Beta decay studies of the most exotic nuclei

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Outline of the lessons:

PARTI: General concepts

How to measure β decay in exotic nuclei

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

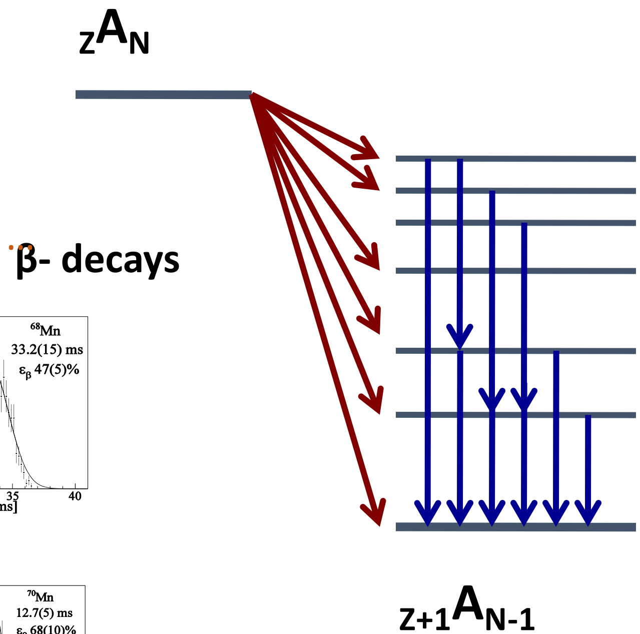
PARTIII: High resolution vs TAS

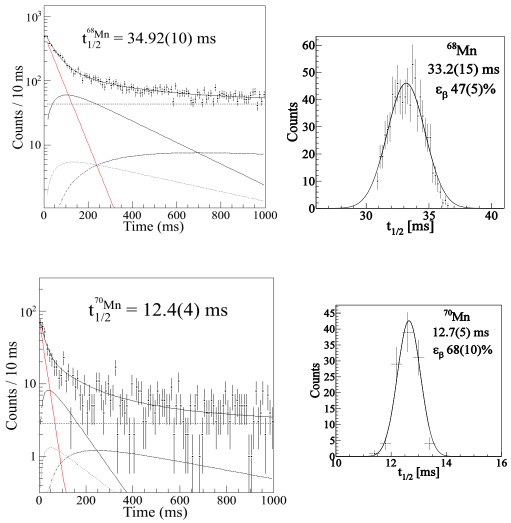
Istituto Nazionale di Fisica Nucleare

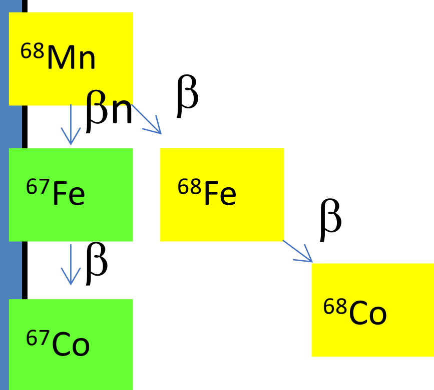
General Properties of β decay

Quantities that can be extracted in a β decay experiment

$T_{1/2}$
P_n
%β, %α ...

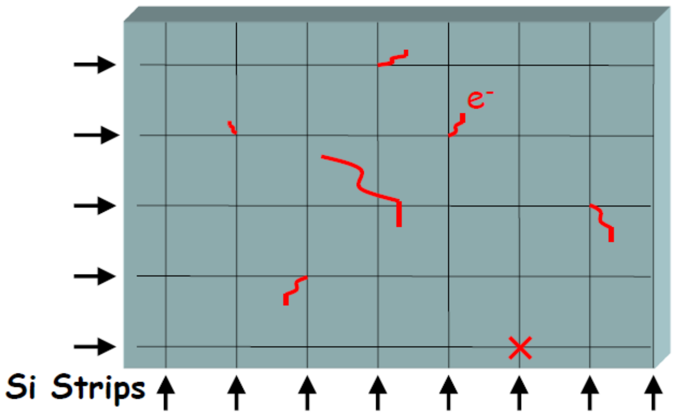






Measuring short half-lives

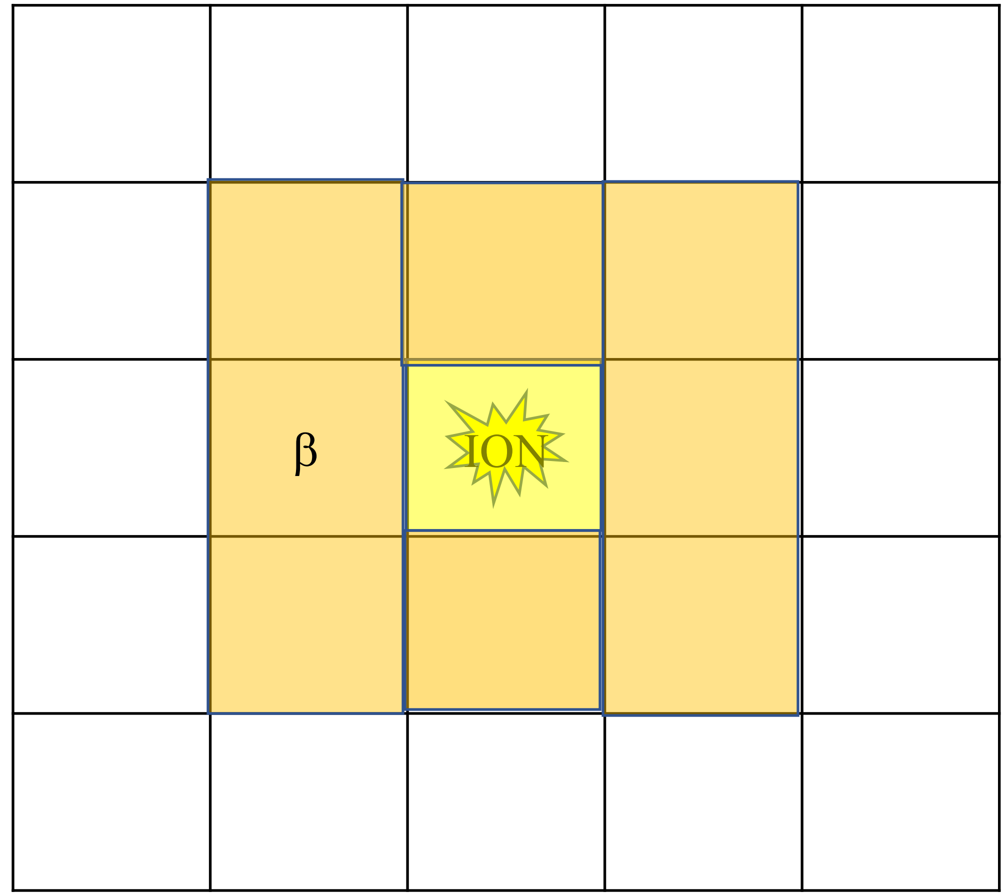
Focal plane implantation detector sensitive to electron emission



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.

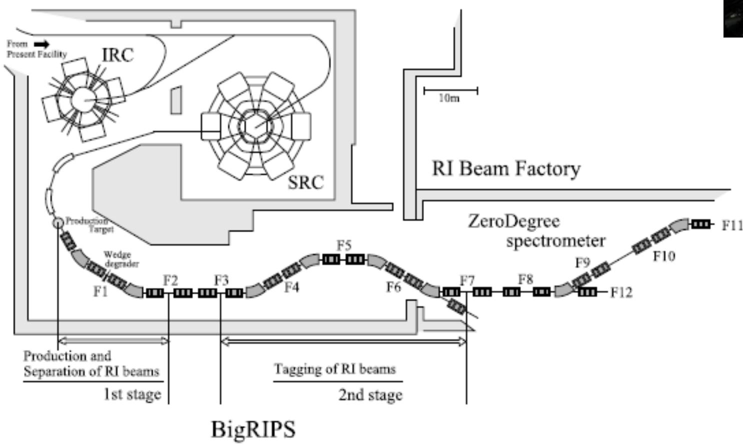
- Limit Ion rate
- Time and space ion-β correlations
- 2 options:
  - Wait for 1st β particle
  - Consider all following β up to next implantation

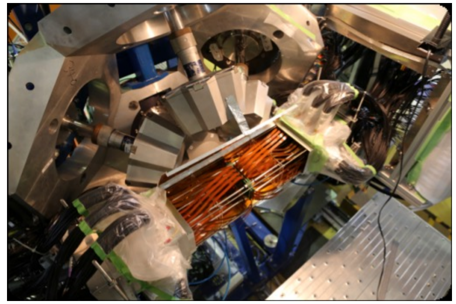
- ΔT(Ion- β) is $T_{1/2}$



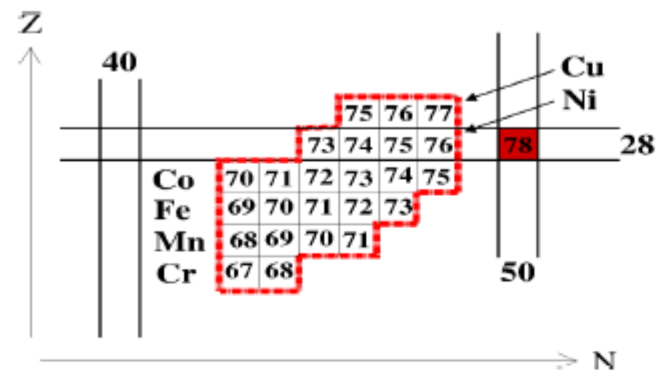
Measuring short half-lives

3 days of beamtime
^{238}U @ 345MeV/u
I_{beam}~ 10 pnA
BigRIPS setting focused on ^{71}Fe

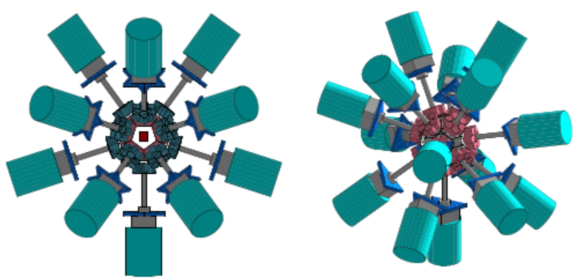




5 DSSSD - WAS3ABI
(64X40 strips)
Ion-beta correlations



12 HPGe Clusters
β–γ correlations



(a) Upstream view

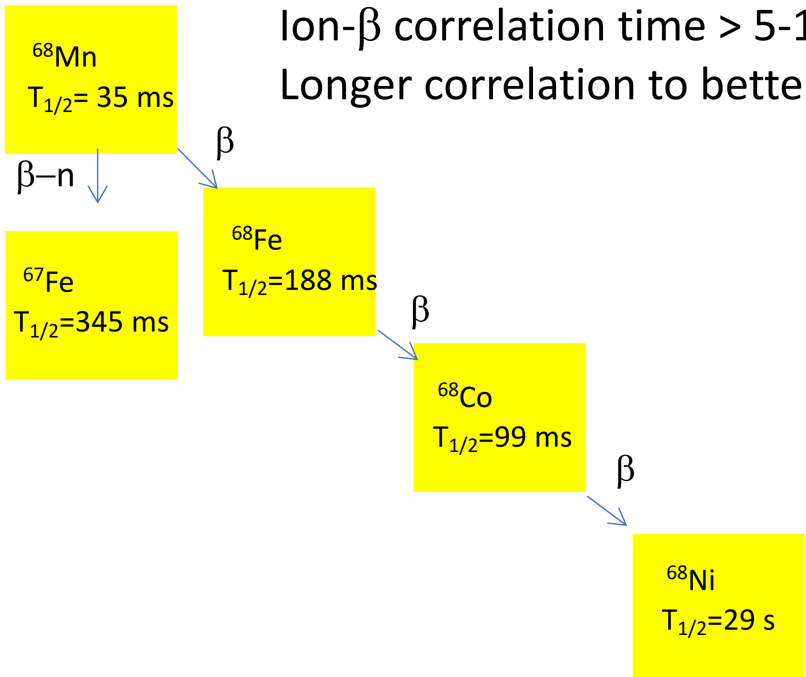
(b) View from 120 degrees

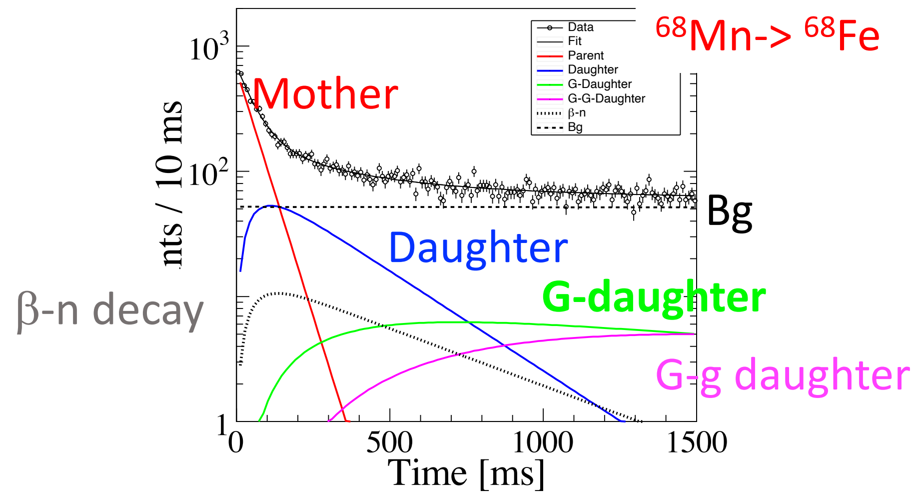
18 $LaBr_3(Ce)$ (1.5”x 2”)
2 BC-418 Plastic 2mm thick
Fast-timing measurements

Measuring short half-lives

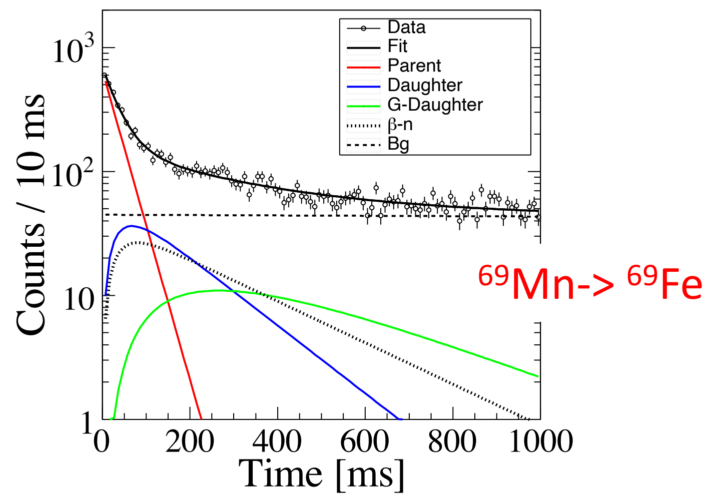
Ion-β correlation time > 5-10 x $T_{1/2}$ ➔ need to include decay chain

Longer correlation to better estimate the bg ➔ 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

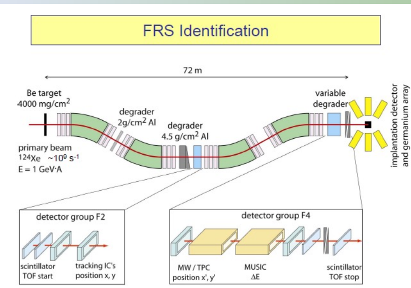


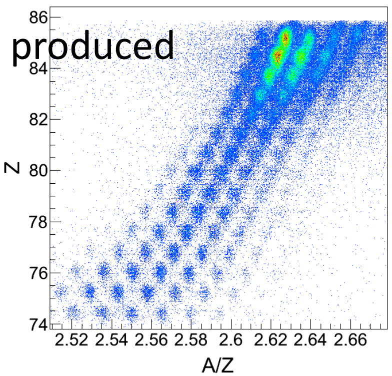
[1] S.N.Liddick et al., PRC 87, 014325 (2013).
[2] J.M.Daugas et al., PRC 83, 054312 (2011)
[3] P.Moller, B.Pfeiffer and K.-L. Kratz,Phys.Rev. C 67, 055802 (2003)

