

# Medidas de emisión de neutrones $\beta$ -retardados

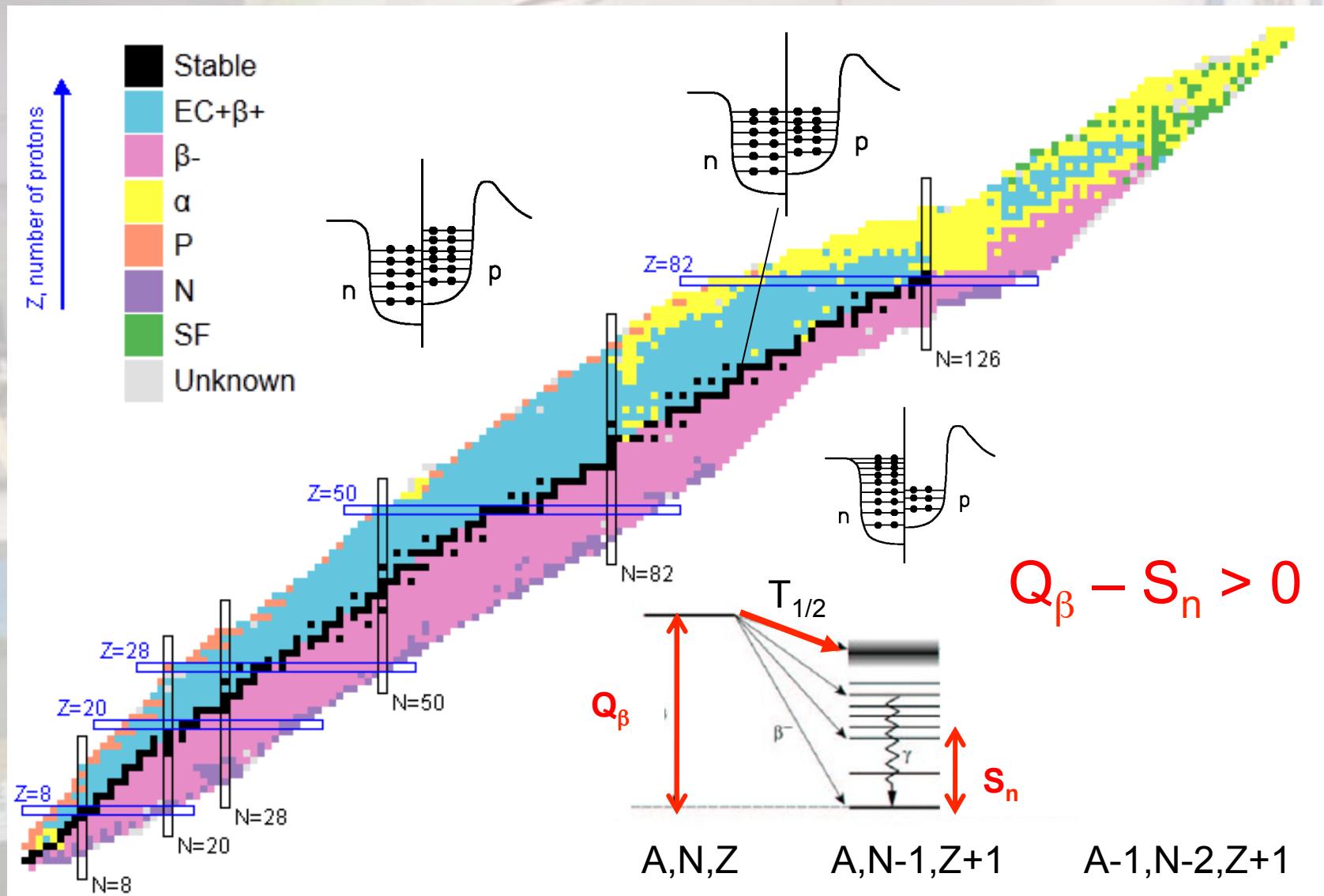
César Domingo Pardo

Instituto de Física Corpuscular  
(CSIC-Universidad de Valencia)

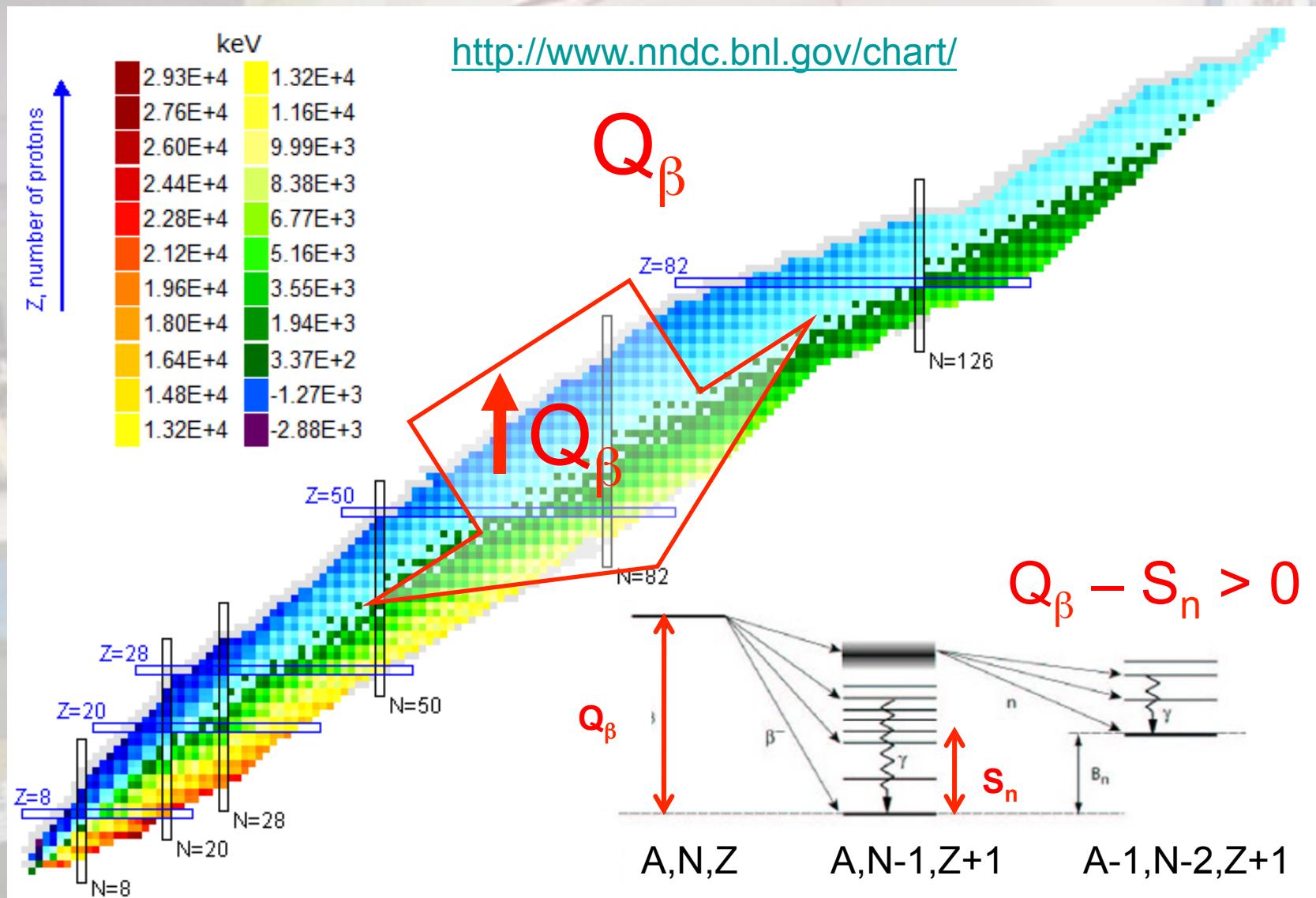
# Contenidos

- Concepto de emisión retardada de neutrones
- Motivación e implicaciones de los neutrones retardados (NR)
  - Técnicas experimentales de medida
  - Ejemplos de experimentos
  - Perspectiva y resumen

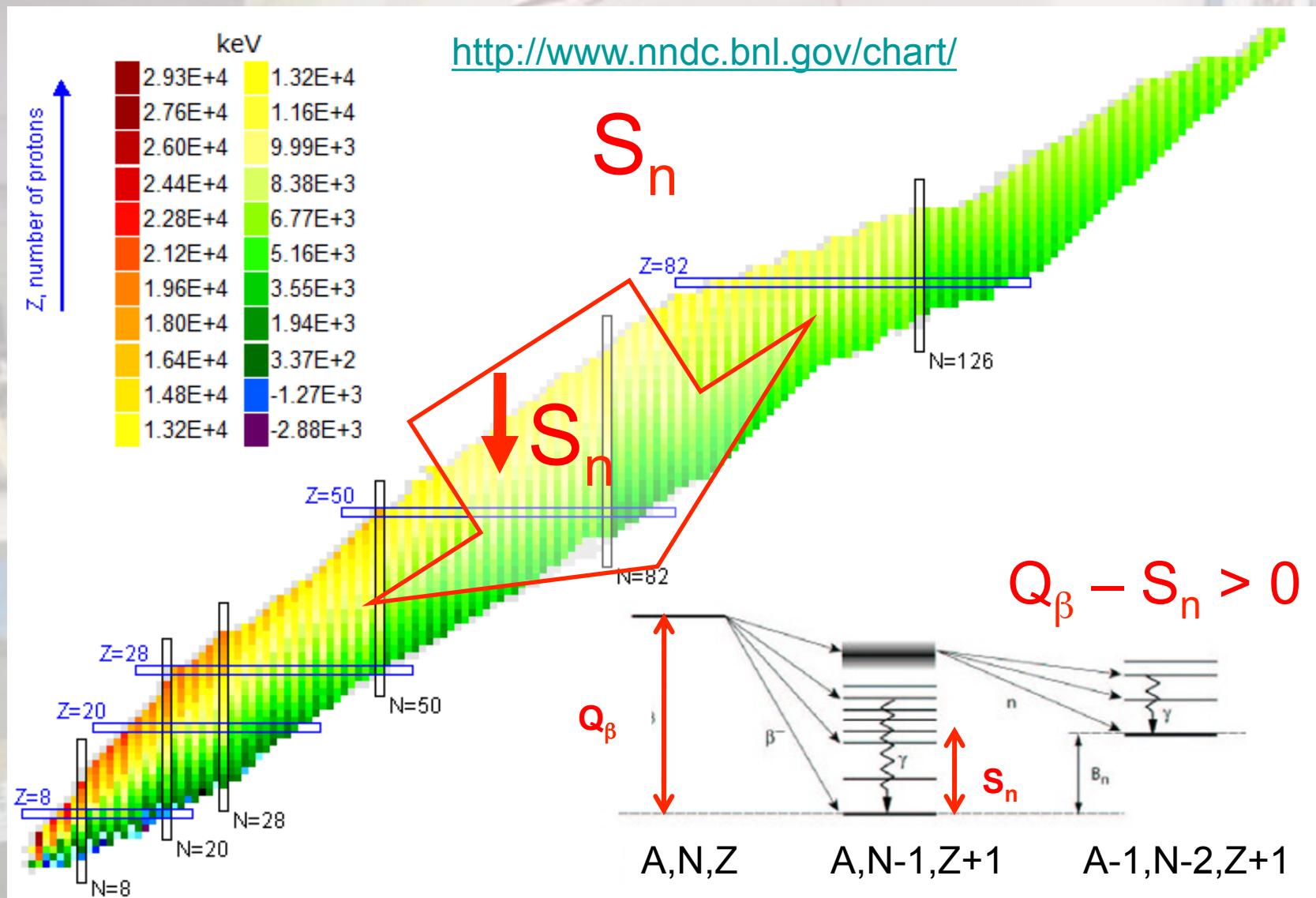
# Concepto de emisión retardada de neutrones



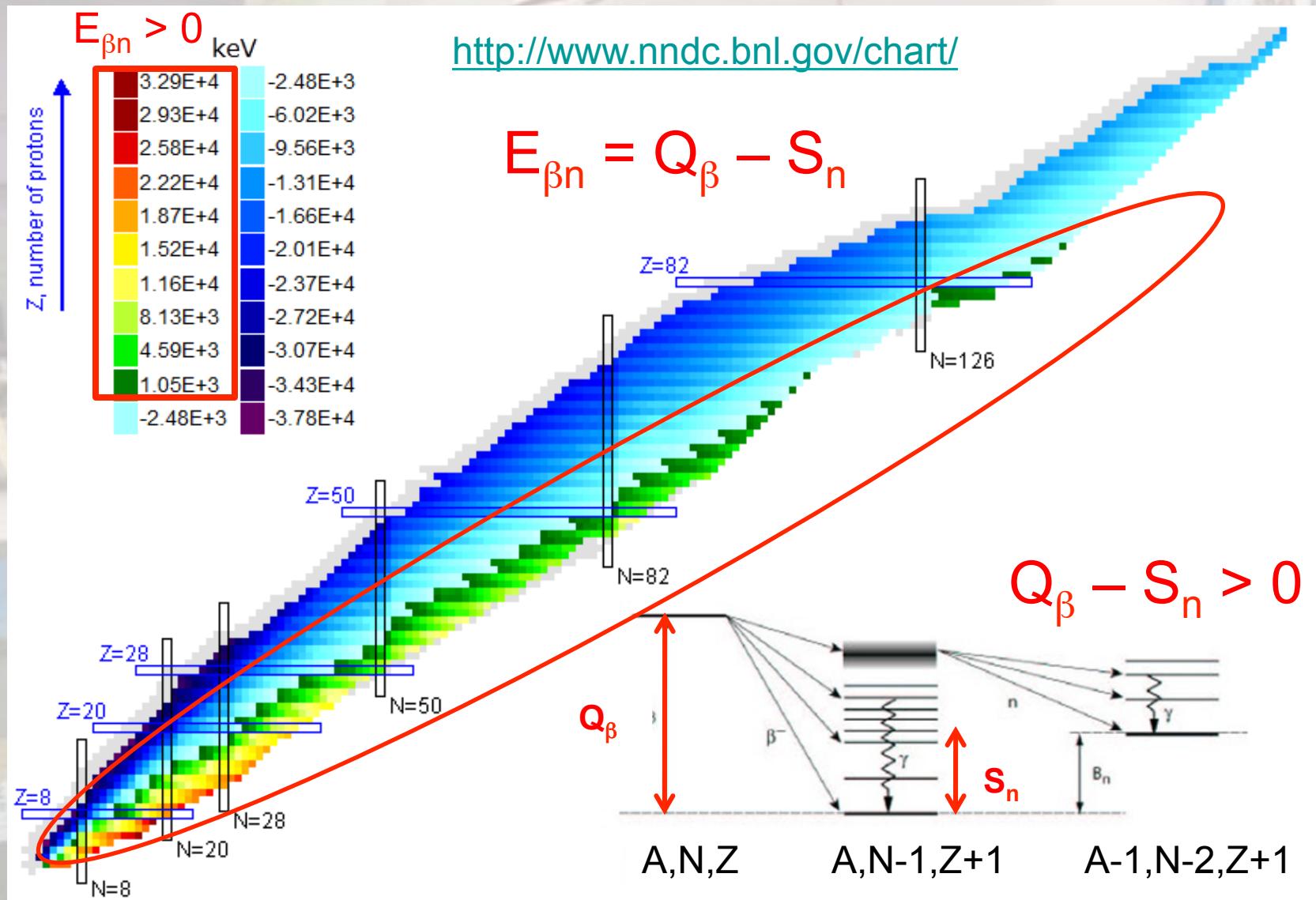
# Concepto de emisión retardada de neutrones



# Concepto de emisión retardada de neutrones



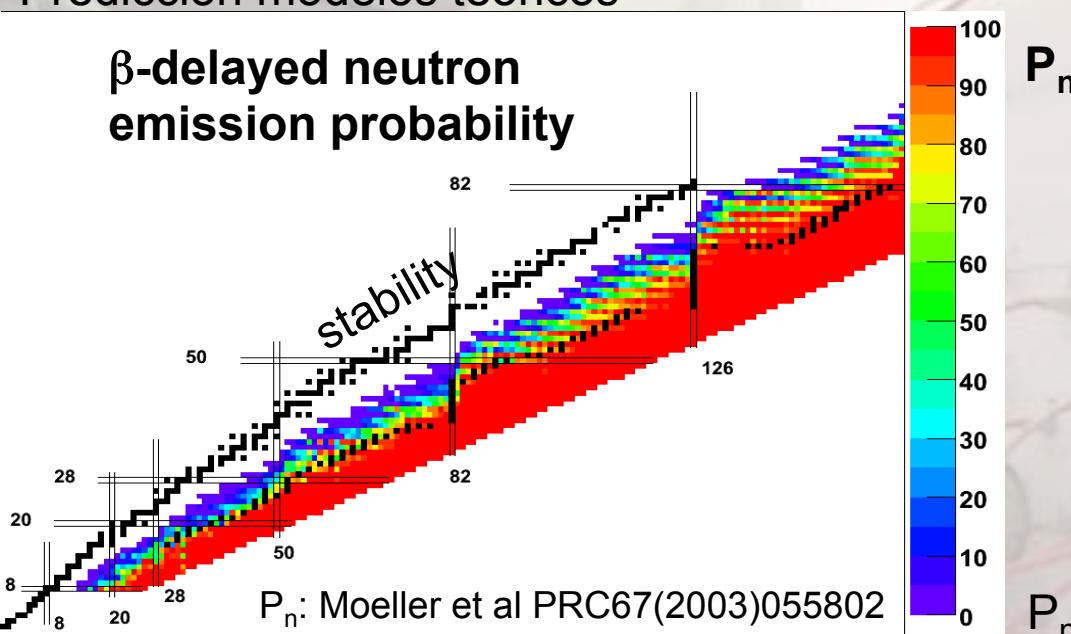
# Concepto de emisión retardada de neutrones



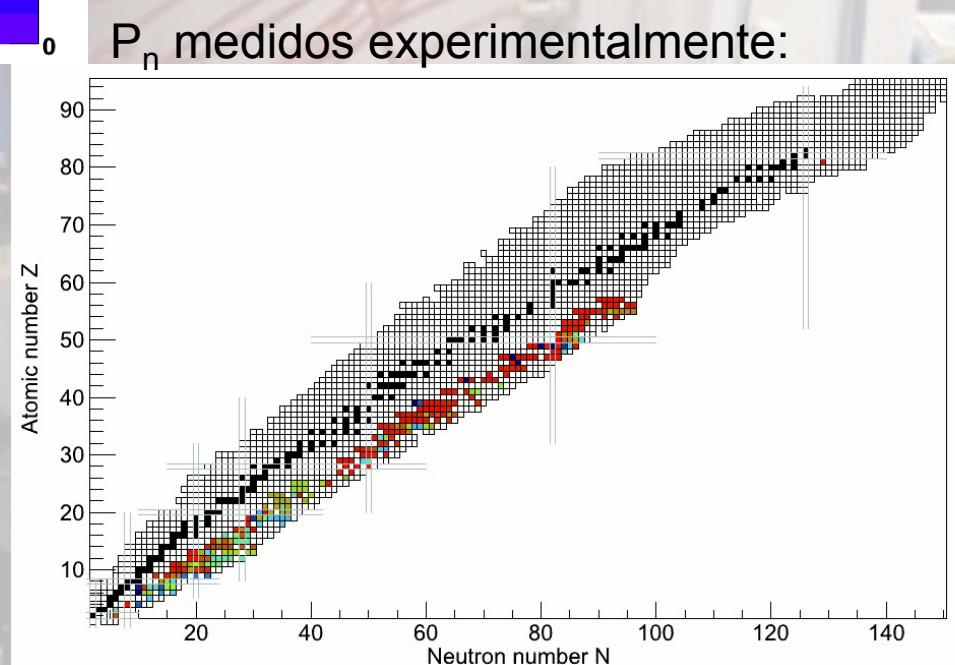
# Concepto de emisión retardada de neutrones

Predicción modelos teóricos

**$\beta$ -delayed neutron emission probability**

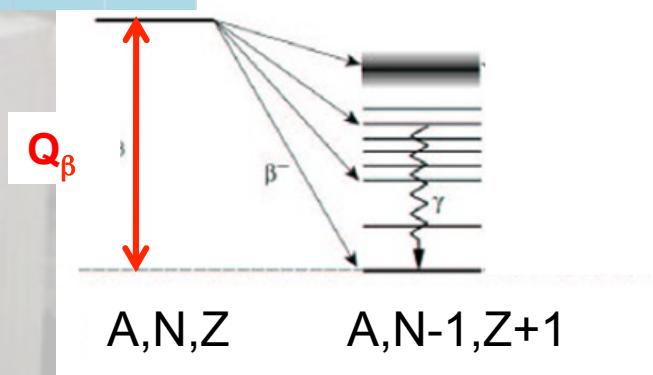
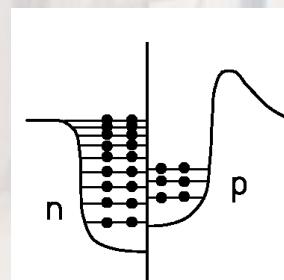
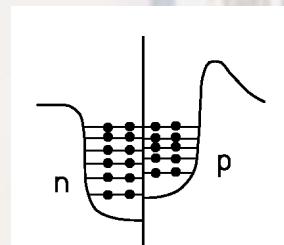


- Need of higher intensity RIBs
- Need of high-efficiency neutron detectors



# Concepto de emisión retardada de neutrones

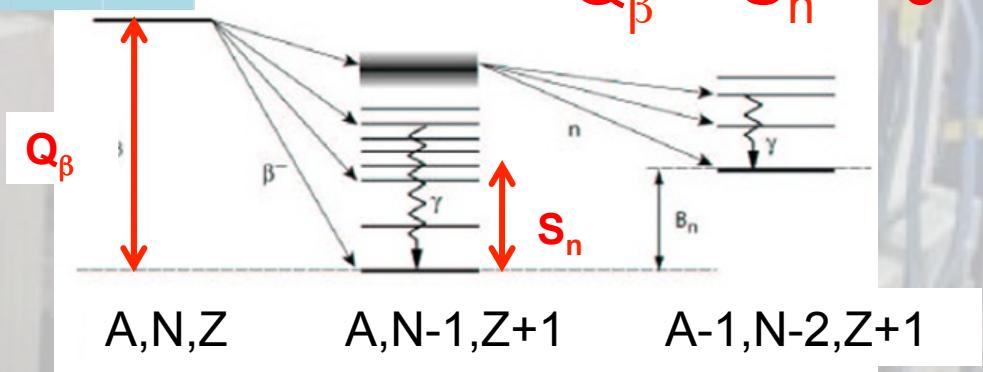
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Ba	133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba	141Ba	142Ba	143Ba	144Ba	145Ba	146Ba	147Ba	148Ba
Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs	142Cs	143Cs	144Cs	145Cs	146Cs	147Cs
Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe	141Xe	142Xe	143Xe	144Xe	145Xe	146Xe
Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te	137Te	138Te	139Te	140Te	141Te	142Te			
Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb	136Sb	137Sb	138Sb	139Sb				
Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn	135Sn	136Sn	137Sn					



# Concepto de emisión retardada de neutrones

La	134La	135La	136La	137La	138La	139La	140La	141La	142La	143La	144La	145La	146La	147La	148La	149La
Ba	133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba	141Ba	142Ba	143Ba	144Ba	145Ba	146Ba	147Ba	148Ba
Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs	142Cs	143Cs	144Cs	145Cs	146Cs	147Cs
Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe	141Xe	142Xe	143Xe	144Xe	145Xe	146Xe
Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te	137Te	138Te	139Te	140Te	141Te	142Te			
Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb	136Sb	137Sb	138Sb	139Sb				
Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn	135Sn	136Sn	137Sn					

$$Q_\beta - S_n > 0$$



# Motivación e implicaciones de los NR

- Aplicaciones tecnológicas: producción de energía en reactores
- Aplicaciones en astrofísica: nucleosíntesis de elementos pesados

# Producción de energía por fisión nuclear

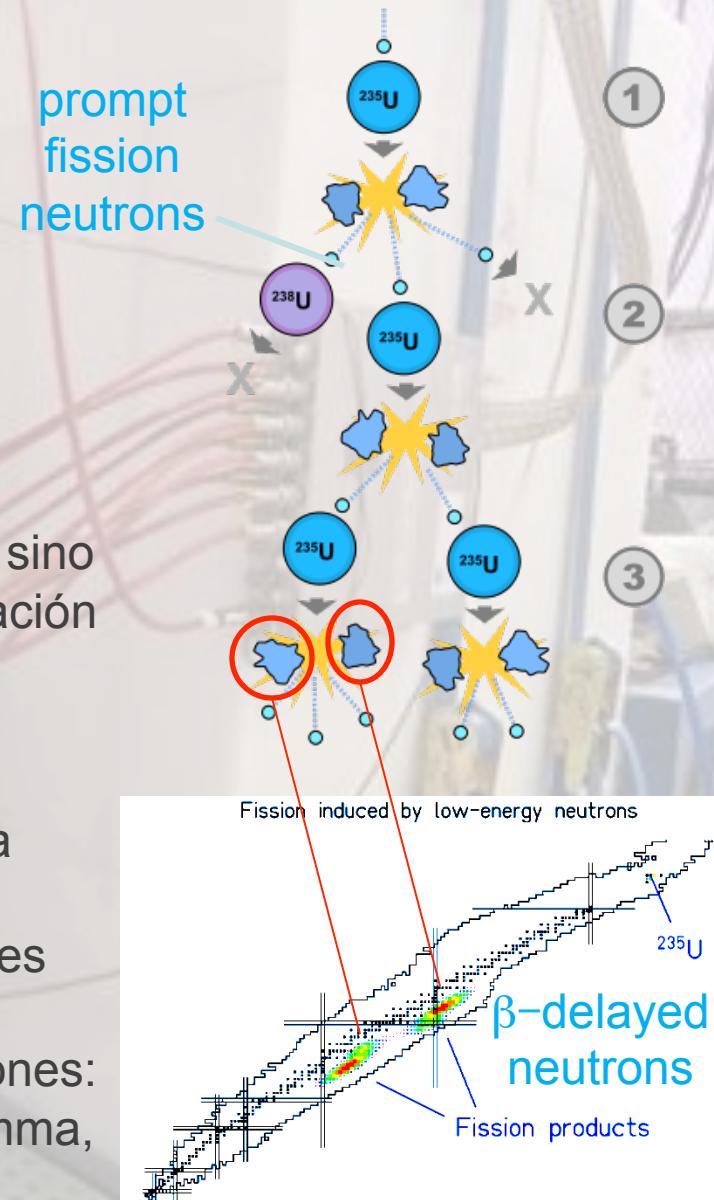
En un reactor nuclear, el objetivo es producir calor (energía) por medio de una reacción en cadena auto-sostenida ( $k = 1$ , sistema crítico).

