,10} P. Doornenbal,¹ G. Gey,^{1,8} H. S. Jung,¹¹ B. Meyer,¹² T. Sumikama,¹³ J. Taprogge,^{1,7,14} Zs. Vajta,^{1,15} J. Wu,^{1,16} H. Baba,¹ G. Benzoni,¹⁷ K. Y. Chae,¹⁸ F. C. L. Crespi,^{17,19} N. Fukuda,¹ R. Gemhäuser,²⁰ N. Inabe,²⁴ T. Isobe,¹ T. Kajino,^{4,21} D. Kameda,¹ G. D. Kim,²² Y.-K. Kim,^{22,23} I. Kojouharov,²⁴ F. G. Kondev,²⁵ T. Kubo,¹ N. Kurz,²⁴ Y. K. Kwon,²² G. J. Lane,²⁶ Z. Li,¹⁶ A. Montaner-Pizá,²⁷ K. Moschner,²⁸ F. Naqvi,²⁹ M. Niikura,⁵ H. Nishibata,³⁰ A. Odahara,³⁰ R. Orlandi,³¹ Z. Patel,³ Zs. Podolyák,¹ H. Sakurai,^{1,5} H. Schaffner,²⁴ P. Schury,¹ S. Shibagaki,^{4,21} K. Steiger,²⁰ H. Suzuki,¹ H. Takeda,¹ A. Wendt,²⁸ A. Yagi,³⁰ and K. Yoshinaga¹²



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

94 β -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

39

General Properties of β decay

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radioactive
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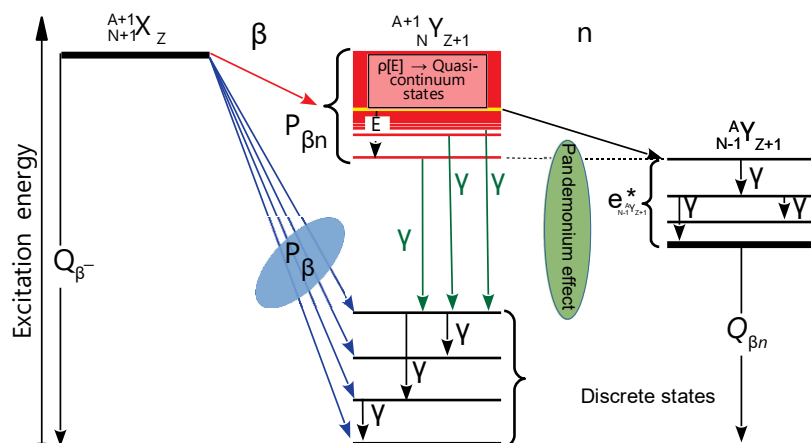
Example of
measurements
of β -decays

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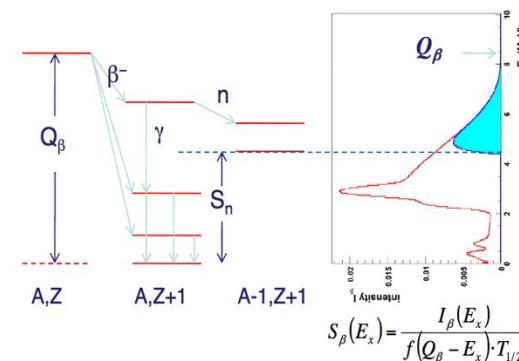
Evolution towards the n-rich side:
 Q_{β^-} generally gets larger while S_n gets smaller

Conditions for **β delayed neutron emission**



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

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



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

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

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

P_n yields information on β feeding above S_n

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

Measuring β decay

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

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

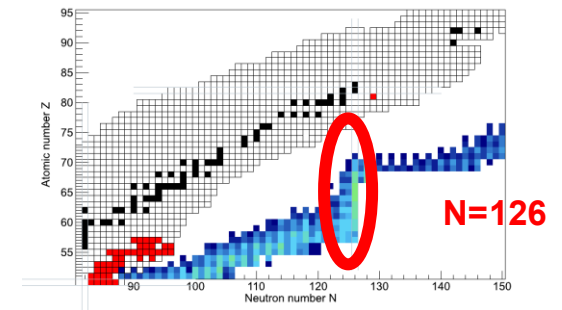
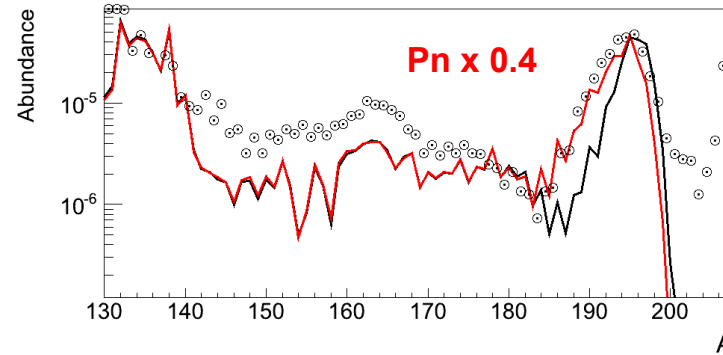
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Sensitivity study of inputs for nucleosynthesis modeling