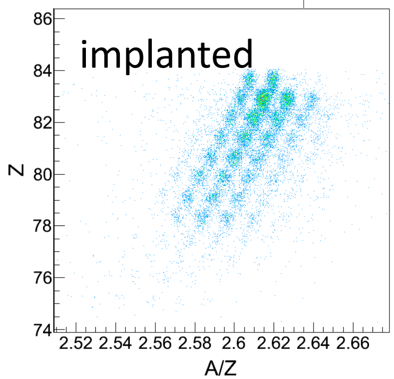
G.Benzoni et al. PLB 751 (2015) 107–112

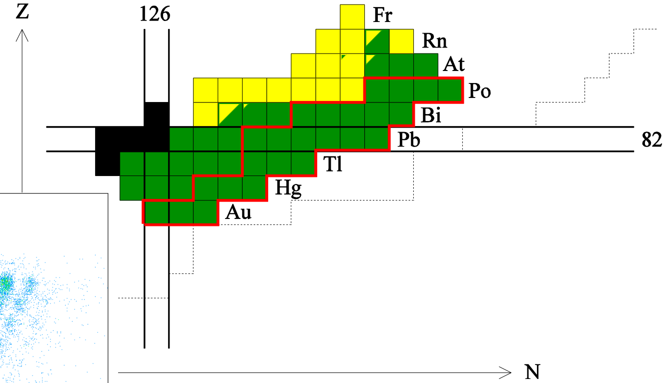
Measuring long half-lives

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

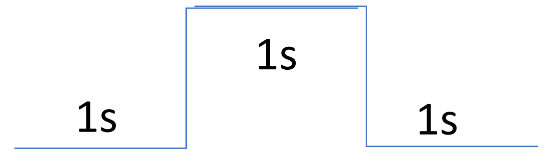








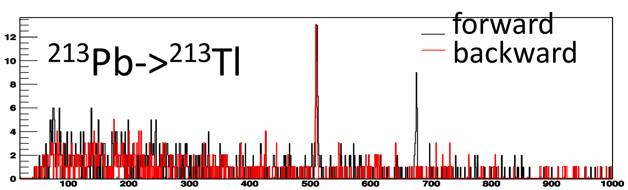
Spill structure @ GSI extraction

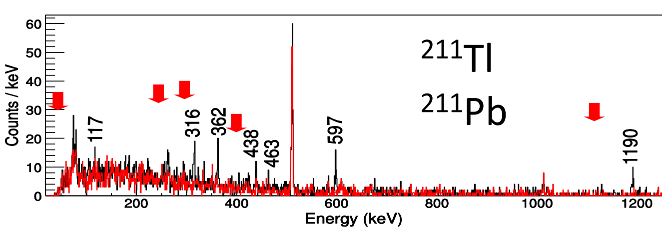


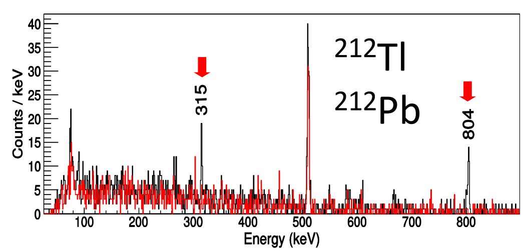
WARNING: long lifetimes and high rates imply a careful study of bg contributions

➔ 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 $^{211\text{-}212\text{-}213}Tl$

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 β decay half life and the β detection efficiency

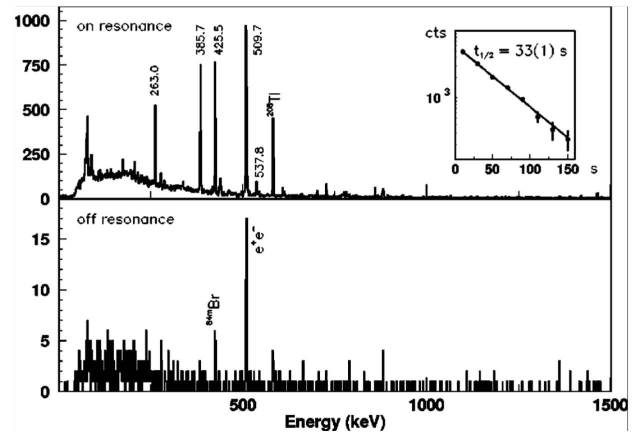
T. Kurtukián-Nieto et al., NIMA (2008)

χ^2 fits to two independent time correlations:

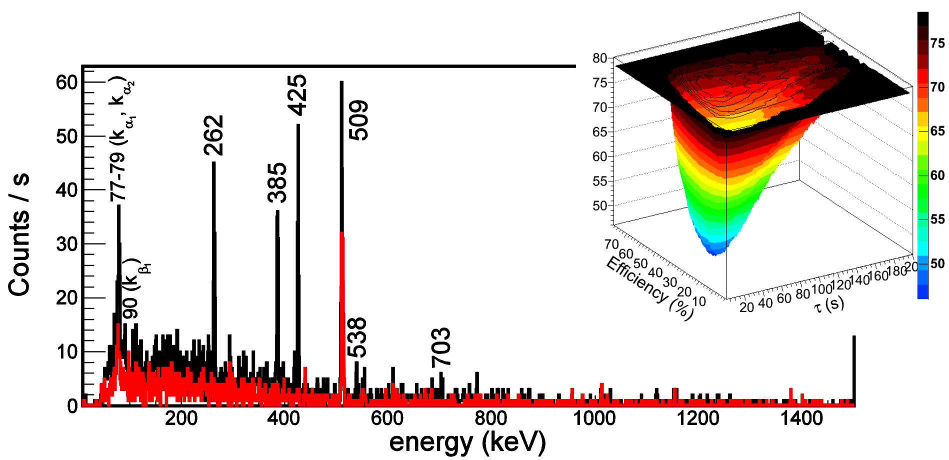
- Experimental ion-β time-correlated spectra
- Calculated time distribution obtained from Monte-Carlo simulations

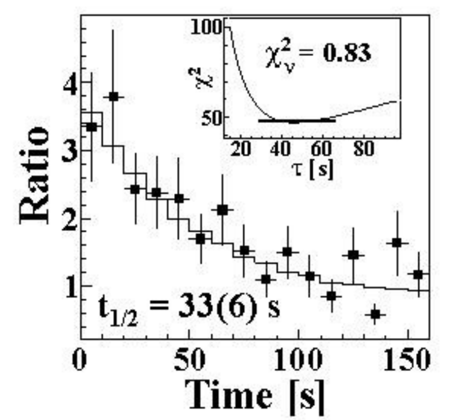
Fitting function: ratio of forward/backward time-distribution functions

^{218}Bi: Benchmark of Analysis

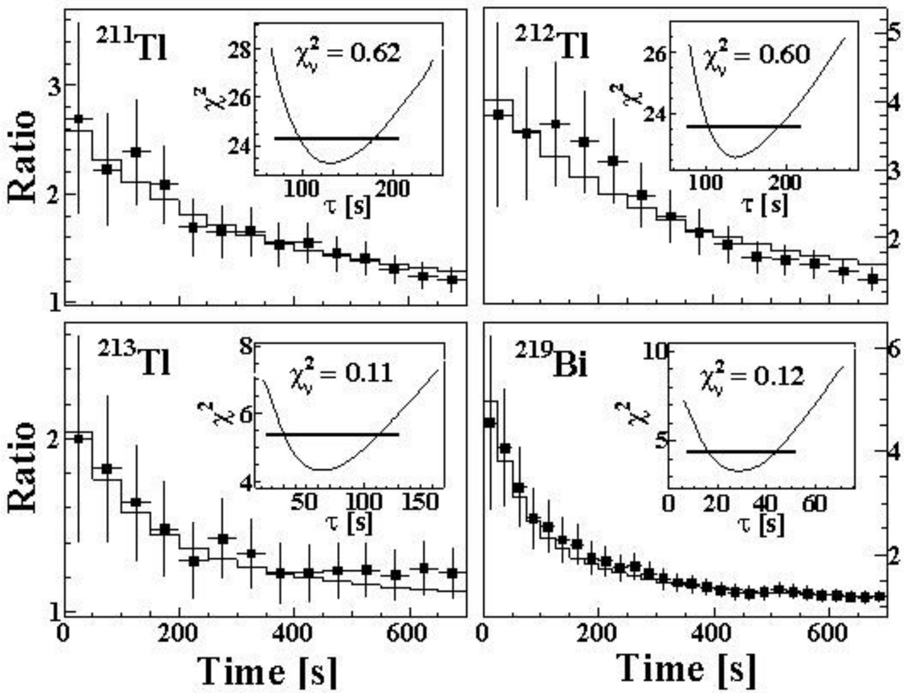


H. de Witte et al., PRC (2004)

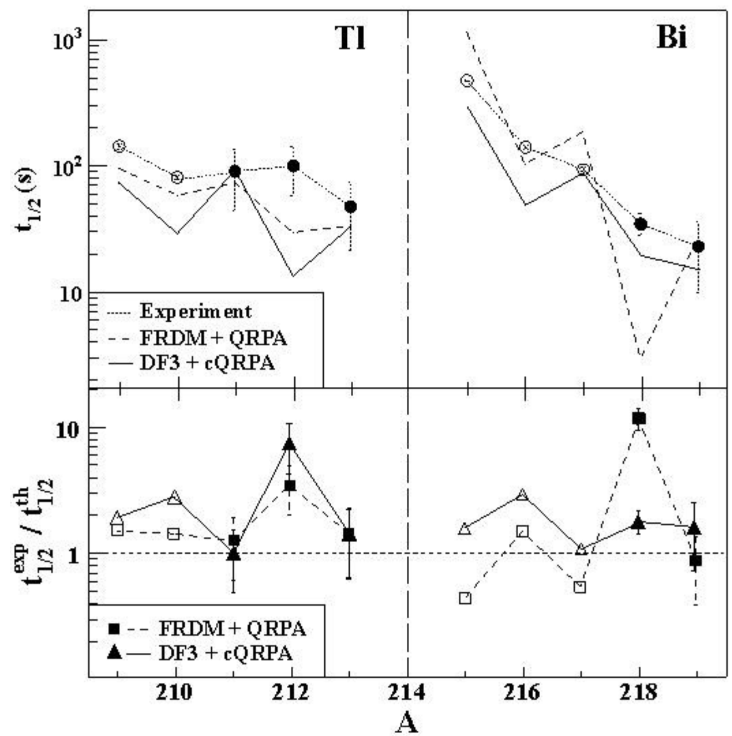




Important results in heavy mass region



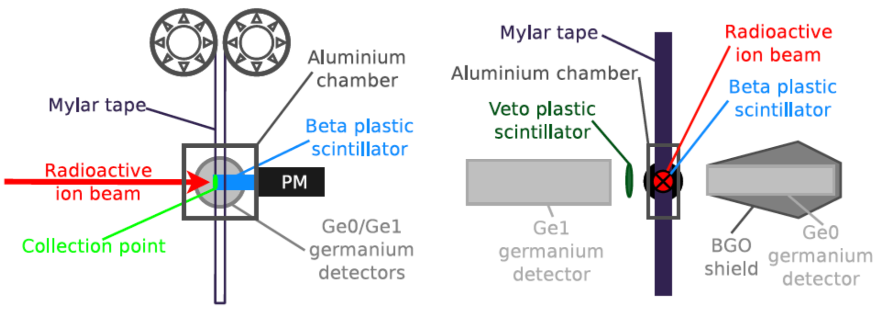
The description of first-forbidden (ff) transitions using macroscopic statistical models seems a good approach for these nuclei at variance from N<126 nuclei



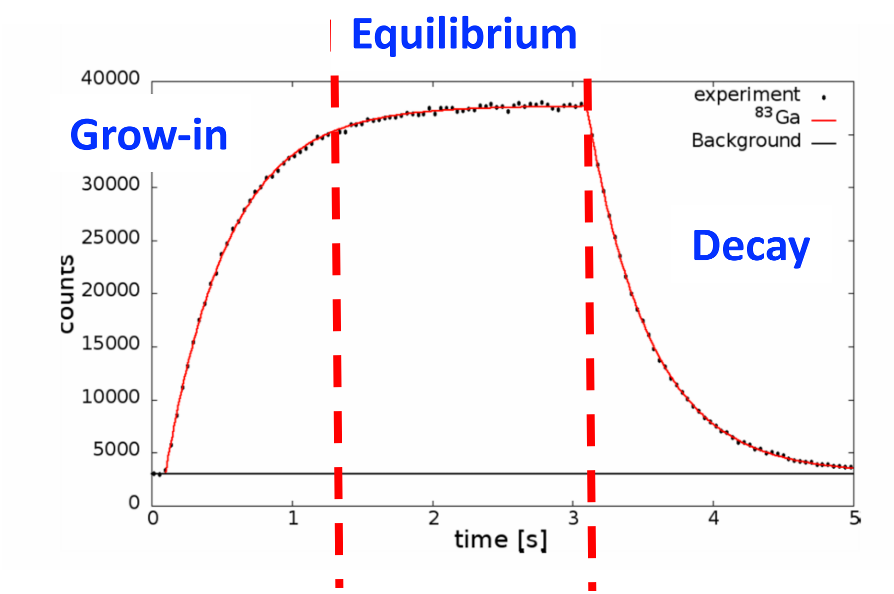
FRDM+QRPA and DF3 + QRPA models in agreement with our measurements

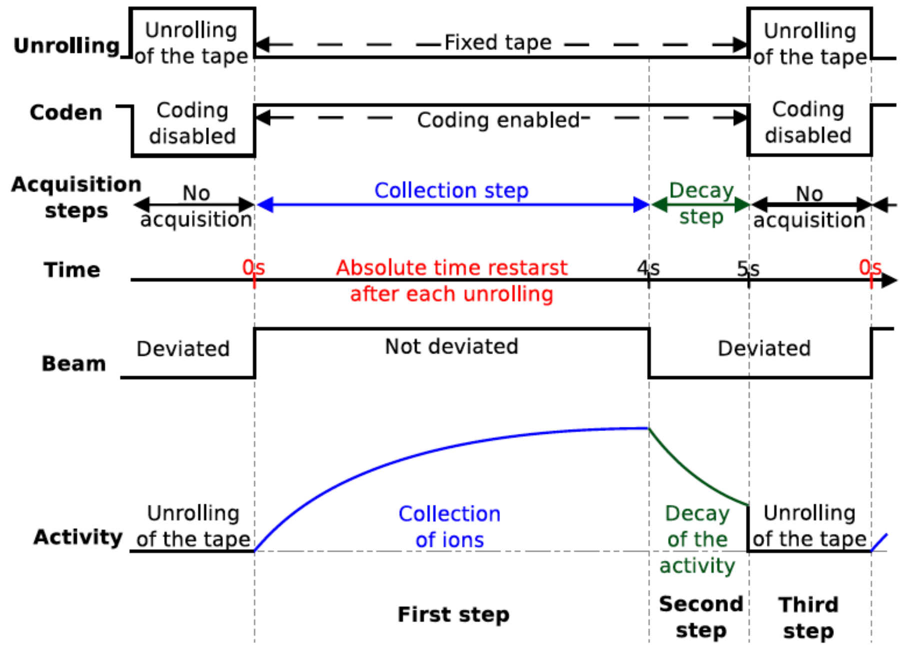
G.Benzoni et al., PLB 715 (2012) 293
A.I.Morales et al., PRC89, 014324 (2014)
A.I.Morales et al.,PRL113, 022702 (2014)

Measuring half-lives with tape system



(a) (b)





G.Germogli PhD Thesis Pd (2012)

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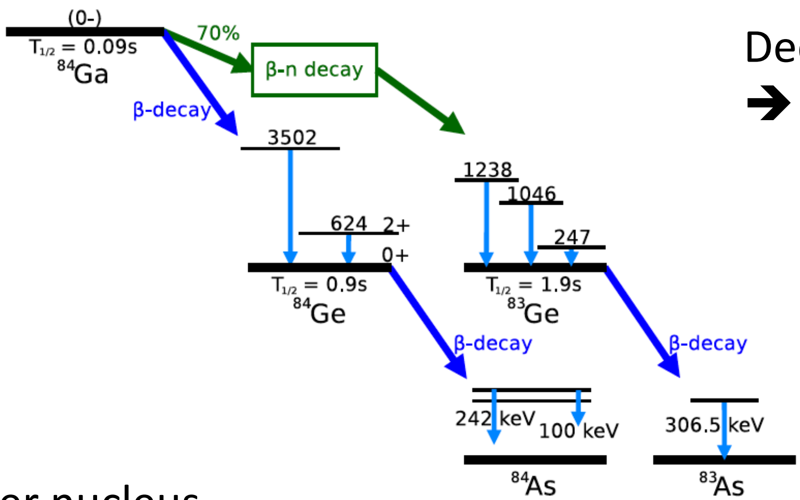
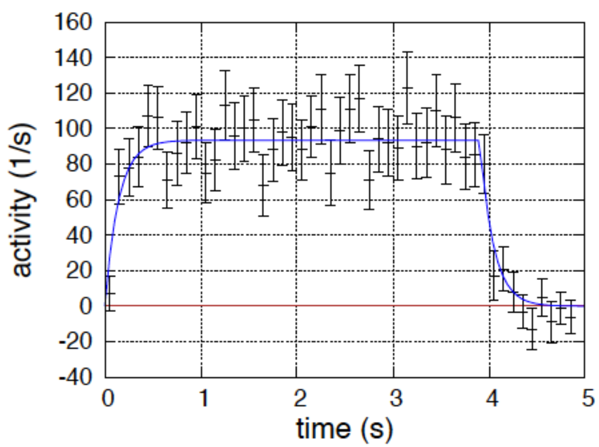


