Overview on
β-delayed neutron emission
measurements made with the BELEN detector at ISOL and In-Flight facilities and future perspective

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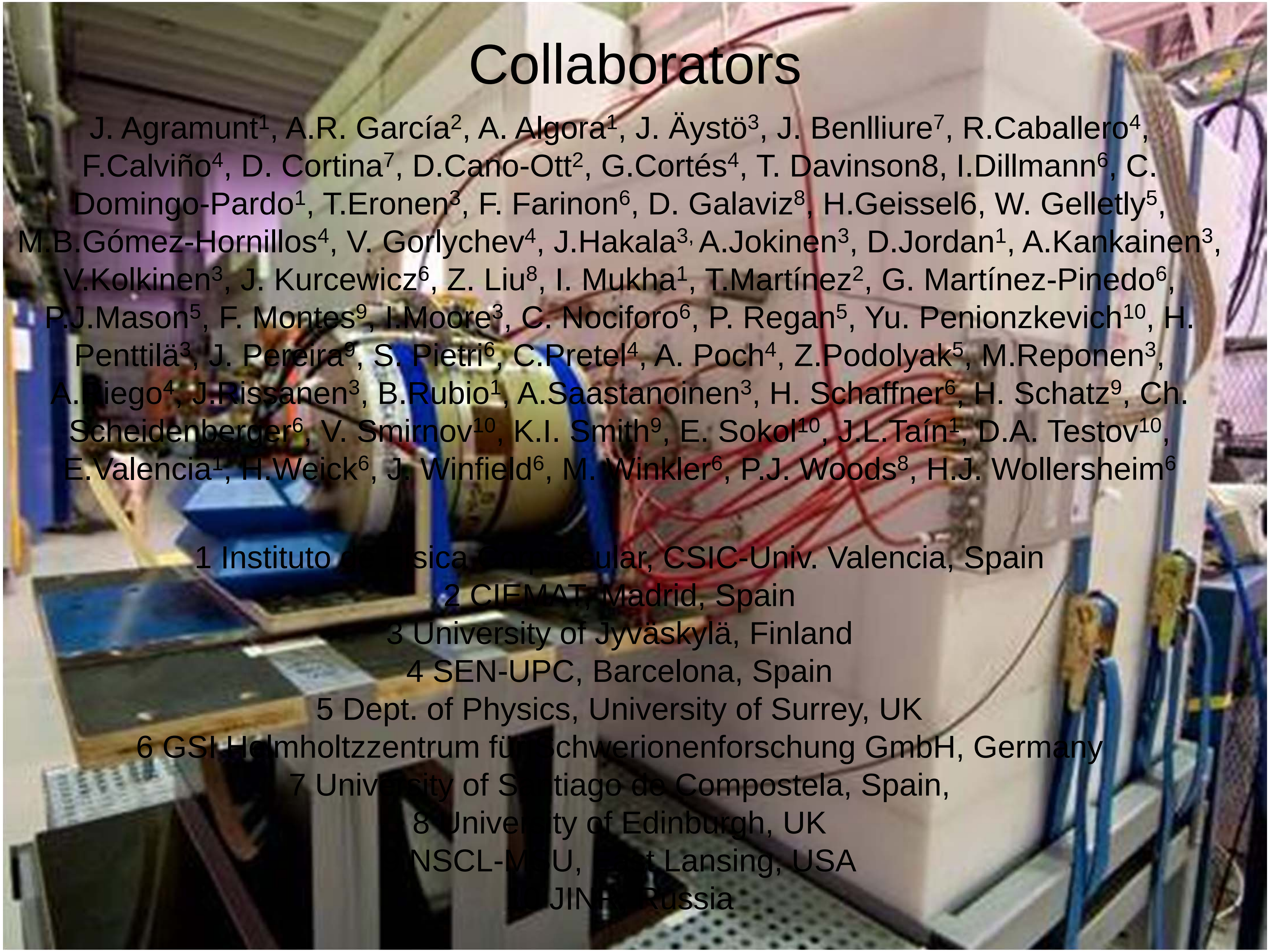