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

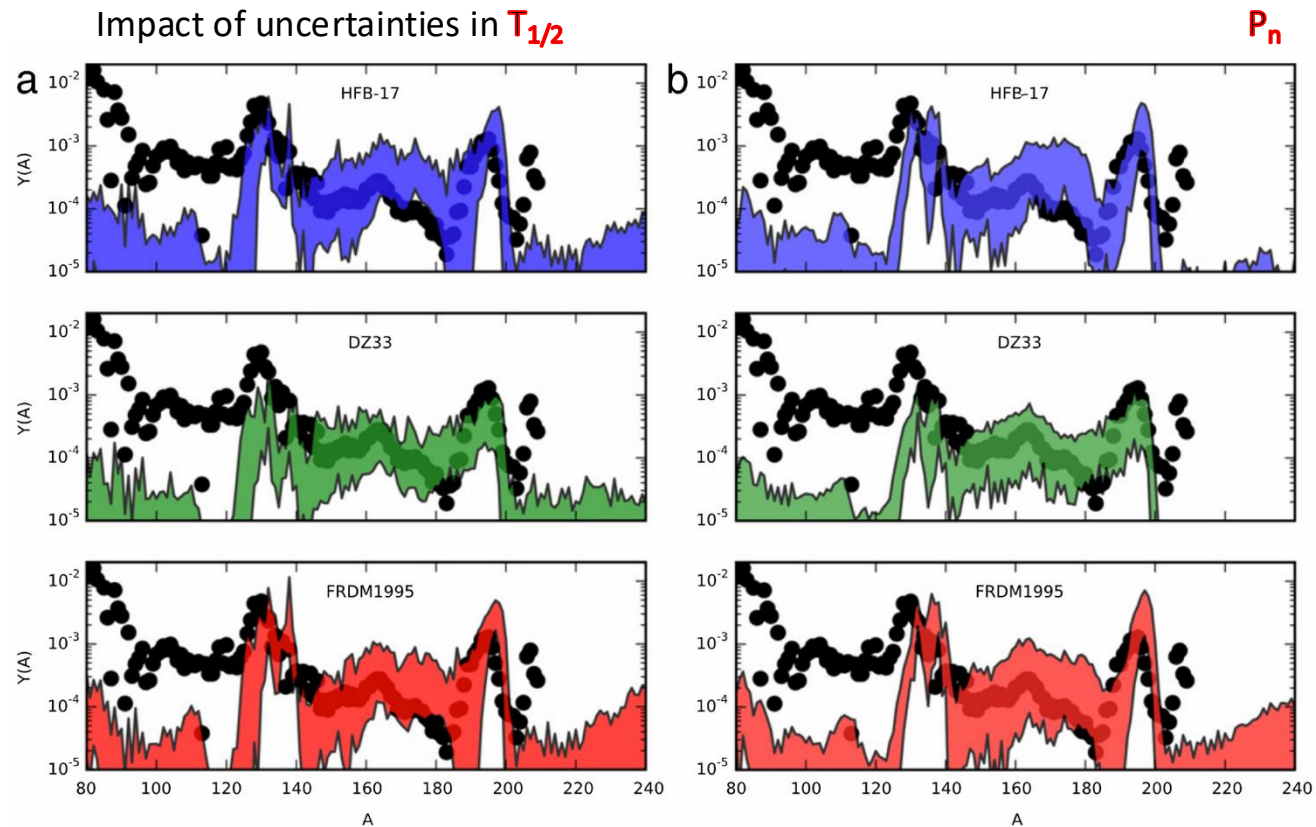
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beta-decay spectroscopy towards the r-process G.Benzoni @ INFN-Milano

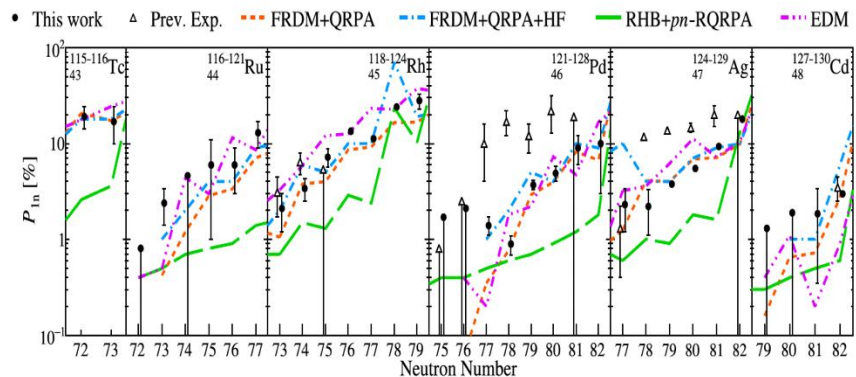
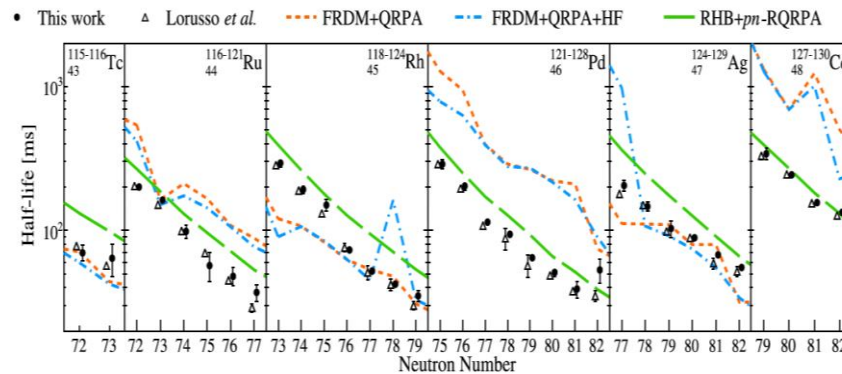
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FRDM+QRPA = cut-off approach: above S_n a neutron is emitted
FRDM+QRPA+HF = statistical decay and γ -ray emission explicitly at every stage
 EDM = semiempirical effective density model



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

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

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 staggering that is observed in the experimental values

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

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The new data not only constrain the theoretical predictions of half-lives and β -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