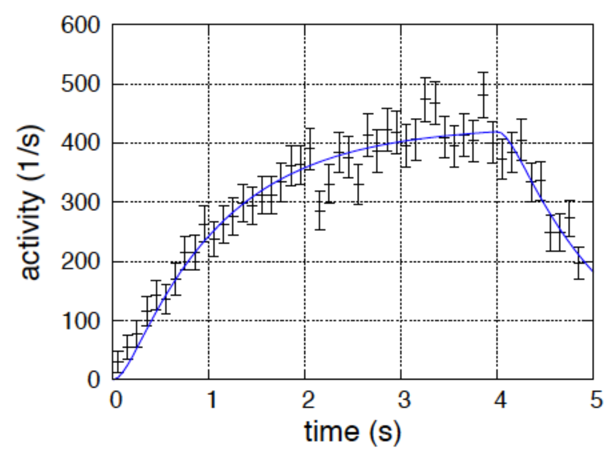
Decay curve can have many components
➔ γ gating helps singling out

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



(a) 624 keV

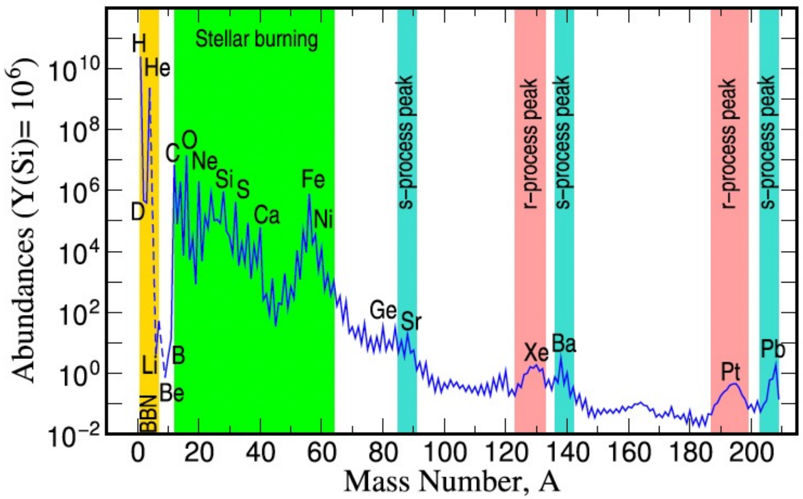
Activity of grand-daughter nucleus



(c) 242 keV

G.Germogli PhD Thesis Pd (2012)

Nucleosynthesis: Element formation in Stars

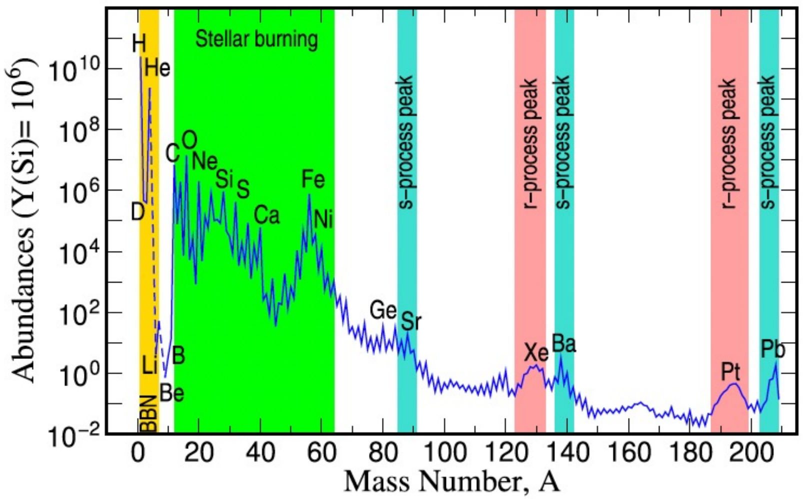


2 sets of data:

- 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



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Main Features:

- H/He most abundant
- Light elements up to A~50 (56Fe)
- Lower abundance for elements A>50, with abundance peaks appearing at specific A values

Nucleosynthesis: Element formation in Stars

Decay of radioactive nuclei

Element formation in stars

Example of measurements of b-decays

Perspectives

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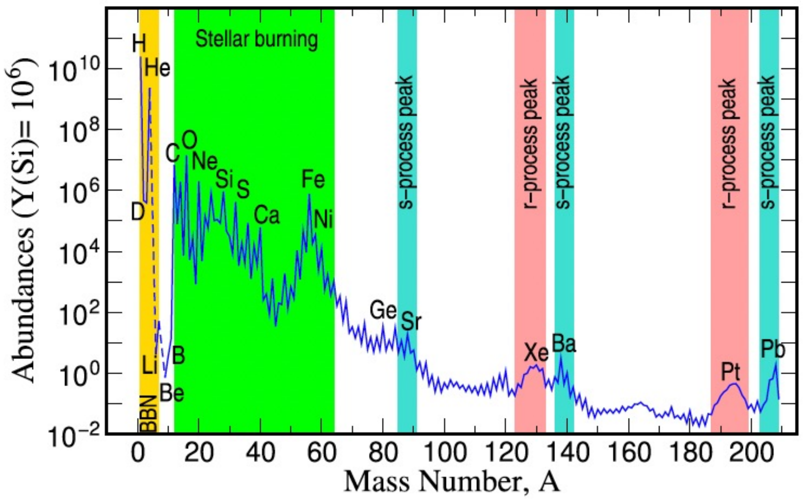

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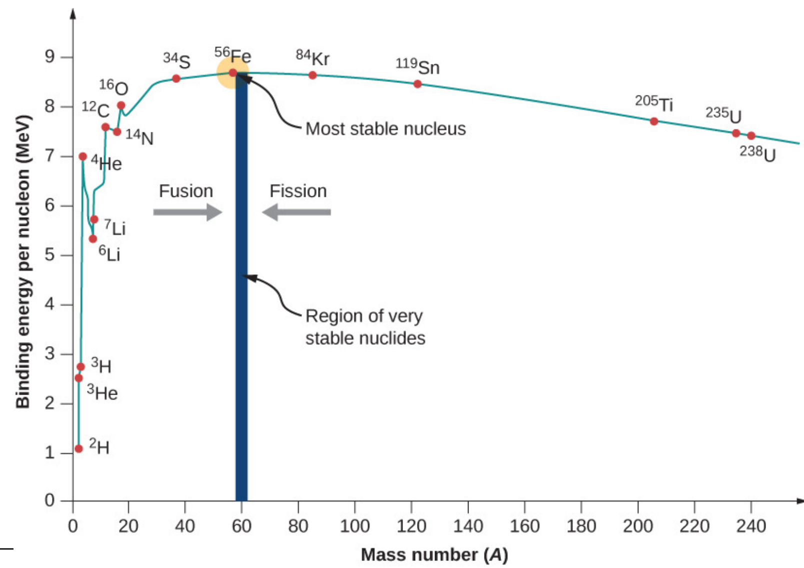

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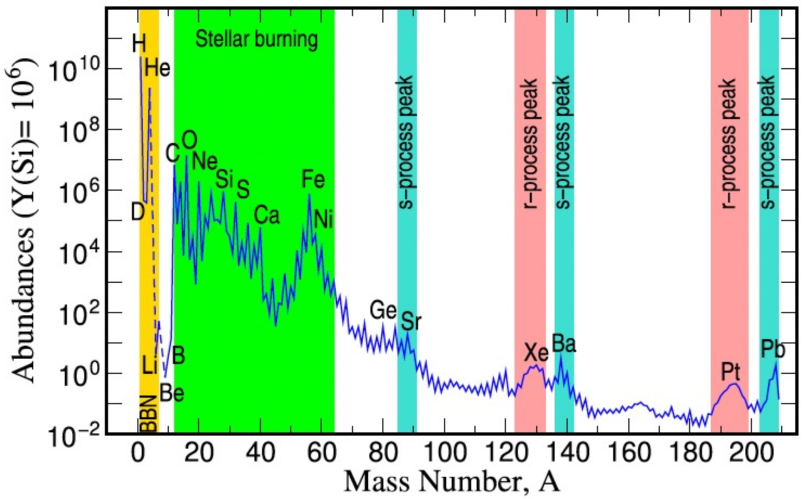

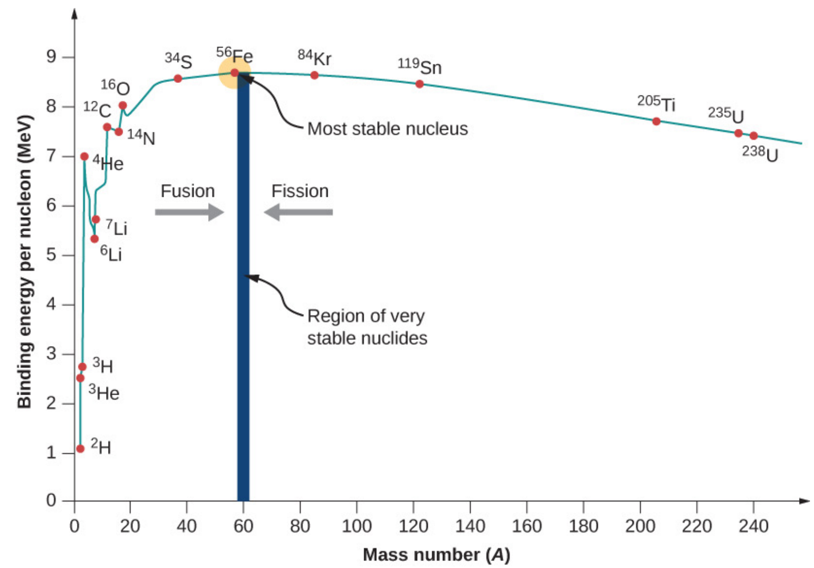

BBN, Primordial

Fusion in stars

Capture processes

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

Decay of radioactive nuclei

Element formation in stars

Example of measurements of b-decays

Perspectives

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The Universe Time Scale

Light elements created following the Big Bang

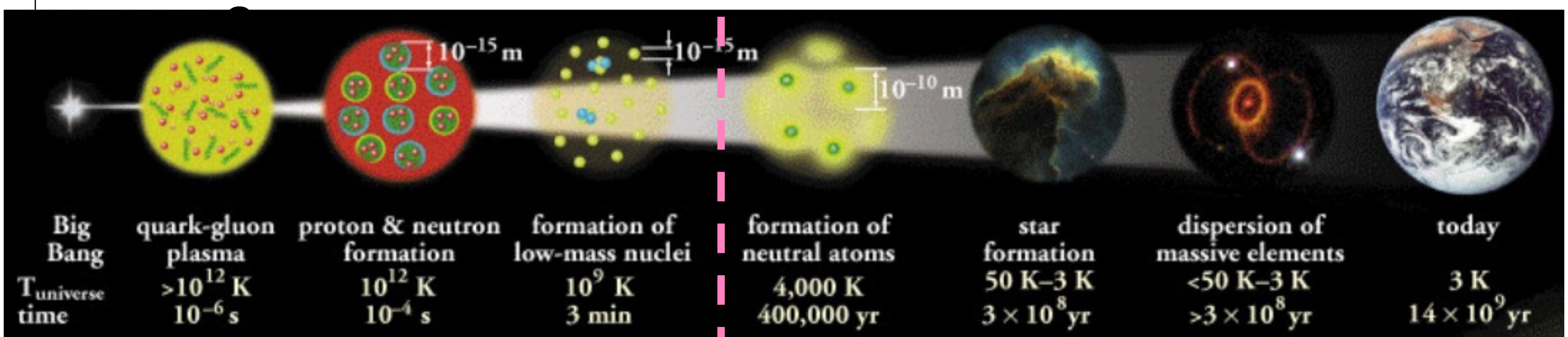
Heavier elements are created in the stars: **stellar nucleosynthesis**

➔ What are the condiitons? T, particles?

➔ What type of stars are location of «creation»?

H, He ➔ C, N,

^{56}Fe - .... - ^{238}Ur- s- p nucleosynthesis



Element formation in stars

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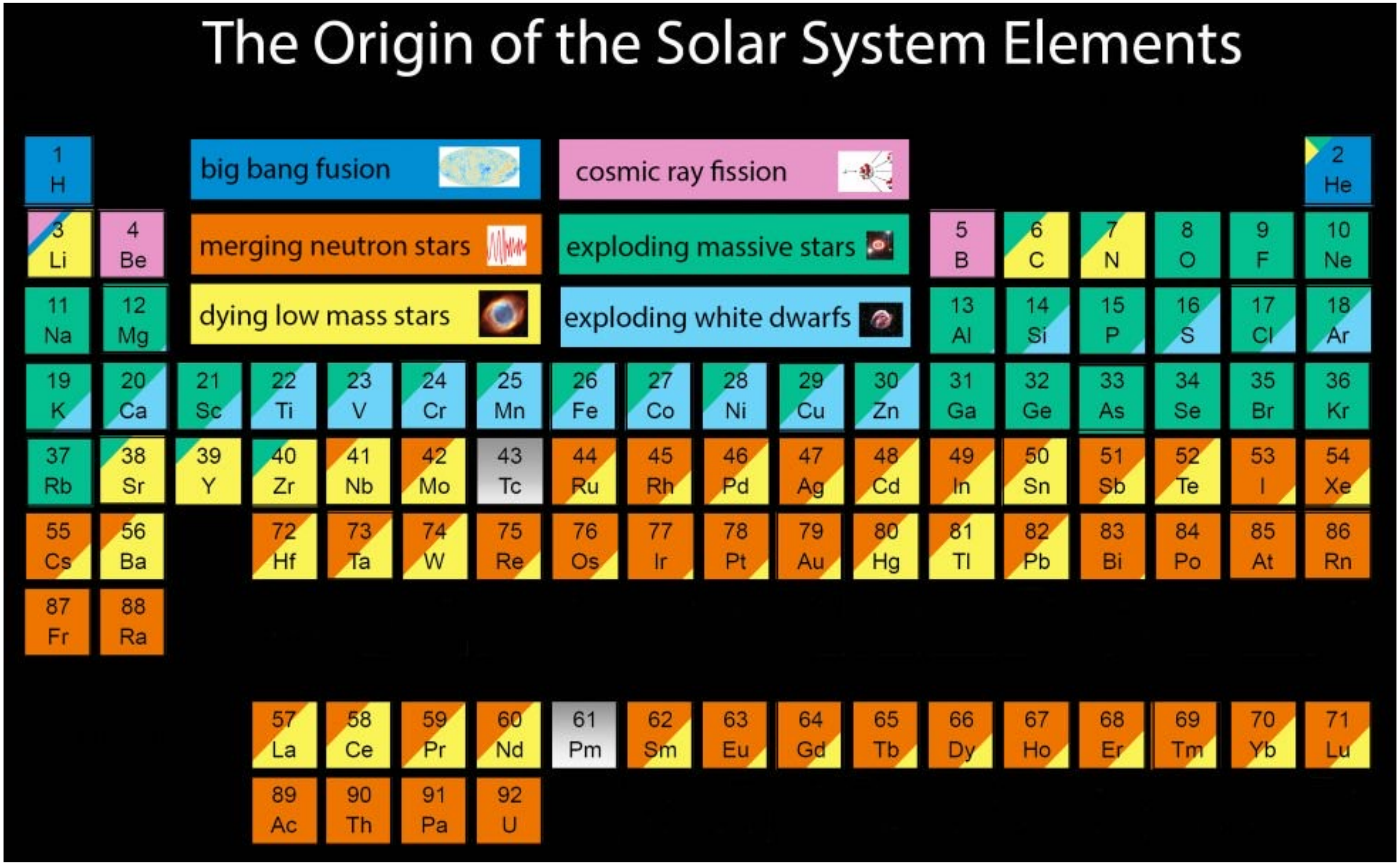

