β-decay studies at RIKEN RIBF for r-process nucleosynthesis

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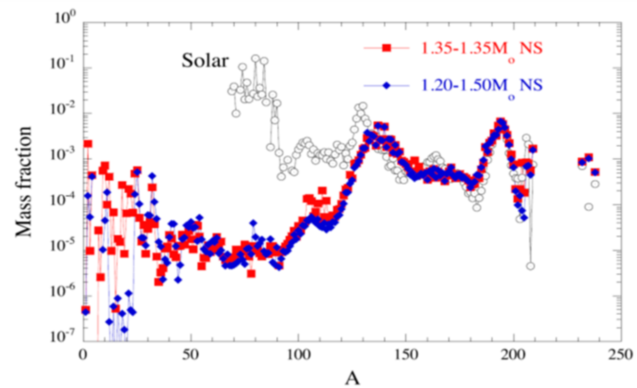
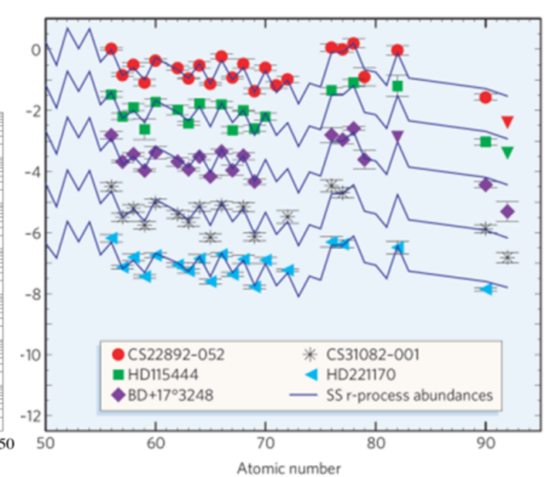
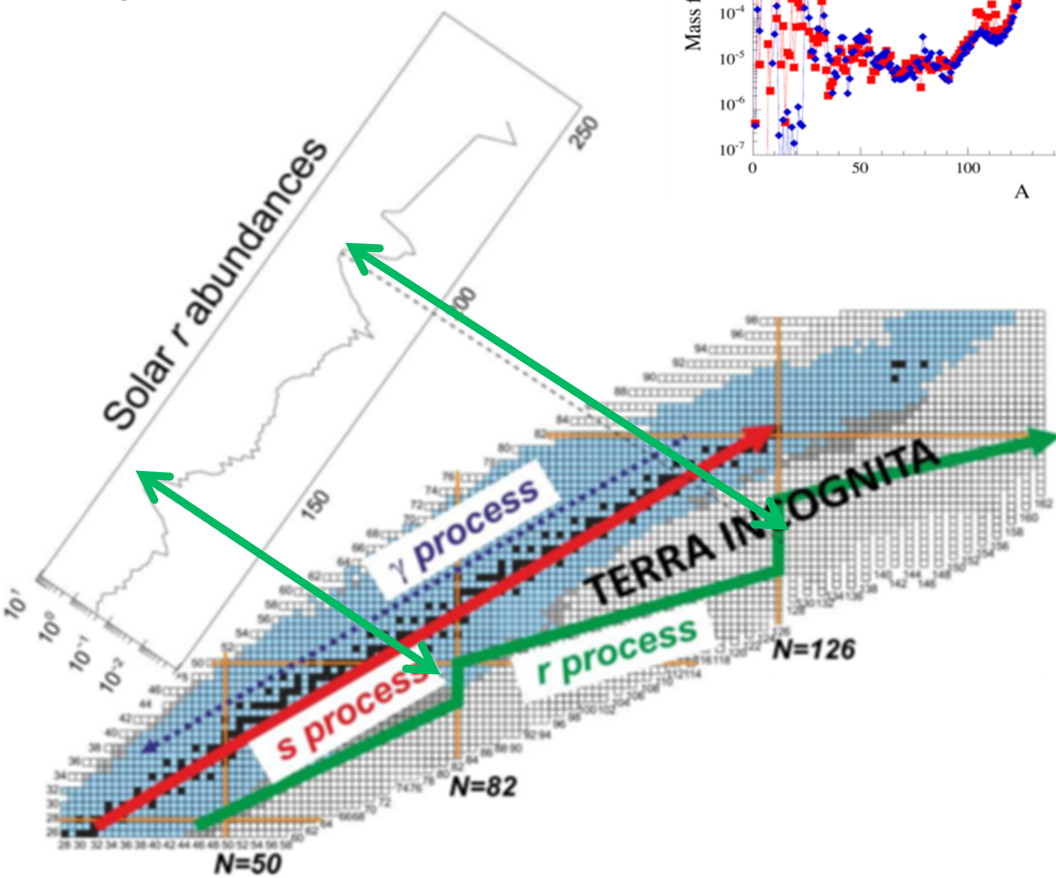
r process nucleosynthesis

Produces ~50% of the stable isotopes heavier than Iron

Site unknown:
Massive stars or Neutron Star Merger?





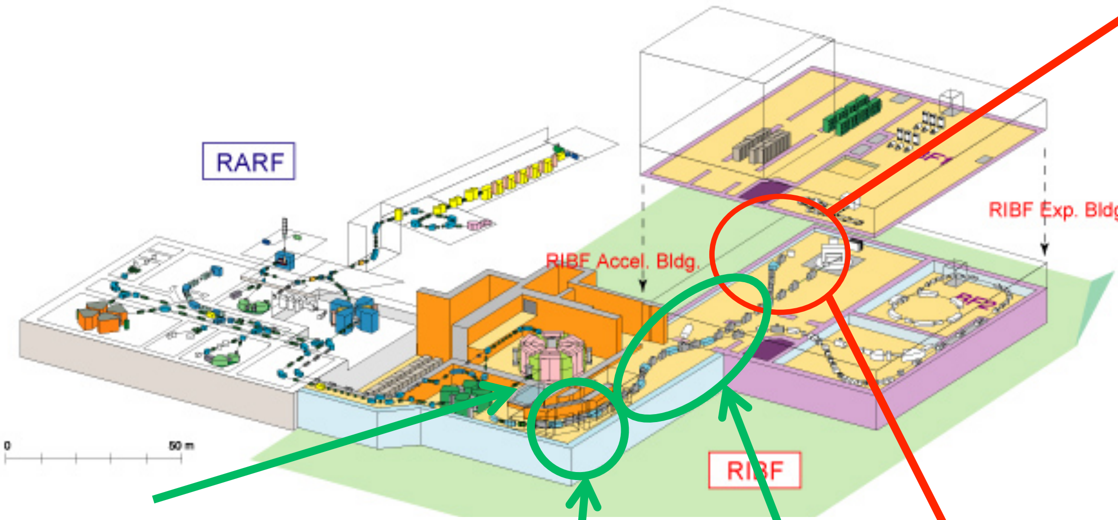


Nuclear Physics input

- **Masses – r process path**
- **Shell structure – peak location**
- **$T_{1/2}$, Pn values and fission parameters – abundance distribution**