[ $k$  := 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 ( $\tau$ ) de **1 ms** (prompt fission n) a unos **100 ms** (fission+ $\beta$ n).

Ejemplo para ilustrar la **relevancia de los NR** en el control de un reactor nuclear:

$N$ := Número de neutrones libres en un reactor

$\tau$  := vida media efectiva promedio de un neutrón libre

La evolución del balance de neutrones en un reactor viene descrita por la siguiente ecuación diferencial:

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

$\alpha$ := constante de proporcionalidad:

$\alpha > 0 \rightarrow$  Supercrítico: tasa de aumento de n aumenta exponencialmente

$\alpha = 0 \rightarrow$  Crítico: numero de neutrones libres permanece constante.

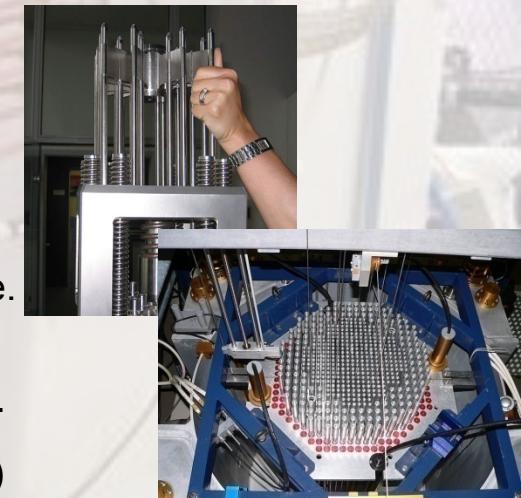
$\alpha < 0 \rightarrow$  Subcrítico: número de neutrones decae exponencialmente

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

1) Asumiendo que **no existen los NR**:  $\tau := 1 \text{ ms}$  (neutrones de fisión)

En 1 s la variación de potencia en el reactor sería:

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



2) **Incluyendo los NR**:  $\tau := 100 \text{ ms}$  (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

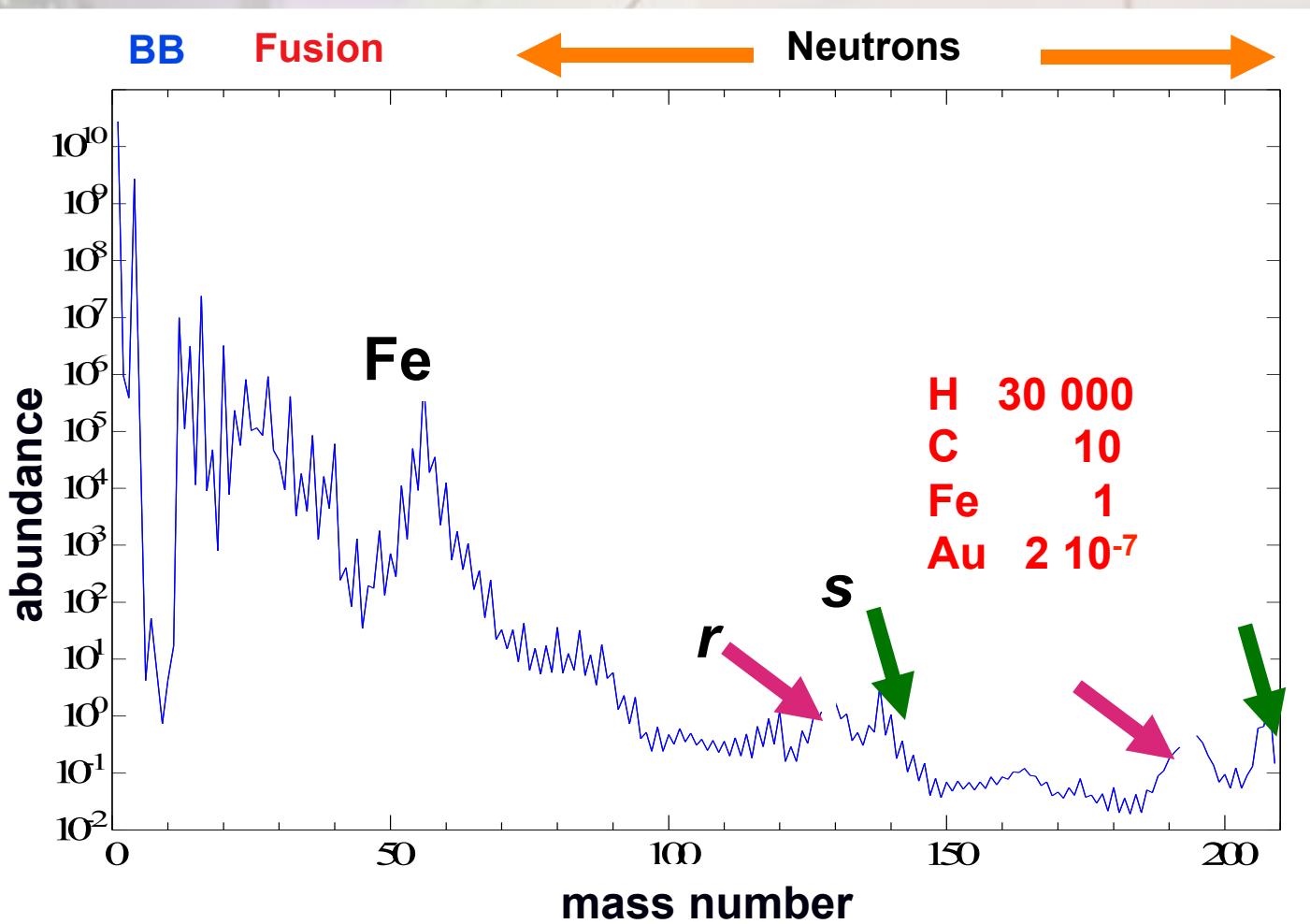
La mayoría de reactores nucleares se operan en modo *prompt subcritical, delayed critical*, es decir, los neutrones prompt de la fisión no son suficientes para sostener una reacción en cadena. Mediante los neutrones retardados se llega a la condición de criticalidad.

Cuando una pequeña porción 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.

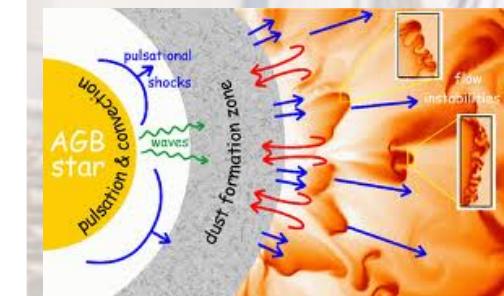
## Conclusión:

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

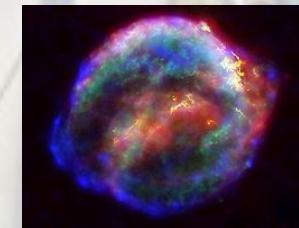
# Nucleosíntesis de elementos pesados en entornos estelares explosivos (r-process)



s-process: slow n-capture in stellar envelopes



r-process: unknown site



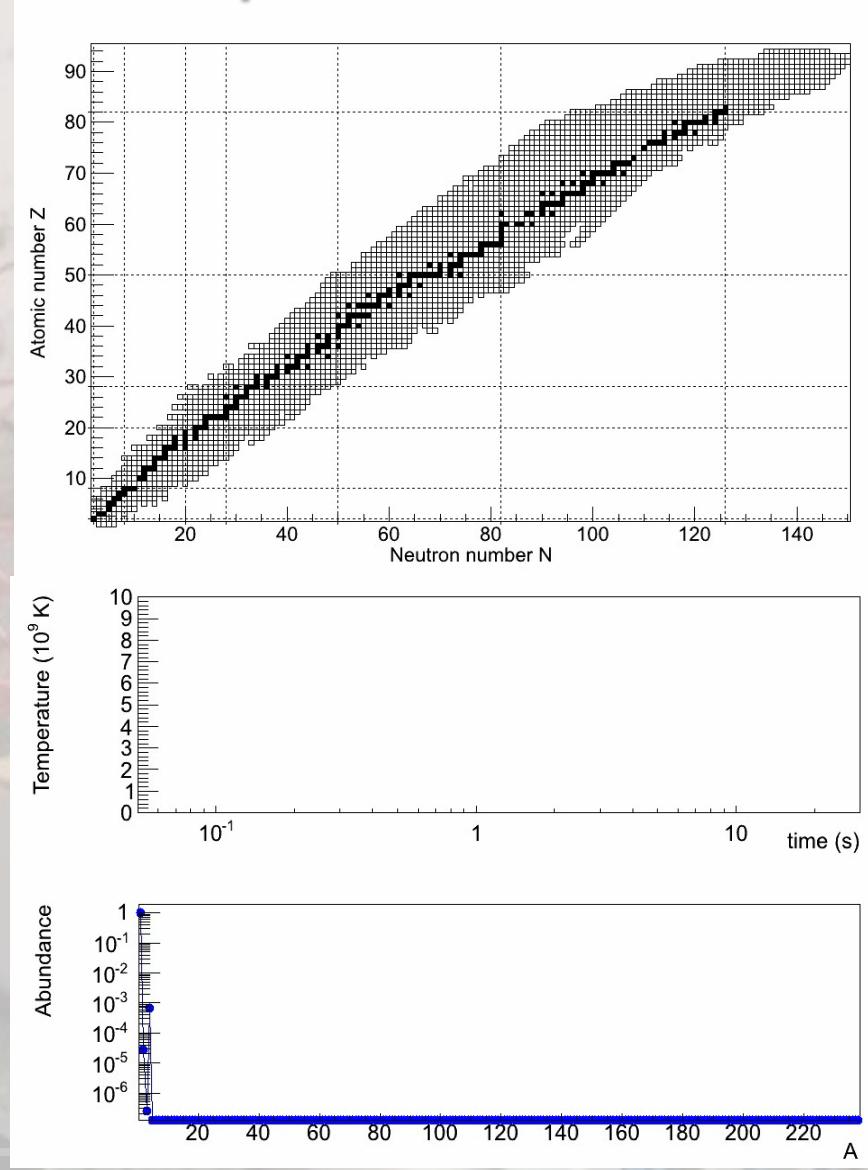
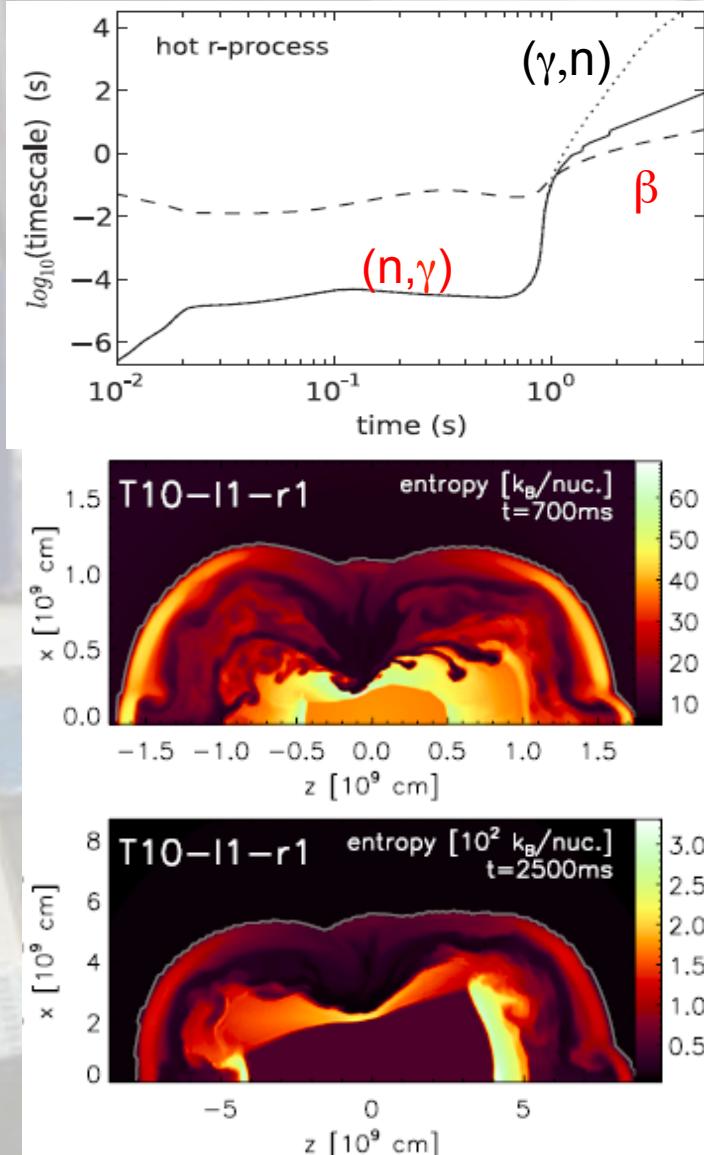
SNe?

NS-Mergers

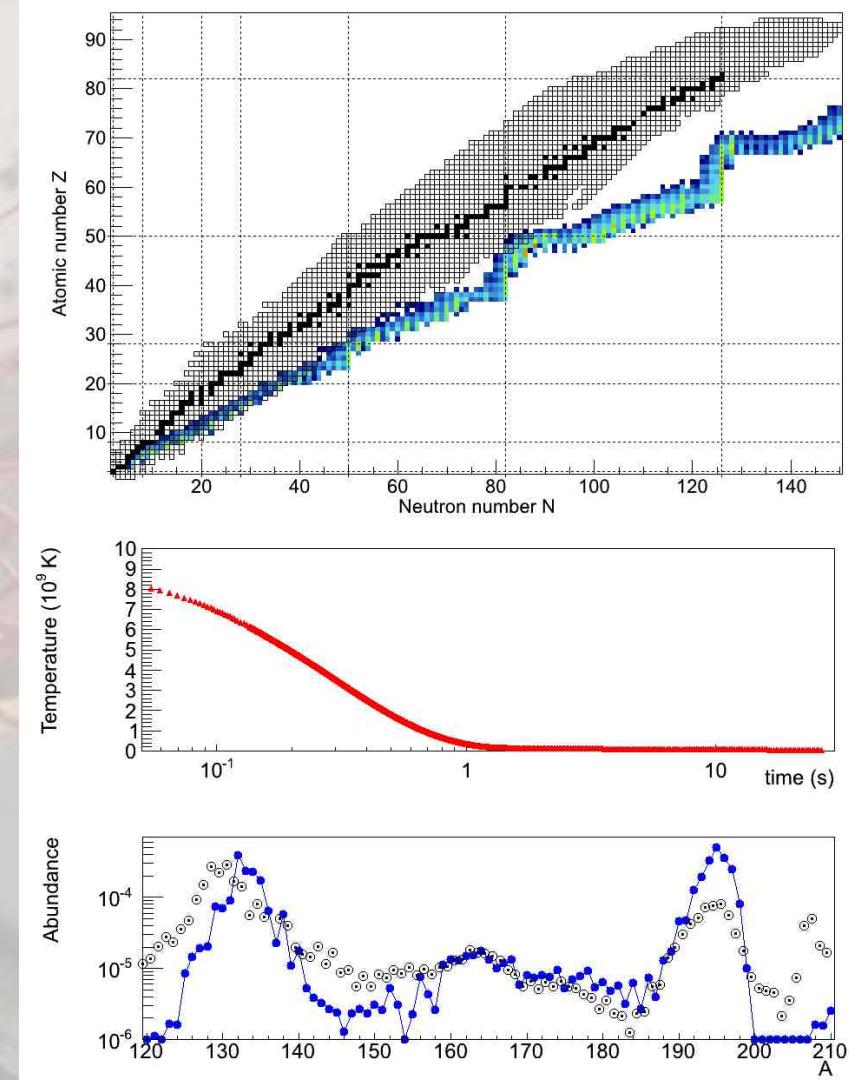
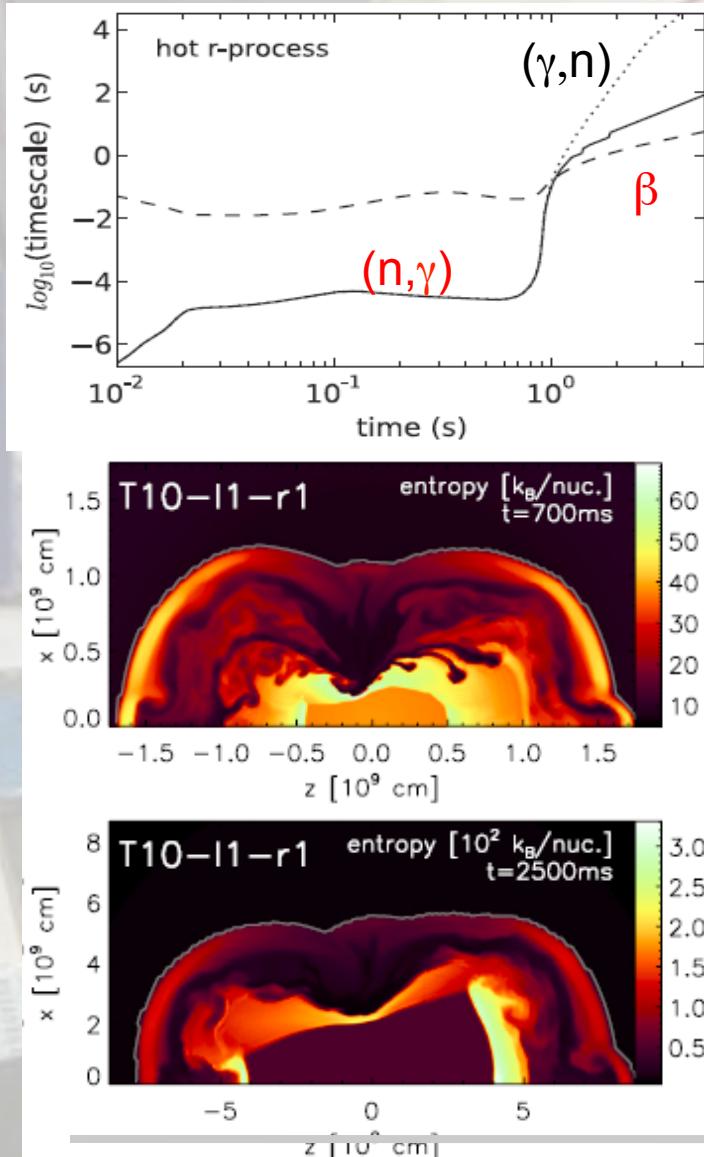


Neutrons produce 75% of the stable isotopes, but only 0.005% of total abundances

# Nucleosíntesis de elementos pesados en entornos estelares explosivos

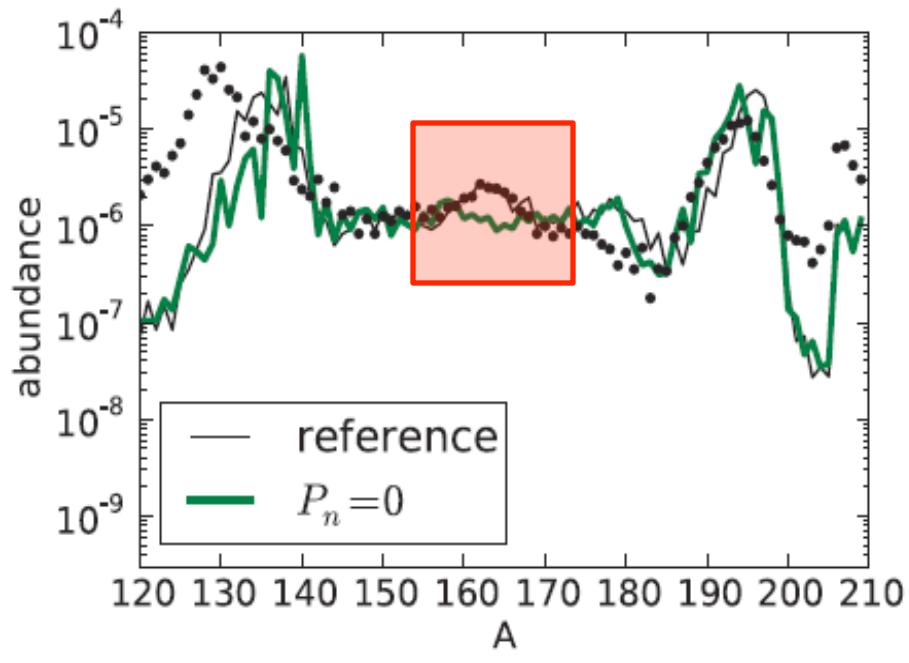


# Nucleosíntesis de elementos pesados en entornos estelares explosivos



# Los Elementos de las Tierras Raras son tan abundantes gracias a los NR

Tierras Raras: Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, etc.



