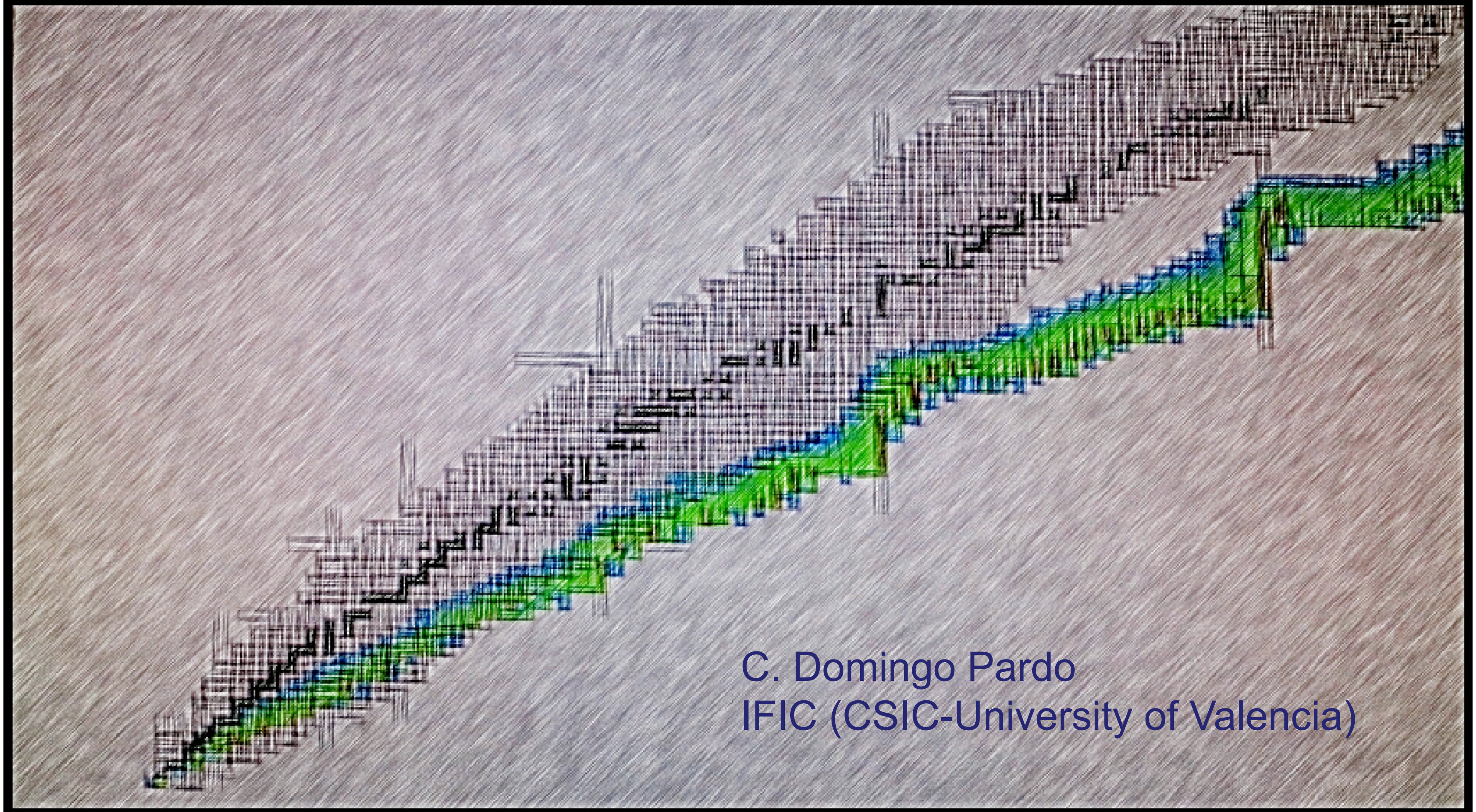
Medidas de emisión de neutrones en β-decay



C. Domingo Pardo
IFIC (CSIC-University of Valencia)

Contenidos

- Introducción y motivación: los neutrones como precursores de los elementos pesados en el universo.
    - R-process nucleosynthesis: neuron capture, β-decay y emisión de neutrones
    - S-process nucleosynthesis: neutron capture, β-decay

- Concepto de emisión retardada de neutrones

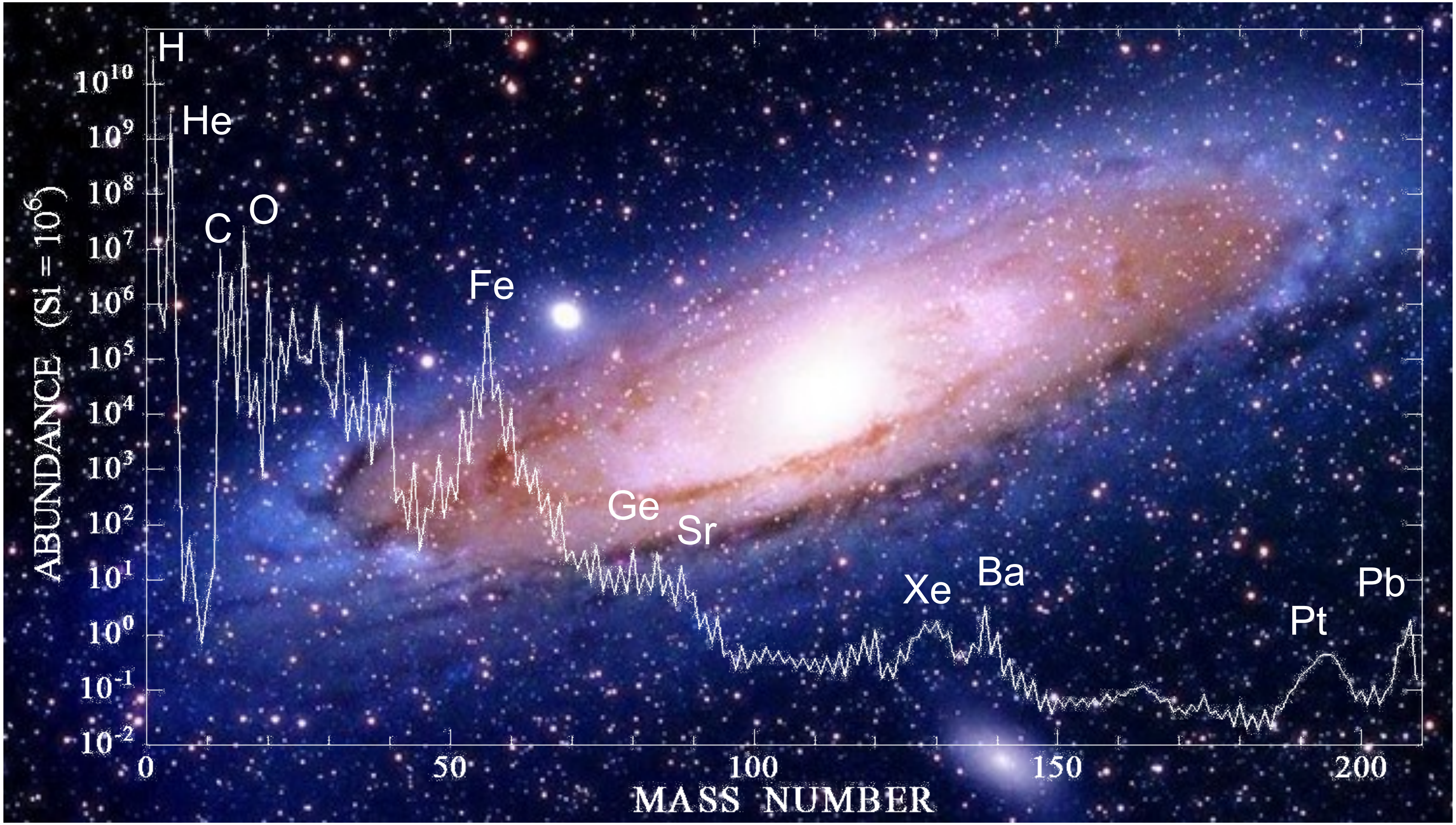
- Ejemplo 1: medidas en GSI para astrofísica (r-process)

- Ejemplo 2: medidas en JYFL para tecnologías nucleares (energía)

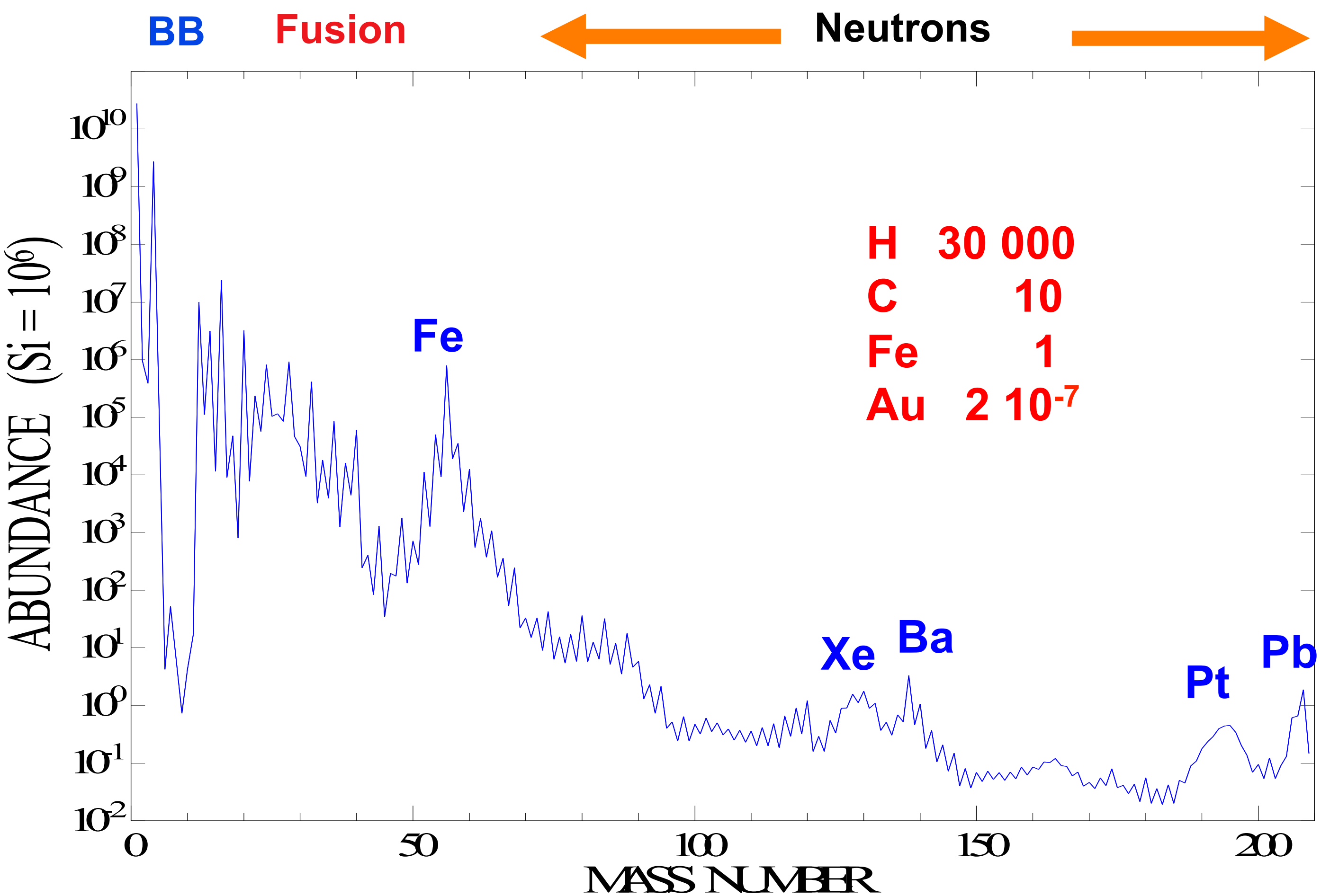
- Perspectiva y resumen

Introducción y motivación:

→los neutrones son el precursor de los elementos pesados (>Fe) en el universo.

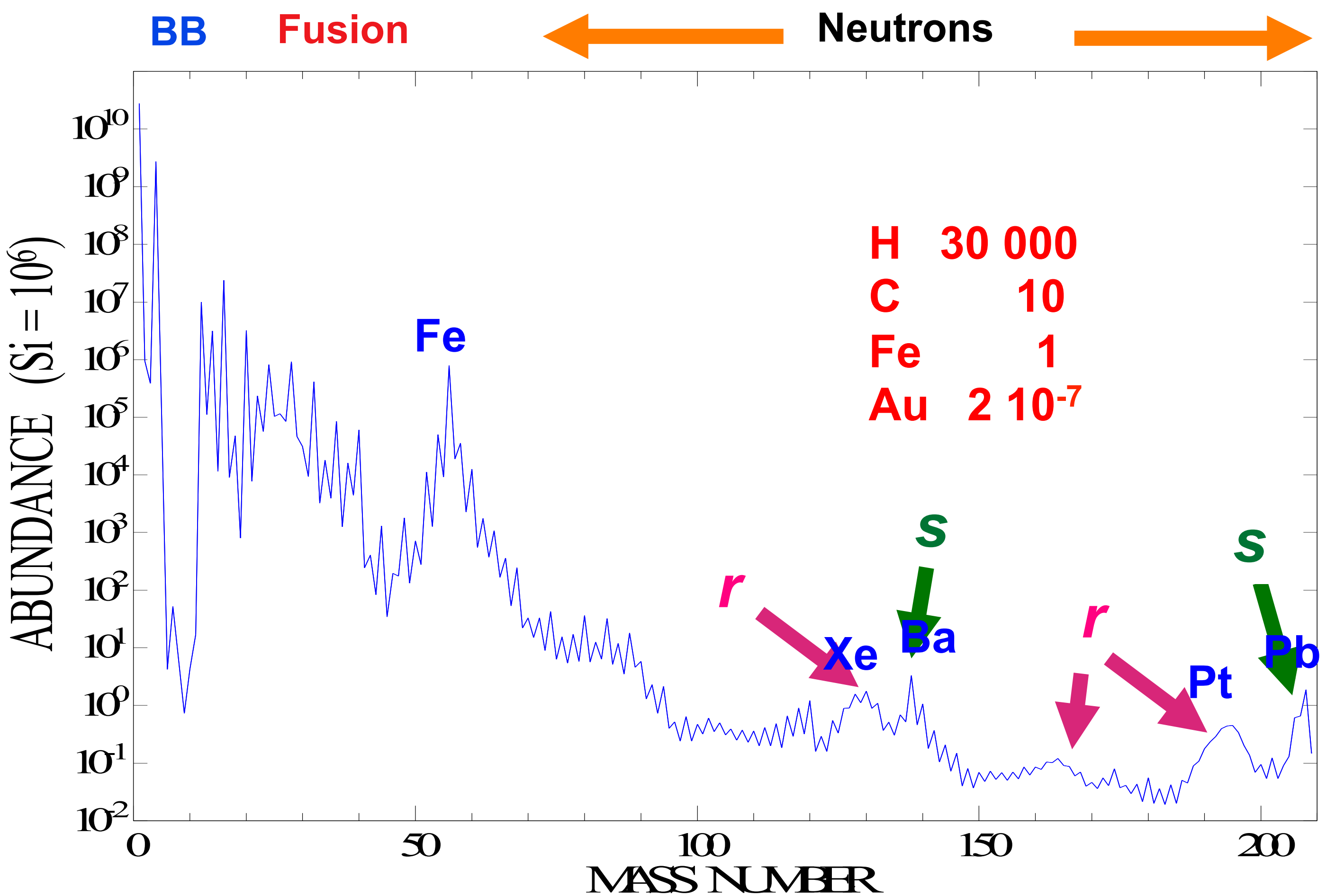


Nucleosíntesis de elementos pesados en entornos estelares explosivos (r-process)



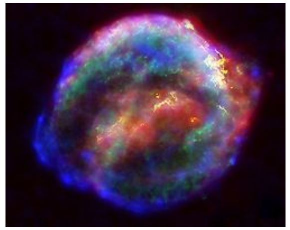
Neutrons produce 75% of the stable isotopes, but only 0.005% of total abundances

Nucleosíntesis de elementos pesados en entornos estelares explosivos (r-process)

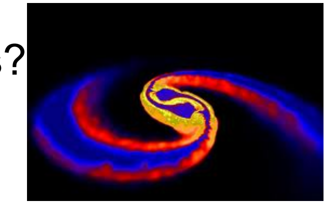


r-process: unkonwn site

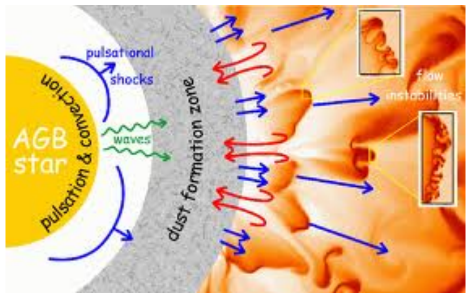
SNe?



NS-Mergers?



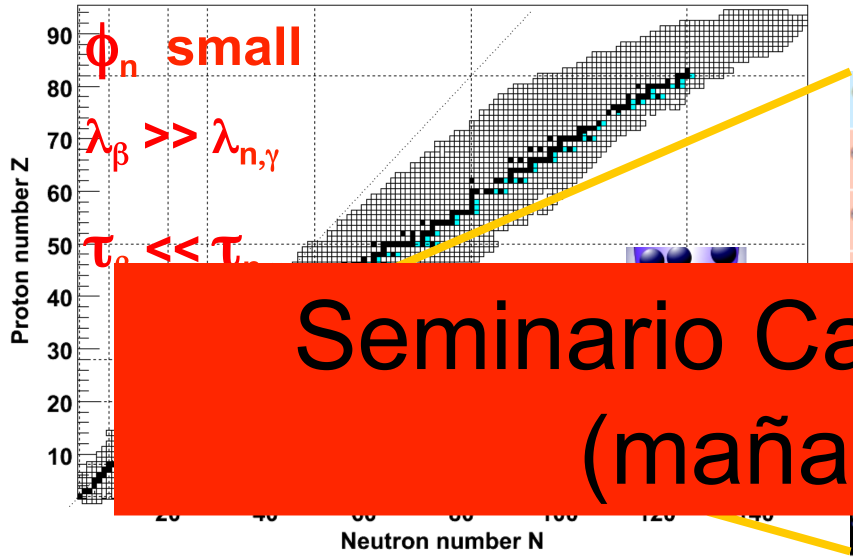
s-process: slow n-capture in stellar envolopes

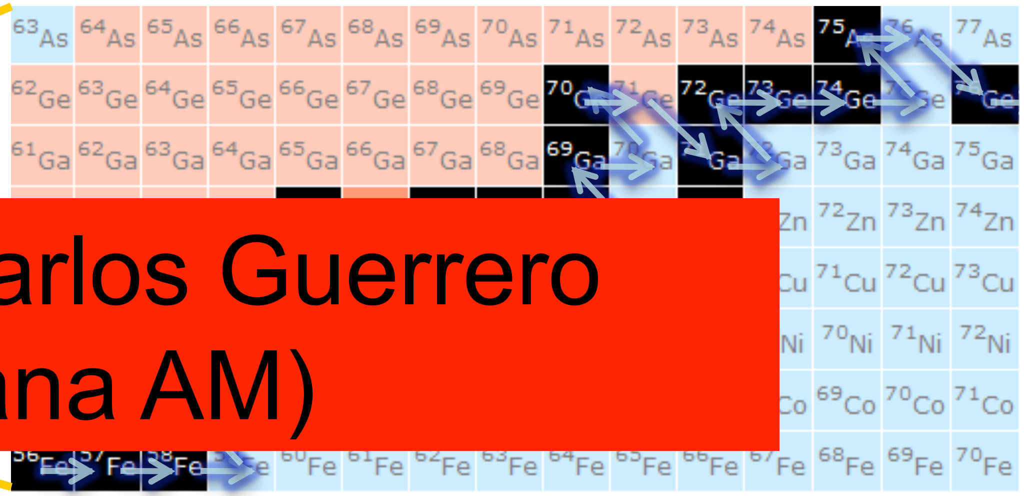


Neutrons produce 75% of the stable isotopes, but only 0.005% of total abundances

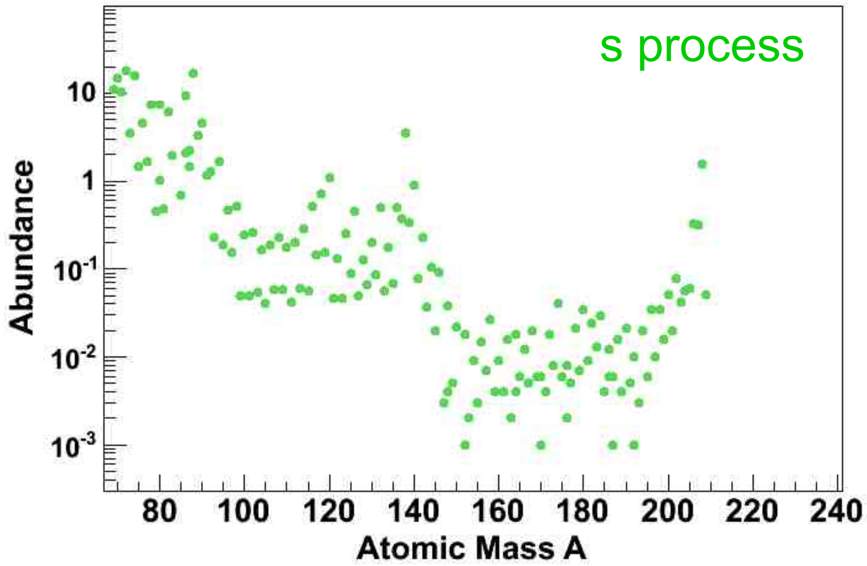
Stellar nucleosynthesis: the **s process**

s process in AGB (Red Giant) Stars





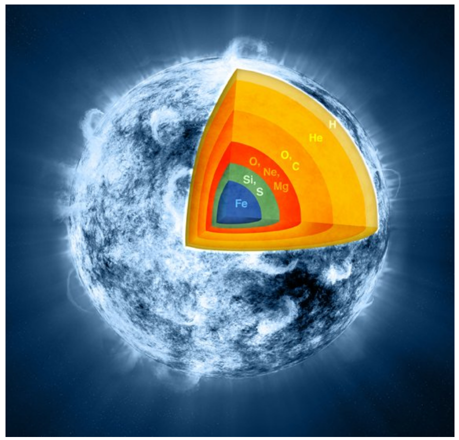
Seminario Carlos Guerrero (mañana AM)



core He-burning
$3\text{-}3.5\cdot10^8$ K
kT=25 keV
10^6 cm^{-3}

shell C-burning
$\sim1\cdot10^9$ K
kT=90 keV
$10^{11}\text{-}10^{12}$ cm^{-3}

$^{22}Ne(\alpha,n)$

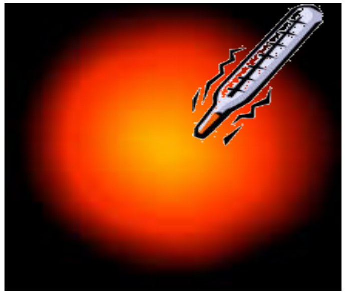


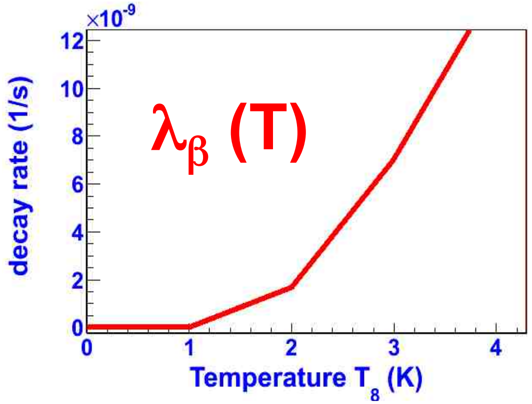
Arlandini et al. , Ap. J. 525 (1999)
Gallino et al., Ap. J. 497 (1998)

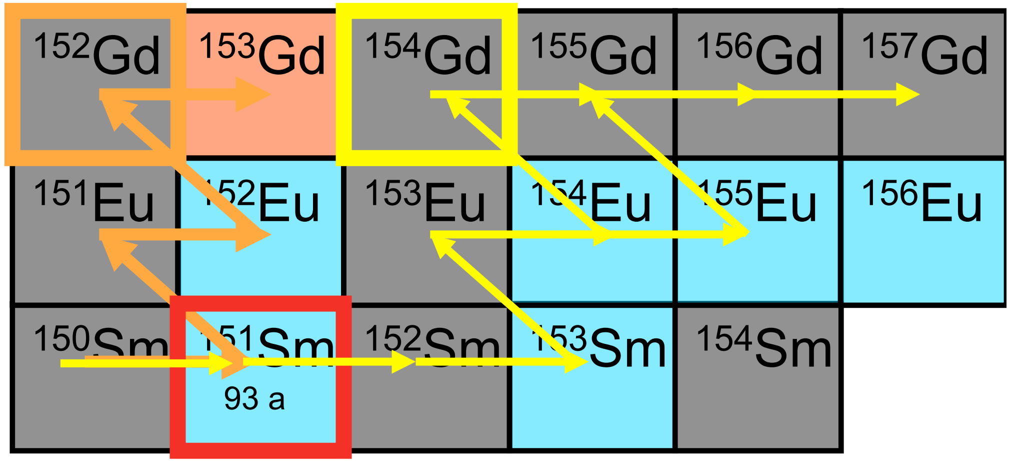
Raiteri et al. , Ap. J. 419 (1993)

Temperature in TP AGB Stars

- How hot is the stellar environment where s-process nucleosynthesis takes place?