J. Covan, Nature **440** 1151, S. Goriely, PRL **111** 242502

Beta-decay experiments at RIKEN

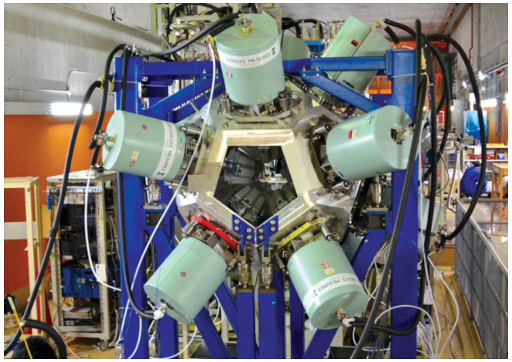


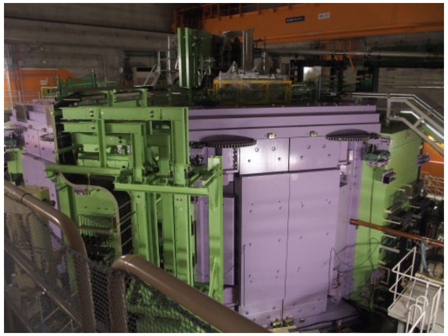
^{238}U primary beam
345 MeV / nucleon & ~50μA

RI separation

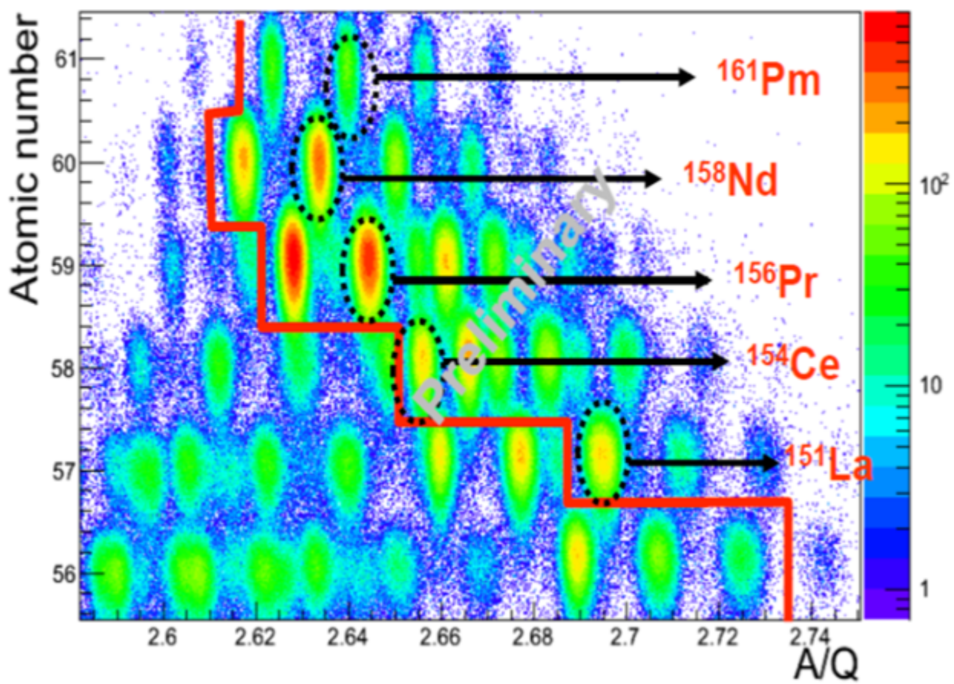
RI identification

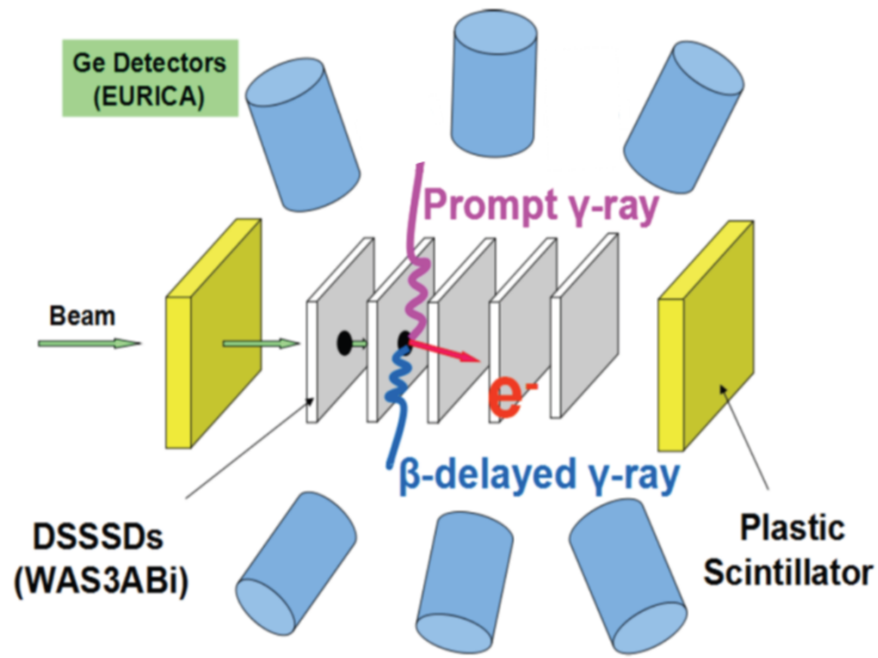
Decay station at F11





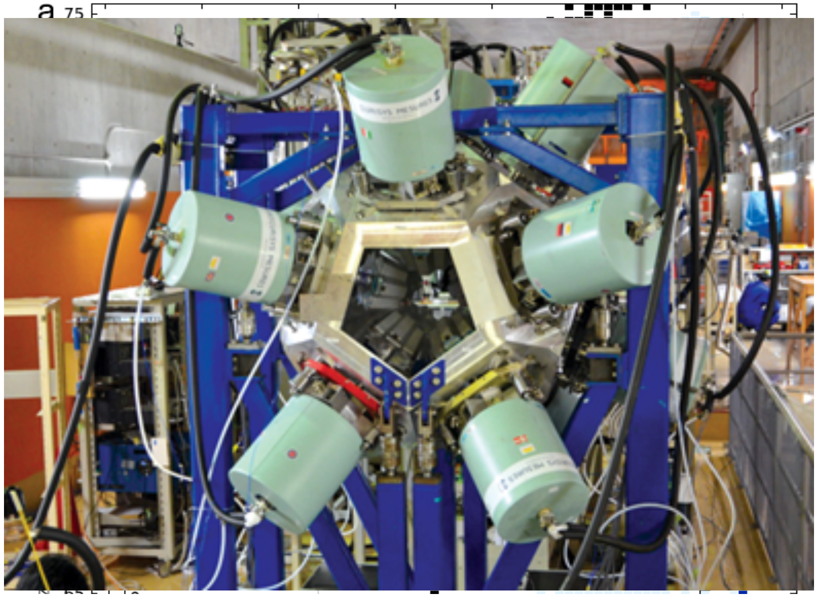
β-decay experiments





Cutting-edge technology detectors:
WAS3ABI: Wide- range Active Silicon-Strip Stopper Array for Beta and ion detection
AIDA: Advanced Implantation Detector Array AIDA
Eurica: EUroball-RIKEN Cluster Array
BRIKEN: The largest β-delayed neutron detector ever built
TAS: Total Absorption Spectrometer (see the talk of J. L. Tain)