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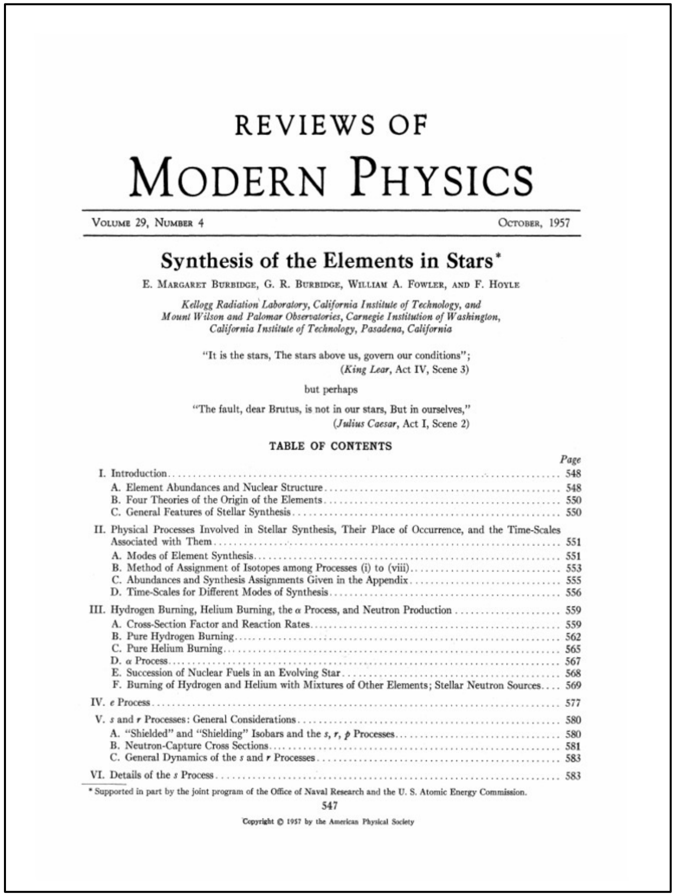

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, 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)

TABLE OF CONTENTS

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

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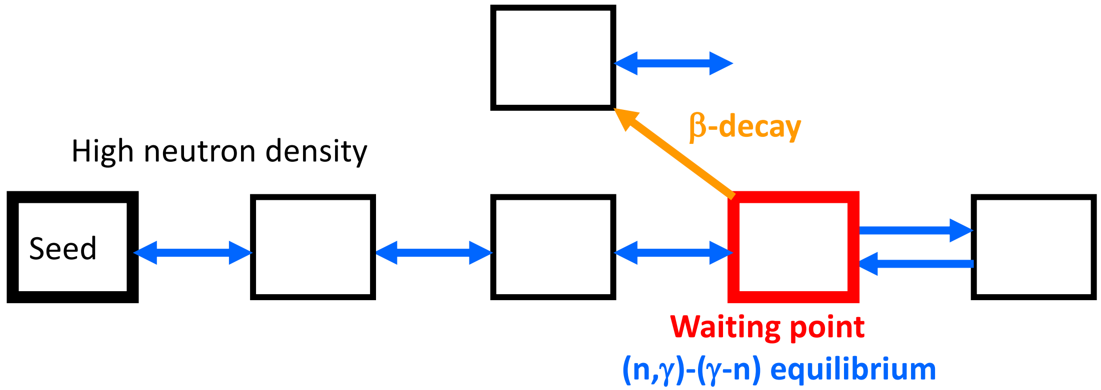
1957: B2FH paper sets the landscape for the synthesis of elements in Stars

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

Nucleosynthesis: Element formation in Stars

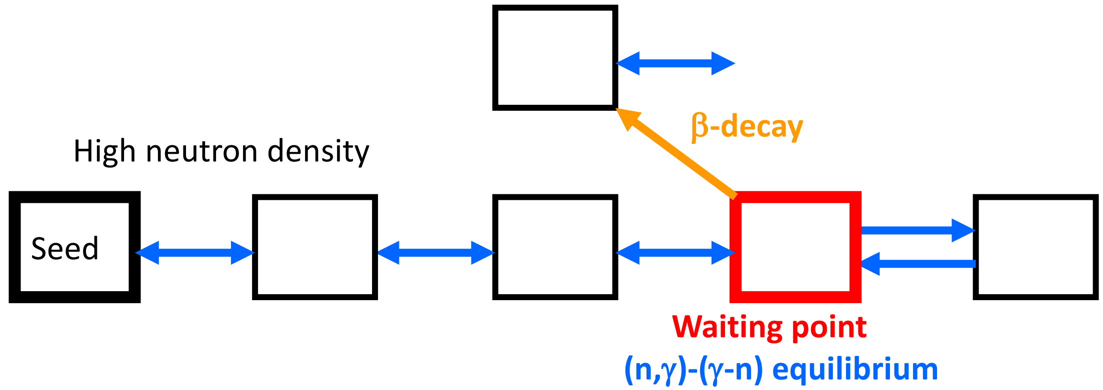


In r- and s- process competition between

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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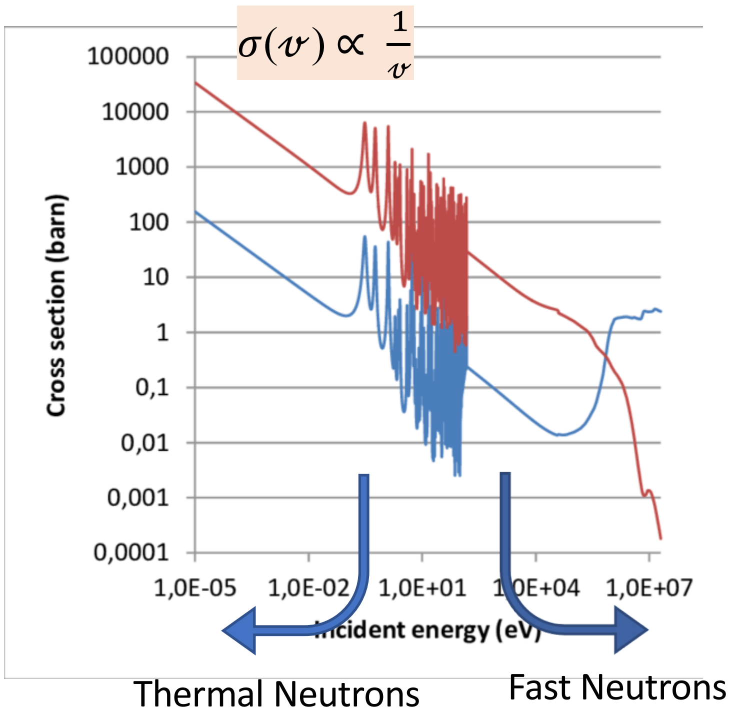
β^- decay $(N+1,Z) \rightarrow (N,Z+1)+e^- + \upsilon_e$

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

Production Decay

Nucleosynthesis: Element formation in Stars



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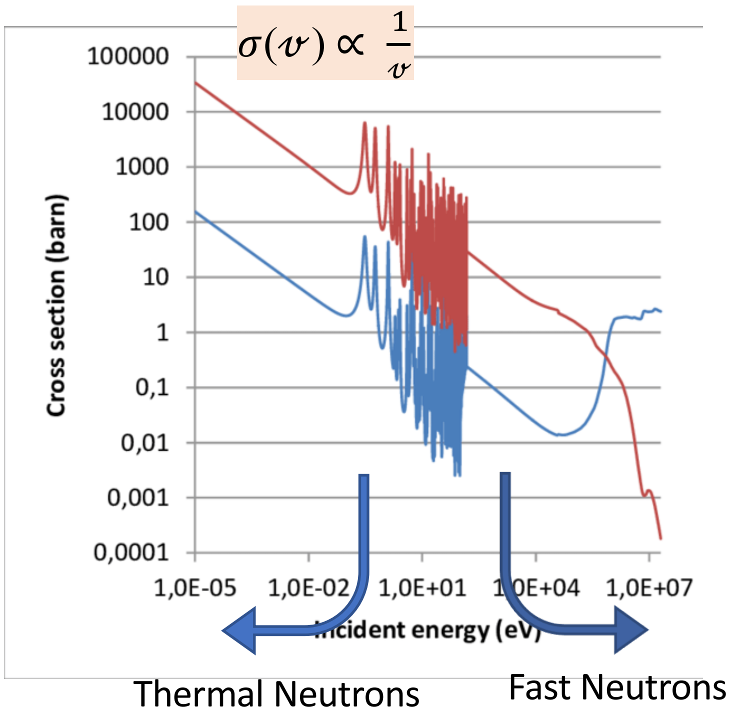


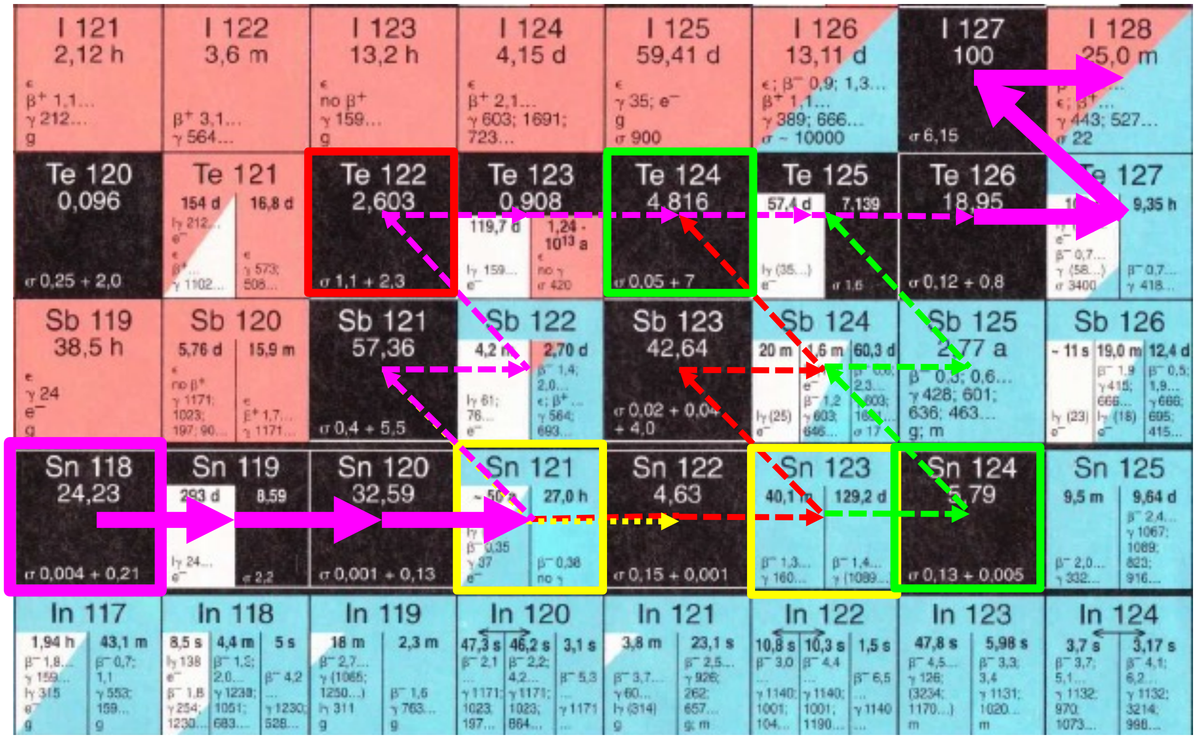
S- process:
Lower Temperatures and lower n density

- 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



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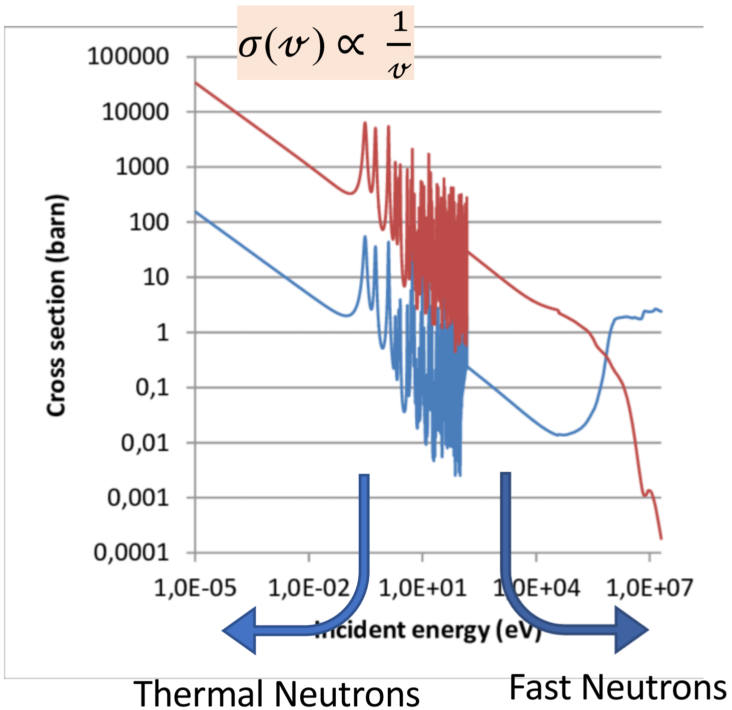

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$$\tau_\beta < \tau_{n,\gamma}$$

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 <u>onde gravitazionali</u> e conseguente produzione di elementi pesanti

