β-delayed neutron emission: Measurement of emission probabilities

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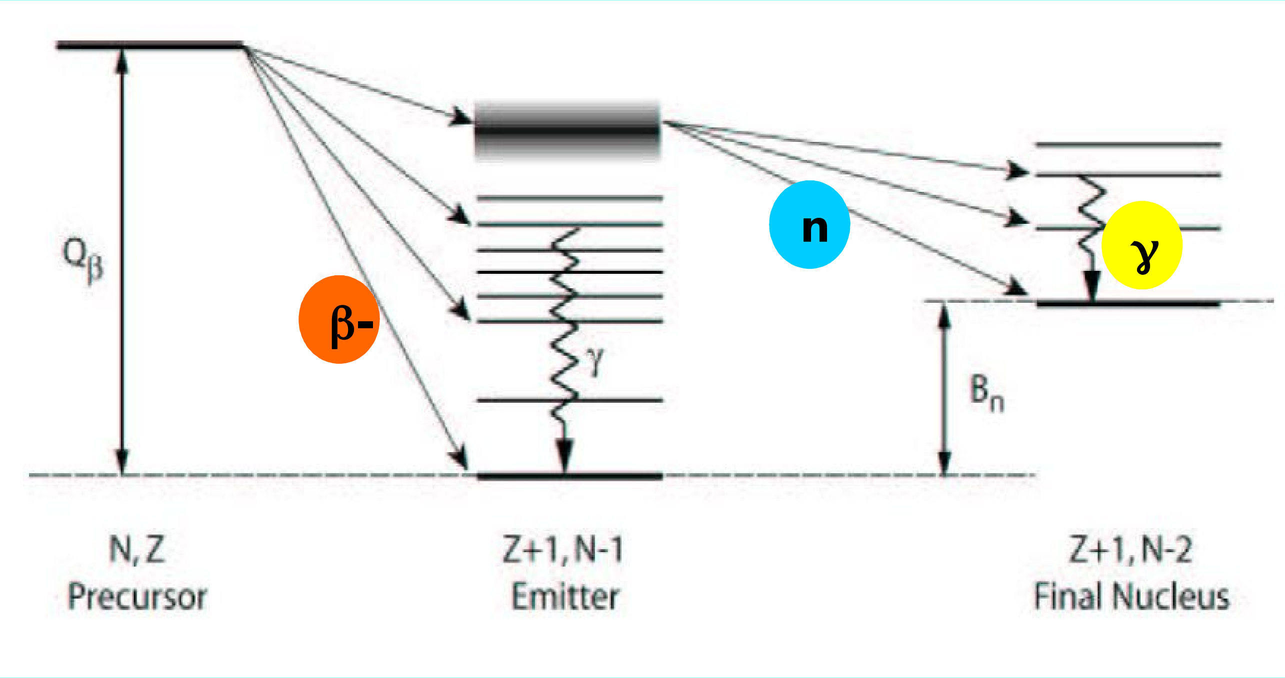
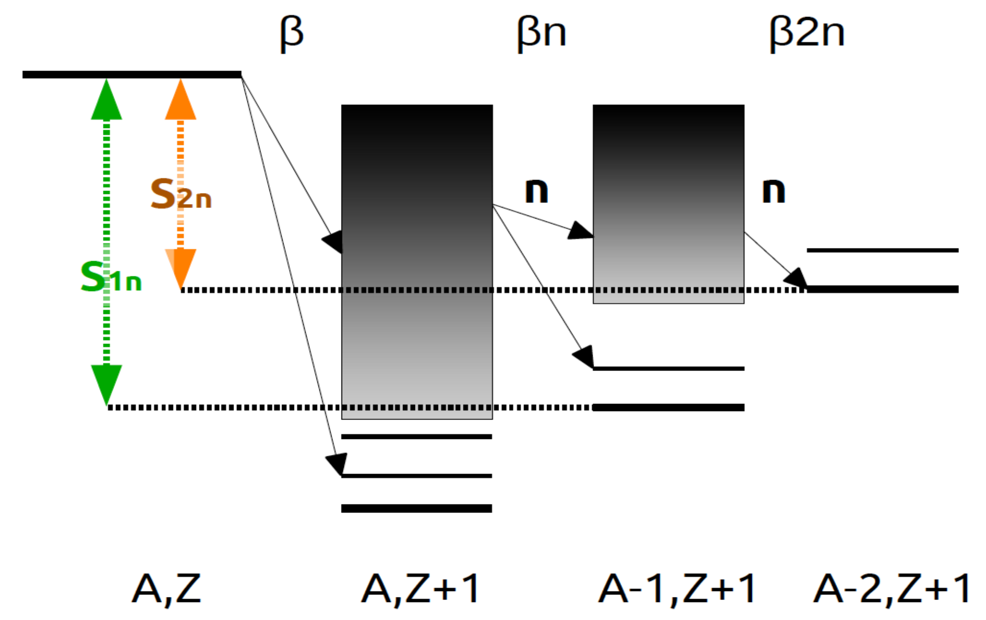
Gamma y Neutrones

Beta-delayed neutron emission is an exotic process that occurs in neutron rich nuclei whenever the neutron separation energy in the daughter S_n is smaller than the available decay energy window Q_β



Beta-delayed multiple neutron emission can also occur whenever S_{2n}, S_{3n}, ... are smaller than Q_β



P_{xn}: x-neutron emission probability

$$P_{1n} = \frac{\displaystyle\int_{S_n}^{Q_\beta} \frac{\Gamma_{1n}(E_x)}{\Gamma_{tot}(E_x)} S_\beta(E_x) \cdot f(Q_\beta - E_x) \cdot dE_x}{\displaystyle\int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x)\, dE_x}$$

$$\Gamma_{tot} = \Gamma_\gamma + \Gamma_{1n} + \Gamma_{2n} + \ldots$$

Total neutron emission probability

$$P_n = \sum_{x>0} P_{xn}$$

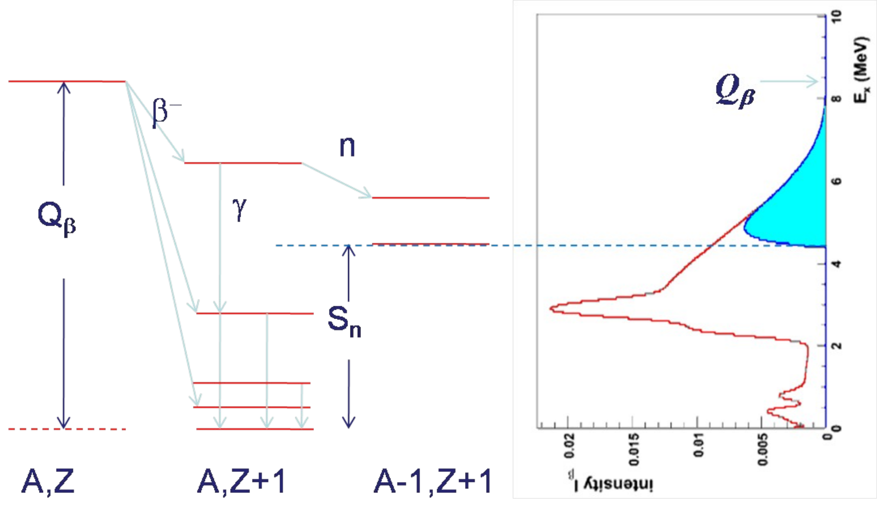
Neutron emission multiplicity

$$\langle n \rangle = \sum_{x>0} x P_{xn}$$

Beta strength:

$$S_\beta(E_x) = \frac{1}{D} \frac{g_A^2}{g_V^2} \frac{1}{2J_i + 1} \left| \left\langle f \middle\| M_{\lambda\pi}^{\beta} \middle\| i \right\rangle \right|^2$$

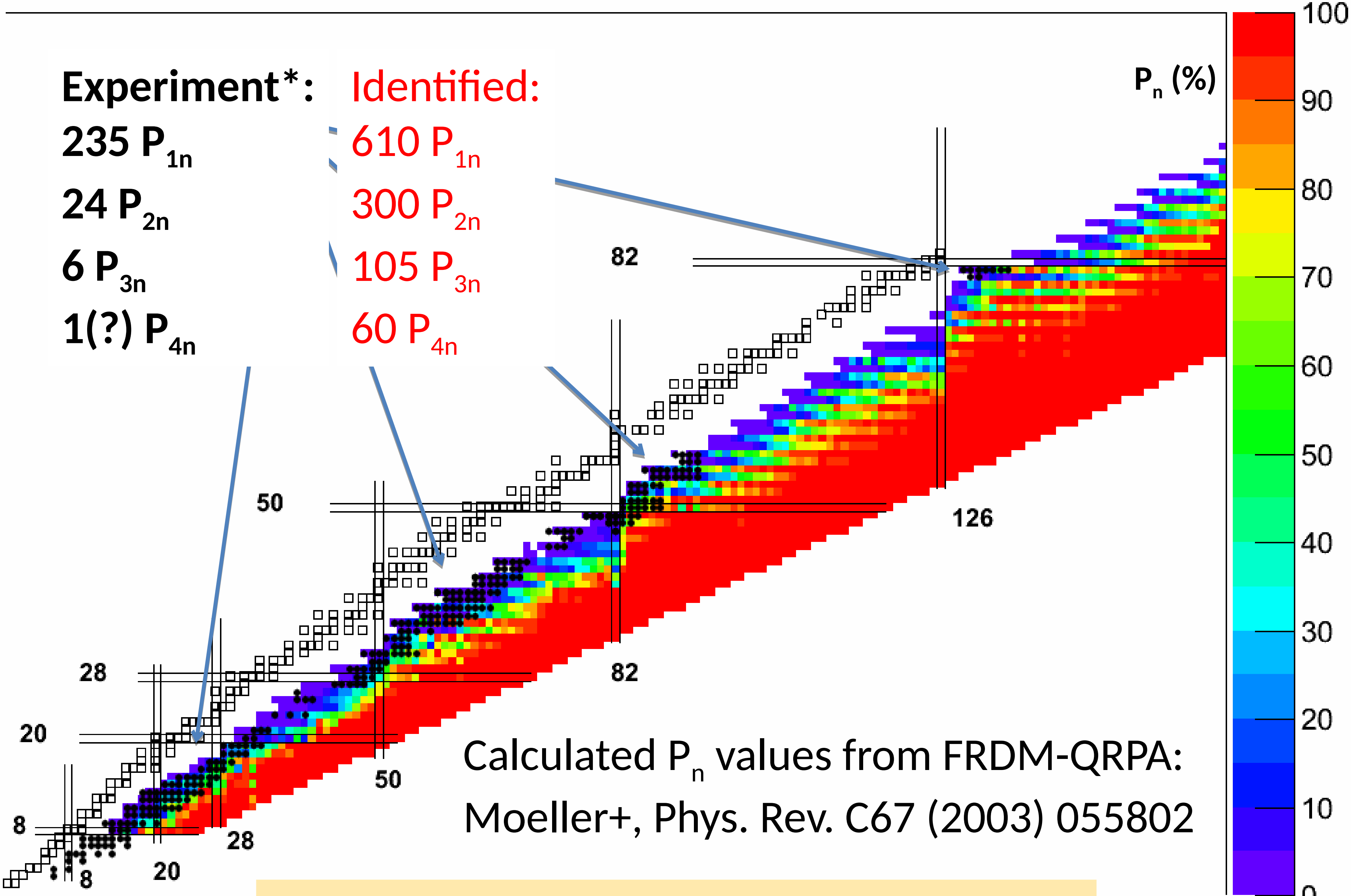
$$= \frac{I_\beta(E_x)}{T_{1/2}\, f(Q_\beta - E_x)}$$



Measured P_n values versus expected

Experiment*:
235 P_{1n}
24 P_{2n}
6 P_{3n}
1(?) P_{4n}

Identified:
610 P_{1n}
300 P_{2n}
105 P_{3n}
60 P_{4n}



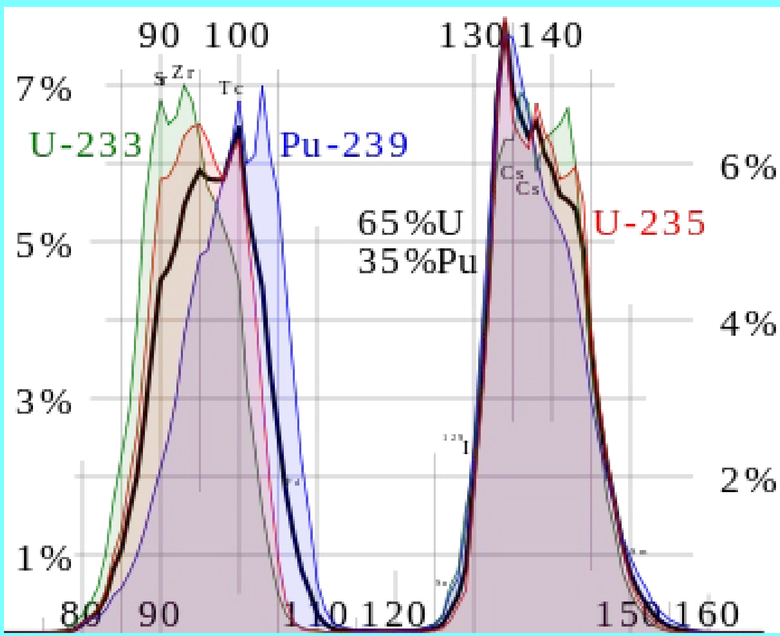
Calculated P_n values from FRDM-QRPA:
Moeller+, Phys. Rev. C67 (2003) 055802

(*) https://www-nds.iaea.org/beta-delayed-neutron/

Nuclear power reactors: delayed neutron fraction

- Some fission products are βn emitters
- They contribute with a small fraction (β<1%) to the total number of neutrons in a reactor
- They are however essential for the mechanical control of reactor power

Fission yields as a function of A



Prompt neutrons vs. delayed neutrons

Isotope	fission cross-section 0.025eV / 2MeV	prompt neutrons 0.025eV / 2MeV	delayed neutrons 0.025eV / 2MeV
235U	585 / 1.27	2.42 / 2.63	0.0162 / 0.0165
238U	0.000027 / 0.57	2.36 / 2.60	0.0478 / 0.0478
233U	531 / 1.98	2.48 / 2.63	0.0067 / 0.0077
239Pu	747 / 1.93	2.87 / 3.16	0.0065 / 0.0067
241Pu	1 012 / 1.76	2.92 / 3.21	0.0160 / 0.0160

Thermal energies

- The time evolution of delayed neutron fraction is represented by six (eight) “groups of isotopes”
- The group parameters are fissile nucleus dependent and neutron energy dependent
- They are obtained from integral measurements