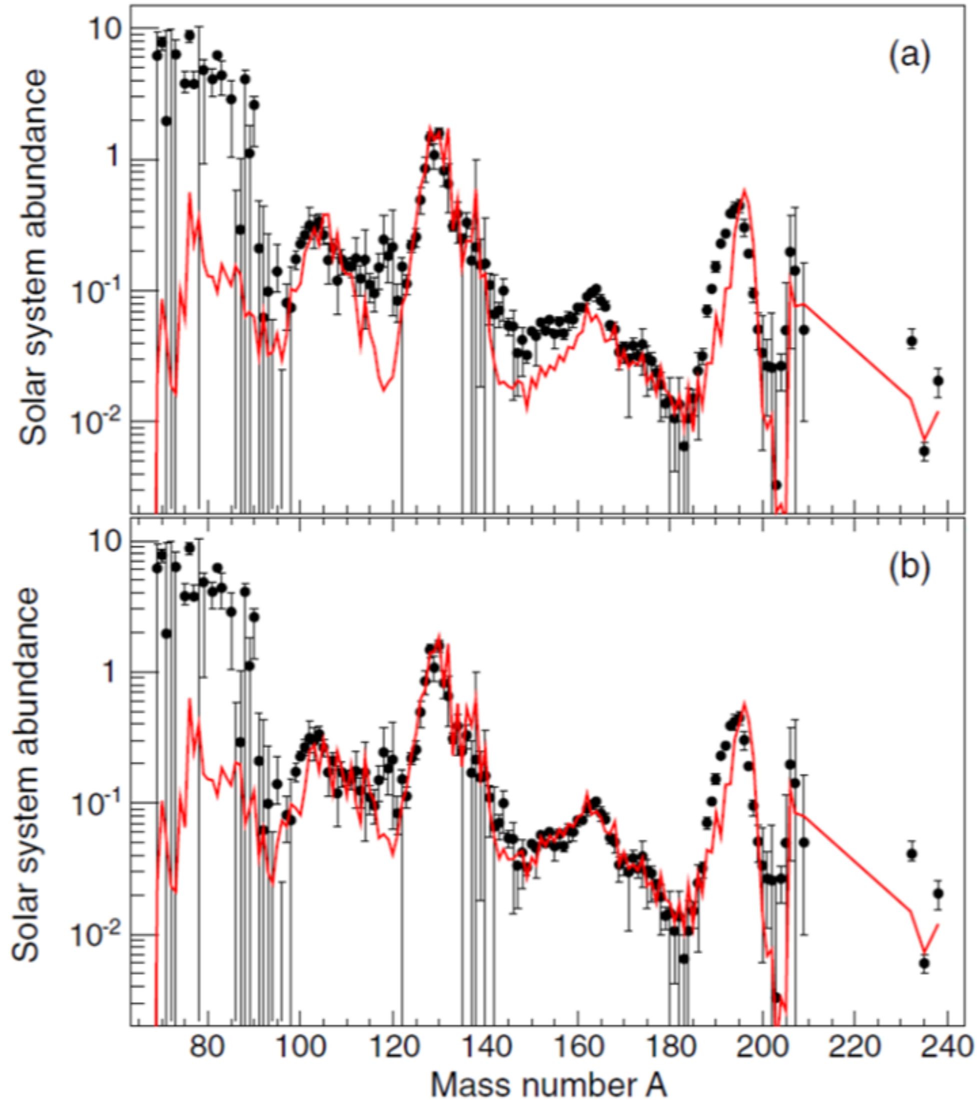
$T_{1/2}$ measurements



Eurica:
84 HPGe detectors,
organised into 12 clusters

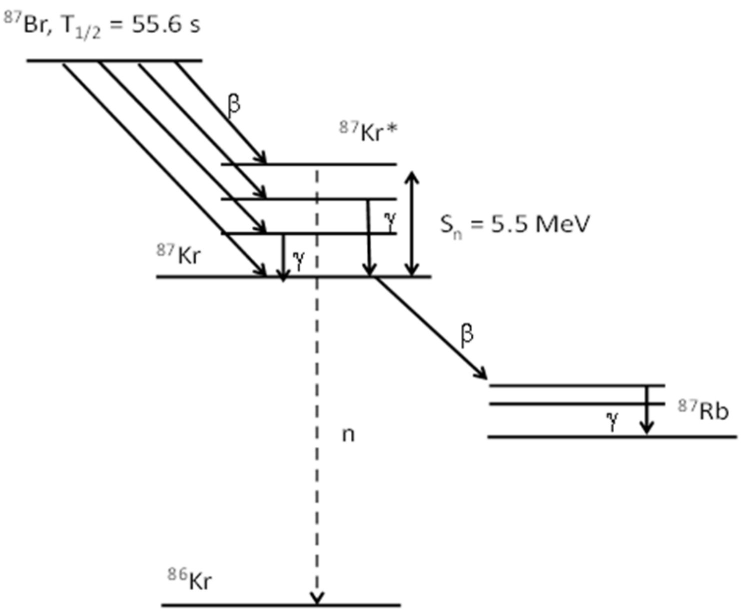
> 100 $T_{1/2}$ values measured for the first time

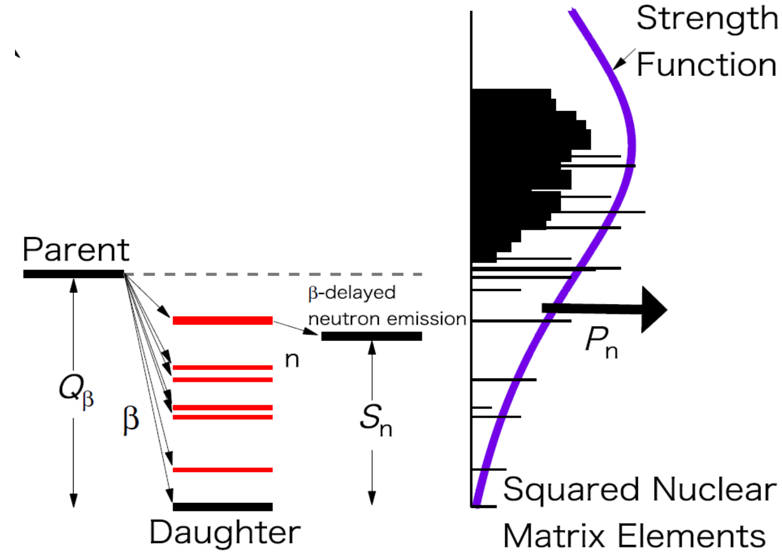
Neutron Number (N)