Collaborators

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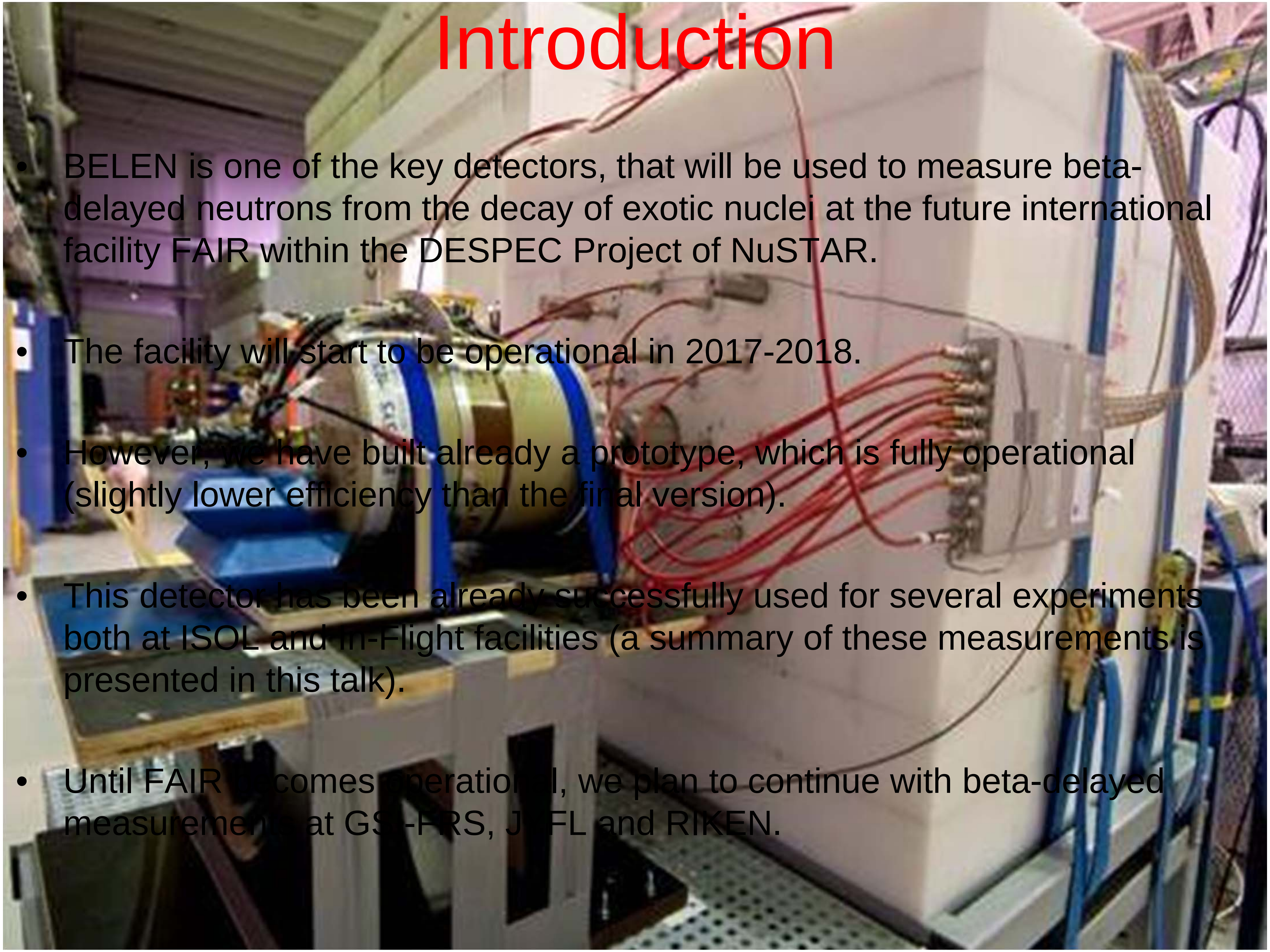
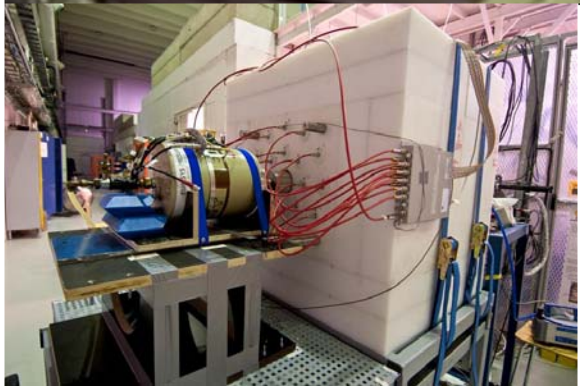
Introduction