PHYSICAL REVIEW C 83, 045809 (2011)

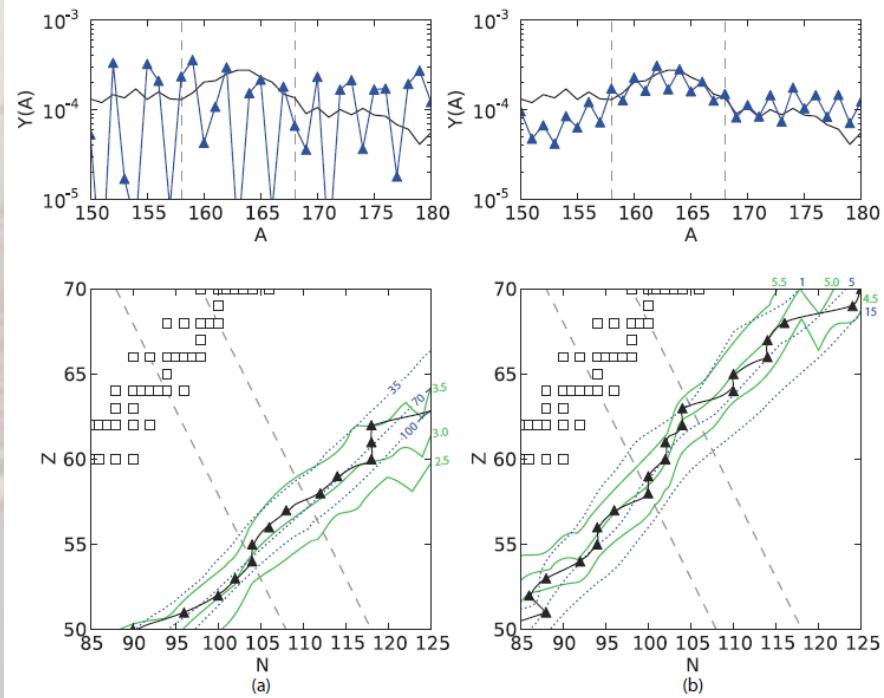
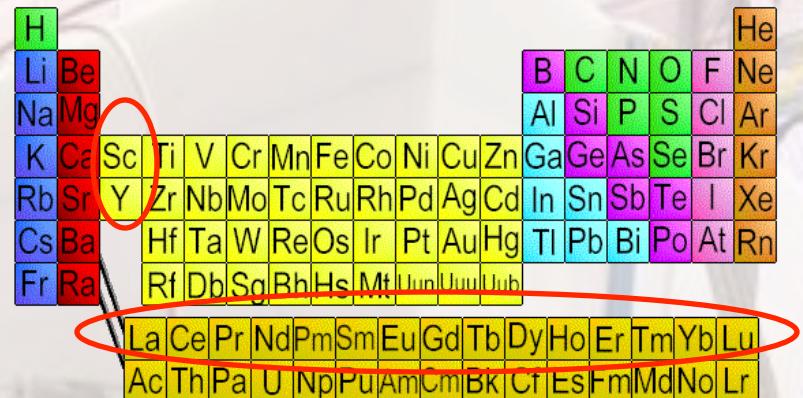
Dynamical  $r$ -process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input<sup>2</sup>

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<sup>1</sup>Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

<sup>2</sup>GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany

(Received 23 August 2010; revised manuscript received 22 December 2010; published 27 April 2011)



PHYSICAL REVIEW C 85, 045801 (2012)

Formation of the rare-earth peak: Gaining insight into late-time  $r$ -process dynamics

Matthew R. Mumpower<sup>\*</sup> and G. C. McLaughlin<sup>†</sup>

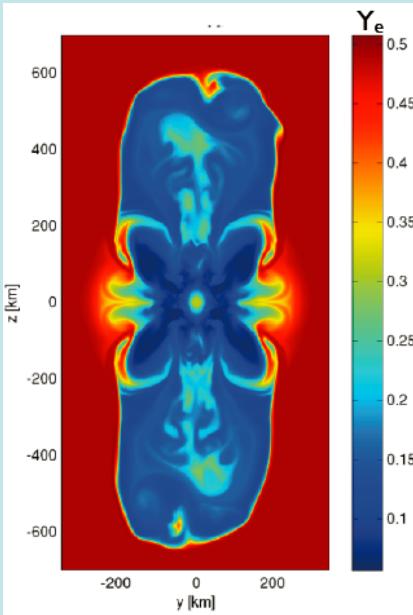
Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202, USA

Rebecca Surman<sup>‡</sup>

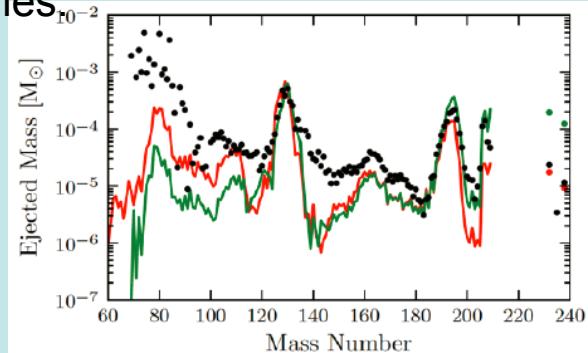
Department of Physics and Astronomy, Union College, Schenectady, New York 12308, USA

(Received 21 September 2011; revised manuscript received 21 November 2011; published 2 April 2012)

## Supernova con explosión en chorro (jet-like explosion)

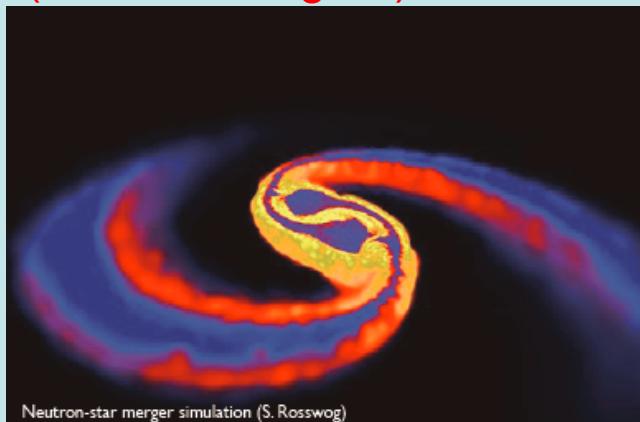


- Simulaciones magneto-HD en 3D: rápida rotación y campos magnéticos intensos.
- Colimación de materia: jets ricos en neutrones



Winteler, Käppeli, Perego et al. 2012

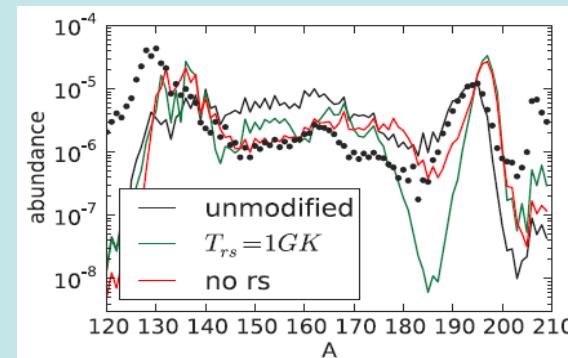
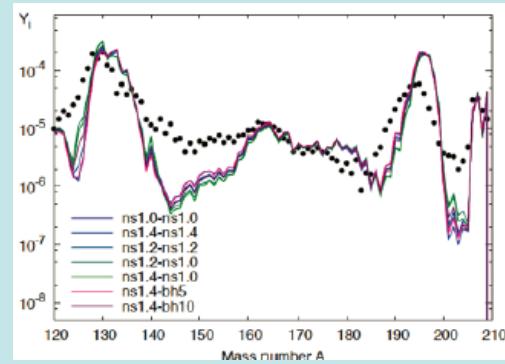
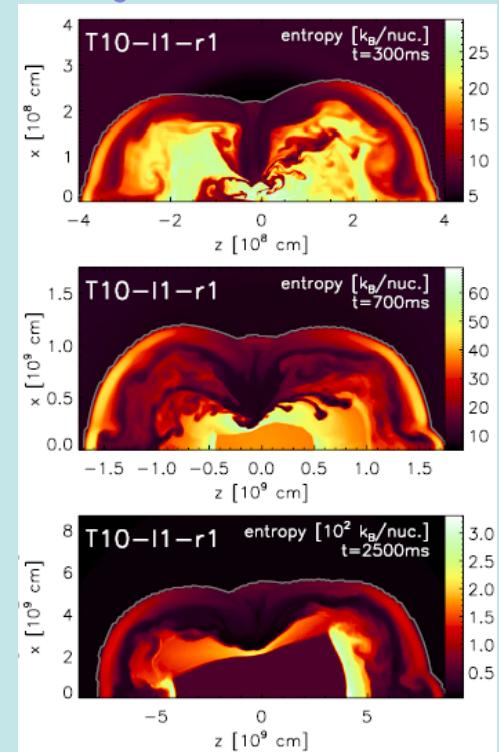
## Sistemas binarios de estrellas de neutrones (neutron mergers)



Neutron-star merger simulation (S. Rosswog)

Korobkin, Rosswog, Arcones, Winteler et al. 2012

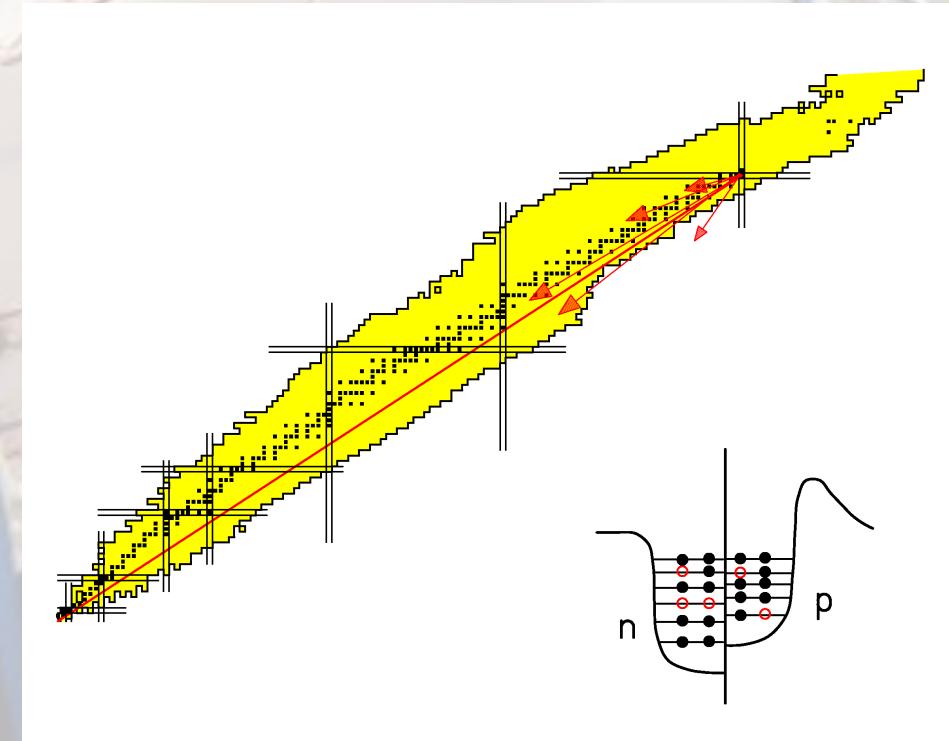
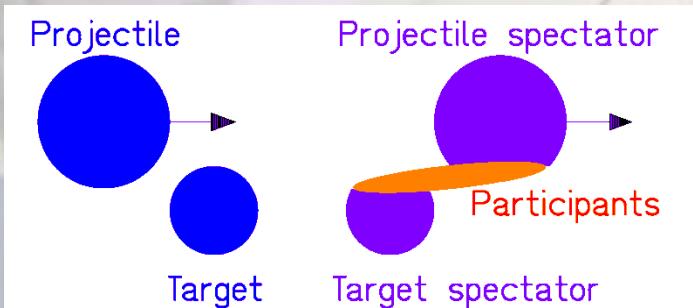
## SN + $\nu$ -driven wind



# TÉCNICAS EXPERIMENTALES DE MEDIDA

1. Producción de los núcleos ricos en neutrones (por fisión y/o fragmentación)
2. Implantación en un blanco (activo)
3. Medida de la desintegración beta
4. Medida de los neutrones
5. Evaluación del “neutron branching”

# Fragmentación



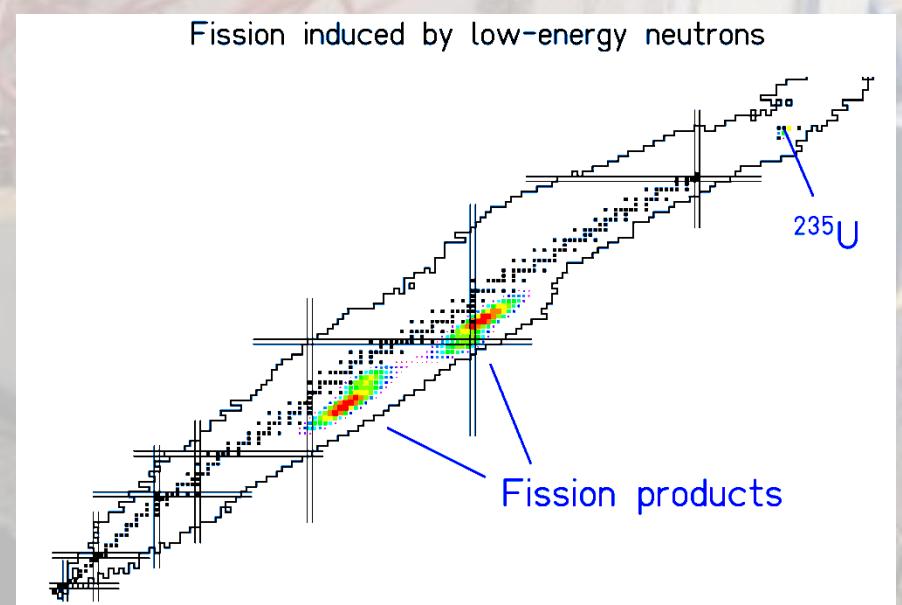
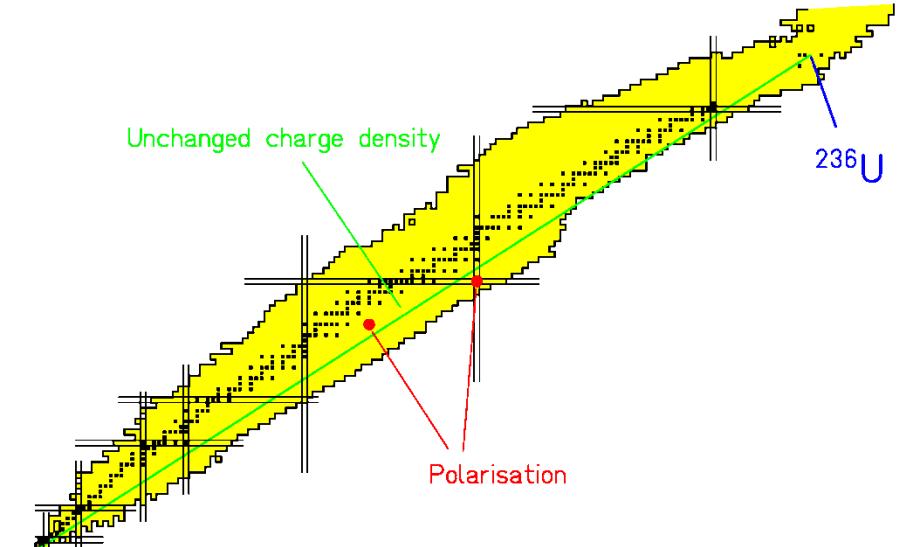
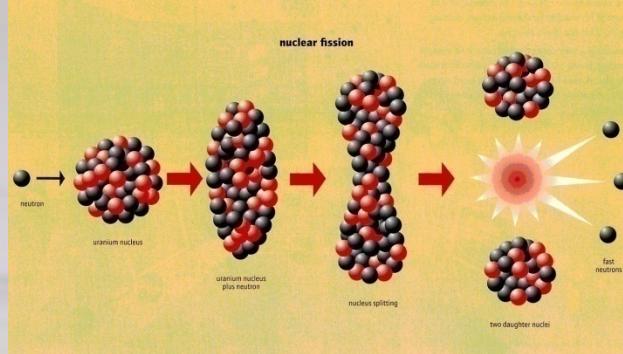
**Removal of nucleons in quasi-free nucleon-nucleon collisions.**

**Basic characteristics:**

- Large fluctuations in N/Z.
- Large fluctuations in excitation energy.

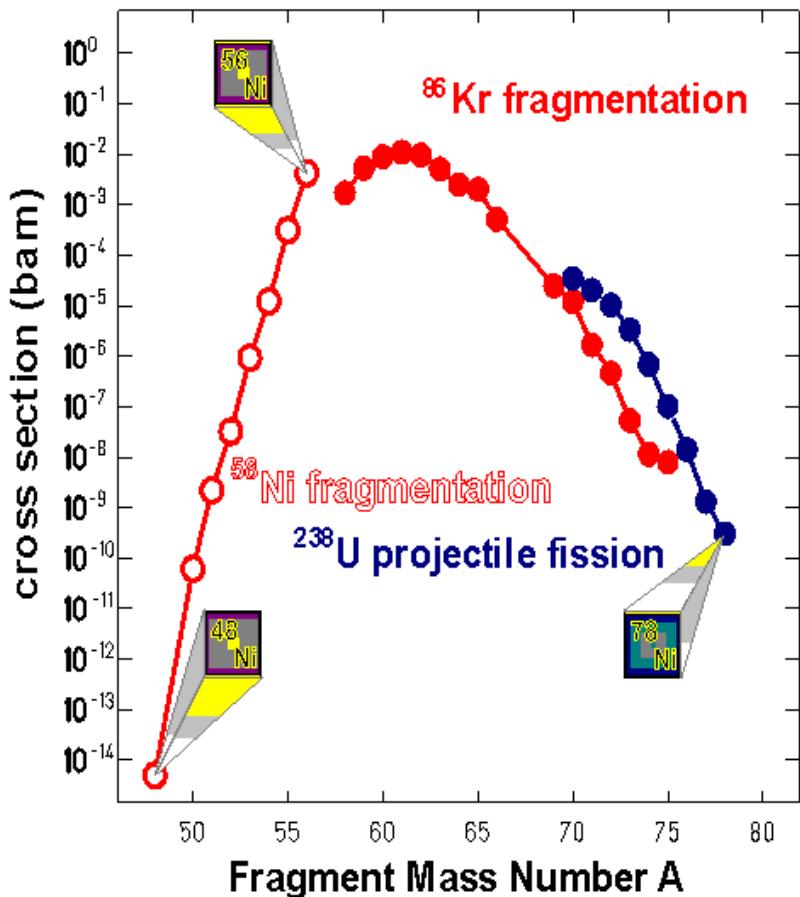
**Highly excited fragments loose additional nucleons by evaporation.**

# Fisión

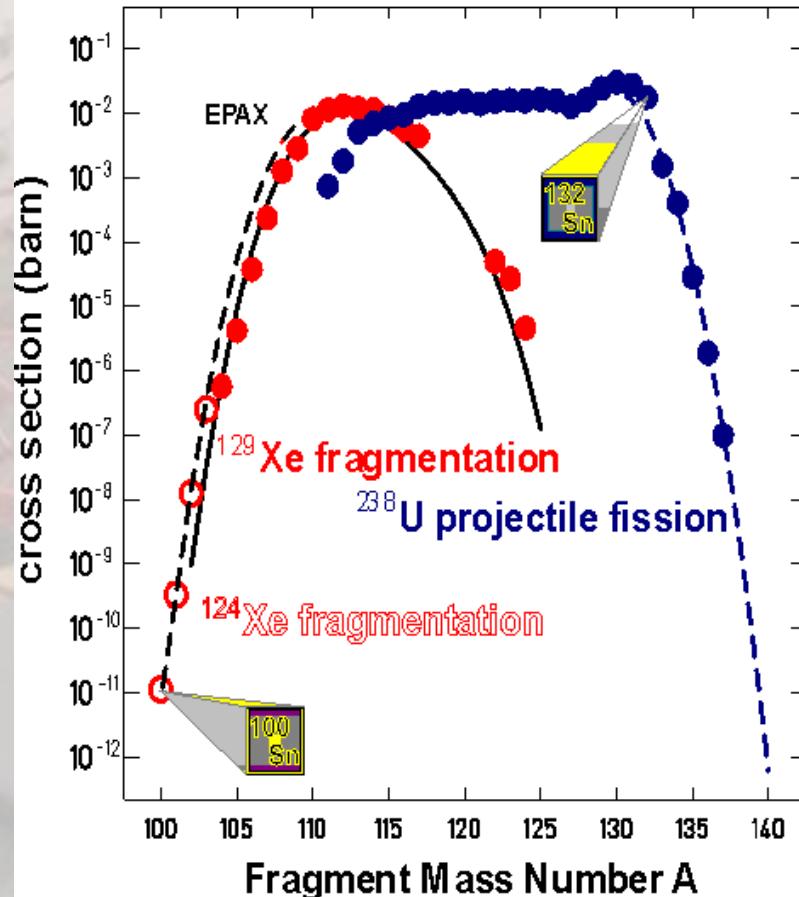


# Producción de iones exóticos

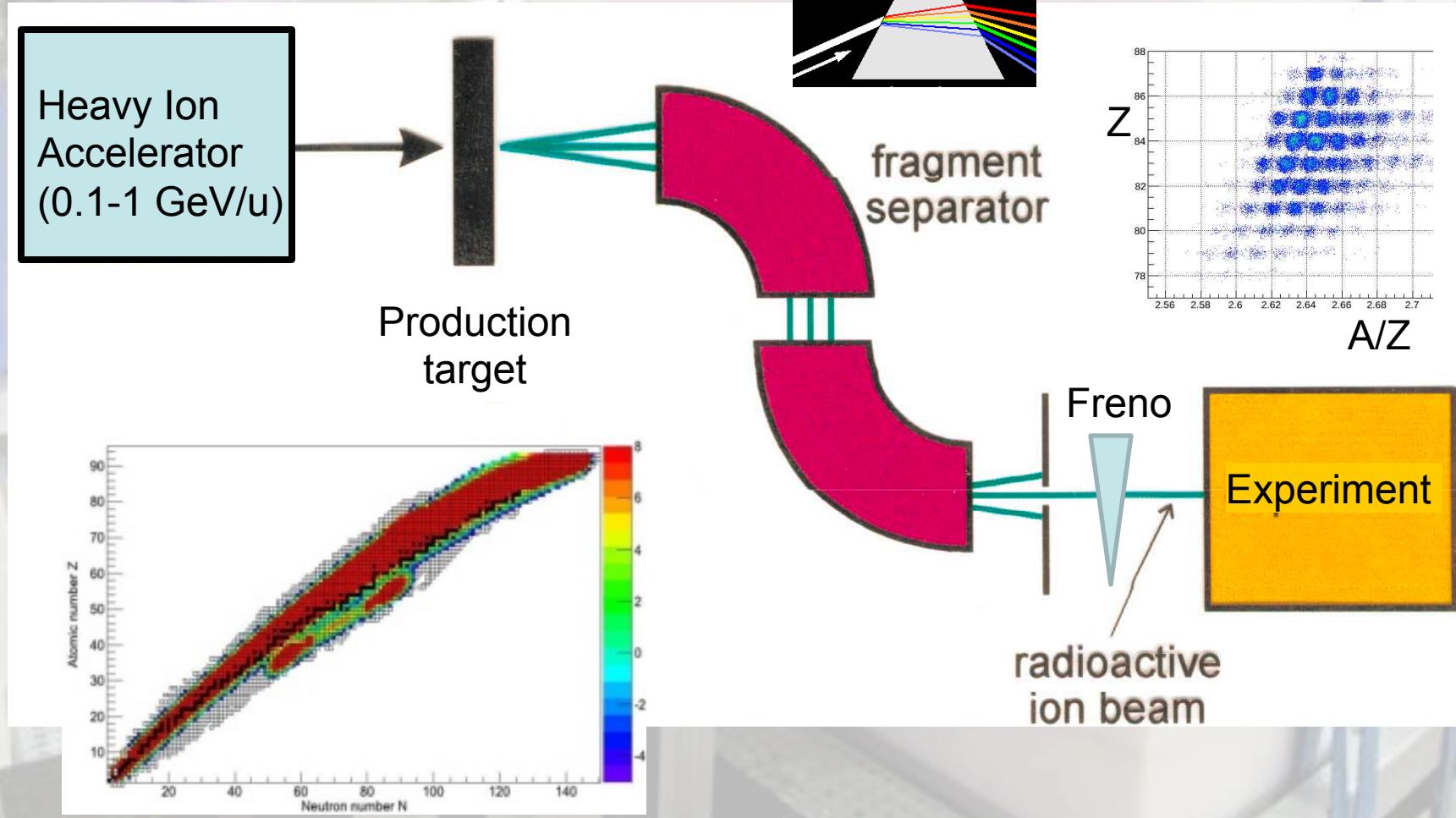
Ni isotopes from  
projectile fragmentation and projectile fission



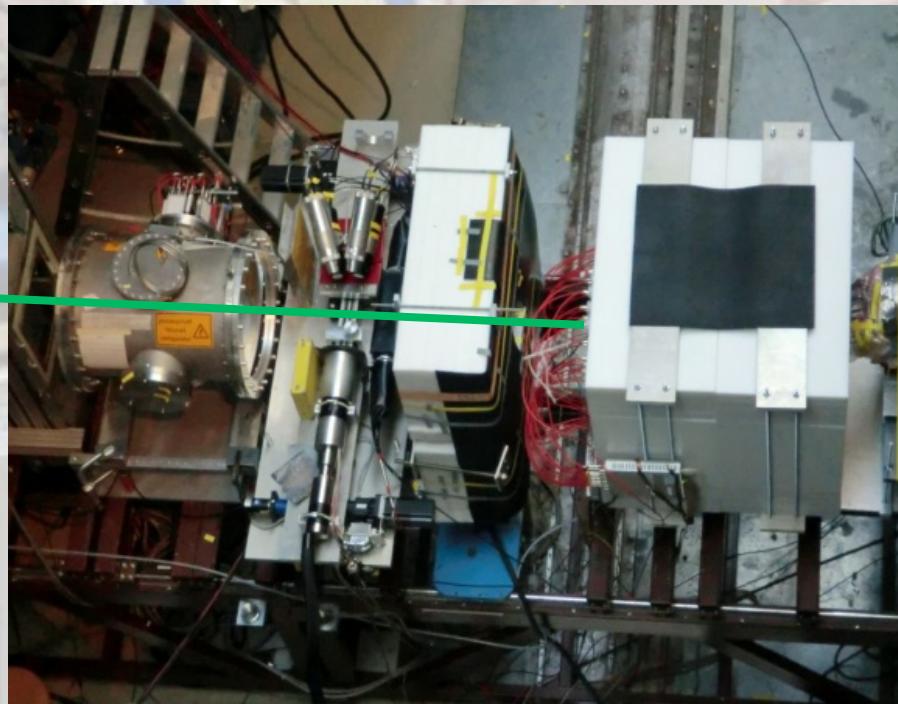
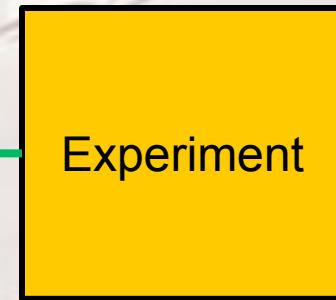
Sn isotopes from  
projectile fragmentation and projectile fission



