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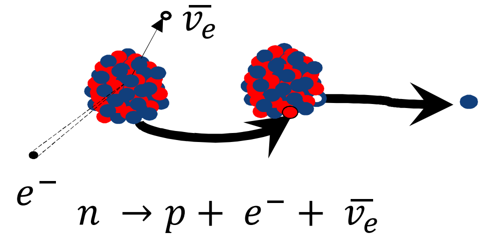
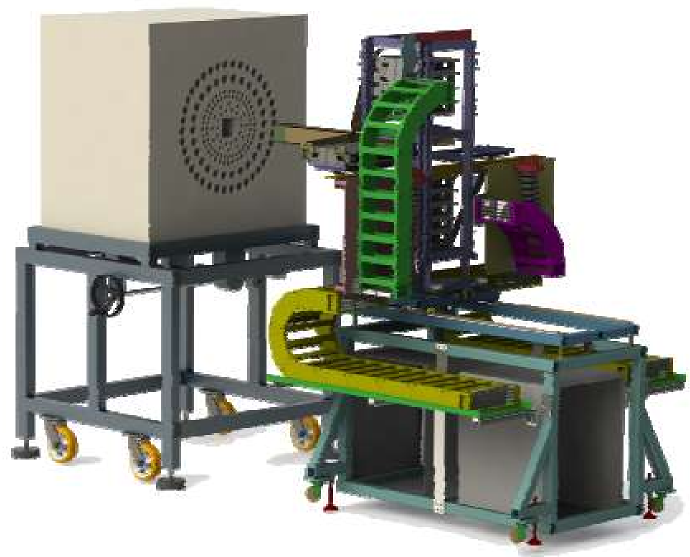
β-delayed neutron measurements at RIKEN for nuclear structure, astrophysics and applications





Roger Caballero-Folch

Postdoc researcher | TRIUMF

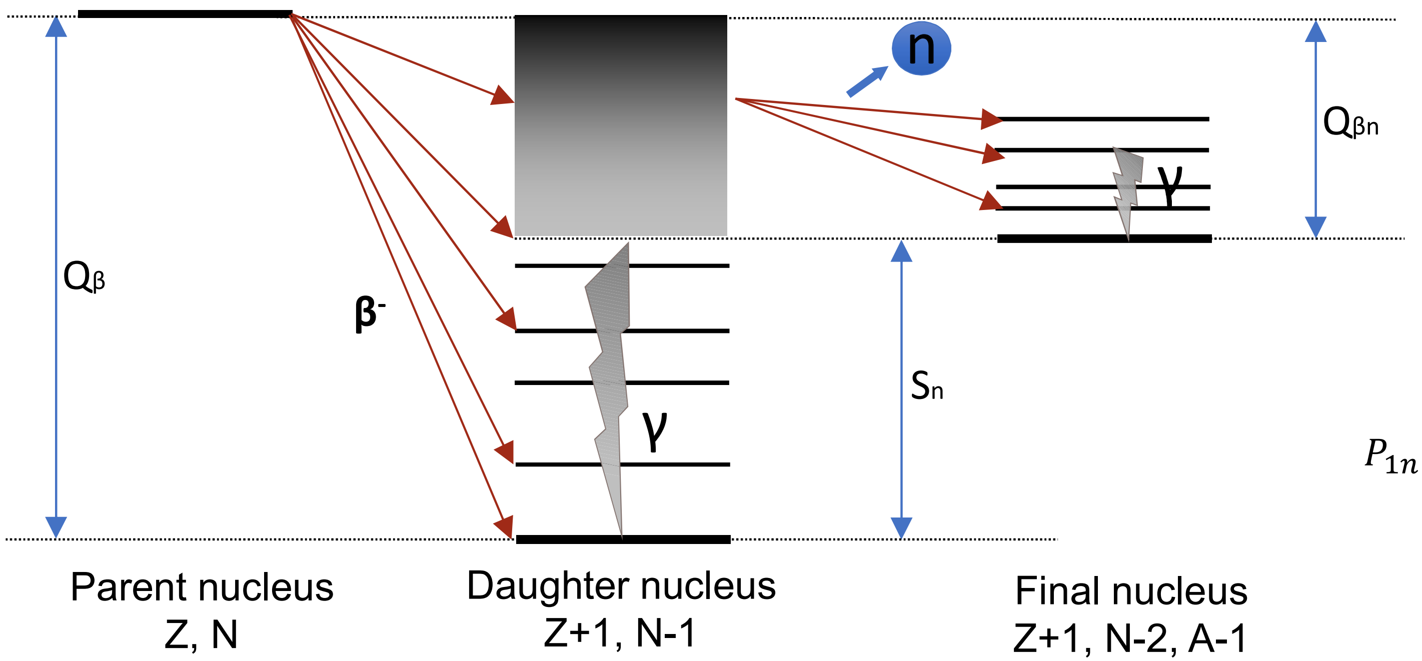
ICTP-IAEA Workshop

Miramare, Grignano - Trieste, Italia, UE, 19 d'octubre de 2018

2018-10-19

Discovery, accelerated

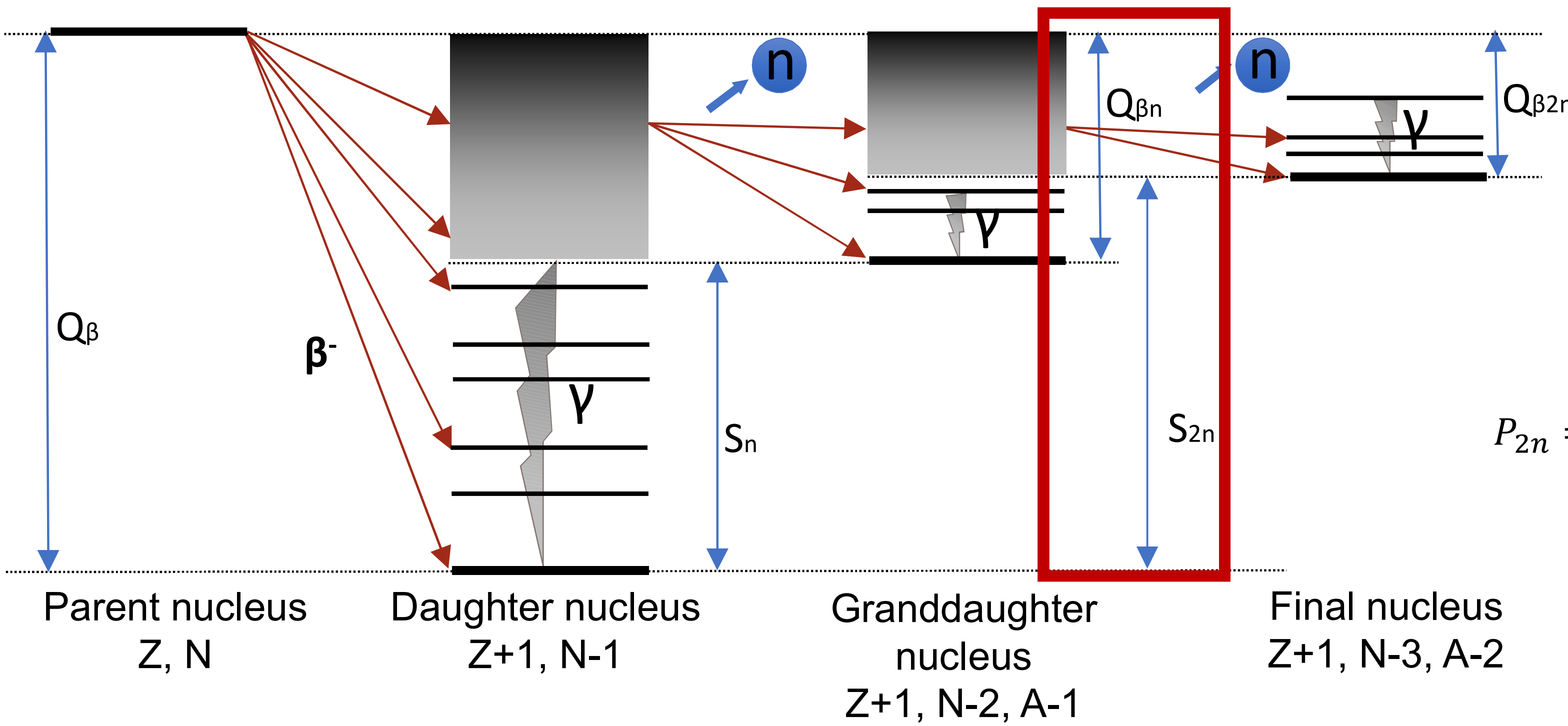
Beta-delayed neutron emission



$$P_{1n} = \frac{1}{\varepsilon_n}\frac{N_{\beta n}}{N_\beta}$$

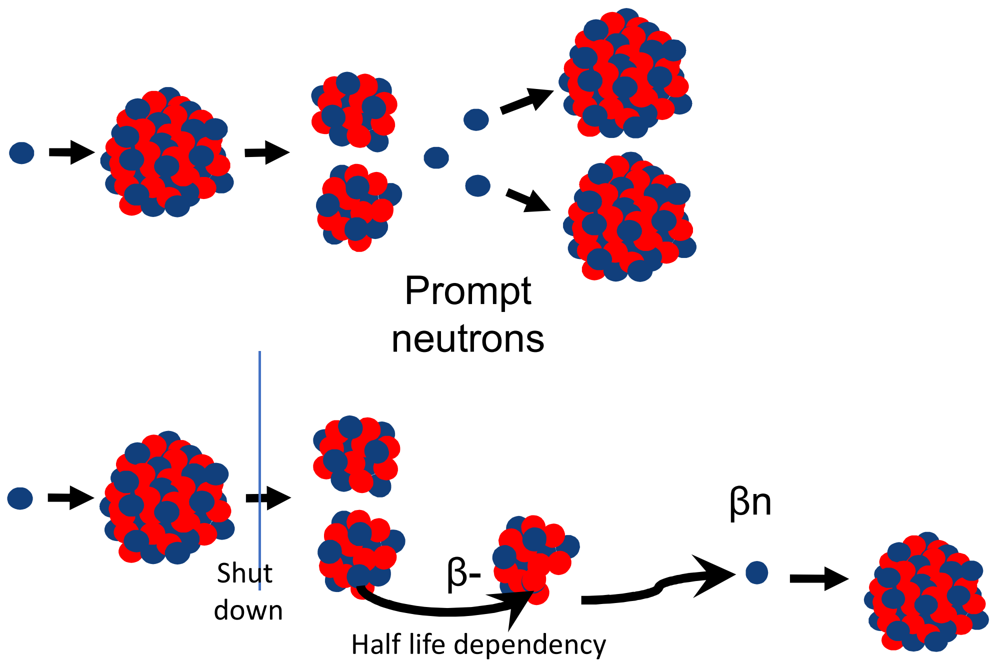
R. B. Roberts et al. "The Delayed Neutron Emission Which Accompanies Fission of Uranium and Thorium," Phys. Rev. 55, 664 (1939).