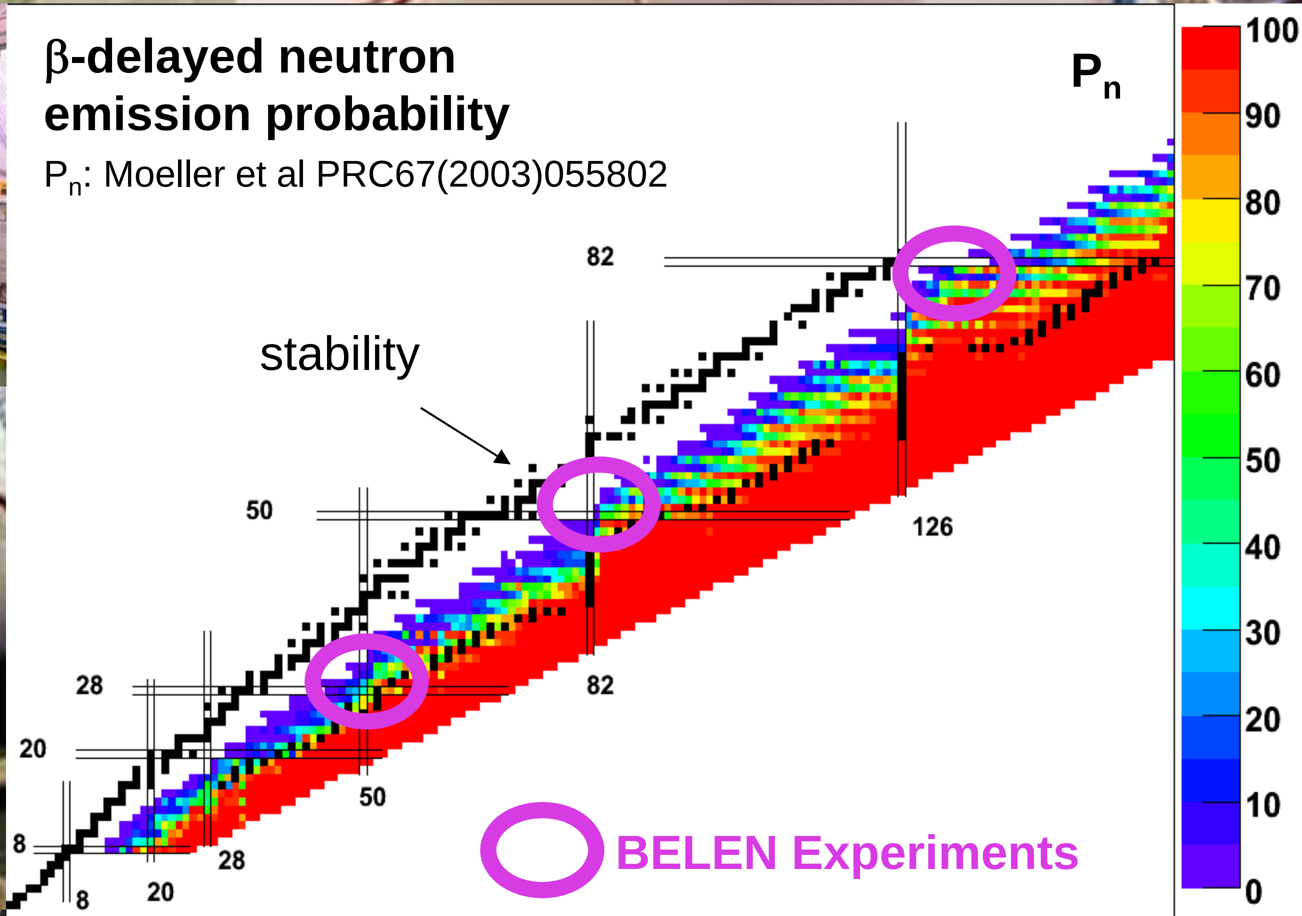


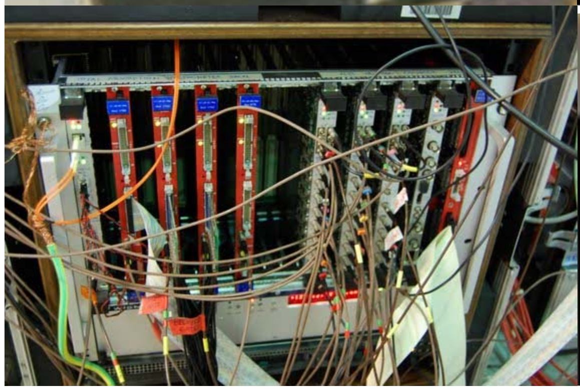
- BELEN is one of the key detectors, that will be used to measure beta-delayed neutrons from the decay of exotic nuclei at the future international facility FAIR within the DESPEC Project of NuSTAR.
- The facility will start to be operational in 2017-2018.
- However, we have built already a prototype, which is fully operational (slightly lower efficiency than the final version).