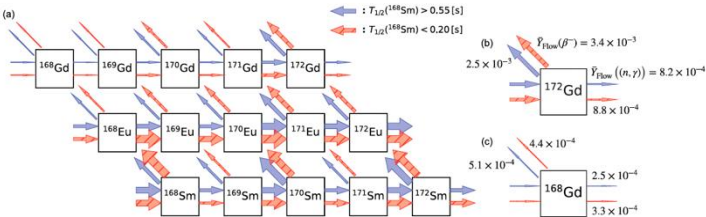
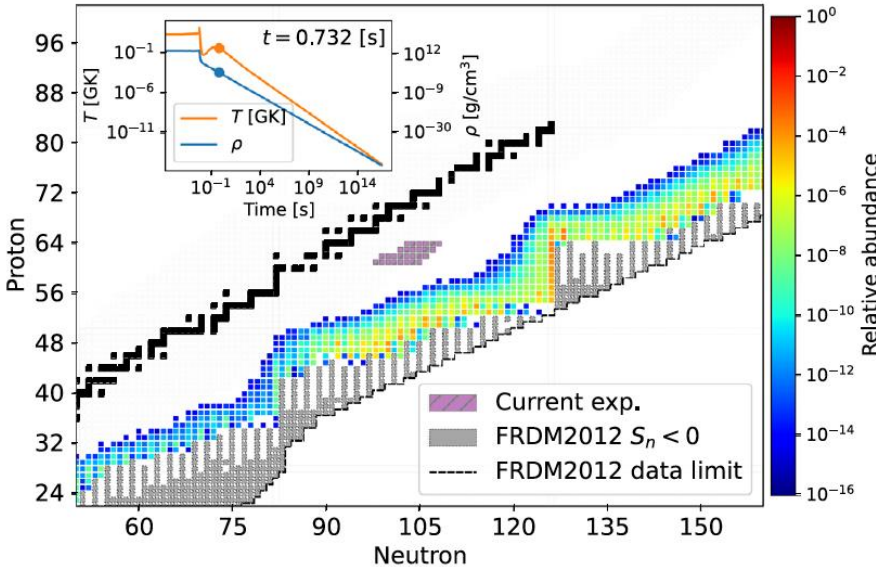


Figure 12. The arrows show the total abundance flow (same quantity as in panels (g)–(i) in Figure 11), averaged over the generated samples in the neutron-star merger scenario. Red corresponds to the case where the half-life of ^{168}Sm is shorter than 0.20 [s], and blue shows a half-life longer than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

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

G. G. Kiss¹, A. Vitéz-Sveicz^{1,2}, Y. Saito^{3,4}, A. Tarifeño-Saldivia^{5,6}, M. Pallas⁵, J. L. Tain⁶, I. Dillmann^{3,7}, J. Agramunt⁶, A. Algara^{1,6}, C. Domingo-Pardo⁸, A. Estrade⁸, C. Appleton⁹, J. M. Allmond¹⁰, P. Aguilera^{11,12}, H. Baba¹³, N. T. Brewer^{10,14}, C. Bruno⁹, R. Caballero-Folch⁸, F. Calvino⁵, P. J. Coleman-Smith¹⁵, G. Cortes⁵, T. Davinson⁹, N. Fukuda¹², Z. Ge¹³, S. Go^{13,16}, C. J. Griffin¹, R. K. Grzywacz^{10,14}, O. Hall⁹, A. Horváth¹⁷, J. Ha^{13,18}, L. J. Harkness-Brennan¹⁹, T. Isobe¹², D. Kahl⁹, T. T. King¹⁴, A. Korgul²⁰, S. Kovács³, R. Krücken^{3,4}, S. Kubono¹³, M. Labiche¹⁵, J. Liu²¹, J. Liang³, M. Madurga¹⁴, K. Miernik²⁰, F. Molina¹¹, A. I. Morales⁵, M. R. Mumpower^{22,23}, E. Nacher⁶, A. Navarro⁵, N. Nepal⁸, S. Nishimura¹³, M. Piersa-Silkowska²⁰, V. Phong¹³, B. C. Rasco^{10,14}, B. Rubio⁵, K. P. Rykaczewski¹⁰, J. Romero-Barrientos¹, H. Sakurai¹³, L. Sexton^{3,9}, Y. Shimizu¹³, M. Singh¹⁴, T. Sprouse^{22,23}, T. Sumikama¹³, R. Surman²⁴, H. Suzuki¹³, T. N. Szegedi¹, H. Takeda¹³, A. Tolosa⁶, K. Wang¹, M. Wolinska-Cichocka²⁵, P. Woods⁵, R. Yokoyama²⁶, and Z. Xu¹⁴