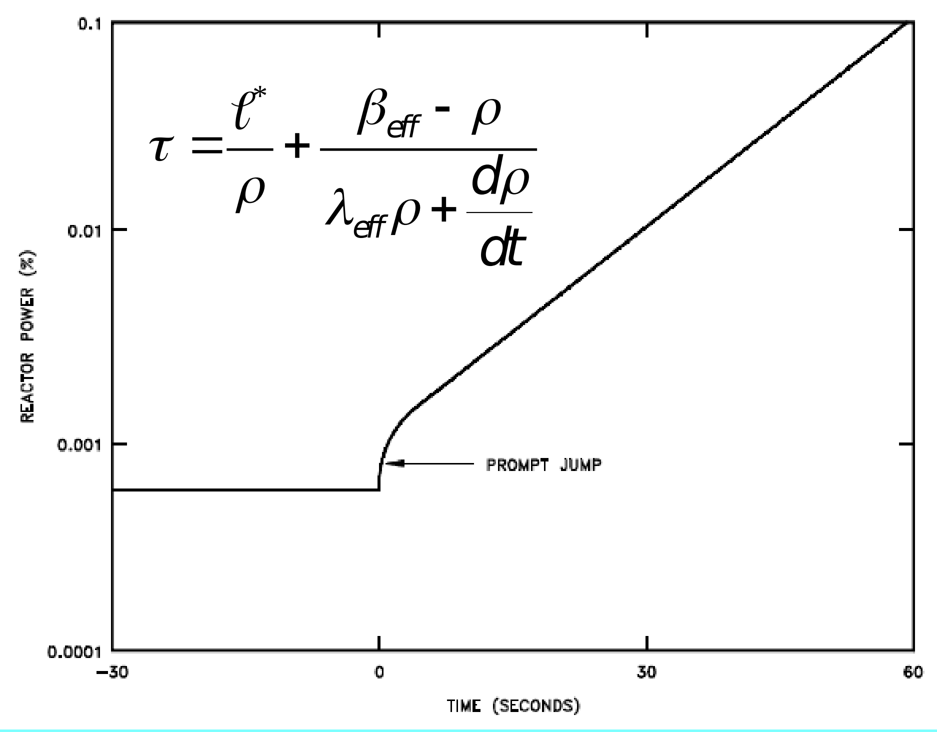
	Possible precursor nuclei	Mean energy (MeV)	Average half-life of the group [s]			Delayed neutron fraction [%]		
i			235U	239Pu	233U	235U	239Pu	233U
1	87Br, 142Cs	0.25	55.72	54.28	55.0	0.021	0.0072	0.0226
2	137I, 88Br	0.56	22.72	23.4	20.57	0.140	0.0626	0.0786
3	138I, 89Br, (93,94)Rb	0.43	6.22	5.60	5.00	0.126	0.0444	0.0658
4	139I, (93,94)Kr 143Xe, (90,92)Br	0.62	2.3	2.13	2.13	0.252	0.0685	0.0730
5	140I, 145Cs	0.42	0.61	0.618	0.615	0.074	0.018	0.0135
6	(Br, Rb, As etc.)	-	0.23	0.257	0.277	0.027	0.0093	0.0087
		Total				0.64	0.21	0.26

Thermal energies

- The time evolution of reactor power after sudden variations of the reactivity ρ is modulated by the delayed neutron fraction β

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

k_{eff}: effective multiplication factor



$$\tau = \frac{\ell^*}{\rho} + \frac{\beta_{eff} - \rho}{\lambda_{eff}\rho + \frac{d\rho}{dt}}$$

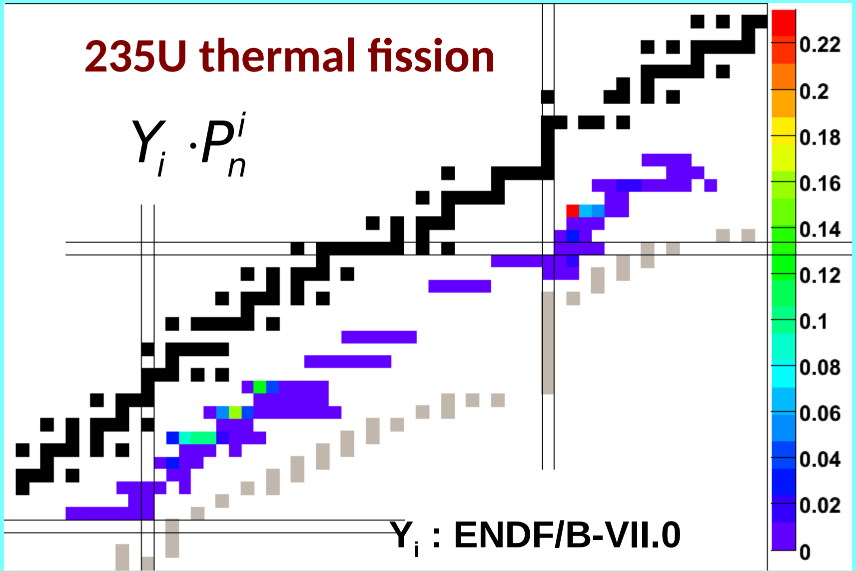
Microscopic summation calculations of $\bar{\nu}_d$

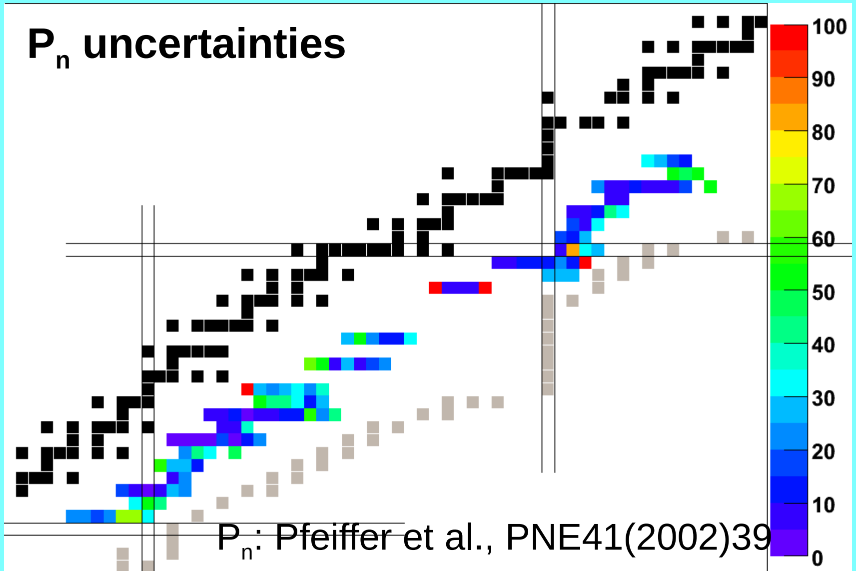
- A more fundamental and generic approach to the estimation of β_{eff}
- Microscopic summation calculations lack still the accuracy of Keepin six-group formula
- Reason: **inaccuracies** in fission yields Y and **delayed neutron emission probabilities** $\boldsymbol{P_n}$
- Improvement of P_n values and comparison with integral measurements can constrain Y

Number of delayed neutrons per fission

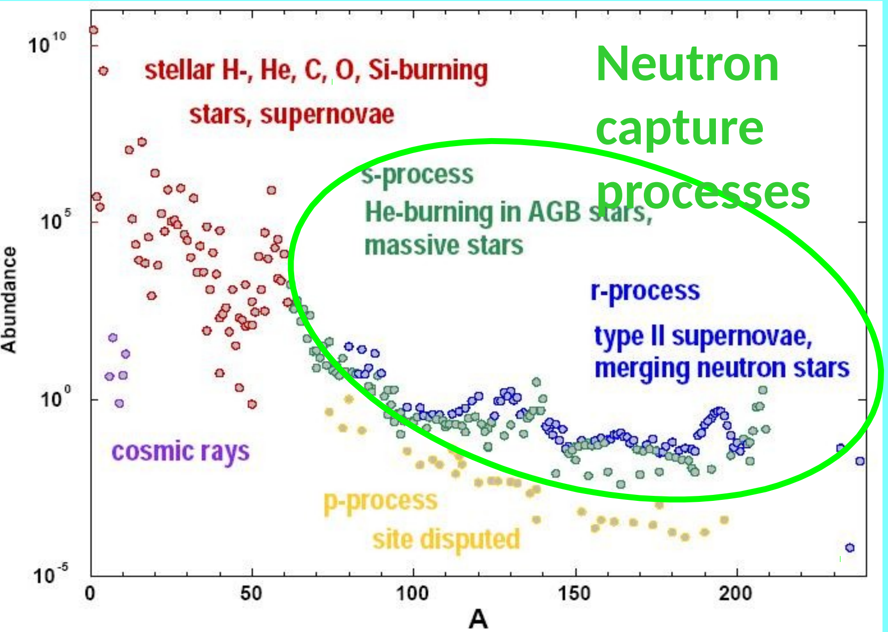
$$\bar{\nu}_d = \sum_i Y_i \cdot P_n^i$$

Can be used to identify P_n values that should be revisited

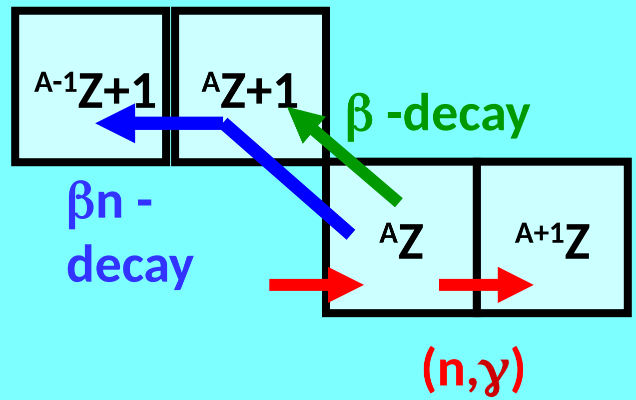


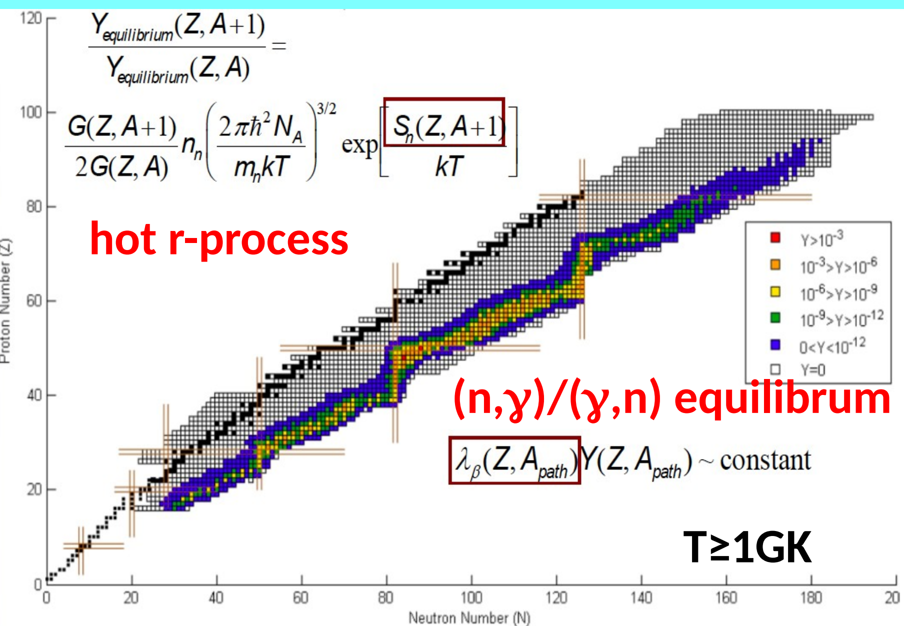


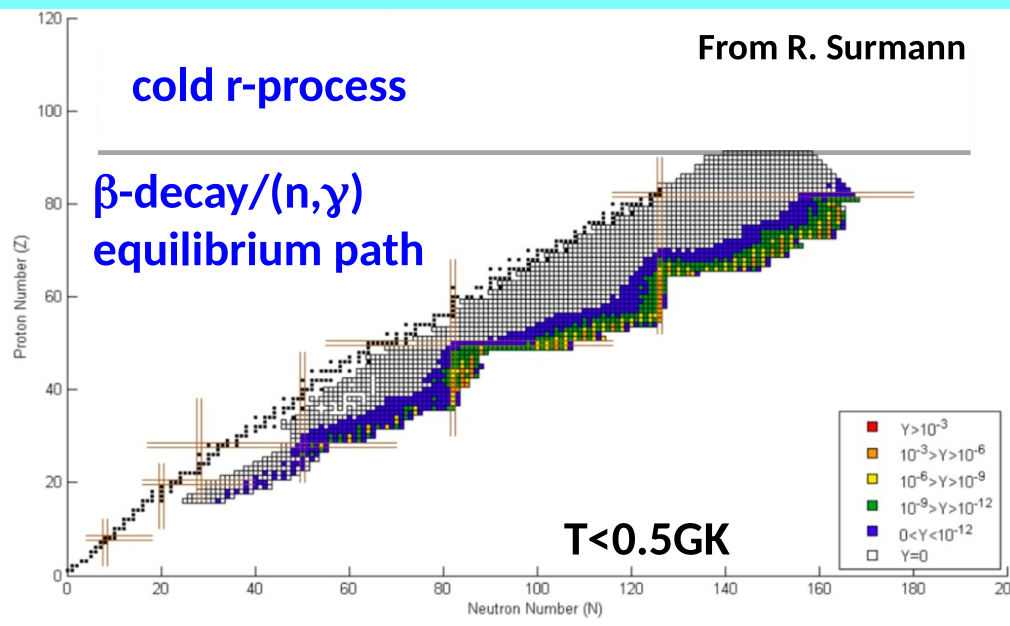
Astrophysics: The r-process



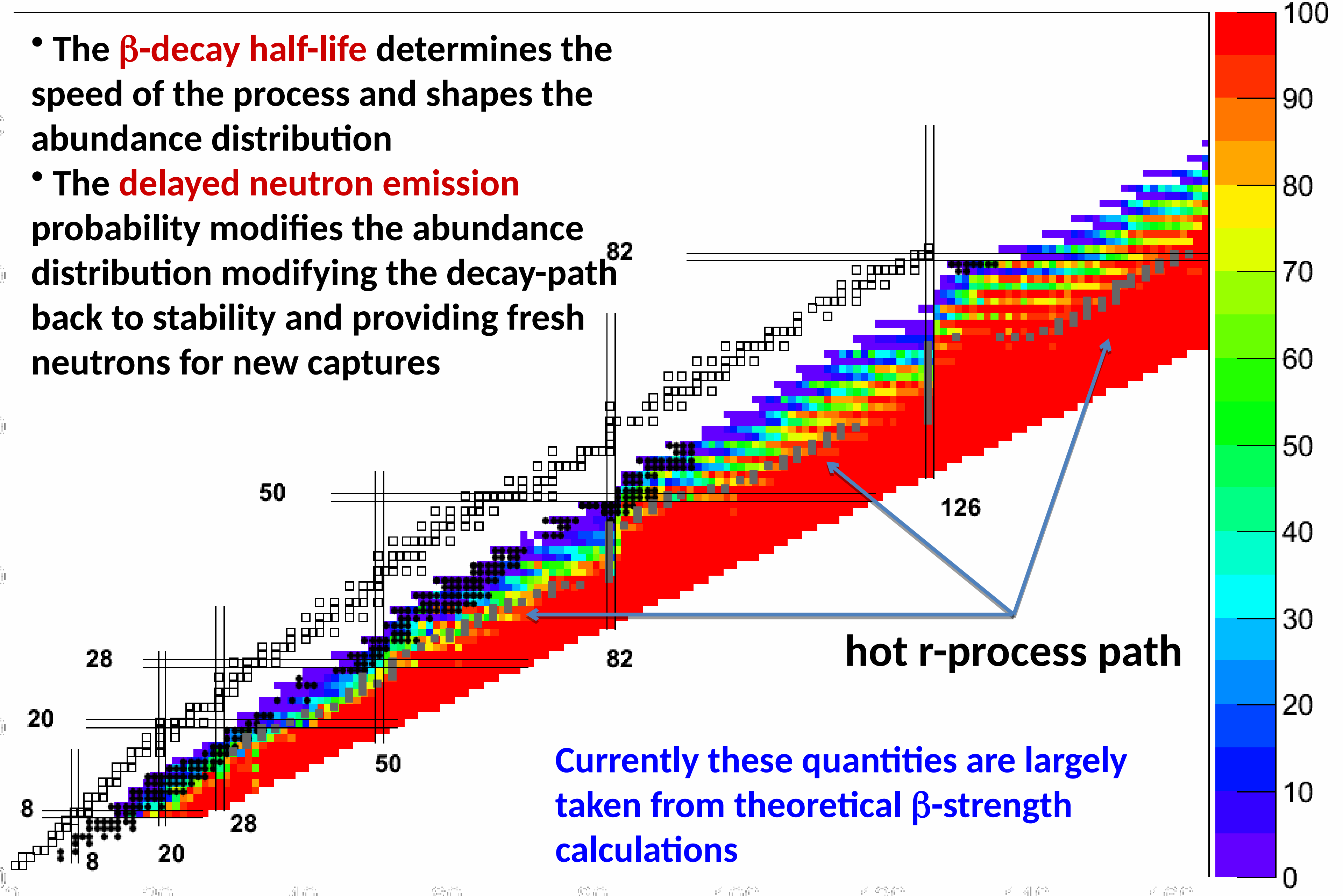
R-process: A short and very high neutron flux (n_n>10^{20} g/cm^3) produces very neutron-rich nuclei by successive neutron captures in a short time, which then decay to stability.