- This detector has been already successfully used for several experiments both at ISOL and in-Flight facilities (a summary of these measurements is presented in this talk).
- Until FAIR becomes operational, we plan to continue with beta-delayed measurements at GSI-FRS, JYFL and RIKEN.

Beta dELayEd Neutron detector - BELEN

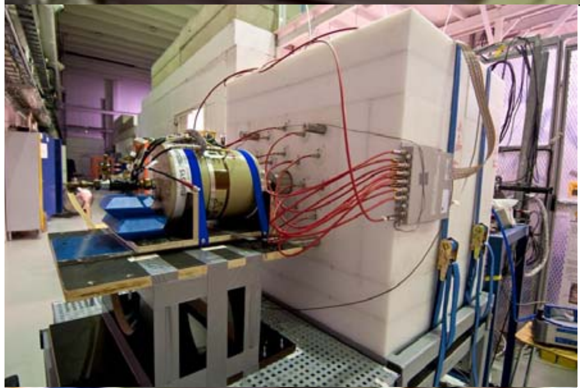


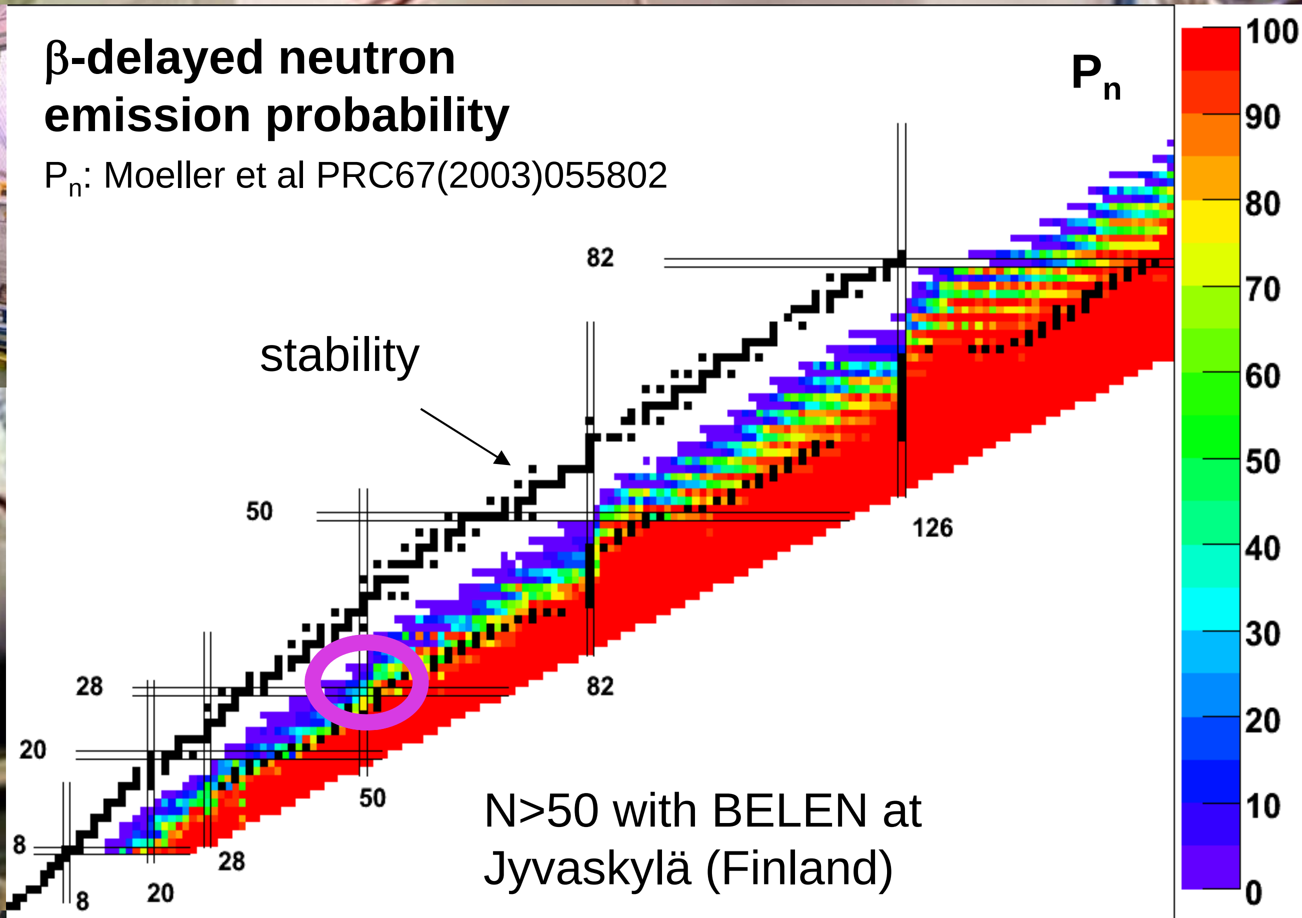
- Motivation
- Experiment
- Data analysis
- Preliminary results
- Perspective