General Properties of β decay

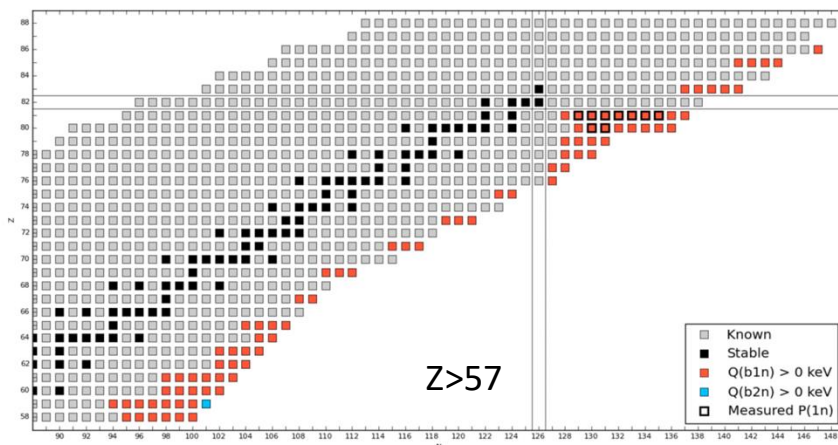
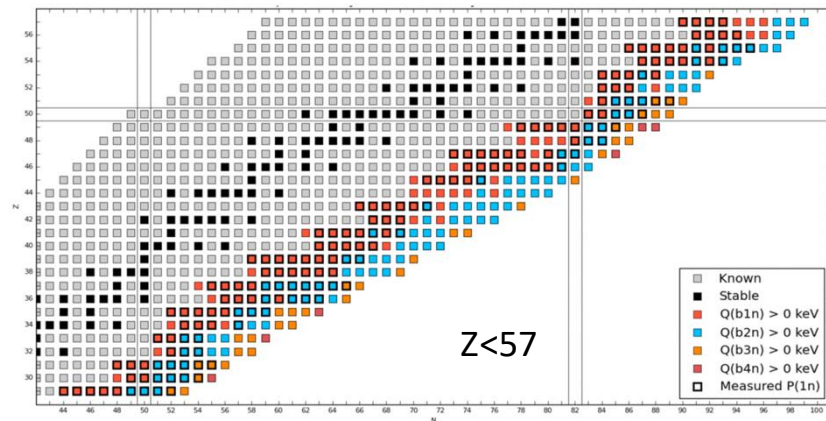
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Available online at www.sciencedirect.com

ScienceDirect

Nuclear Data Sheets 168 (2020) 1–116

**Nuclear Data
Sheets**

www.elsevier.com/locate/nds

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

J. Liang,¹ B. Singh,^{1,*} E.A. McCutchan,² I. Dillmann,^{3,4} M. Birch,¹ A.A. Sonzogni,² X. Huang,⁵ M. Kang,⁵ J. Wang,⁵ G. Mukherjee,⁶ K. Banerjee,⁶ D. Abriola,⁷ A. Algorta,^{8,9} A.A. Chen,¹ T.D. Johnson,² and K. Miernik¹⁰

Little data for heavy nuclei:

- Difficult access to nuclei
- Difficulty in measuring neutrons

General Properties of β decay

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

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

- 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/β separate but simultaneous $P_n = \frac{\epsilon_\beta}{\epsilon_n} \frac{N_{\beta n}}{N_\beta}$

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

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- γ - γ : Total counting of all γ -rays emitted by daughter and/or βn -daughter, but no counting of neutrons is carried out.

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

Detecting α β γ n particles: reminder of basic properties

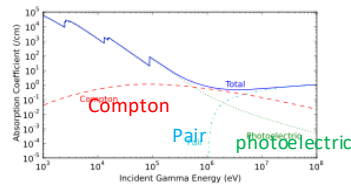
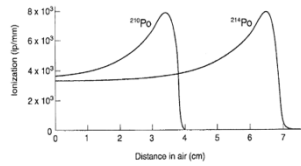
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α particle: massive, charged

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

β particles: light, charged

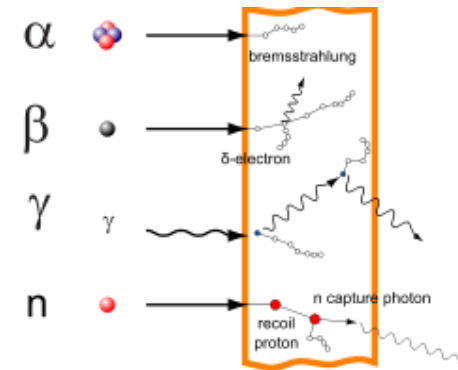
- interested in energy and correlations
- e^+ annihilates into two 511-keV γ rays
- spectrometers, Si, plastic detectors

γ particles: massless, neutral

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

Neutrons: massive, neutral

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

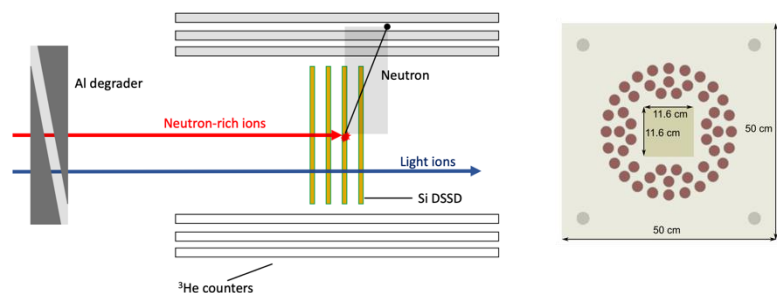


2 ways:

- TOF
- ^3He counters

General Properties of β decay

BEta-deLAYEd Neutron detector (BELEN):
48 ^3He cylindrical counters in Polyethylene moderator



Commissioning of the BRIKEN detector for the measurement of very exotic β -delayed neutron emitters

A. Tolosa-Delgado^a, J. Agramunt^a, J. L. Tain^{a,*}, A. Algorta^{a,b}, C. Domingo-Pardo^a, A. I. Morales^a, B. Rubio^a, A.

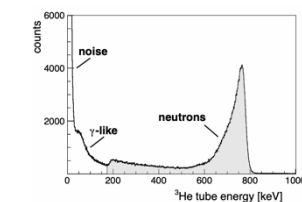


Figure 7: Distribution of energies registered in the ^3He tubes of the BRIKEN neutron counter. The spectrum contains the sum of all ^3He tube signals in one run. The shaded area represents the range of signals accepted as valid neutron signals. See text for details.