Importance of $T_{1/2}$ and P_n values in r-process nucleosynthesis



- The β-decay half-life determines the speed of the process and shapes the abundance distribution
- The delayed neutron emission probability modifies the abundance distribution modifying the decay-path back to stability and providing fresh neutrons for new captures

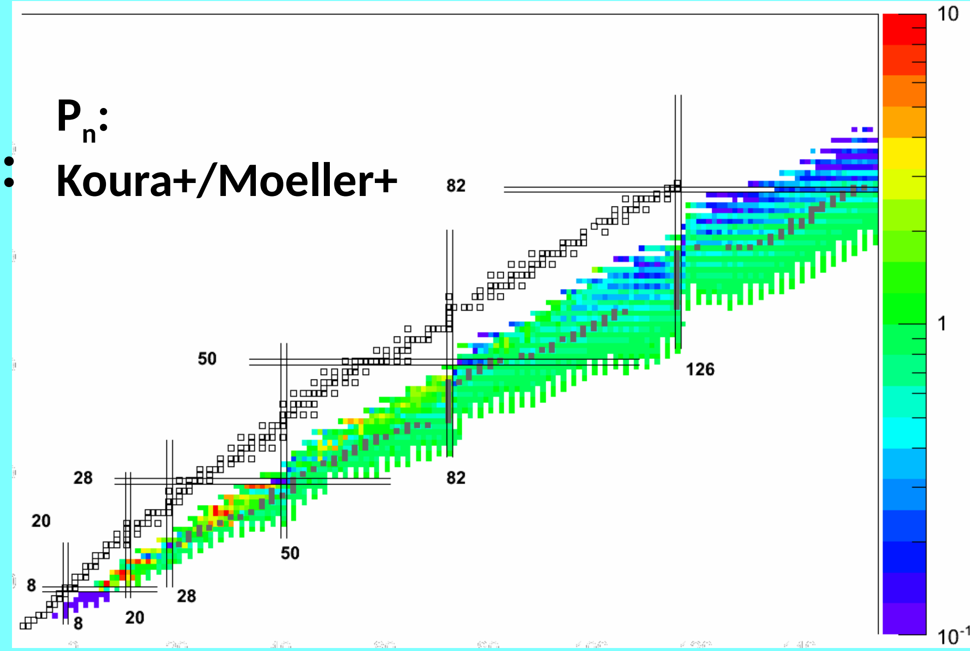
hot r-process path

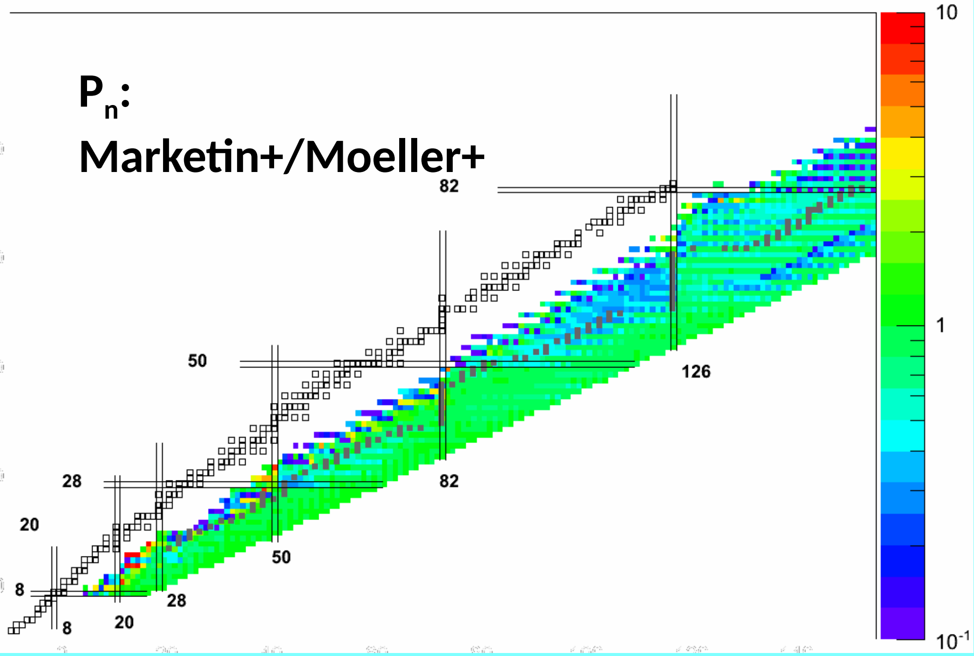
Currently these quantities are largely taken from theoretical β-strength calculations

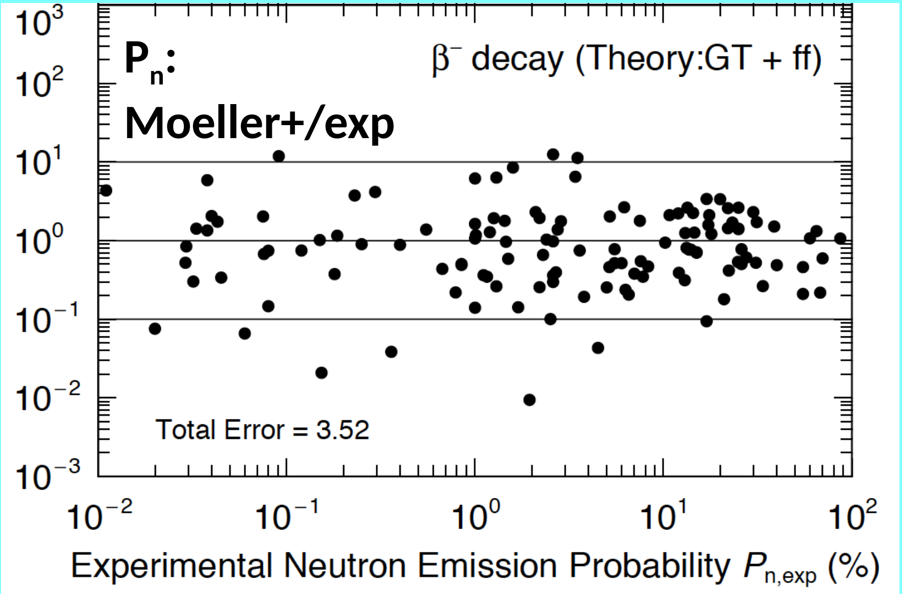
Comparison of global calculations: P_n

How reliable are the calculations?

- **Moeller+, PRC67 (2003) 055802: FRDM+QRPA**
- **Marketin+, PRC93 (2016) 025805: RHB+RQRPA**
- **Koura+, PTP113(2005)305 & PTP84(1990)641 : KTUY+GT2**

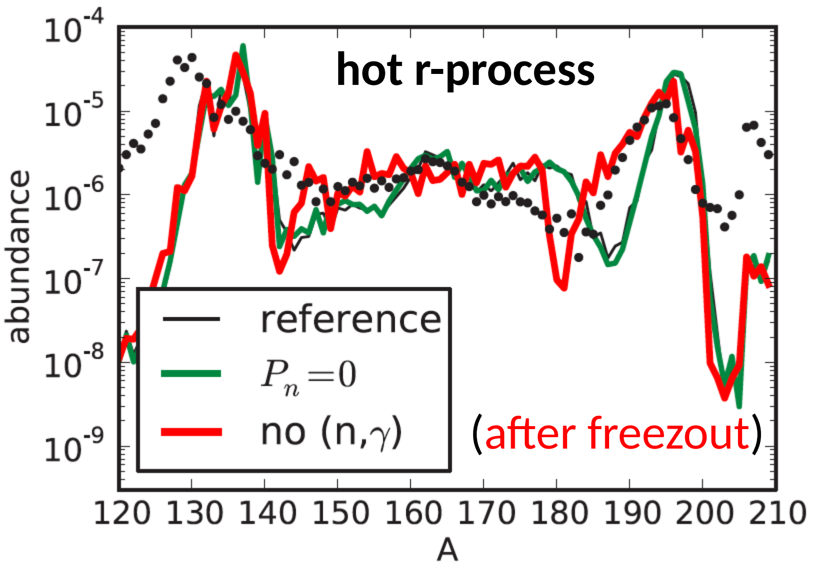


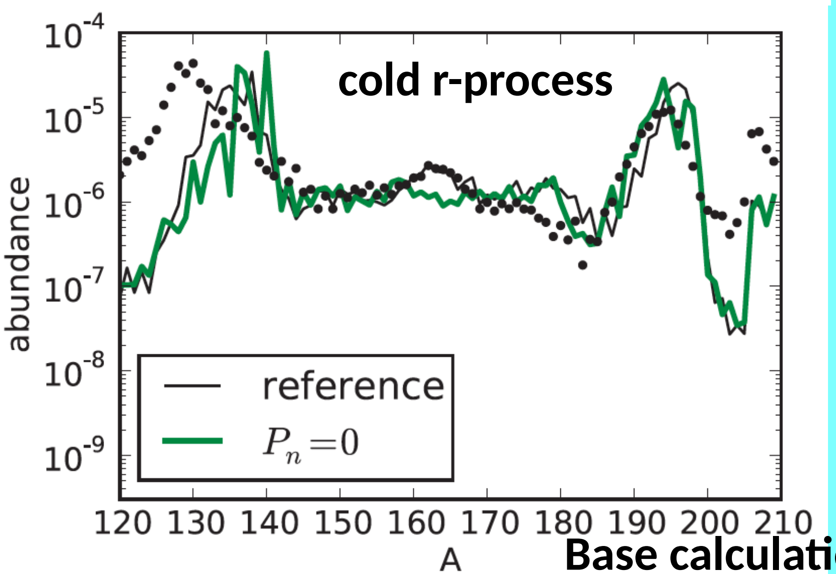




Impact of P_n

Arcones+, PRC83(2011)045809

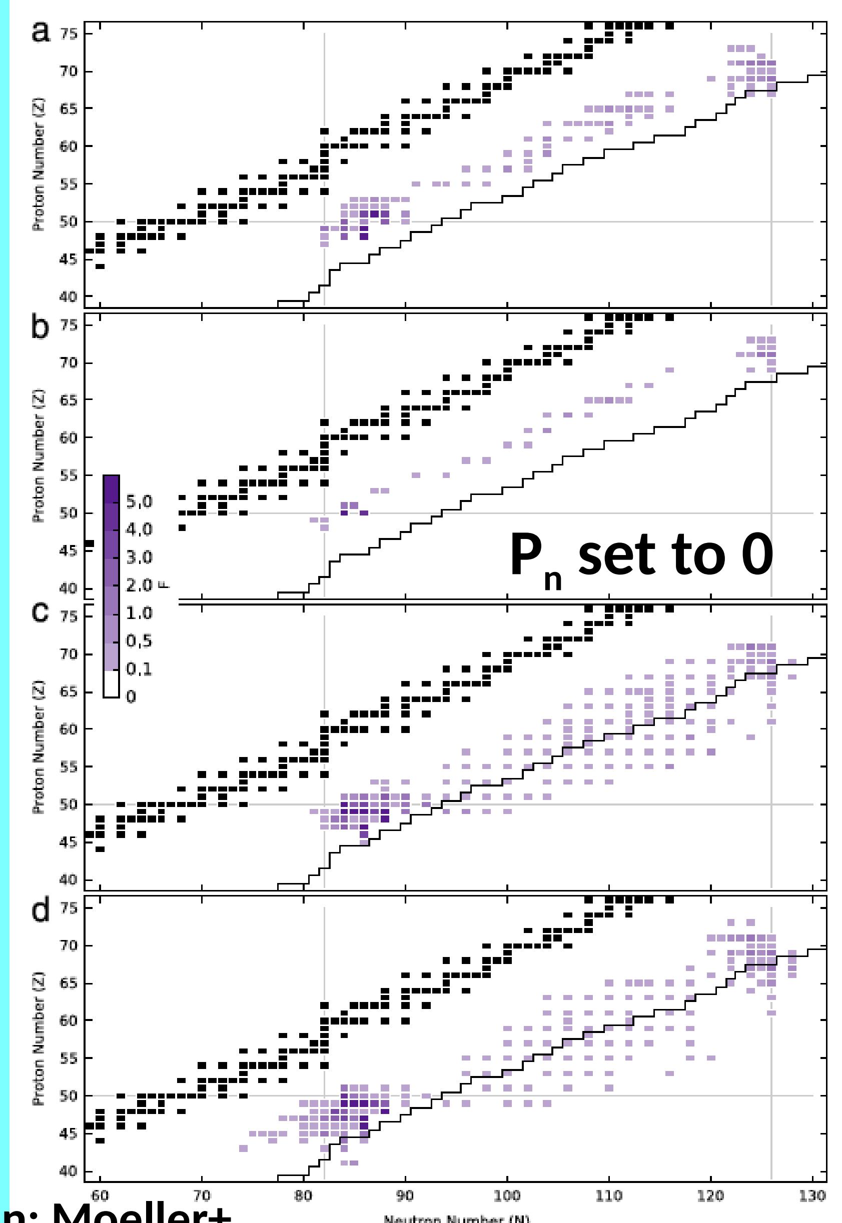




Sensitivity check:

$$F = 100 \sum_A |X(A) - X_b(A)|$$

Mumpower+, ProgPartNucPhys86 (2016) 86



low entropy hot wind

high entropy hot wind

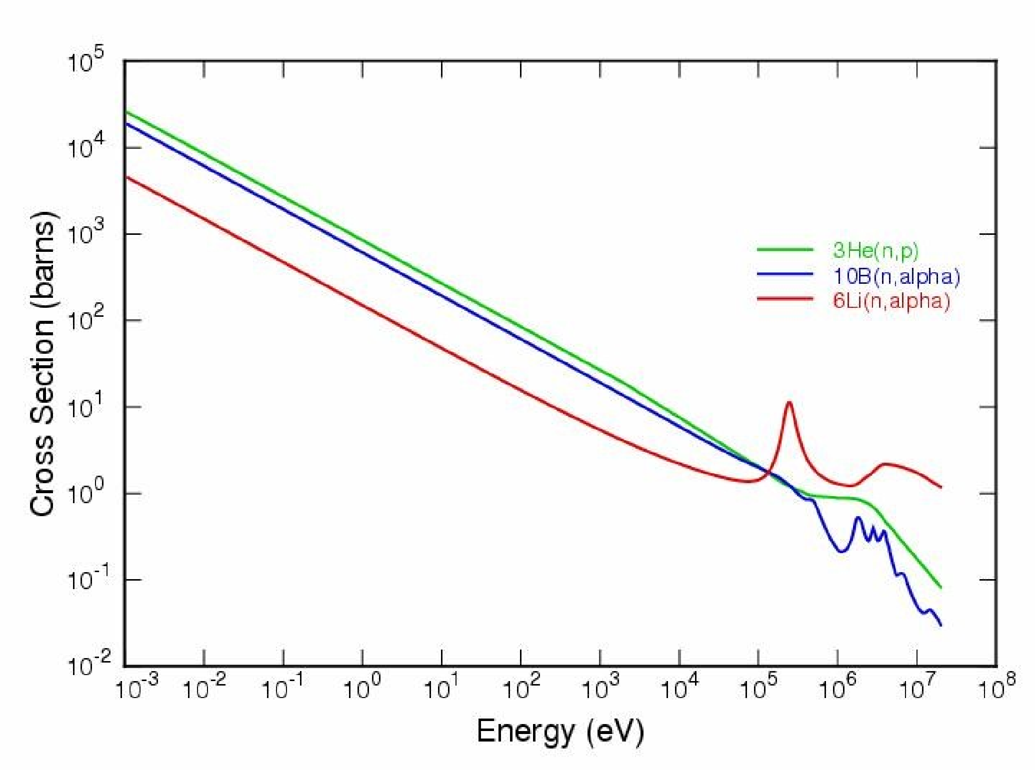
cold wind

neutron star merger

Base calculation: Moeller+

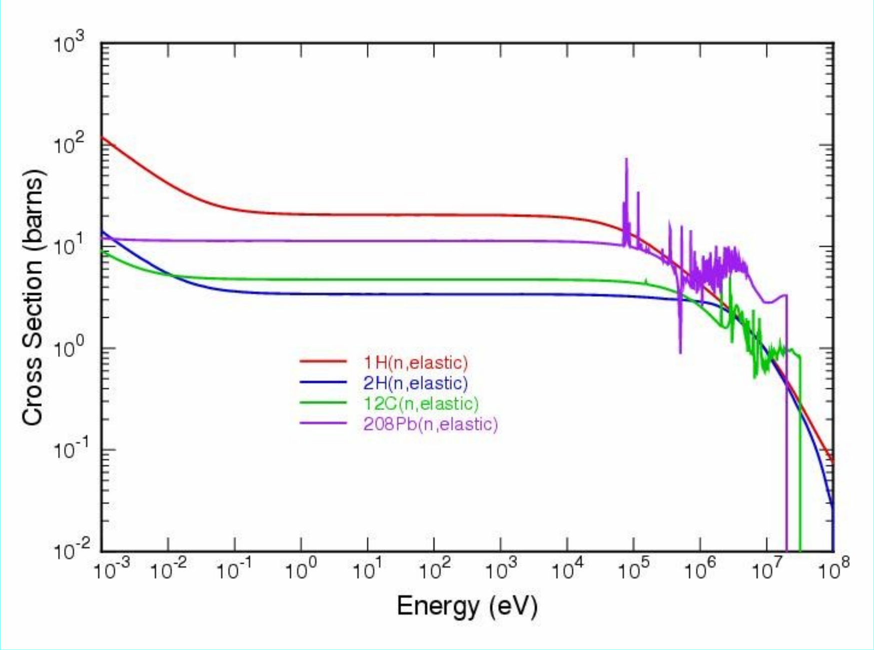
Measurement of P_n values

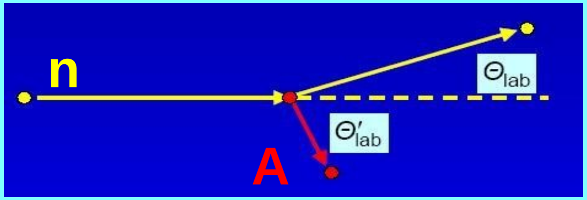
- The best method is by direct detection of the neutrons emitted
- Neutrons are neutral particles thus their detection require the production of electromagnetically interacting particles
- Reactions used: nucleus scattering, charged particle producing reactions, radiative capture, fission
- A useful reaction is $^3He(n,^3H)^1H$, with Q=+764keV which has a large cross-section at thermal energies



- ^{3}He is a (rare) gas that can be used as the sensitive gas of proportional counters

- Moderation of neutron energy by scattering on hydrogen is very useful to thermalize its energy





$$\left[\frac{E}{E_0}\right]_{max} = \frac{(A^2-1)^2}{(A+1)^2} = \alpha$$

Maximum energy loss: 1-α

Slowing down parameter:

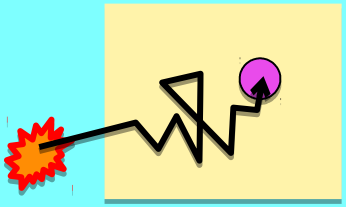
$$\xi = \left\langle \ln \frac{E_0}{E} \right\rangle = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}$$

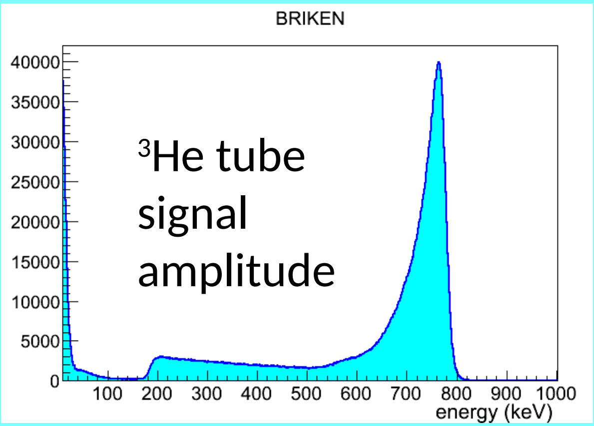
Nucleus	1-α	ξ	N
^{1}H	1	1	18
^{2}H	0.889	0.725	24
^{4}He	0.640	0.425	41
^{12}C	0.284	0.158	111
^{56}Fe	0.069	0.035	500
^{208}Pb	0.019	0.010	1823

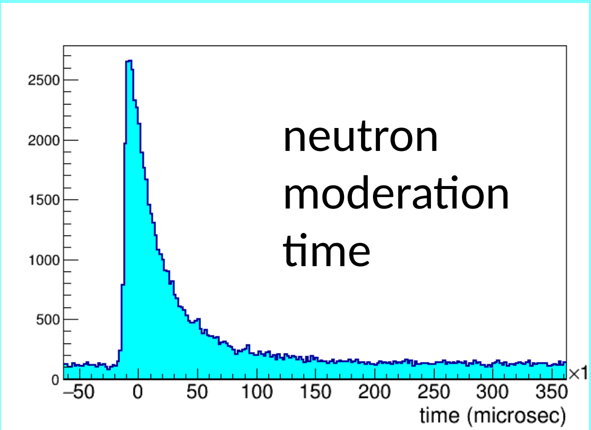
N: cumber of collisions to bring E_n from 1MeV to 25meV

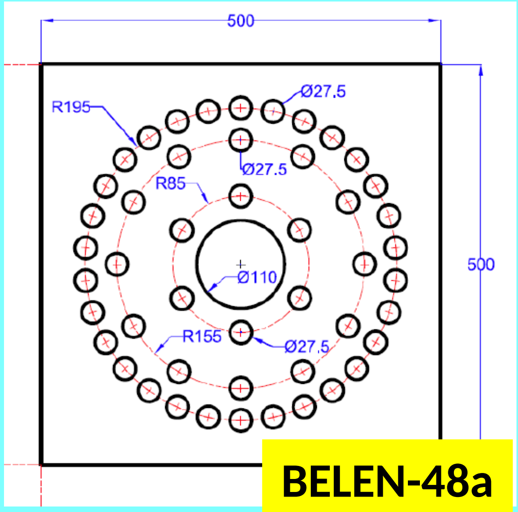
Moderated neutron neutron counter

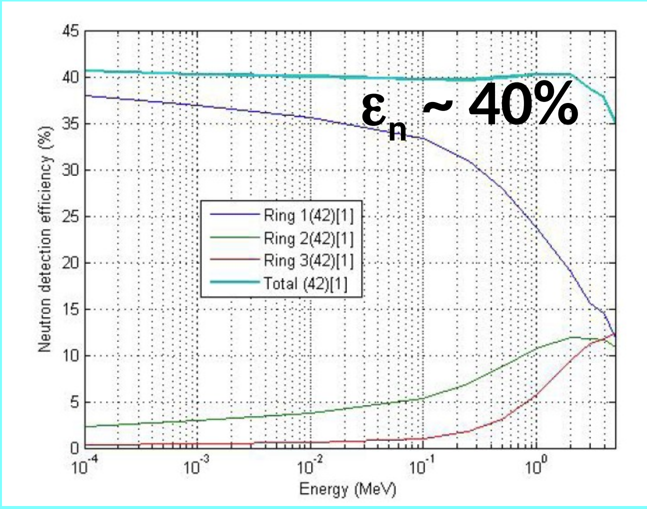
- Array of ^{3}He filled proportional tubes inside a neutron energy moderator polyethylene (PE) matrix

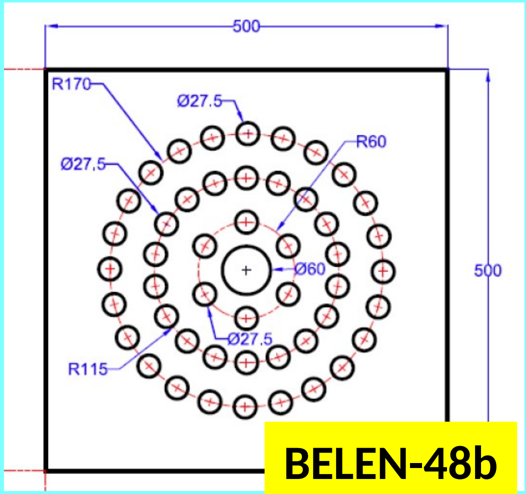


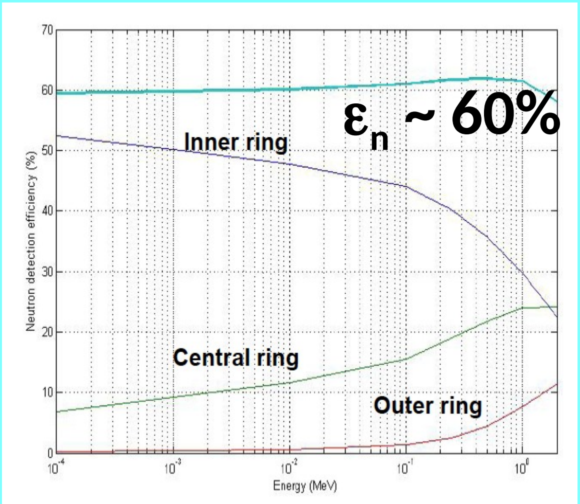










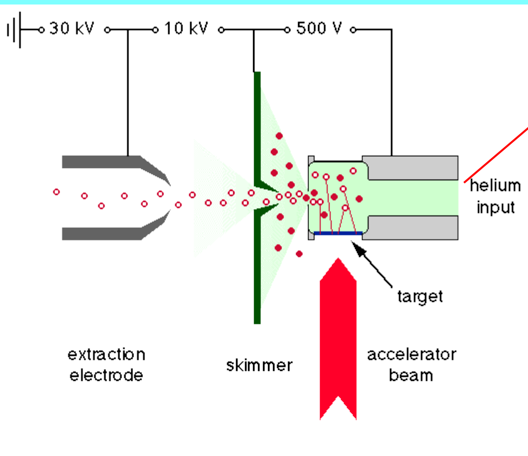


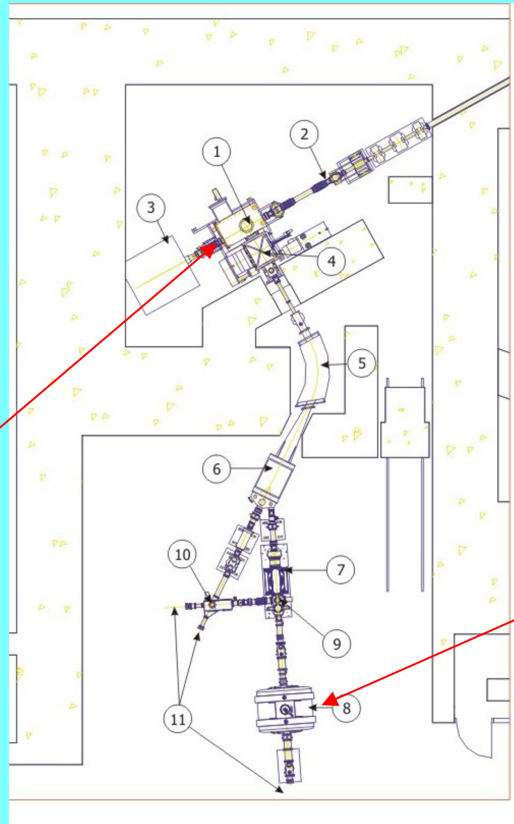
Experiment at ISOL facility: production and selection of isotopes

JYFL Accelerator Laboratory

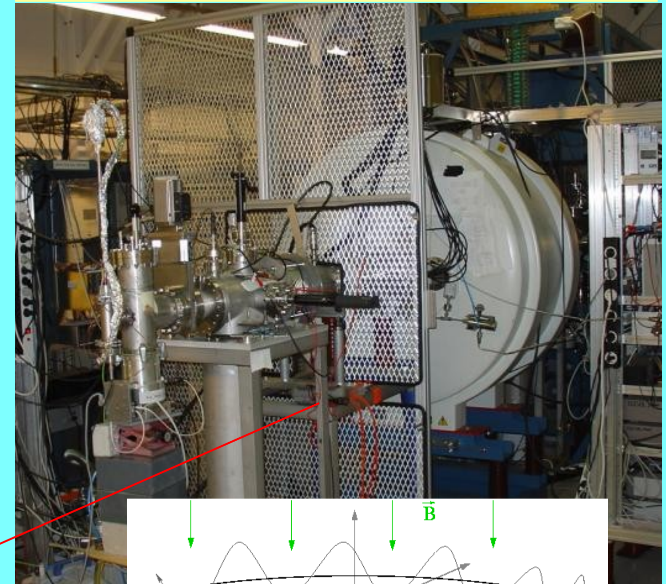
IGISOL separator **+ ion guide** source: refractory elements

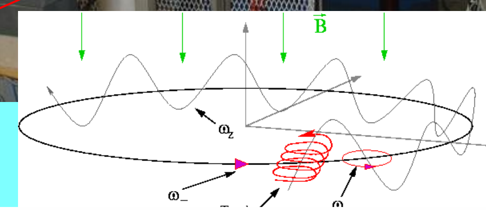
p(25MeV) + Th => FF

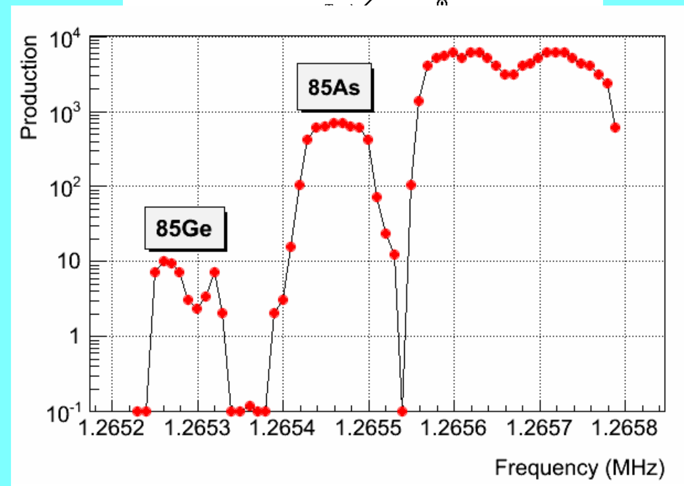




JYFLTRAP Penning trap: isotopic purification







Isotope	Rate (s^{-1})	Isotope	Rate (s^{-1})
^{88}Br	1450	^{85}Ge	6
^{94}Rb	1030	^{85}As	175
^{95}Rb	760	^{86}As	30
^{137}I	100	^{91}Br	80