S. Nishimura et al., Phys. Rev. Lett. 106 (2011), Z. Y. Xu et al., Phys. Rev. Lett. 113 (2014)
G. Lorusso et al., Phys. Rev. Lett. 114 (2015), J. Wu et al., Phys. Rev. Lett. 118 (2017)

β-delayed neutrons



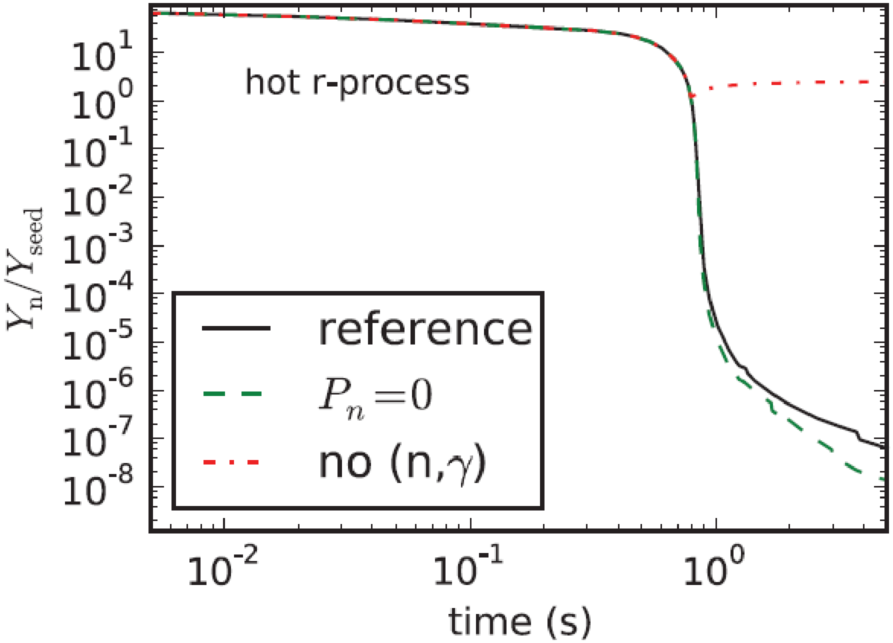


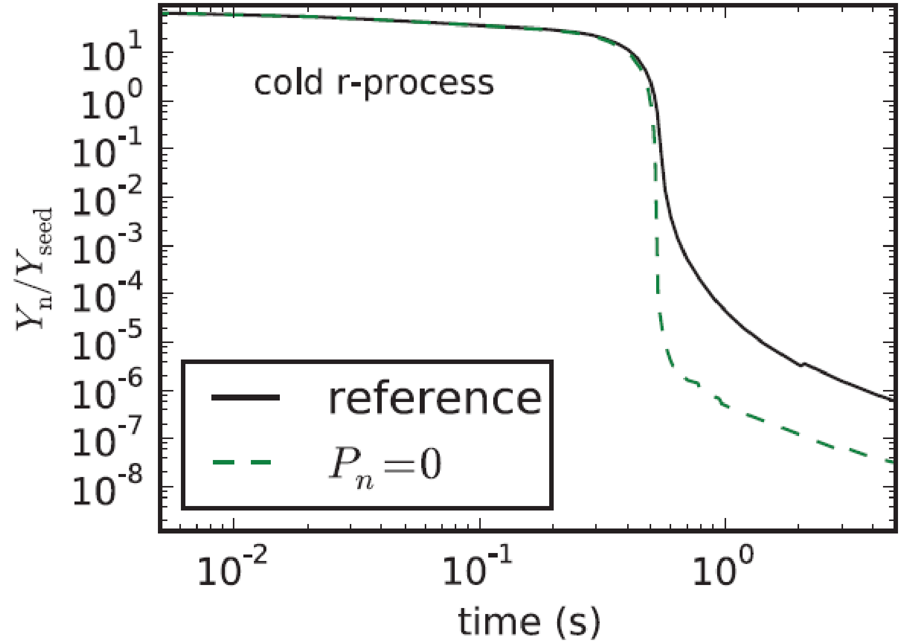
$$P_n = \int_{S_n}^{Q_\beta} S_\beta(E_x) f(Q_\beta - E_x$$

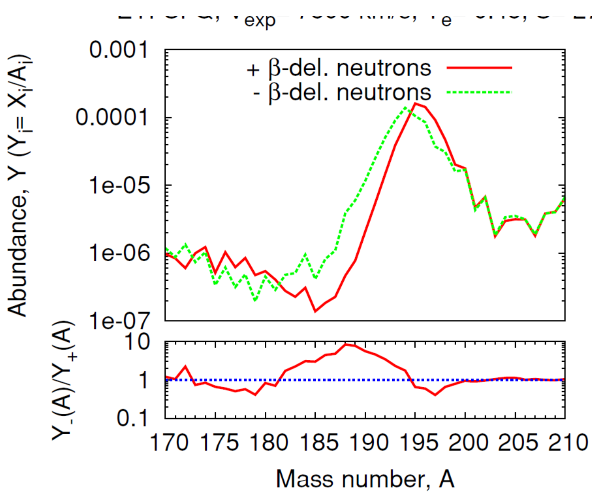
- The Pn value is the % that the β-decay is followed by at least one neutron emission.
- The P1n value is the % that the β-decay is followed by one neutron emission.
- Pn= P1n+P2n+P3n+…
- P0n=100-Pn

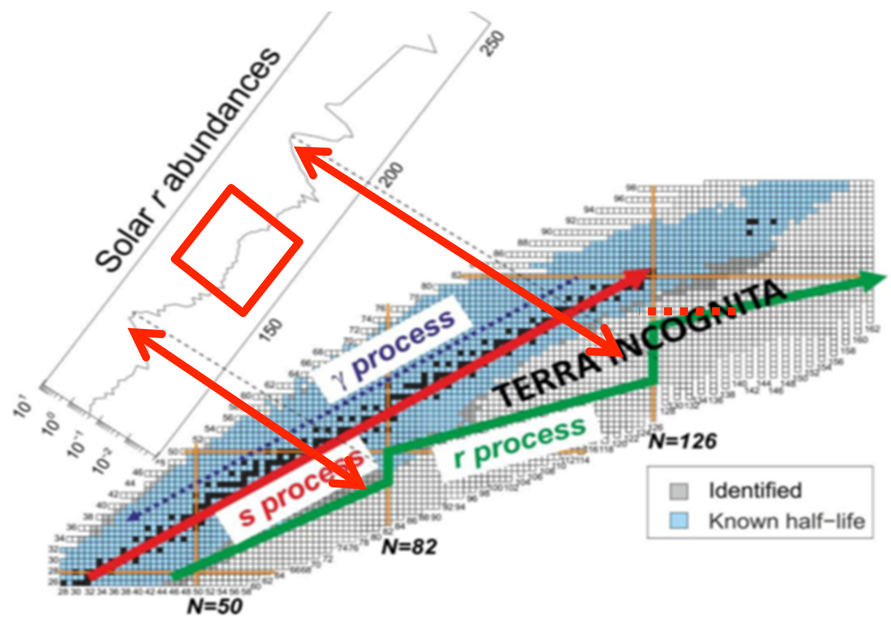
- The neutron emission probability Pn measures the fraction of β-strength above the neutron separation energy S_n
- For n-rich nuclei very far from stability $T_{1/2}$ and Pn will provide (the only) access to nuclear structure information