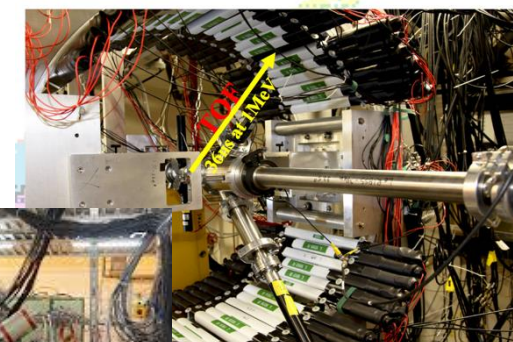
NIMA [925](#), 1 May 2019, Pages 133-147

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

VANDLE array : plastic scintillator bars, coupled to β - γ det.
neutron multiplicity and energy via TOF

The neutron reactions involved in the case of a ^3He counter are four:

- 1.1. ^3He recoil $^3\text{He}+n \rightarrow ^3\text{He}' + n'$ (elastic scattering),
- 2.2. (n,p) $^3\text{He}+n \rightarrow p + T + 764 \text{ keV}$,
- 3.3. (n,d) $^3\text{He}+n \rightarrow ^2\text{H} + ^2\text{H} - 3.27 \text{ MeV}$,
- 4.4. γ -rays.



Existing arrays

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- ^3He counters

- B-Riken (Japan)
- Tetra (Dubna-Orsay)
- ^3He 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:

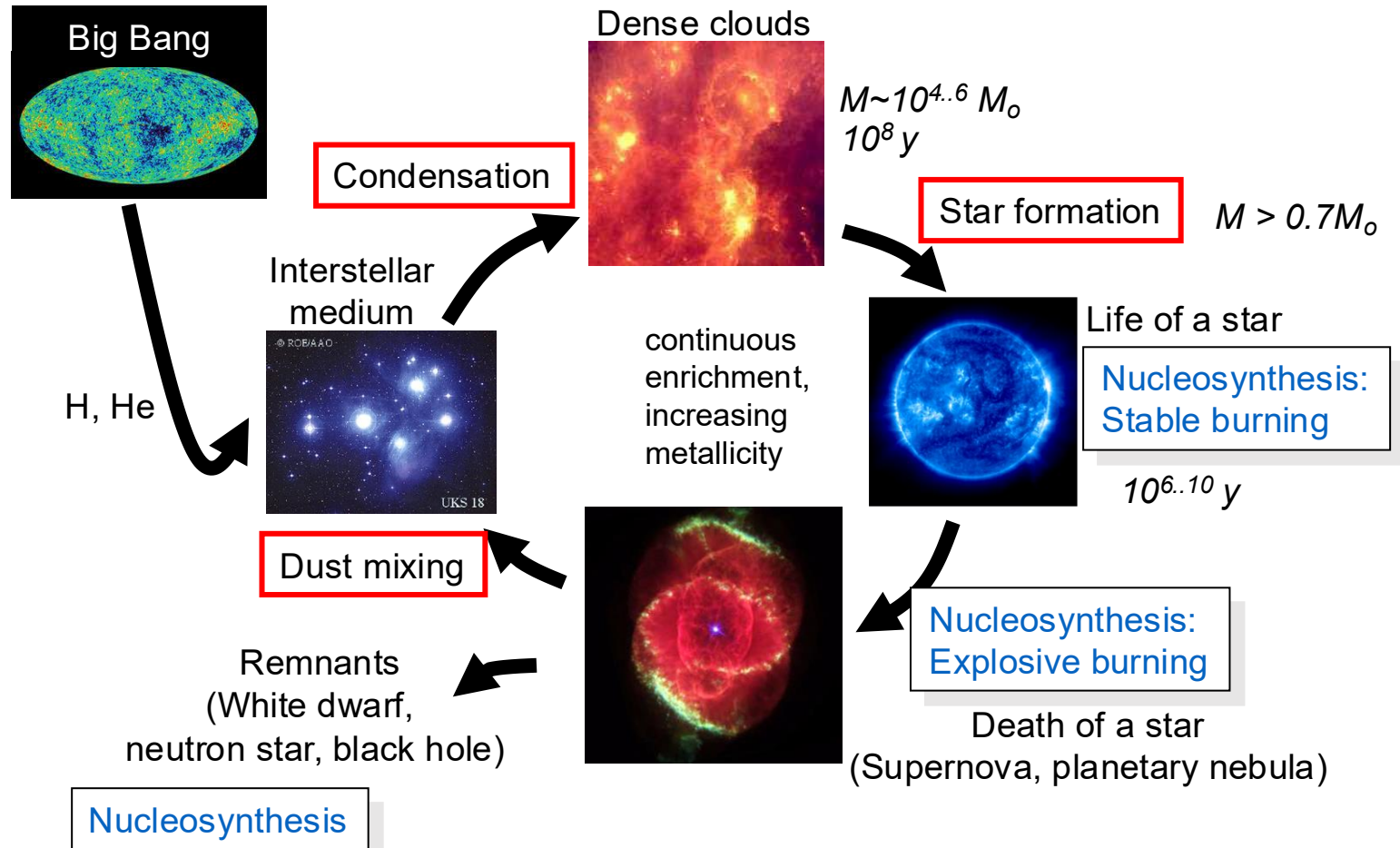
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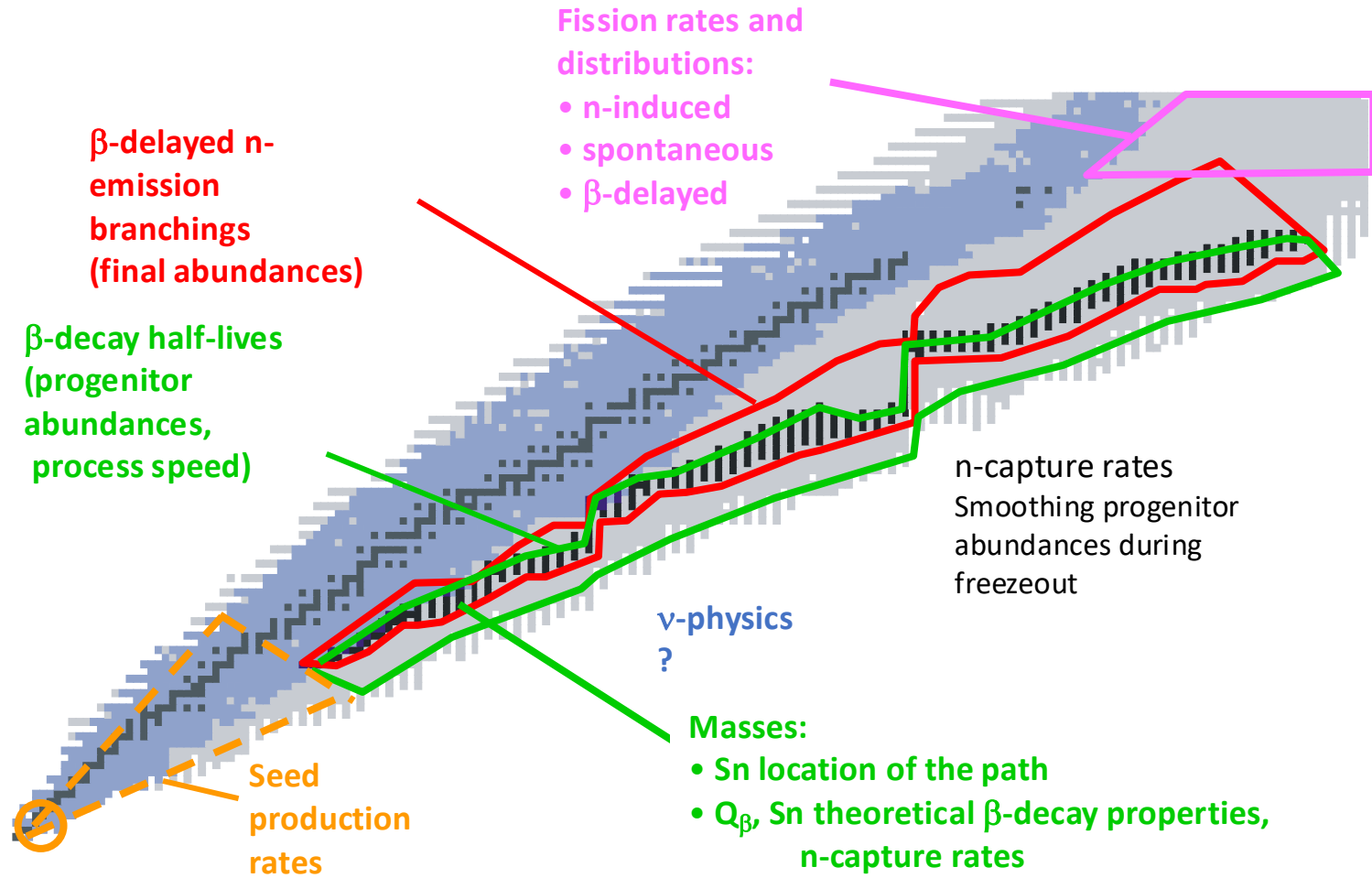
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Conclusions