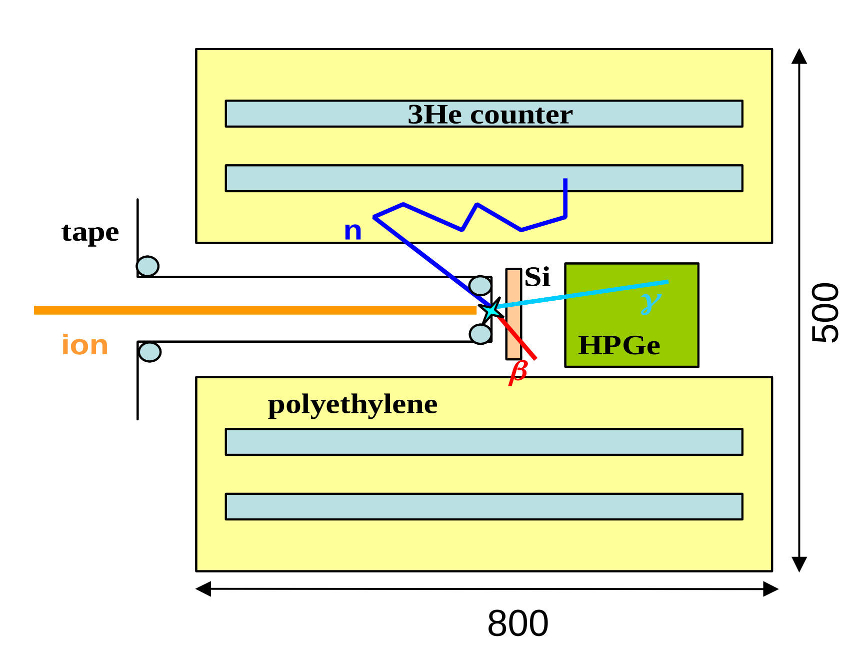
Pure isotopic beams

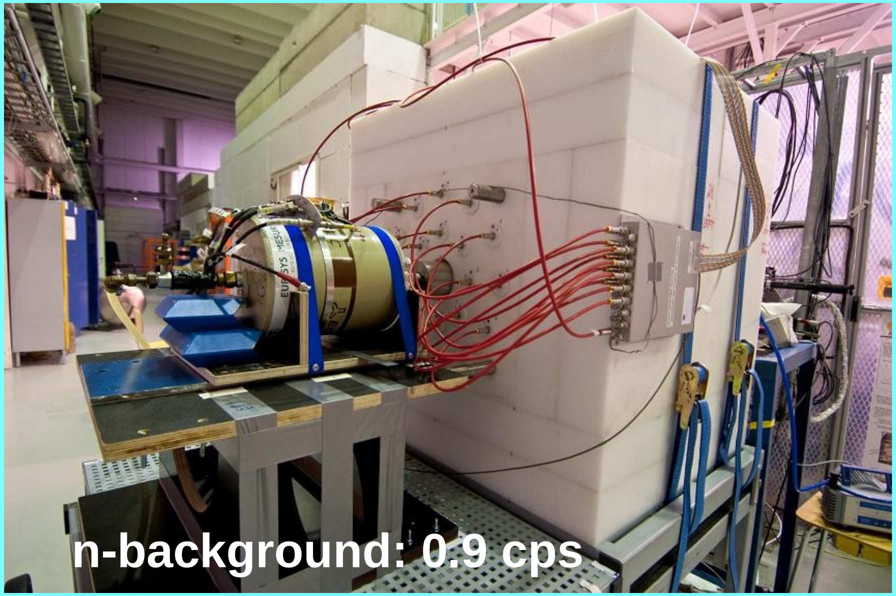
Experimental setup:

BELEN-20 detector

20 ⊘2.5cm×60cm 3He tubes @20atm

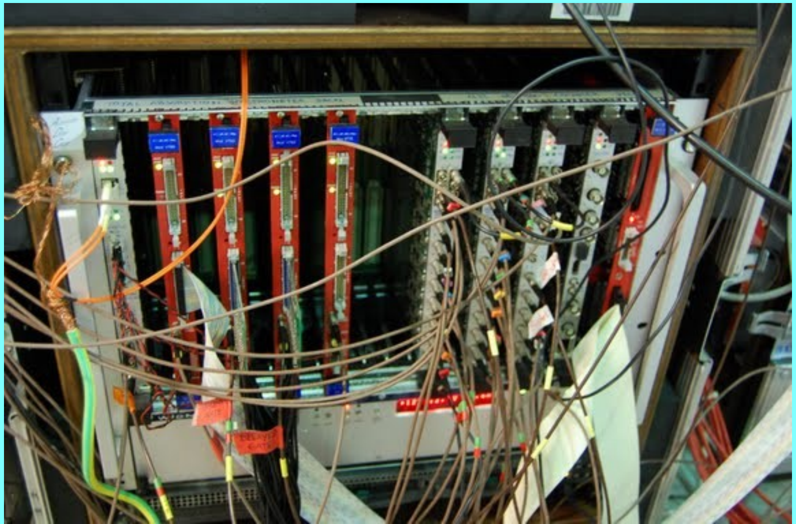
- 30keV beam implanted on tape
- Si or plastic detector for β detection
- HPGe detector for γ detection





Neutron background shield: 20cm PE

Self triggered DACQ:
-Time-energy pairs for every neutron or β
-Clean noise separation
-Minimum dead time:<0.5%



Data analysis

- To obtain P_n we need to count the total number of decays and the number of decays followed by n emission
- For this we count β and n or βn coincidences

$$N_\beta = \bar{\varepsilon}_\beta N_{dec}$$

$$N_n = \bar{\varepsilon}_n P_n N_{dec}$$

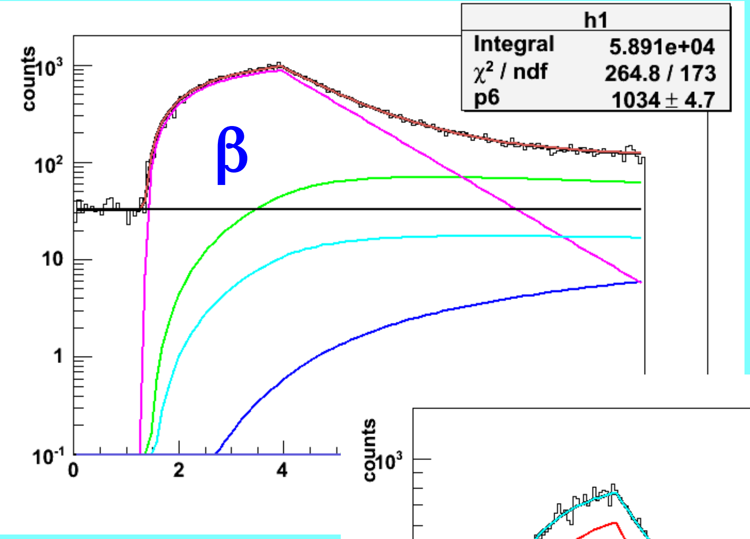
$$N_{\beta n} = \bar{\varepsilon}'_\beta \bar{\varepsilon}_n P_n N_{dec}$$

NOTE: average efficiencies over all transitions

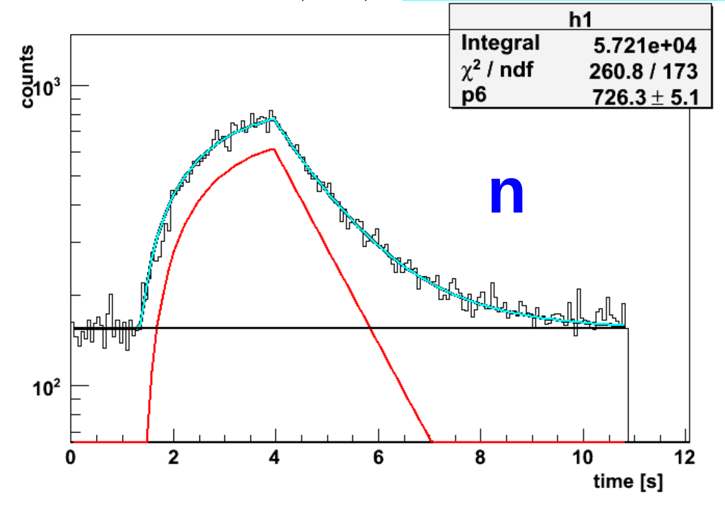
$$P_n = \frac{\bar{\varepsilon}_\beta}{\bar{\varepsilon}_n} \frac{N_n}{N_\beta}$$

$$P_n = \frac{\bar{\varepsilon}_\beta}{\bar{\varepsilon}'_\beta \bar{\varepsilon}_n} \frac{N_{\beta n}}{N_\beta}$$

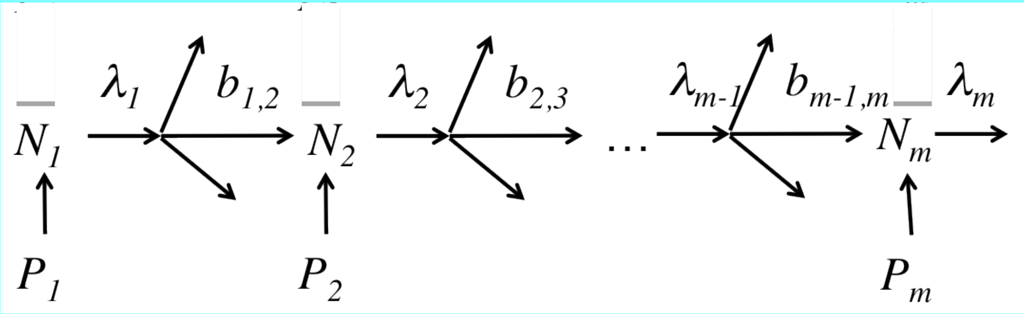
- We need to disentangle the counts from the nucleus of interest from other nuclei
- For this we measure grow and/or decay curves of the activity and fit with appropriate solutions of the Bateman equations



^{86}As



Solution of Bateman equations from Skrable et al., Health. Phys. 27 (1974) 155)



Equations:

$$\frac{dN_1}{dt} = P_1 - \lambda_1 N_1$$

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

$$\ldots$$

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

Activity:

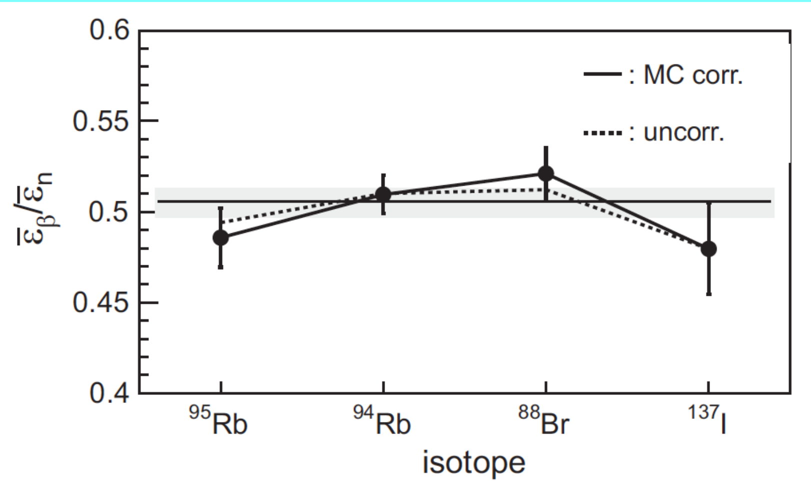
$$A_m^{\beta}(t) = \bar{\varepsilon}_{\beta} \lambda_m N_m(t)$$

$$A_m^{n}(t) = \bar{\varepsilon}_{n} P_n \lambda_m N_m(t)$$

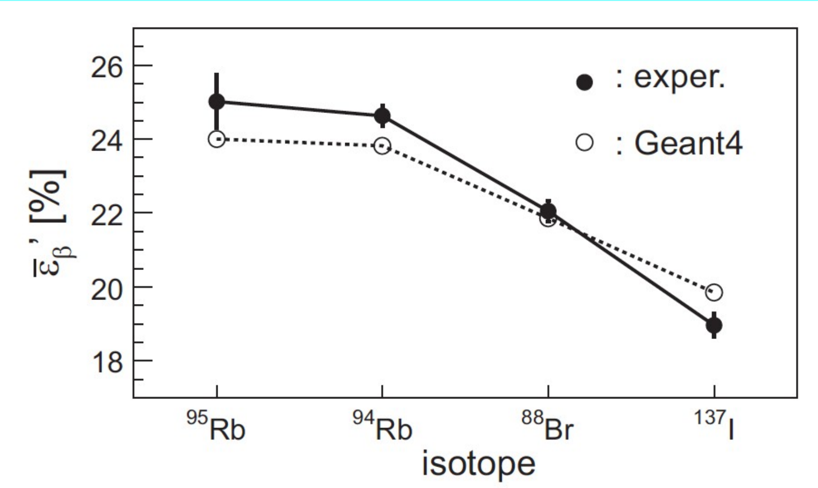
Solution (number of nuclei as a function of time):

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

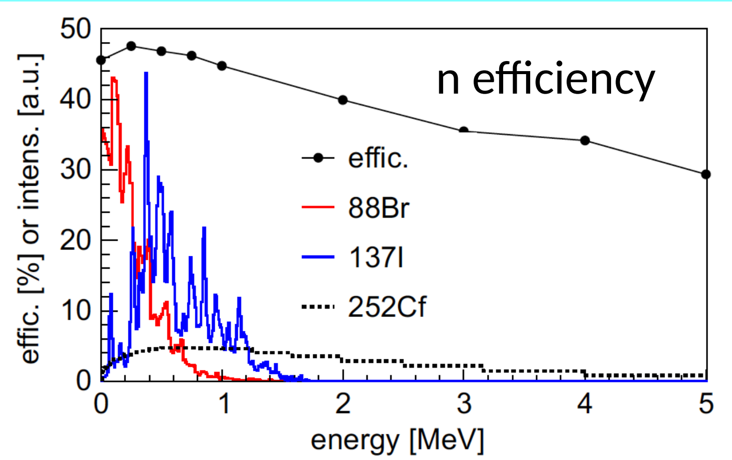
Determination of average efficiencies (nucleus dependent): source of systematic errors