The role of β-delayed neutrons









A. Arcones, PRC **83** 045809, A. Farouqi, **APJ** 712 1359,
R Surman, JPS conf. Proc. **6** 010010 M. Mumpower, PRC **85** 045801

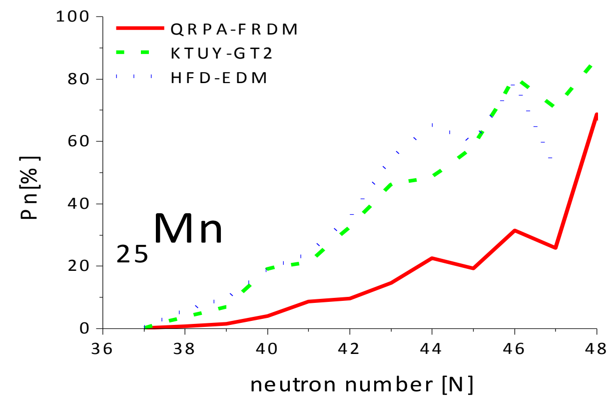
Available information for r process simulations

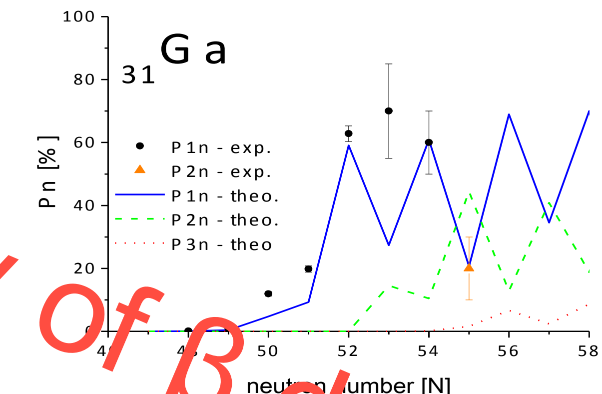
Lack of available data:

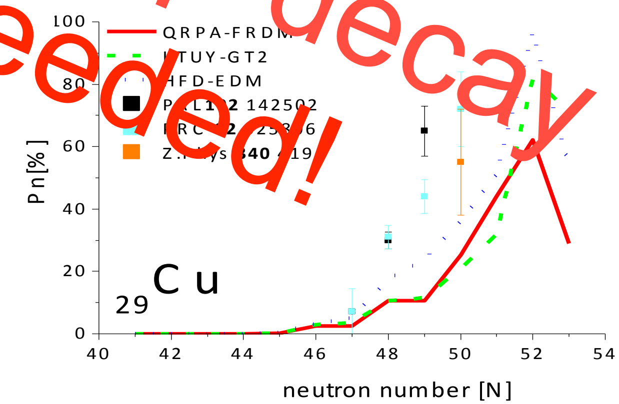
(Jeff 3.1 vs number of isotopes with $Q_{\beta n}$ >0
(using known masses from AME12)

	Energetically possible	Experimental information	Fraction measured	Mass region
β1n	606	~ 241	37.5%	^{8}He-^{150}La & $^{213,214}Tl$
β2n	295	~ 24	8.1%	^{11}Li-^{52}K & $^{98,100}Rb$
β3n	104	~ 4	3.8%	^{11}Li, $^{17,19}B$, ^{23}N
β4n	60	1	1.7%	^{17}B

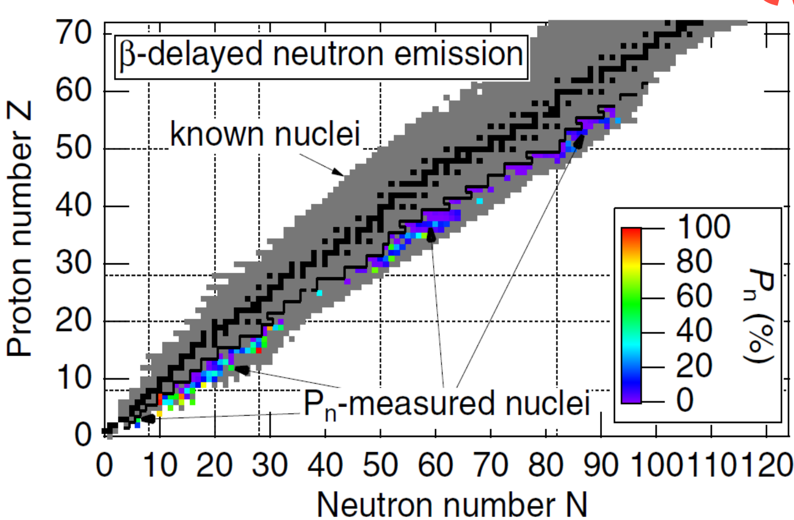
Large differences:







Distribution of the data:



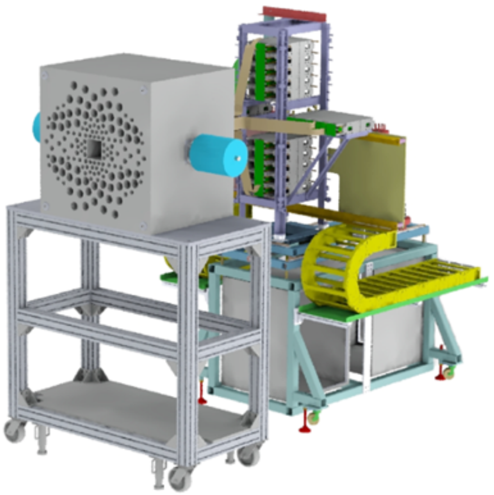
- ~ 40% in the non-fission region (A < 75)
- ~ 33% for nuclear industry (Br, Kr, Rb, I, Cs, Xe)
- No data above ^{150}La except $^{213,214}Tl$

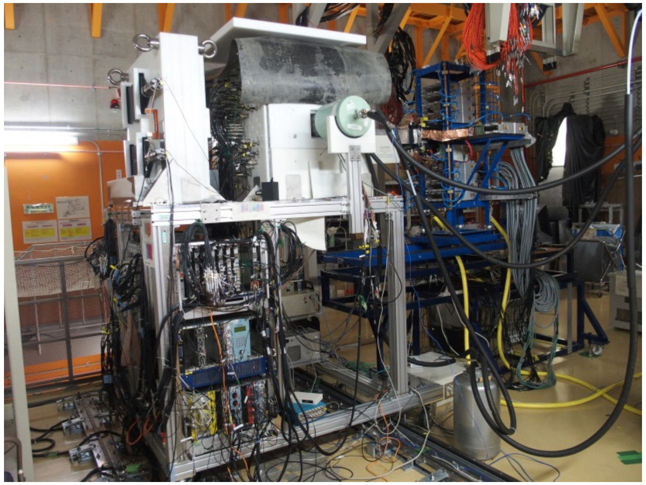
Large scale survey of β decay parameters is needed!