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

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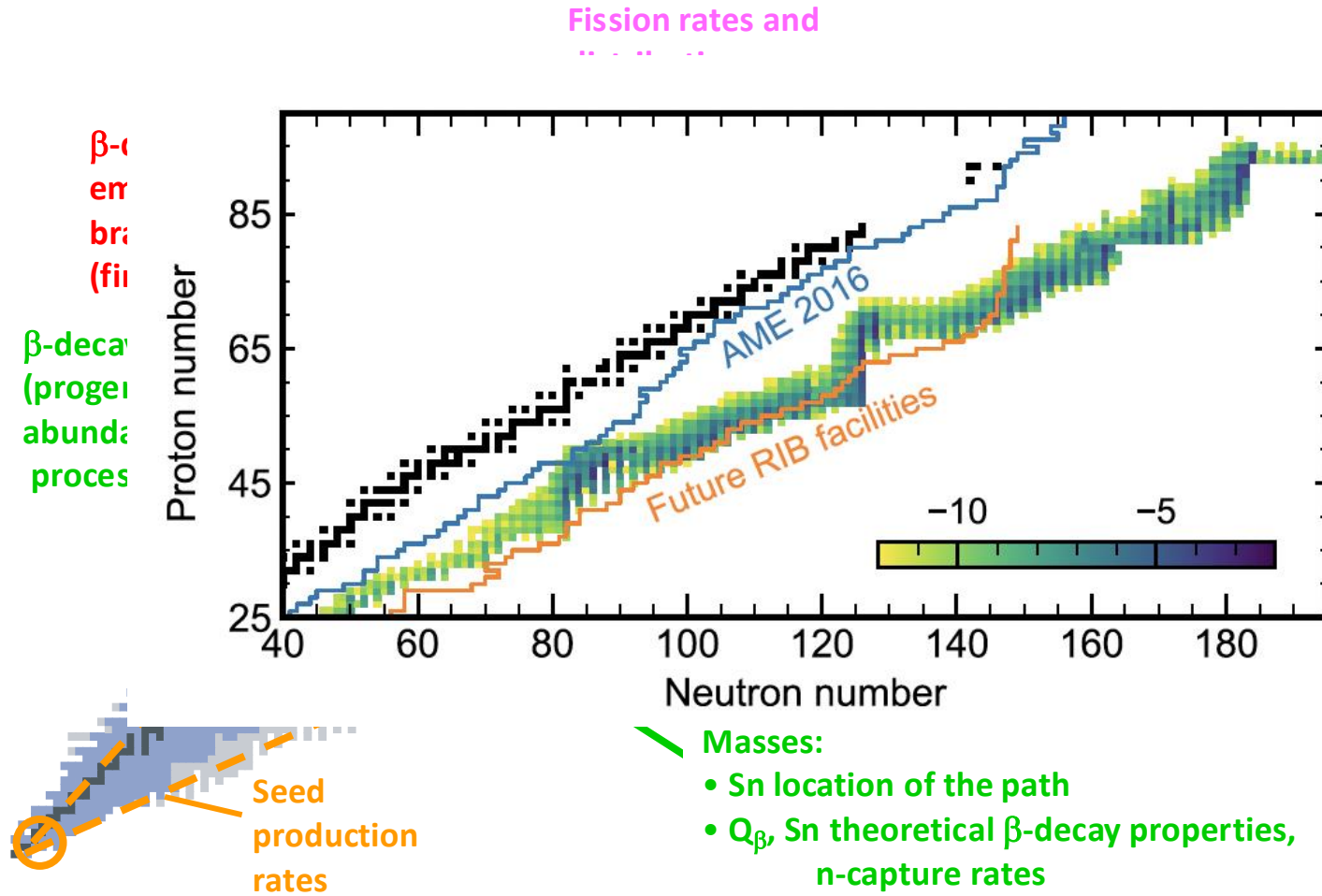