# Identificación y separación de los núcleos exóticos de interés

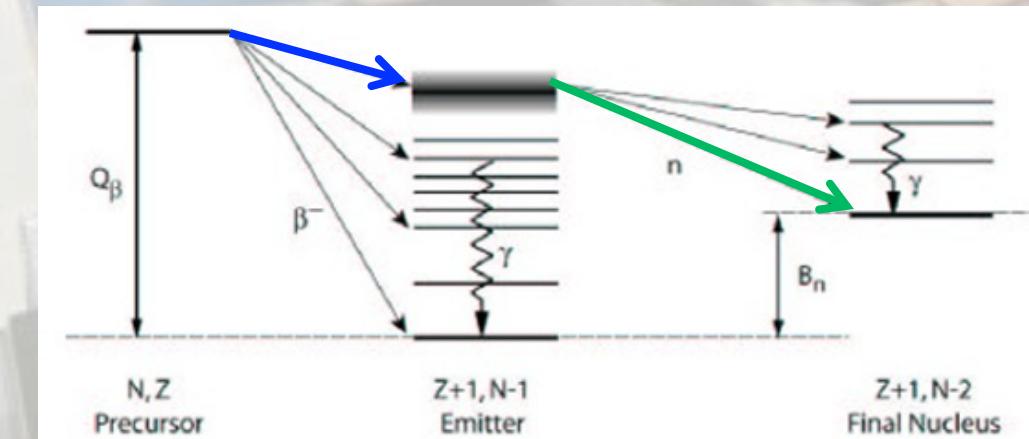


# Implantación en un blanco

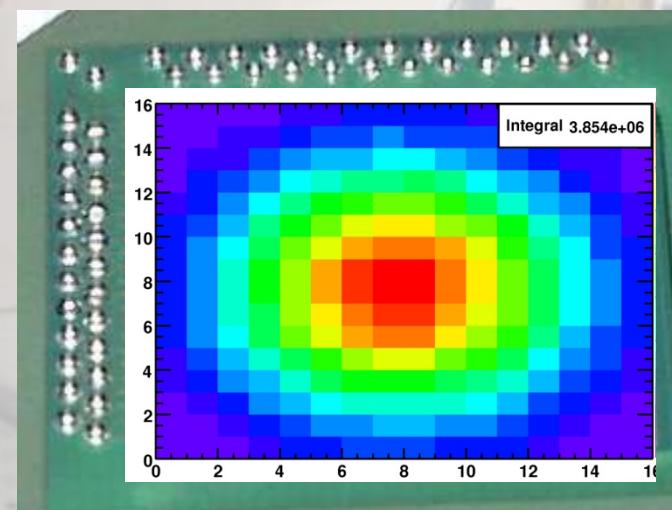


# Implantación y decay en un blanco activo

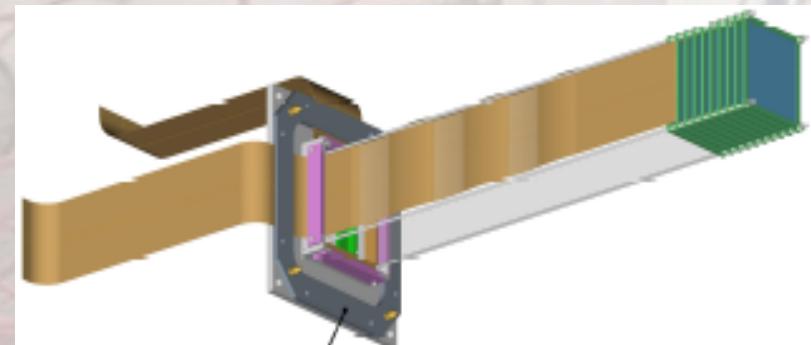
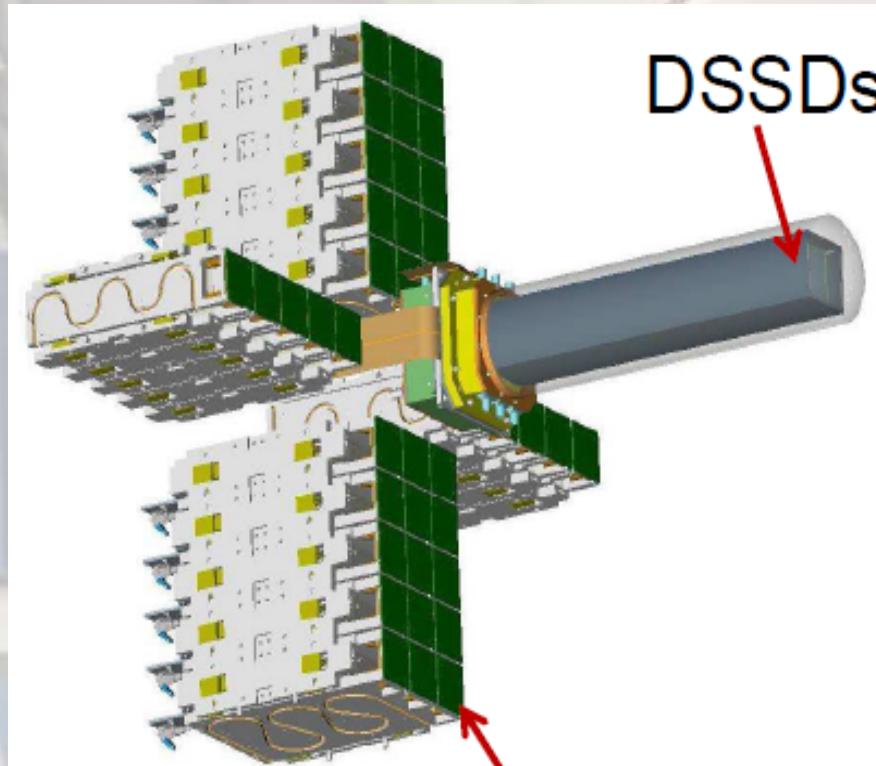
Degrador  
(Freno)



SIMBA (TUM, Germany)



# Implantación y decay en un blanco activo

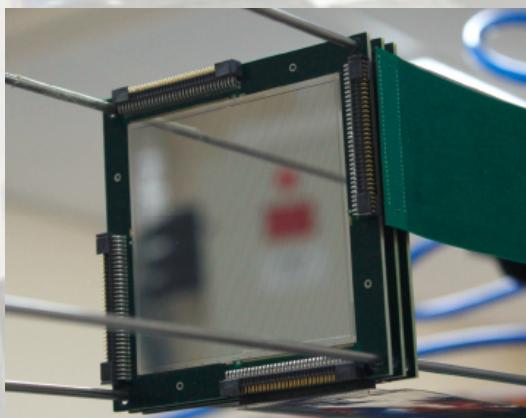


12xDSSDs, 8x8cm, 1mm Si, 625 $\mu$ m,  
>5000 channels

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)

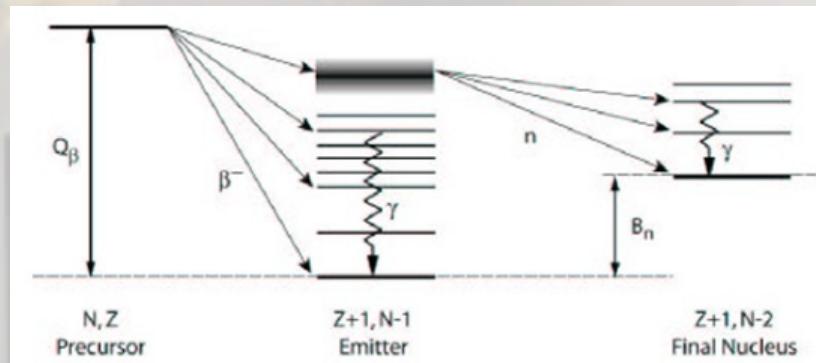


PJ Woods: PI of AIDA  
collaboration  
(Edinburgh – Liverpool – STFC  
DL & RAL)

# Implantación y decay en un blanco activo

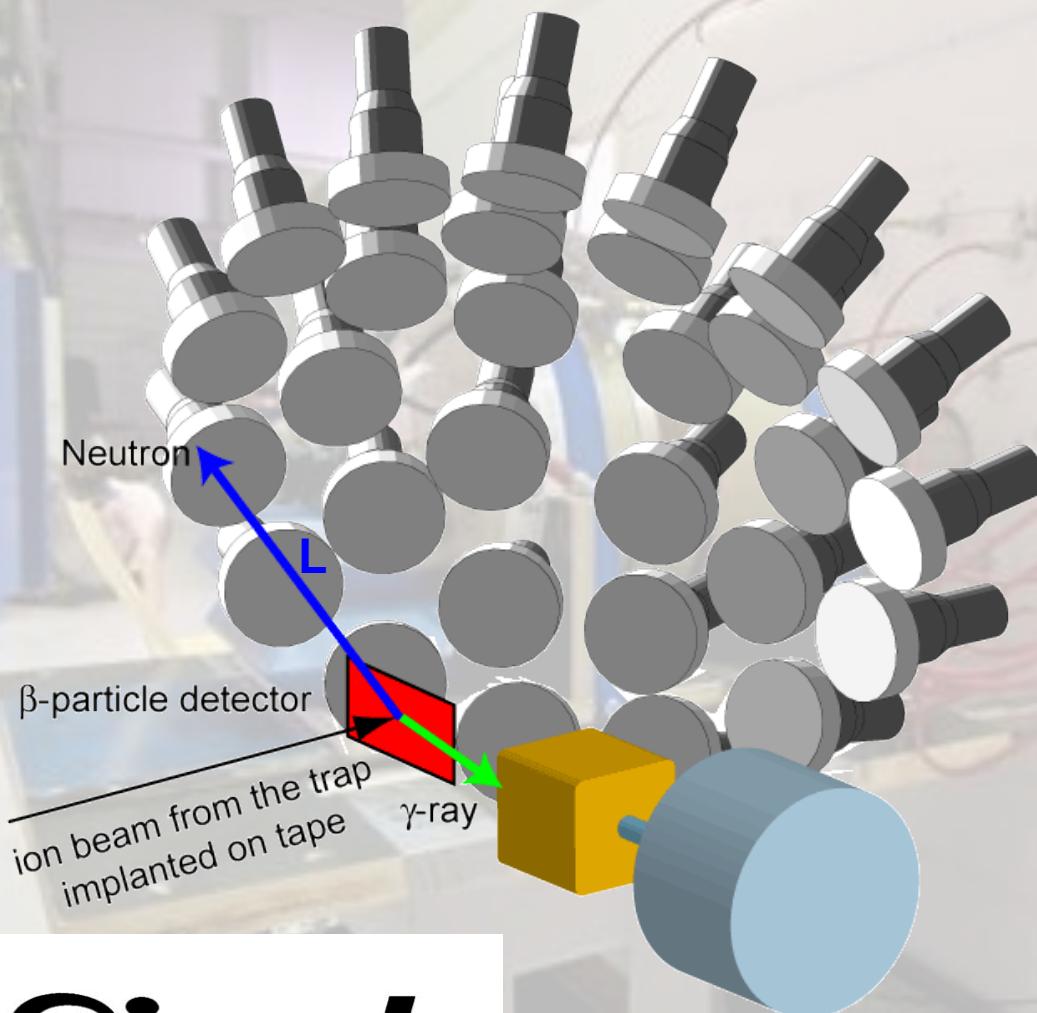
Implantes e.g.  $^{209}\text{Bi}$  a 40 MeV/u:

$\beta$ -decays:

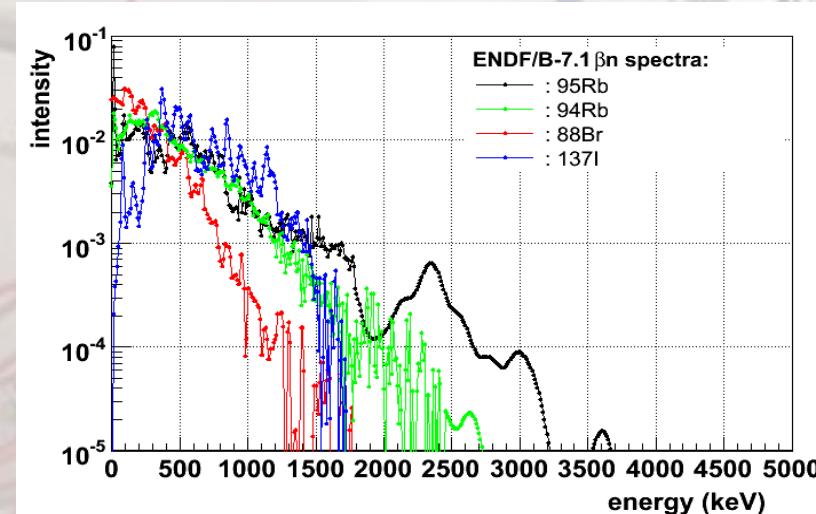


# Detección de los neutrones retardados-beta

MONSTER Detector:



$$tof \rightarrow E_n = \frac{1}{2} m_n (L/tof)^2$$



# Detección de los neutrones retardados-beta

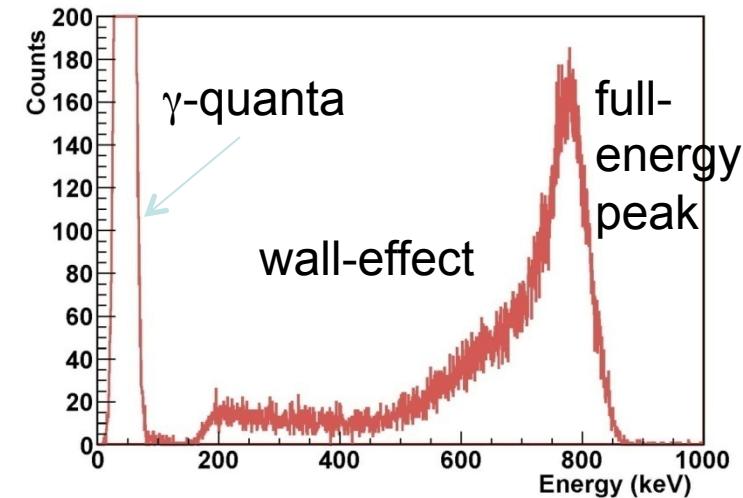
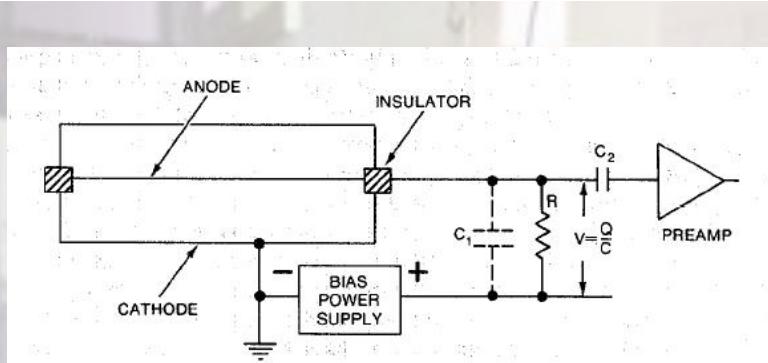
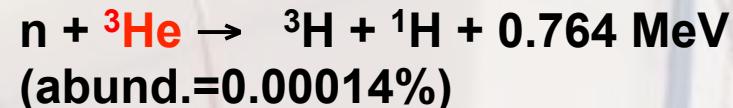
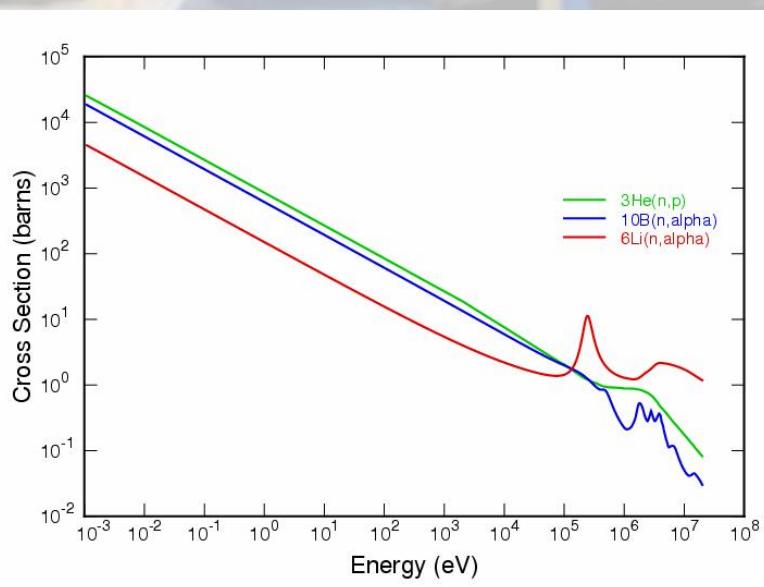


Figure 1: Expected pulse height spectrum from a  ${}^3\text{He}$  tube. The two steps in the spectrum are caused by one of the reaction products hitting the detector wall. In area (a), the triton energy is fully deposited, but the proton only deposited a fraction of its energy, and vice versa in area (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	$1-\alpha$	$\xi$	$N$
$^1H$	0.000	1.000	0
$^2H$	0.000	1.000	0
$^4He$	0.000	1.000	0
$^{12}C$	<b>0.284</b>	<b>0.158</b>	<b>111</b>
$^{56}Fe$	<b>0.069</b>	<b>0.035</b>	<b>500</b>
$^{208}Pb$	<b>0.019</b>	<b>0.010</b>	<b>1823</b>



## PRACTICA LABORATORIO DE CONTADORES DE NEUTRONES (SONJA ORRIGO)

Number of collisions to reach an energy:

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

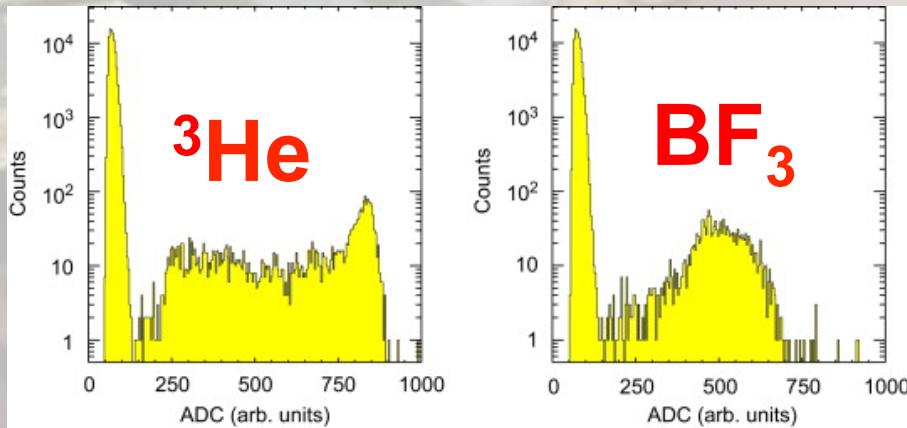
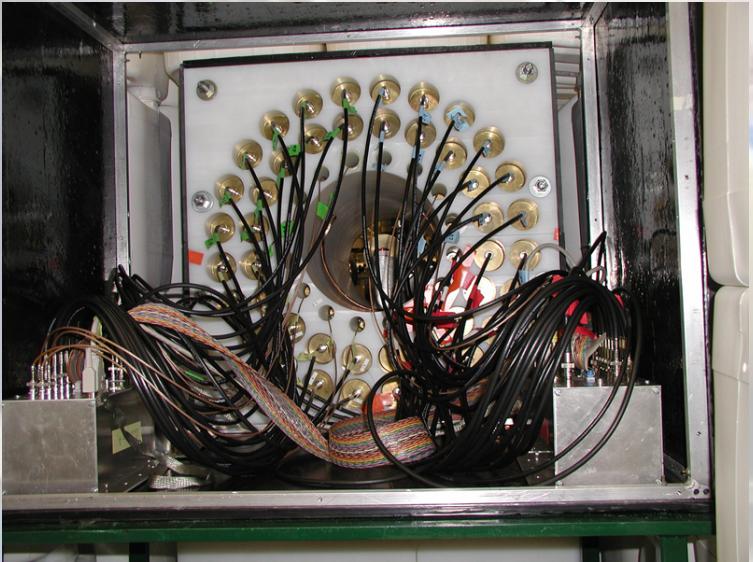
Slowing-down time:  $t = \sqrt{\frac{K}{E_f}} - t_0 : K(\xi, \sigma_{ela}); t_0(E_0, \xi, \sigma_{ela})$

# Contadores $4\pi$ : NERO @ NSCL-MSU

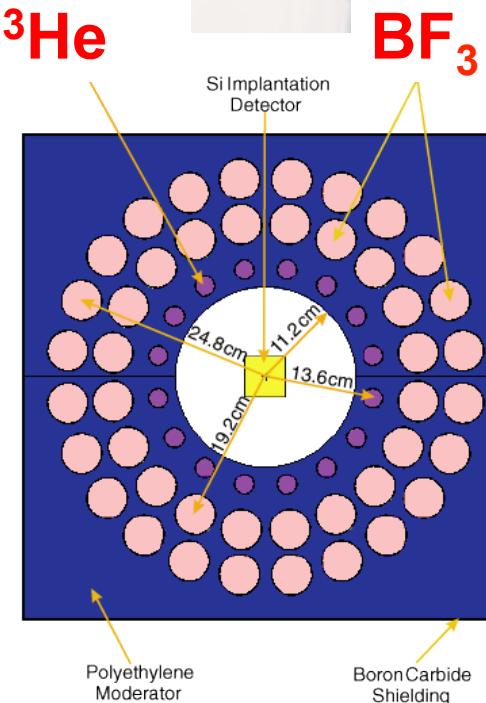


Polyethylene block (60x60x80cm<sup>3</sup>)

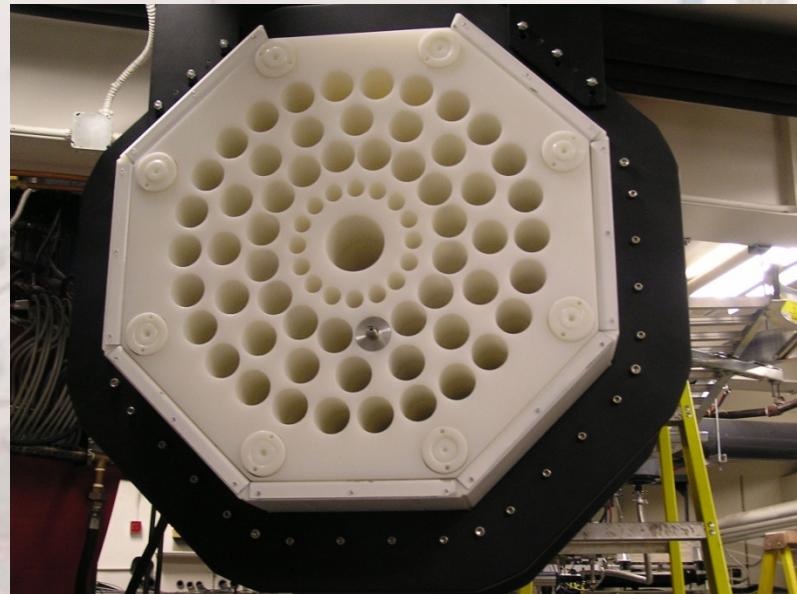
16  $^3\text{He}$  and 44  $\text{BF}_3$  proportional counters



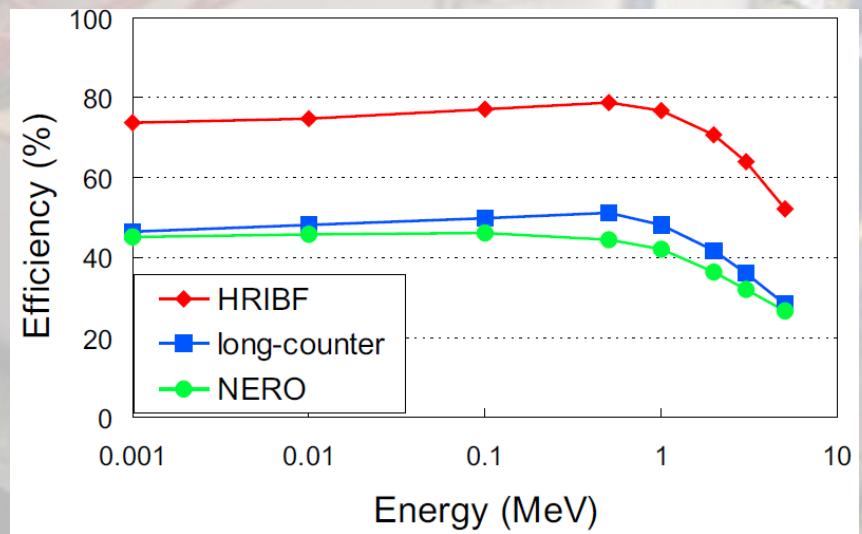
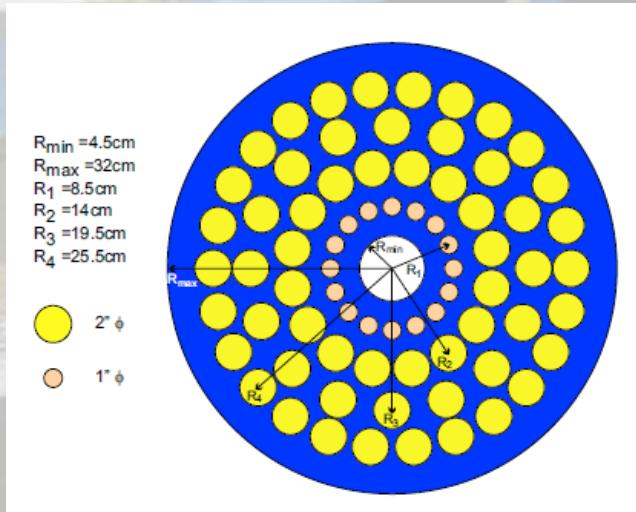
NERO (NSCL-MSU)