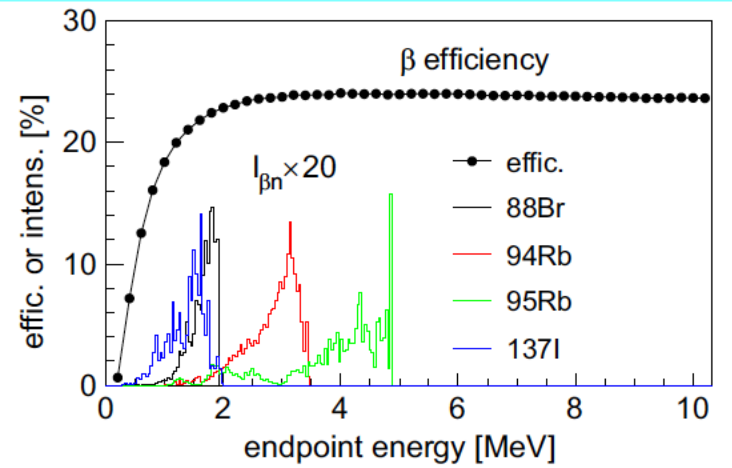


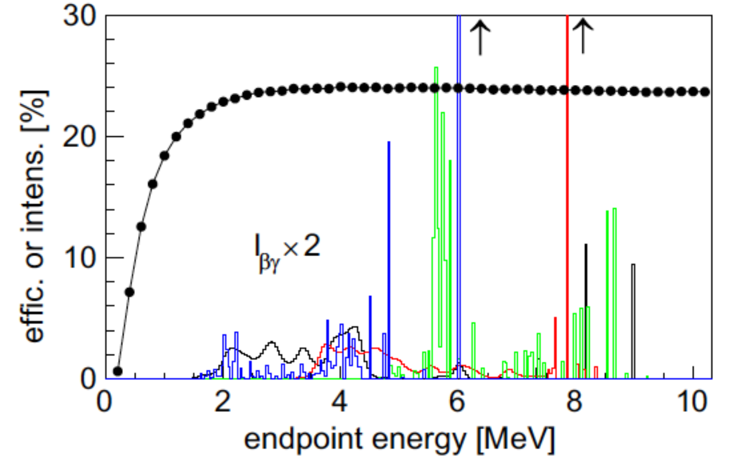
$$\frac{\overline{\varepsilon}_\beta}{\overline{\varepsilon}_n} = P_n \frac{N_\beta}{N_n}$$



$$\overline{\varepsilon}'_\beta = \frac{N_{\beta n}}{N_n}$$

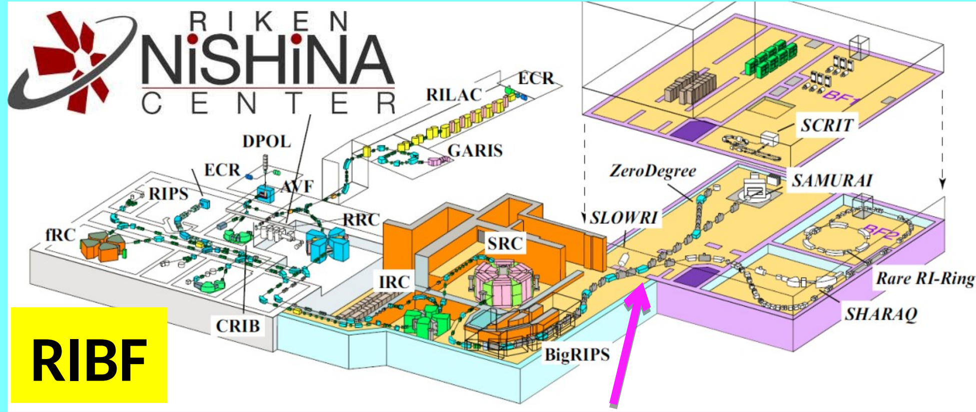






Experiment at fragmentation facility: production and selection of isotopes

345 MeV/u ^{238}U + ^{9}Be(4mm): fragmentation/fission



ΔE-TOF-Bρ method with track reconstruction → Improve Bρ and TOF resolution

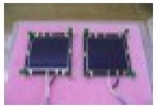
Measure ΔE, TOF, Bρ @ 2nd stage

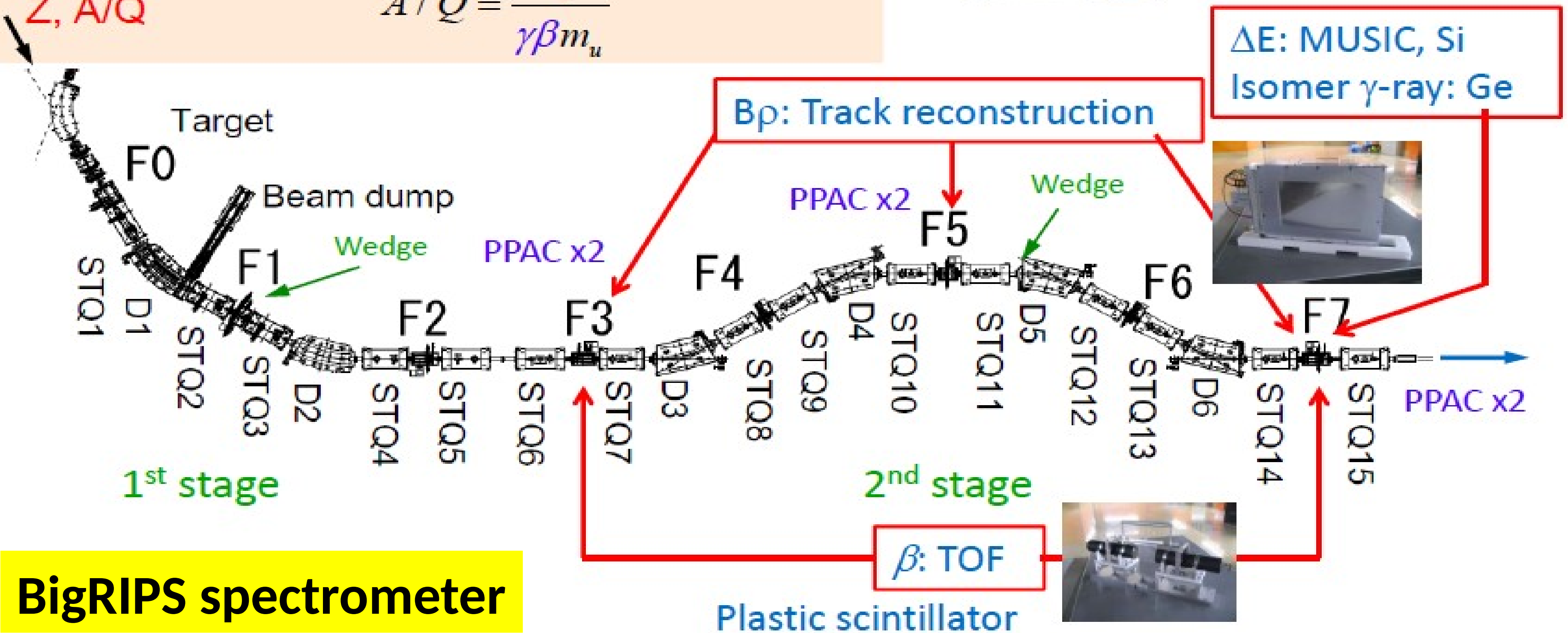
+ isomeric γ-ray

Z, A/Q

$$Z \leftarrow -dE/dx = \mathrm{f}(Z, \beta)$$

$$A/Q = \frac{B\rho}{\gamma\beta m_u}$$

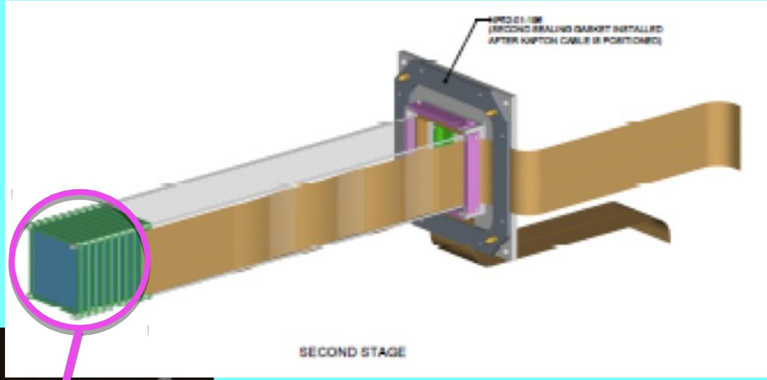


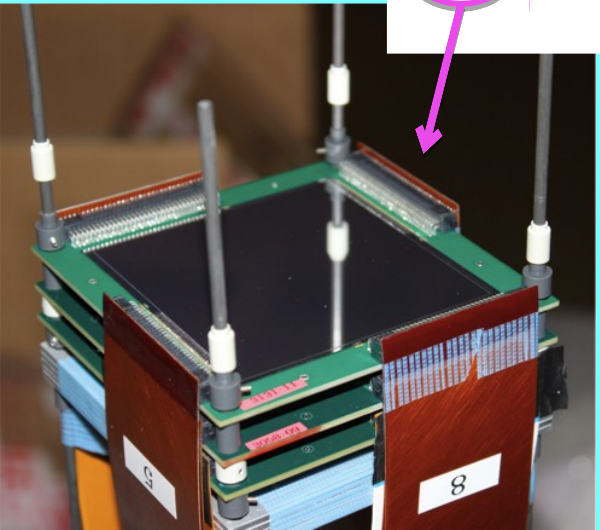


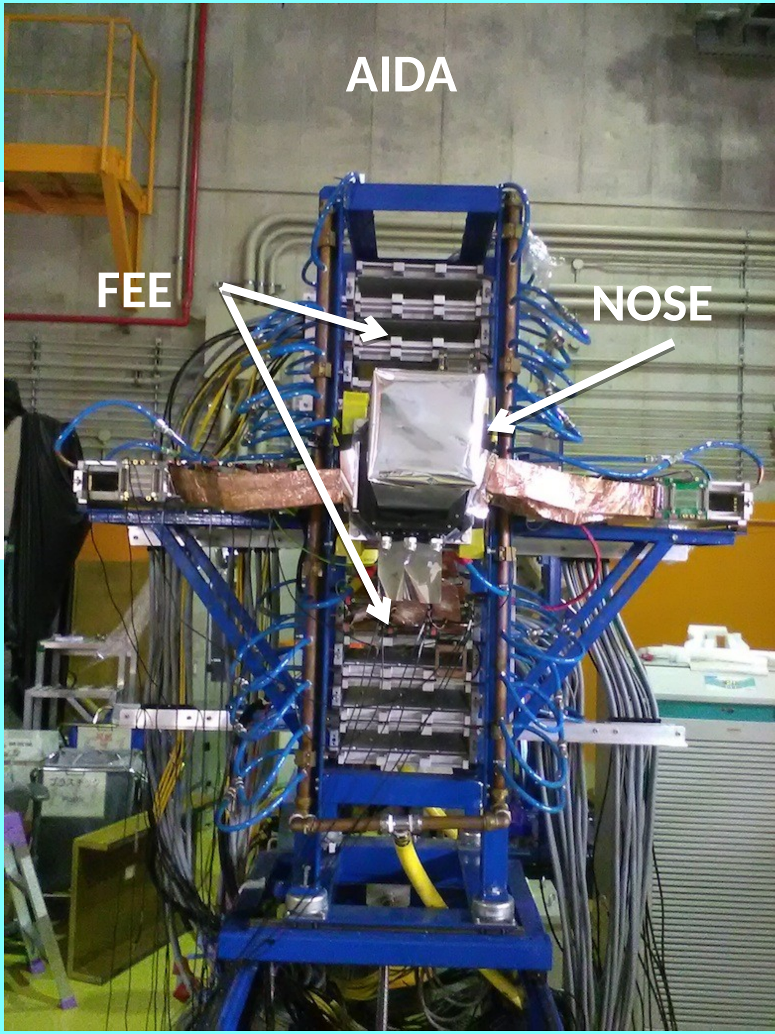
BigRIPS spectrometer

Advanced Implantation Detector Array (AIDA)

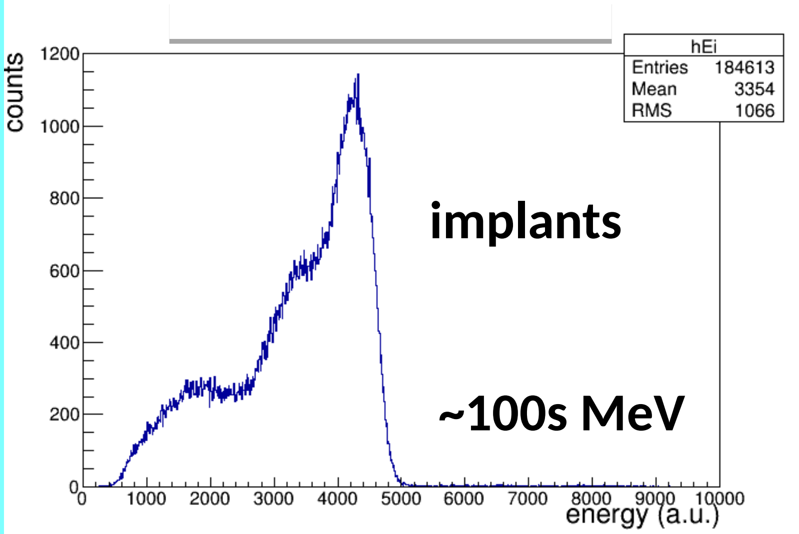
- Stack of six Si DSSD
- Size: 1mm×72mm×72mm
- Granularity: 128×128 pixels (0.51mm strip)
- Low gain (implant) and high gain (betas) preamplifiers
- Total data readout DACQ (1536 ch)

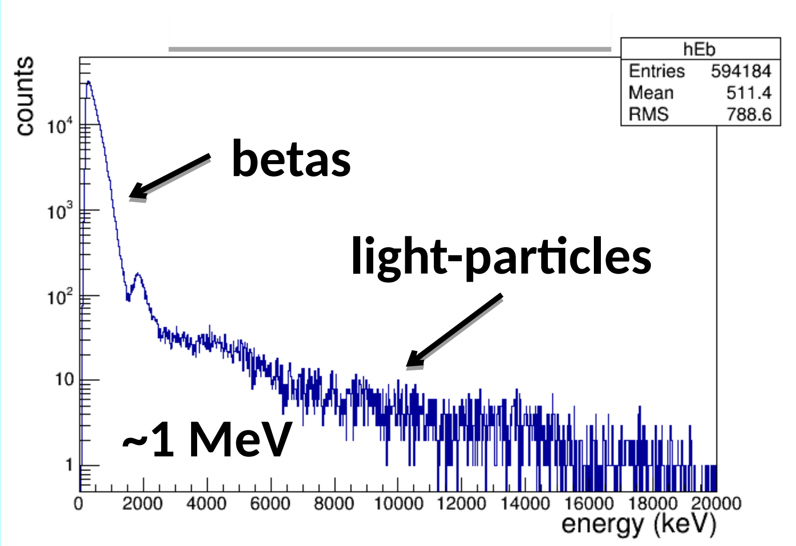




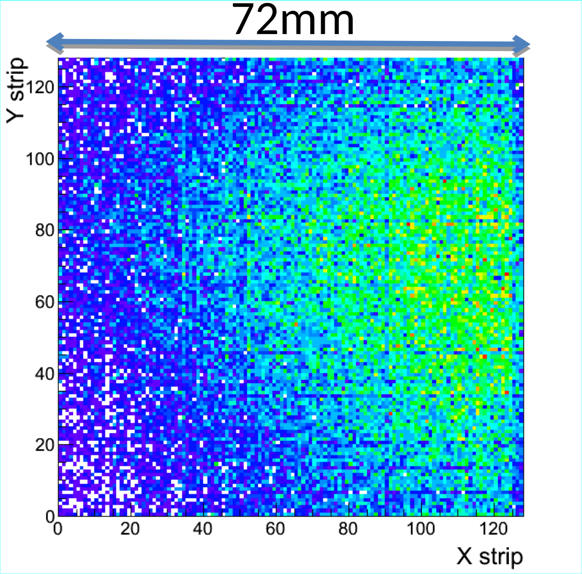


- Implants and betas are distinguished by the energy released in the detector
- Betas corresponding to each implanted ion are associated by spatial correlations