Beta dELayEd Neutron detector - **BELEN**





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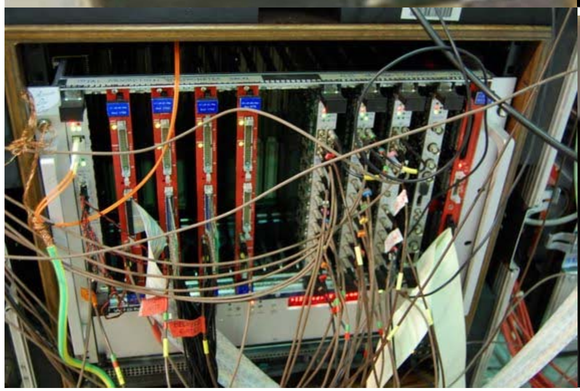


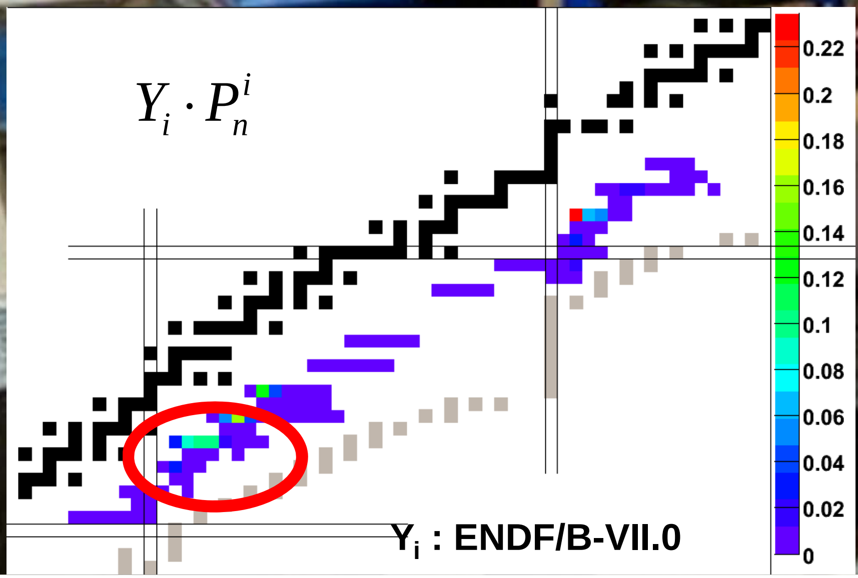
Motivation (I): microscopic summation calculations of $\bar{\nu}_d$