Beta-delayed neutron emission



$$P_{2n} = \frac{1}{{\varepsilon_n}^2}\frac{N_{\beta 2n}}{N_\beta}$$

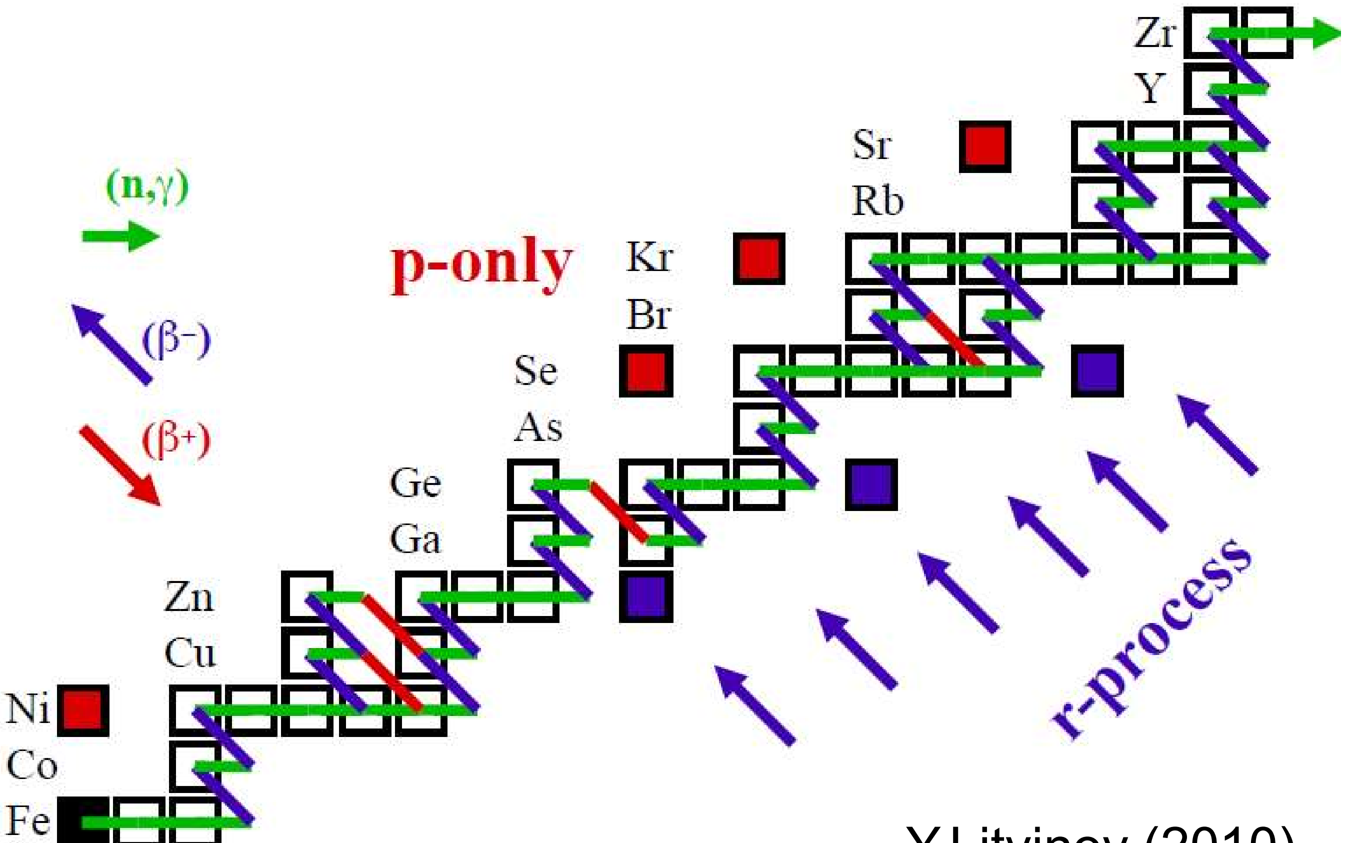
Beta-delayed neutron emission in nuclear reactors



- Important role in the reactor control $t_{\beta n} \gg t_{prompt}$
- Maintaining the reactor in prompt subcritical condition.

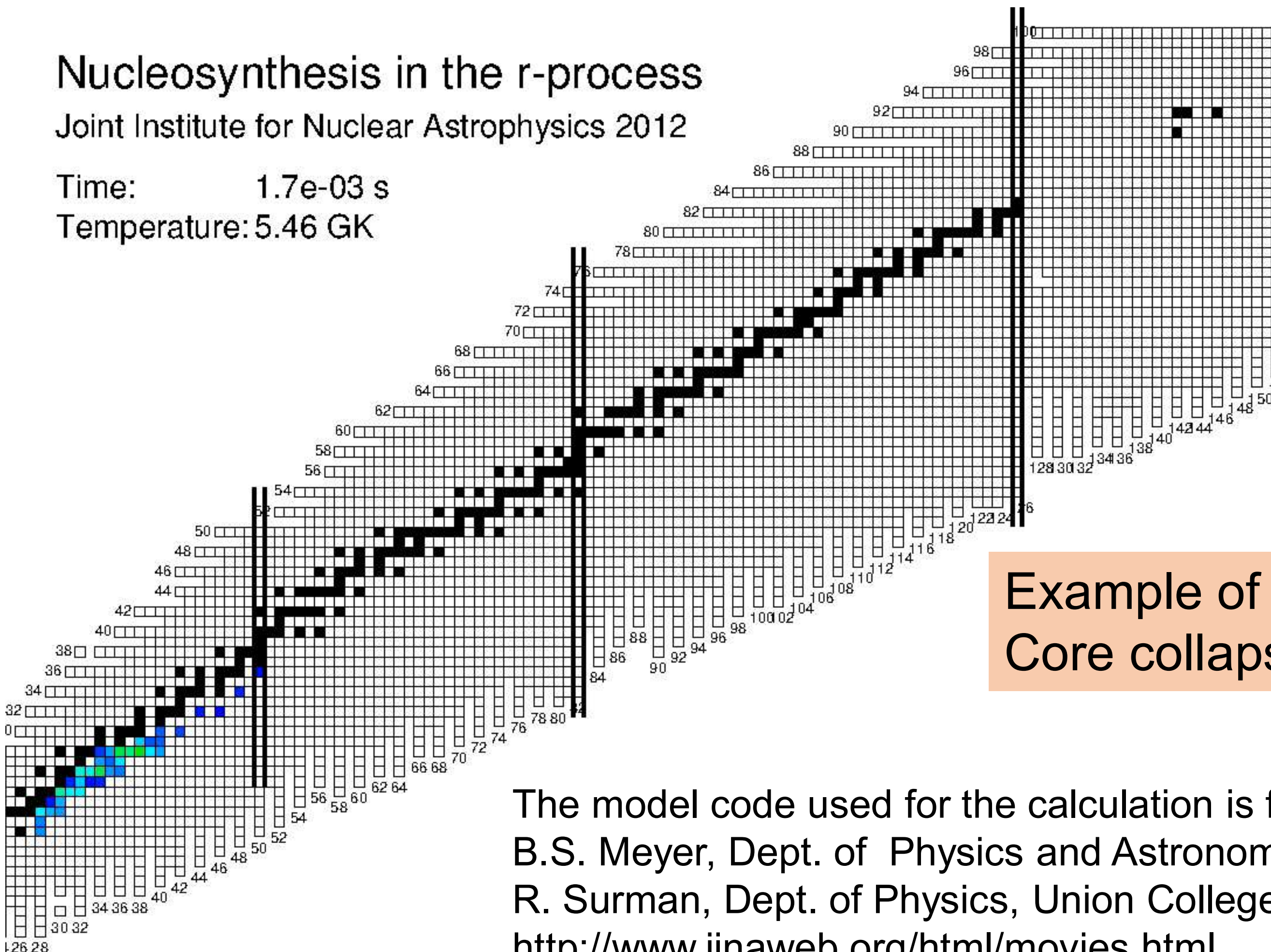
Beta-delayed neutron emission to understand the origin of the elements

s process: slow n-capture and β- decay near valley of β stability at kT = 30 keV



Y.Litvinov (2010)

Beta-delayed neutron emission and the r-process

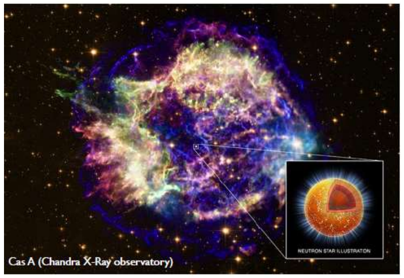


Example of r-process path:
Core collapse SN simulation

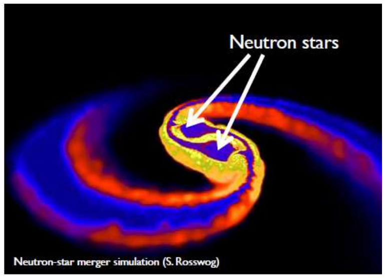
The model code used for the calculation is from:
B.S. Meyer, Dept. of Physics and Astronomy, Clemson University
R. Surman, Dept. of Physics, Union College
http://www.jinaweb.org/html/movies.html

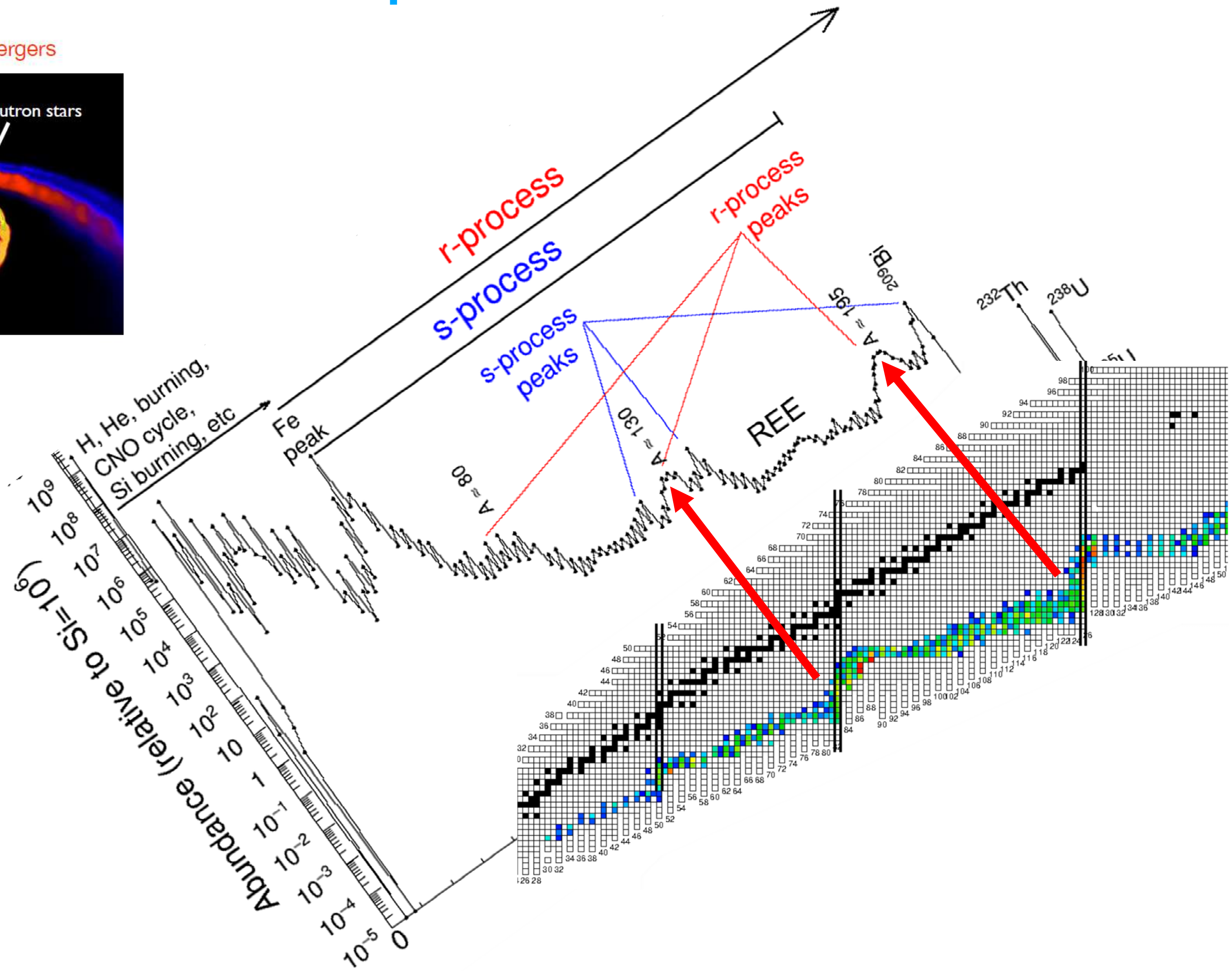
Beta-delayed neutron emission and the r-process