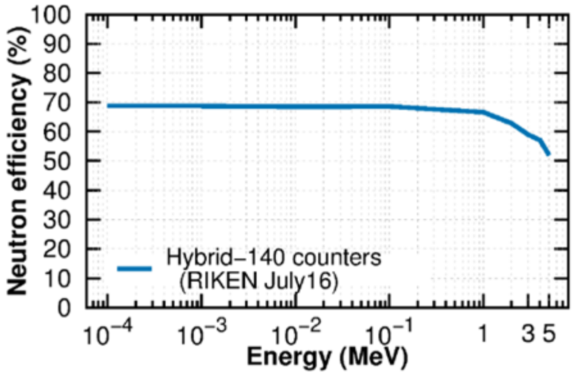
Decay setup

- AIDA: most advanced implantation array
  - Accept 1 kHz implantation rate
  - Several (6-7) highly (128 x 128) segmented DSSD detectors
- BRIKEN: highest efficiency counter setup ever built (~68%-76%)!
  - ^{3}He filled proportional counters from embedded in a ~ 1m^{3} polyethylene moderator

    ORNL (84), UPC (42), RIKEN (26), GSI (10)
  - Flat efficiency curve led to minimalized systematical uncertainty
  - Hybrid geometry (148 tubes + 2 clovers)
  - Compact geometry (166 tubes)







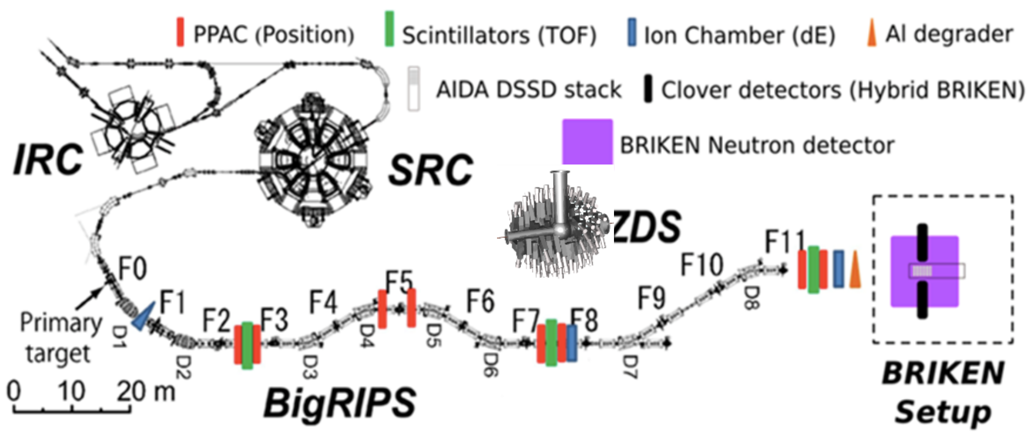
Detector	Number of counters	Setup type	$F(1MeV)$	$\langle\eta\rangle(1MeV)$
BRIKEN	166	Compact	1.029	75.7%
	148	Compact	1.07	73.3%
	148	Hybrid	1.036	68.6%
TETRA[24]	80	Hybrid	1.133	61.1%
MAINZ[25]**	64	Compact	1.130	47.0%
NERO[11]	60	Compact	1.157	43.1%
Hybrid-3Hen[10]	48	Hybrid	1.103	36.8%
BELEN-20[4]	20	Compact	1.062	46.2%
LOENI[25]**	18	Hybrid	1.016	17.4%

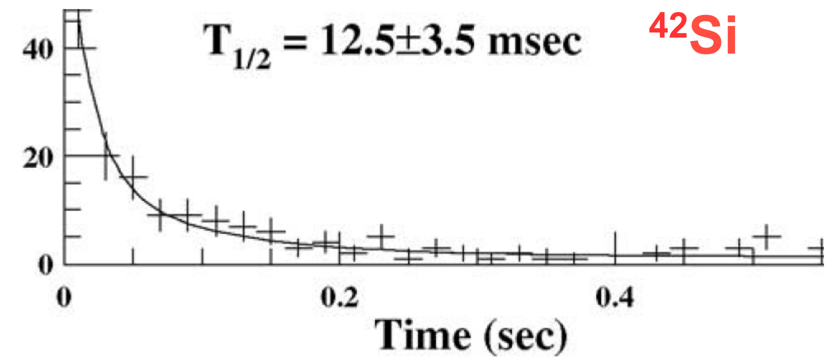
BRIKEN sensitivity

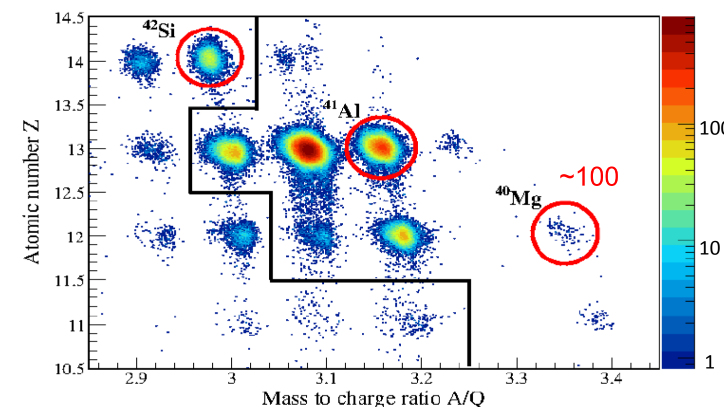
^{159}Pr (stable on is ^{141}Pr!):
Pn: ~ 20% (from QRPA)
Rate: 1 x 10^{-3} 1/s
only 3.6 counts / hour!
6 days of beamtime ↔ 10% precision