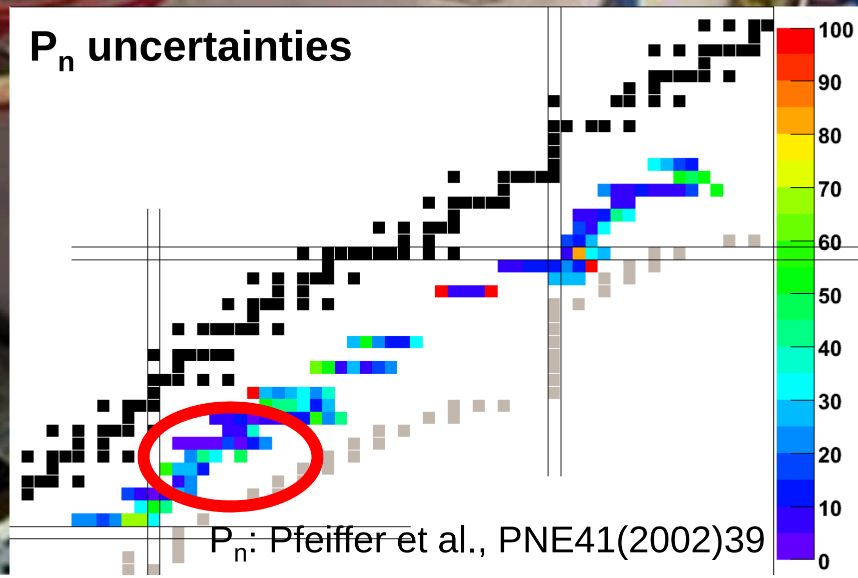
- The delayed neutron fraction β_{eff} is a key parameter in the control of reactor power
- Microscopic summation calculations lack still the accuracy of Keepin six-group formula
- Reason: **inaccuracies** in fission yields Y and **delayed neutron emission probabilities** P_n

Number of delayed neutrons per fission

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

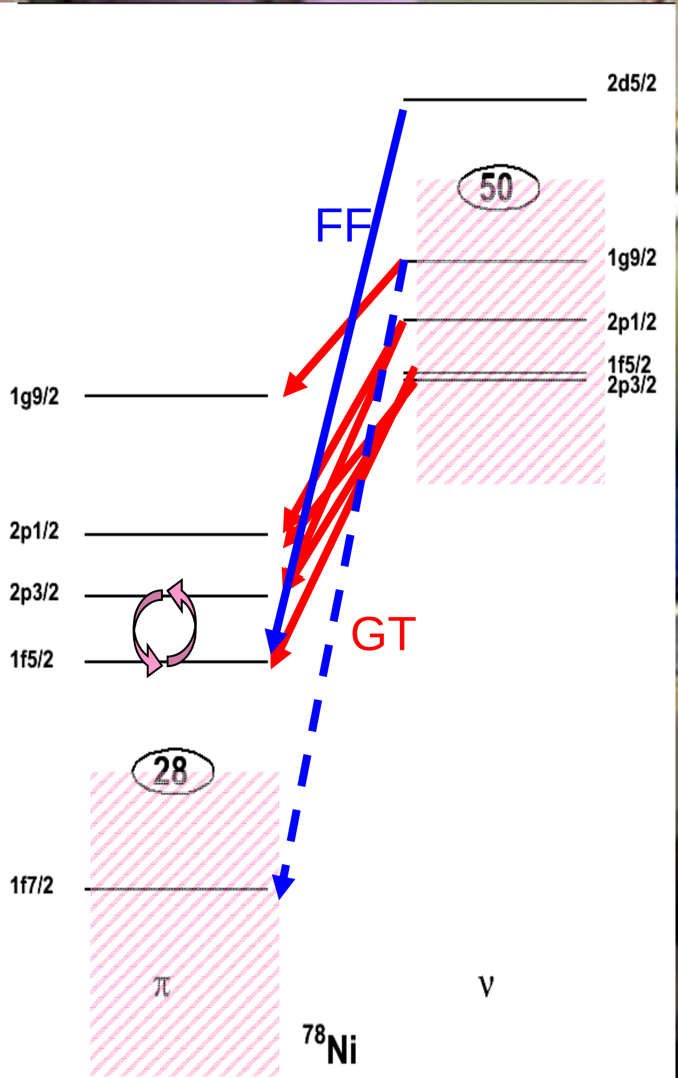
Can be used to identify P_n values that should be re-measured with improved accuracy