Beta-decay spectroscopy towards the r-process path

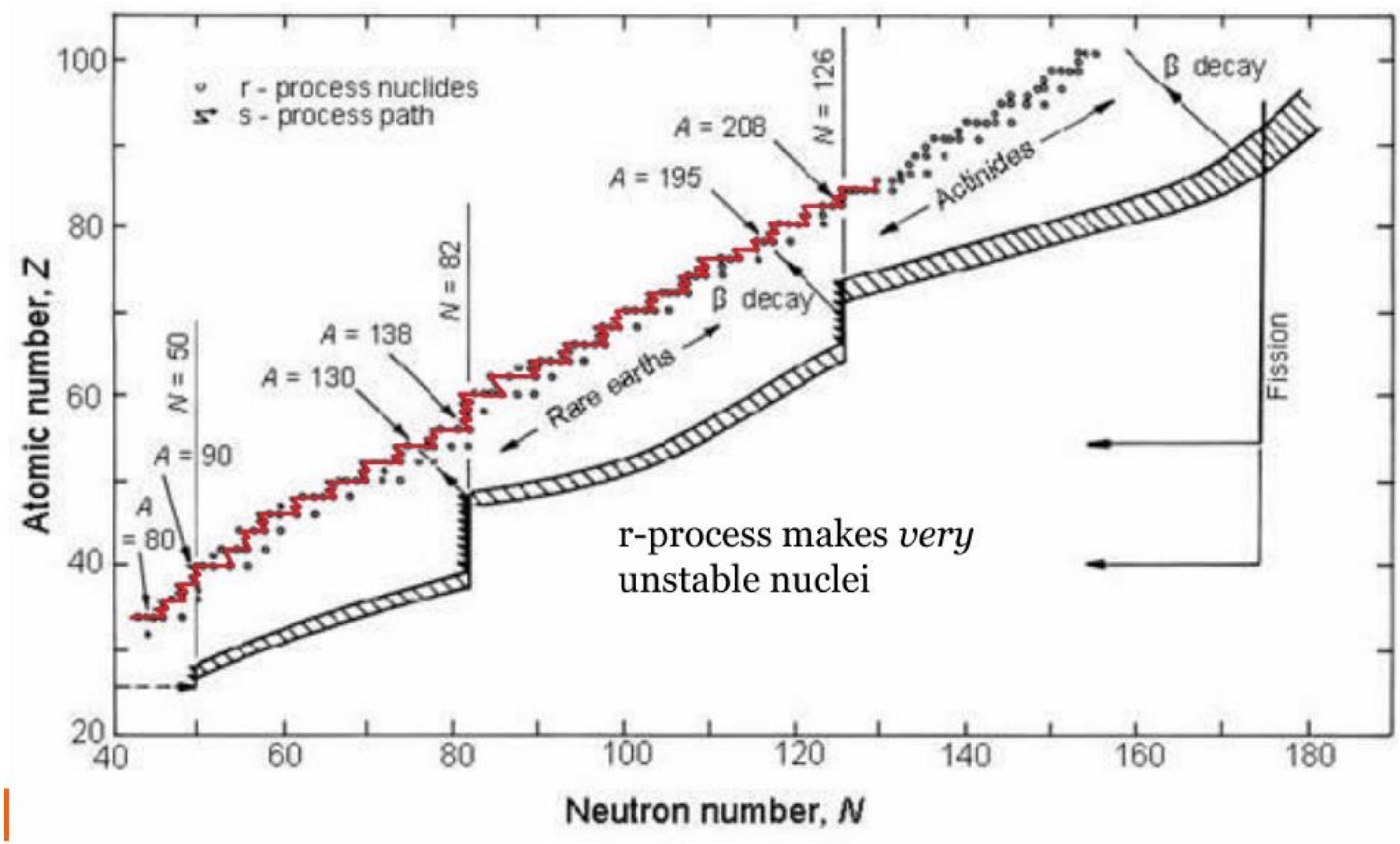
Decay of radioactive nuclei

Element formation in stars

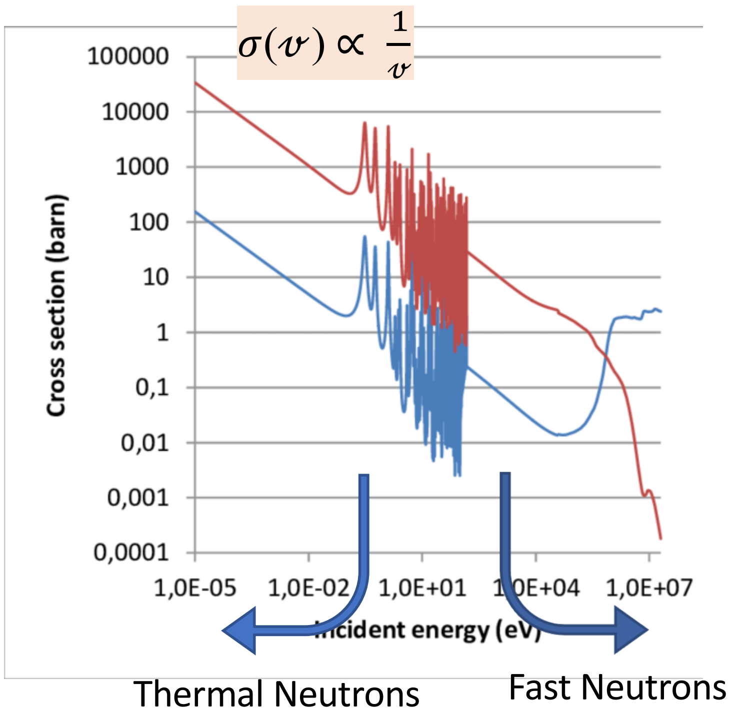
Example of measurements of b-decays

Perspectives

Conclusions



Nucleosynthesis: Element formation in Stars



S- process:
Lower Temperatures and lower n density

➔ Astrophysical locations are Aysimptotic 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

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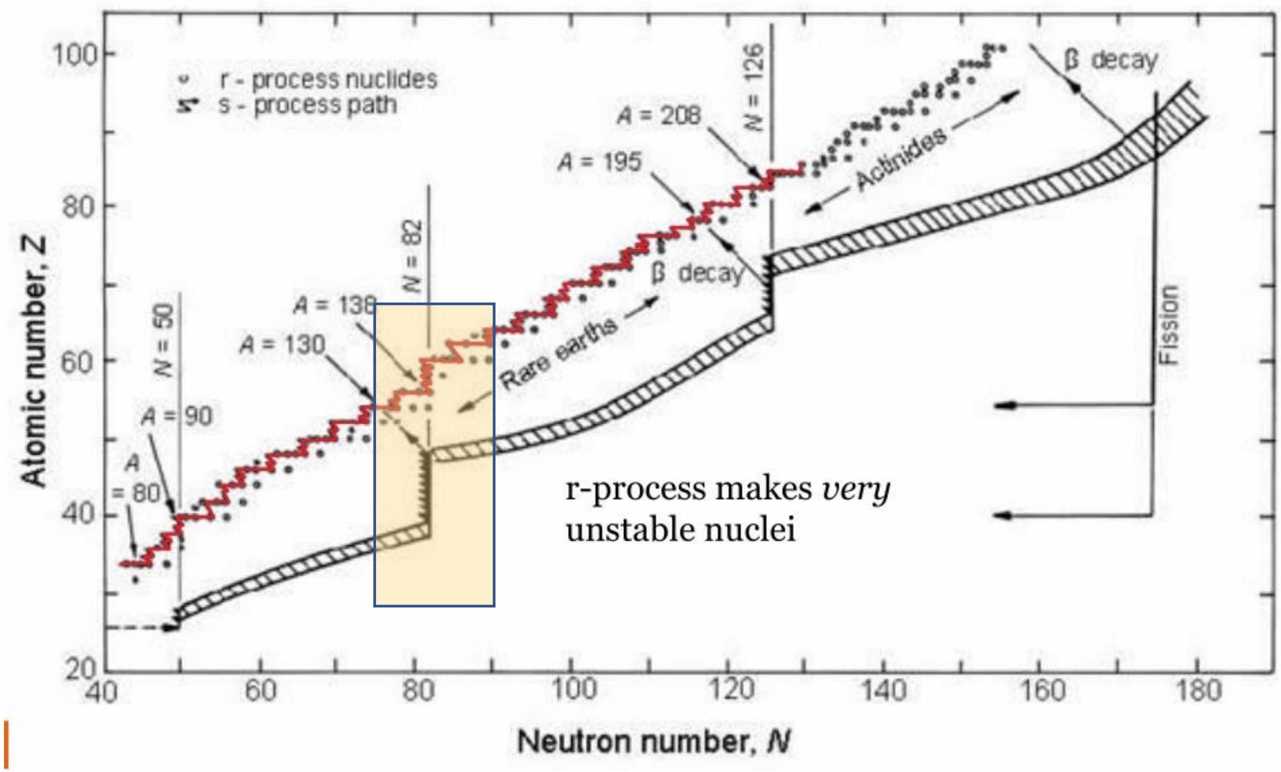
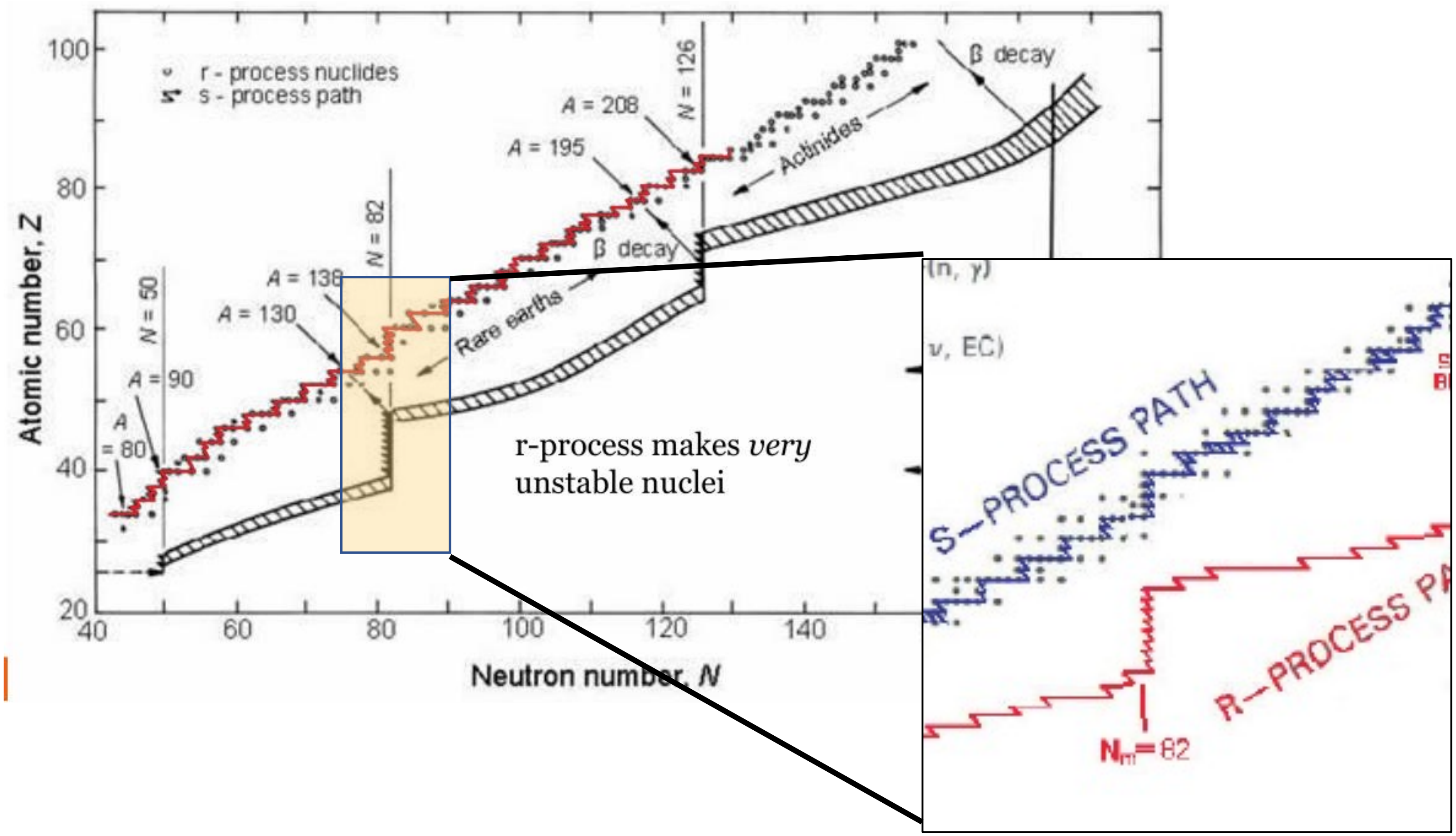


Beta-decay spectroscopy towards the r-process path



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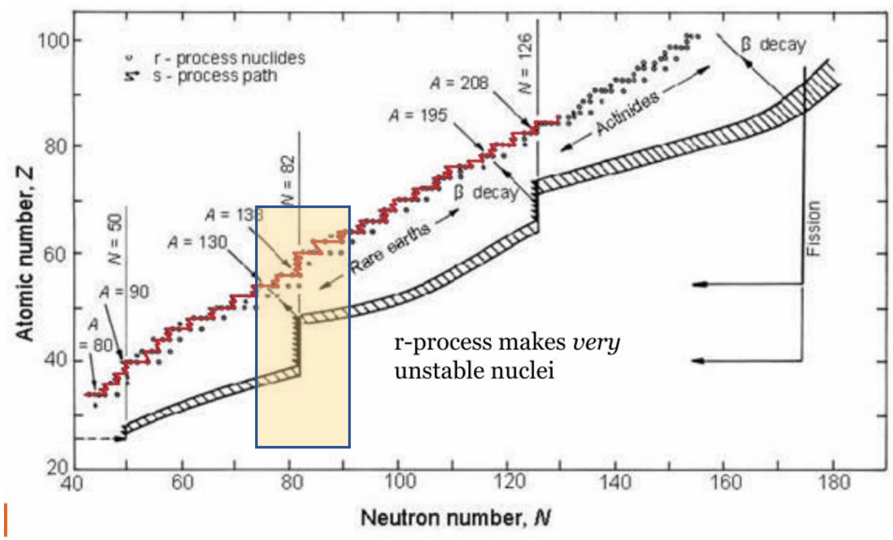
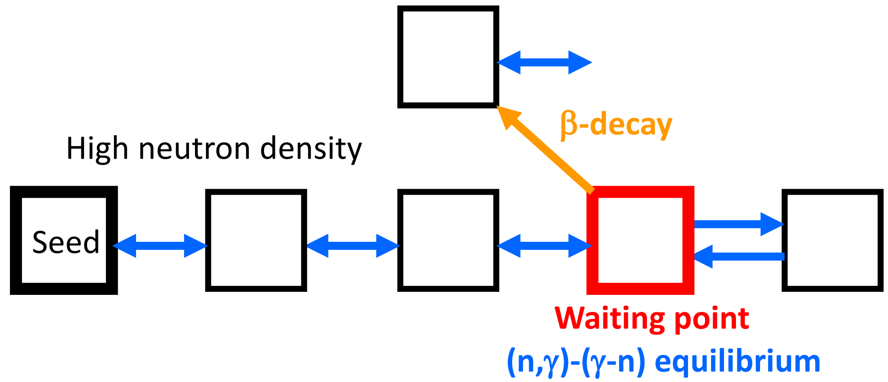
Perspectives (10')

Conclusions





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

Element formation in stars

Example of measurements of b-decays

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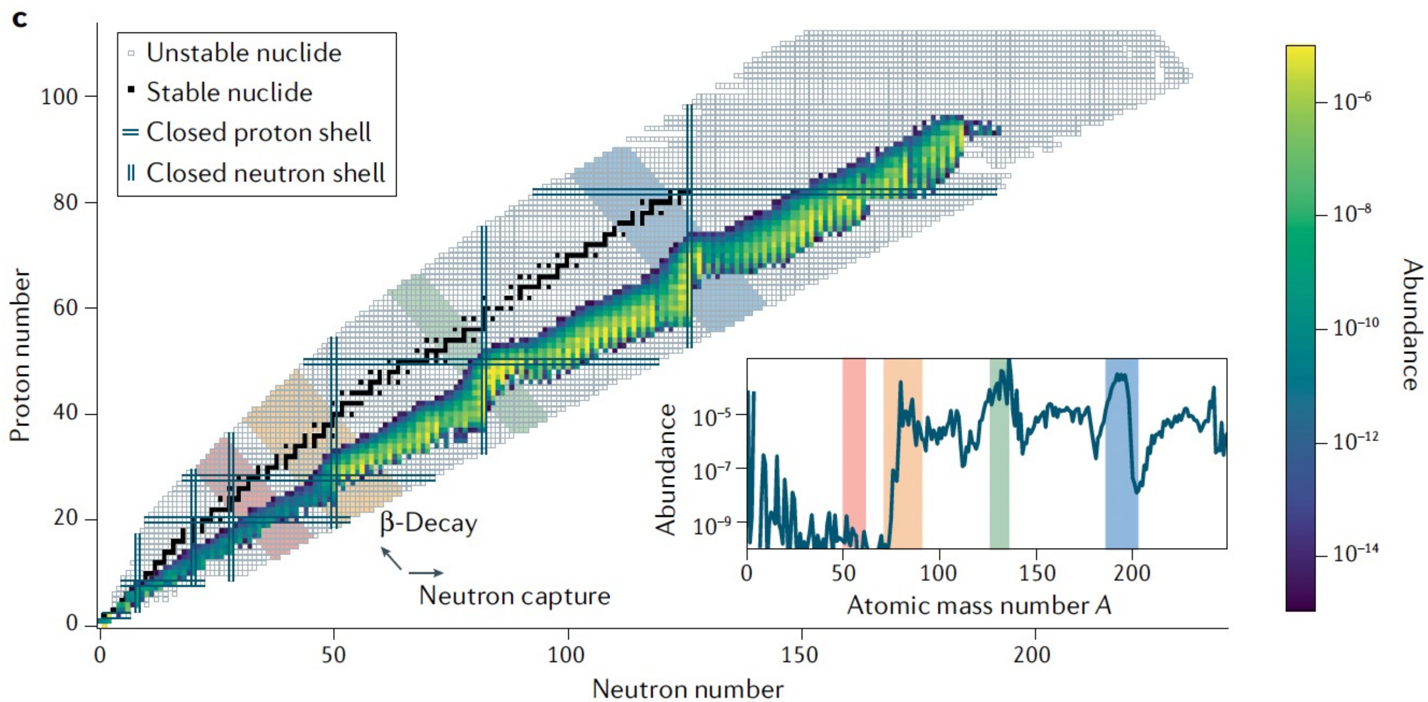
Conclusions