beta-decay spectroscopy towards the r-process G.Benzoni @ INFN-Milano

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

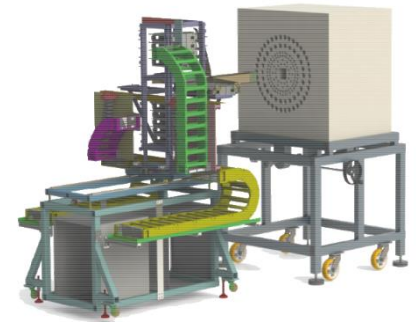
Measuring neutrons after β decay



The BEta deLAYed Neutron detector (BELEN) array of ^3He tubes arranged in crowns around the beam hole embedded in a polyethylene matrix. Coupled to β - γ detectors

Currently measuring at B-Riken

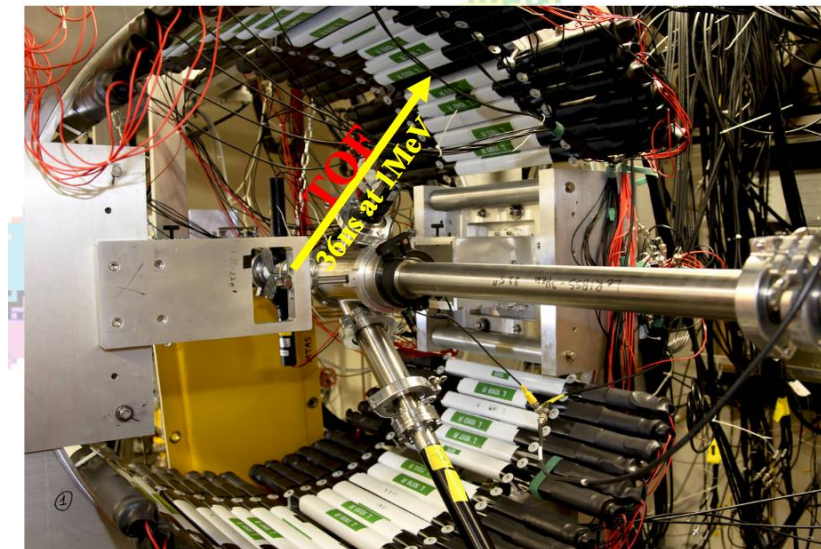
Competition with 3Hen / Tetra



VANDLE array : plastic scintillator bars, coupled to β - γ det.
neutron multiplicity and energy via TOF