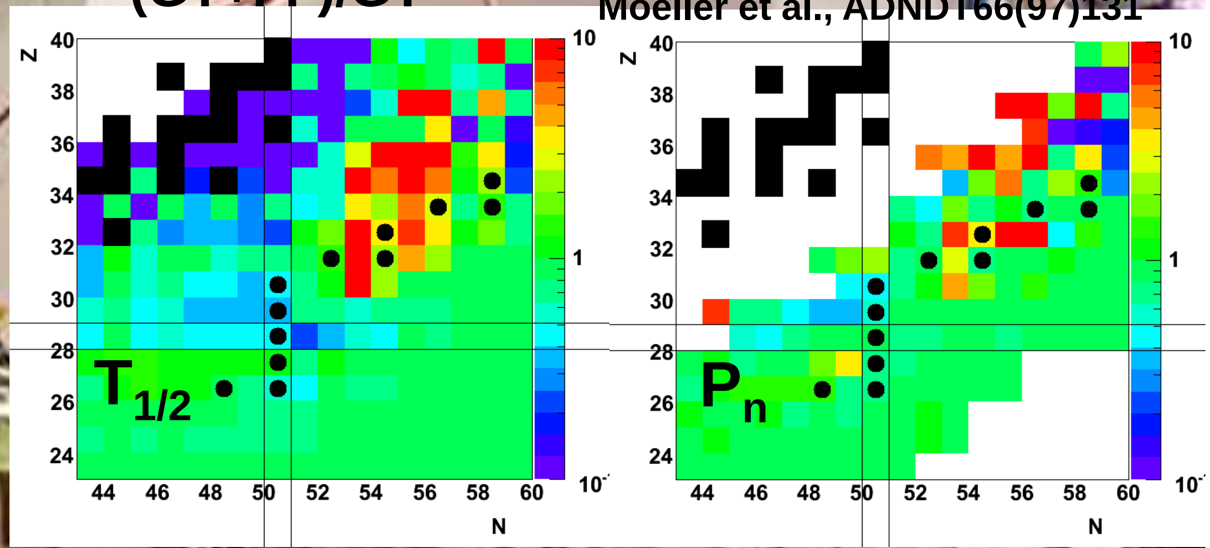
Motivation (II): nuclear structure for Z>28, N>50