Core-collapse supernovae



Neutron star mergers

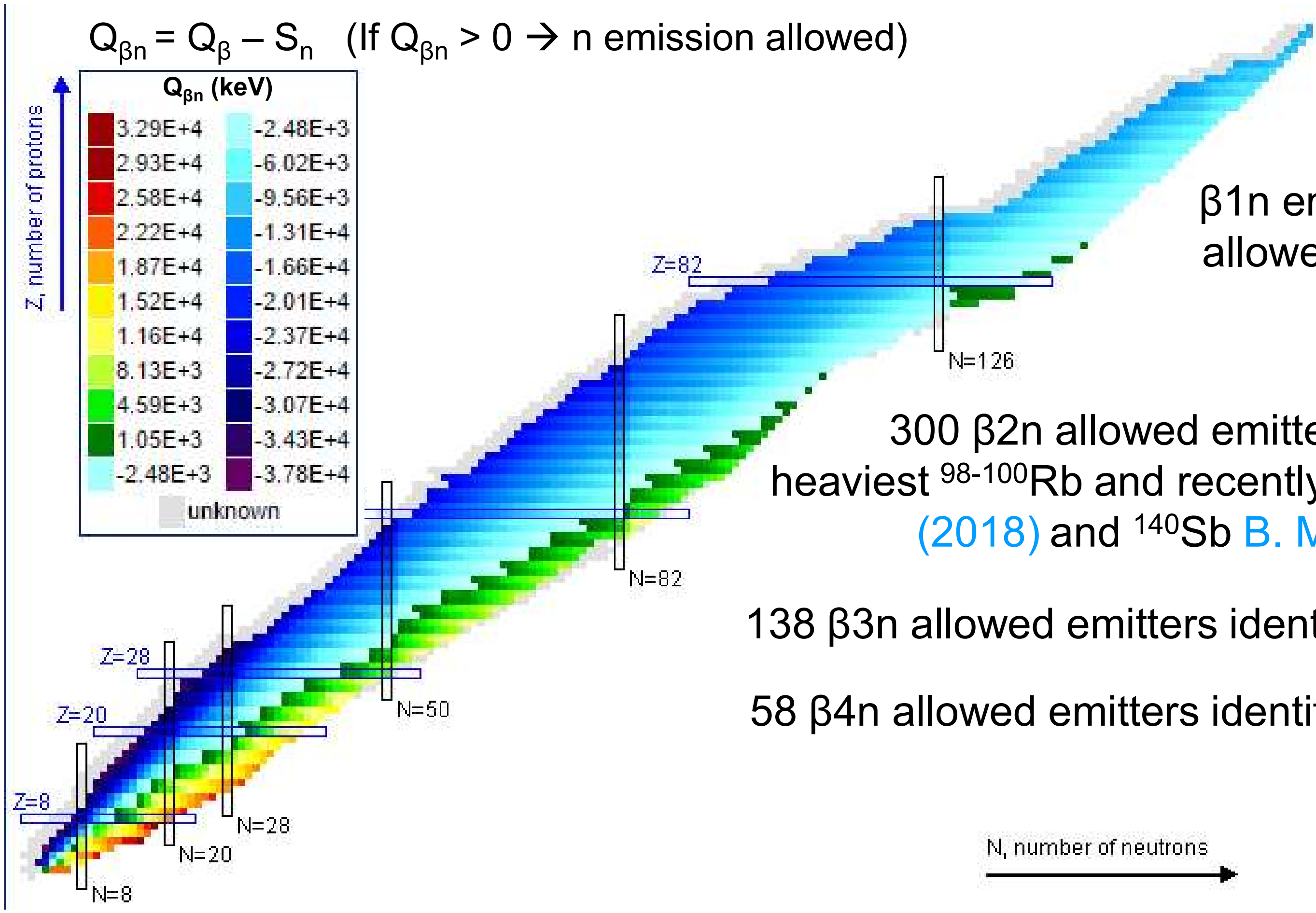




Data from Looders et al. Vol. VI/4B, Chap. 4.4 (2009).

State of the art of beta-delayed neutron emission measurements

$Q_{\beta n} = Q_{\beta} - S_n$ (If $Q_{\beta n} > 0$ → n emission allowed)



β1n emitters: 621 known energetically allowed, around 300 measured so far.

300 β2n allowed emitters identified. So far 25 measured - heaviest $^{98-100}$Rb and recently ^{136}Sb RCF et al. PRC 98, 034310 (2018) and ^{140}Sb B. Moon et al. PRC 95, 44322, (2017).

138 β3n allowed emitters identified. So far 4 measured (^{11}Li-^{23}N).

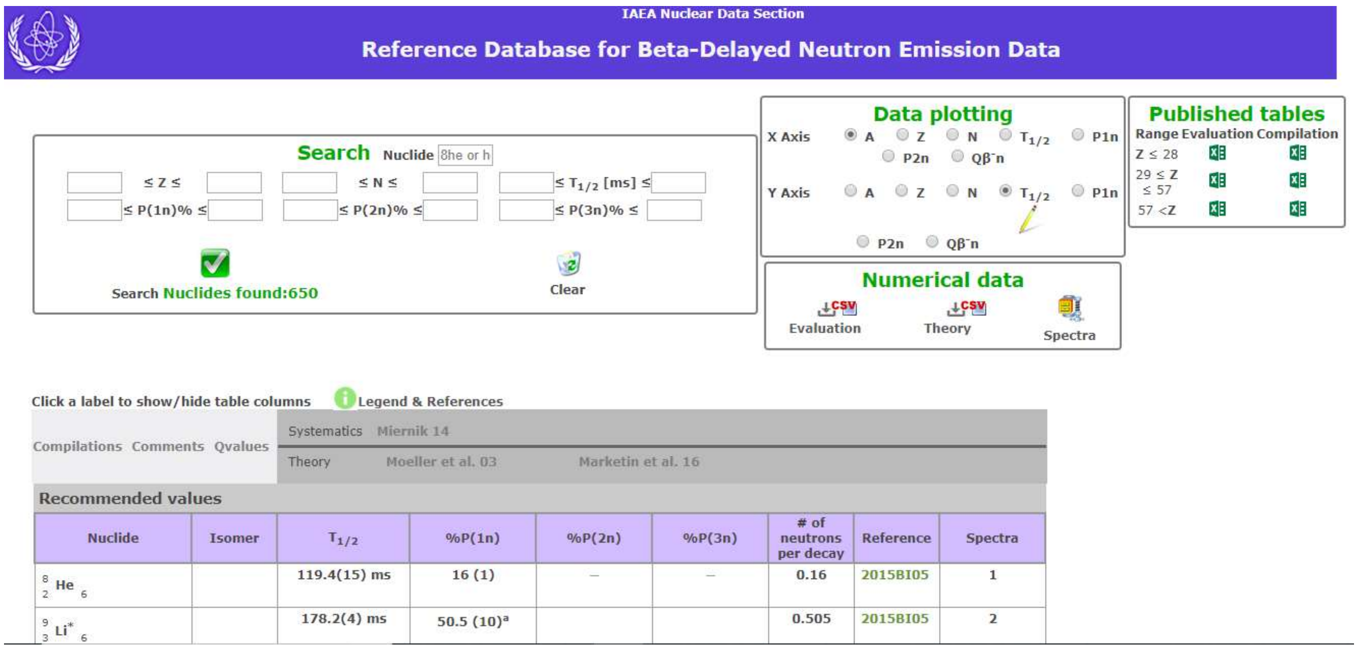
58 β4n allowed emitters identified. Only ^{17}B has been measured.

More info: I. Dillmann, A. Tarifeño-Saldivia Nucl. Phys News Vol.28, 1 (2018).

IAEA coordinated Research Projects (CRP)

IAEA

Coordinated Research Projects (CRP) on the Development of a Reference Database for Beta-Delayed Neutron Emission and on β-delayed neutron emission EVALUATION



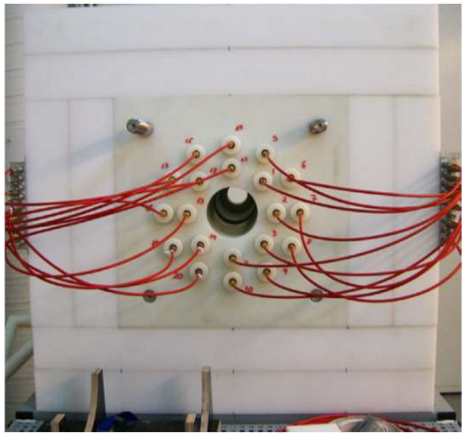
Nuclide	Isomer	$T_{1/2}$	%P(1n)	%P(2n)	%P(3n)	# of neutrons per decay	Reference	Spectra
$^{8}_{2}He_{6}$		119.4(15) ms	16 (1)	–	–	0.16	2015BI05	1
$^{9}_{3}Li^{*}_{6}$		178.2(4) ms	50.5 (10)^{a}			0.505	2015BI05	2

https://www-nds.iaea.org/relnsd/delayedn/delayedn.html

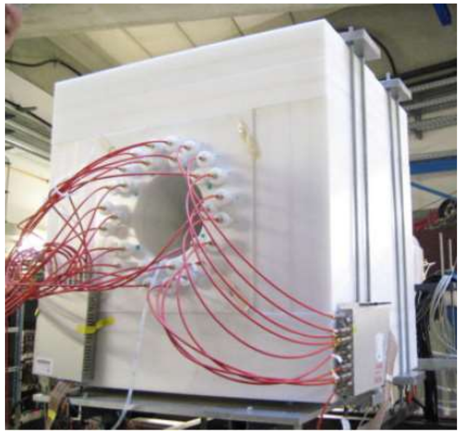
It has been included a high priority list of nuclei to be measured

D. Abriola, B. Singh, and I. Dillmann, Beta-Delayed Neutron Emission Evaluation, Tech. Rep. (INDC(NDS)-0599 - IAEA, 2011).
I. Dillmann, P. Dimitriou, and B. Singh, Development of a Reference Database for Beta-delayed Neutron Emission Evaluation, Tech. Rep. (INDC(NDS)-0643 - IAEA,2014).
I. Dillmann, P. Dimitriou, and B. Singh, et al. Development of a Reference Database for Beta-Delayed Neutron Emission, Tech. Rep. (INDC(NDS)-0735 - IAEA, 2017).