Branchings:

- neutron density
- temperature

Sample:

- 206 mg $^{151}Sm_2O_3$ (Oak Ridge)
- 90 % enrichment
- $t_{1/2}$ = 93a, activity: **156 GBq**

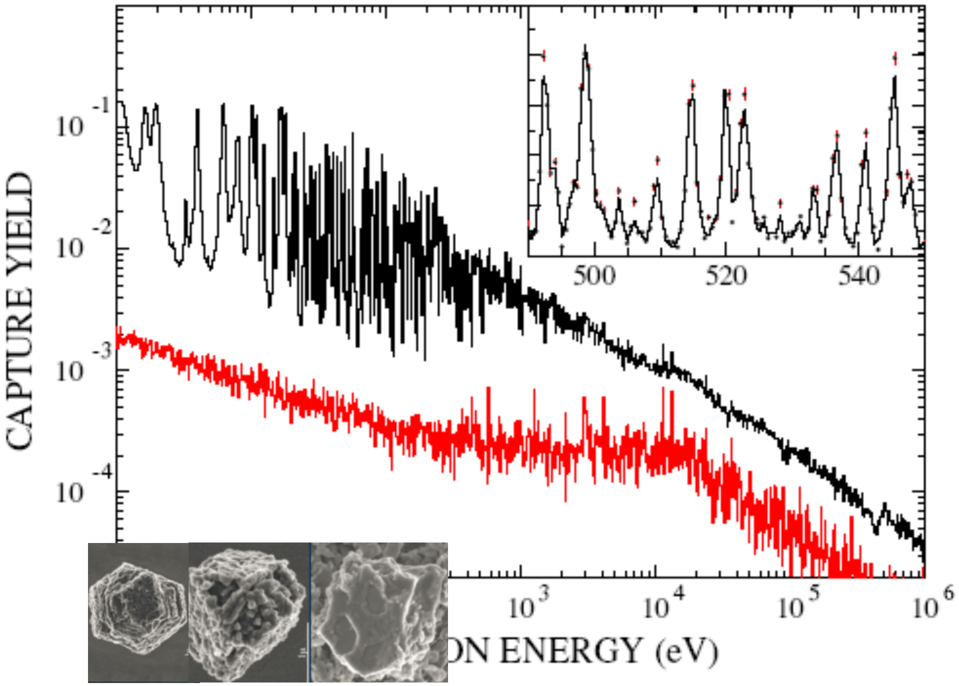
$$f_\beta = \frac{(<\sigma_\gamma> N_s)_{152Gd}}{(<\sigma_\gamma> N_s)_{150Sm}} = \frac{\lambda_\beta^{151Sm}(T)}{\lambda_\beta^{151Sm} - v_T n_n <\sigma_\gamma>_{151Sm}}$$

First s-process branch point which was directly measured via TOF n_TOF largest instantaneous luminosity worldwide key for this measurement

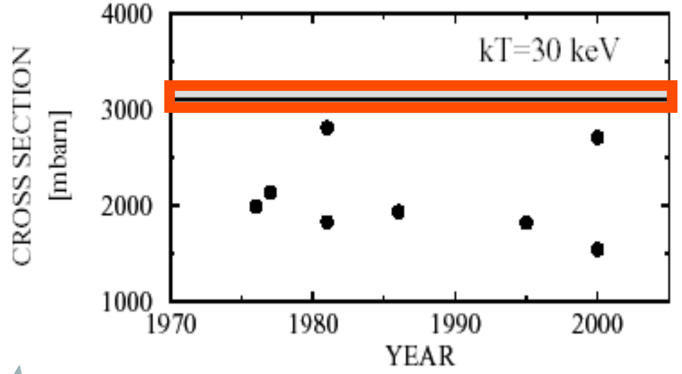
VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Neutron Capture Cross Section Measurement of ^{151}Sm at the CERN Neutron Time of Flight Facility (n_TOF)

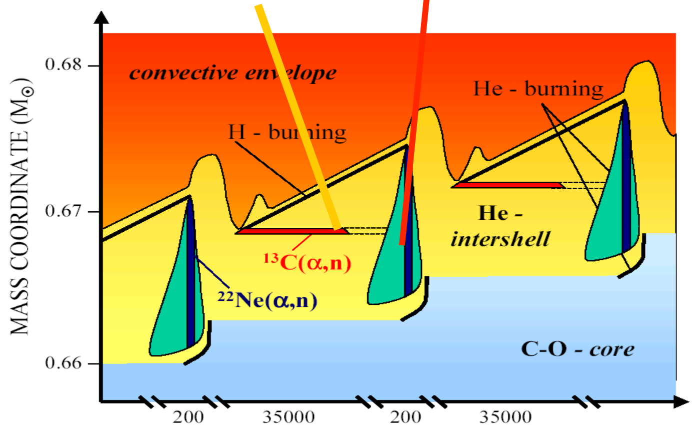
Temperature in TP AGB Stars



MACS-30 = 3100 ± 160 mb



T_{He} = 2.5-2.8x10^8 K
T_H = 1x10^8 K



U Abbondanno et al. Phys. Rev. Lett. 93 (2004), 161103
S. Marrone et al. Phys. Rev. C 73 (2006) 03604

Hot-topics in s-process nucleosynthesis: stellar rotation and mixing

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

Rotating massive stars: From first stars to gamma ray bursts

André Maeder* and Georges Meynet†

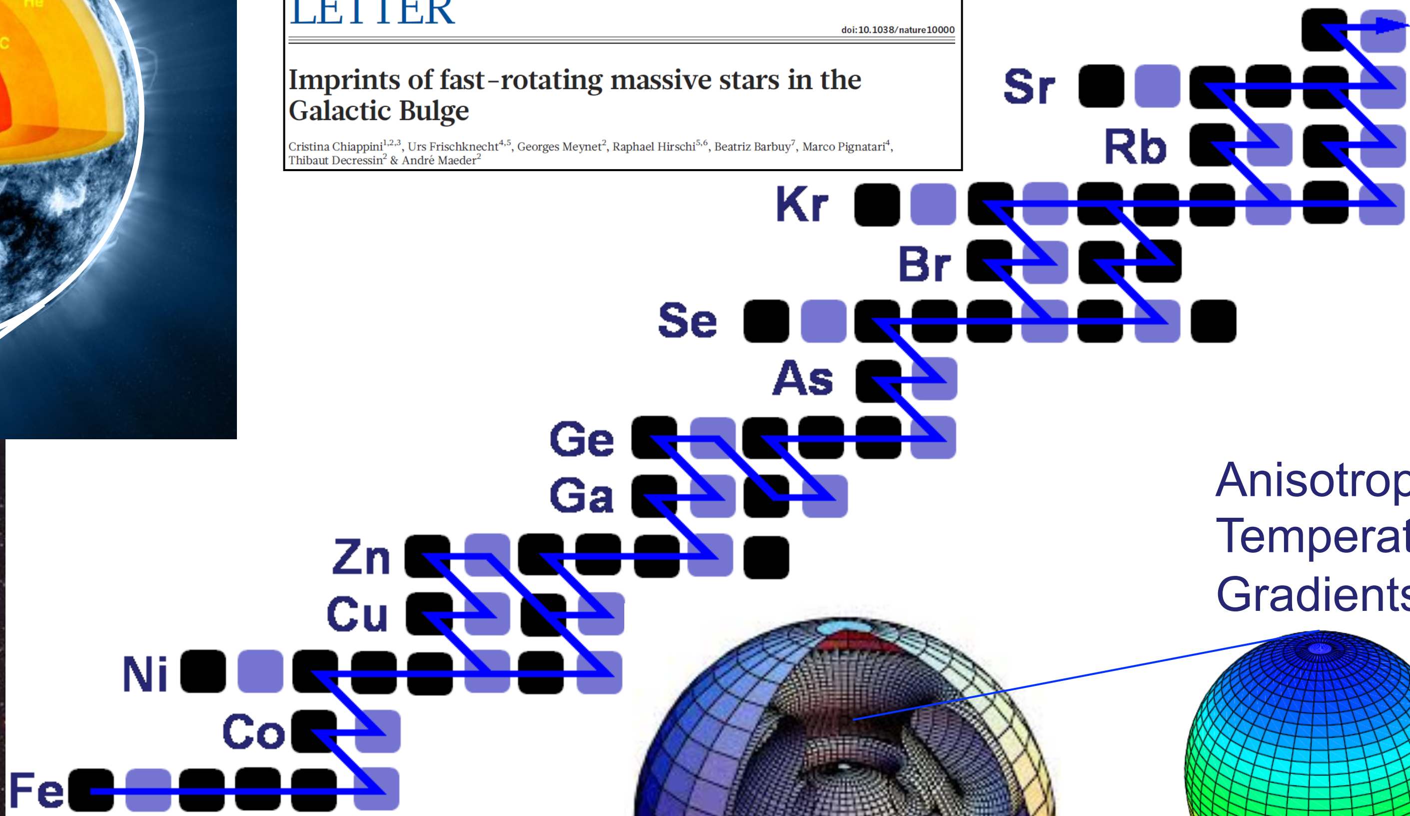
Geneva Observatory, University of Geneva, 51 chemin des Maillettes, CH-1290 Versoix, Switzerland

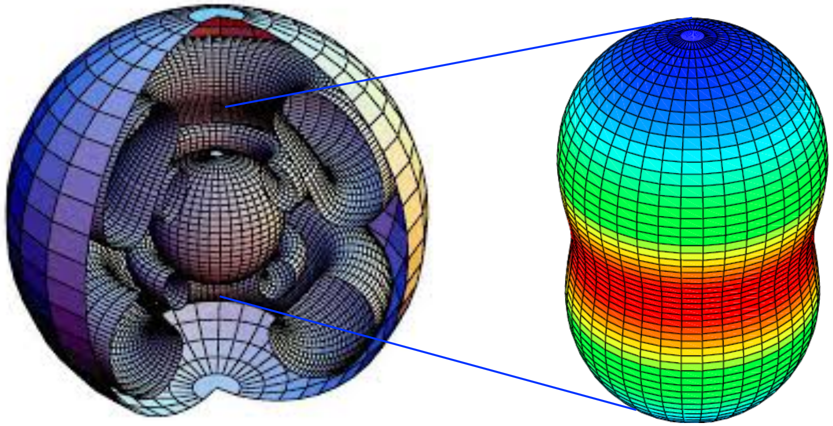
LETTER

doi:10.1038/nature10000

Imprints of fast-rotating massive stars in the Galactic Bulge

Cristina Chiappini[1,2,3], Urs Frischknecht[4,5], Georges Meynet[2], Raphael Hirschi[5,6], Beatriz Barbuy[7], Marco Pignatari[4], Thibaut Decressin[2] & André Maeder[2]



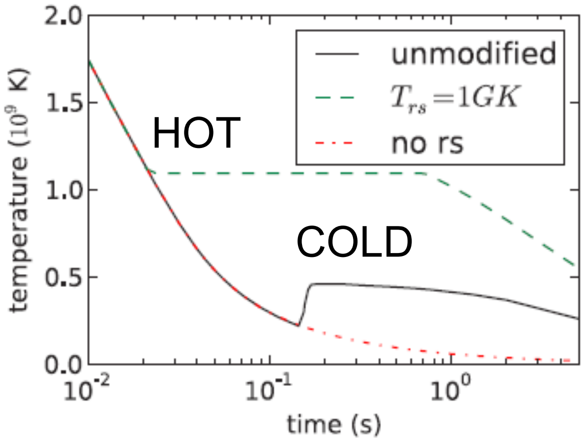


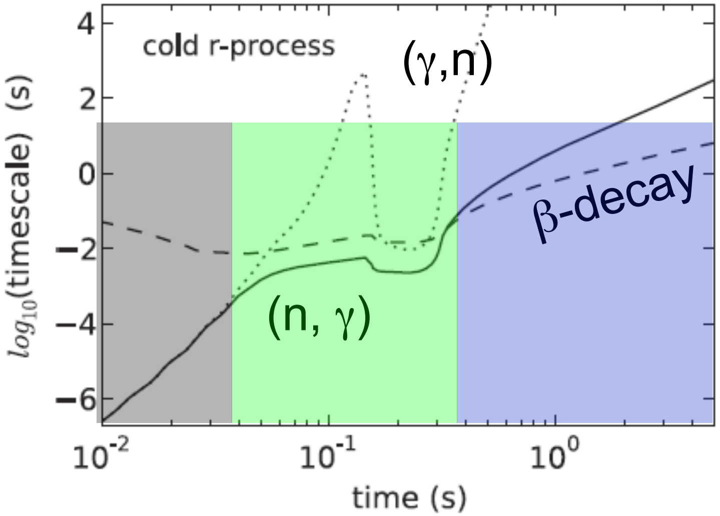
R-process nucleosynthesis

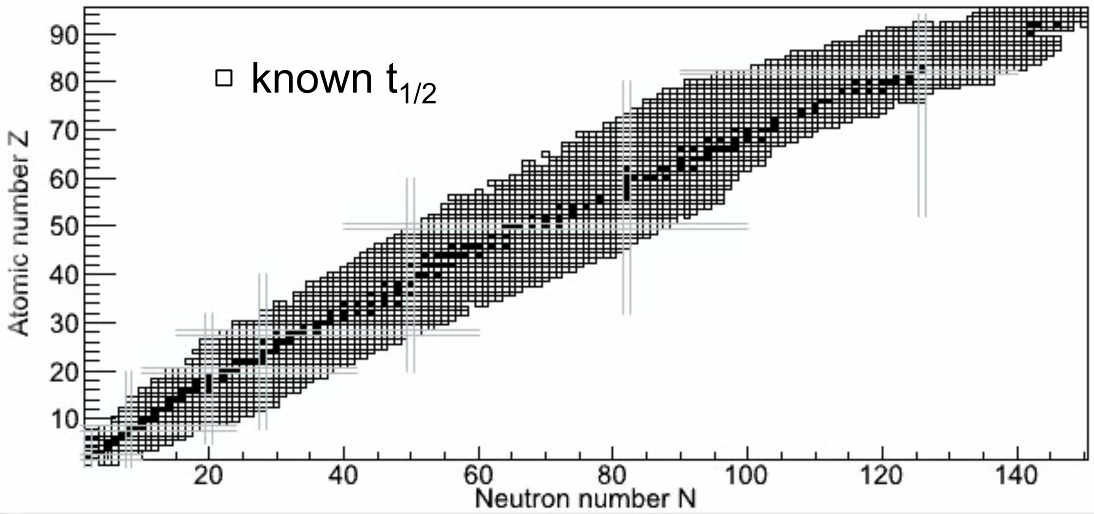
PHYSICAL REVIEW C **83**, 045809 (2011)

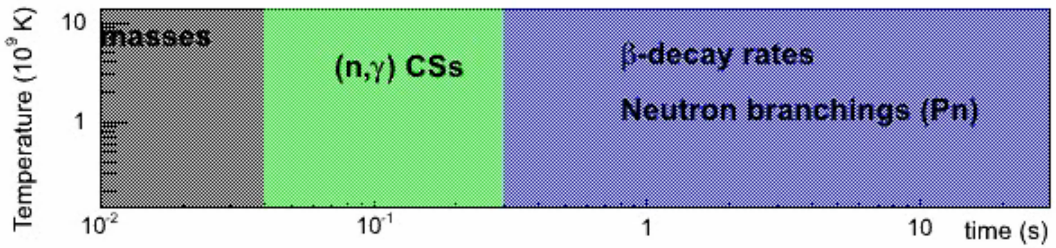
Dynamical *r*-process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input

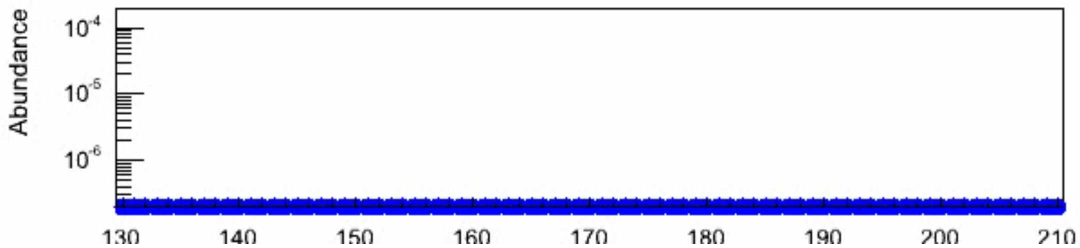
A. Arcones[1,2,*] and G. Martínez-Pinedo[2]
[1]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*











NucNet network code, B. Meyer et al., Clemson University
FRDM+QRPA (P. Möller) + JINA Reaclib Database

Nucleosynthesis of the heaviest elements

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A. Arcones[1,2,*] and G. Martínez-Pinedo[2]
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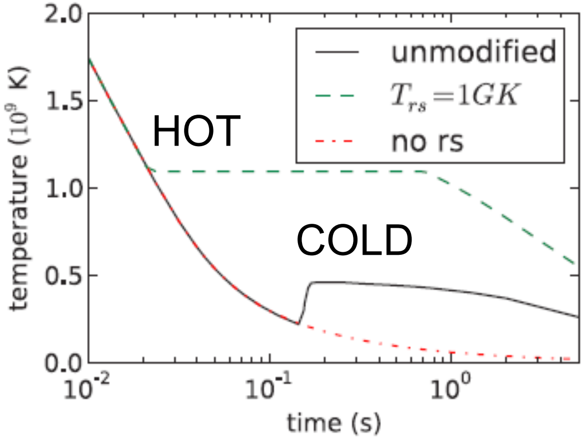

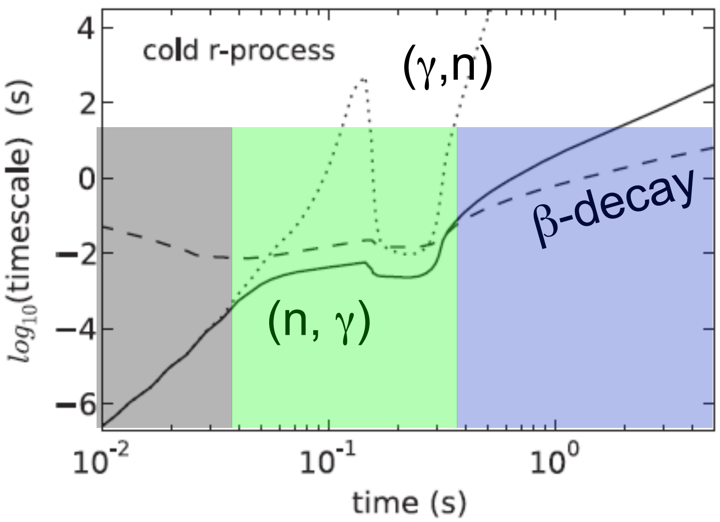

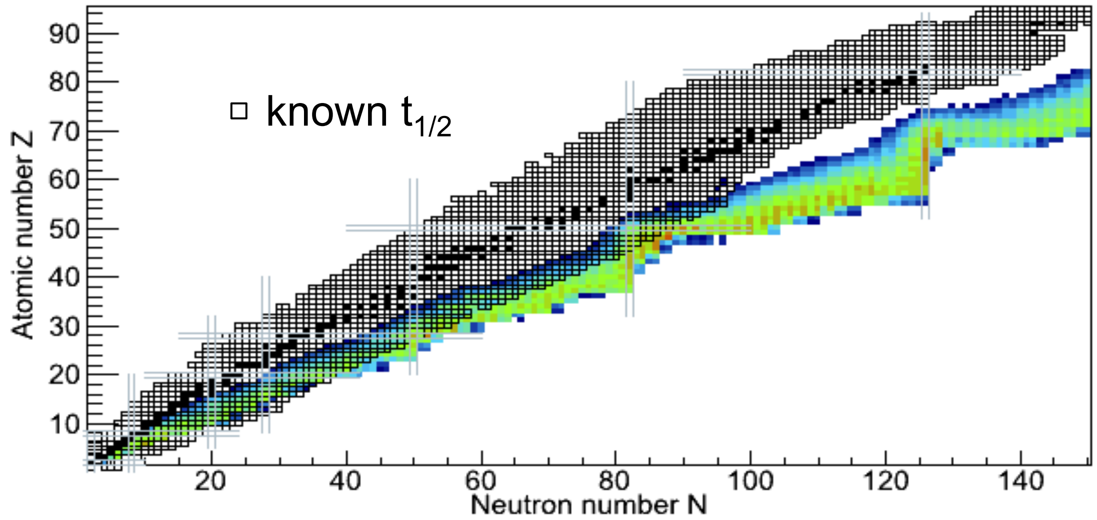

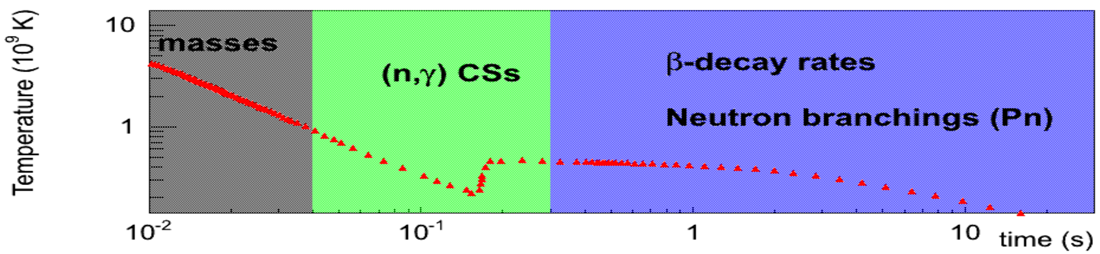

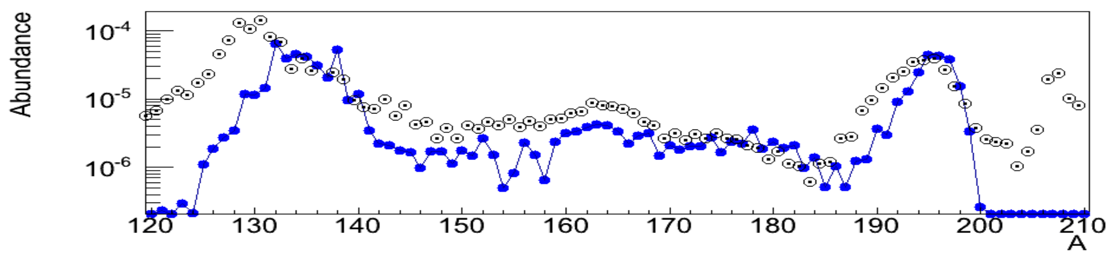

→ Beta-decays dominate shape the abundance pattern

Contenidos

- Introducción y motivación: los neutrones como origen de los elementos pesados en el universo.
  - R-process nucleosynthesis: β-decay y emisión de neutrones
  - S-process nucleosynthesis: neutron capture

- Concepto de emisión retardada de neutrones

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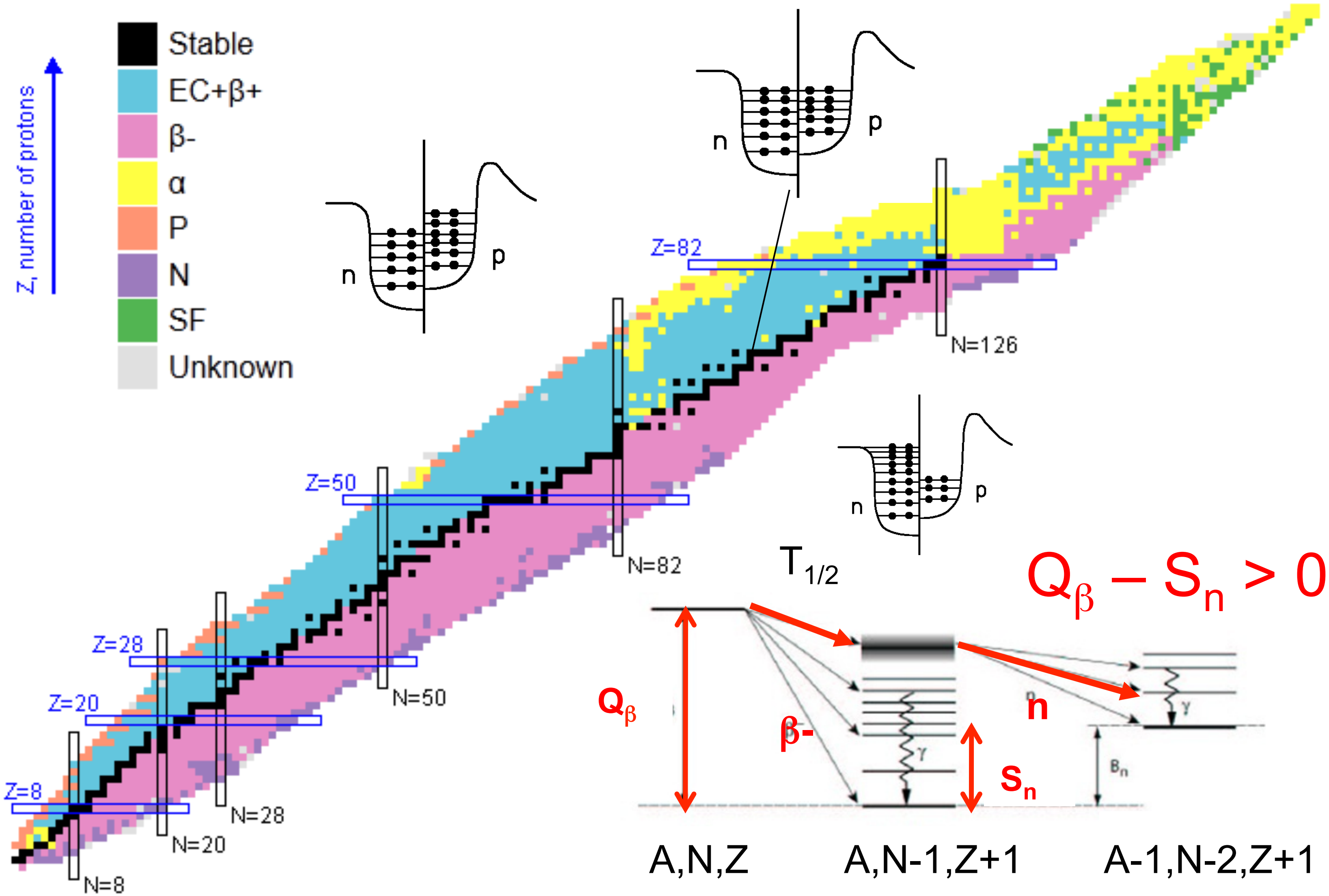
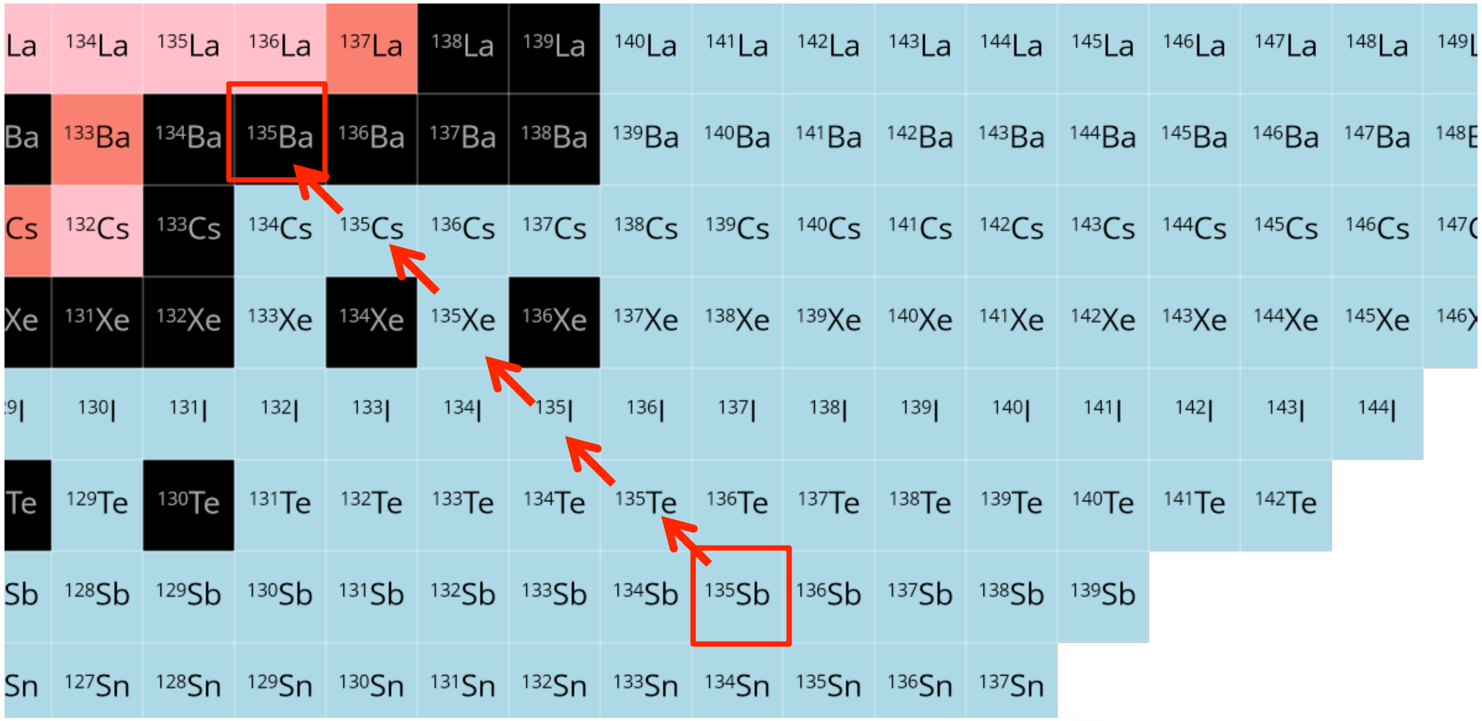
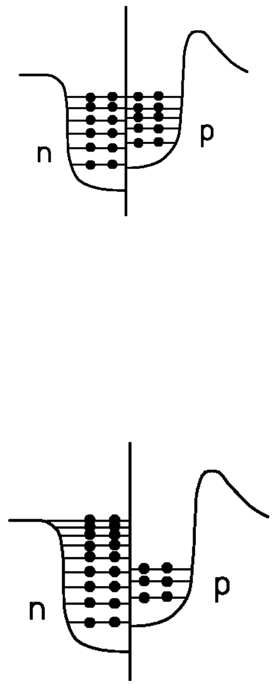
Concepto de emisión retardada de neutrones