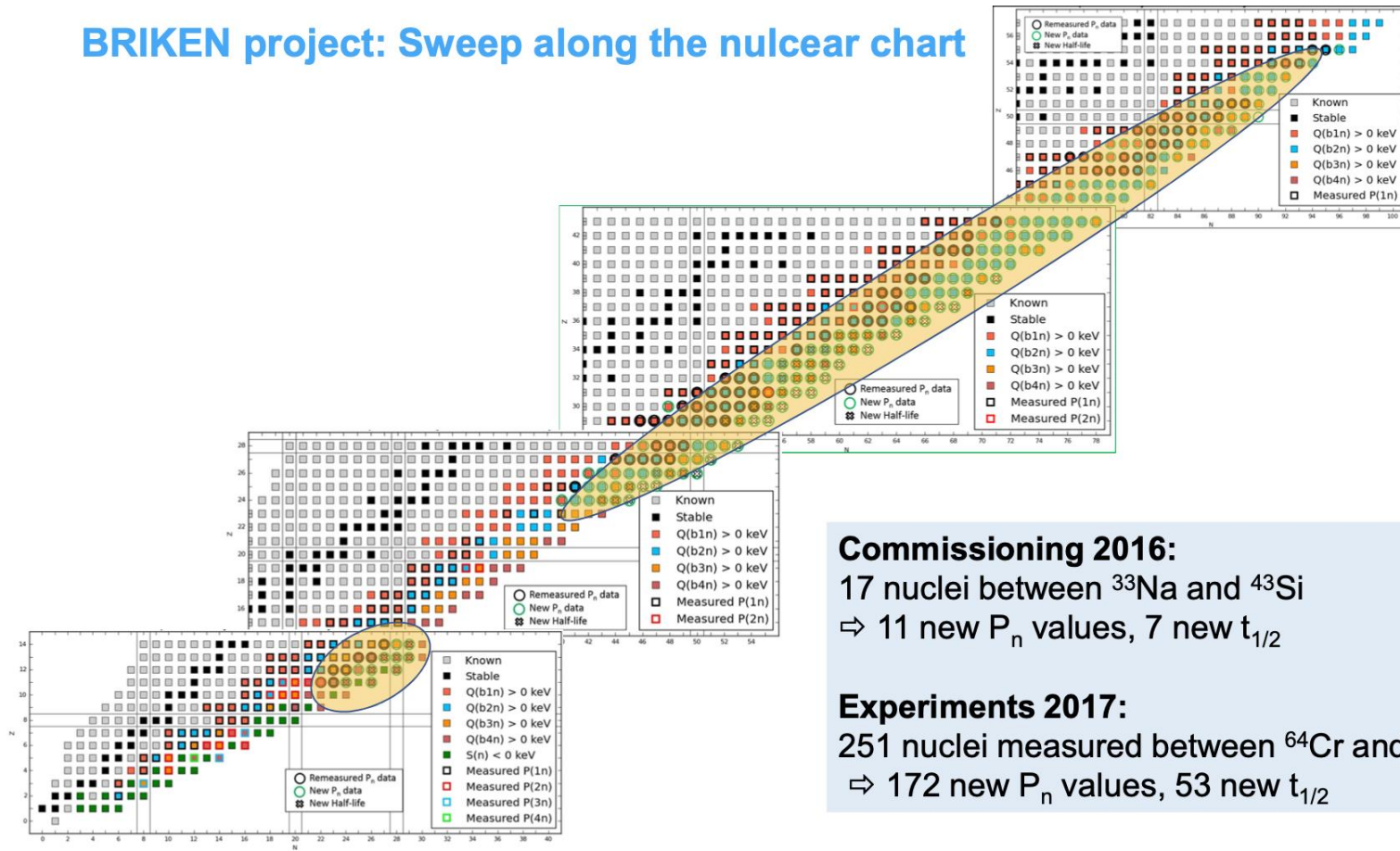


Currently measuring at IDS ISOLDE



BRIKEN campaign: measurement of P_n values at RIKEN

BRIKEN project: Sweep along the nuclear chart



Commissioning 2016:

17 nuclei between ^{33}Na and ^{43}Si

⇒ 11 new P_n values, 7 new $t_{1/2}$

Experiments 2017:

251 nuclei measured between ^{64}Cr and ^{170}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

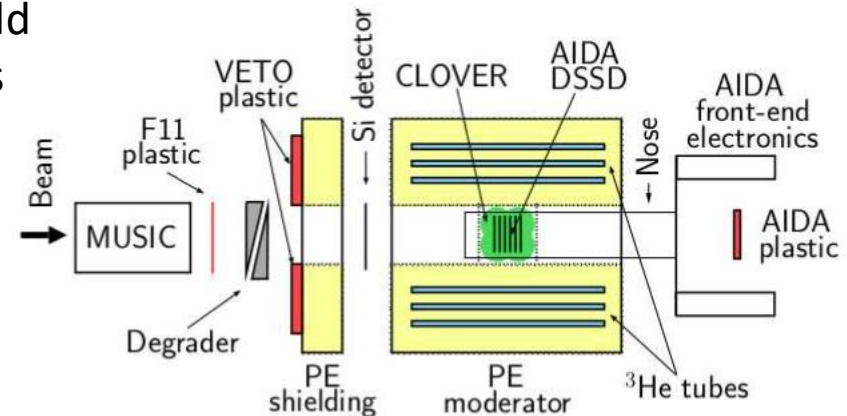


Figure 1: Arrangement of elements in the experimental setup mentioned in the text. The drawing is not to scale.

Commissioning of the BRIKEN detector for the measurement of very exotic β -delayed neutron emitters

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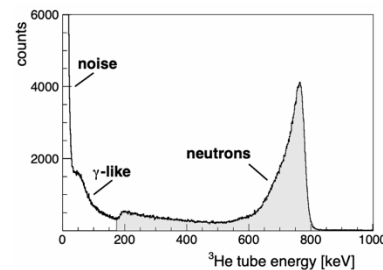


Figure 7: Distribution of energies registered in the ^3He tubes of the BRIKEN neutron counter. The spectrum contains the sum of all ^3He tube signals in run. The shaded area represents the range of signals accepted as valid net signals. See text for details.

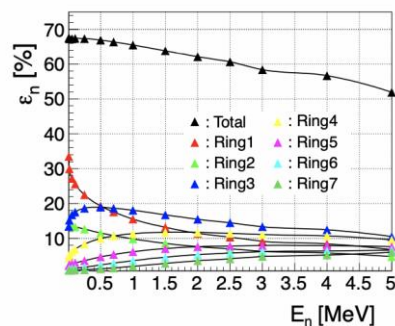


Figure 4: Efficiency of the BRIKEN neutron counter as a function of neutron energy. The total efficiency (black symbols) and the contribution of each ring (colored symbols) is shown. See Fig. 3 for the definition of rings.