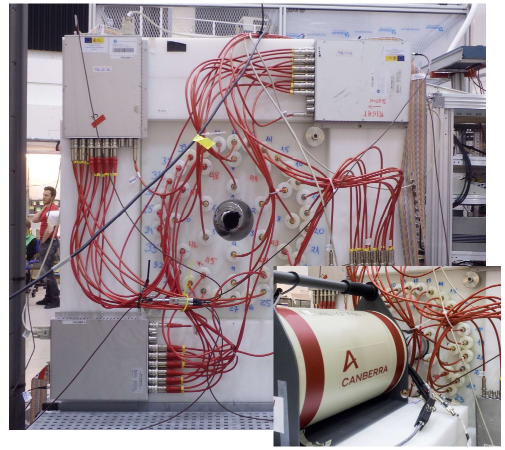
BRIKEN project background: BELEN detector (2009-2014) – BRIKEN 2016...



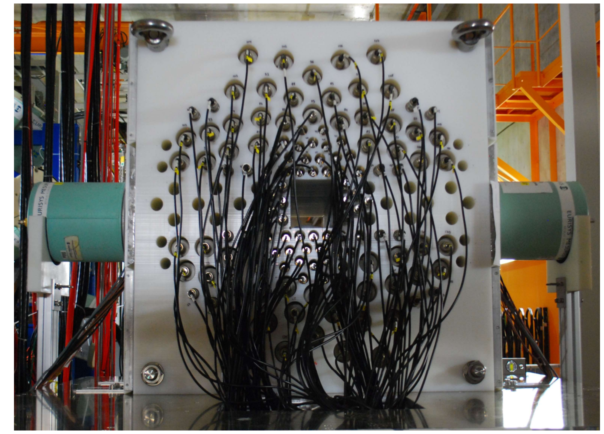
20 ^{3}He counters in 2 rings. IGISOL Jyväskylä (2010).
$\varepsilon_{1n} \approx 47\%$



30 ^{3}He counters in 2 rings. GSI-FRS (2011).
$\varepsilon_{1n} \approx 38\%$

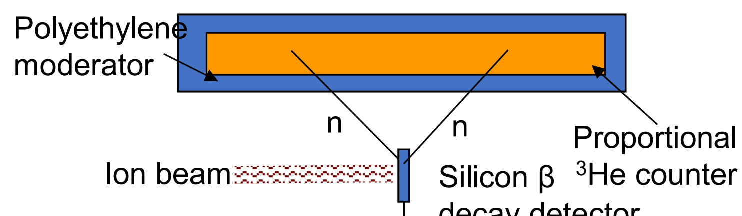


48 ^{3}He counters in 3 rings. IGISOL Jyväskylä (2014).
$\varepsilon_{1n} \approx 40\%$ (HPGe)
$\varepsilon_{1n} \approx 60\%$



140 ^{3}He counters in 7 rings. BRIKEN (2016…)
$\varepsilon_{1n} \approx 68.6\%$ (HPGe)

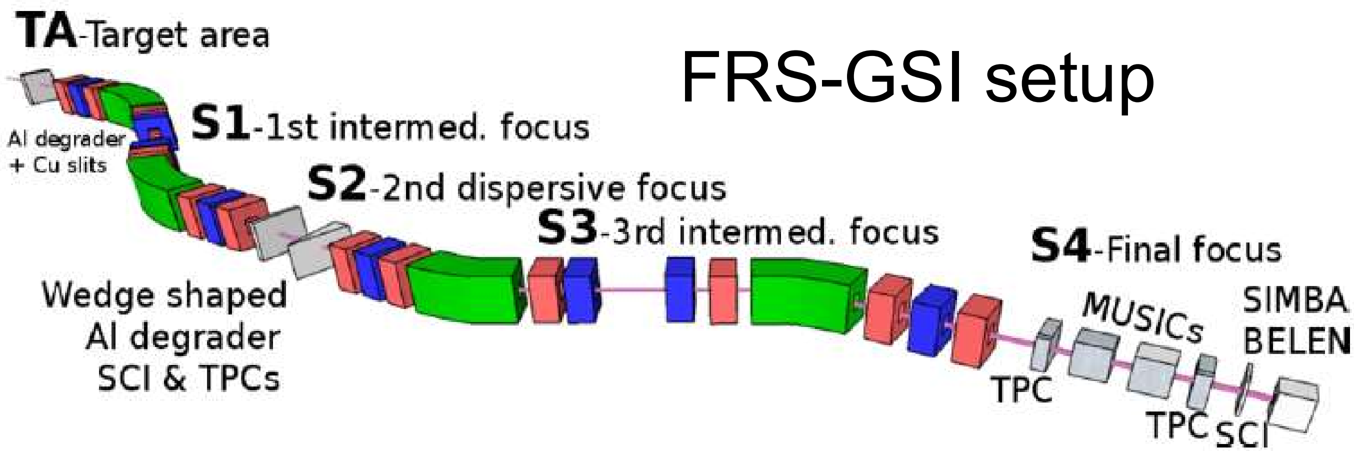
$$^{3}He + n \rightarrow {}^{3}H + p + 764keV$$



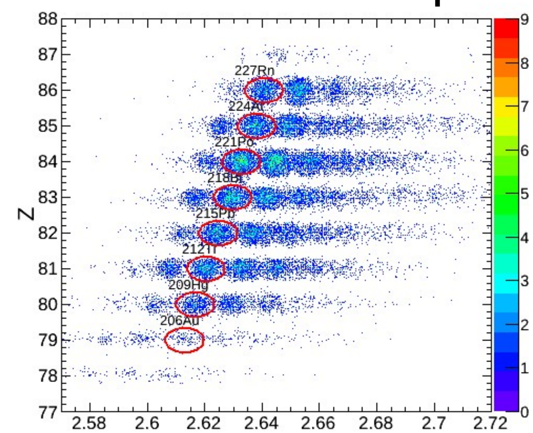
All efficiencies are up to 1MeV

Fragmentation facilities (GSI & RIKEN)

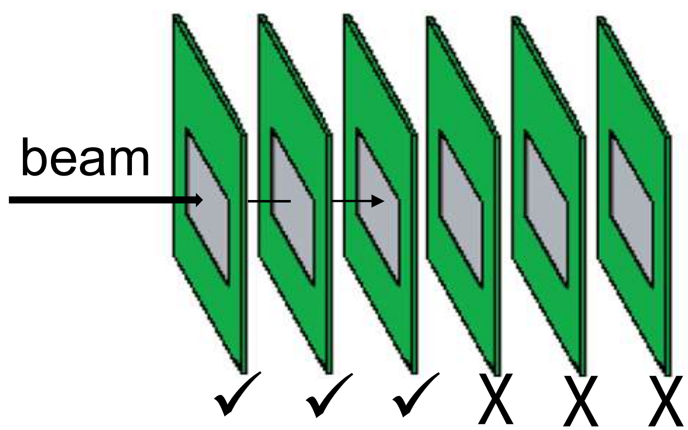
FRS-GSI setup

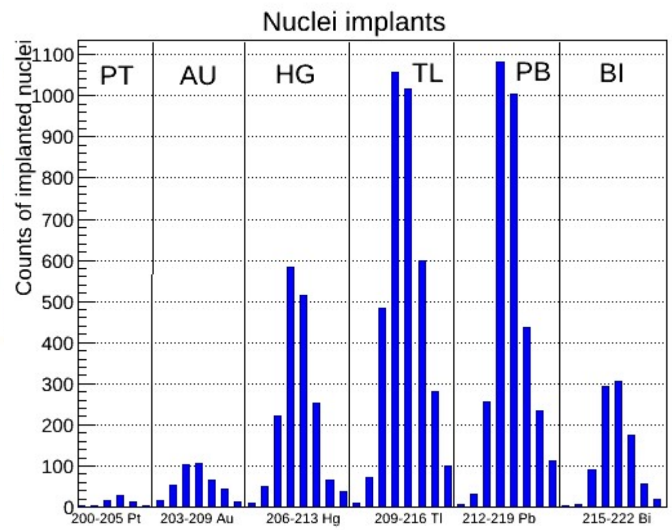


"Cocktail of isotopes"



DSSD multilayer implantation and decay detector SIMBA/AIDA

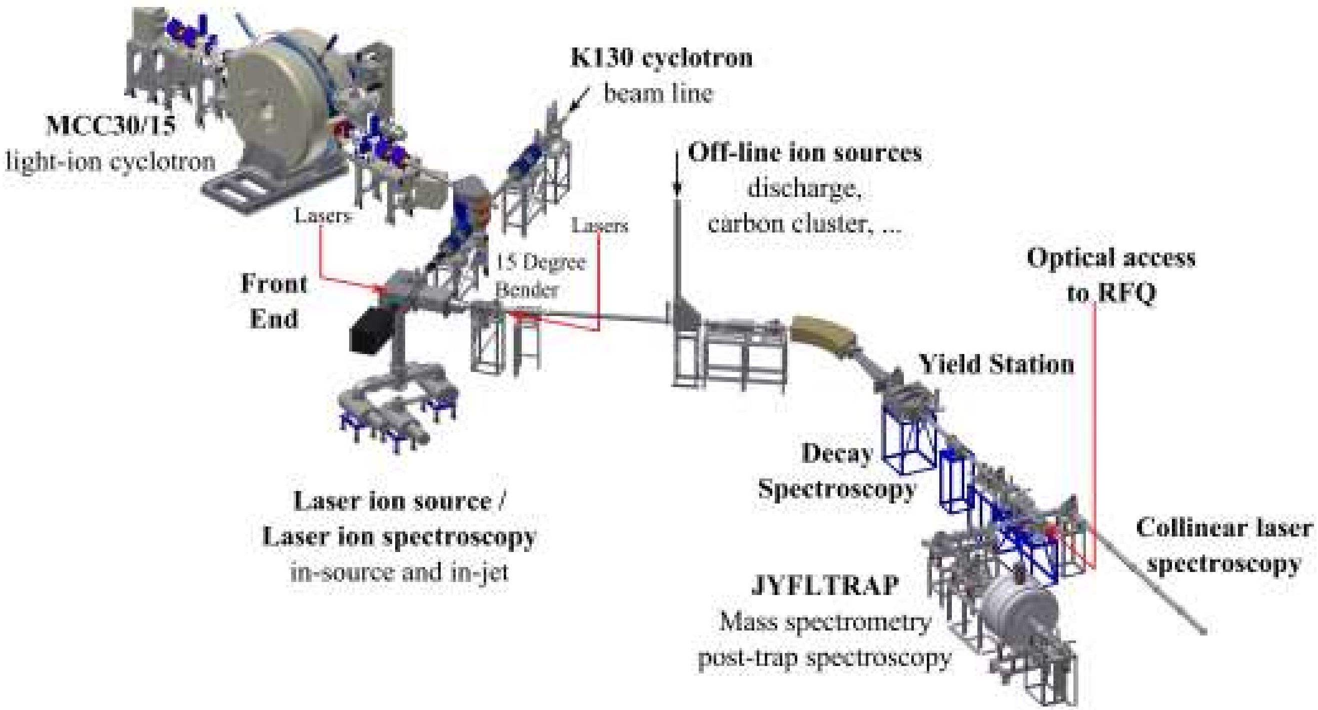




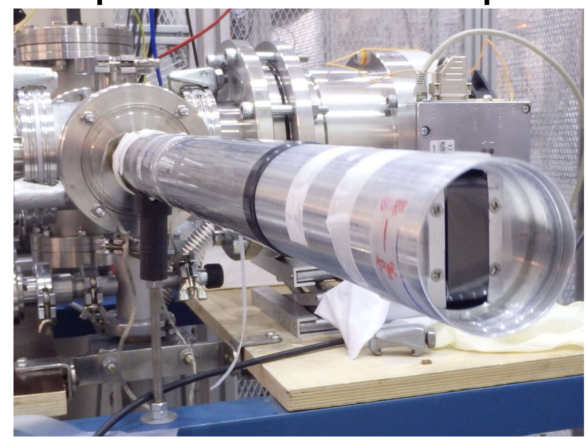
RCF PhD thesis (2015)