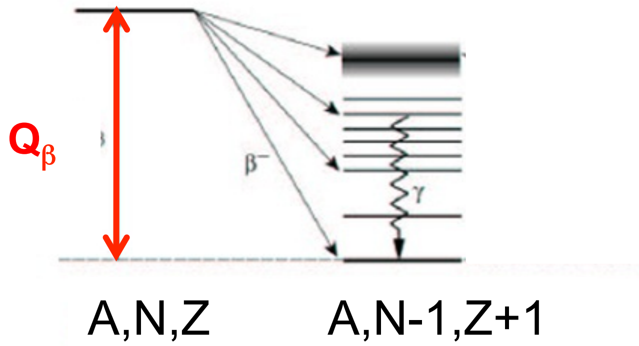


$Q_\beta - S_n > 0$

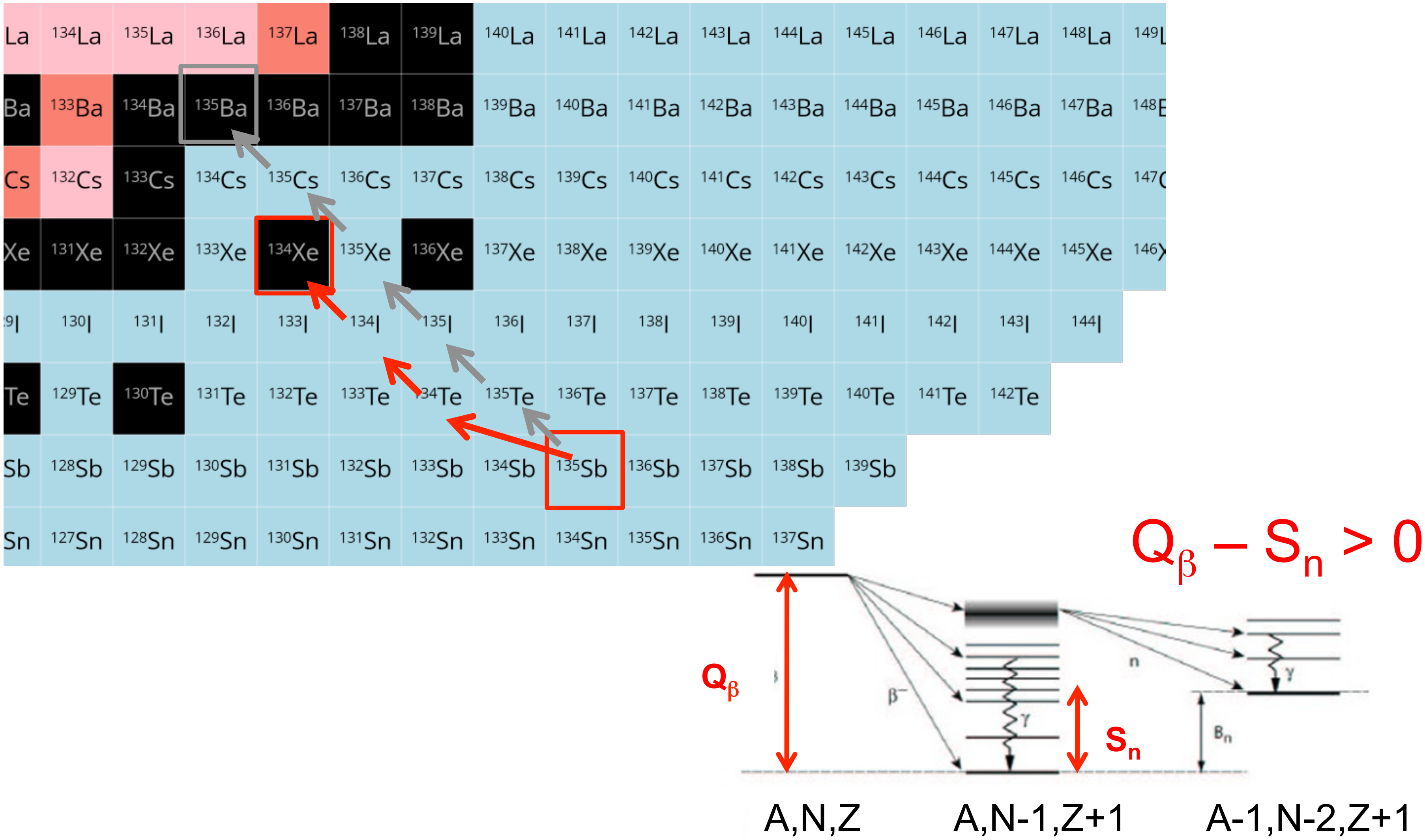
Concepto de emisión retardada de neutrones







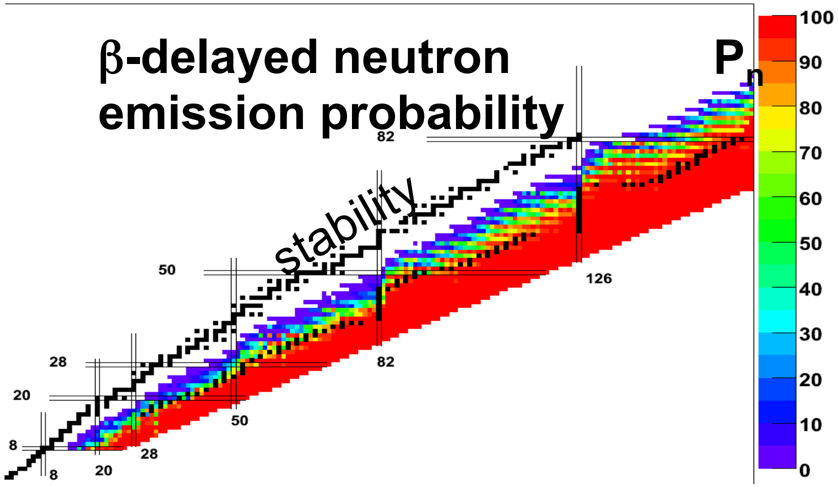
Concepto de emisión retardada de neutrones



$Q_\beta - S_n > 0$

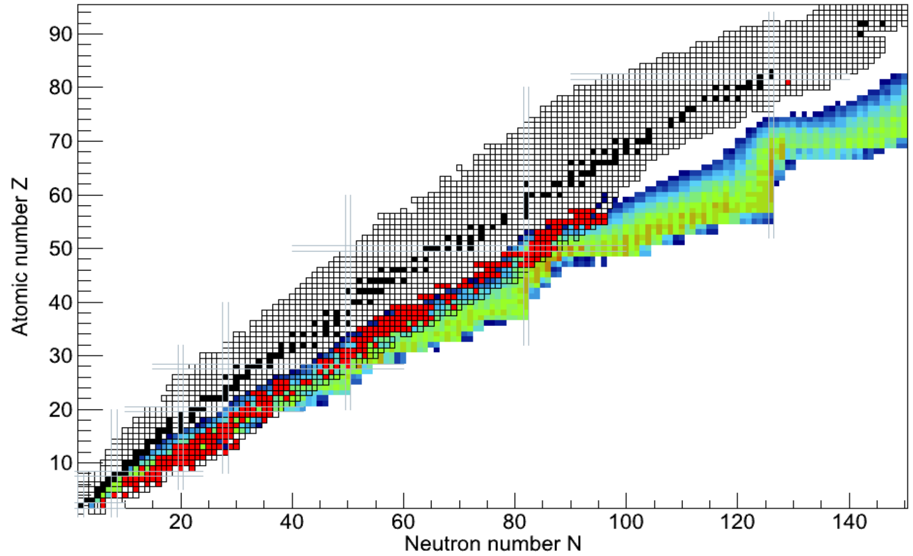
Concepto de emisión retardada de neutrones

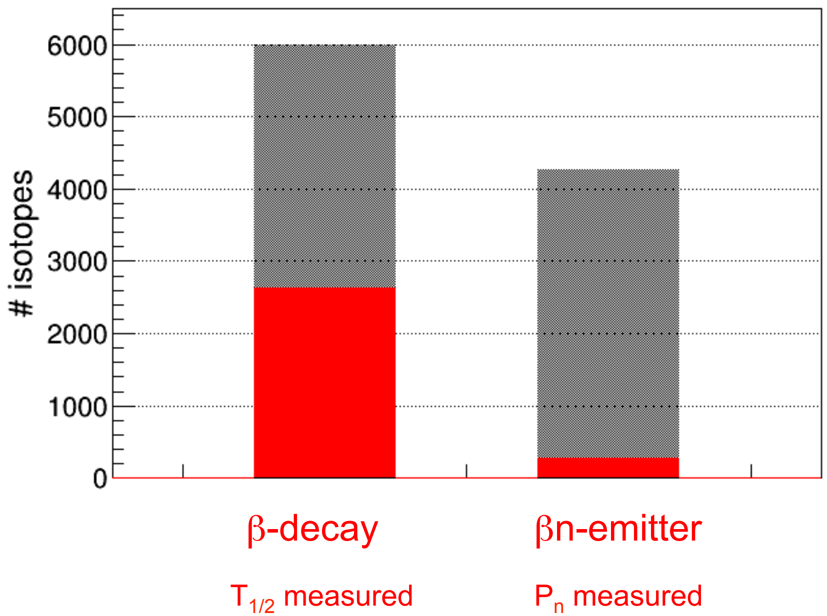
Predicción modelos teóricos



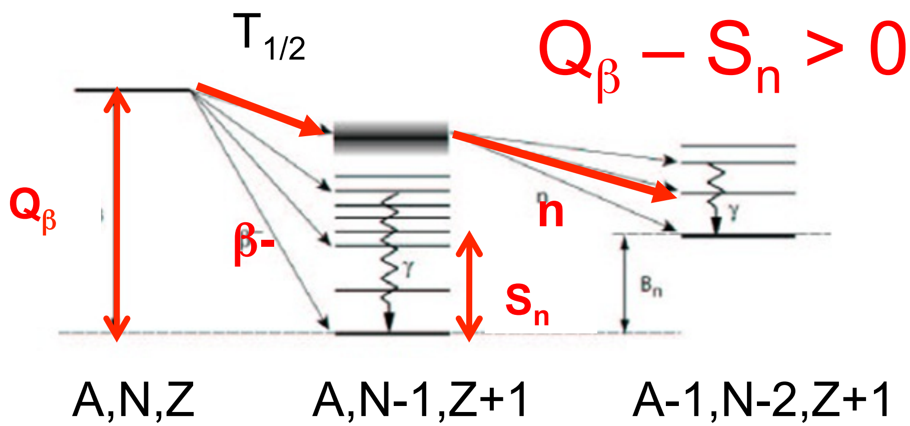
P_n: Moeller et al PRC67(2003)055802

P_n medidos experimentalmente:





Only 227 known Pn values
out of 4274 predicted n-emitters !!



Contenidos

- Introducción y motivación: los neutrones como origen de los elementos pesados en el universo.
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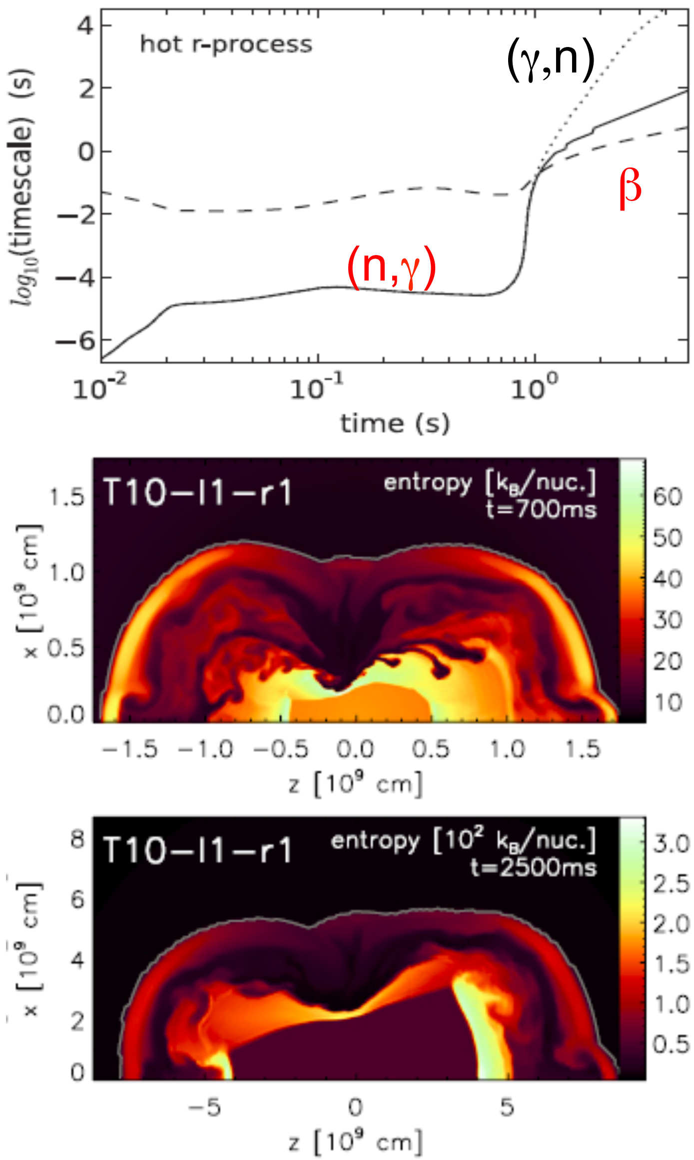
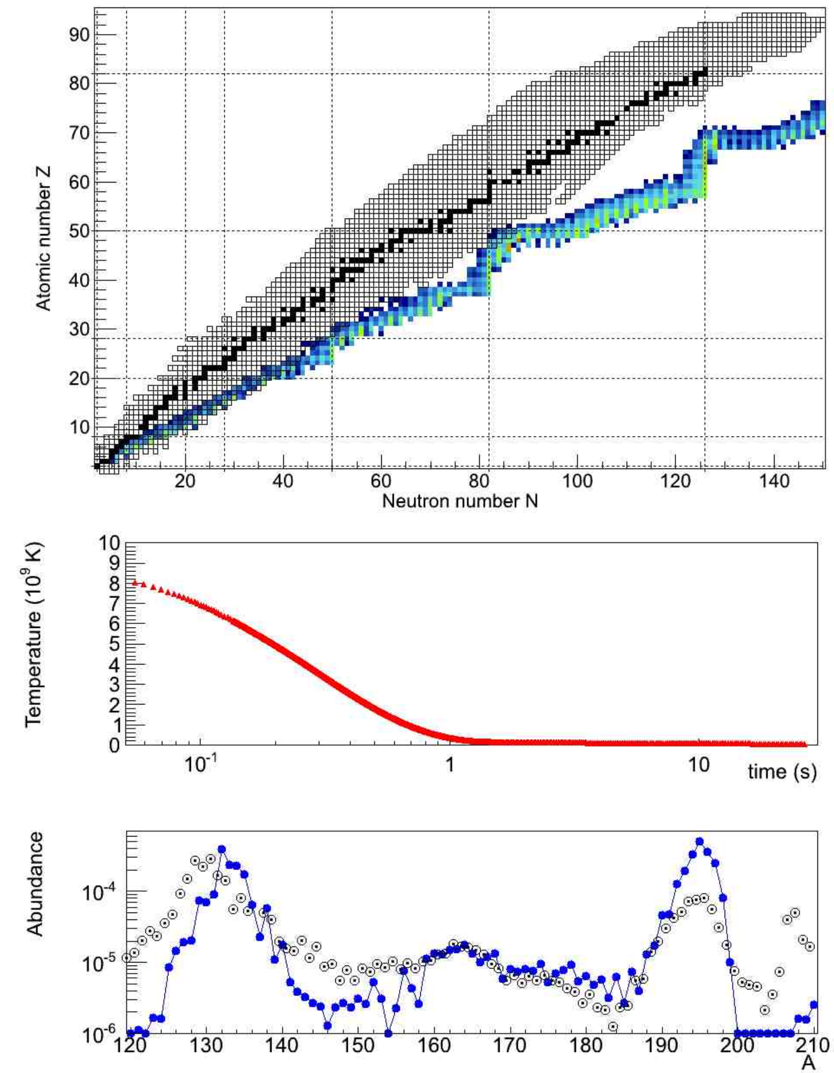
- Ejemplo 2: medidas en JYFL para tecnologías nucleares (energía)

- Perspectiva y resumen

- R-process nucleosynthesis in the heavy mass region
- Ejemplo de medidas en una instalación tipo in-flight con un *cocktail* de RIs

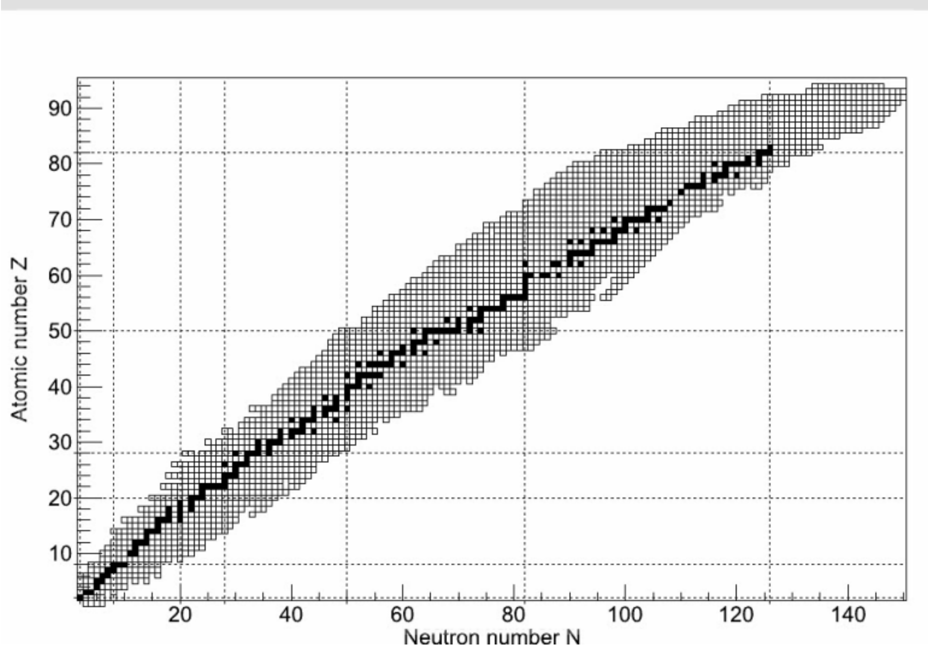
Nucleosíntesis de elementos pesados en entornos estelares explosivos

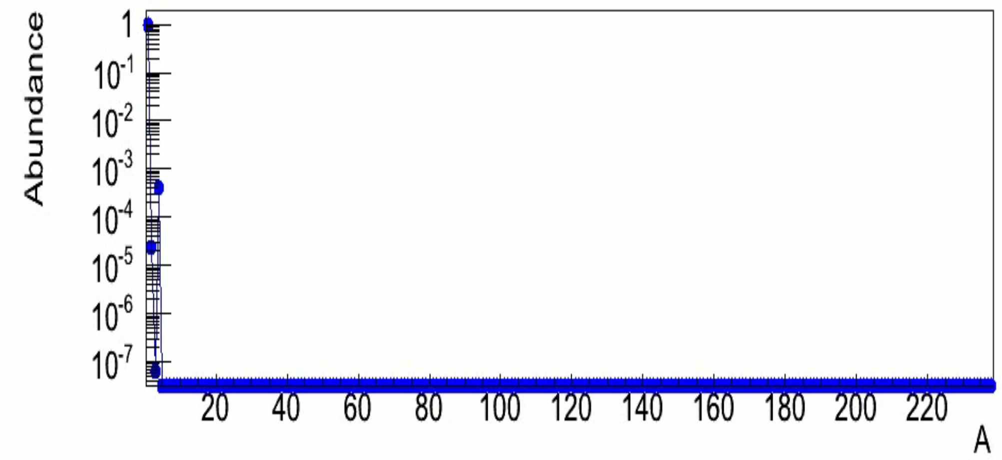




→ Need to artificially enhance entropy in order to reach the Pt-peak (Why?): model wrong, data inaccurate, or both?

Nucleosynthesis around the 3rd r-process peak





PHYSICAL REVIEW C **83**, 045809 (2011)

Dynamical *r*-process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input

A. Arcones[1,2,*] and G. Martínez-Pinedo[2]
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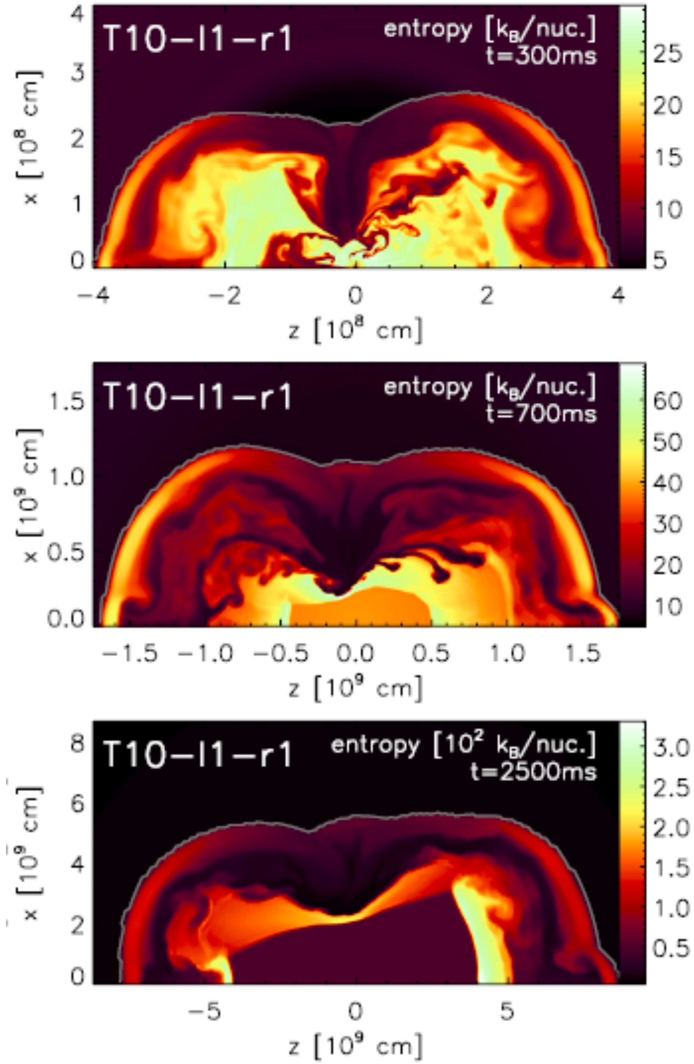

Nucleosynthesis around the 3rd r-process peak

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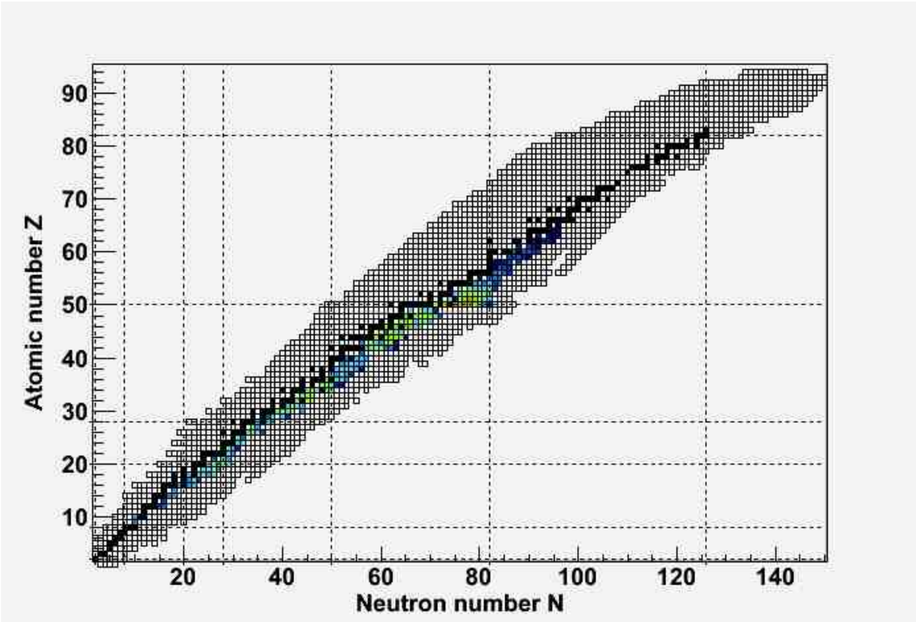
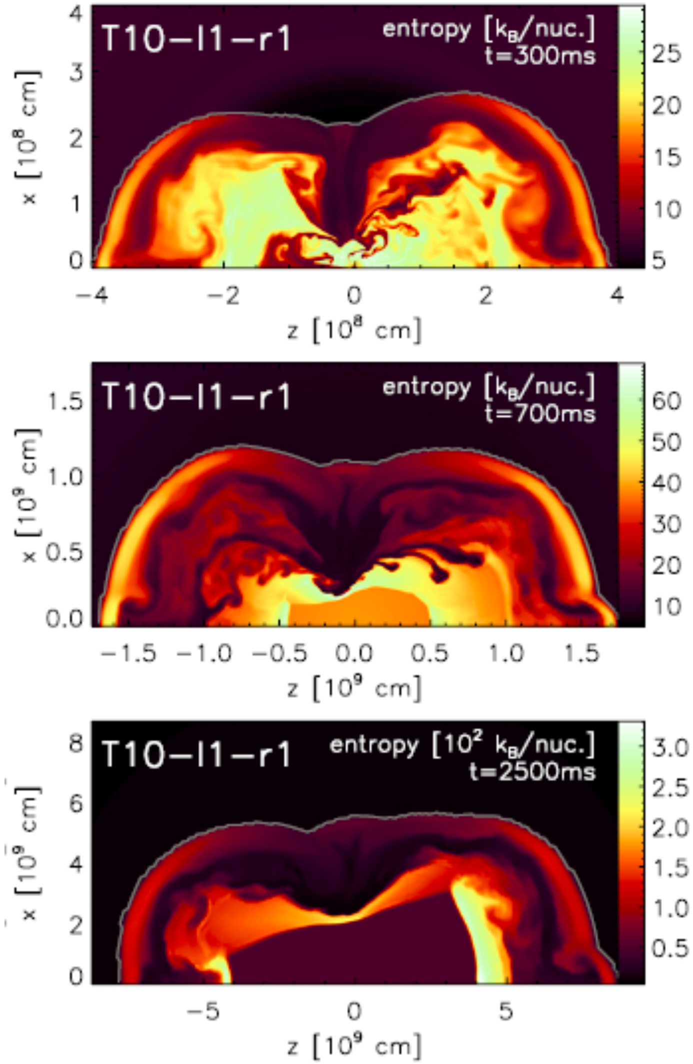
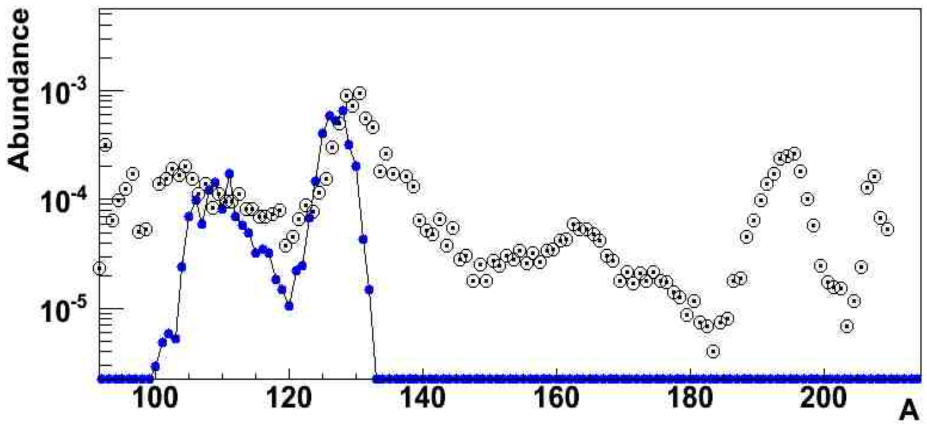