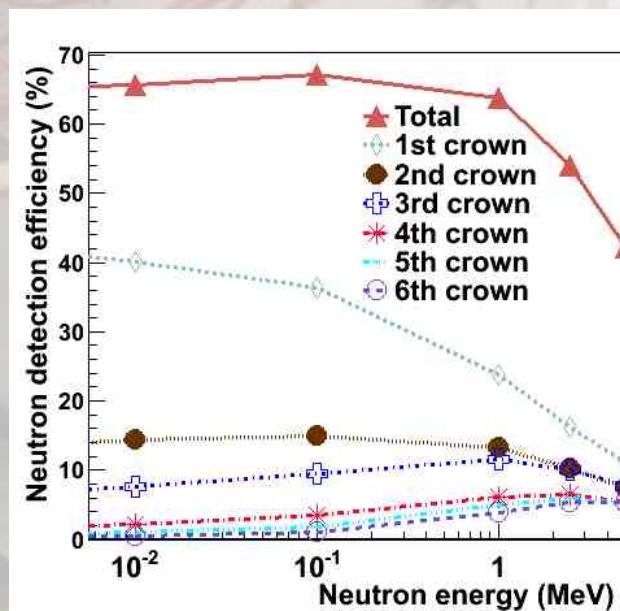
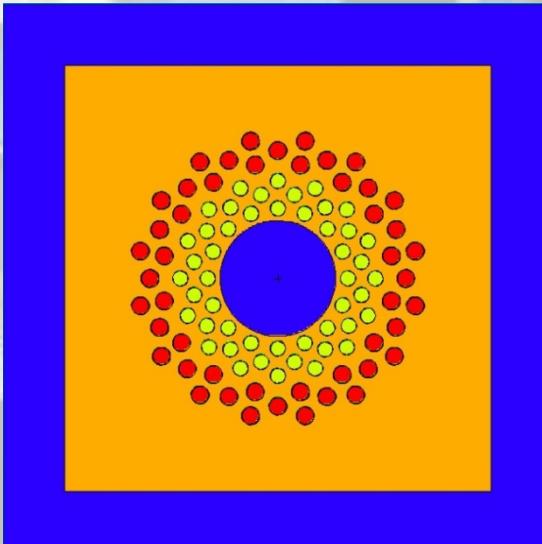
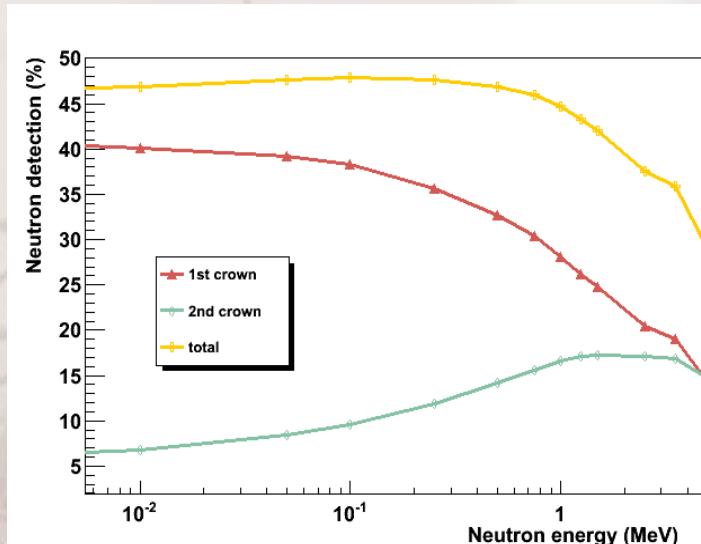
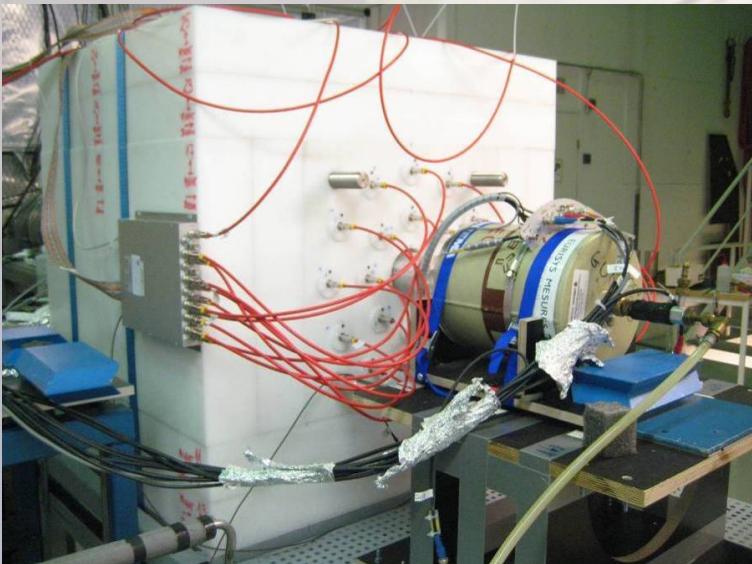
# Contadores $4\pi$ : 3Hen @ ORNL



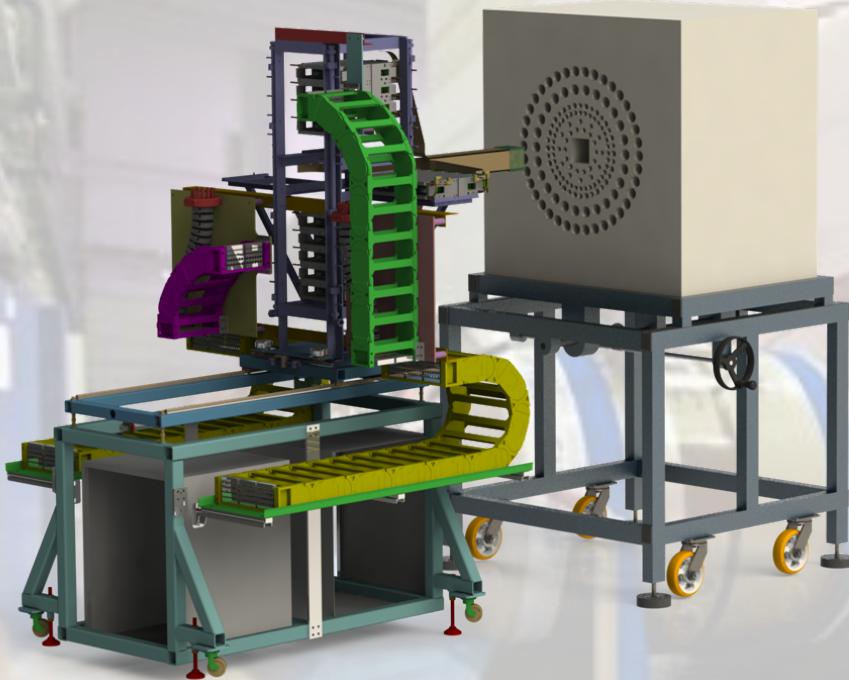
74 Tubos de  $^3\text{He}$



# Contadores 4 $\pi$ : BELEN @ JYFL, GSI, FAIR

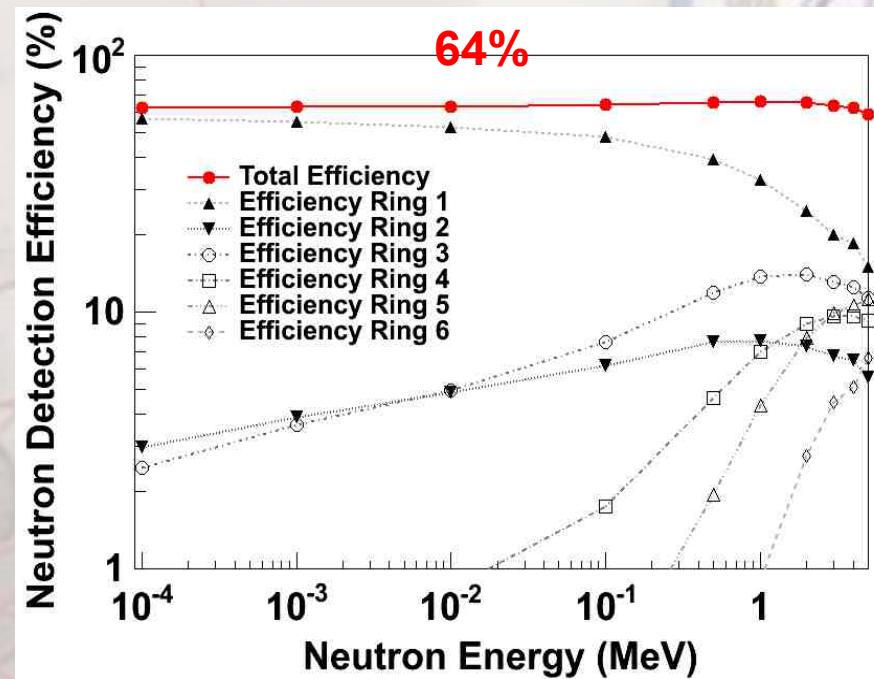


# Contadores $4\pi$ : BRIKEN

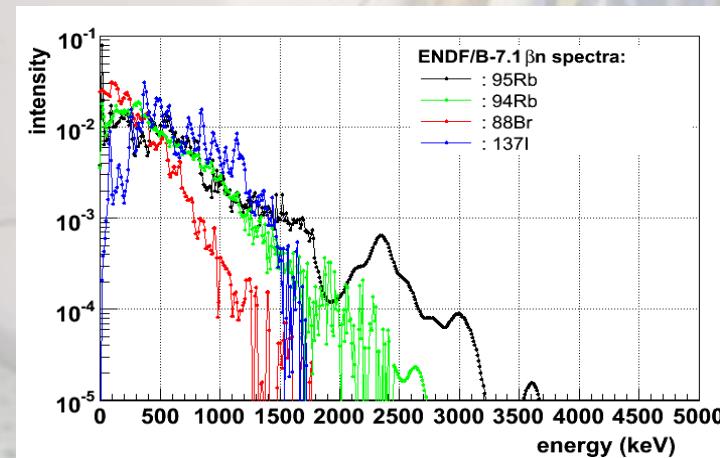


174 Tubos de  ${}^3\text{He}$

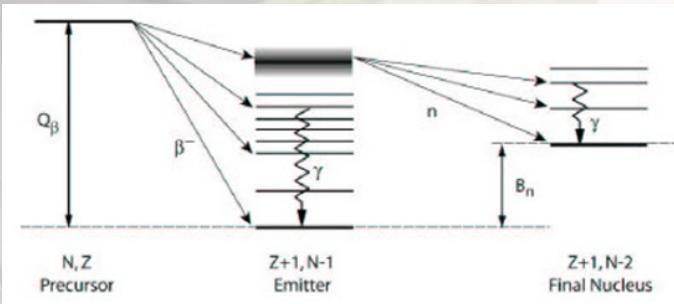
Ring	Radius (cm)	# ${}^3\text{He}$ Tubes	Pressure (atm)	Diameter (inch)	Institute
1	9.4	14	10	1	ORNL
2	13	12+12	5.13	1	RIKEN
3	16.8	10+26	10/8	1	GSI/UPC
4	20	18+18	5/8	1.18/1	JINR/UPC
5	27	26	10	2	ORNL
6	35	38	10	2	ORNL



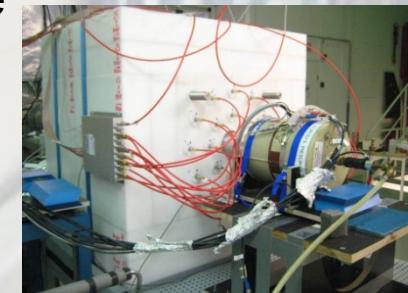
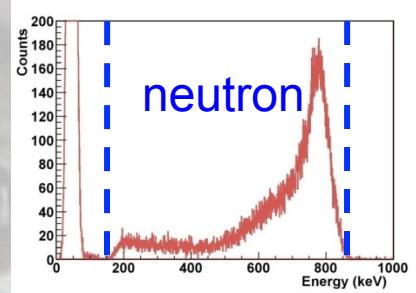
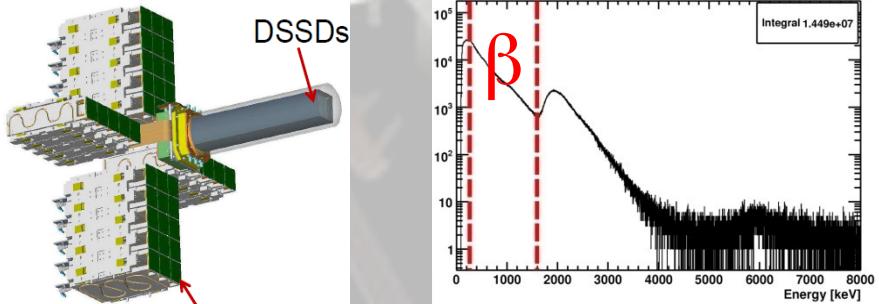
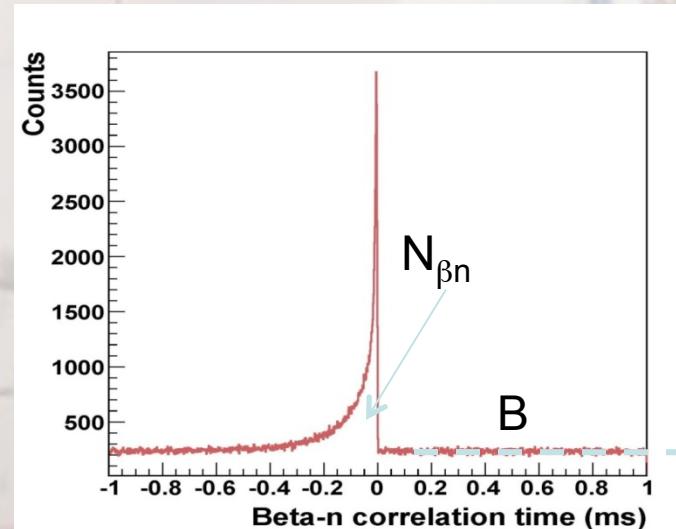
Eficiencia constante para cualquier  $E_n$



# Determinación del $P_n$



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

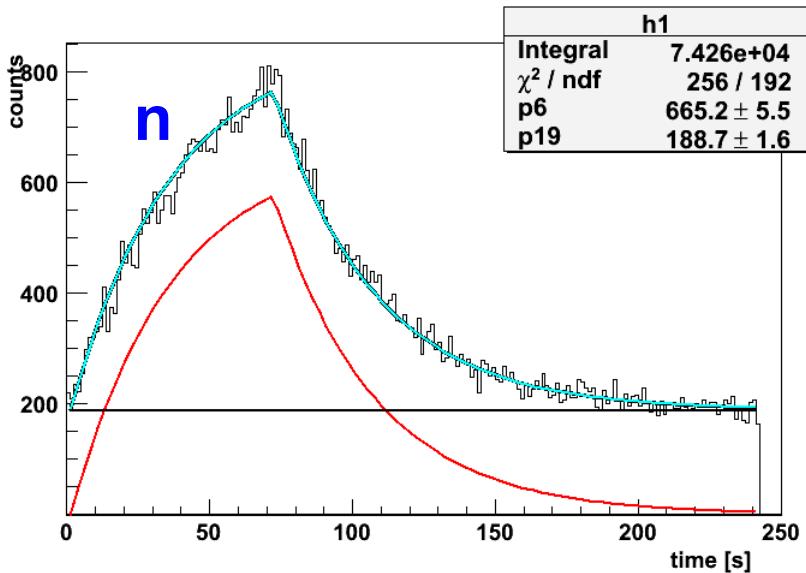
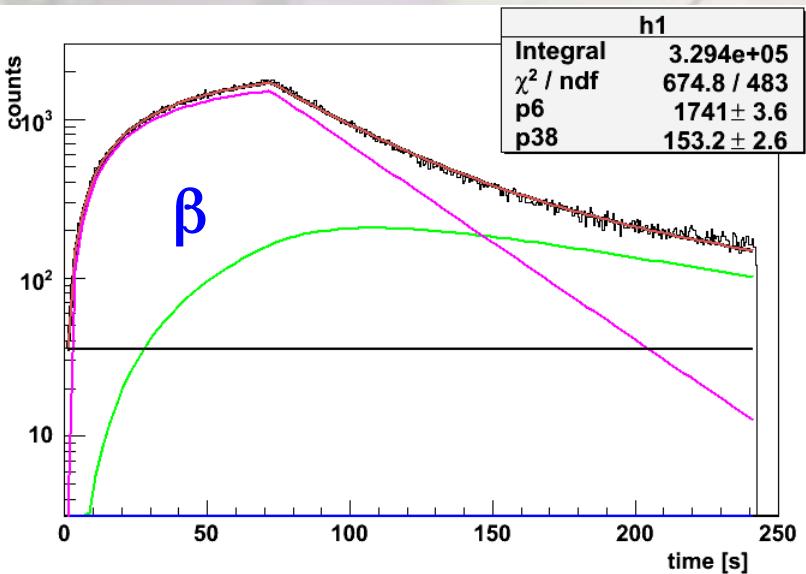


# Contenidos

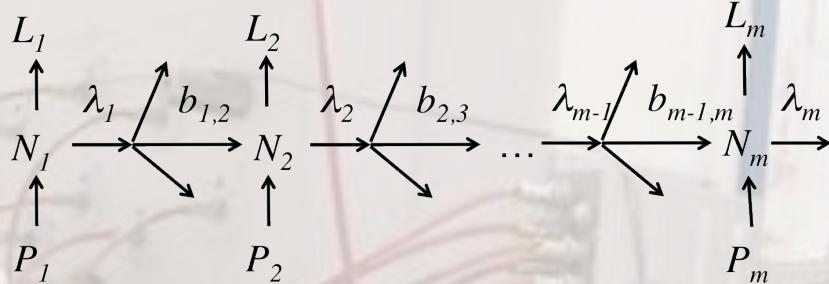
- Concepto de emisión retardada de neutrones
- Motivación e implicaciones de los neutrones retardados (NR)
  - Técnicas experimentales de medida
  - Ejemplos de experimentos
  - Perspectiva y resumen

# B-delayed neutrons in the fission fragments region at JYFL

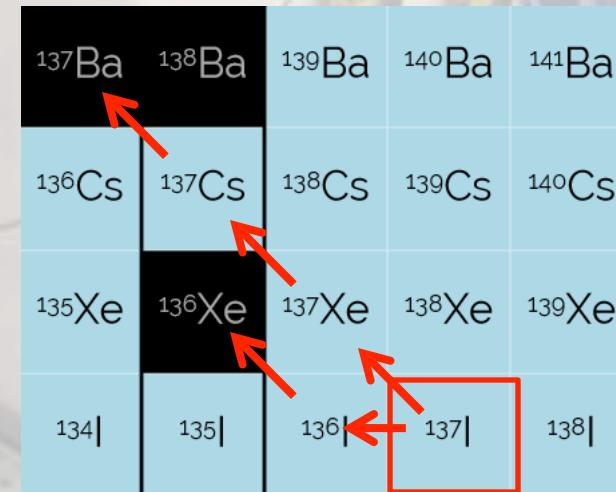
137|



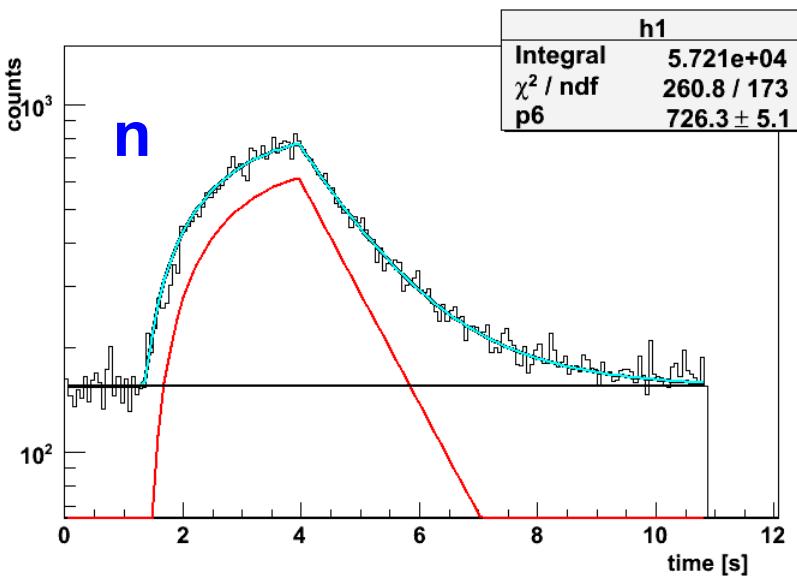
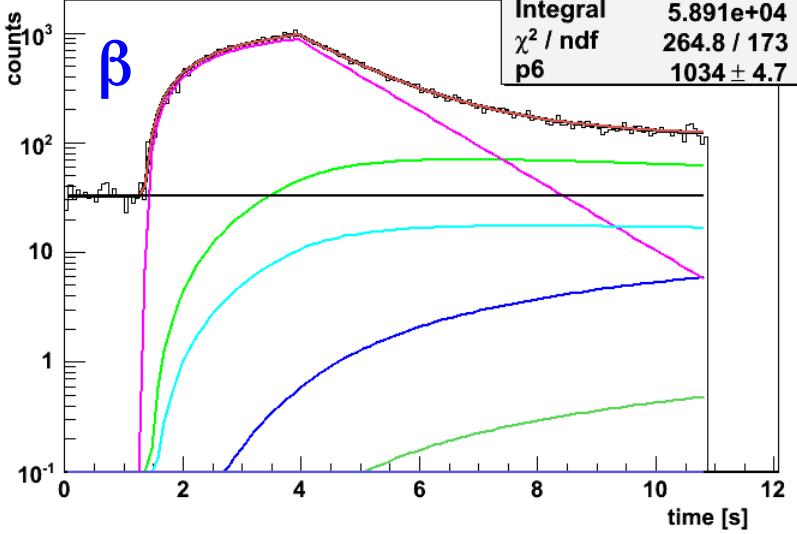
- Disentangle contributions fitting with solution of Bateman equations
- All parameters fixed except production



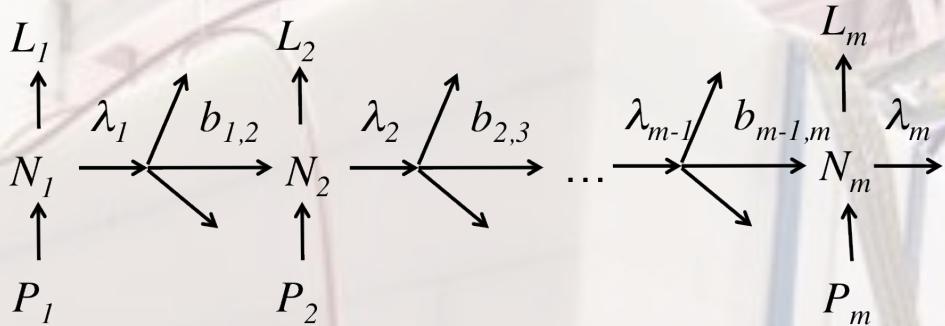
$$P_n = \frac{\epsilon_\beta}{\epsilon_n} \frac{N_n}{N_\beta} = 7.75(12)\%$$



# 86As



$P_n = 35.5(6)\%$



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

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

$\dots$

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

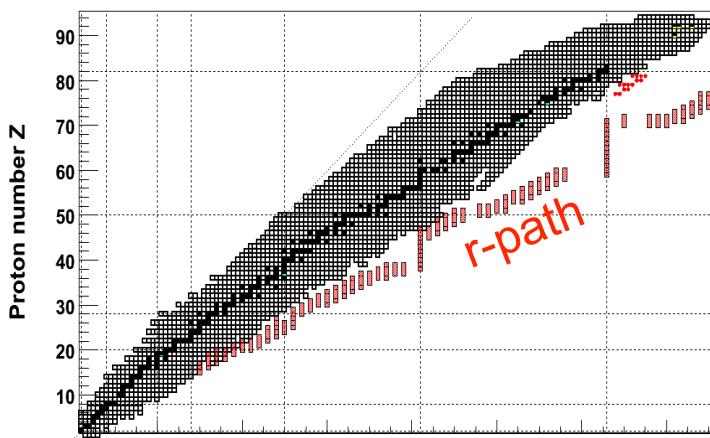
$$A_m^\beta(t) = \varepsilon_\beta \lambda_m N_m(t)$$

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

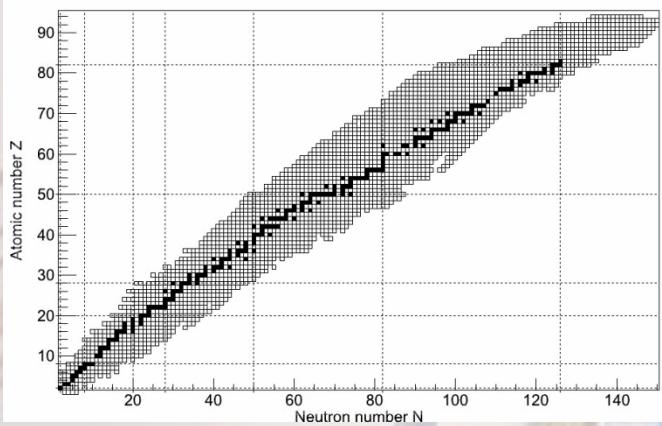
$$N_m(t) = \sum_{i=1}^m \left[ \left( \prod_{j=i}^{m-1} \lambda_j b_{j,j+1} \right) \times \sum_{j=i}^m \left( \frac{N_i^0 e^{-\tilde{\lambda}_j t}}{\prod_{k=i, k \neq j}^n (\tilde{\lambda}_k - \tilde{\lambda}_j)} + \frac{P_i (1 - e^{-\tilde{\lambda}_j t})}{\tilde{\lambda}_j \prod_{k=i, k \neq j}^n (\tilde{\lambda}_k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

# Nucleosynthesis around the 3<sup>rd</sup> r-process peak

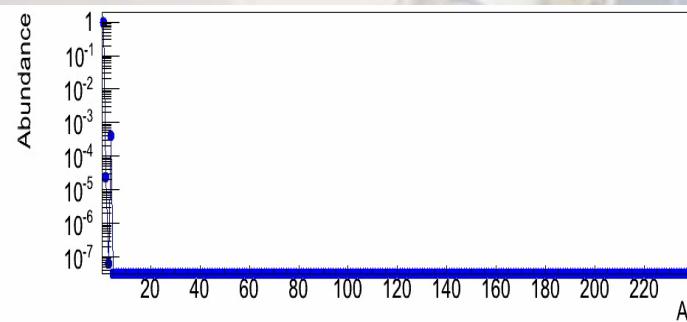
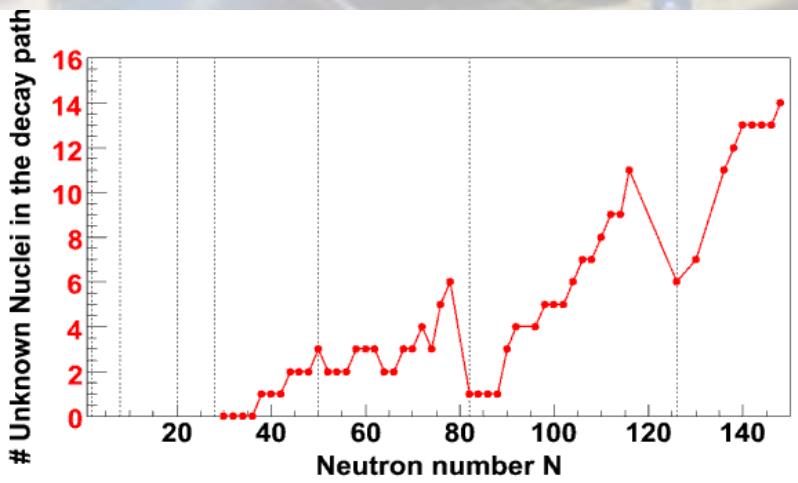
BELEN-30 @ GSI



State of the art SNe simulations do NOT yield the thermo-conditions (entropy) for the reproduction of the third r-process peak → SNe are not the r-process environment?