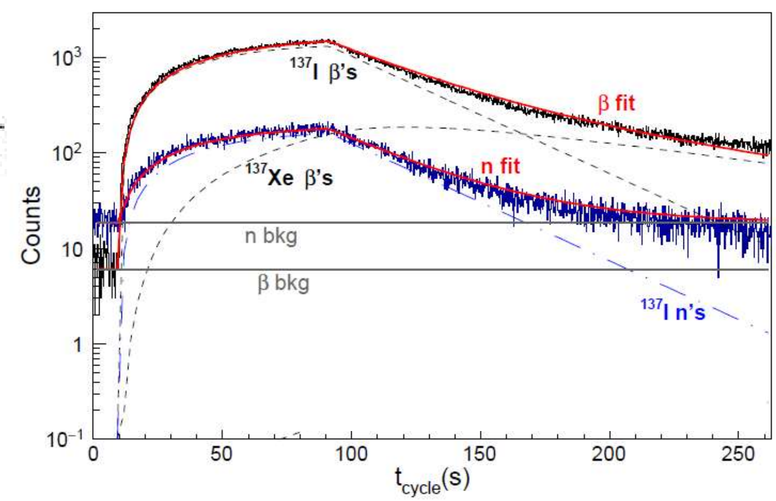
ISOL facilities (IGISOL – Jyväskylä)

Very clean beam!



Implantation in a tape

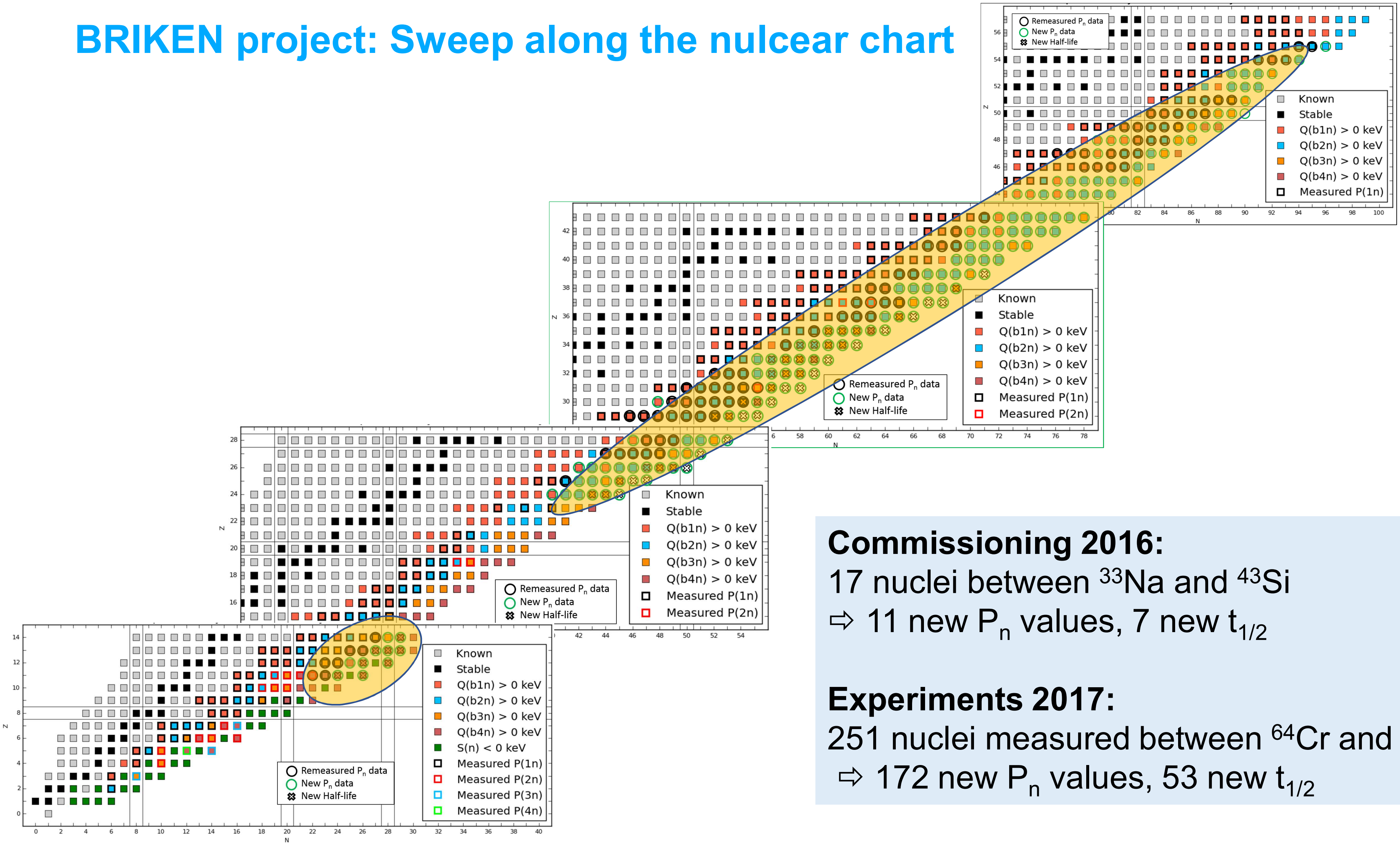




JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

J.Aysto et al. Hyperfine interactions 223, 1 (2014)

BRIKEN project: Sweep along the nulcear chart



Commissioning 2016:

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

⇨ 11 new P_n values, 7 new $t_{1/2}$

Experiments 2017:

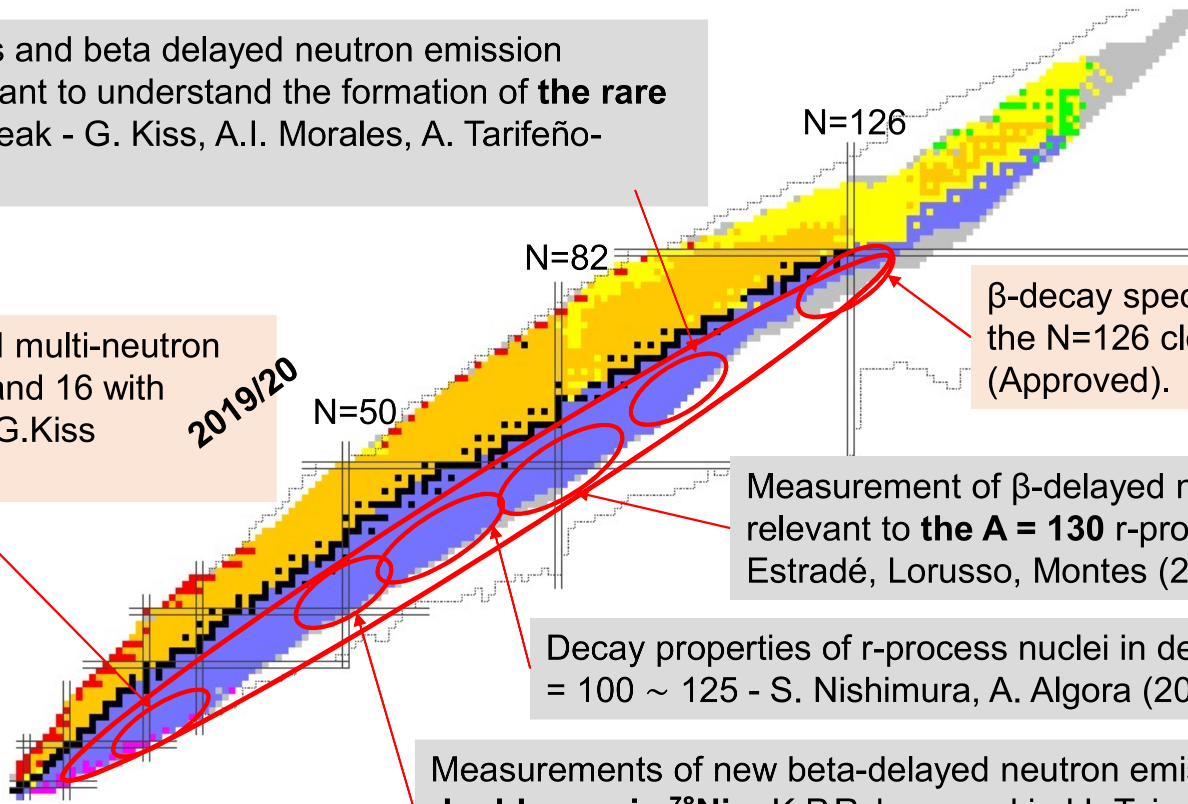
251 nuclei measured between ^{64}Cr and ^{170}Gd

⇨ 172 new P_n values, 53 new $t_{1/2}$

BRIKEN experimental campaign

Masses, half-lives and beta delayed neutron emission probabilities relevant to understand the formation of **the rare earth** r process peak - G. Kiss, A.I. Morales, A. Tarifeño-Saldiva (2017).

Study of light β-delayed multi-neutron emitters between Z=9 and 16 with BRIKEN – I. Dillmann, G.Kiss (Approved).



β-decay spectroscopy in the vicinity of the N=126 closed shell – J. Wu et al. (Approved).

Measurement of β-delayed neutron emission probabilities relevant to **the A = 130** r-process abundance peak - Estradé, Lorusso, Montes (2017).

Decay properties of r-process nuclei in deformed region around A = 100 ~ 125 - S. Nishimura, A. Algora (2017).

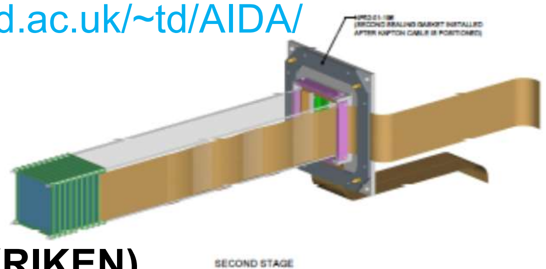
Measurements of new beta-delayed neutron emission properties around **doubly-magic ^{78}Ni** - K.P.Rykaczewski, J.L.Tain, R.K.Grzywacz, I.Dillmann (2017).

Other proposals ongoing for the next committee in Ca region.