→State of the art hydrodynamical SN simulations do NOT produce heavy elements at all !!!
→ Need to measure Nuclear Physics input: beta-decays, beta-delayed neutrons

Técnica de in-flight production / GSI

1. Producción de los núcleos ricos en neutrones (por fisión y/o fragmentación)

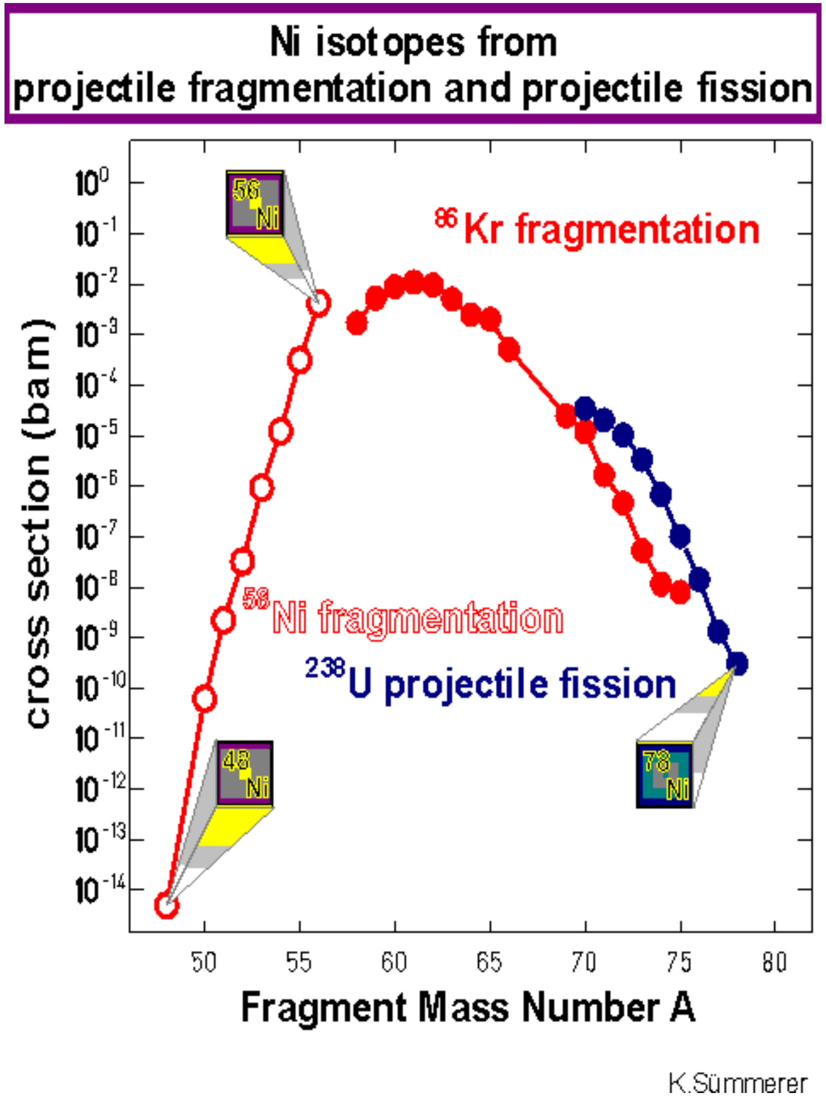
2. Implantación en un blanco (activo)

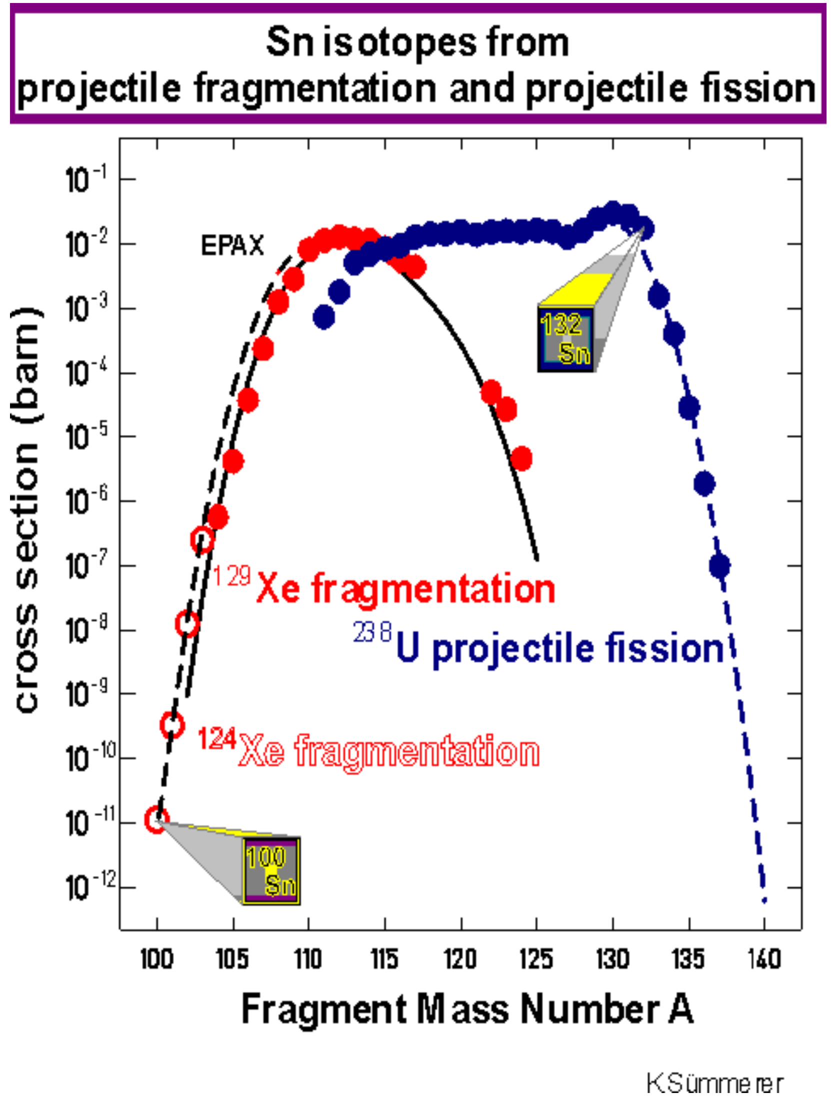
3. Medida de la implantación y de la desintegración beta

4. Medida de los neutrones

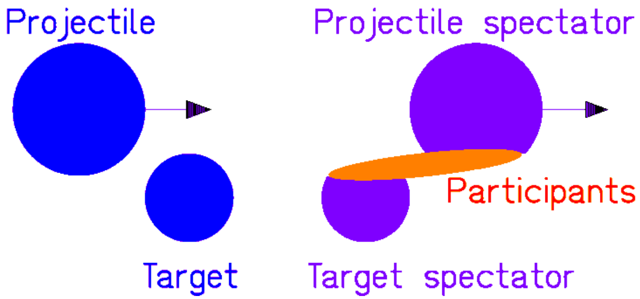
5. Evaluación del “neutron branching”

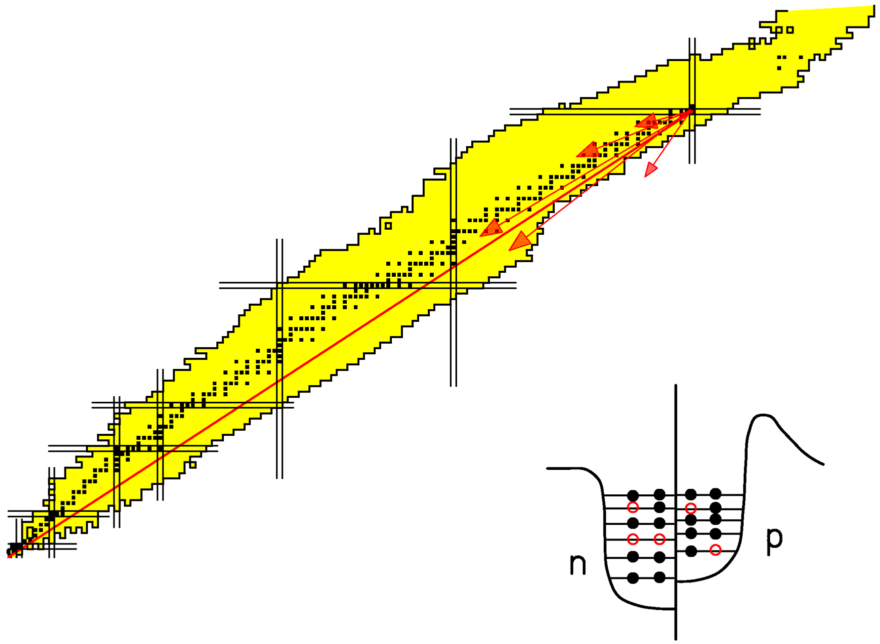
Producción de iones exóticos





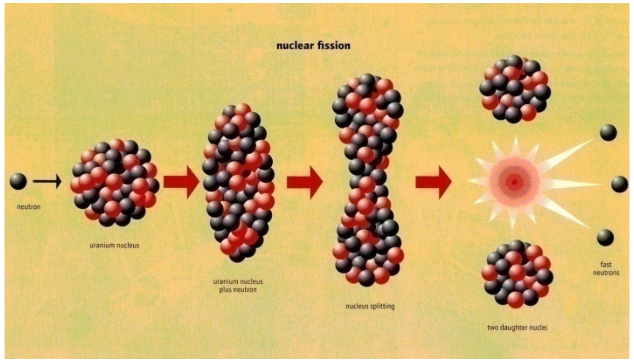
Fragmentación

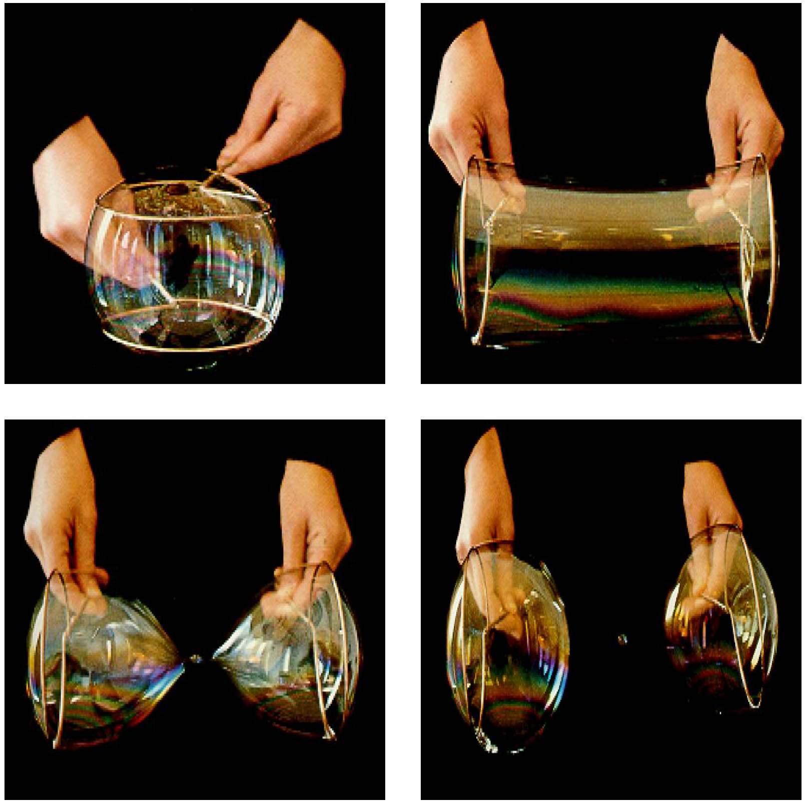


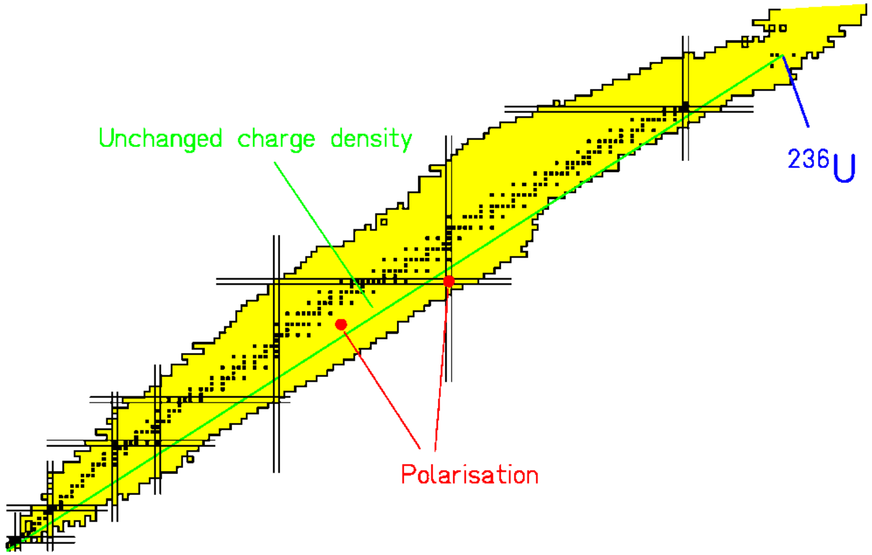


Removal of nucleons in quasi-free nucleon-nucleon collisions.
Basic characteristics:
•Large fluctuations in N/Z.
•Large fluctuations in excitation energy.
Highly excited fragments loose additional nucleons by evaporation.

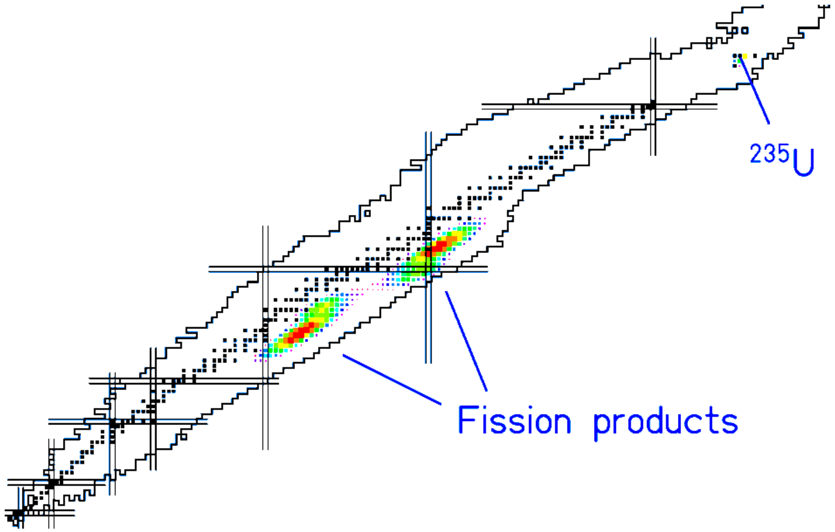
Fisión





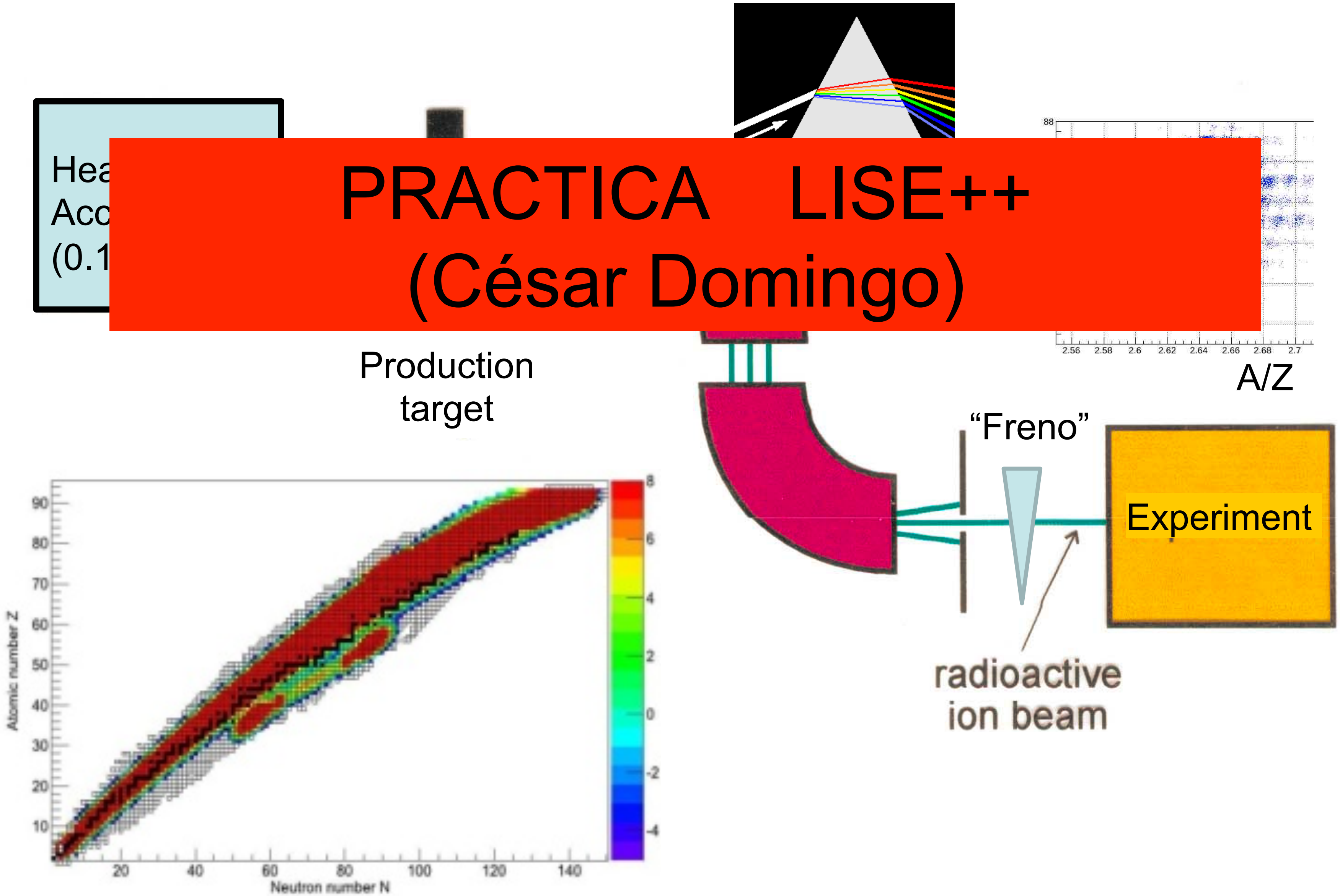


Fission induced by low-energy neutrons

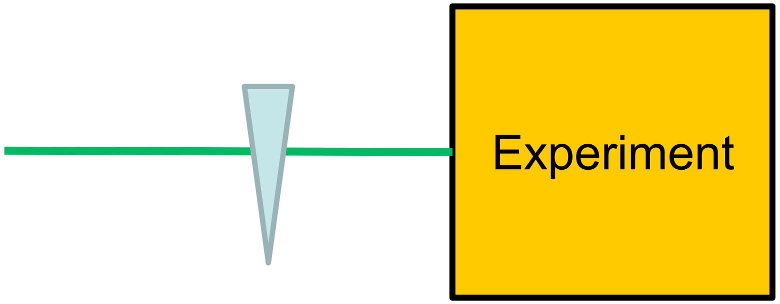


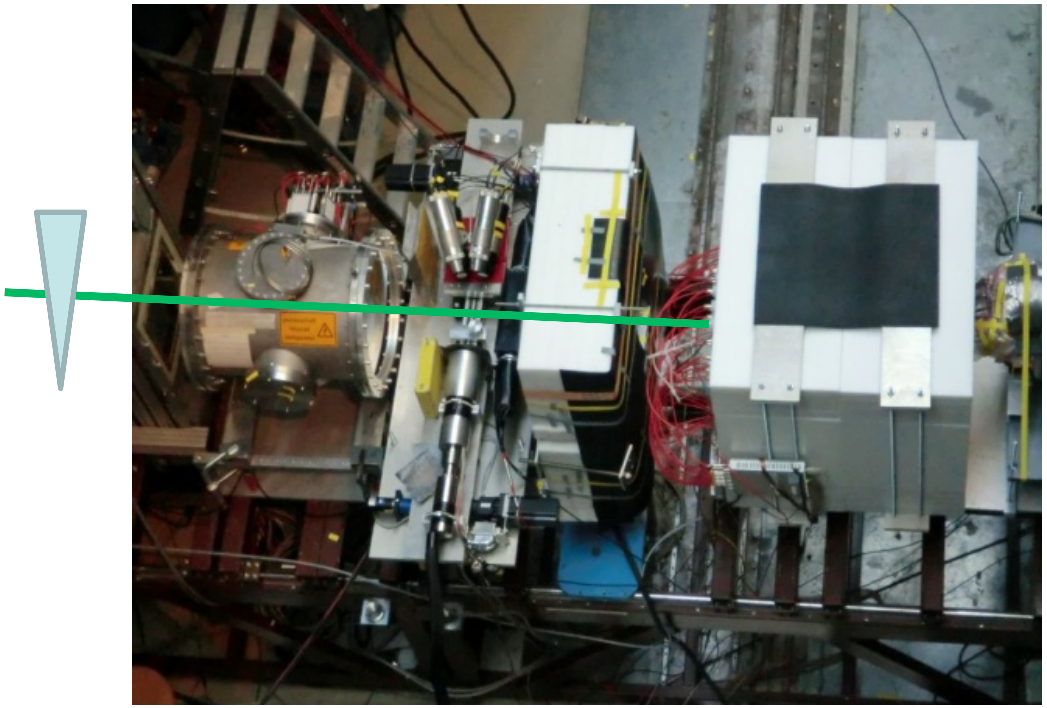
Identificación y separación de los núcleos exóticos de interés

PRACTICA LISE++
(César Domingo)

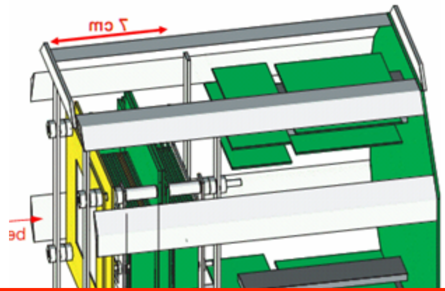


Implantación en un blanco





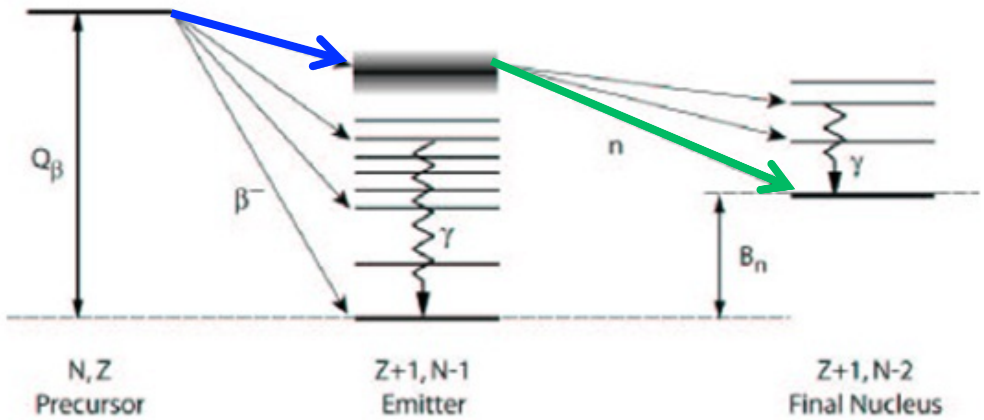
Implantación y decay en un blanco activo

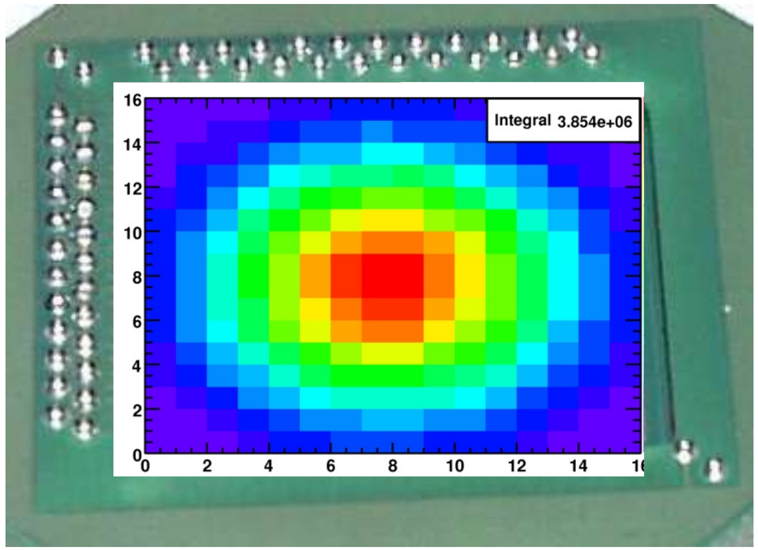


SIMBA (TUM, Germany)