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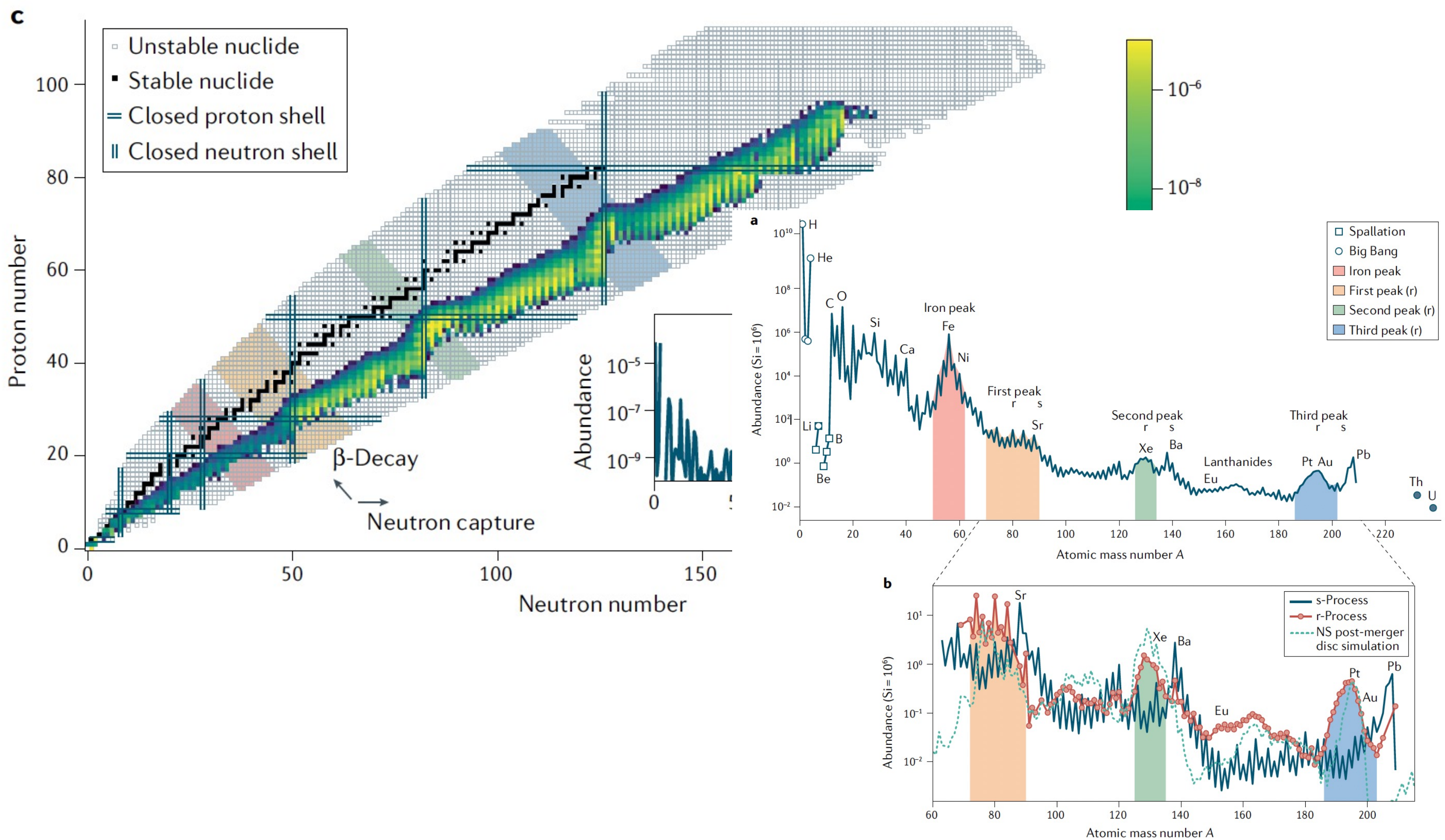

Nucleosynthesis: Element formation in Stars

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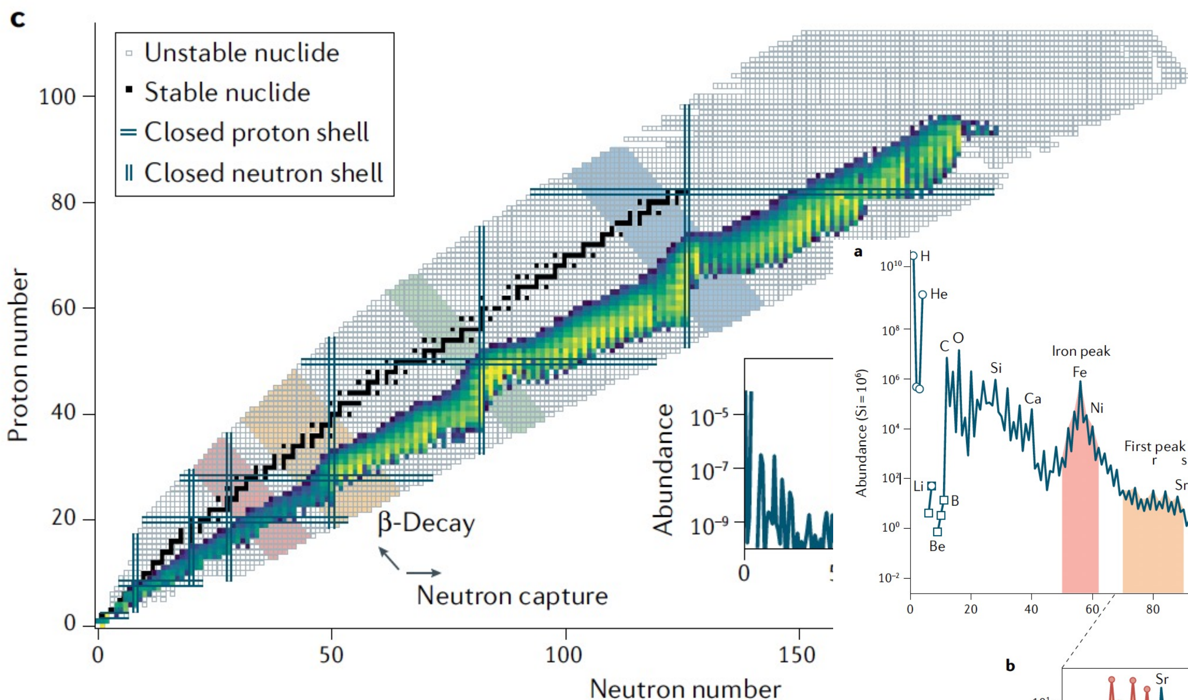
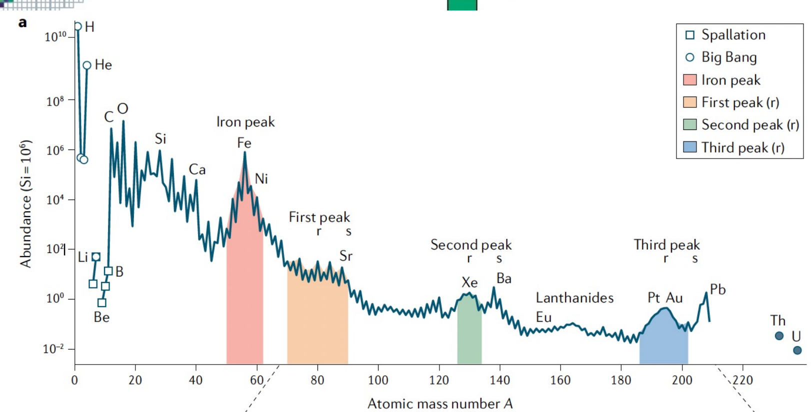
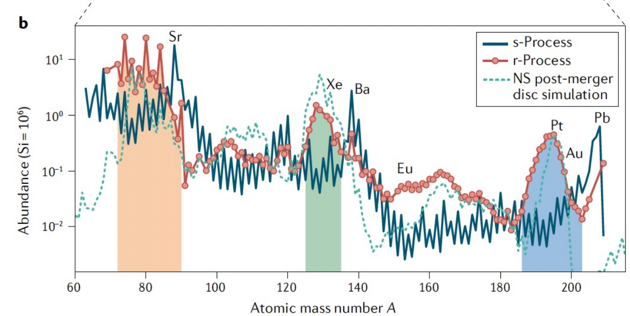
- Conclusions







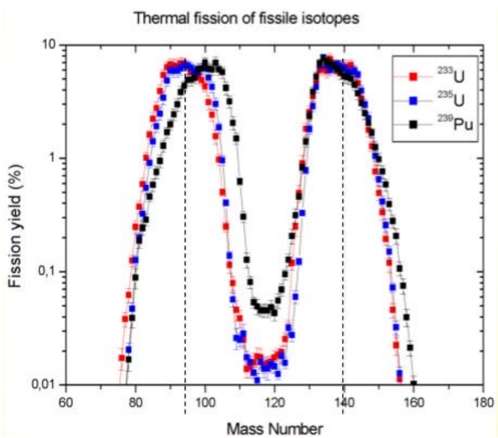
s process: N=50, ^{88}Sr, N=82, ^{138}Ba, N=126 ^{208}Pb
r process: A~ 80, 130, 194

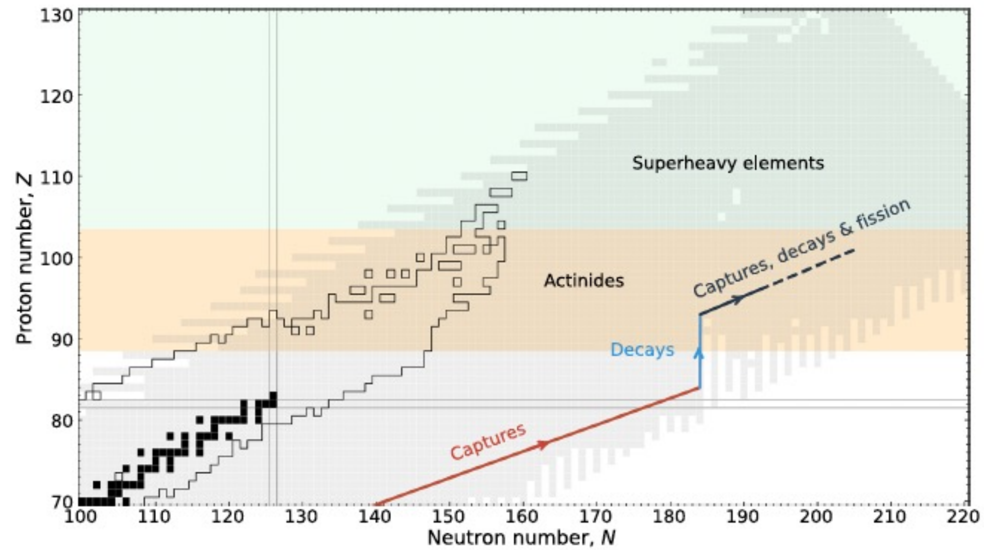
How heavy does the r-process go?

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

Fission has two effects

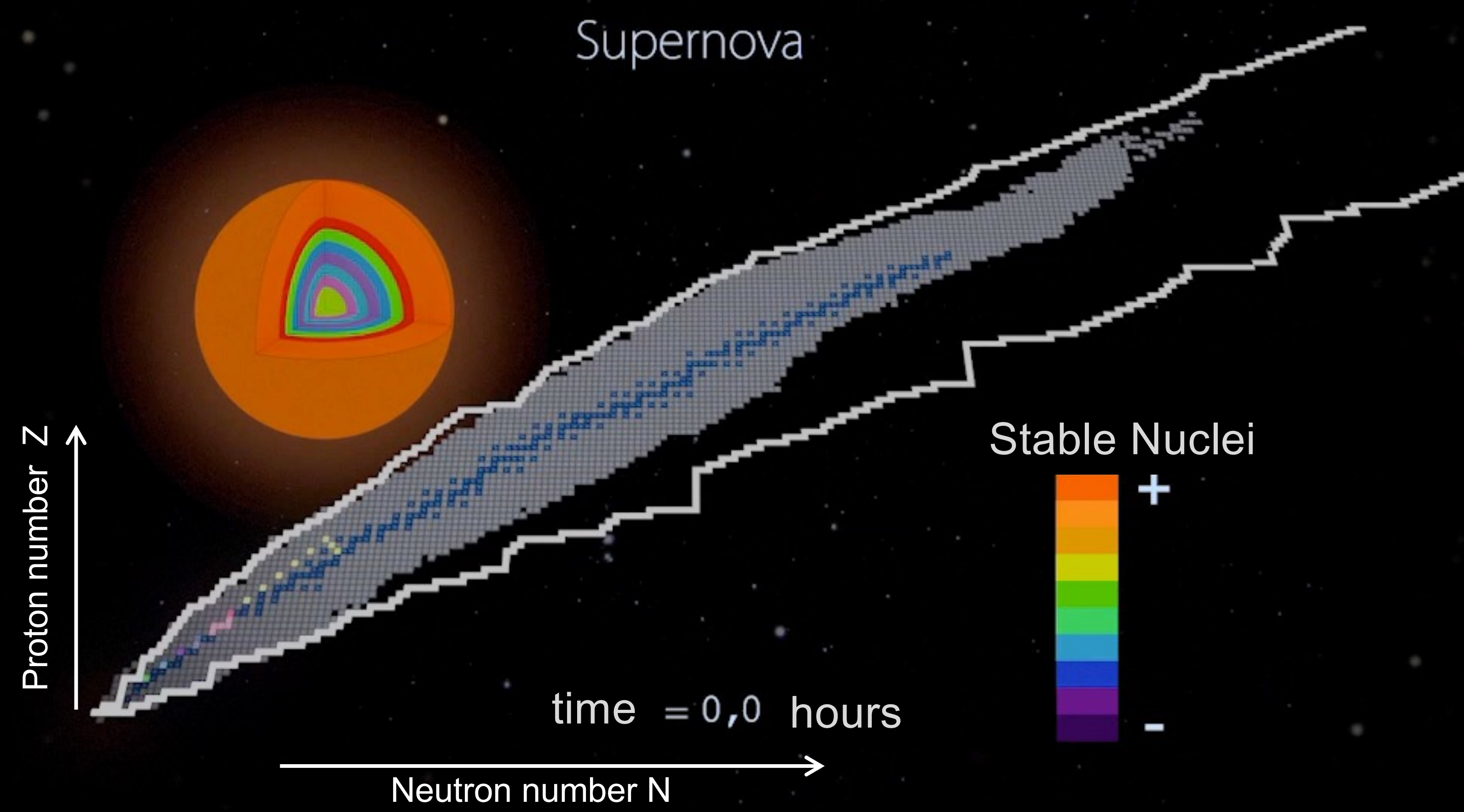
1) Formation of 2 n-rich lighter ions that enter the r-process cycle again





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 Nuclèaire"

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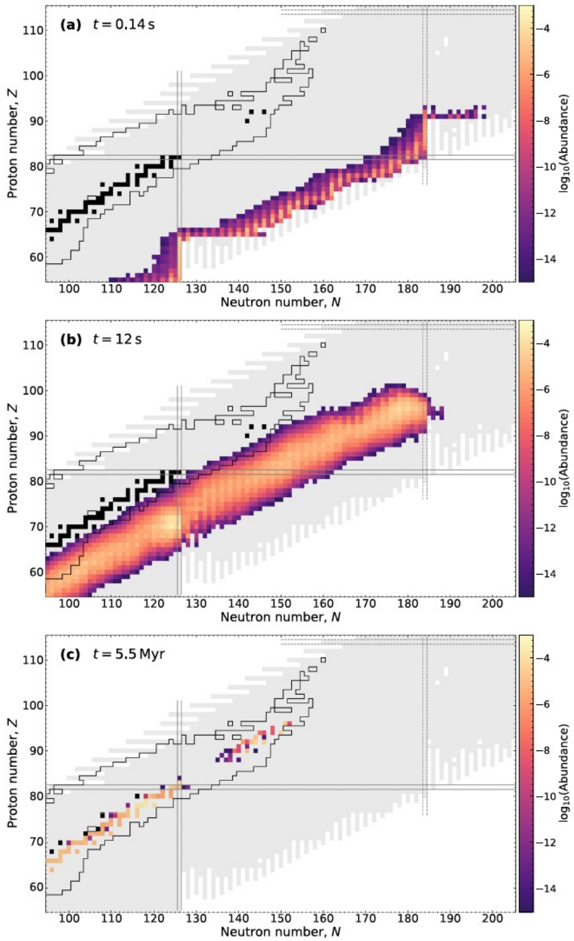
Stopping the video at different stages