BRIKEN: Technical design

Advanced Implantation Detector Array (AIDA) – Univ. of Edinburgh, UK.
- Stack of 6 DSSD Si layers (8 in further exp.).
- 1 mm thickness per strip
- Area: 71.68 mm x 71.68 mm with 128 horizontal (X) and 128 vertical (Y) strips 0.51 mm wide.

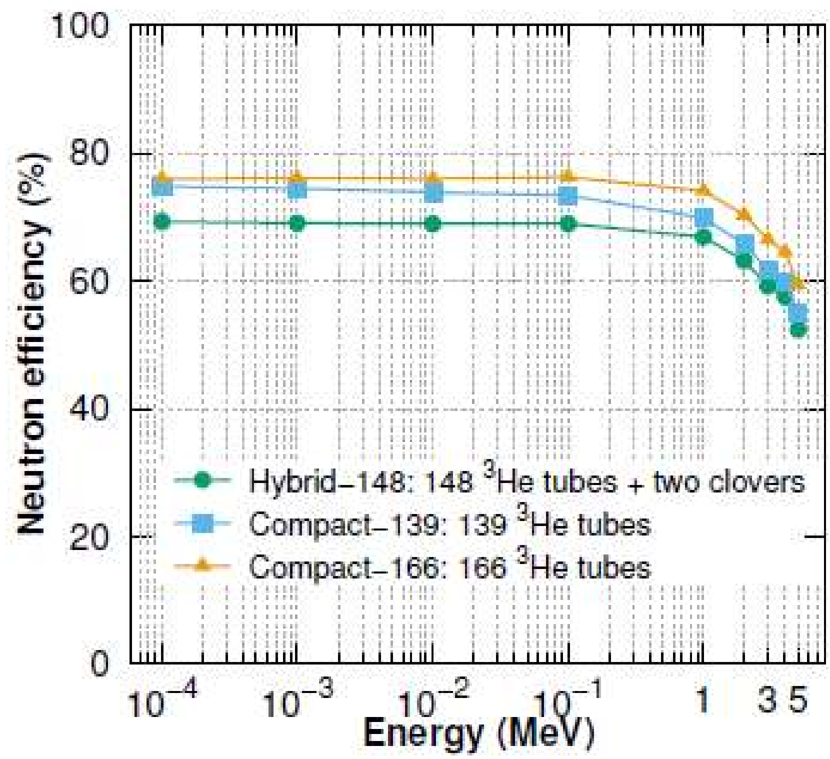
https://www2.ph.ed.ac.uk/~td/AIDA/



WASABI detector (RIKEN)
- Stack of 4 DSSD Si layers.
- Area: 40 mm x 60 mm with strips 3 mm wide.
- This allowed to increase γ efficiency.

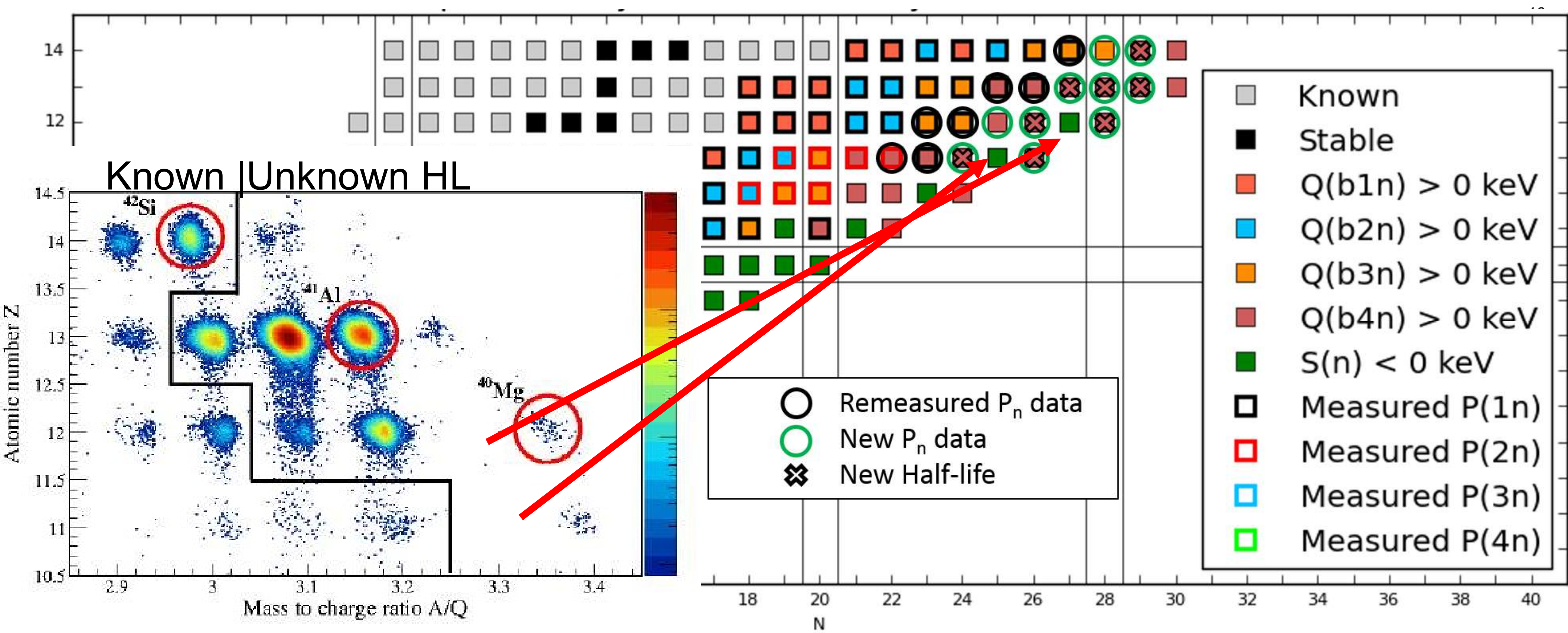
S.Nishimura et al. RIKEN Accel. progress report 46 (2013) 182

Beta delayed neutron at RIKEN (BRIKEN):



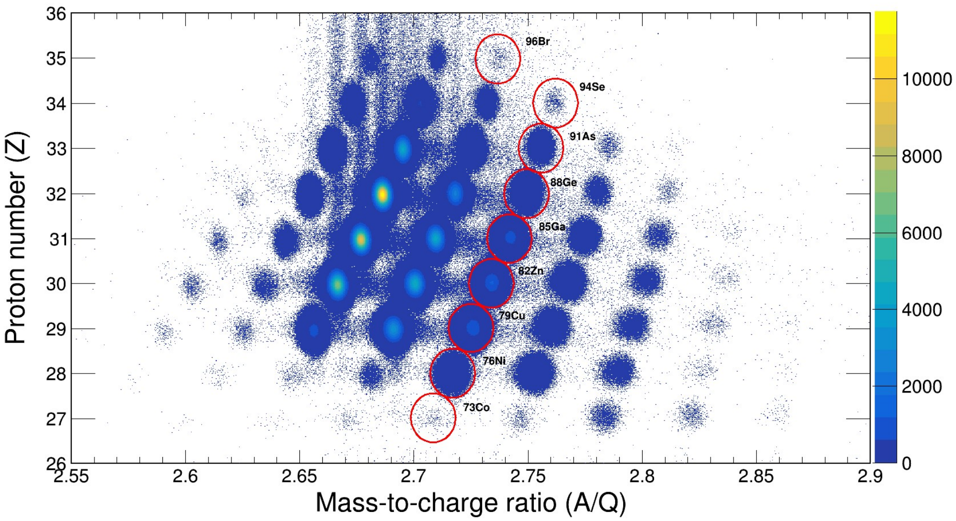
A.Tarifeño-Saldivia, et al, Journal of Instr. 12, P04006 (2017).
I. Dillmannand A. Tarifeño-Saldivia, Nucl. Phys. News 28,28 (2018).

BRIKEN Parasitic beam at N=28 region (Fall 2016)