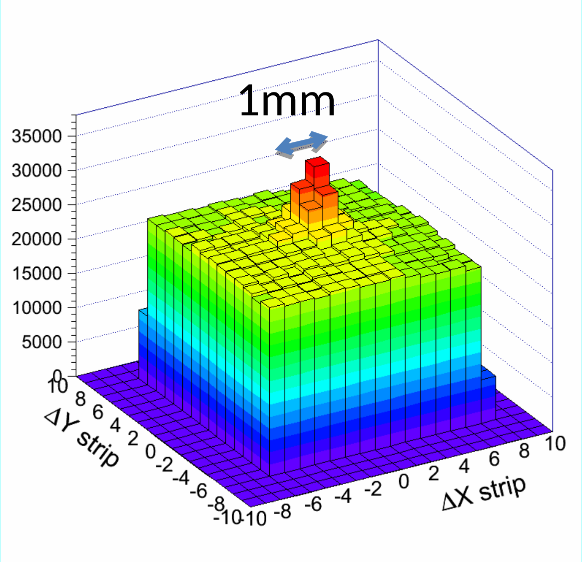




Implant position distribution

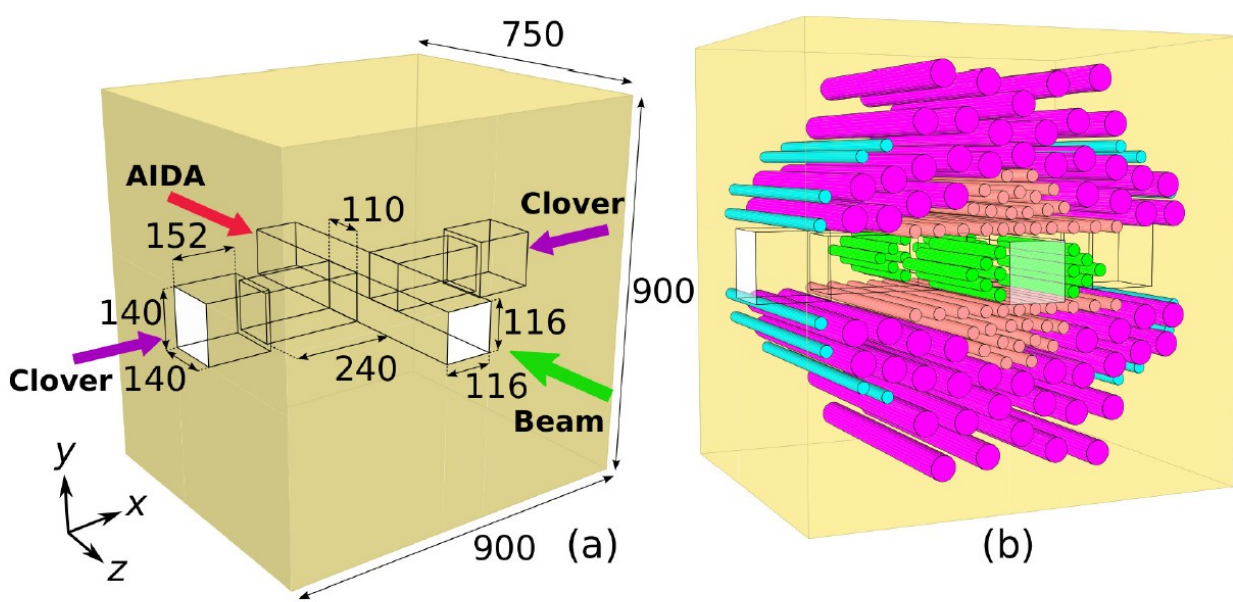


Implant-beta spatial correlation



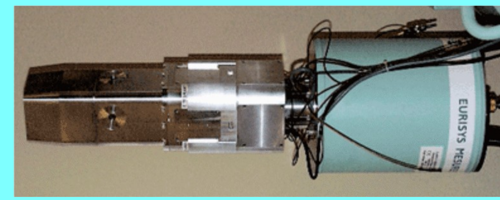
BRIKEN neutron counter

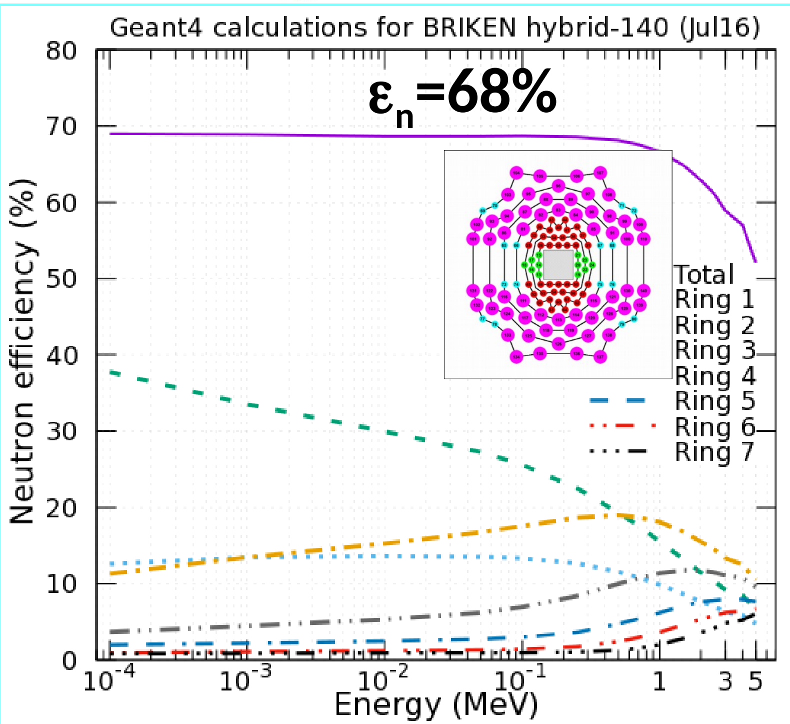
Tarifeño+, JInstr1(2017)P04006

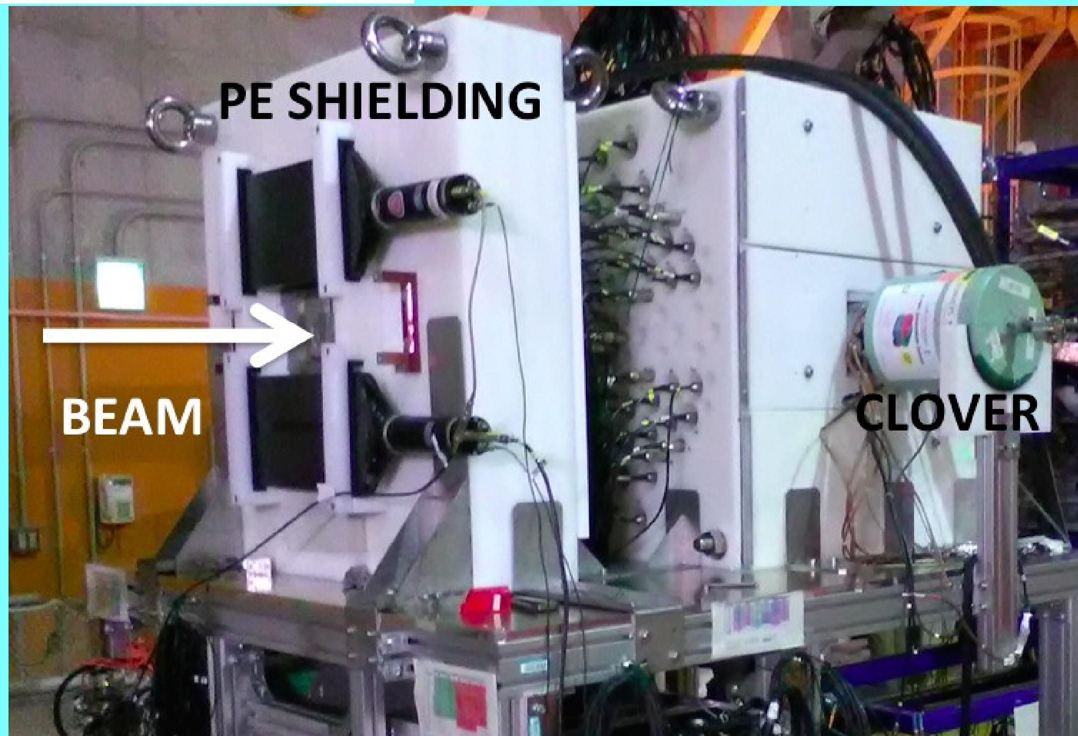


Hybrid setup:

- 140 ^{3}He tubes (4 types)
- 2 CLOVER HPGe

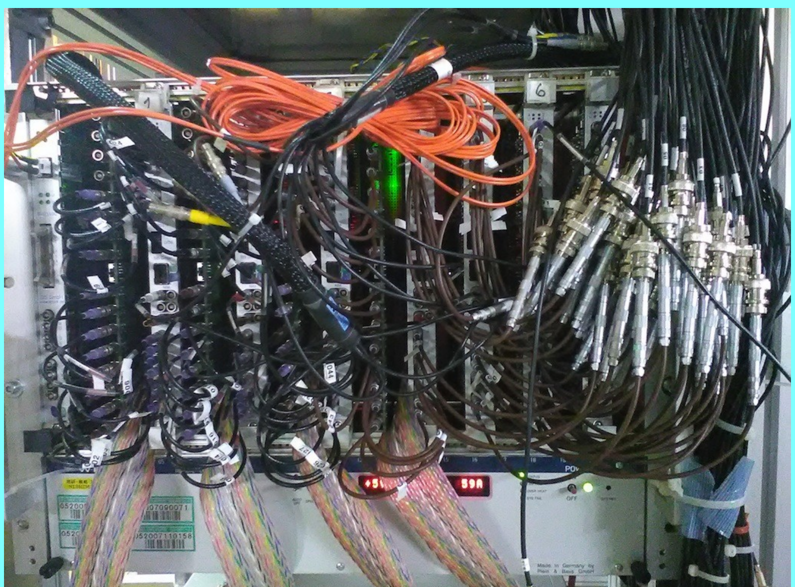






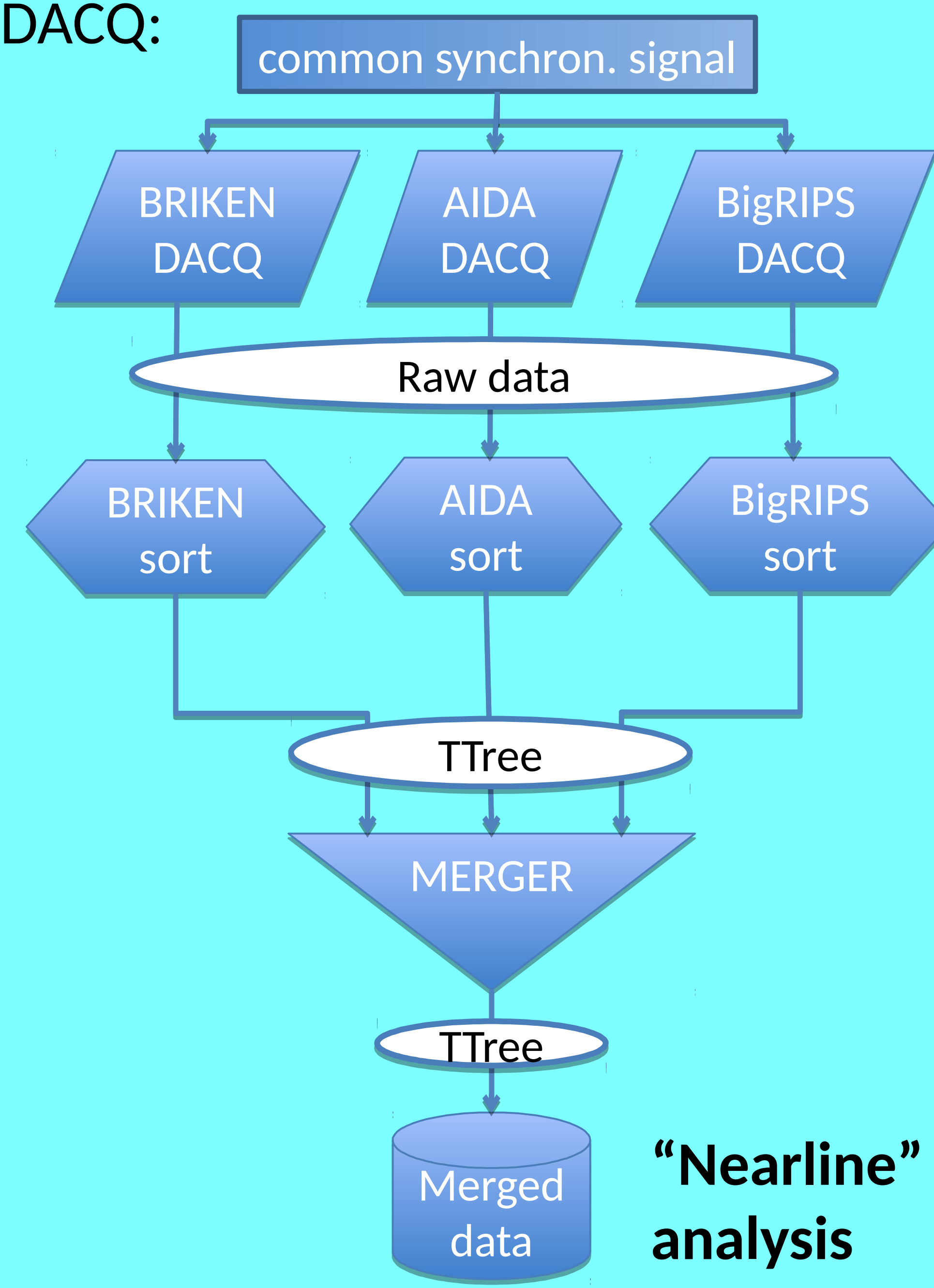
BRIKEN Gasific70 DACQ:

- ^{3}He tubes, CLOVER, ancillaries
- SIS3316 and SIS3302 digitizers
- Self triggered, common clock



Agramunt+, NIMA807(2016)69

Merging of data from 3 independent DACQ:

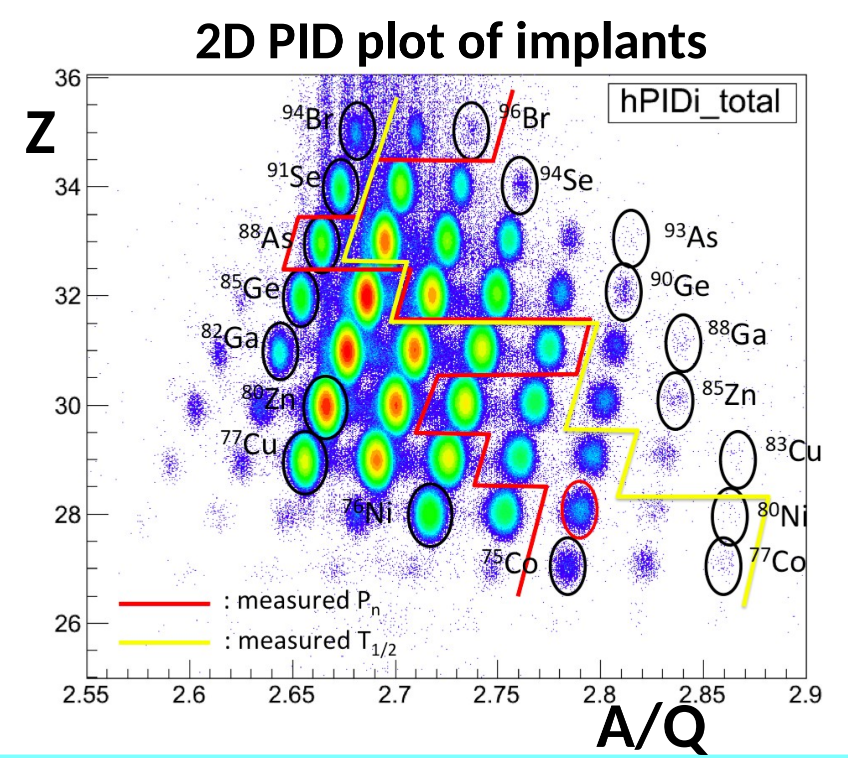


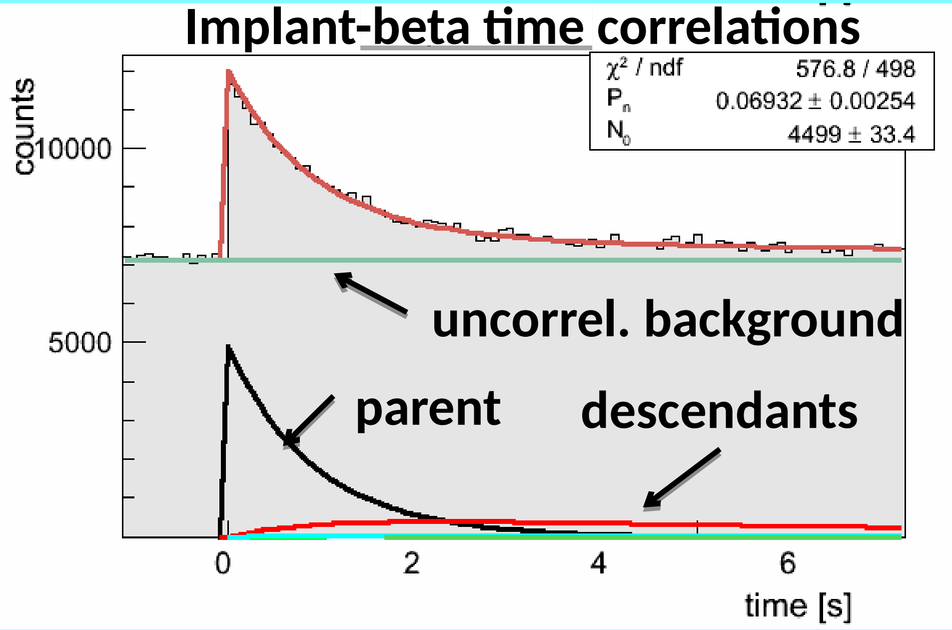
"Nearline" analysis

Data analysis:

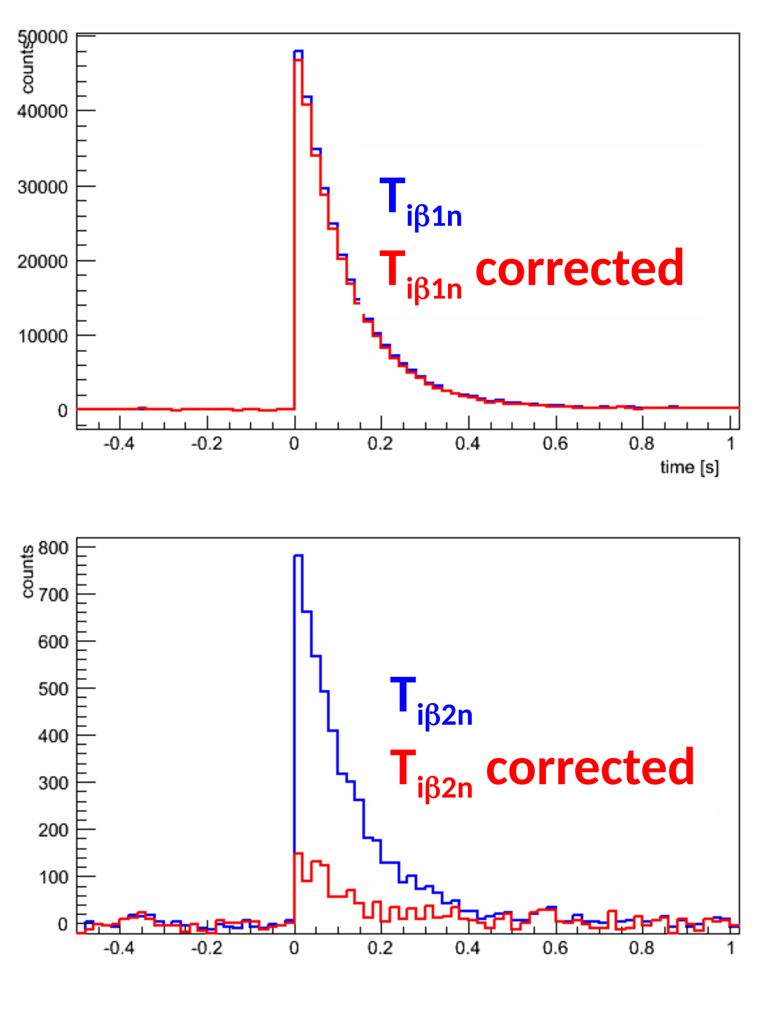
- Each implanted ion in AIDA is identified using the information from BigRIPS in prompt coincidence
- The associated β decay is assigned to the identified ion on a statistical basis from implant-β space-time correlations (delayed coincidence)
- Random coincidences are quantified from the backwards in time correlations
- Fitting with appropriate solutions of the Bateman equations serves to separate parent from descendant β signals

Tolosa+, NIMA925(2019)133





- Adding the condition that 1, 2, … neutrons come within ~200μs of the β we obtain the implant-β1n, implant-β2n, … time correlations
- Random 1n, 2n, … events contribute to the implant-βxn correlated background and must be corrected



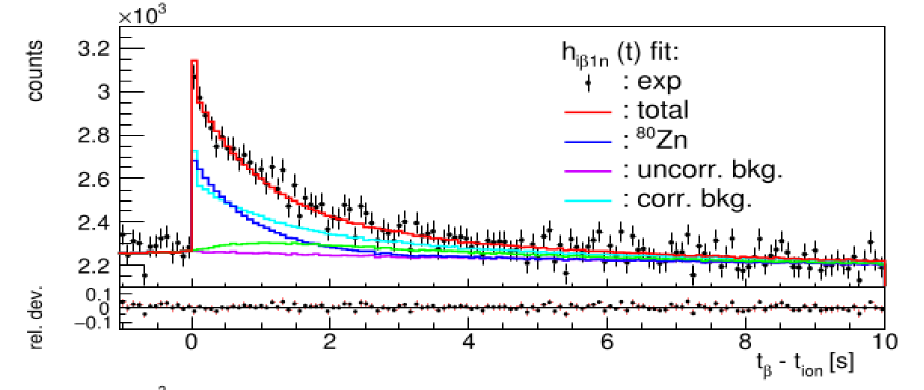
- β2n decay contributes to the counts observed in β1n correlations and should be corrected

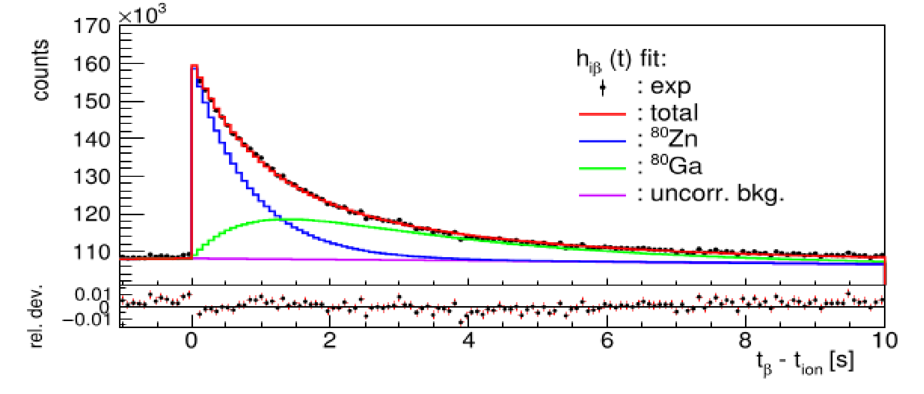
$$N_{1n}(t) = \varepsilon_n P_{1n} N_{dec} + 2\varepsilon_n (1 - \varepsilon_n) P_{2n} N_{dec}$$

$$N_{2n}(t) = (\varepsilon_n)^2 P_{2n} N_{dec}$$

$$N_{1n(2n)}(t) = 2\frac{1 - \varepsilon_n}{\varepsilon_n} N_{2n}(t)$$

- To disentangle parent and descendant contributions we fit the time spectra with appropriate solutions of Bateman equations





Fit functions:

$$f_\beta(t) = \sum_{i\in\beta} \bar{\varepsilon}_\beta^i \lambda_i N_i(t)$$

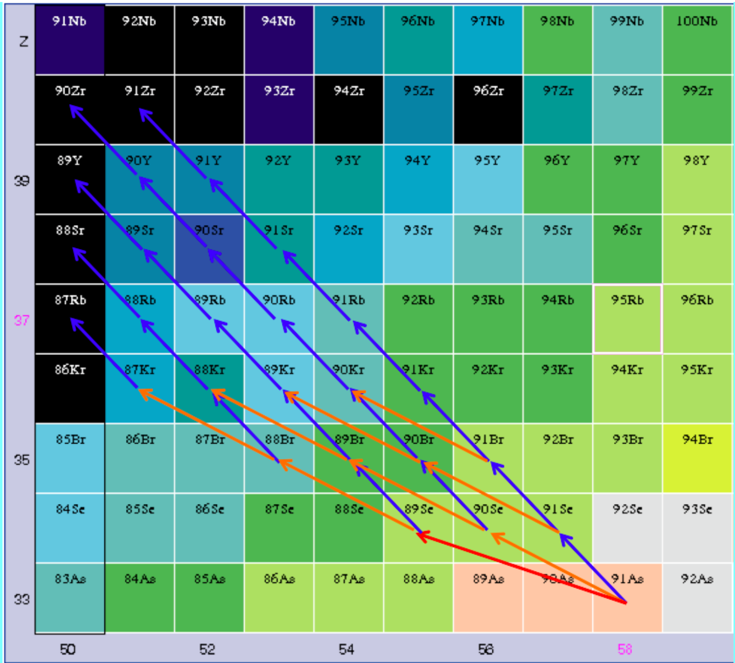
$$f_{\beta 1n}(t) = \sum_{j\in\beta 1n} \bar{\varepsilon}_\beta^j \bar{\varepsilon}_n^j P_{1n}^j \lambda_j N_j(t)$$

$$f_{\beta 2n}(t) = \sum_{k\in\beta 2n} \bar{\varepsilon}_\beta^k \left(\bar{\varepsilon}_n^k\right)^2 P_{2n}^k \lambda_k N_k(t)$$

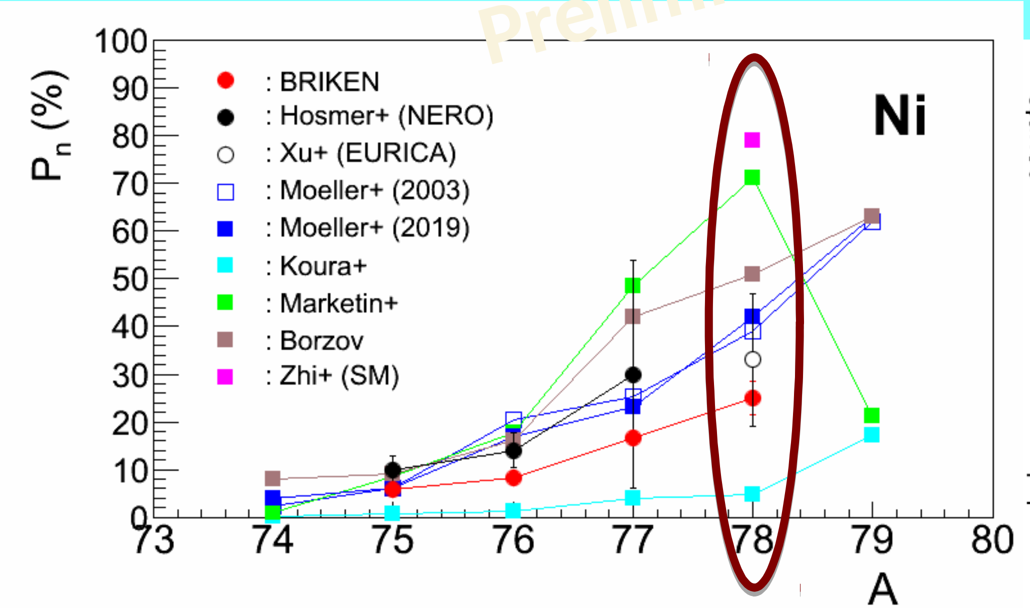
$$N_k(t) = N_1 \prod_{i=1}^{k-1} \left(b_{i,i+1}\lambda_i\right) \times \sum_{i=1}^{k} \frac{e^{-\lambda_i t}}{\prod_{j=1, j\neq i}^{k} \left(\lambda_j - \lambda_i\right)}$$

$$b_{i,i+1} = P_{1n}^i,\ P_{2n}^i \text{ or } 1 - P_{1n}^i - P_{2n}^i$$

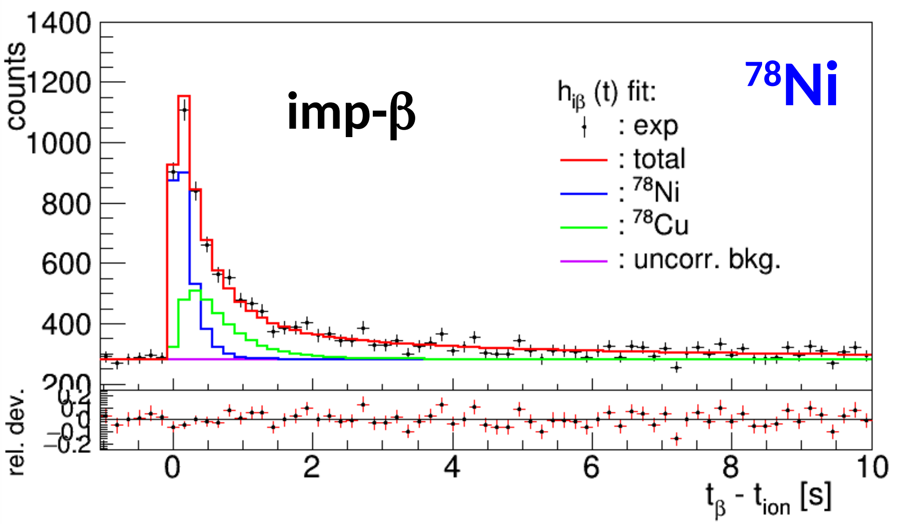
Decay pattern can be quite complex far from stability

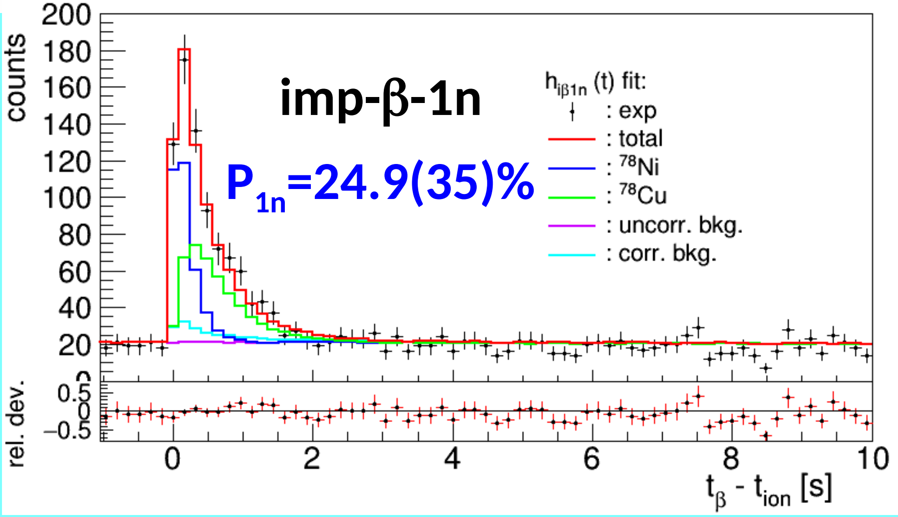


Ni isotopes: P_{1n} compared with theory and previous data



First detection of n from ^{78}Ni





Hosmer+, PRC82(2010)025806
Z.Y.Xu, PhD Thesis (2014)
Borzov, PRC71(2005)065801
Zhi+, PRC87(2013)025803

- **At shell closure: large spread of theoretical estimates, all off the experiment**

(from Alvaro Tolosa)