Before freeze-out

$(n,\gamma) \rightleftarrows (\gamma,n)$ *are blocked by low n density*

n captures dominant

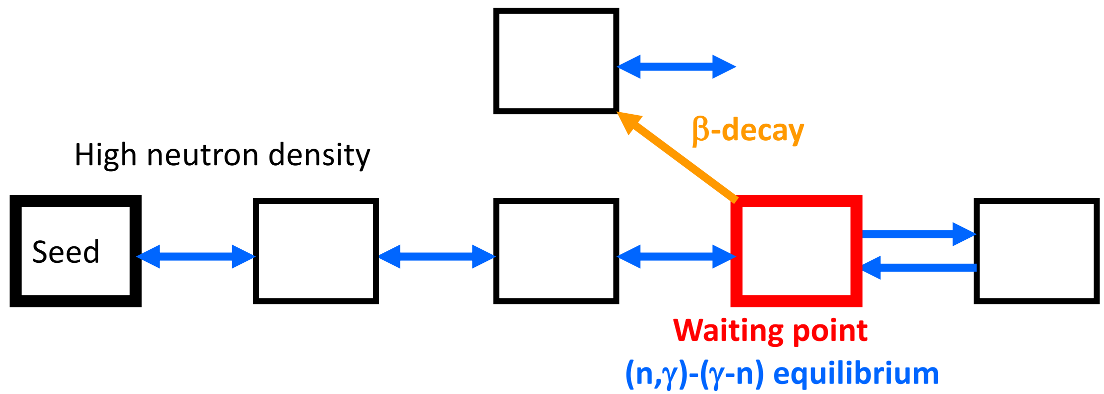
After freeze-out

β decay becomes dominant

Well after r process is ended

Gray shaded area, theoretical extension of the process

Nucleosynthesis: Element formation in Stars



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

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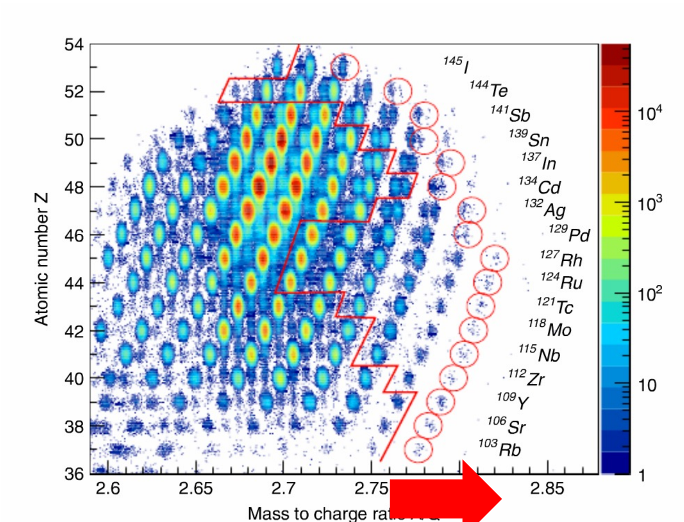
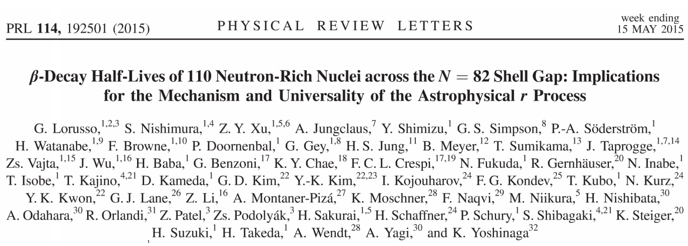


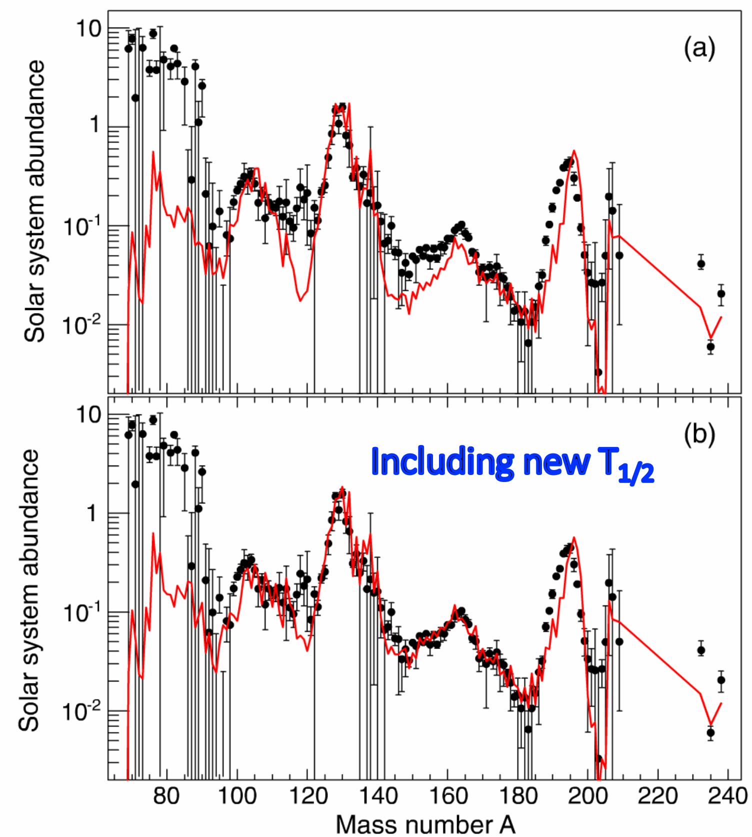
Newly measured $T_{1/2}$



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. Gernhäuser,[20] N. Inabe,[1] 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,[3] 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. Yoshinaga[32]



Measuring β decay

- Decay of radioactive nuclei
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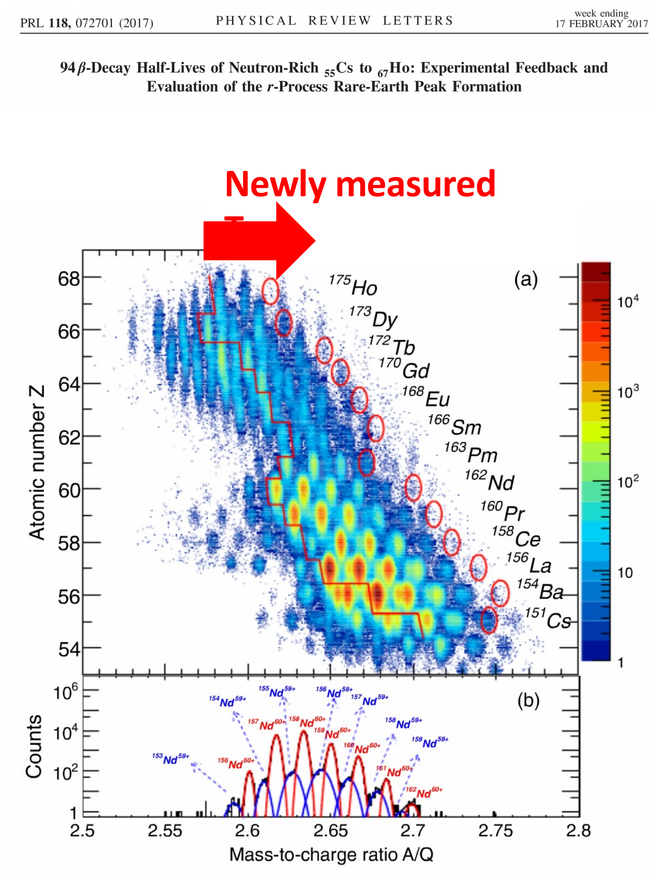
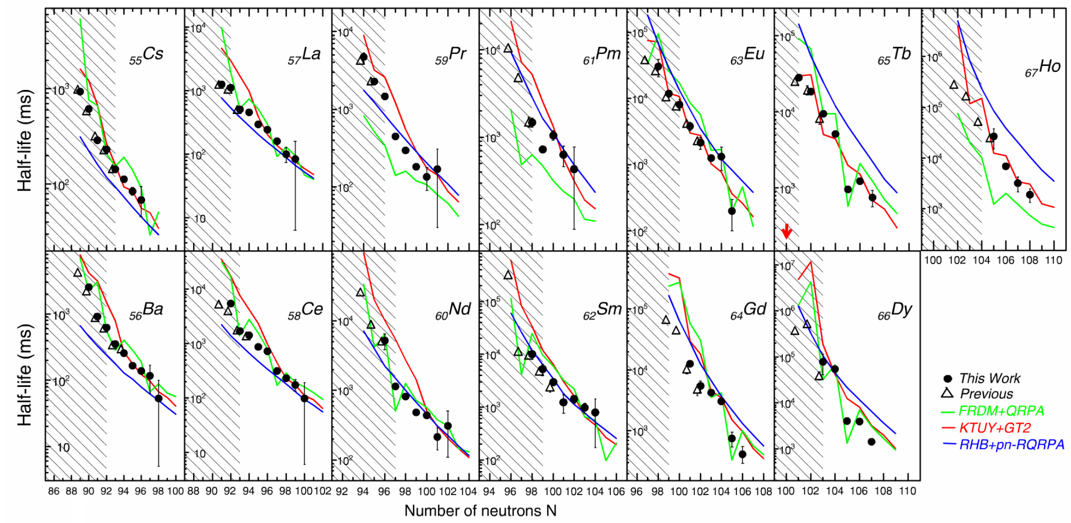
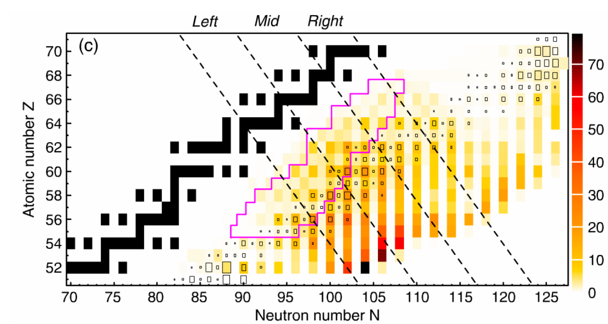


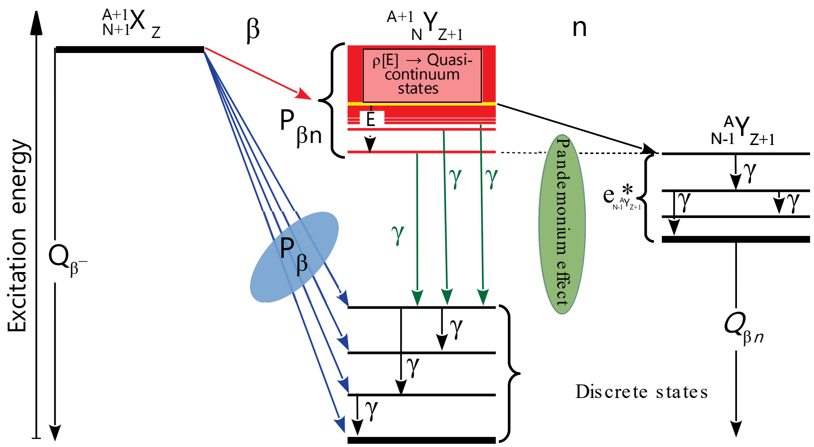




General Properties of β decay

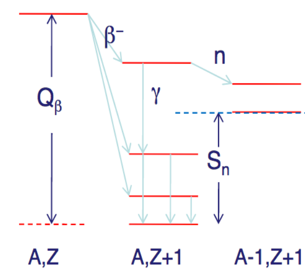
Evolution towards the n-rich side:
$Q_{\beta-}$ generally gets larger while Sn gets smaller

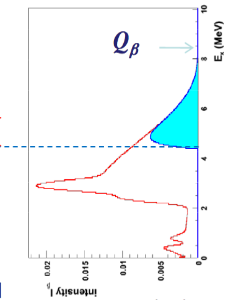
Conditions for **β delayed neutron emission**



$$\frac{1}{T_{1/2}} = \sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)$$

$$P_n = \frac{\sum_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}{\sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}$$





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

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 Sn

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

22/05/2023

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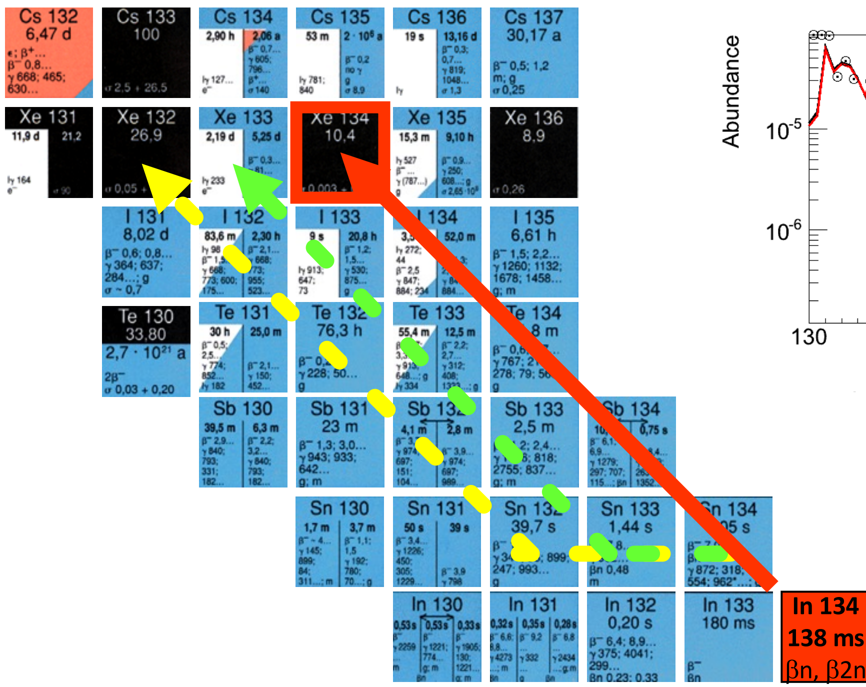
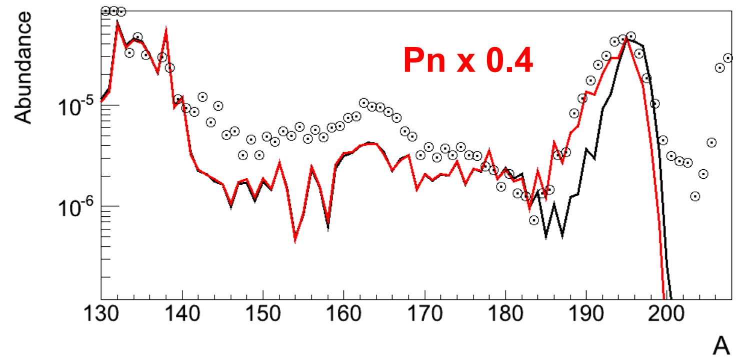
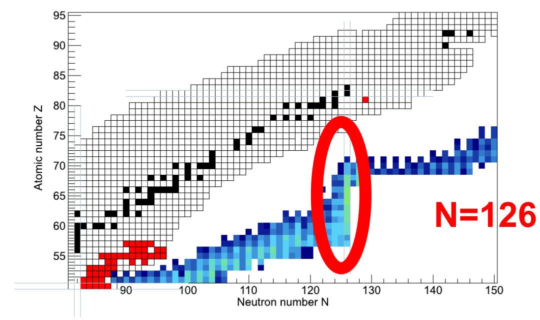
During „Freeze-out“:
detour of β-decay chains
⇨ *r-abundance changes*