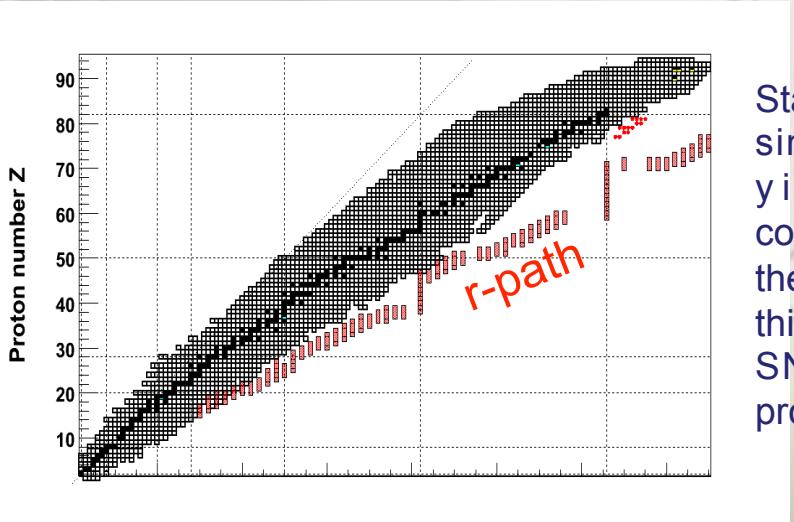
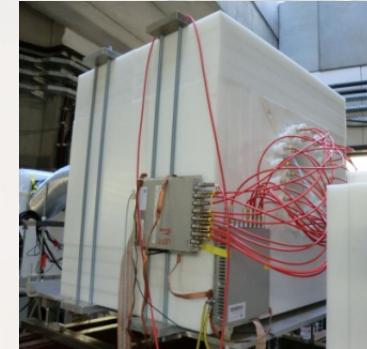


“Ignorance”-Curve



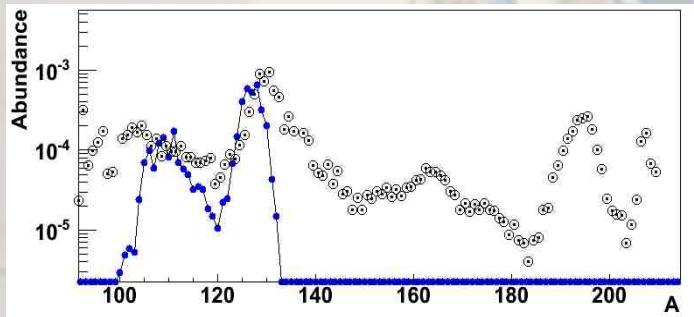
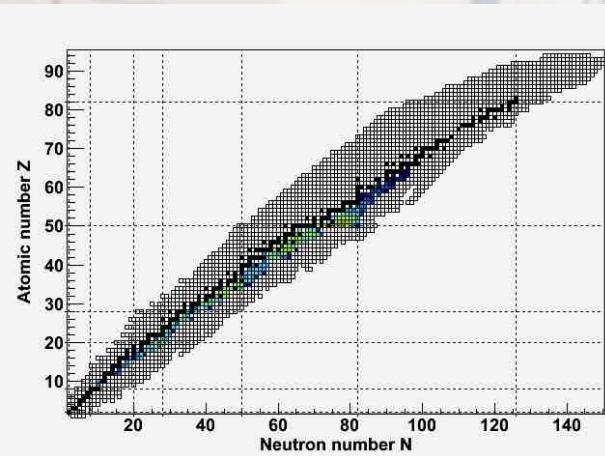
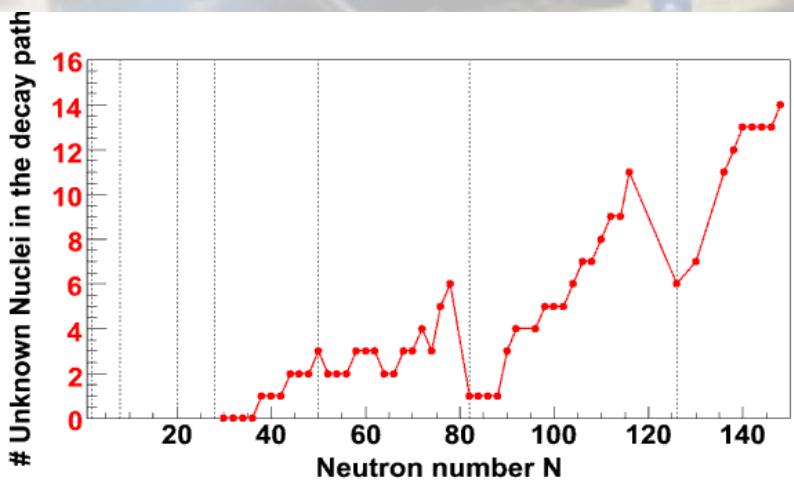
# Nucleosynthesis around the 3<sup>rd</sup> r-process peak

BELEN-30 @ GSI

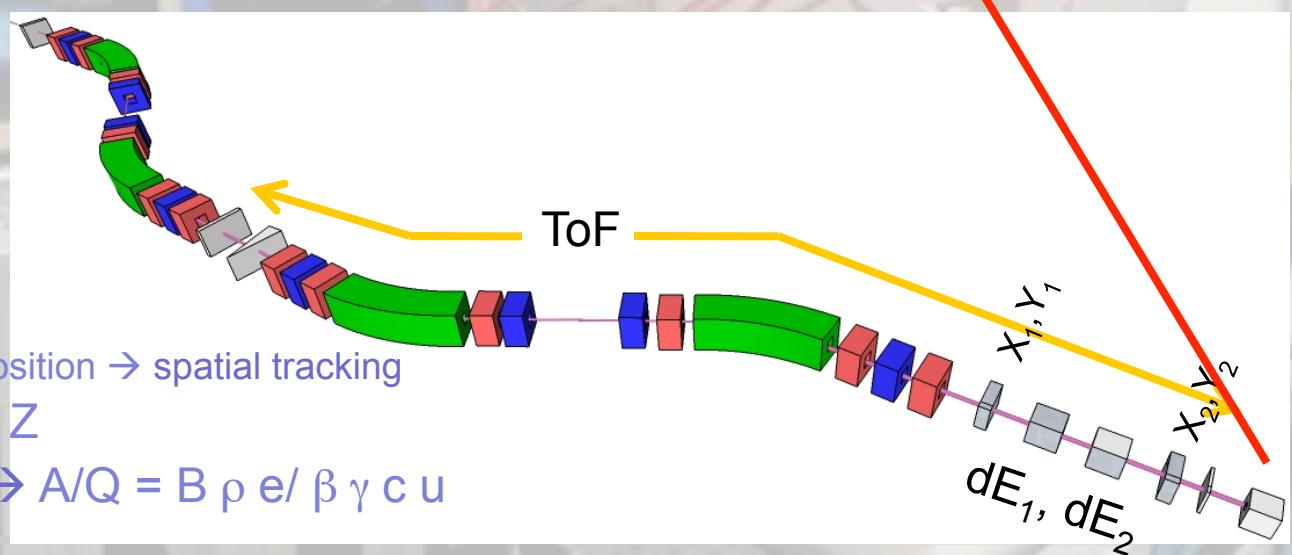
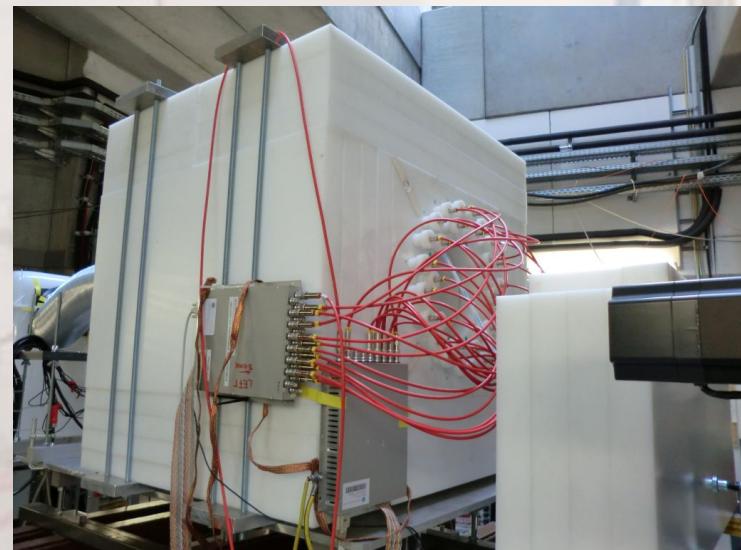
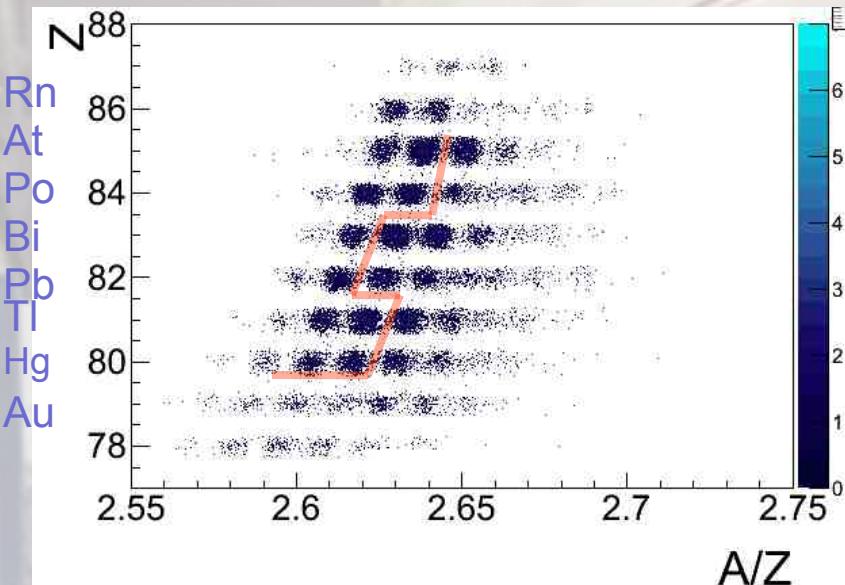


State of the art SNe simulations do NOT yield the thermo-conditions (entropy) for the reproduction of the third r-process peak → SNe are not the r-process environment?

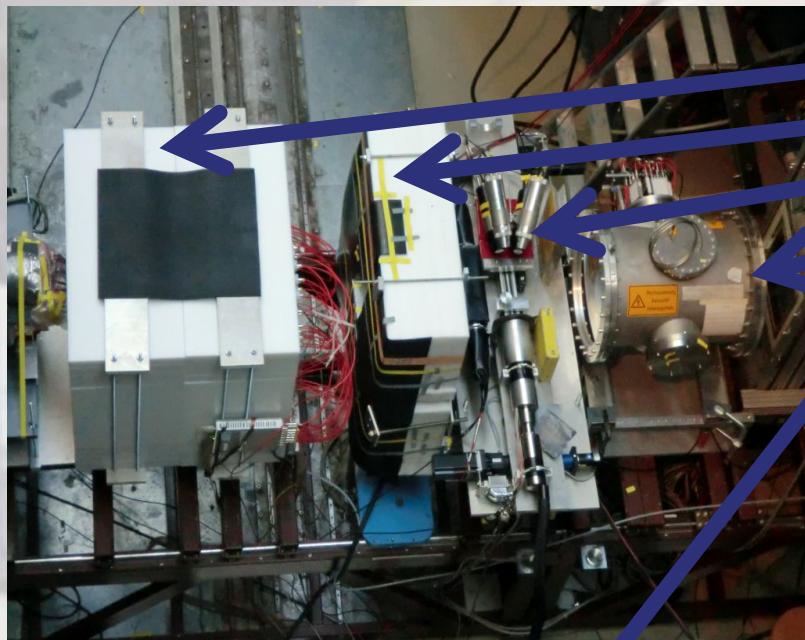
“Ignorance”-Curve



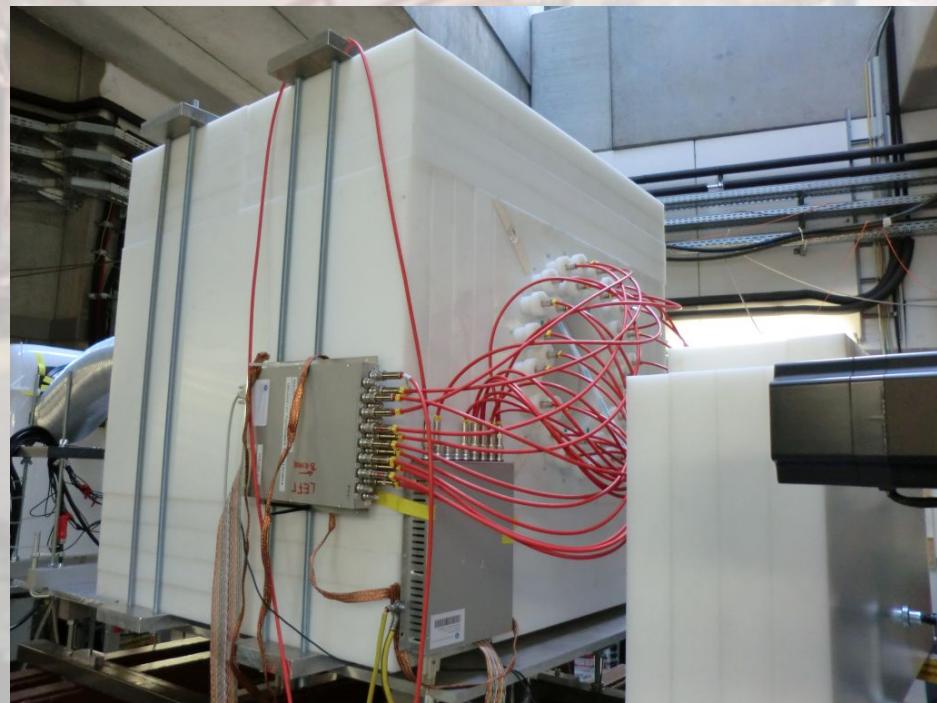
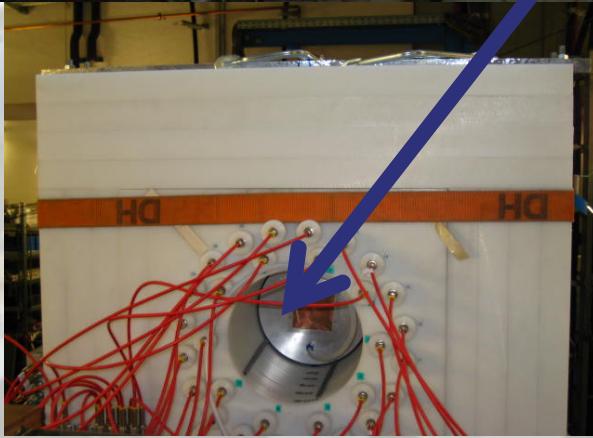
# Nucleosynthesis around the 3<sup>rd</sup> r-process peak



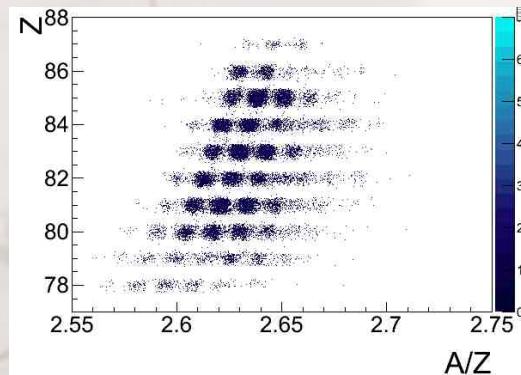
# Nucleosynthesis around the 3<sup>rd</sup> r-process peak



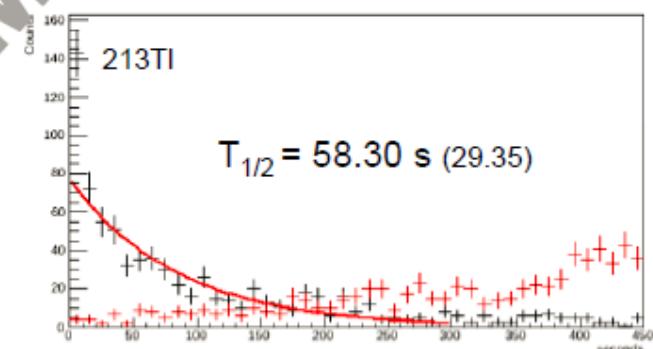
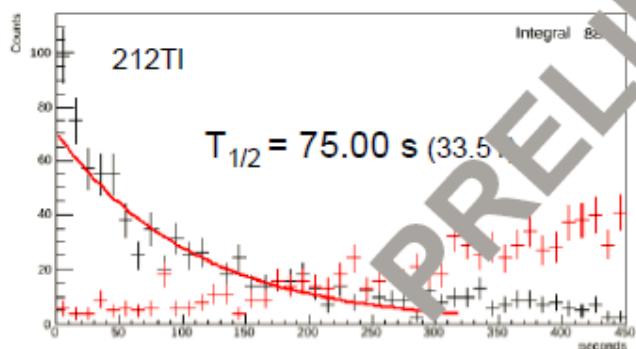
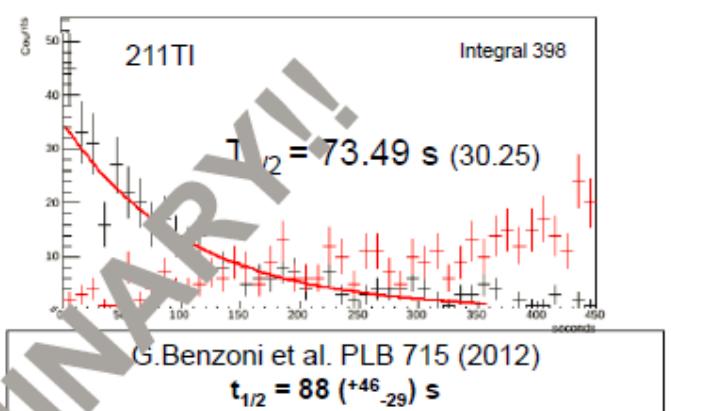
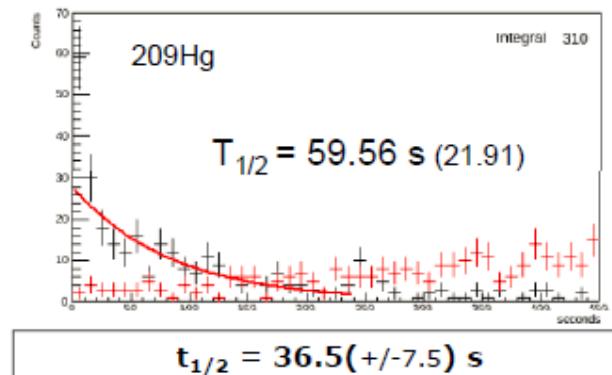
BELEN-30  
Polyethylene shielding  
Isomer tagger  
MUSIC  
SIMBA implantation det



# Nucleosynthesis around the 3<sup>rd</sup> r-process peak



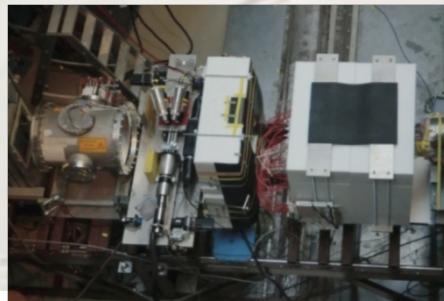
Implant-Beta Correlations  $\rightarrow t_{1/2}$



# Nucleosynthesis around the 3<sup>rd</sup> r-process peak

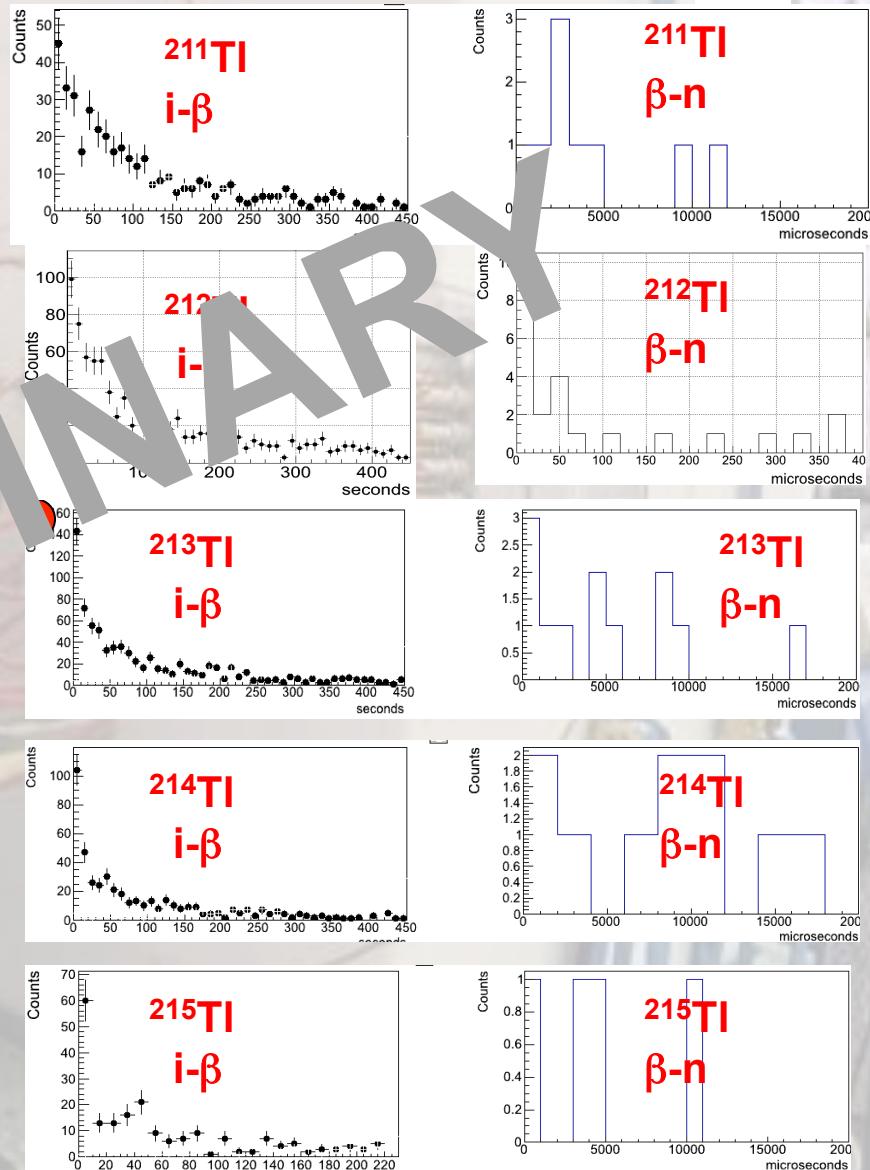
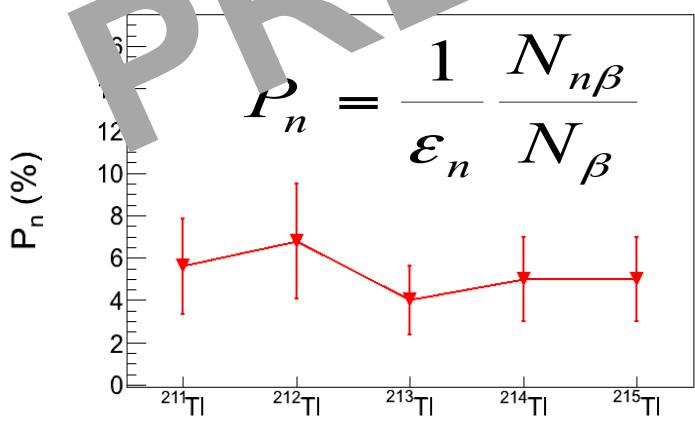
BELEN