Degra
(Fre

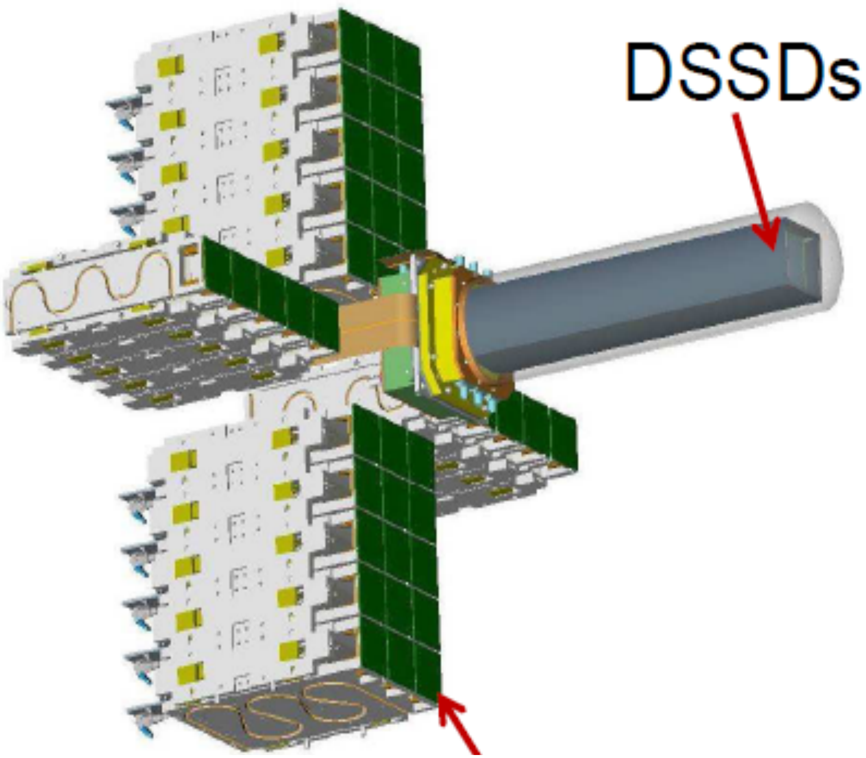
PRACTICA LABORATORIO
DETECTORES DE SILICIO
(VICTOR GUADILLA)

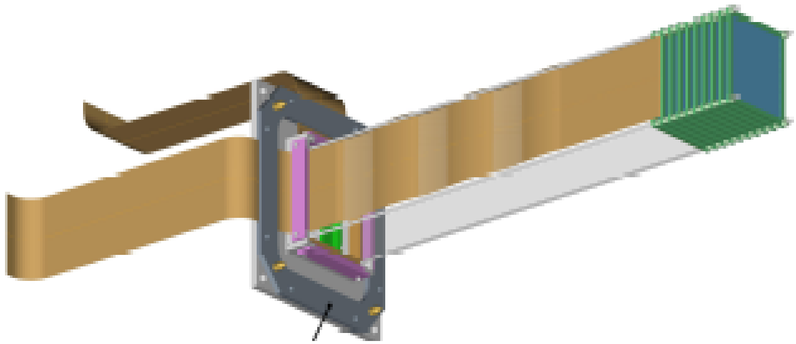




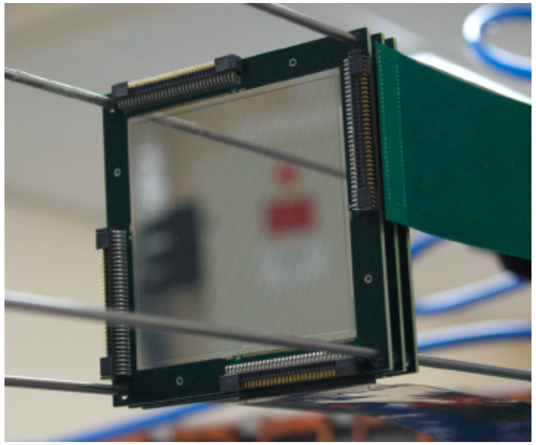
Implantación y decay en un blanco activo

The state-of-the-art in DSSDs: AIDA





12xDSSDs, 8x8cm, 1mm Si, 625um, >5000 channels



Implant – decay correlations

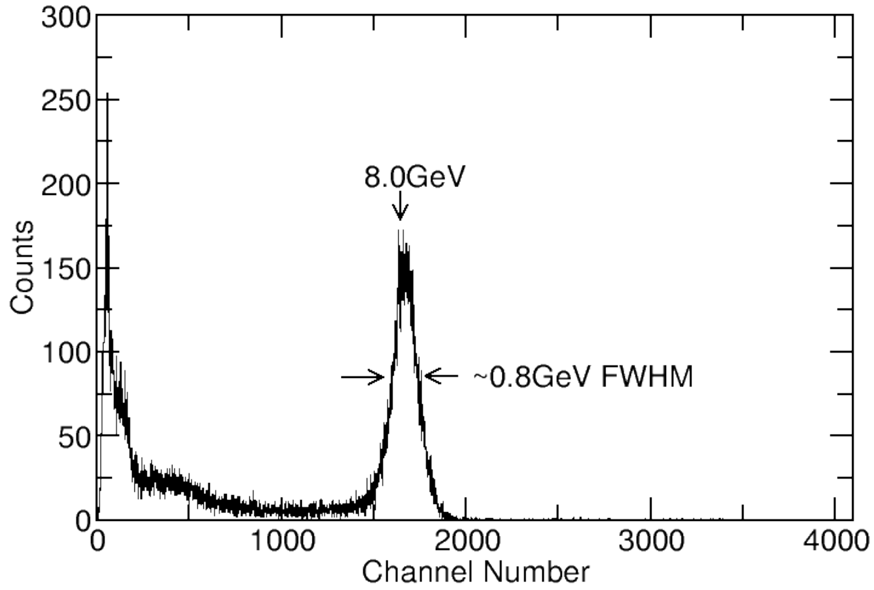
- Multi-GeV implantation events
- Subsequent low-energy decays
- Tag events for gamma and neutron detector arrays

Detector: multi-plane Si DSSD array
wafer thickness 1mm
8cm x 8cm (128x128 strips)

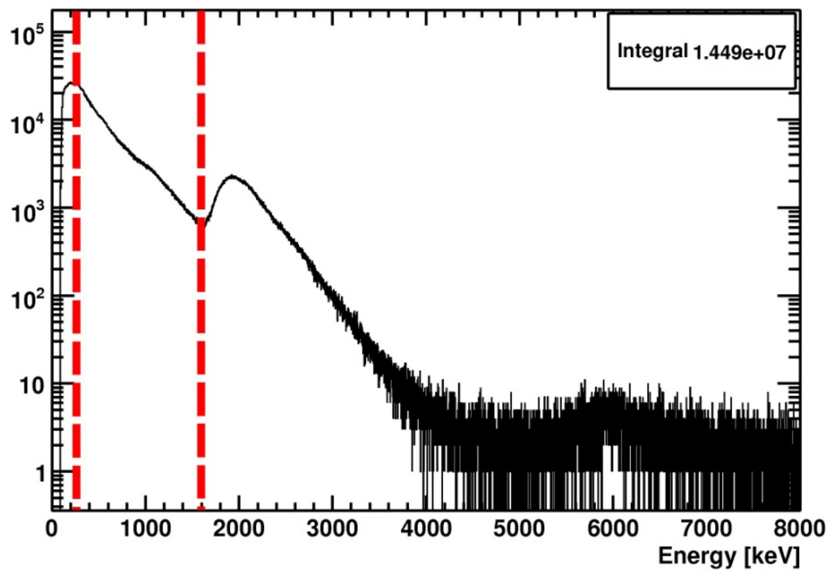
PJ Woods: PI of AIDA collaboration
(Edinburgh – Liverpool – STFC DL & RAL)

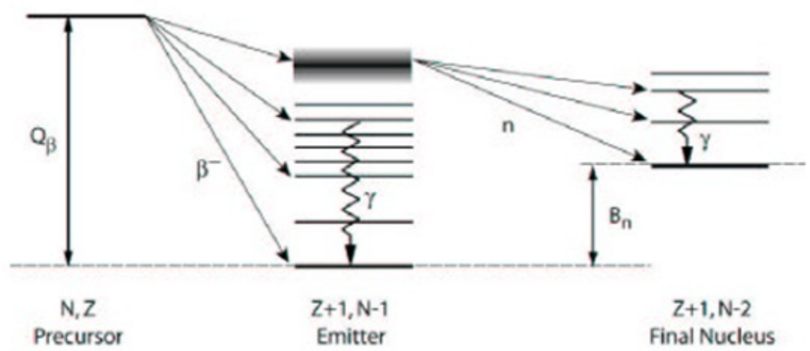
Implantación y decay en un blanco activo

Implantes e.g. ^{209}Bi a 40 MeV/u:



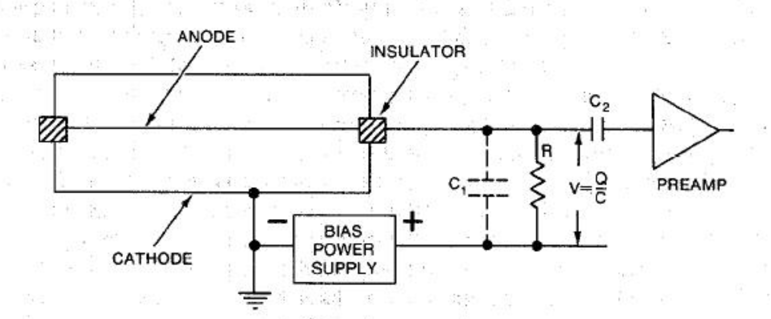
β-decays:





Detección de los neutrones retardados-beta

n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV
(abund.=0.00014%)



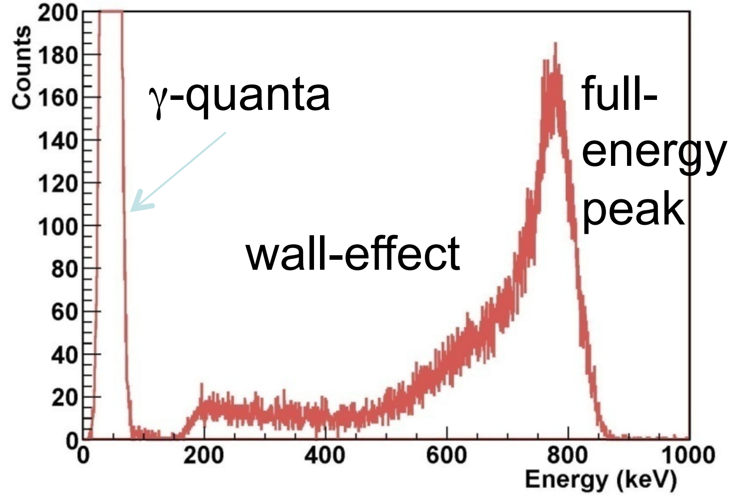
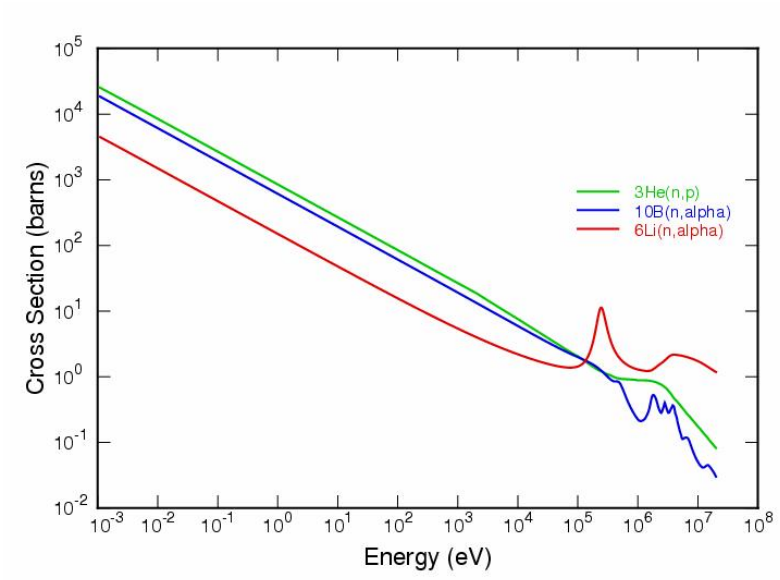


Figure 1: Expected pulse height spectrum from a ^{3}He tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vise versa in area (b).



The lower the neutron energy, the better for detection!

“truco”

Termalizar/moderar los neutrones (reducir su E) !

Moderar para detectar…

After many collisions:

Nucleus	1-α	ξ	N
^{1}H	[illegible]	[illegible]	[illegible]
^{2}H	[illegible]	[illegible]	[illegible]
^{4}He	[illegible]	[illegible]	[illegible]
^{12}C	0.284	0.158	111
^{56}Fe	0.069	0.035	500
^{208}Pb	0.019	0.010	1823

PRACTICA LABORATORIO DE CONTADORES DE NEUTRONES (Álvaro Tolosa)

…eter:

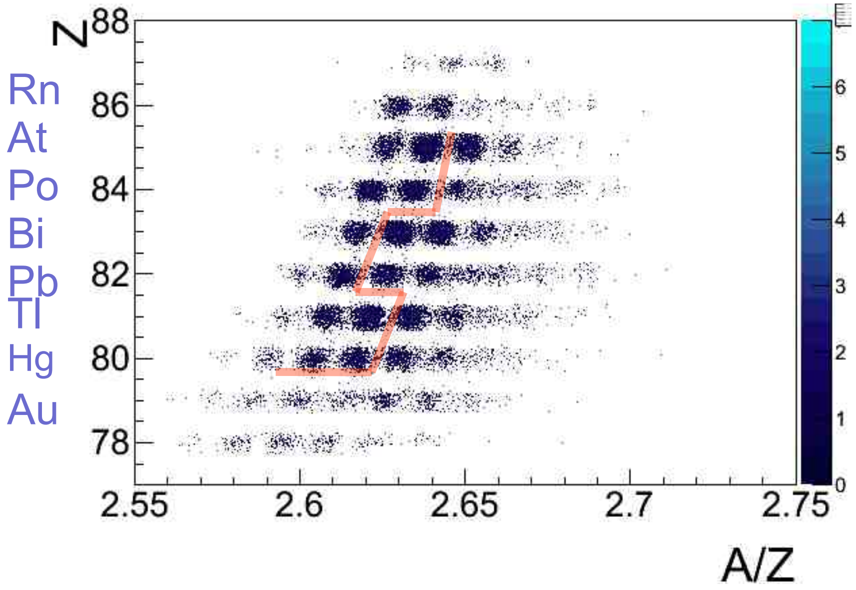
$$\ldots \ln\frac{A-1}{A+1}$$

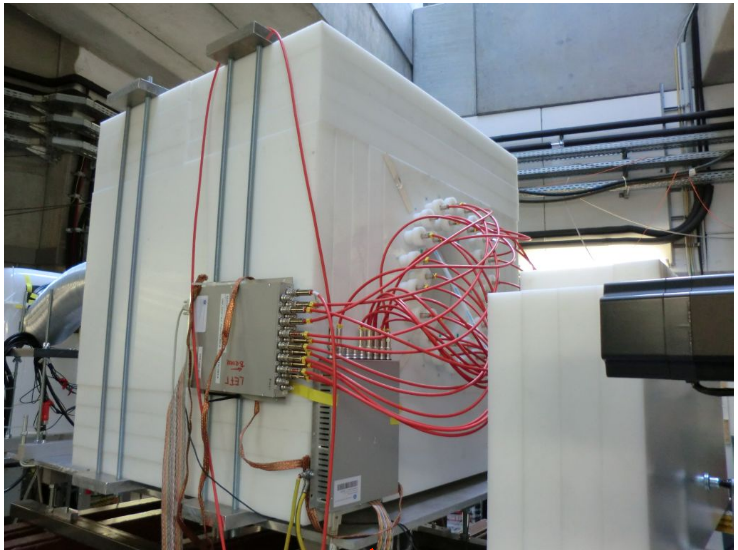
Number of collisions to reach an energy:

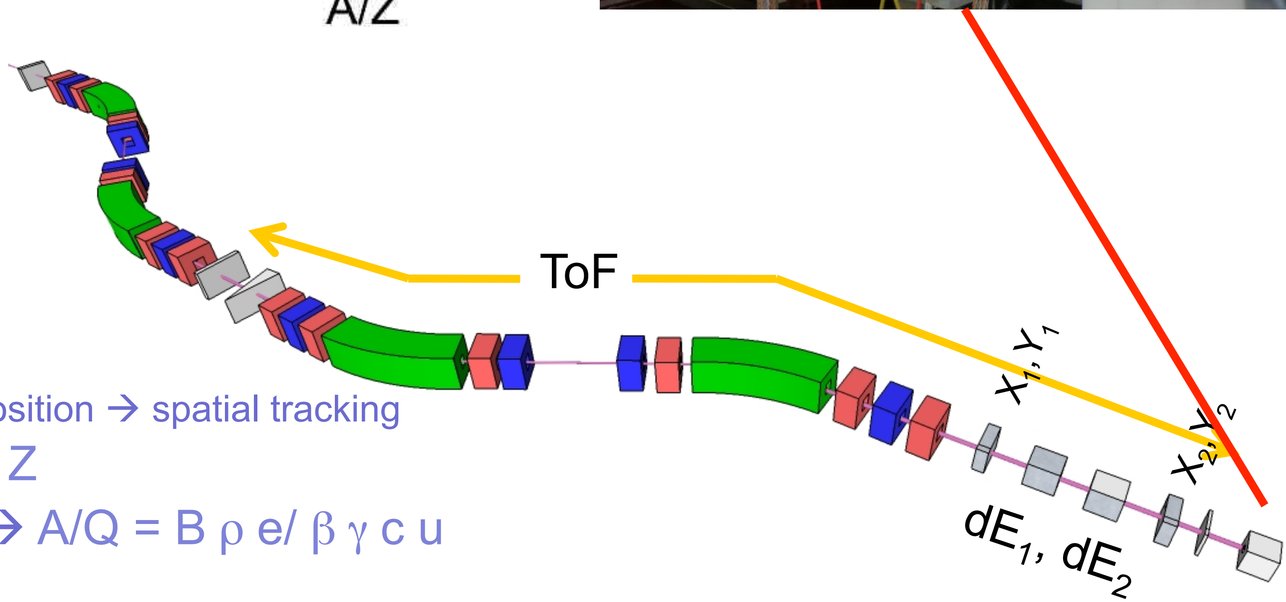
$$N = \frac{\ln E_0 / E_f}{\xi}$$

Slowing-down time: $t = \sqrt{\frac{K}{E_f}} - t_0 : \quad K(\xi, \sigma_{ela});\ t_0(E_0, \xi, \sigma_{ela})$

Nucleosynthesis around the 3rd r-process peak





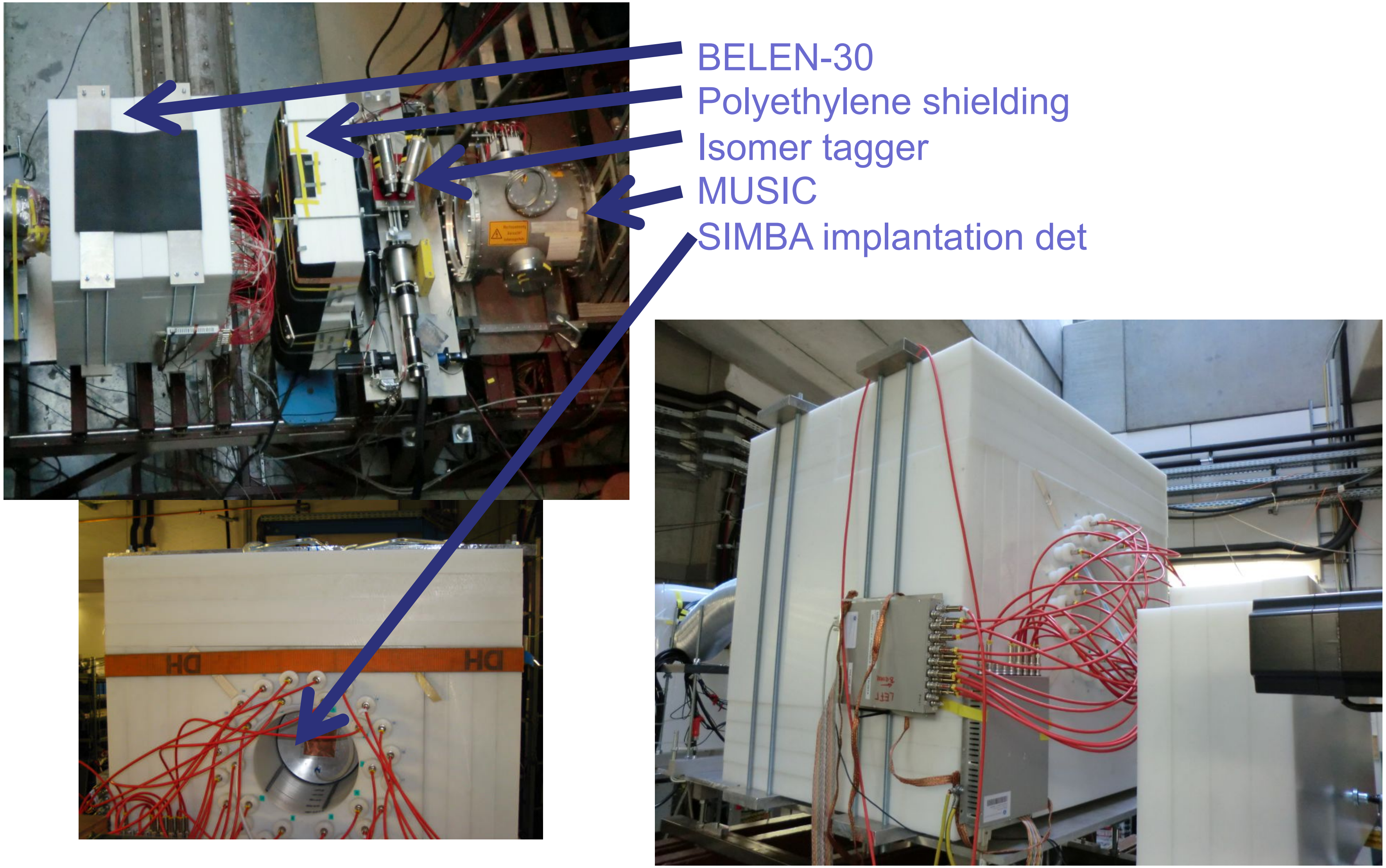


TPC21,22, 41, 42 x, y → position → spatial tracking

MUSIC41, 42 → dE
Sci21, Sci41 → ToF } → Z
Dipole Magnet → Bρ } → $A/Q = B\rho\, e / \beta \gamma c\, u$

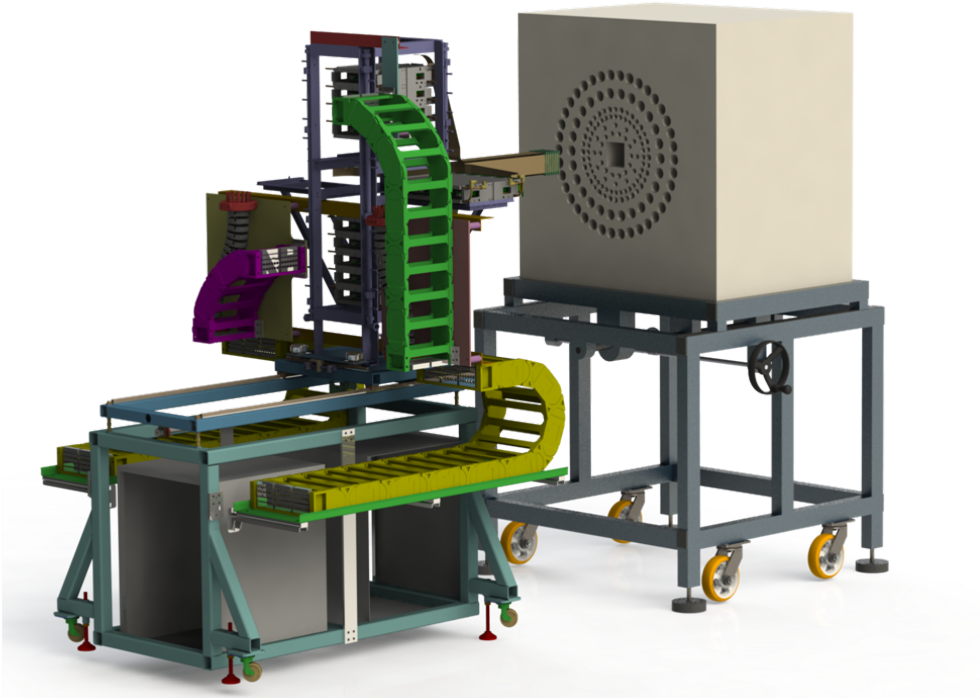
R. Caballero-Folch (PhD)

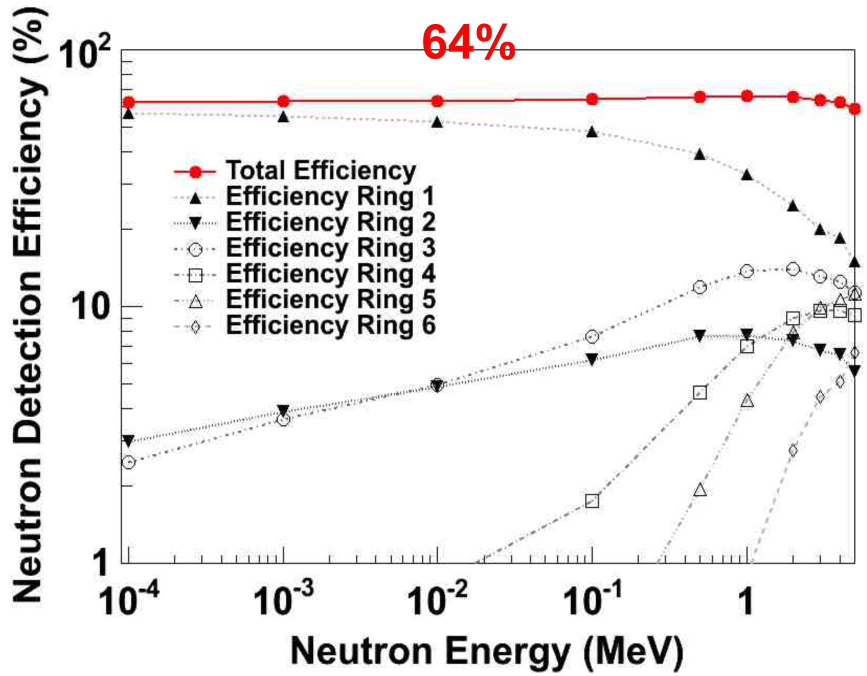
Nucleosynthesis around the 3rd r-process peak