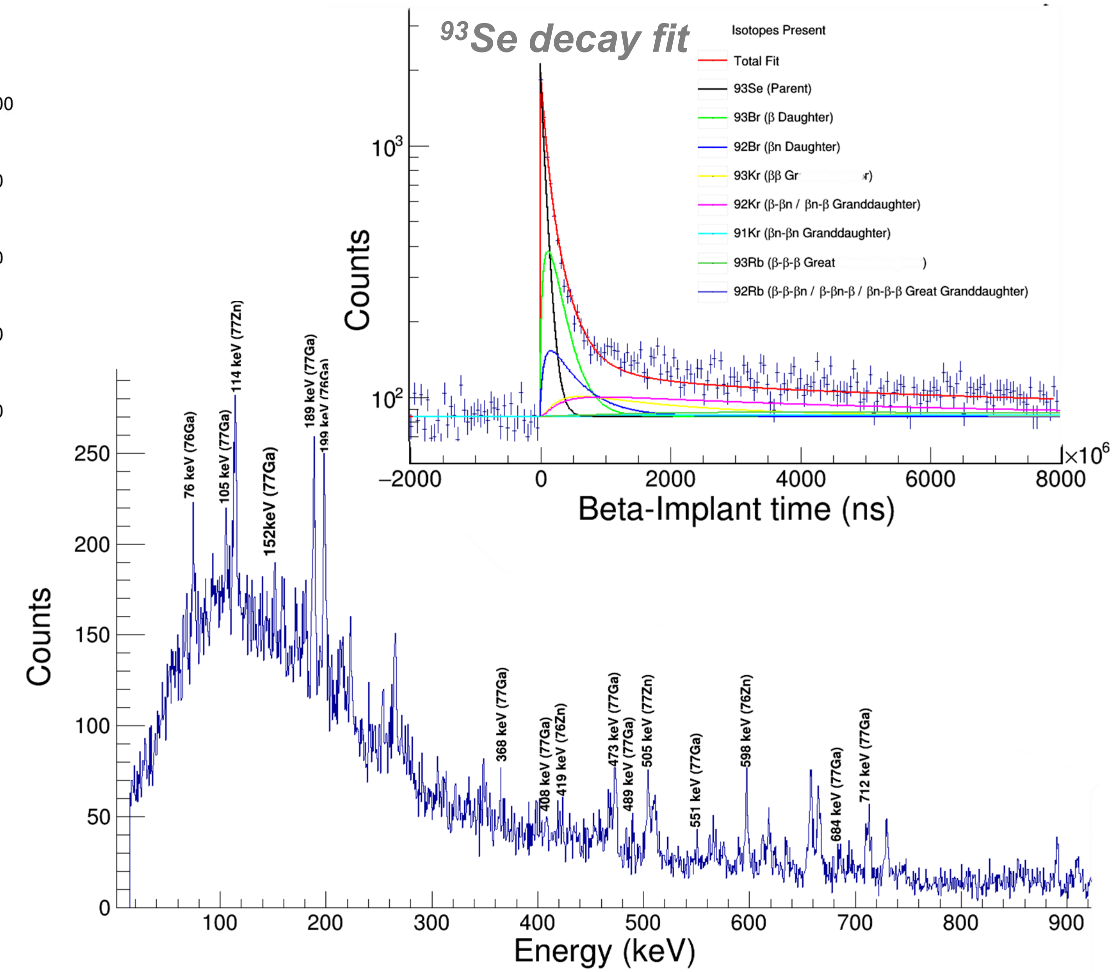


PID courtesy of V.H. Phong, RIKEN annual report

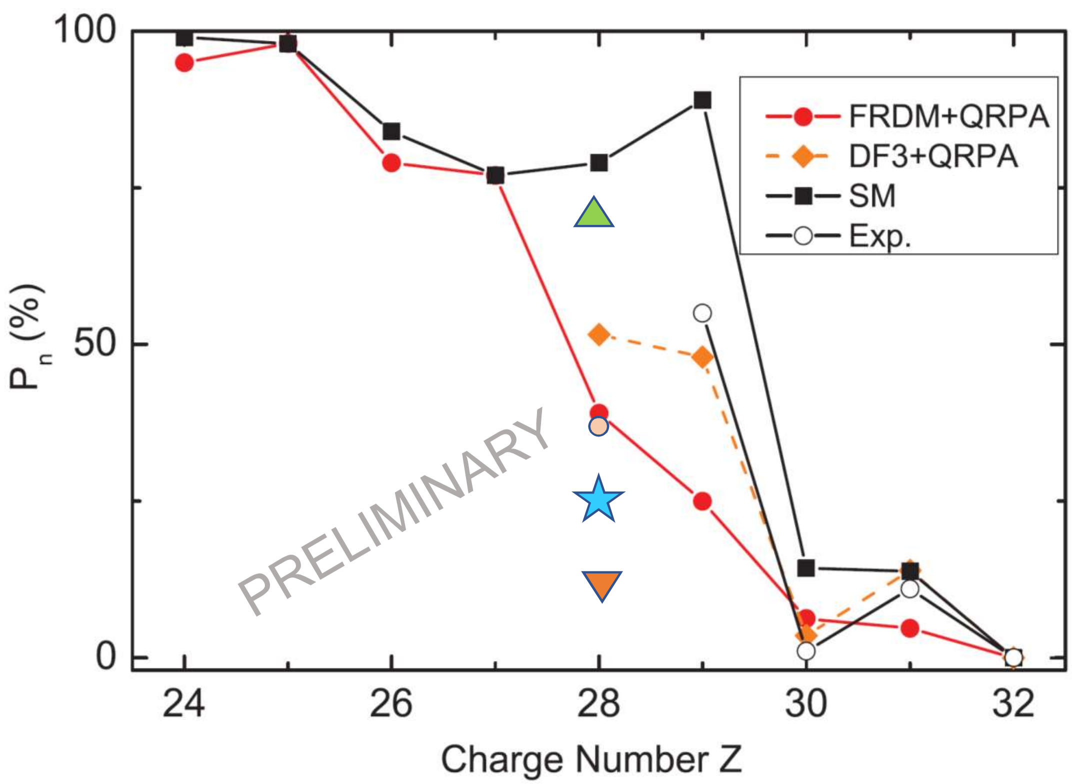
BRIKEN project preliminary results in ^{78}Ni region



Plots from Lewis Sexton (TRIUMF/U.Surrey)
Master Thesis work



^{78}Ni P_{1n} value: Comparison with theory



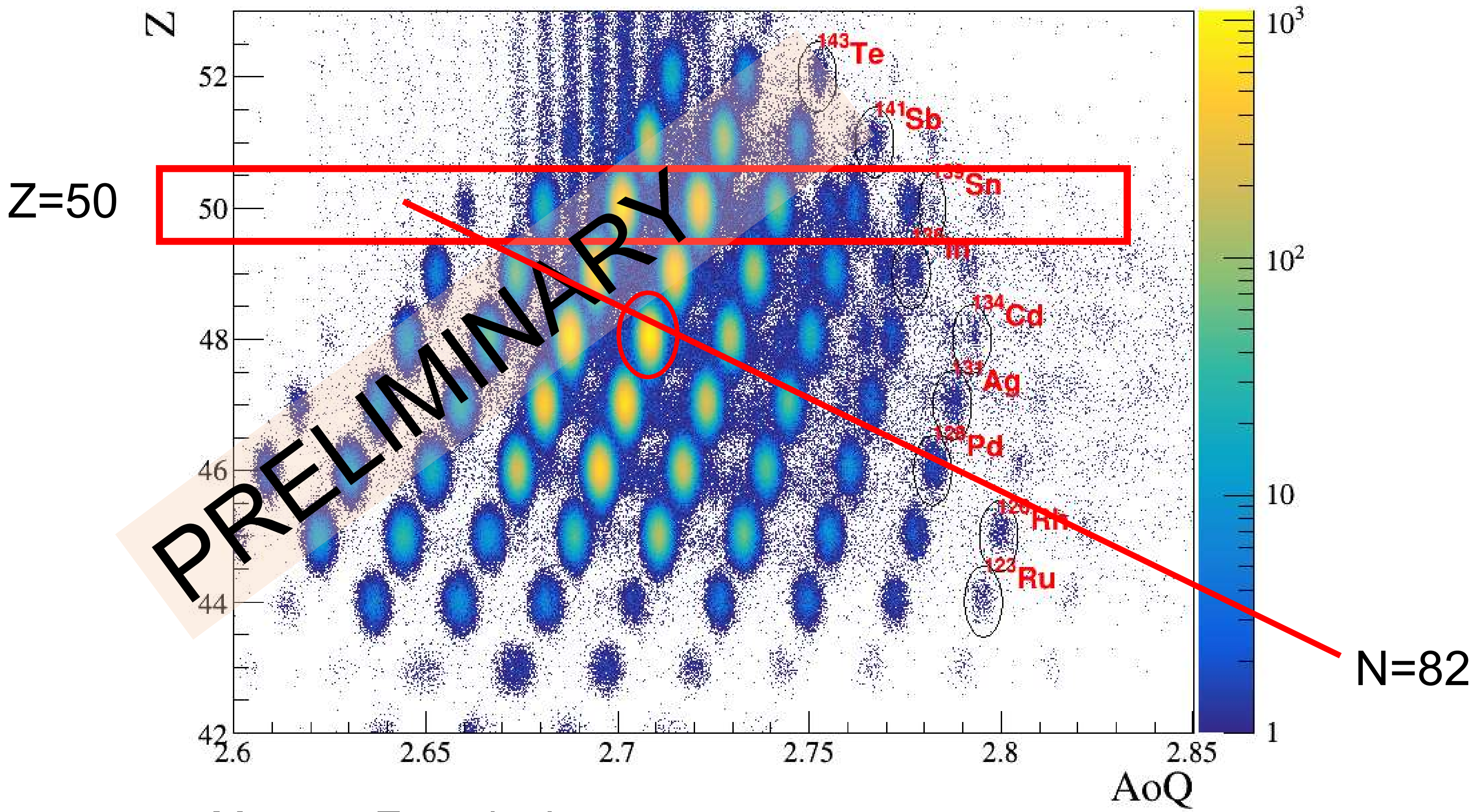
Picture adapted from Zhi et al., PRC87 (2013)

Moeller et al., PRC 2003
Borzov et al., PRC 2000
Zhi et al., PRC 2013

- RHB+ RQRPA (Marketin et al., PRC 2016)
- pn-QRPA + HF (FRDM2012) (Moeller et al., PRC 2016)
- DF3a+ cQRPA (Borzov et al., PRC 2005,2017)
- **BRIKEN experiment**

Factor ~8 spread!

BRIKEN project preliminary results PID experiment A~130

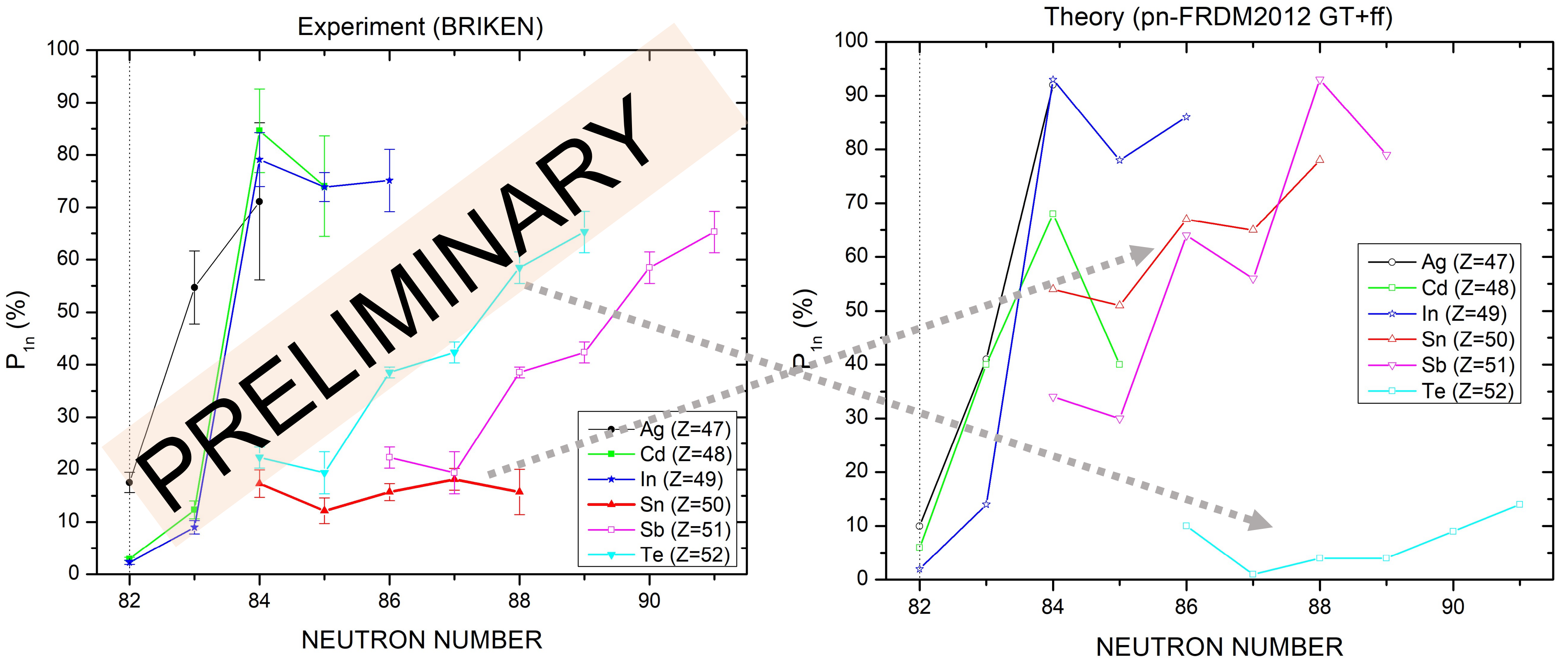


Spokespersons: Montes, Estrade, Lorusso

Courtesy: Vi Phong

BRIKEN project preliminary results (A=130 region)