Beta dELayed Neutron  
emission detector



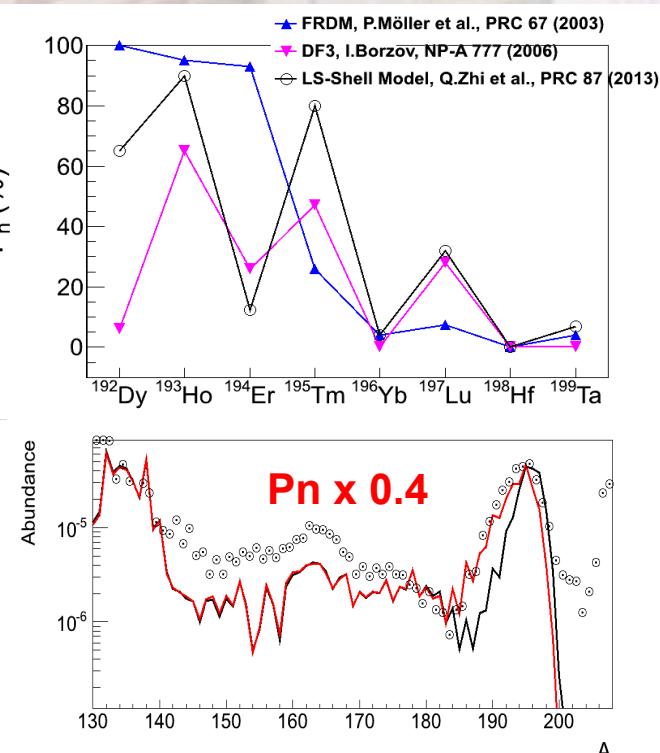
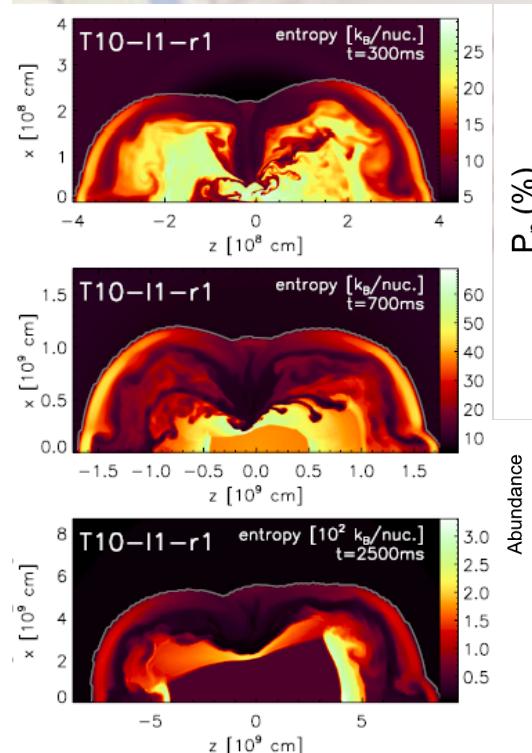
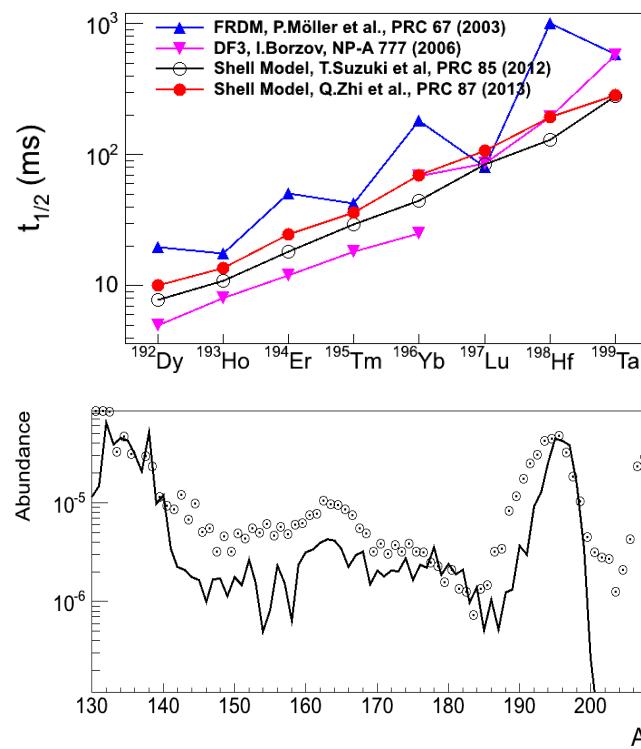
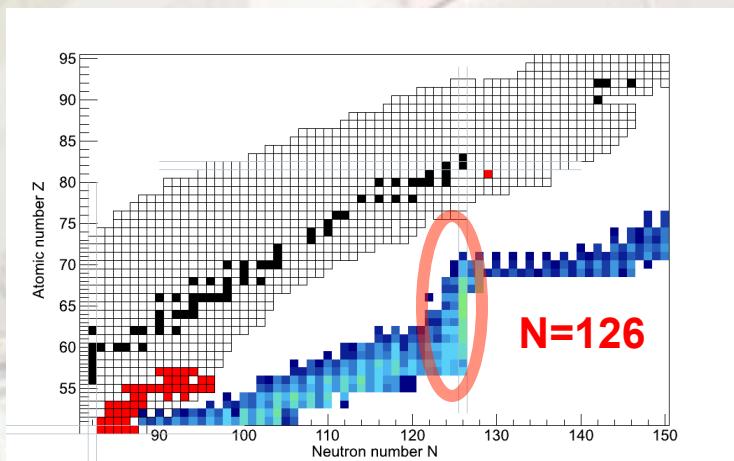
Bi202	Bi203	Bi204	Bi205	Bi206	Bi207	Bi208	Bi209	Bi210	Bi211	Bi212	Bi213	Bi214	
82	Pb201	Pb202	Pb203	Pb204	Pb205	Pb206	Pb207	Pb208	Pb209	Pb210	Pb211	Pb212	Pb213
80	Tl200	Tl201	Tl202	Tl203	Tl204	Tl205	Tl206	Tl207	Tl208	Tl209	Tl210	Tl211	Tl212
	Hg199	Hg200	Hg201	Hg202	Hg203	Hg204	Hg205	Hg206	Hg207	Hg208	Hg209	Hg210	Hg211
88	Au198	Au199	Au200	Au201	Au202	Au203	Au204	Au205	Au206	Au207	Au208	Au209	Au210
78	Pt197	Pt198											
	Ir196	Ir197											
76	Os195	Os196											
	Re194												
74													
120													

$$P_n = \frac{1}{\epsilon_n} \frac{N_{n\beta}}{N_\beta}$$



# Nucleosynthesis around the 3<sup>rd</sup> r-process peak

**N=126**

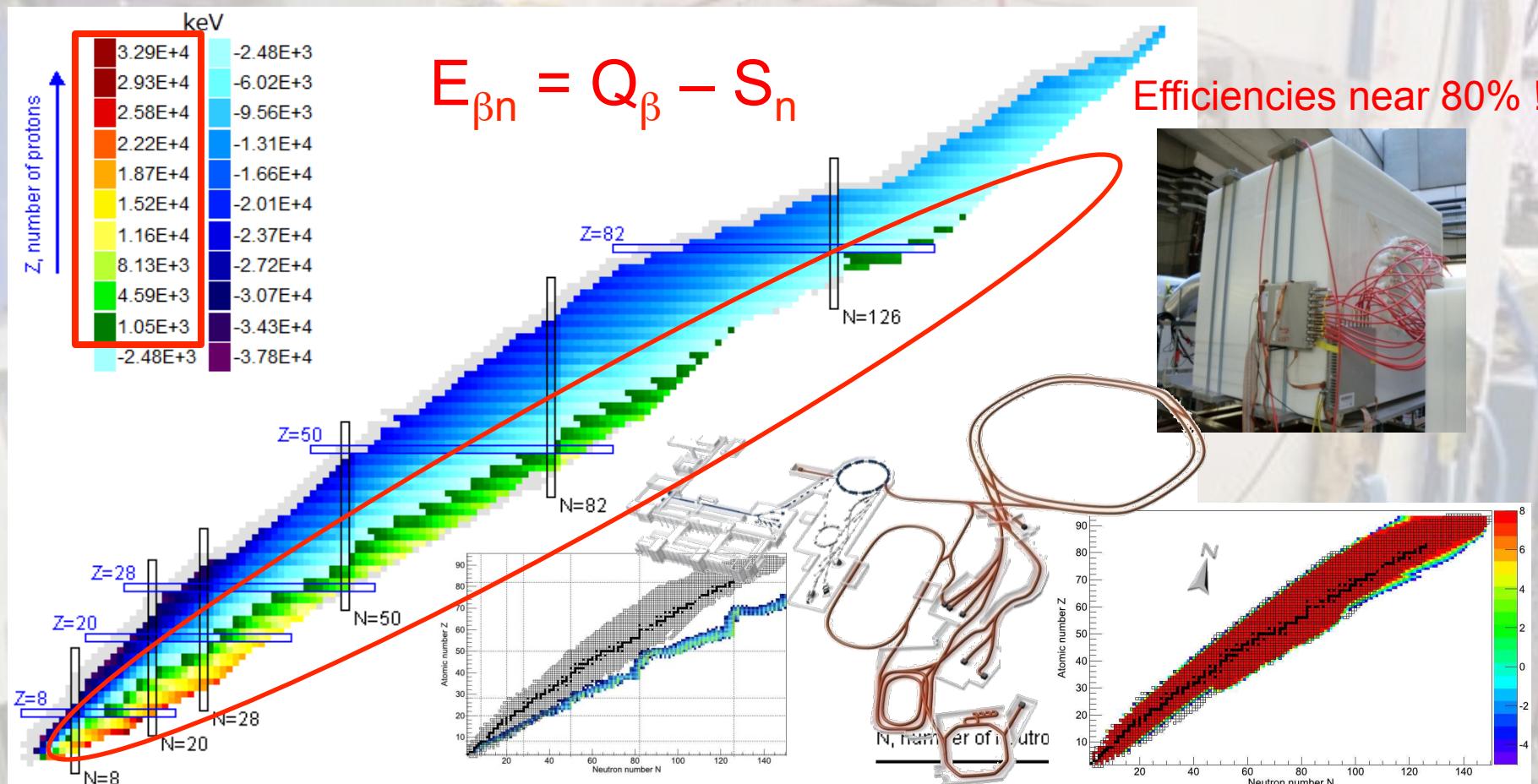


# Resumen

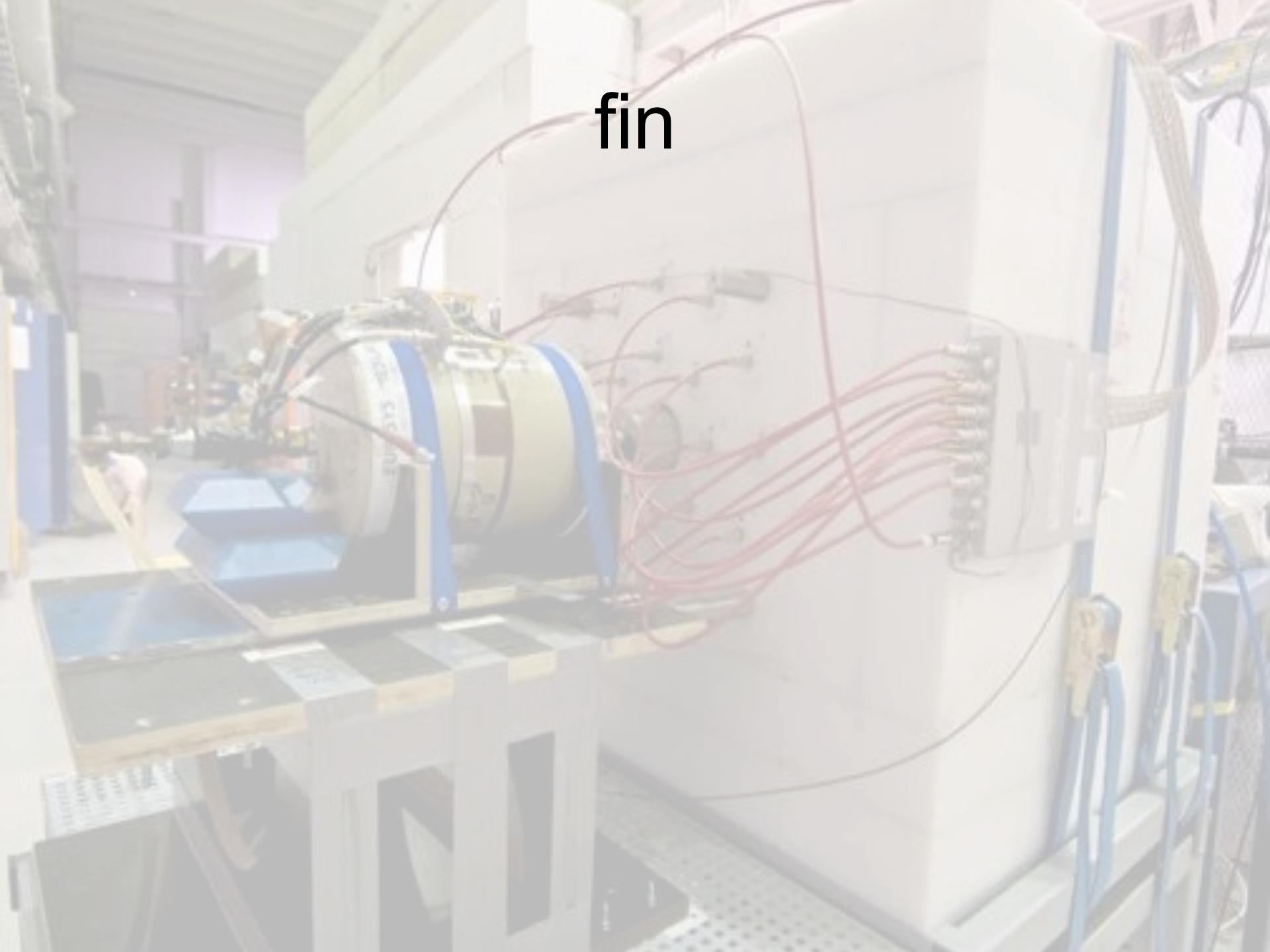
- El proceso de emisión de neutrones retardados, es un efecto que puede tener lugar siempre que esté energéticamente permitido, es decir, cuando  $Q_\beta - S_n > 0$ .
- En los casos en los que es energéticamente factible, la probabilidad emisión retardada de neutrones depende de la distribución energética del  $\beta$ -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  $\beta$ - de la desintegración) como los neutrones.
- El método más común para la medida de NR consiste en el uso de contadores gaseosos ( $^3\text{He}$  y/o  $^{10}\text{B}$ ) 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.

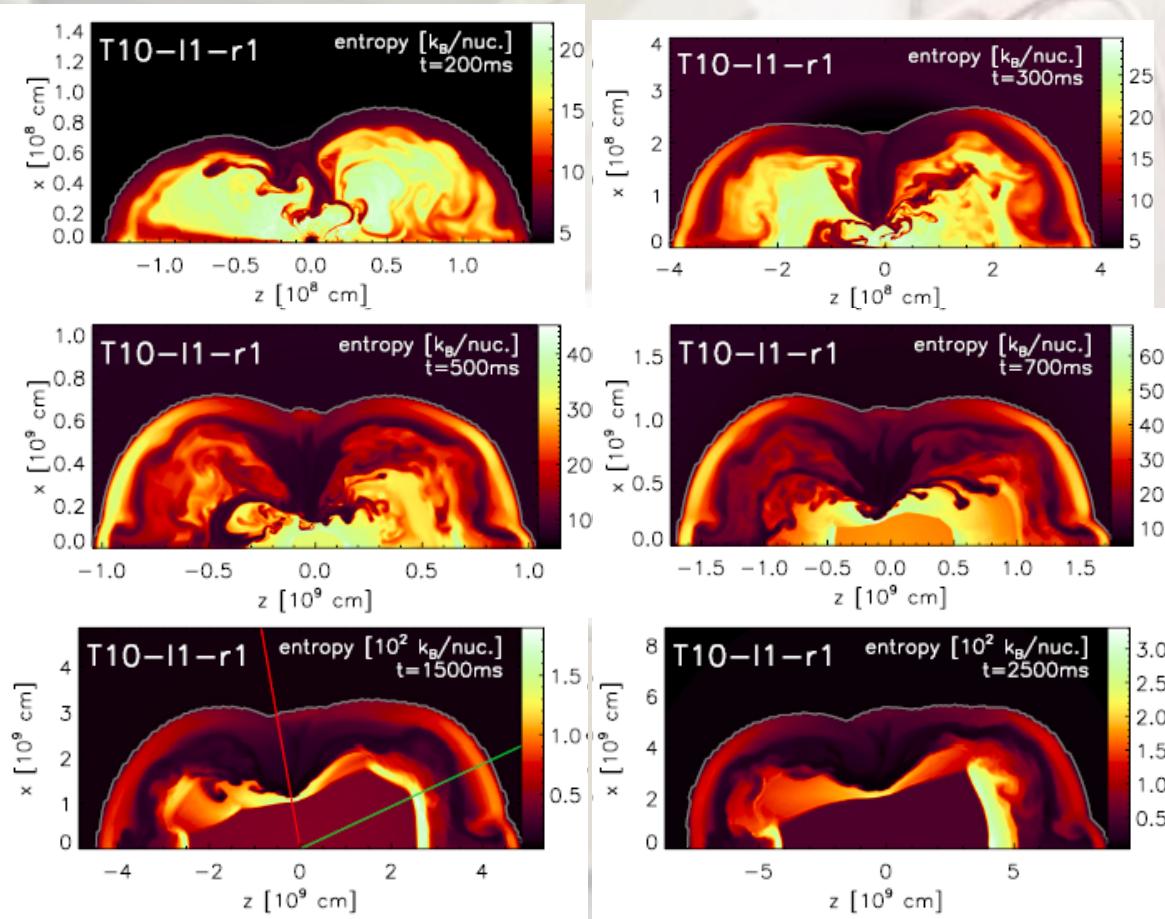
# Perspectiva:

- 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.

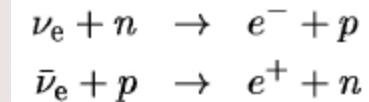


fin





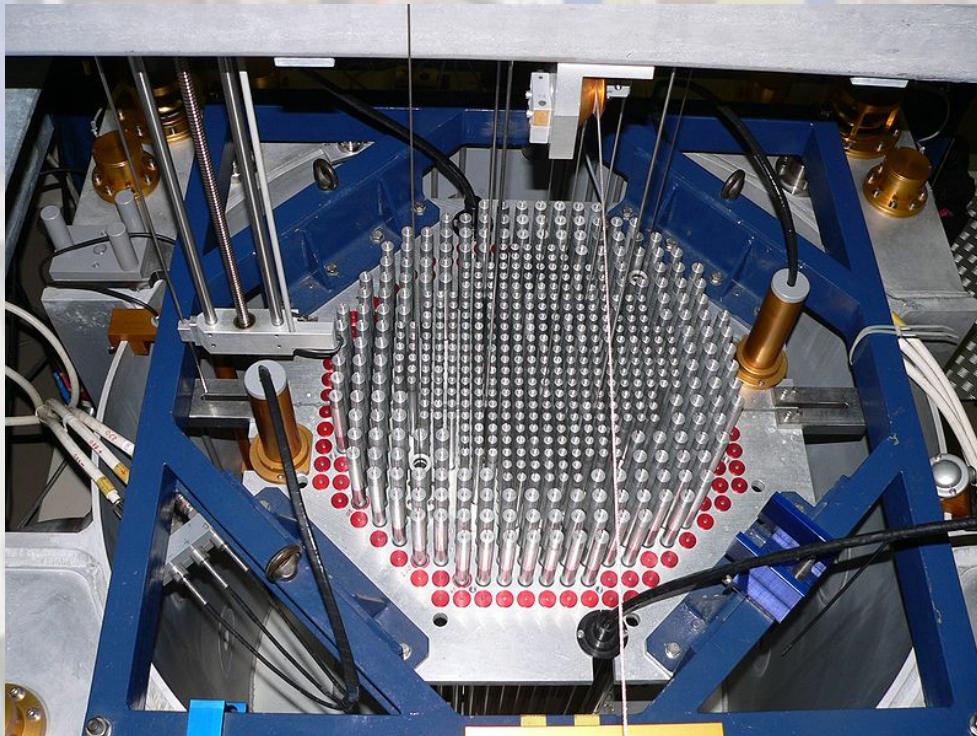
SN con  $\nu$ -driven Wind



# Producción de energía por fisión nuclear

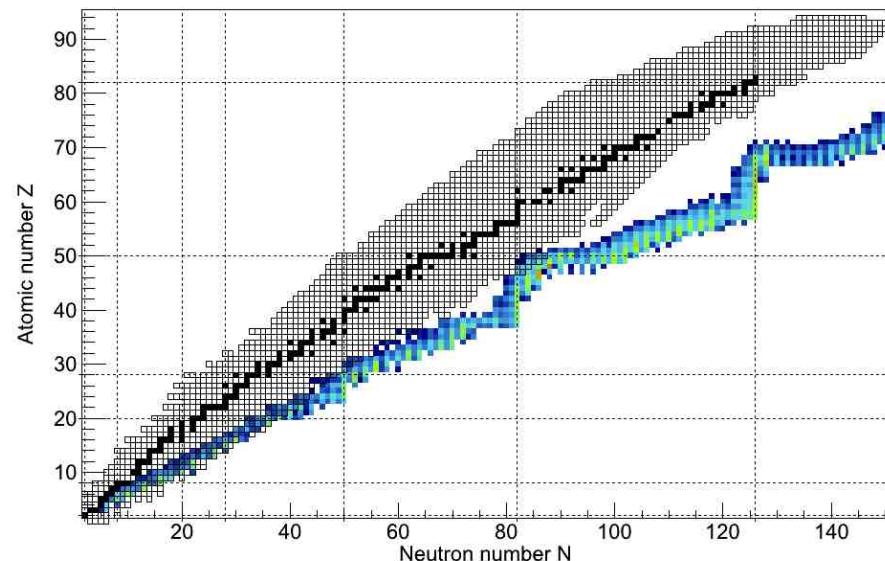
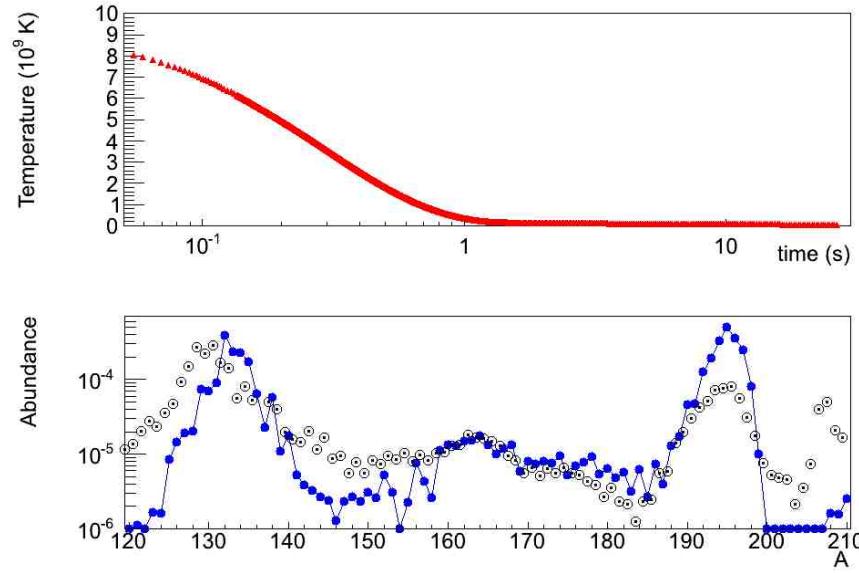
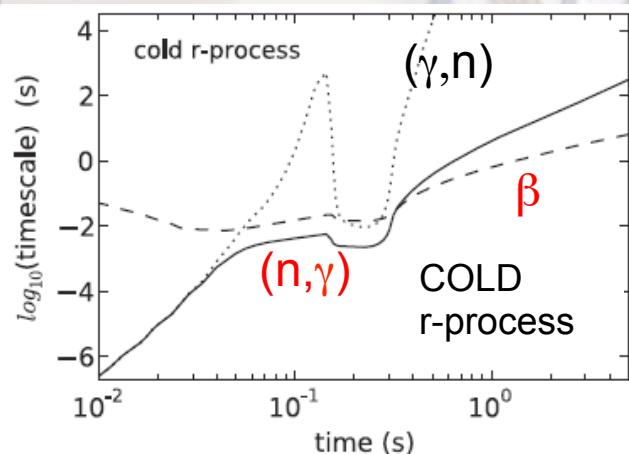
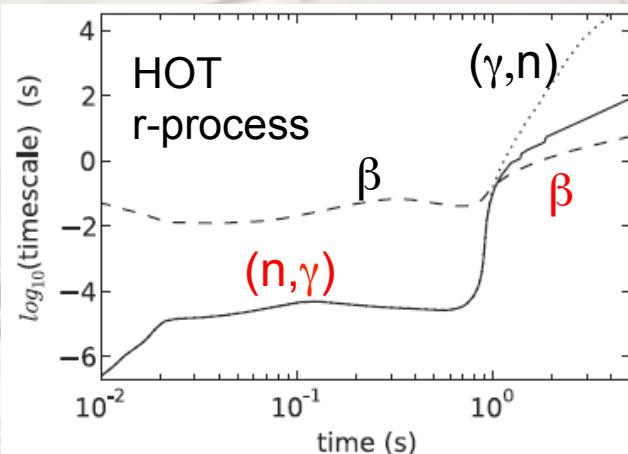
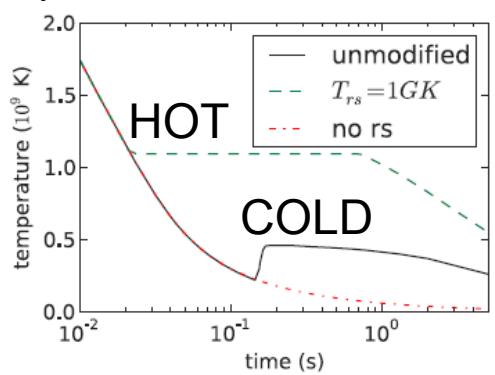
La producción de energía en un reactor se ajusta controlando el número de neutrones disponibles para producir fisión.