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

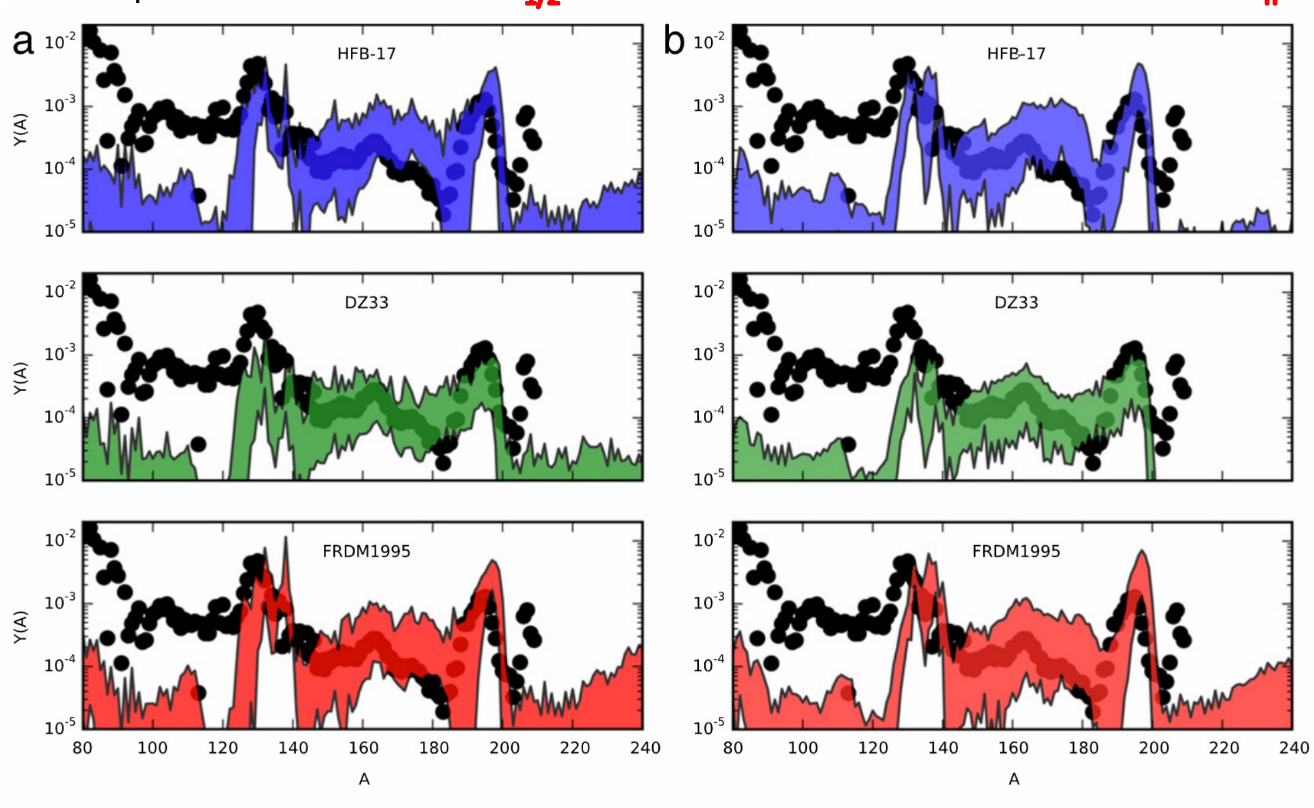




Sensitivity study of inputs for nucleosynthesis modeling

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

Impact of uncertainties in $T_{1/2}$ P_n



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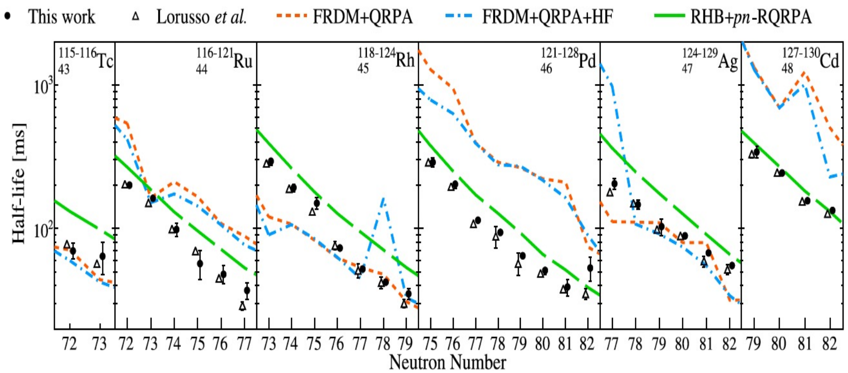
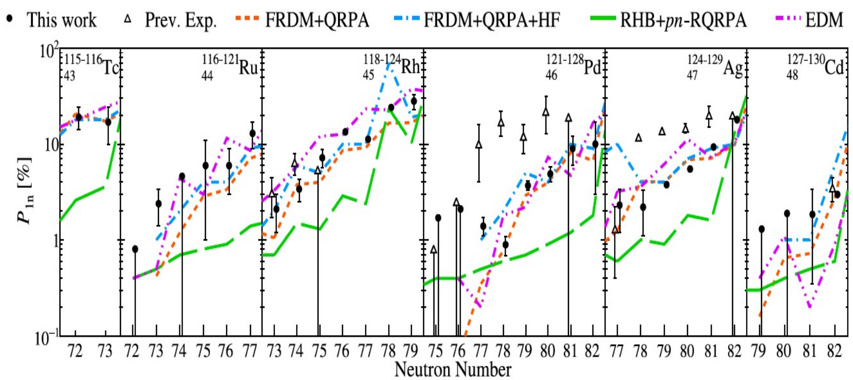
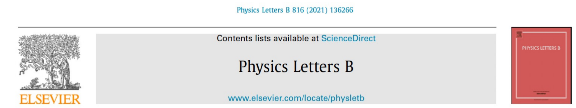




FRDM+QRPA= cut-off approach: above Sn a neutron is emitted
FRDM+QRPA+HF = statistical decay and γ-ray emission explicitly at every stage
EDM = semiempirical effective density model



Physics Letters B 816 (2021) 136266
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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[c,e,f], F. Montes[g], S. Nishimura[c], V.H. Phong[c,h], P.J. Woods[a], J. Agramunt[i], D.S. Ahn[c,j], A. Algora[i], J.M. Allmond[k], H. Baba[c], S. Bae[m], N.T. Brewer[k,l], C.G. Bruno[a], R. Caballero-Folch[n], F. Calviño[o], P.J. Coleman-Smith[p], G. Cortes[o], I. Dillmann[n,q], C. Domingo-Pardo[i], A. Fijalkowska[r], N. Fukuda[c], S. Go[c], C.J. Griffin[a], R. Grzywacz[l], J. Ha[m,c], L.J. Harkness-Brennan[s], T. Isobe[c], D. Kahl[a], L.H. Khiem[t,u], G.G. Kiss[c,v], A. Korgul[r], S. Kubono[c], M. Labiche[p], I. Lazarus[p], J. Liang[w], Z. Liu[x,y], K. Matsui[c,z], K. Miernik[r], B. Moon[aa], A.I. Morales[i], P. Morrall[p], M.R. Mumpower[ab], N. Nepal[b], R.D. Page[s], M. Piersa[r], V.F.E. Pucknell[p], B.C. Rasco[k], B. Rubio[i], K.P. Rykaczewski[k], H. Sakurai[c,z], Y. Shimizu[c], D.W. Stracener[k], T. Sumikama[c], H. Suzuki[c], J.L. Tain[i], H. Takeda[c], A. Tarifeño-Saldivia[o], A. Tolosa-Delgado[i], M. Wolińska-Cichocka[ac], R. Yokoyama[l]

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 P1nvalues is observed for the lighter elements, such as Tc, Ru and Rh, though this is seen to diminish for nuclei close to Z=50where 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}

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The Astrophysical Journal, 936:107 (18pp), 2022 September 10 https://doi.org/10.3847/1538-4357/ac80fc

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

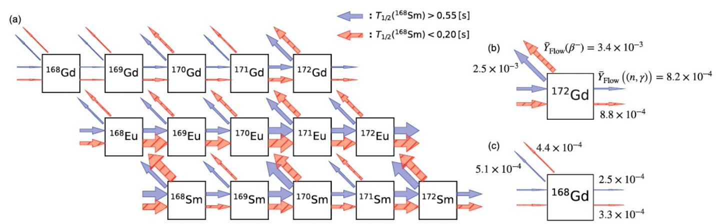
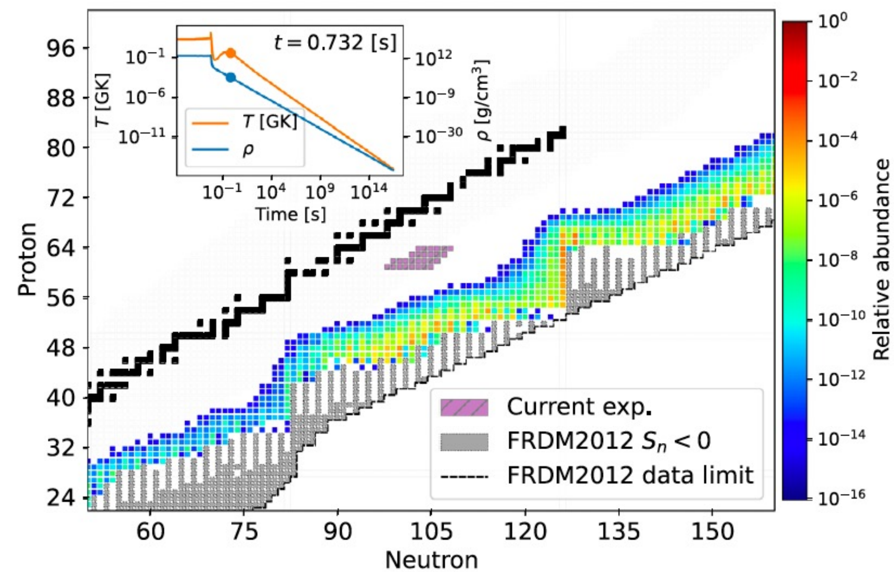


Figure 12. The arrows show the total abundance flow (same quantity as in panels (g)–(i) in Figure 11), averaged over the generated samples in the neutron-star merger scenario. Red corresponds to the case where the half-life of ^{168}Sm is shorter than 0.20 [s], and blue shows a half-live longer than 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.

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 ≈ 160 in the r-process abundance distribution through astrophysical reaction network calculations



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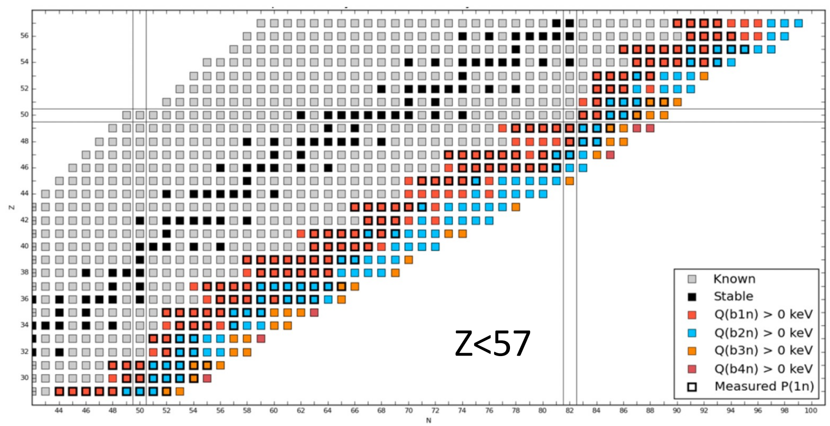

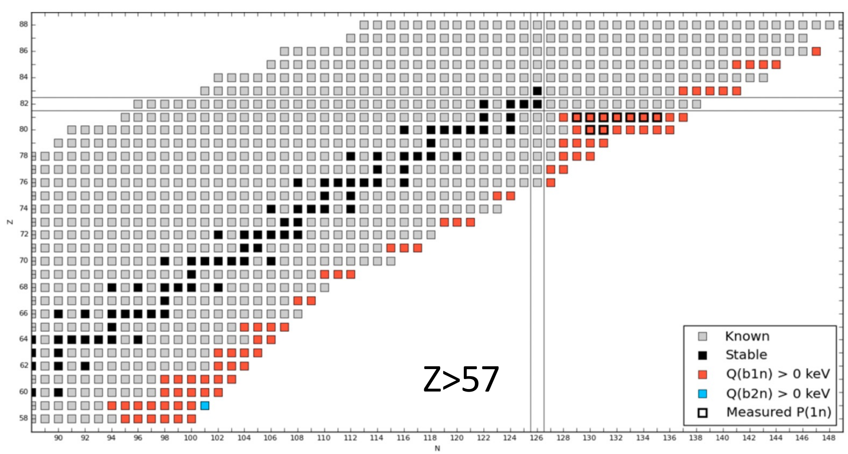

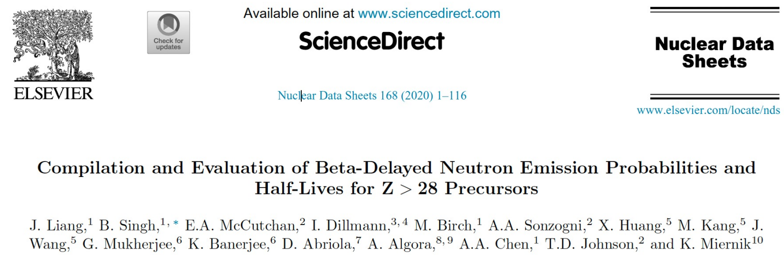

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Nuclear Data Sheets 168 (2020) 1–116
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Compilation and Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for Z > 28 Precursors

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. Algora,[8,9] A.A. Chen,[1] T.D. Johnson,[2] and K. Miernik[10]

Little data for heavy nuclei:

- Difficult access to nuclei
- Difficulty in measuring neutrons

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

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

- ➔ 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 (T1/2) is needed.

2- n/β 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 were the detectors cover a solid angle close to 4pi

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.

$$P_n = \frac{\varepsilon_{\gamma,daughter} * I_{abs,daughter,\gamma}}{N_{daughter.\gamma}} \Big/ \frac{\varepsilon_{\gamma,final} * I_{abs,final,\gamma}}{N_{final,\gamma}}$$

Detecting α β γ n particles: reminder of basic properties

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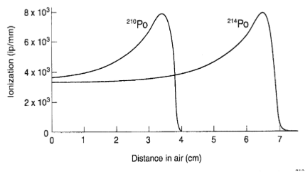
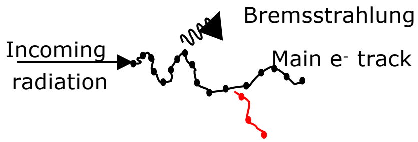


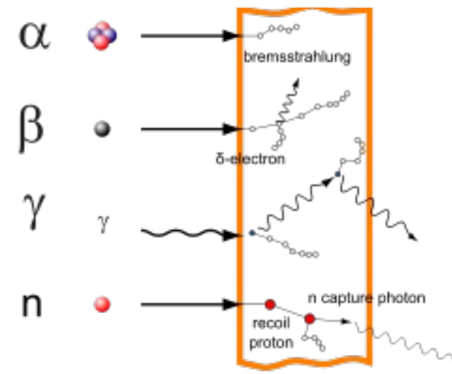
α particle: massive, charged

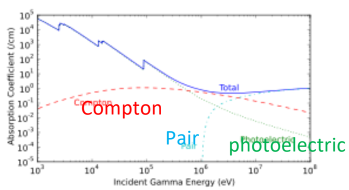
- ➔ interested in energy, angular distribution
- ➔ spectrometers, Si, plastic detectors



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

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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

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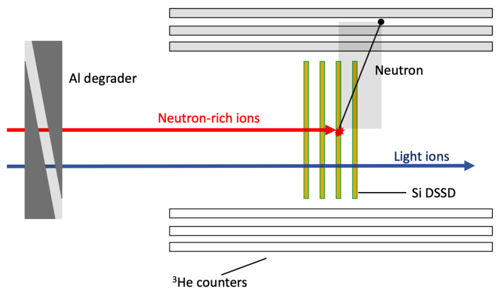

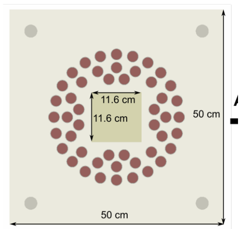

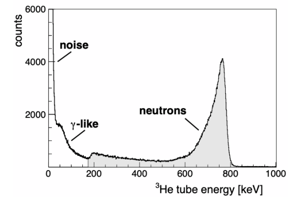

Figure 7: Distribution of energies registered in the ^{3}He tubes of the BRIKEN neutron counter. The spectrum contains the sum of all ^{3}He tube signals in one run. The shaded area represents the range of signals accepted as valid neutron signals. See text for details.

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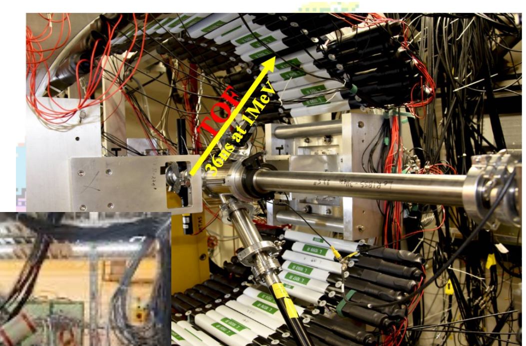
- Successful 5-years BRIKEN campaign to measure β1n and β2n emission

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

Existing arrays

- 3He counters
  - B-Riken (Japan)
  - Tetra (Dubna-Orsay)
  - 3Hen (Oak Ridge)
  - BELEN (GSI-FAIR)

✓ High angular coverage
✓ High efficiency (~65 %)
~ 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
~ Good Resolution
~ Position independent eff.
X low detection threshold
X high background