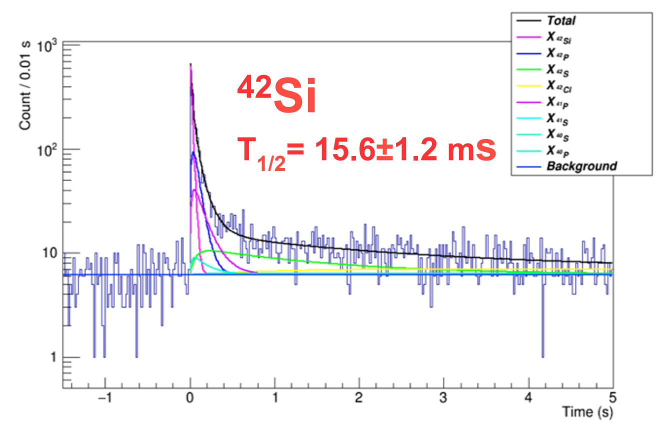
Experimental rate: 3.2 x 10^{-3} 1/s

BRIKEN commissioning using ^{40}Al secondary beam





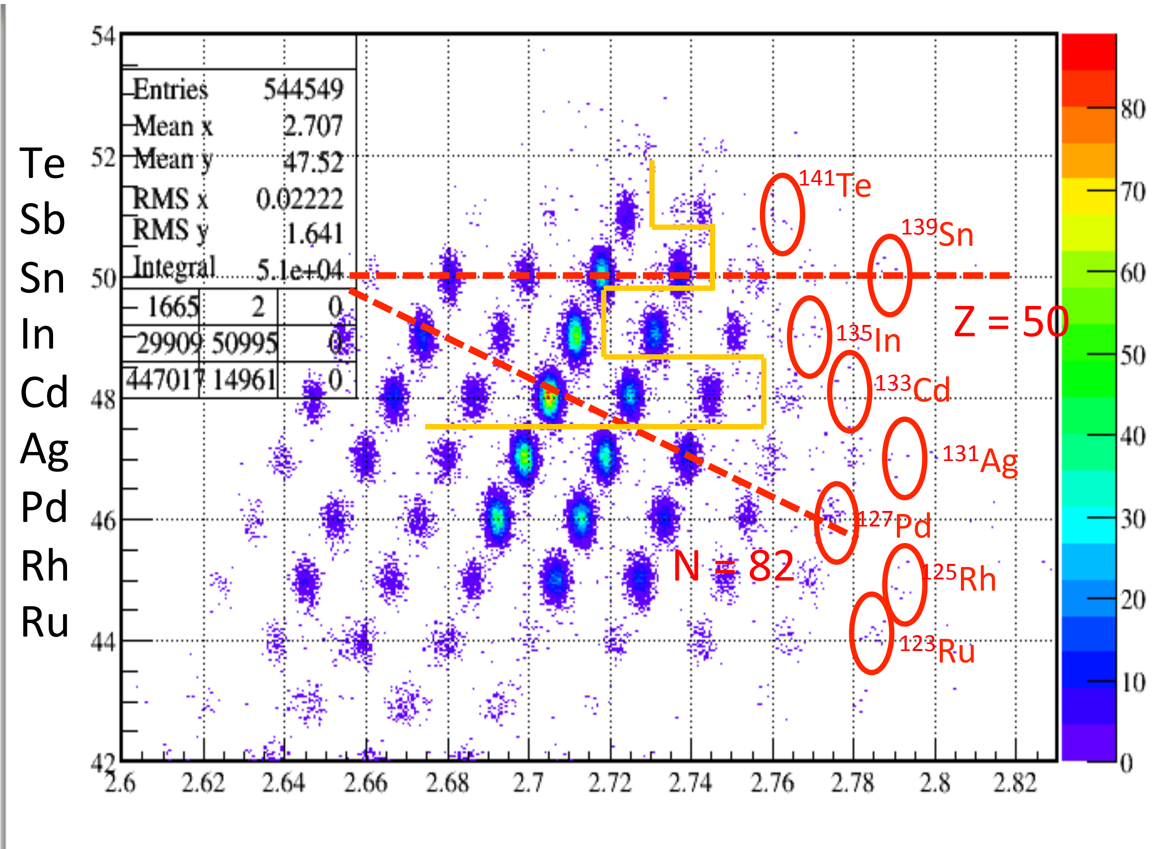


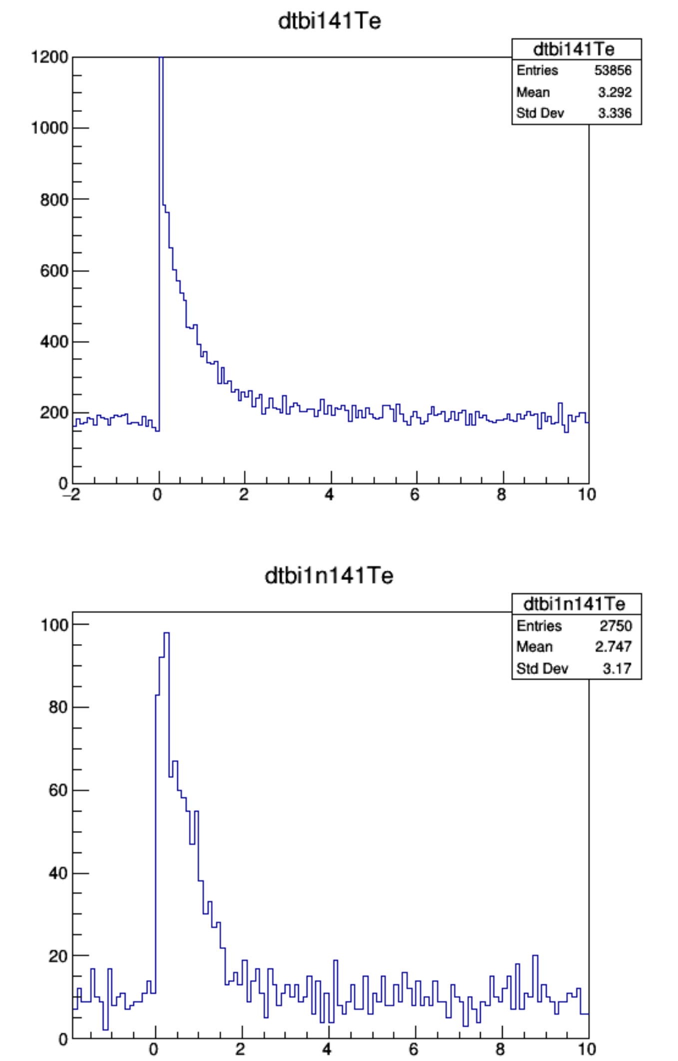


- Experiment has been performed in parasitic mode with an in-beam gamma experiments
- During about 5.5 days, about 300,000 RIs near neutron number N=28 has been identified by ZDS and implant in AIDA detector

Nucleus	P_{1n}	P_{2n}	P_{3n}
^{37}Mg	39.75	24.3	0.3
^{38}Mg	70.91	8.5	12.48
^{39}Al	88.08	1.97	6.26
^{40}Al	15.57	73.83	8.53
^{41}Al	39.99	7.3	10.45
^{41}Si	48.8	9.8	
^{42}Si	23.7	29.42	2.95

Measurement of β-delayed neutron emission probabilities relevant to the A = 130 r-process abundance peak





6.5 days beamtime,
settings were centered on ^{130}Ag (~4.5 d) and ^{149}Xe (~1.5 d).
More than 25 P1n were measured for the first time, data analysis is in progress (^{127}Pd, ^{131}Ag, ^{133}Cd…).