Para ello se utilizan “barras de control”, que están hechas de un material que absorbe neutrones (alta CS de captura). Cuanto más se introduce la barra de control en el reactor, más se suprime los neutrones y por lo tanto la fisión y la producción de energía.

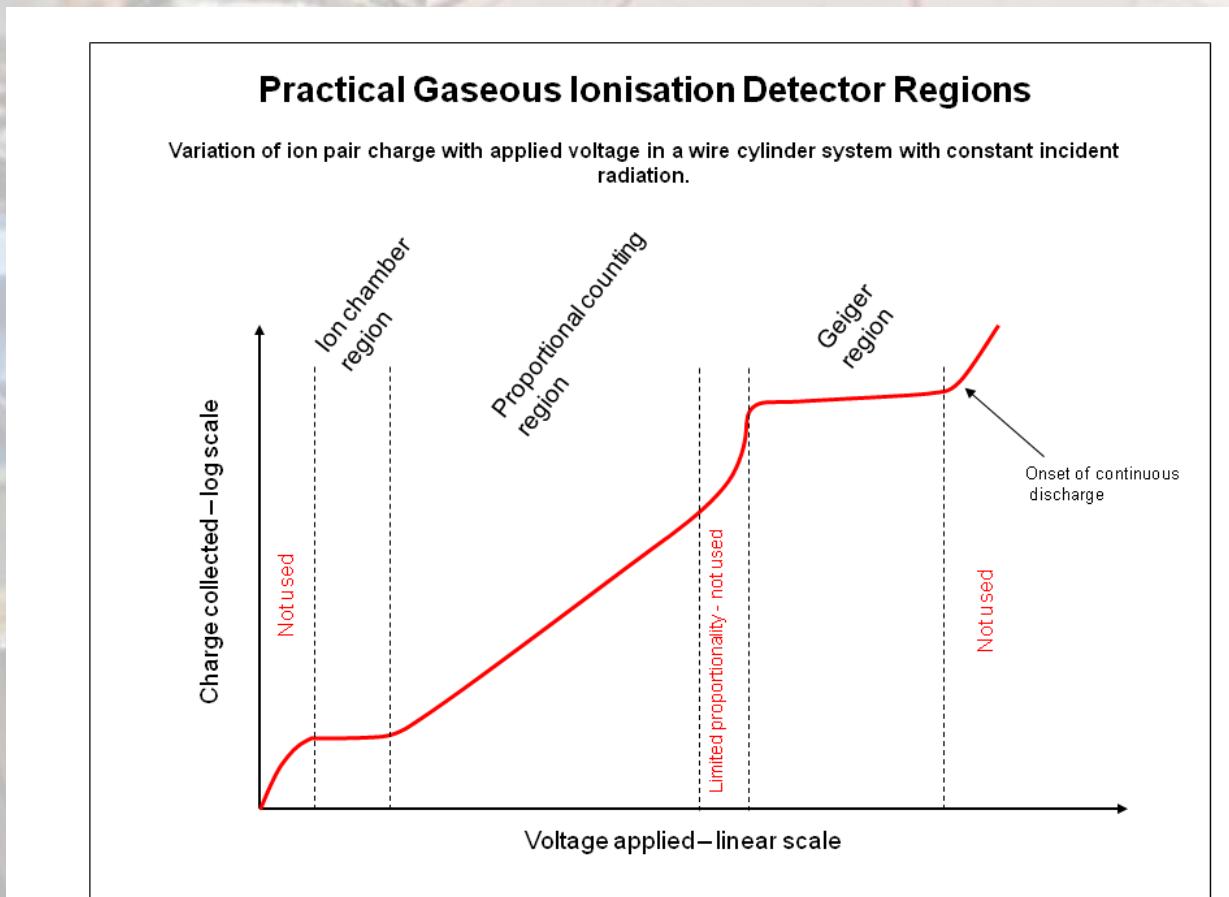


# Nucleosíntesis de elementos pesados en entornos estelares explosivos

Phys. Rev. C, 83, A.Arcones 2011



# Gas detector modes: ion-chamber, proportional counter, Geiger

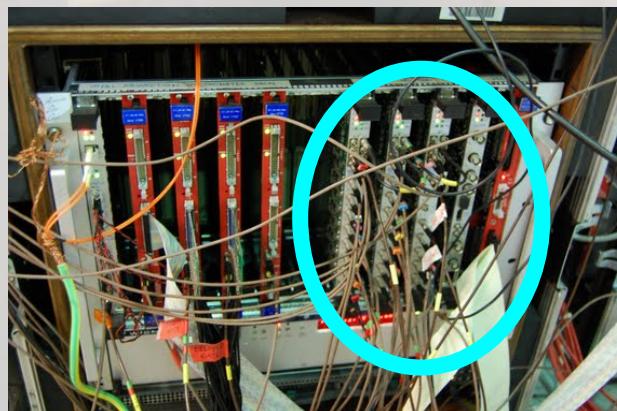
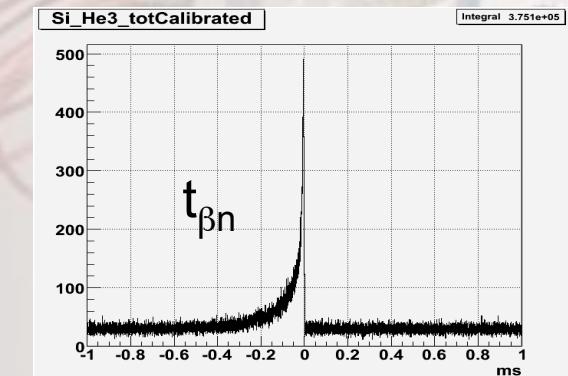
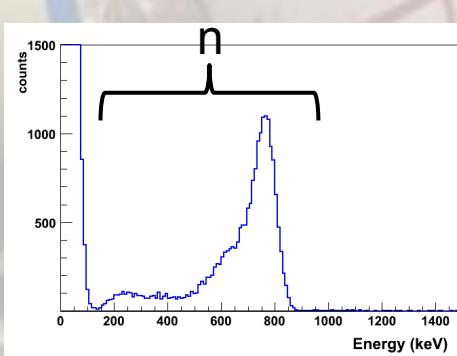
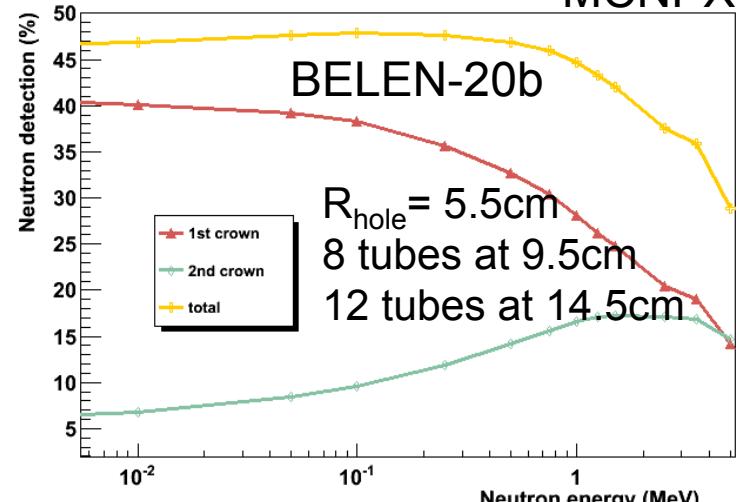
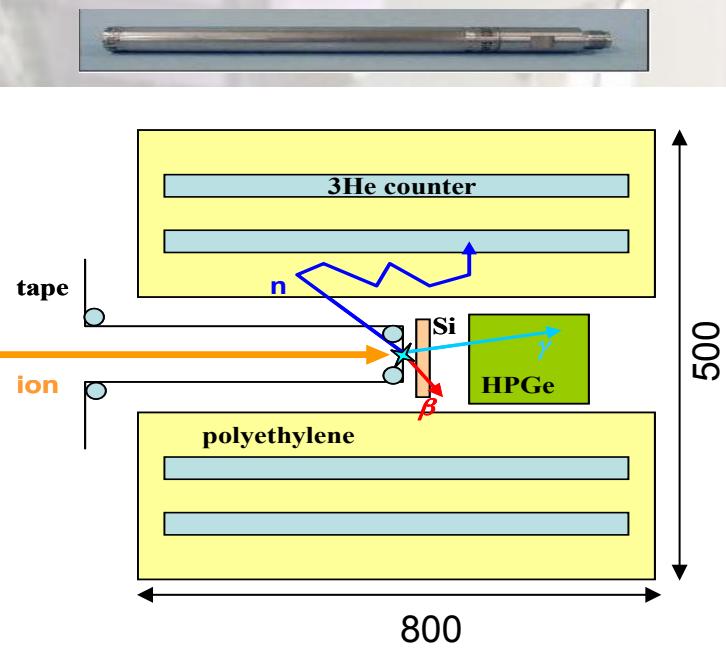


# Ejemplos de experimentos

efficiency up to 48%  
MCNPX

## BELEN

20 Ø2.5cm×60cm 3He tubes @20atm



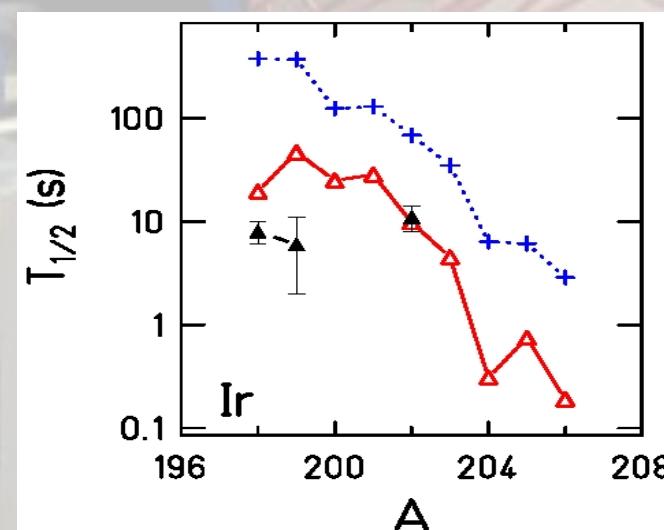
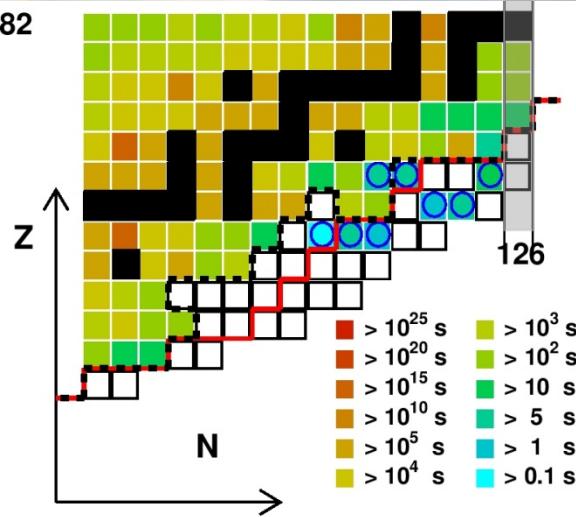
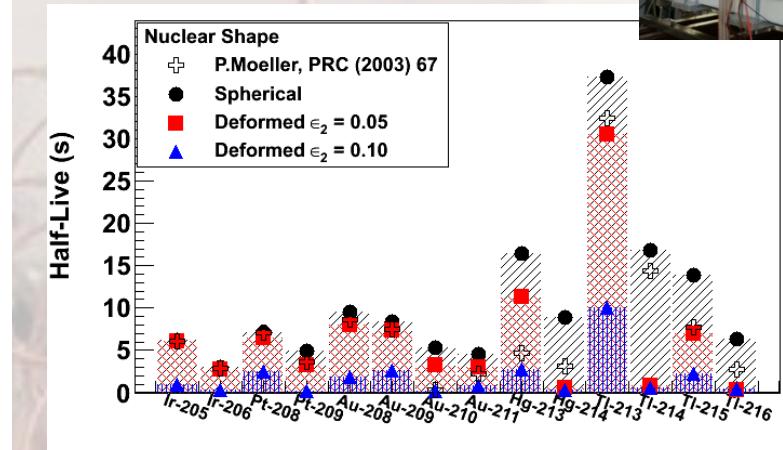
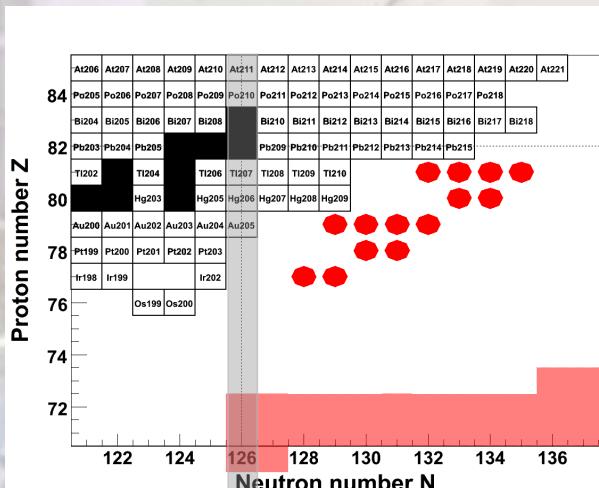
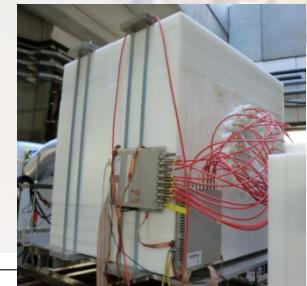
**GasificTL:**  
**Self triggered DACQ:**  
-Time-energy pairs for every neutron or  $\beta$   
-Clean noise separation  
-Minimum dead time:<0.5%

# Ejemplos de experimentos:

BELEN-30 @ GSI

Estudio de la formación del tercer pico de abundancias en el proceso r

- Difficult to calculate/predict half-live of the nuclei in this region:



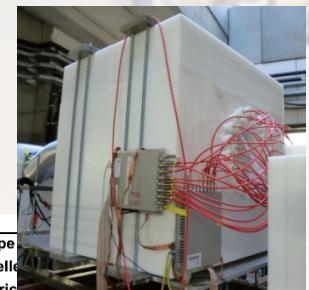
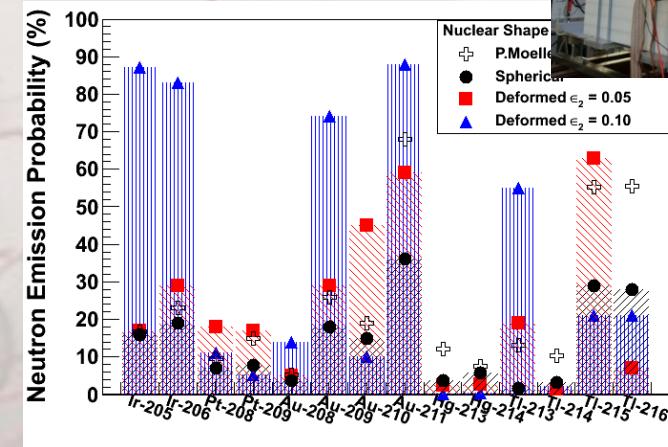
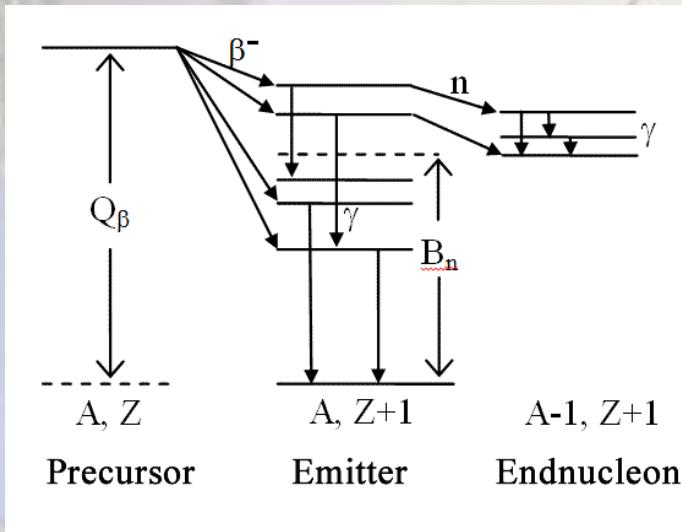
△ DF3 + QRPA  
 (I.Borzov, et al. 2003)  
+ FRDM + QRPA  
 (P.Moeller, et al. 2003)  
▲ Exp. T. Kurtukian et al.

# Ejemplos de experimentos:

BELEN-30 @ GSI

Estudio de la formación del tercer pico de abundancias en el proceso r

- Difficult to calculate/predict Pn-values of the nuclei in this region:



197 Bi	198 Bi	199 Bi	200 Bi	201 Bi	202 Bi	203 Bi	204 Bi	205 Bi	206 Bi	207 Bi	208 Bi	209 Bi	210 Bi	211 Bi	212 Bi
196 Pb	197 Pb	198 Pb	199 Pb	200 Pb	201 Pb	202 Pb	203 Pb	204 Pb	205 Pb	206 Pb	207 Pb	208 Pb	209 Pb	210 Pb	211 Pb
195 Tl	196 Tl	197 Tl	198 Tl	199 Tl	200 Tl	201 Tl	202 Tl	203 Tl	204 Tl	205 Tl	206 Tl	207 Tl	208 Tl	209 Tl	210 Tl
194 Hg	195 Hg	196 Hg	197 Hg	198 Hg	199 Hg	200 Hg	201 Hg	202 Hg	203 Hg	204 Hg	205 Hg	206 Hg	207 Hg	208 Hg	209 Hg
193 Au	194 Au	195 Au	196 Au	197 Au	198 Au	199 Au	200 Au	201 Au	202 Au	203 Au	204 Au	205 Au			
192 Pt	193 Pt	194 Pt	195 Pt	196 Pt	197 Pt	198 Pt	199 Pt	200 Pt	201 Pt	202 Pt					
191 Ir	192 Ir	193 Ir	194 Ir	195 Ir	196 Ir	197 Ir	198 Ir	199 Ir							
190 Os	191 Os	192 Os	193 Os	194 Os	195 Os	196 Os	197 Os								
189 Re	190 Re	191 Re	192 Re	193 Re	194 Re										
188 W	189 W	190 W	191 W	192 W											
187 Ta	188 Ta	189 Ta	190 Ta												

$\beta$ -delayed neutron emission has a twofold effect on the r-process:

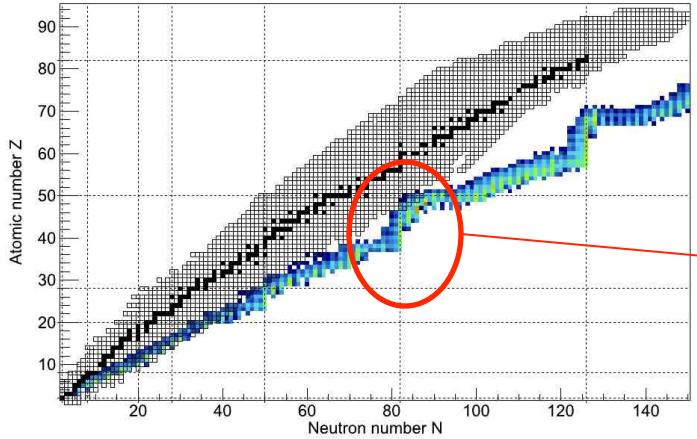
1. Increases the neutron density
2. Shifts the pattern towards lower A

# Nucleosynthesis around the 2<sup>nd</sup> r-process peak

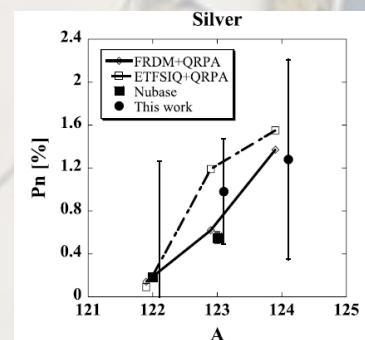
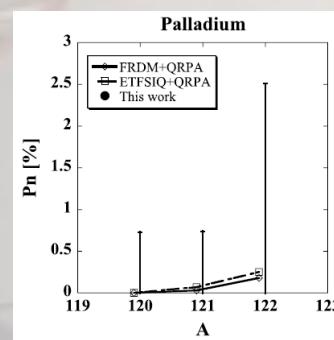
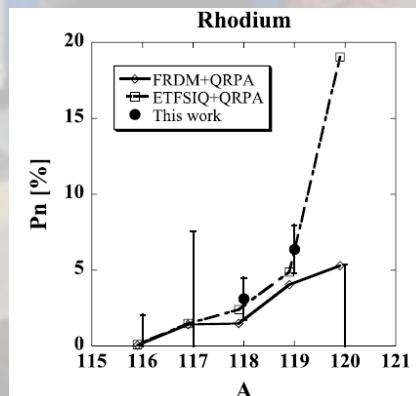
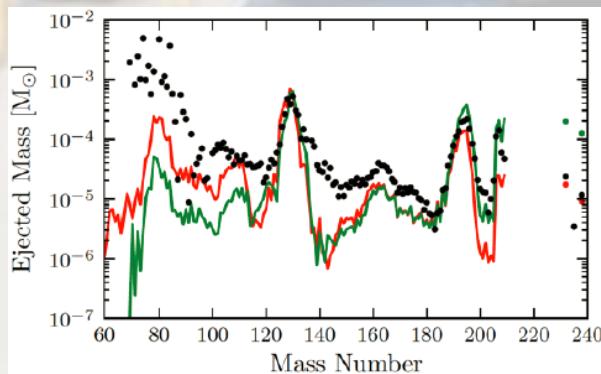
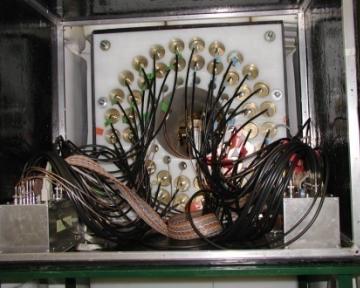
PHYSICAL REVIEW C 73, 035801 (2006)

$\beta$ -decay half-lives and  $\beta$ -delayed neutron emission probabilities for neutron rich nuclei close to the  $N = 82$  r-process path

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NERO @ NSCL-MSU



r-process model  
calculation with  
new Pn's:

$N_n = 5 \cdot 10^{23} \text{ cm}^{-3}$   
 $T_9 = 1.35 \text{ K}$   
 $\tau = 2 \text{ s}$

$\rightarrow ^{120}\text{Sn}/^{119}\text{Sn} = 1.66$  instead of 1.22 (40% increase!)