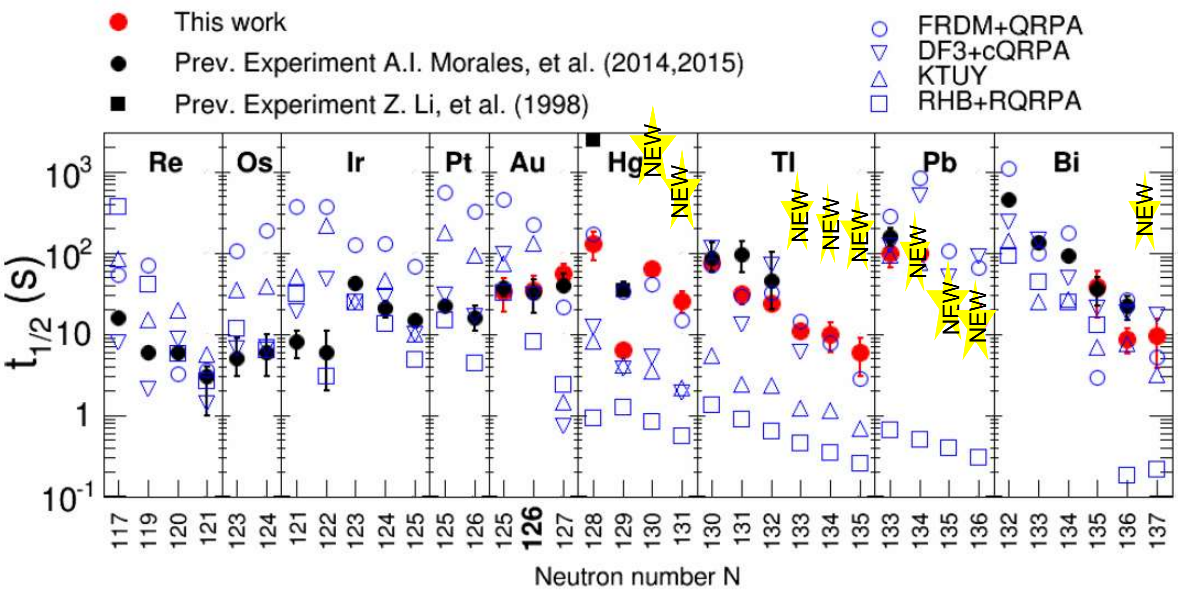
QRPA+Hauser Feshbach
FRDM 2012 + AME2012 masses



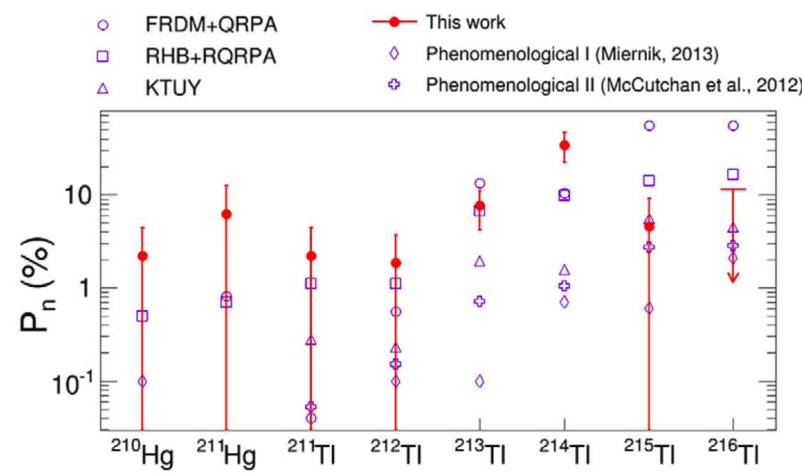
Courtesy of Alfredo Estradé et al.

Moeller, Mumpower, Kawano et al., At. Data Nucl. Data Tabl. ***109*** *(2016) 1*
https://t2.lanl.gov/nis/molleretal/publications/ADNDT-BETA-2018.html

Results: Half-lives and P_{1n} in A>200 and N~126 region (GSI)



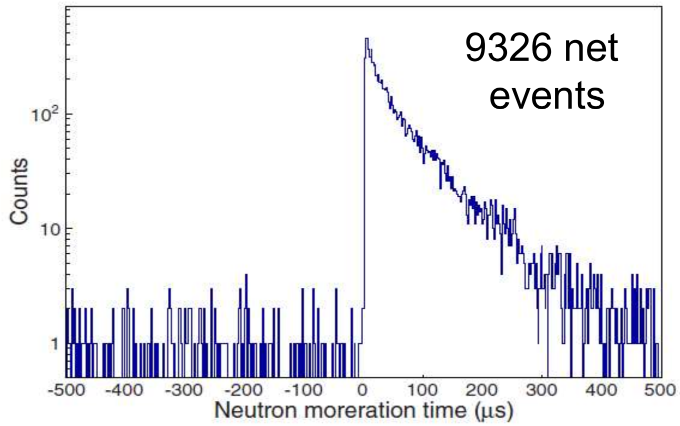
- ✓ 18 β-decay half-lives (9 for the first time)
- ✓ 8 P_{1n} values measured for the first time



RCF et al, Nuclear Data Sheets, 120, 81-83 (2014).
RCF et al, Phys. Rev. Lett. 117, 012501 (2016)
RCF et al, Phys. Rev. C 95, 064322 (2017)

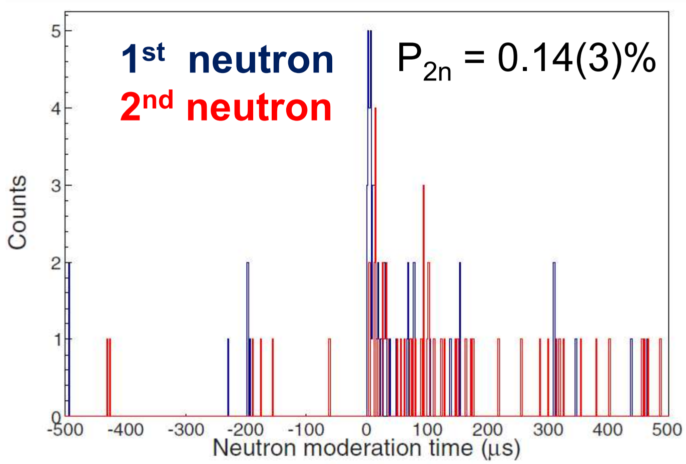
^{136}Sb measurement (β2n emitter)

^{136}Sb β1n correlation



6 days of beamtime

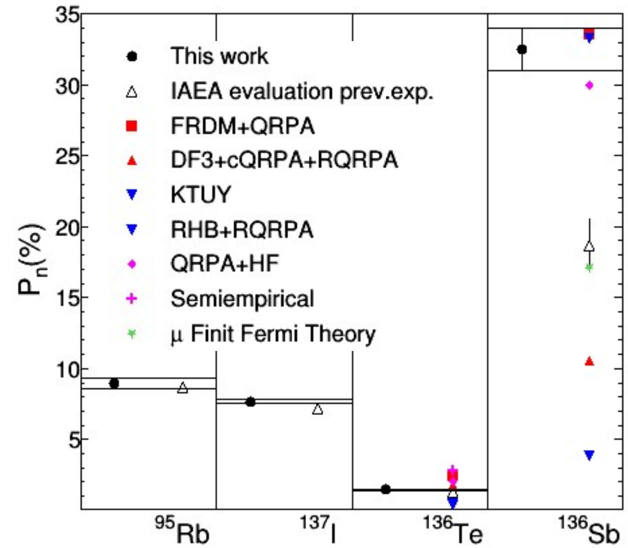
β-1st n & β-2nd n correlated events



P_{2n} (%)	Model
6.19	FRDM+QRPA
4.15(1.05)	DF3+cQRPA+RQRPA
0.0	KTUY
0.2	RHB+RQRPA
0	QRPA-HF
0.0	Semiempirical
0.28	Microscopic Finite Fermi-system theory

Exp. ALTO Not published / Isobars Estimation P_{2n} =1.4±0.2%

^{136}Sb and ^{136}Te and calibration isotopes P_{1n} results



RCF Acta Physica Polonica B, 48 (2017) 517-522.
RCF EPJ Web of Conferences, 146 (2017) 01005.
RCF et al., Physical Review C 98 (2018) 034310.

Summary and outlook

Estimations on new Pn values within the BRIKEN project data:

Emission type	Energetically allowed	Already measured	New Pn values expected
β1n	621	298	~250
β2n	300	23 + 2 approx	~50
β3n	138	4	~10
β4n	58	1	~5

Be able to determine information on gamma-neutron competition above Sn.

Certify βn is the dominant decay in very exotic neutron-rich region.

Relevant input for theoretical models to predict properties in the neutron-rich region either for nuclear structure and astrophysics.

First scientific papers have been already submitted. So far 4 experiments done and two approved

This work is supported by:

NSERC CRSNG

TRIUMF

RIKEN NiSHiNA CENTER

IFIC INSTITUT DE FÍSICA CORPUSCULAR

THE UNIVERSITY OF EDINBURGH

OAK RIDGE National Laboratory

NSCL

GSI

UPC

TRIUMF

Moltes gràcies
Thank you
Merci
Grazie!

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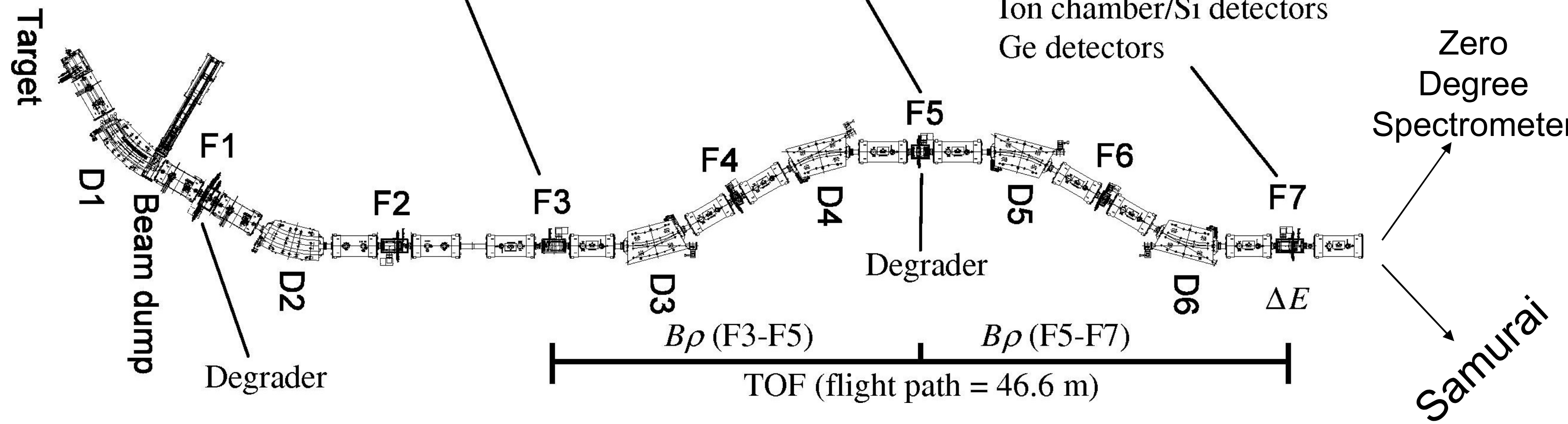
Discovery, accelerated

BRIKEN Experimental setup

^{Nat}U ^{70}Zn… beam at 345MeV/n
Be or other target



N. Fukuda et al. NIM B-317 (2013)

$$Method \quad B\rho - \Delta E - B\rho$$

$$\frac{A}{Q} = B\rho \frac{e_0}{\mu}\frac{1}{\gamma}\frac{tof}{L}$$

$$Z \sim \sqrt{E_{Loss}}$$

More details at: http://ribf.riken.jp/BigRIPSInfo/daq/fig/pid.pdf