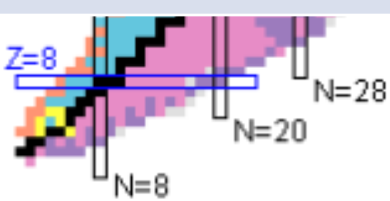
Roederer, APJ. Lett. **747** L8, Mumpower, Prog. Part. Nucl. Phys. **86** 86

Scientific cases

Title	Approved Length [days]	Aims	Spokespersons
Measurements of new beta-delayed neutron emission properties around doubly-magic ^{78}Ni	3.5	~ 20 new P1n & ~ 14 new P2n	**K.P. Rykaczewski**, J. L. Tain, R. Grzywacz, I. Dillmann
Decay properties of r-process nuclei in deformed region around A = 100 ~ 125	6.5	~ 60 new P1n & ~ 30 new P2n	**S. Nishimura,** A. Algora
Measurement of β-delayed neutron emission probabilities relevant to the A = 130 r-process abundance peak	6.5	~33 new P1n & ~ 6 new P2n &	**A. Estrade**, G. Lorusso, F. Montes
Half-lives and beta delayed neutron emission probabilities relevant to understand the formation of the rare earth r process peak	10	~ 36 new P1n	**G. G. Kiss**, A. Morales, A. Tarifeño-Saldivia, A. Estrade

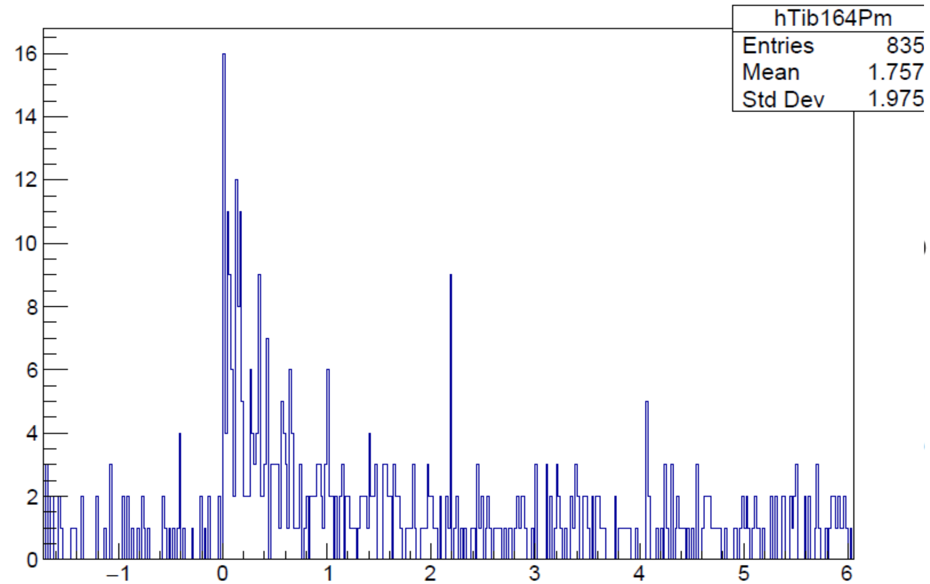
To be submitted newt PAC meeting (2017 December)

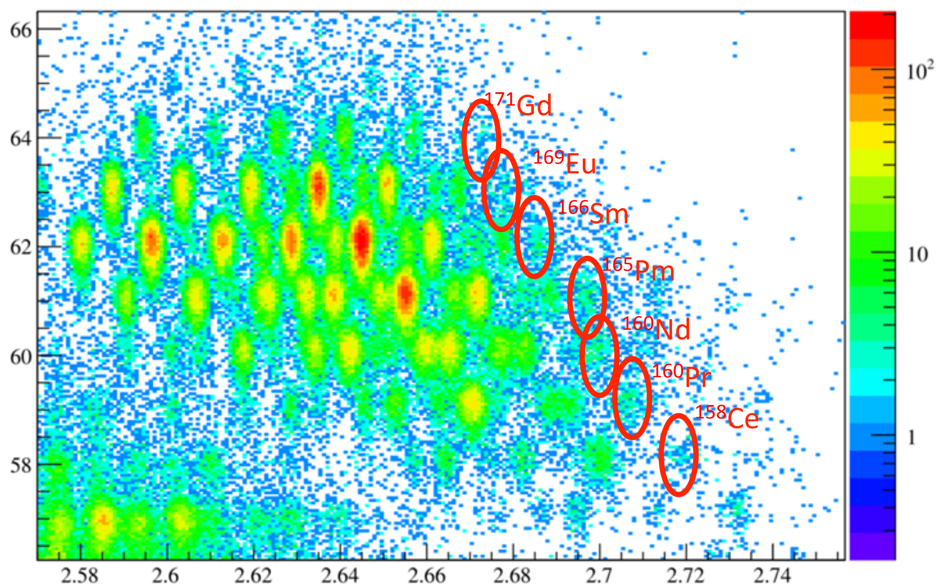
Study of the multiple delayed neutron emission	?	15 new P1n & 21 new P2n & 21 new P3n	**I. Dillmann**

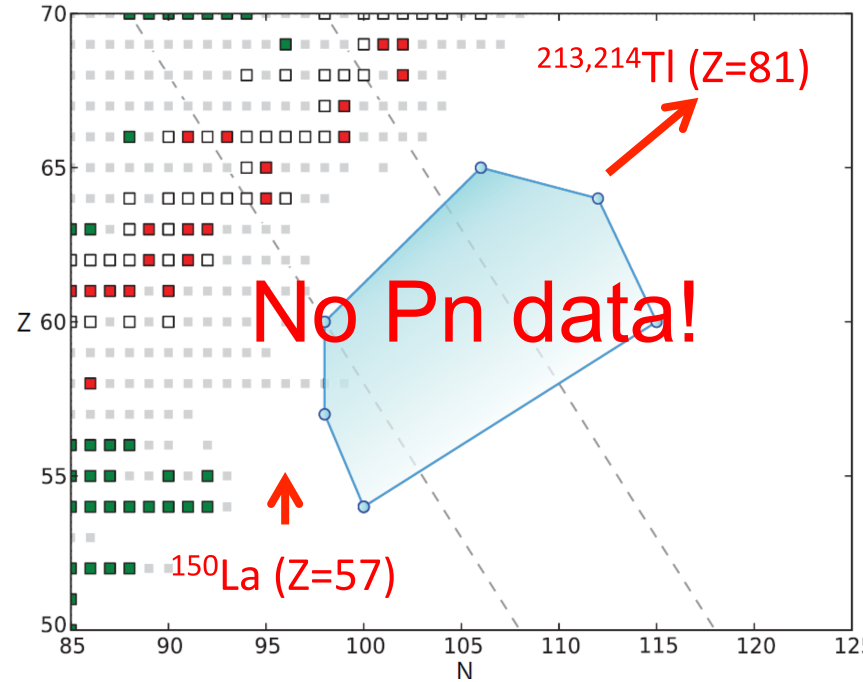


N, number of neutrons

The Origin of the Rare Earth Peak







2.5 days beamtime, setting was centered on ^{167}Sm.

Several new P1n values and $T_{1/2}$ were measured

(Pr, Pm, Eu, ^{158}Ce, ^{164,165}Pm, ^{168,169}Eu, ^{170,171}Gd).

Summary

- β-decay rates are important for r process nucleosynthesis calculations
- There is lack of experimental data
- The BRIKEN collaboration aims a large scale survey of β decay parameters for isotopes located far from the valley of stability
- Measurements and data analysis are in progress

Vielen Danke für Ihre Aufmerksamkeit

Thank you for your attention!

ご清聴ありがとうございました

(Go seichō arigatōgozaimashita)