BRIKEN

state-of-the-art in (high-efficiency) beta-n detection

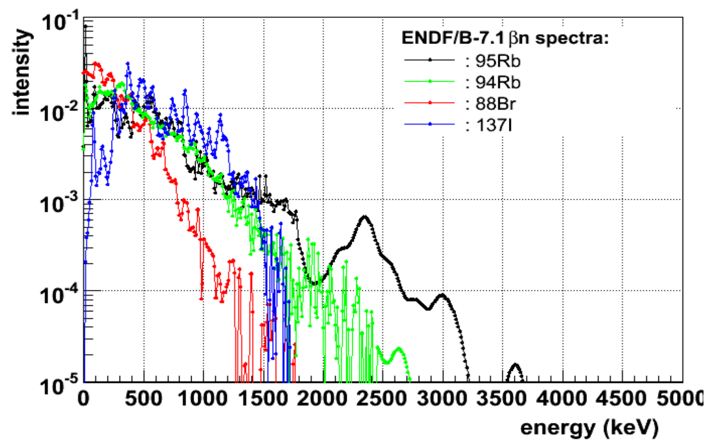




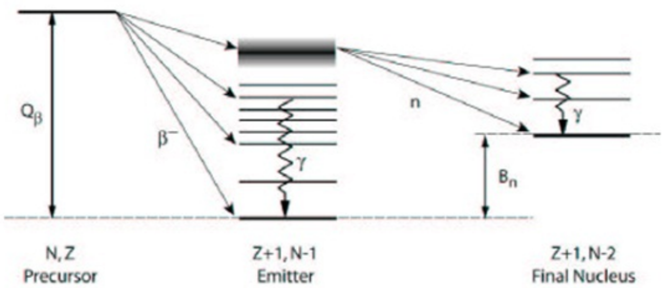
174 Tubos de ^{3}He

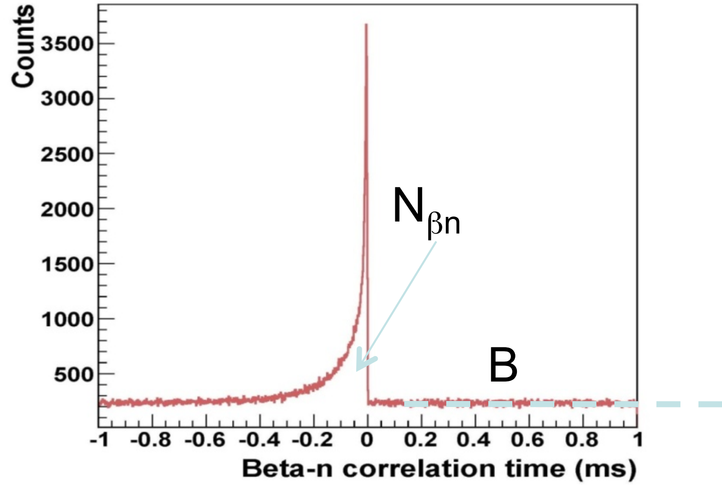
Ring	Radius (cm)	# ^{3}He Tubes	Pressure (atm)	Diameter (inch)	Institute
1	9.4	14	10	1	ORNL
2	13	12+12	5.13	1	RIKEN
3	16.8	10+26	10/8	1	GSI/UPC
4	20	18+18	5/8	1.18/1	JINR/UPC
5	27	26	10	2	ORNL
6	35	38	10	2	ORNL

Eficiencia constante para cualquier E_n

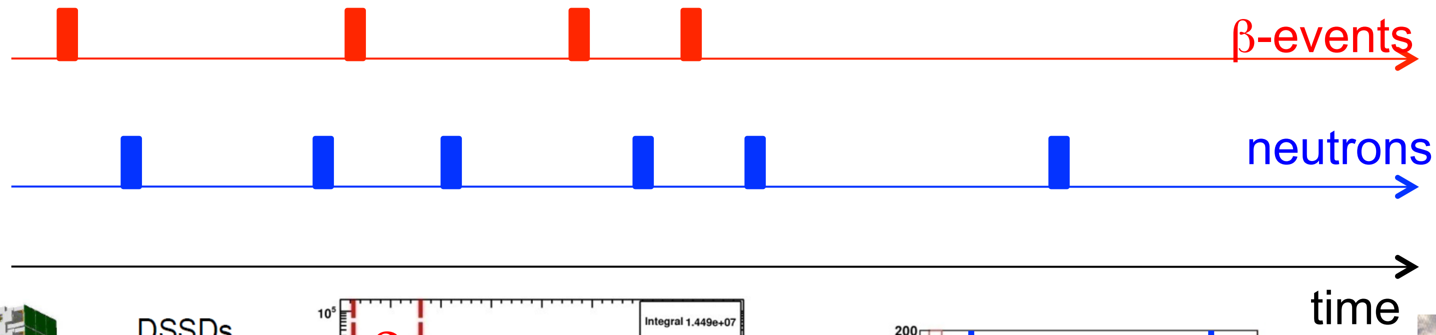


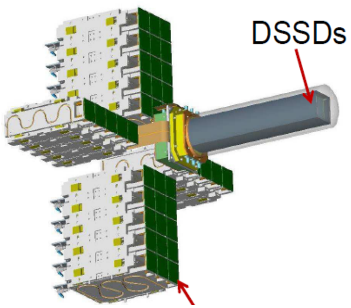
Determinación del P_n

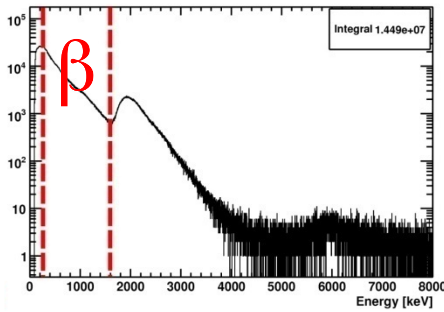


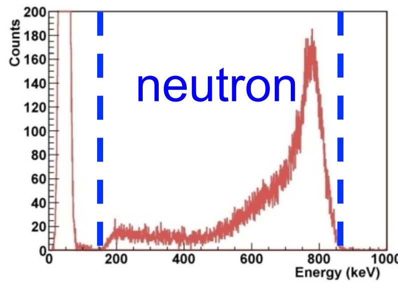


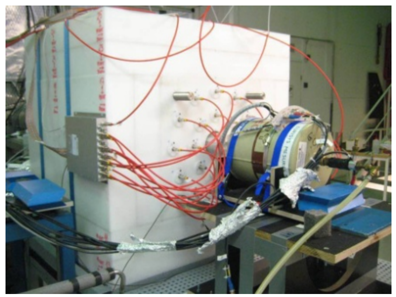
$$P_n = \frac{N_{\beta n} - B}{\varepsilon_n \cdot N_\beta}$$



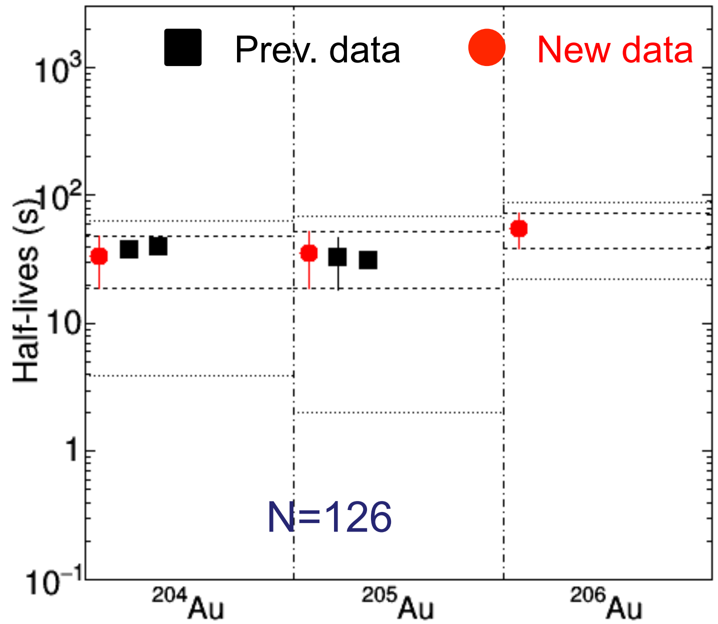


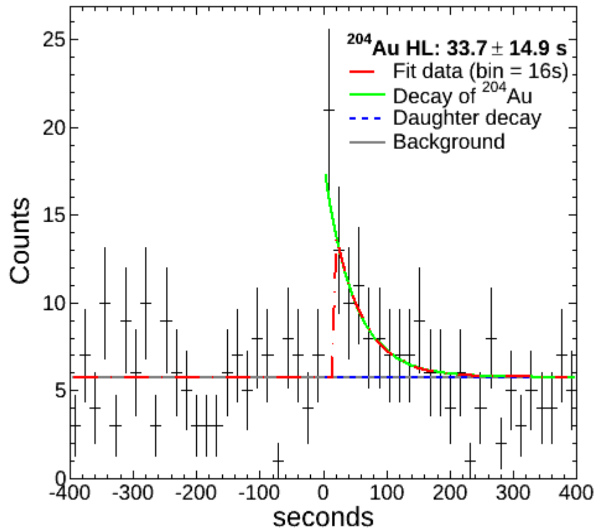






New half-life results beyond N = 126





Previous experimental data from

✓H.W. Taylor D.A. Craig. Journal of Physics, G10:1133, 1984. (^{204}Au)

✓ A.I. Morales, et al. Physical review letters, 113(2):022702, 2014. (^{204,205}Au)

✓ Ch. Wennemann, et al. Zeitschrift für Physik A Hadrons and Nuclei, 347(3):185–189, 1994. (^{205}Au)

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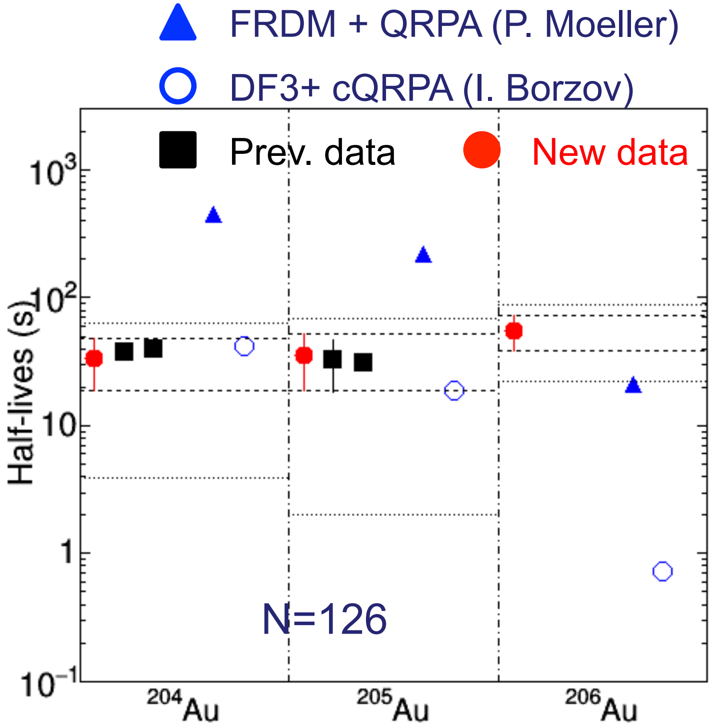

- Good agreement with DF3 (up to N=126), but…
- Very different trend beyond N=126, both DF3 & FRDM predicted $T_{1/2}$ drop not found experimentally!

→ The trend is not reproduced, extrapolability power (?)
→ Lower contribution of FF-transitions beyond N=126 (?)

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✓ A.I. Morales, et al. Physical review letters, 113(2):022702, 2014. (^{204,205}Au)
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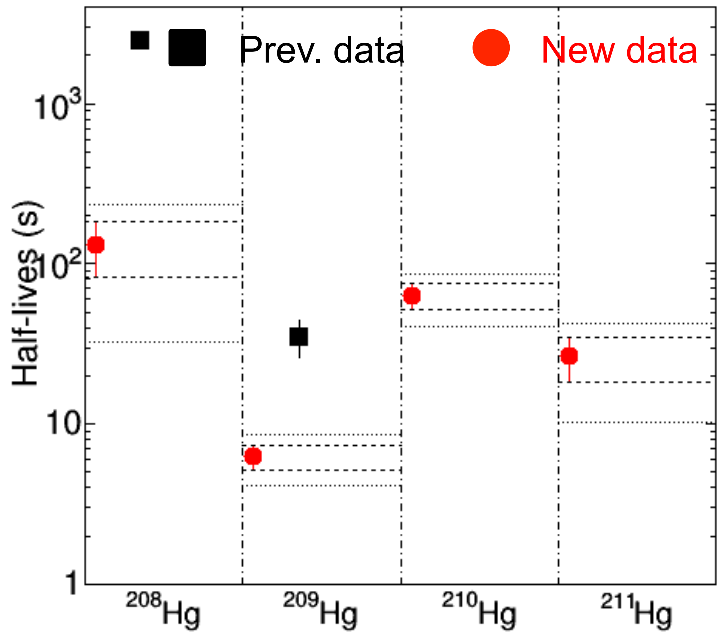

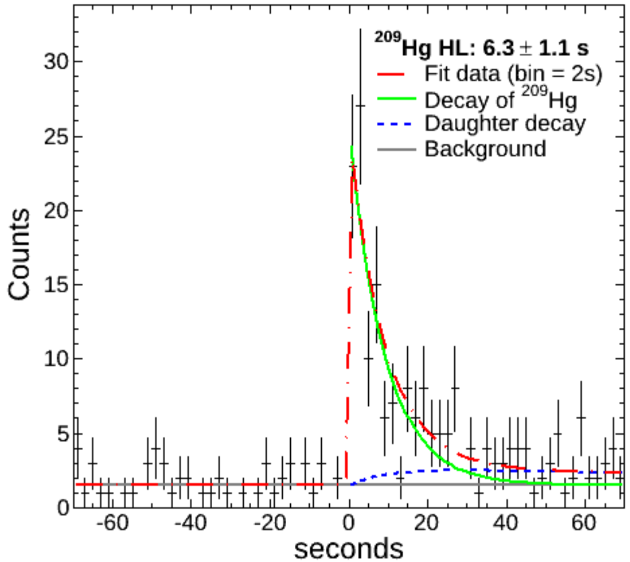

Previous experimental data from

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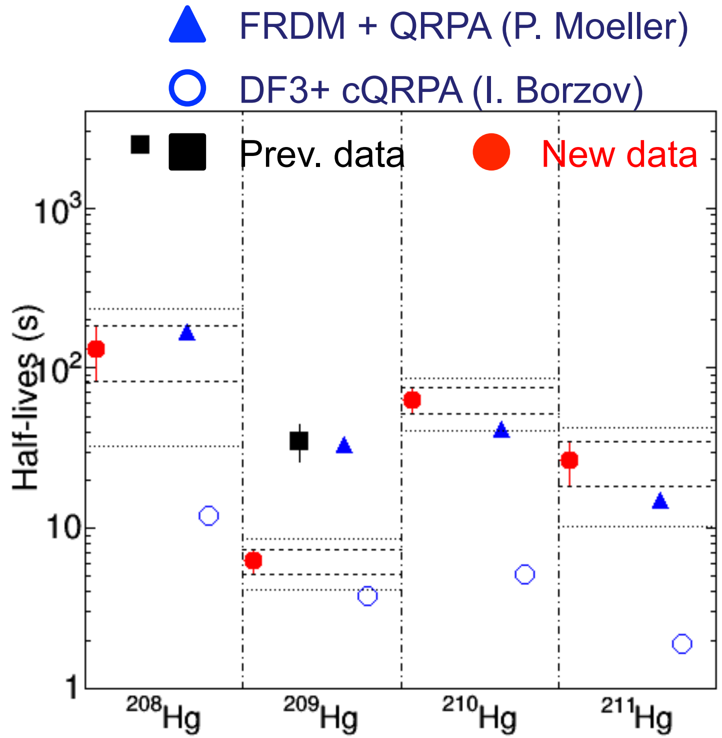
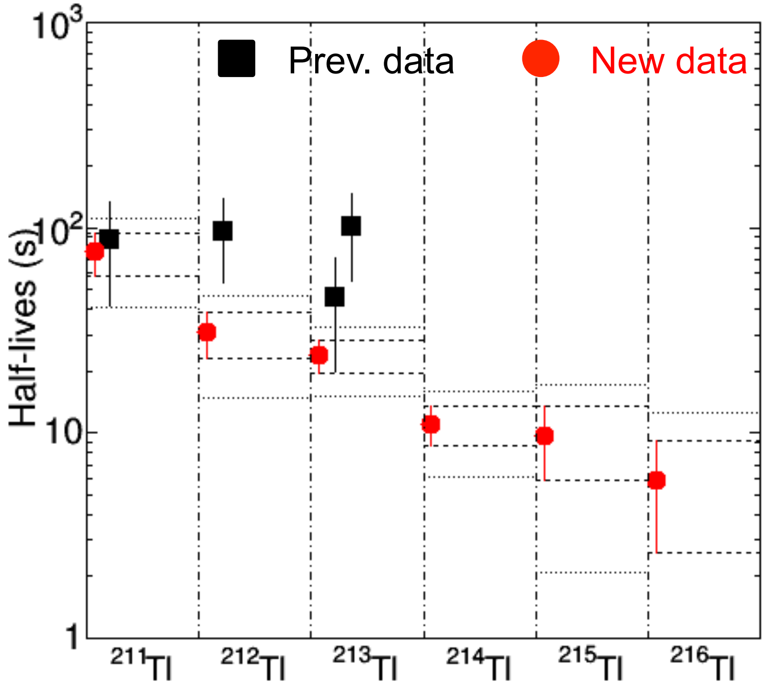


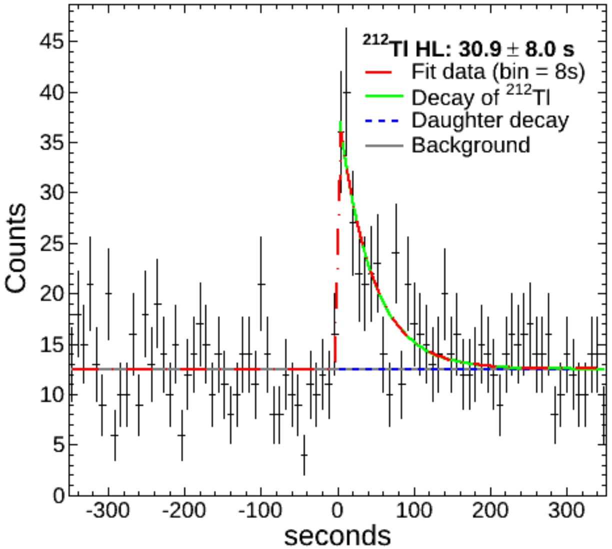
- Better (absolute) agreement with FRDM+QRPA
- Trend (odd/even) reproduced by both FRDM & DF3 (T1/2 enhancement after 209Hg)

Previous experimental data from

✓ Zhang Li, et al. Physical Review C, 58(1):156, 1998. (^{208,209}Hg)

New half-life results beyond N = 126

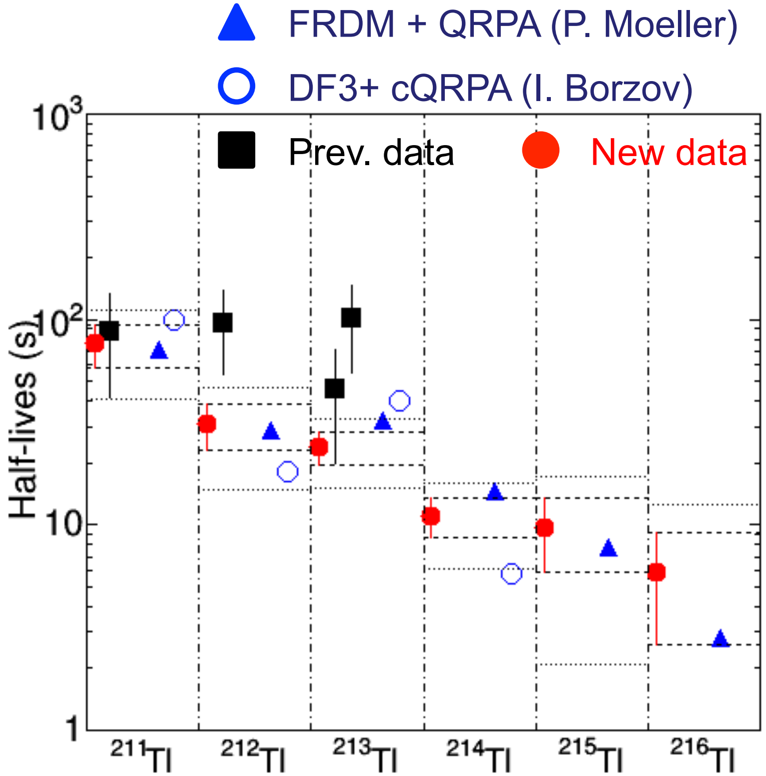




Previous experimental data from

- ✓ G. Benzoni, et al. Physics Letters B, 715(4):293–297, 2012. ($^{211-213}$Tl) A.I. Morales, et al., Phys. Rev. C, 89, 2014 ($^{211-213}$Tl)
- ✓ Lixin Chen, et al. Physics Letters B, 691(5):234–237, 2010. (^{213}Tl)

New half-life results beyond N = 126



- Astonishing agreement with FRDM !
- Good agreement with models, GT and FF realistically implemented for these nuclei

Previous experimental data from

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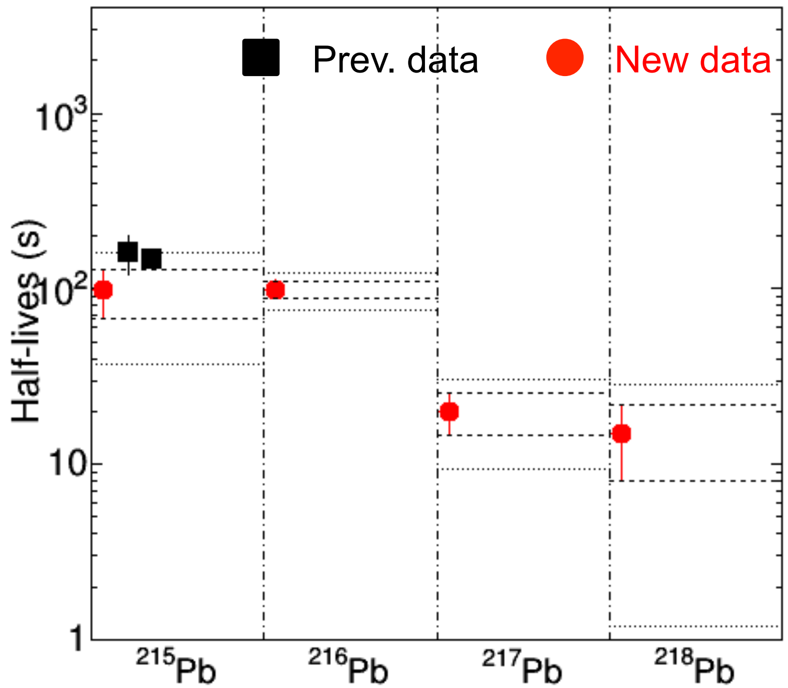

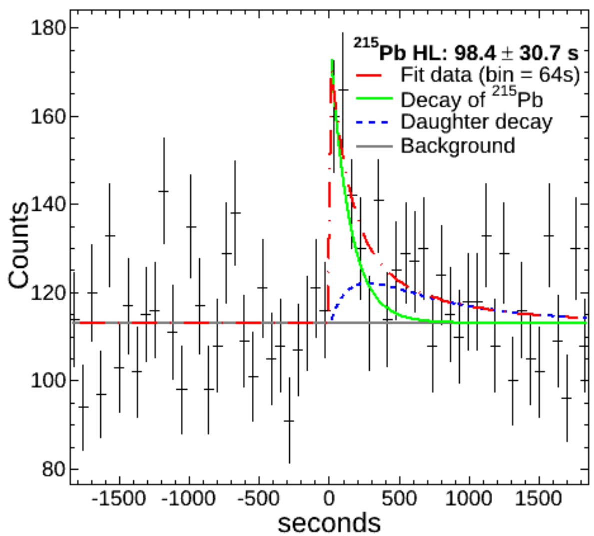

Previous experimental data from

- ✓ A.I. Morales, et al. Physical Review C, 89(1):014324, 2014. (^{215}Pb)
- ✓H. Sagawa, et al. Nuclear Physics A, 474(1):155–172, 1987. (^{215}Pb), H. de Witte, Phys. Rev. C, 87 (2013)

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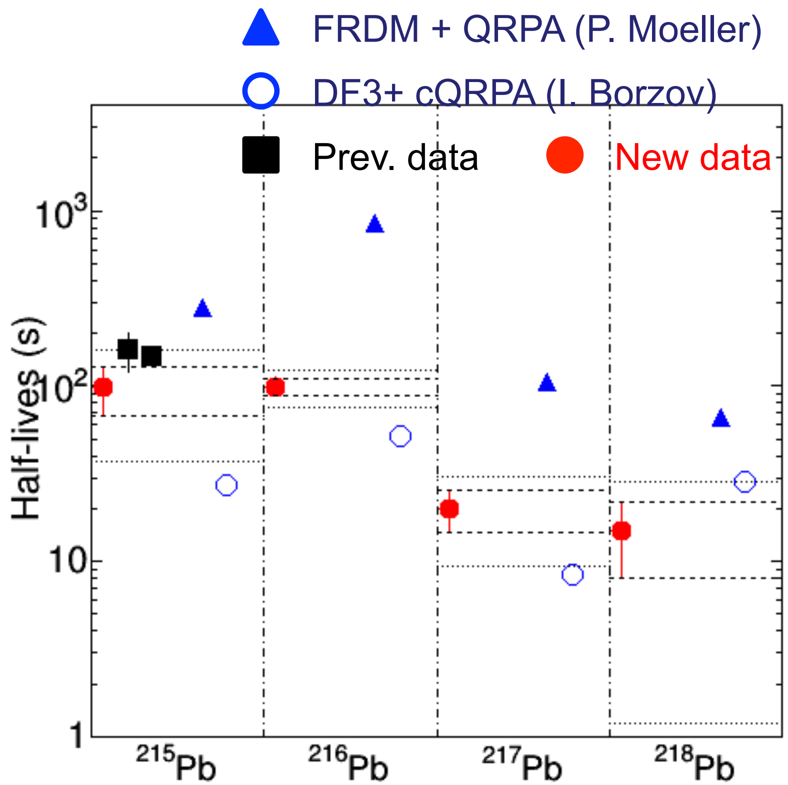

- Reasonable agreement with DF3+cQRPA
- As for the Au-isotopes, in the shell-closures (N=126) and here for (Z=82), DF3 seems to perform better, whereas in the region in between FRDM performs quite well.

Previous experimental data from

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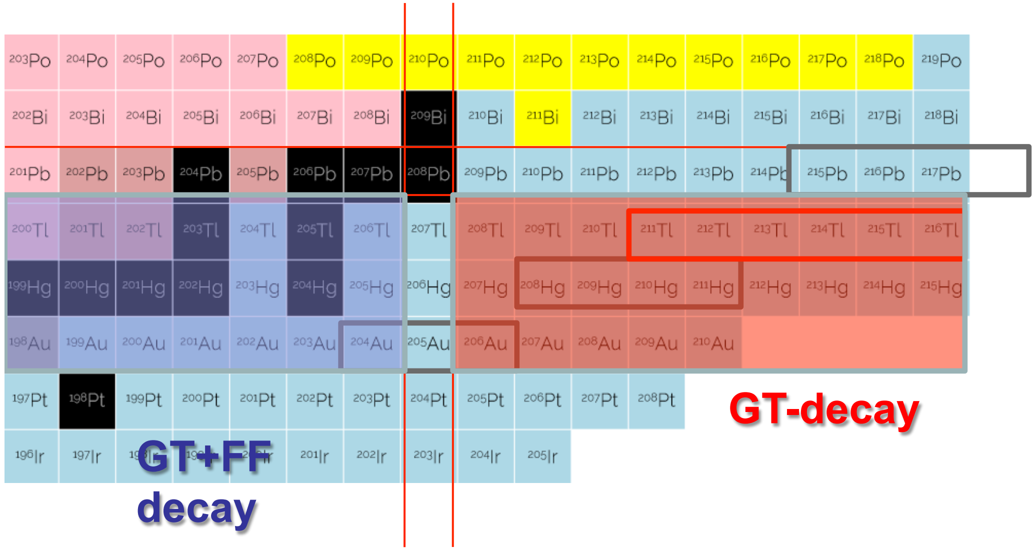
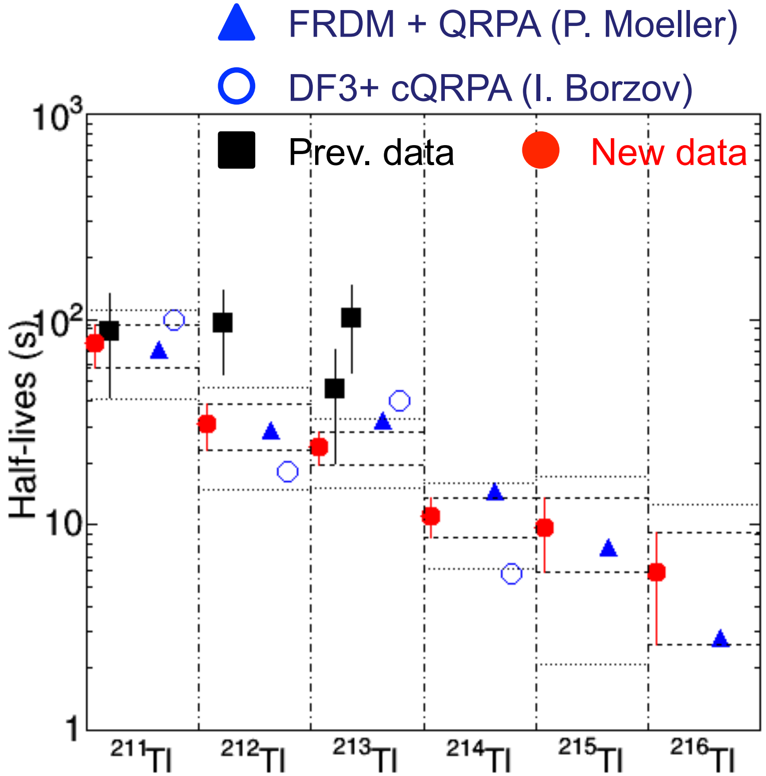
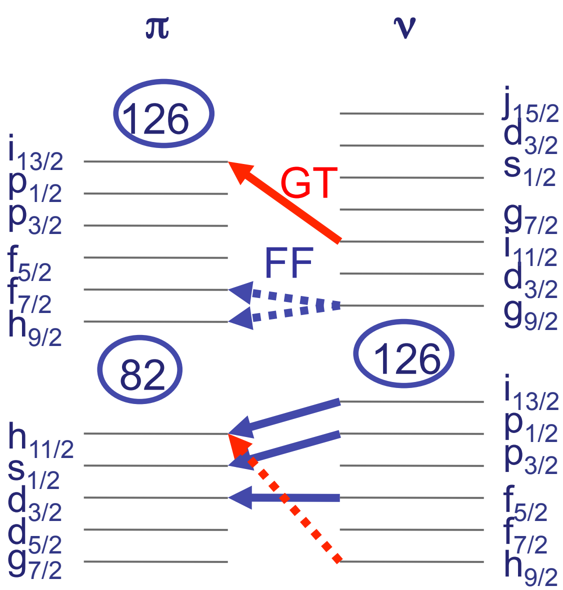
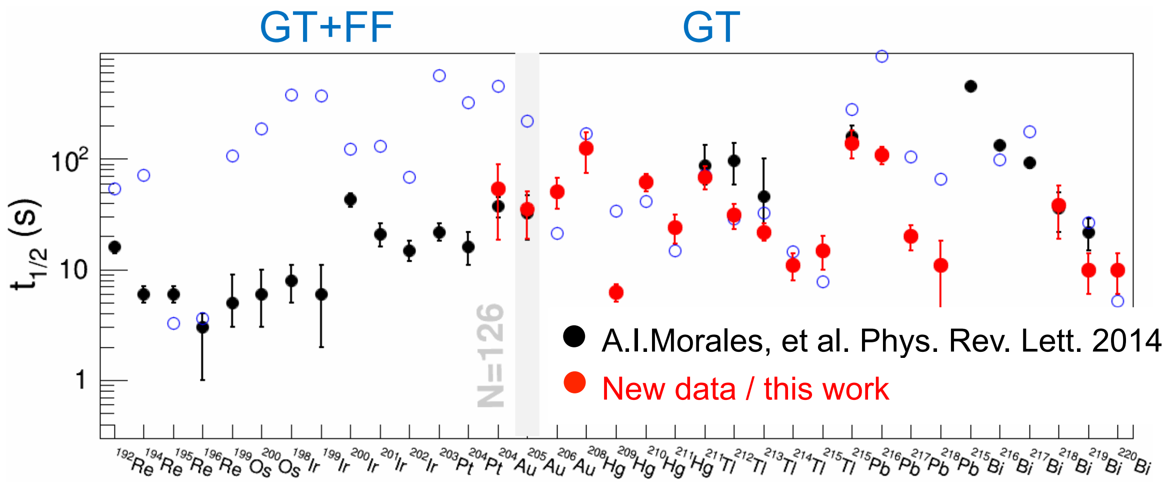
✓H. Sagawa, et al. Nuclear Physics A, 474(1):155–172, 1987. (^{215}Pb), H. de Witte, Phys. Rev. C, 87 (2013)

Half-lives beyond N=126 and nuclear structure

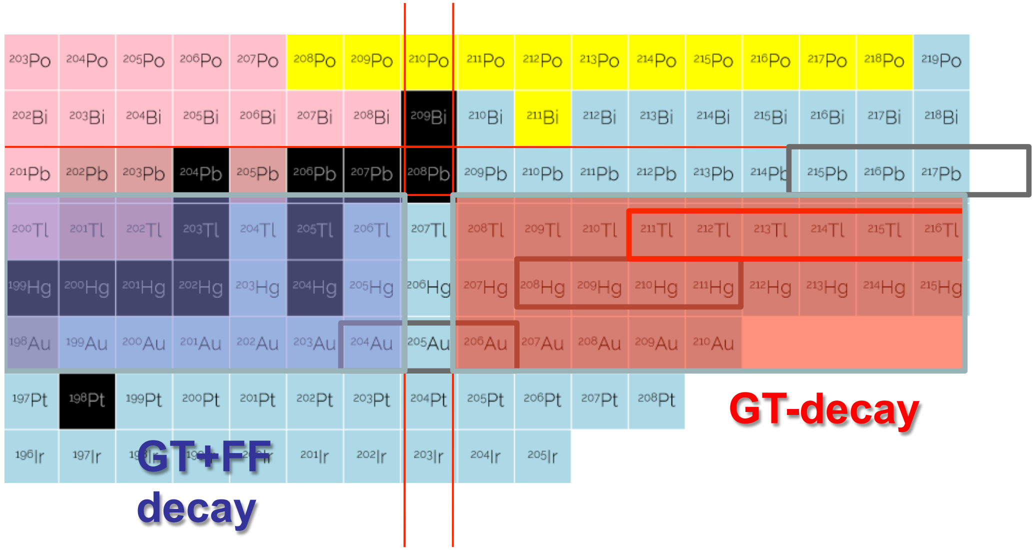


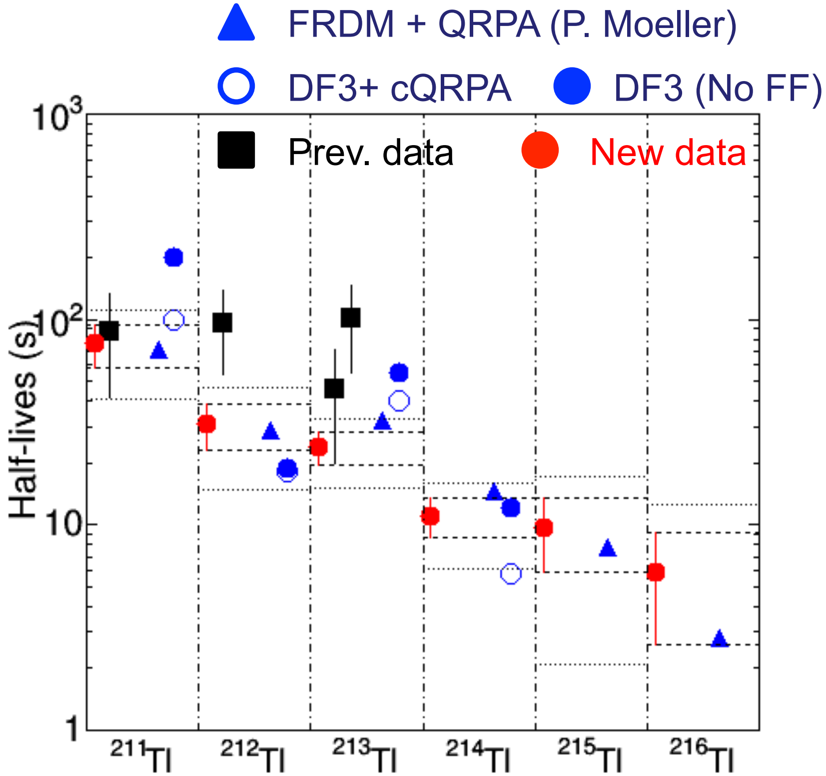


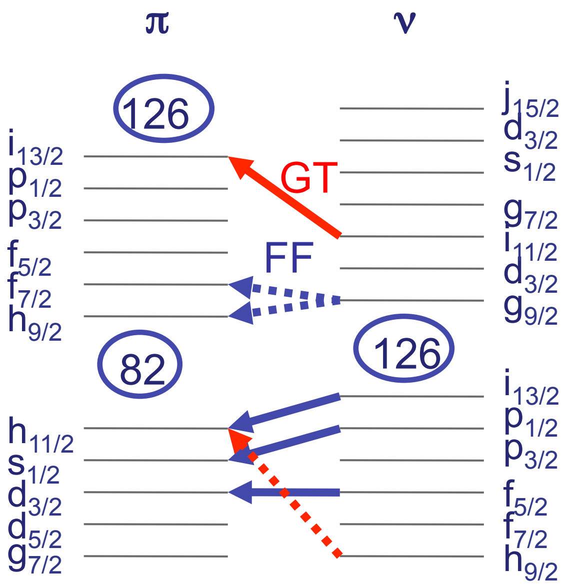


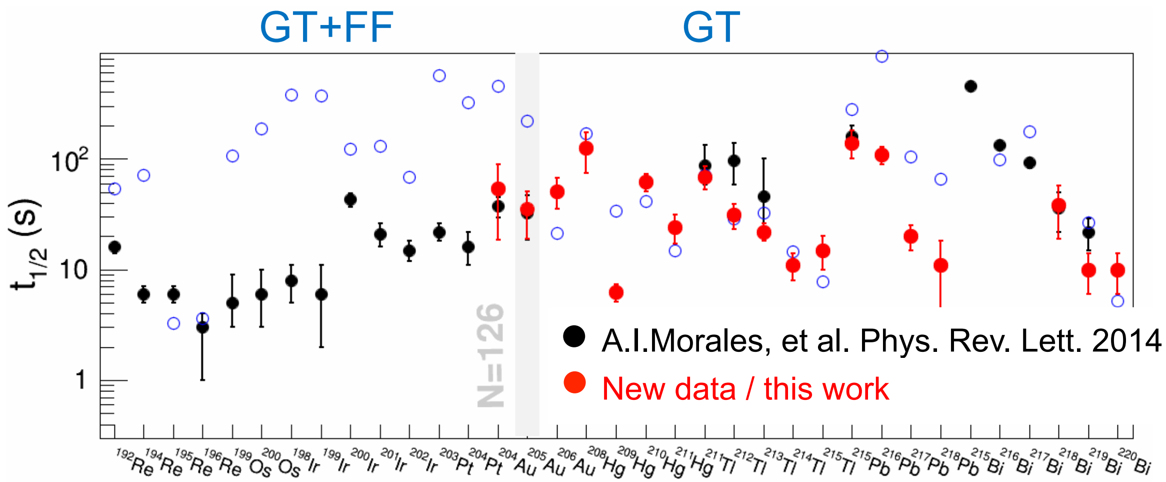


Half-lives beyond N=126 and nuclear structure

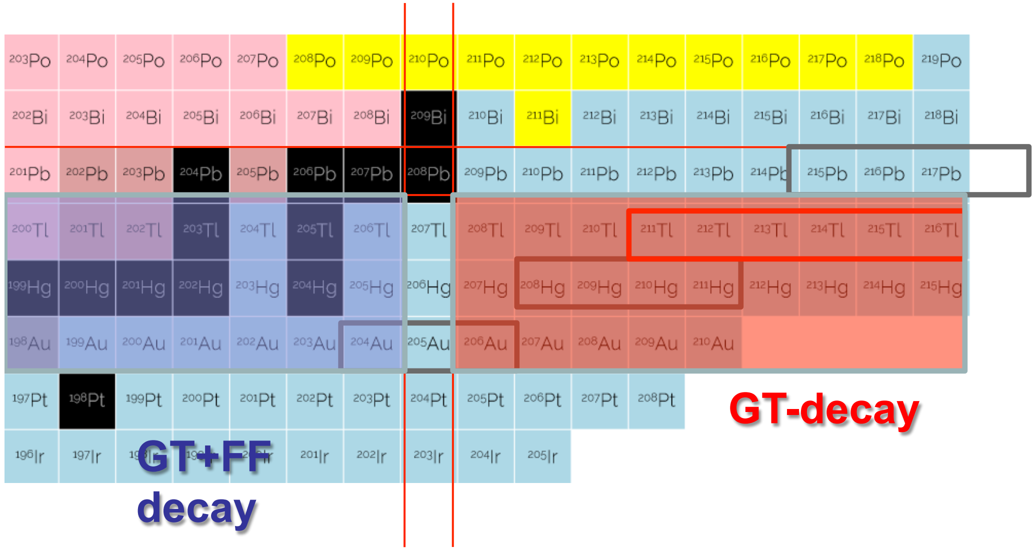


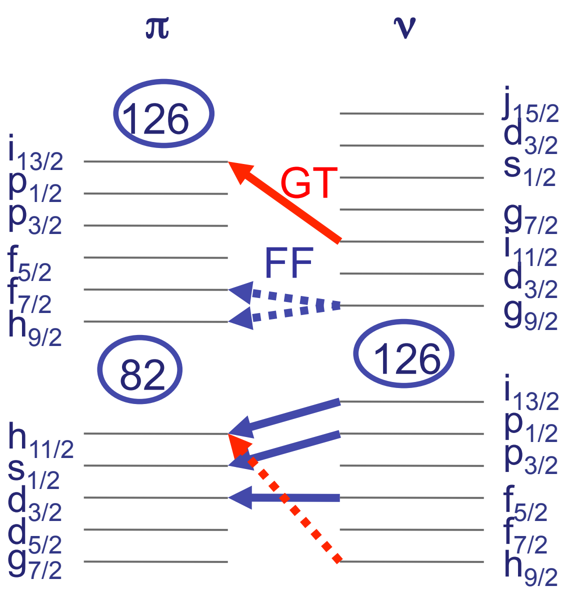


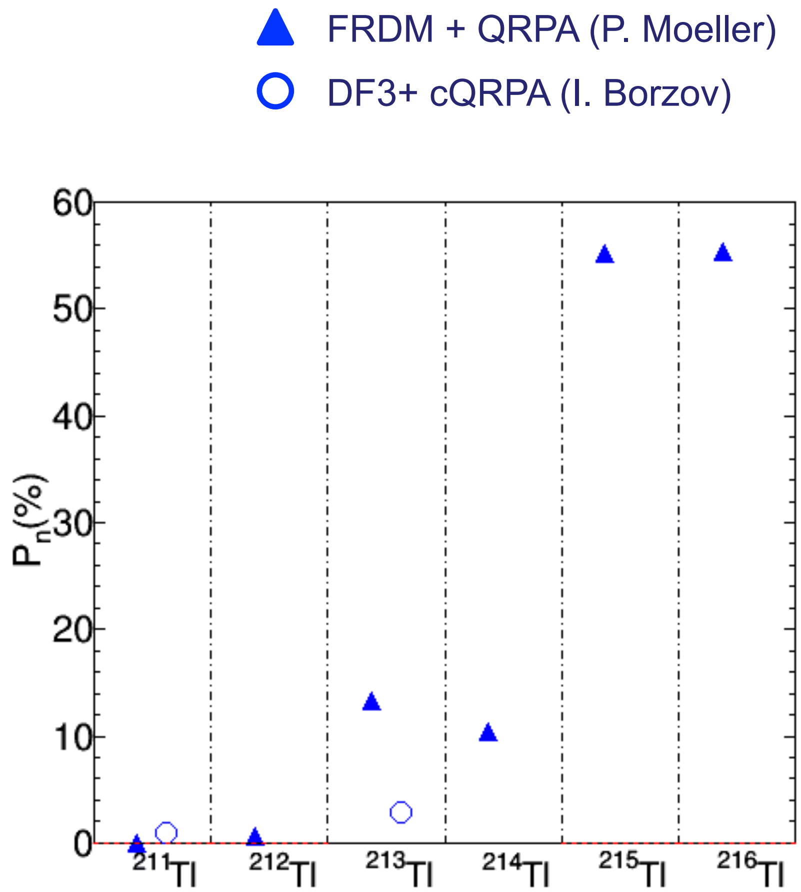




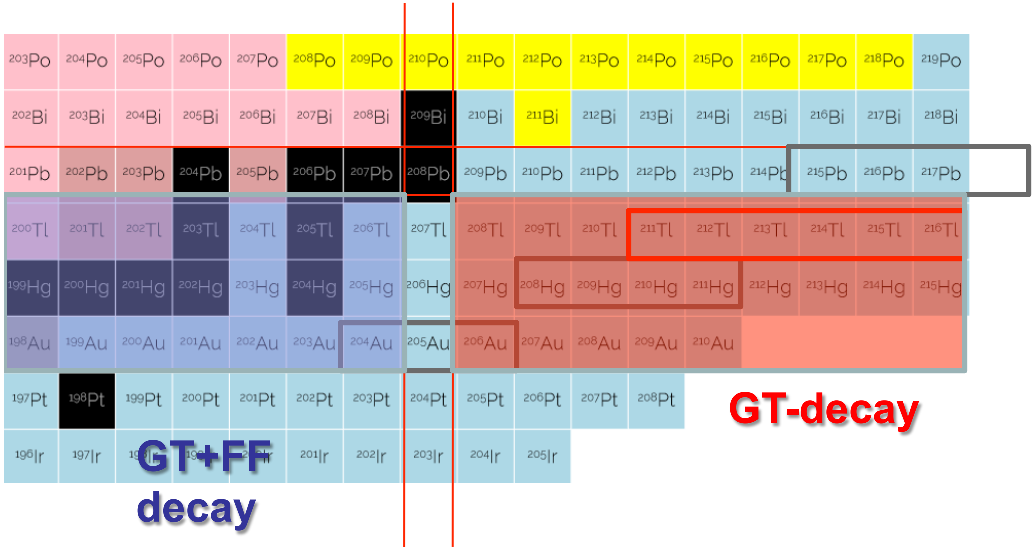
Neutron branchings beyond N=126 and nuclear structure

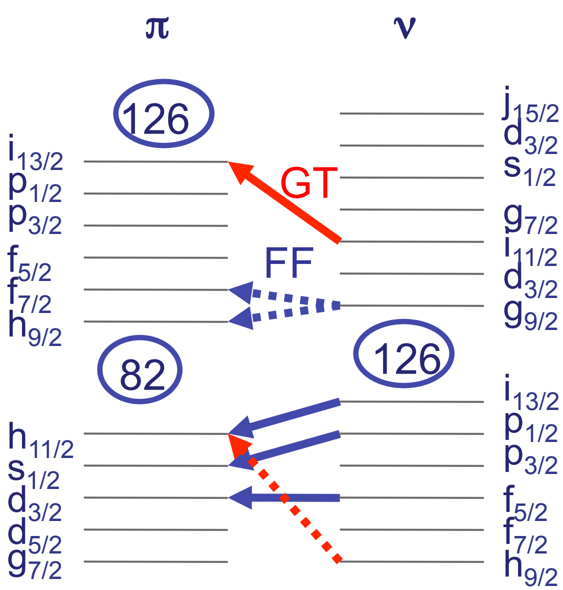


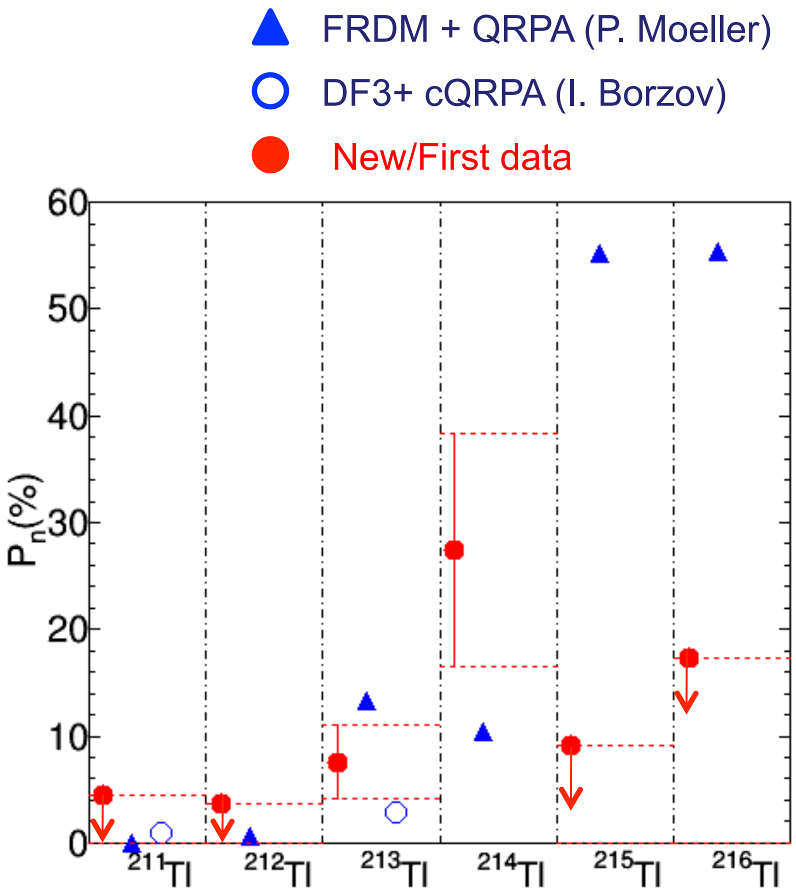




Neutron branchings beyond N=126 and nuclear structure

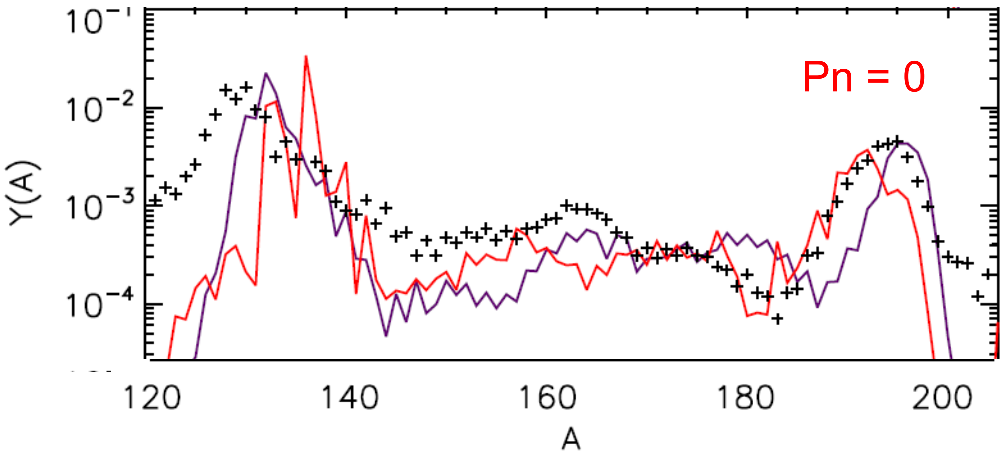






→Large discrepancy for ^{215}Tl and ^{216}Tl
→ If HE-FF transitions would dominate (215,216), this should be also reflected in the half-lives, which show an excellent agreement with theory (FRDM+QRPA).
→ Change in the nuclear structure beyond 215Tl? (not predicted by models).

Impact of Pn-values around N=126 in r-process



→ Nuclear physics (Pn) uncertainties, still very large for conclusive r-process calculations around the third r-process peak.
→Need more measurements to guide models!

Proc. Conf. Advances in Radioactive Isotope Science (ARIS2014)
JPS Conf. Proc. **6**, 010010 (2015)
http://dx.doi.org/10.7566/JPSCP.6.010010

The Sensitivity of *r*-Process Nucleosynthesis to Individual *β*-Delayed Neutron Emission Probabilities

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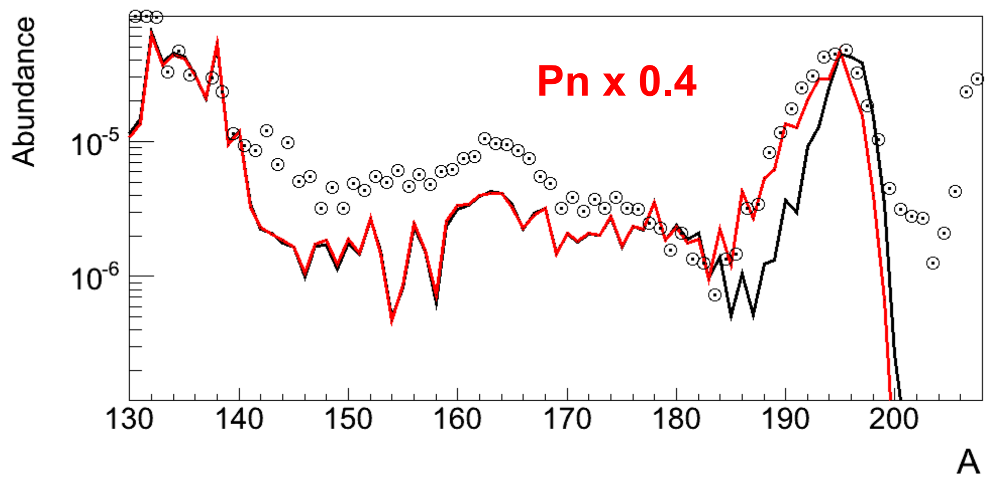


MEDIDAS DE EMISIÓN DE NEUTRONES EN JYFL:

- Aplicación al diseño de reactores nucleares seguros y estables
- Ejemplo de medidas en una instalación tipo ISOL con haces puros

Producción de energía por fisión nuclear

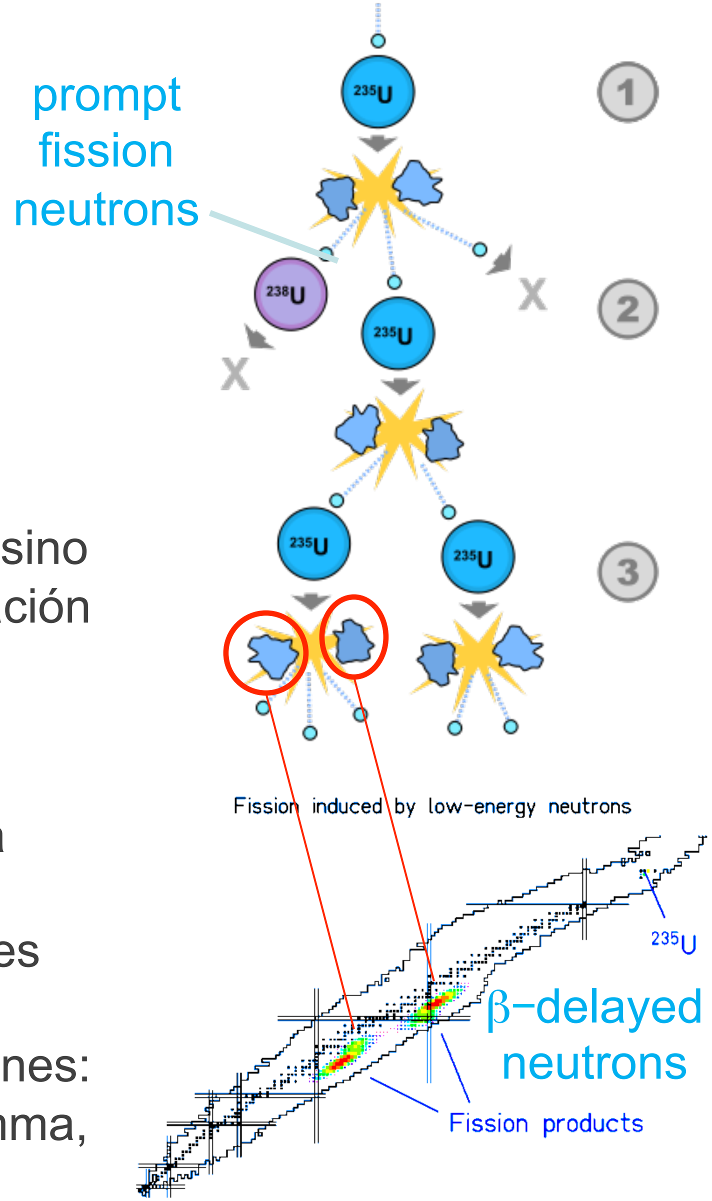
En un reactor nuclear, el objetivo es producir calor (energía) por medio de una reacción en cadena auto-sostenida (k = 1, sistema crítico).

[k := factor efectivo de multiplicación neutrónica]

En este sentido el equilibrio o balance de neutrones es muy importante. Un cálculo preciso del balance de neutrones debe incluir, no solo los neutrones "prompt" emitidos en cada fisión (2-3) sino también los neutrones provenientes de la desintegración beta de los productos de fisión (NR) (0.6% del total).

Son necesarias librerías "precisas" de:

- Secciones eficaces de reacciones: fisión, captura neutrónica, dispersión elástica, etc
- Productos residuales producidos en las reacciones de fisión, "minor actinides".
- Partículas secundarias producidas en las reacciones: numero de neutrones "prompt" por fisión, radiación gamma, emisión retardada de neutrones y rayos gamma.

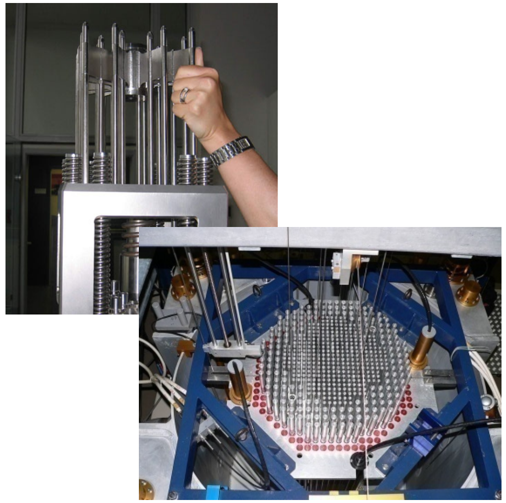


Producción de energía por fisión nuclear

En un reactor, los NR tienen el efecto de prolongar la vida media efectiva de los neutrones libres (τ) de 1 ms (prompt fission n) a unos 100 ms (fission+βn).

Ejemplo para ilustrar la relevancia de los NR en el control de un reactor nuclear:
N:= Numero de neutrones libres en un reactor

τ := vida media efectiva promedio de un neutrón libre
La evolución del balance de neutrones en un reactor viene descrita por la siguiente ecuación diferencial:



$$dN/dt = \alpha\, N/\tau$$

α:= constante de proporcionalidad:
- $\alpha > 0$ → Supercrítico: tasa de aumento de n aumenta exponencialmente
- $\alpha = 0$ → Crítico: equilibrio, numero de neutrones libres permanece constante.
- $\alpha < 0$ → Subcrítico: número de neutrones decae exponencialmente

Imaginemos un sistema (reactor nuclear) en el que $\alpha = 0 \rightarrow \alpha = 0.01$.

1) Asumiendo que no existen los NR: τ := 1 ms (neutrones de fisión)
En 1 s la variación de potencia en el reactor sería:

$$\Delta P = (1 + \alpha)^{1/\tau} = (1 + 0.01)^{1000} = 2.09\text{x}10^4, \text{ cuatro o.d.m.!!!}$$

2) Incluyendo los NR: τ := 100 ms (dominada por los NR)
En 1 s la variación de potencia en el reactor sería:

$$\Delta P = (1 + \alpha)^{1/\tau} = (1 + 0.01)^{10} = 1.1046, \text{ es decir, solo un 10\%.}$$

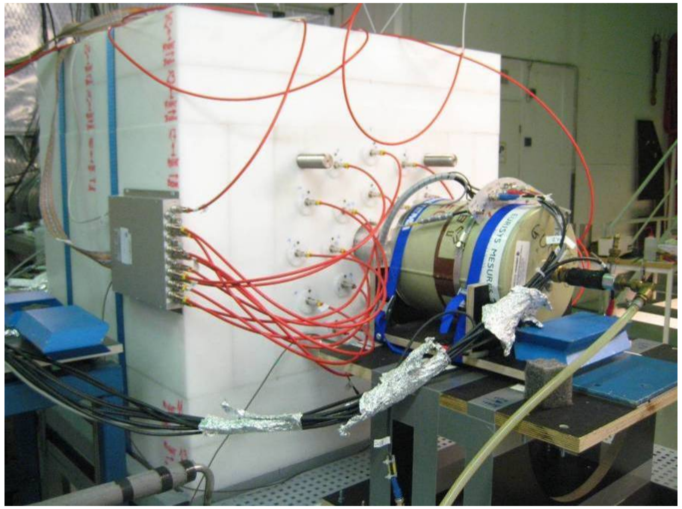
Producción de energía por fisión nuclear

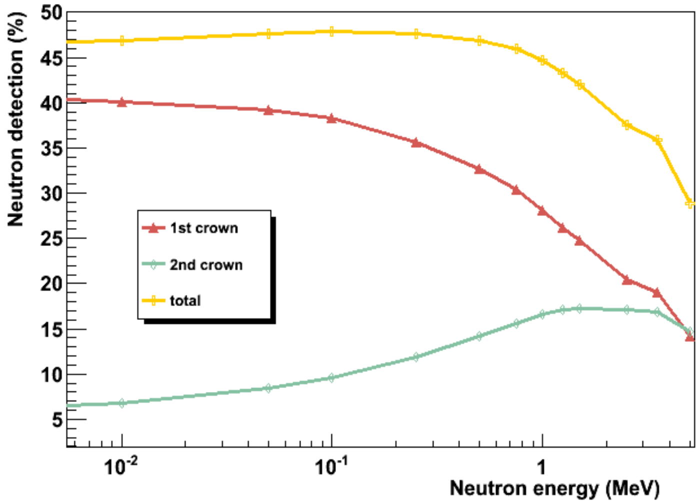
La mayoría de reactores nucleares se operan en modo *prompt subcritical*, *delayed critical,* es decir, los neutrones prompt de la fisión no son suficientes para sostener una reacción en cadena. Mediante los neutrones retardados se llega a la condición de criticalidad.

Cuando una pequeña porcion de “barra de control” se inserta en el núcleo del reactor, al principio la potencia cambia muy rápido (por los neutrones de fisión), y posteriormente más gradualmente (exponencialmente) debido a los neutrones retardados.

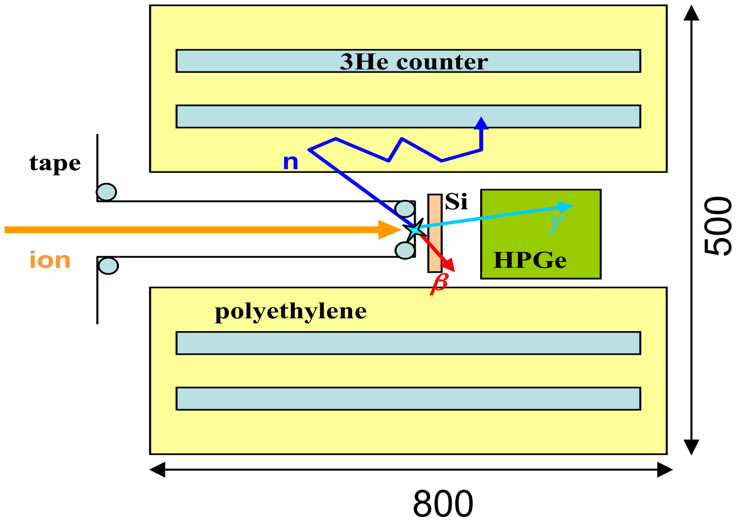
Conclusión:
Sin los neutrones retardados, las centrales nucleares tal y como están concebidas actualmente, serían inoperables.

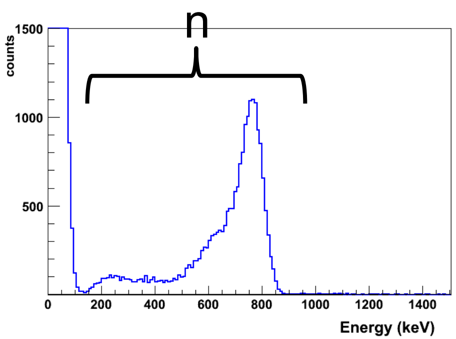
Contadores 4π: BELEN @ JYFL, GSI, FAIR

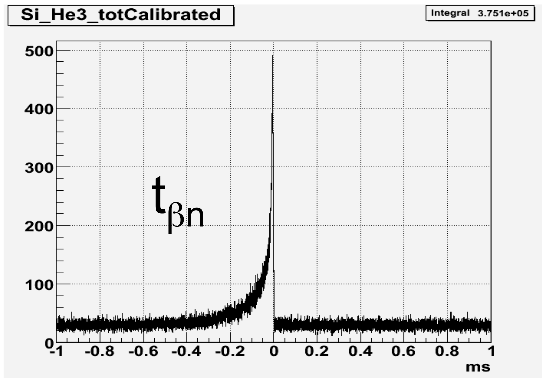




20 ∅2.5cm×60cm 3He tubes @20atm







B-delayed neutrons in the fission fragments region at JYFL

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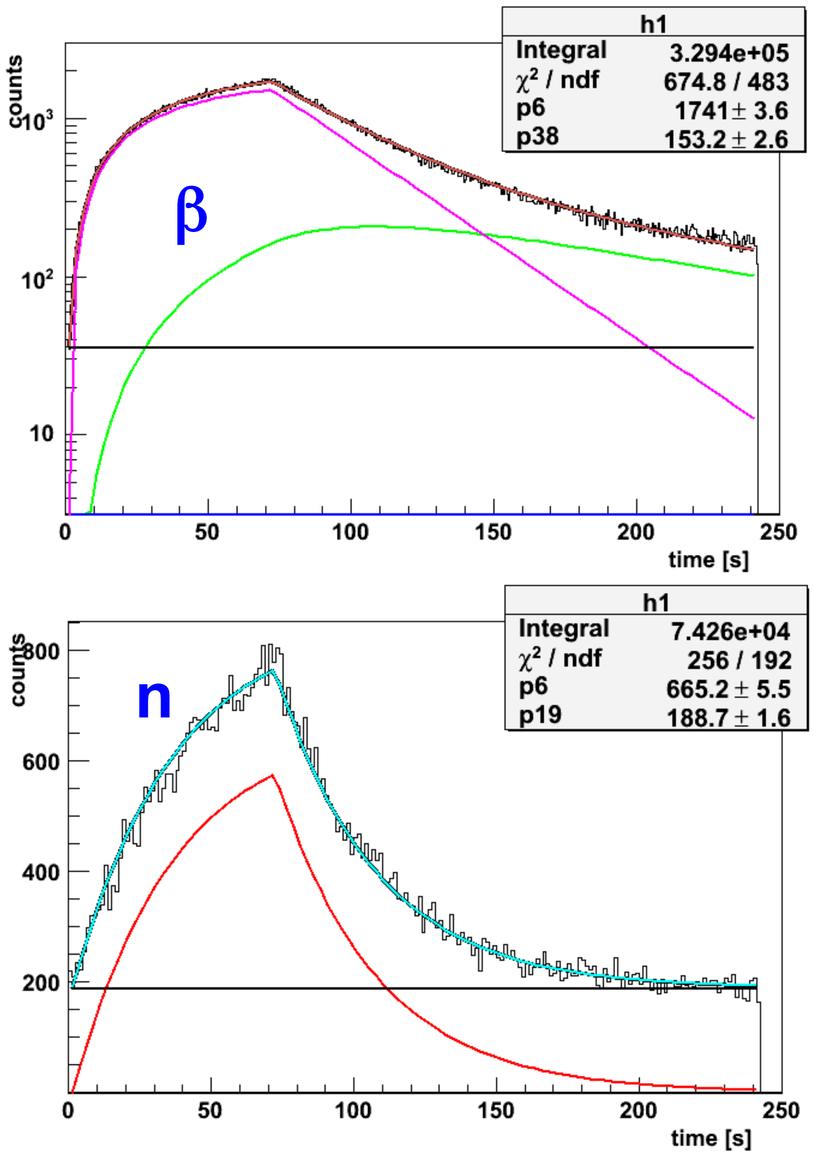
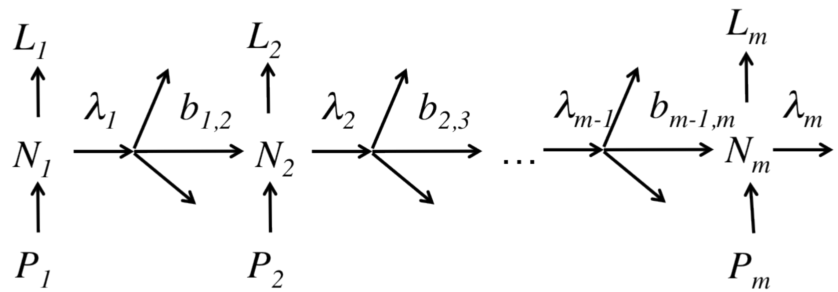
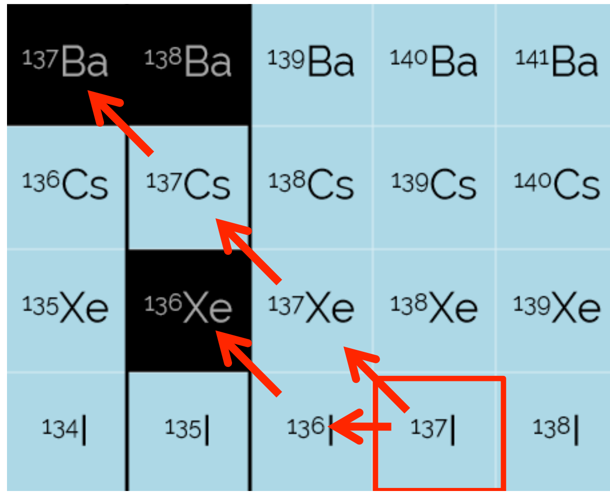


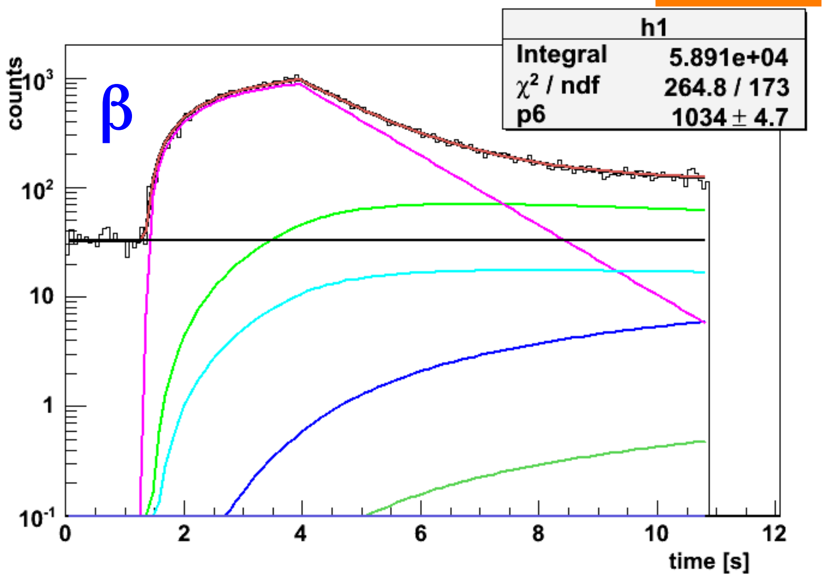
- Disentangle contributions fitting with solution of Bateman equations
- All parameters fixed except production

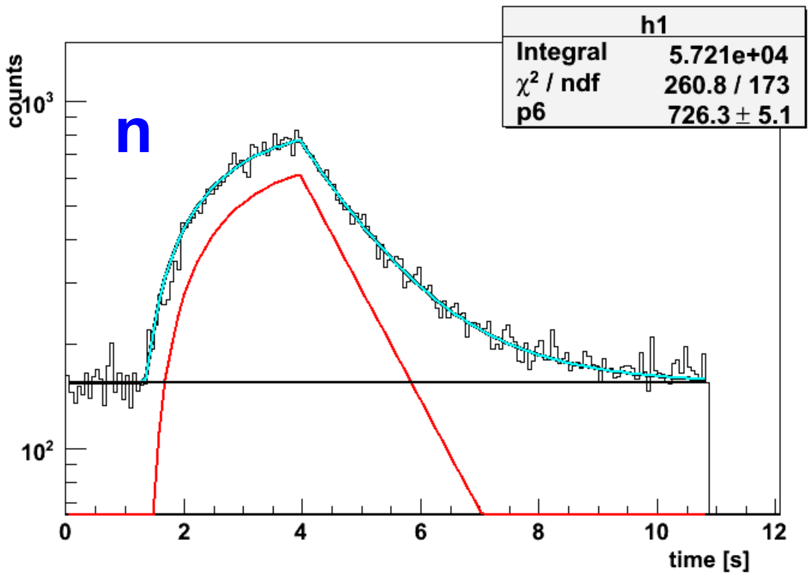


$$P_n = \frac{\varepsilon_\beta}{\varepsilon_n}\frac{N_n}{N_\beta} = 7.75(12)\%$$

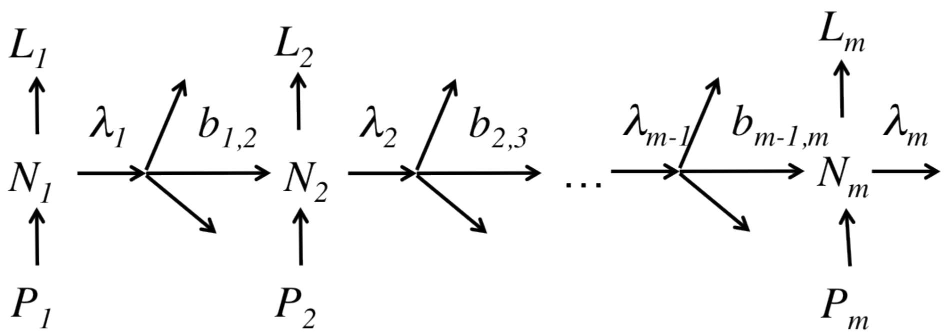


^{86}As





$P_n = 35.5(6)\%$



$$\frac{dN_1}{dt} = P_1 - (\lambda_1 + L_1) N_1$$

$$\frac{dN_2}{dt} = P_2 + \lambda_1 b_{1,2} N_1 - (\lambda_2 + L_2) N_2$$

...

$$\frac{dN_m}{dt} = P_m + \lambda_{m-1} b_{m-1,m} N_{m-1} - (\lambda_m + L_m) N_m$$

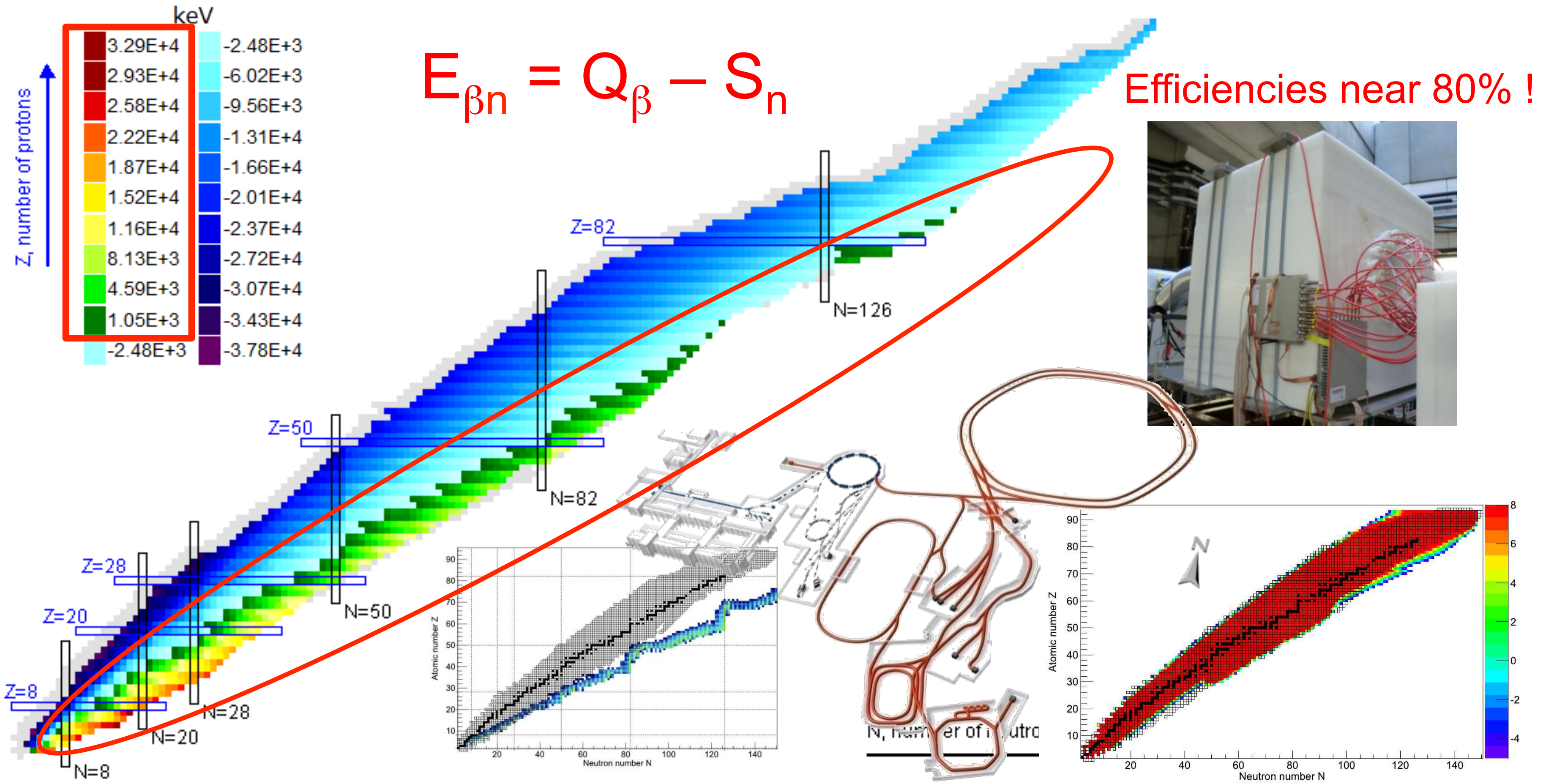
$$A_m^\beta(t) = \varepsilon_\beta \lambda_m N_m(t)$$

$$A_m^n(t) = \varepsilon_n P_n \lambda_m N_m(t)$$

$$N_m(t) = \sum_{i=1}^{m} \left[\left(\prod_{j=i}^{m-1} \lambda_j b_{j,j+1} \right) \times \sum_{j=i}^{m} \left(\frac{N_i^0 e^{-\tilde{\lambda}_j t}}{\prod_{k=i,k\neq j}^{n} (\tilde{\lambda}_k - \tilde{\lambda}_j)} + \frac{P_i (1 - e^{-\tilde{\lambda}_j t})}{\tilde{\lambda}_j \prod_{k=i,k\neq j}^{n} (\tilde{\lambda}_k - \tilde{\lambda}_j)} \right) \right]$$

Perspectiva:

- **La mayoría de los núcleos que quedan por descubrir son emisores de neutrones!**
- Hemos desarrollado detectores con eficiencias próximas al 70-80% (por desgracia no podremos pasar del 100% de eficiencia;-)).
- El siguiente paso es desarrollar nuevas instalaciones de RIB que permitan alejarnos más del valle de estabilidad beta: FAIR, SPIRAL2, FRIB, RIKEN, etc.



$$E_{\beta n} = Q_{\beta} - S_n$$

Resumen

• El proceso de emisión de neutrones retardados, es un efecto que puede tener lugar siempre que esté energéticamente permitido, es decir, cuando $Q_{\beta} - S_n > 0$.

• En los casos en los que es energéticamente factible, la probabilidad emisión retardada de neutrones depende de la distribución energética del β-decay, y por lo tanto representa una herramienta muy útil para obtener información sobre la estructura y la desintegración nuclear, en los casos más exóticos donde las tasas de producción son generalmente débiles.

• La emisión retardada de neutrones juega un papel fundamental tanto en aplicaciones técnicas (funcionamiento de los reactores nucleares), como en estudios astrofísicos de nucleo-síntesis estelar en entornos estelares explosivos (SN, Mergers, etc), donde se producen de modo natural estos emisores exóticos ricos en neutrones.

• Experimentalmente se pueden producir núcleos emisores de neutrones utilizando reacciones nucleares de fragmentación o de fisión.

• Para poder determinar la probabilidad de emisión retardada de neutrones, es necesario detectar tanto los electrones (las partículas β- de la desintegración) como los neutrones.

• El método más común para la medida de NR consiste en el uso de contadores gaseosos (^{3}He y/o ^{10}B) integrados en una “matriz” de polietileno, que actúa como moderador para los NR, reduciendo su energía y aumentando así la probabilidad de detección. Una matriz con un gran número de contadores, permite alcanzar eficiencias de detección muy altas (entorno al 70-80%), lo cual es una ventaja fundamental para la medida de los núcleos más exóticos.

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