- Role of FF transitions

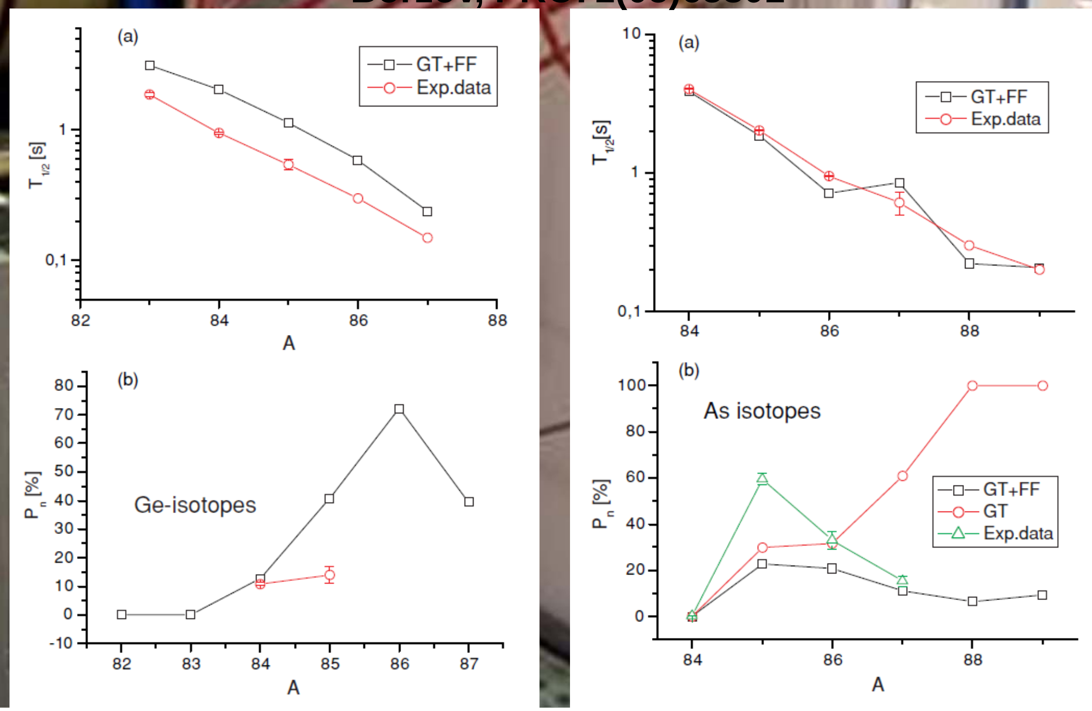


(GT+FF)/GT

Moeller et al., PRC67(03)55802
Moeller et al., ADNDT66(97)131

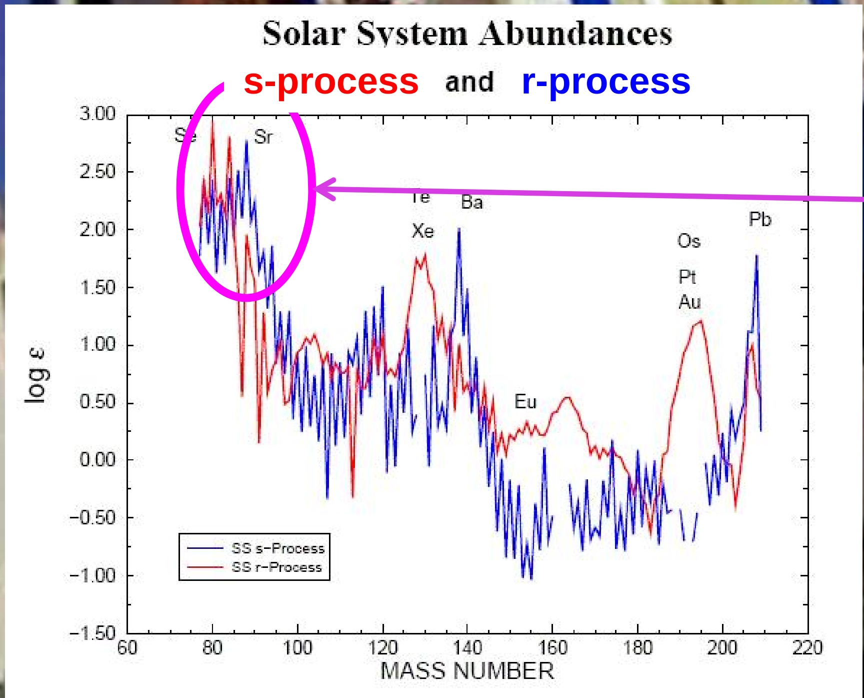


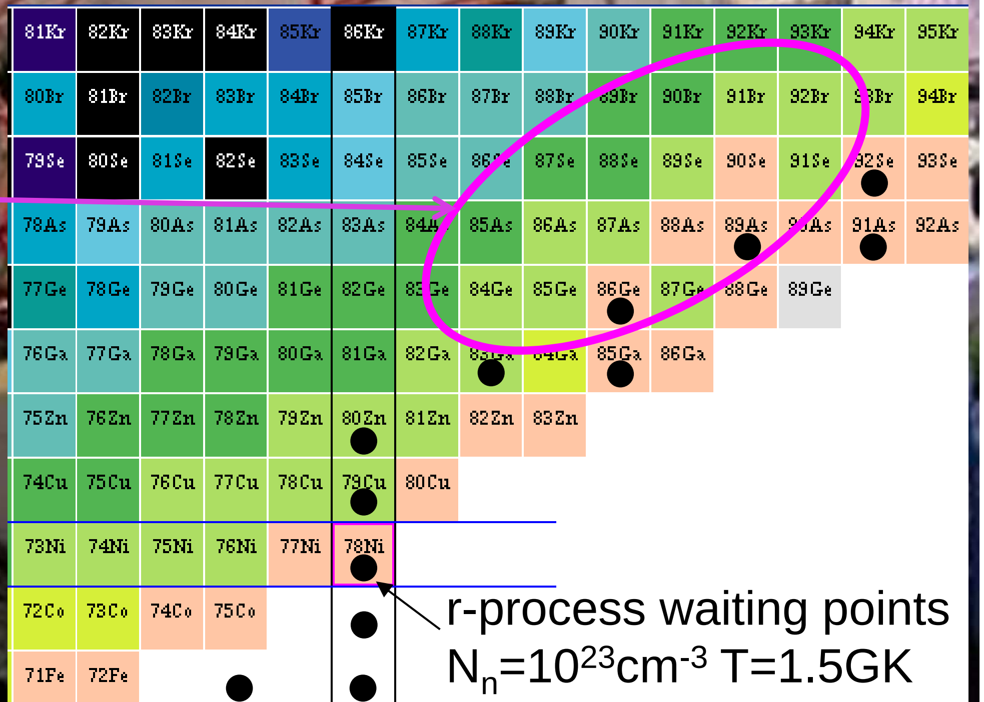
Borzov, PRC71(05)65801



Motivation (III): r-process close to the 1st abundance peak

- Beta delayed neutron emission alters the final abundances by shifting the decay path toward lower masses and providing neutrons reactivating the r-process after freeze-out.
- Disentangling weak s-process, cold and hot r-process.

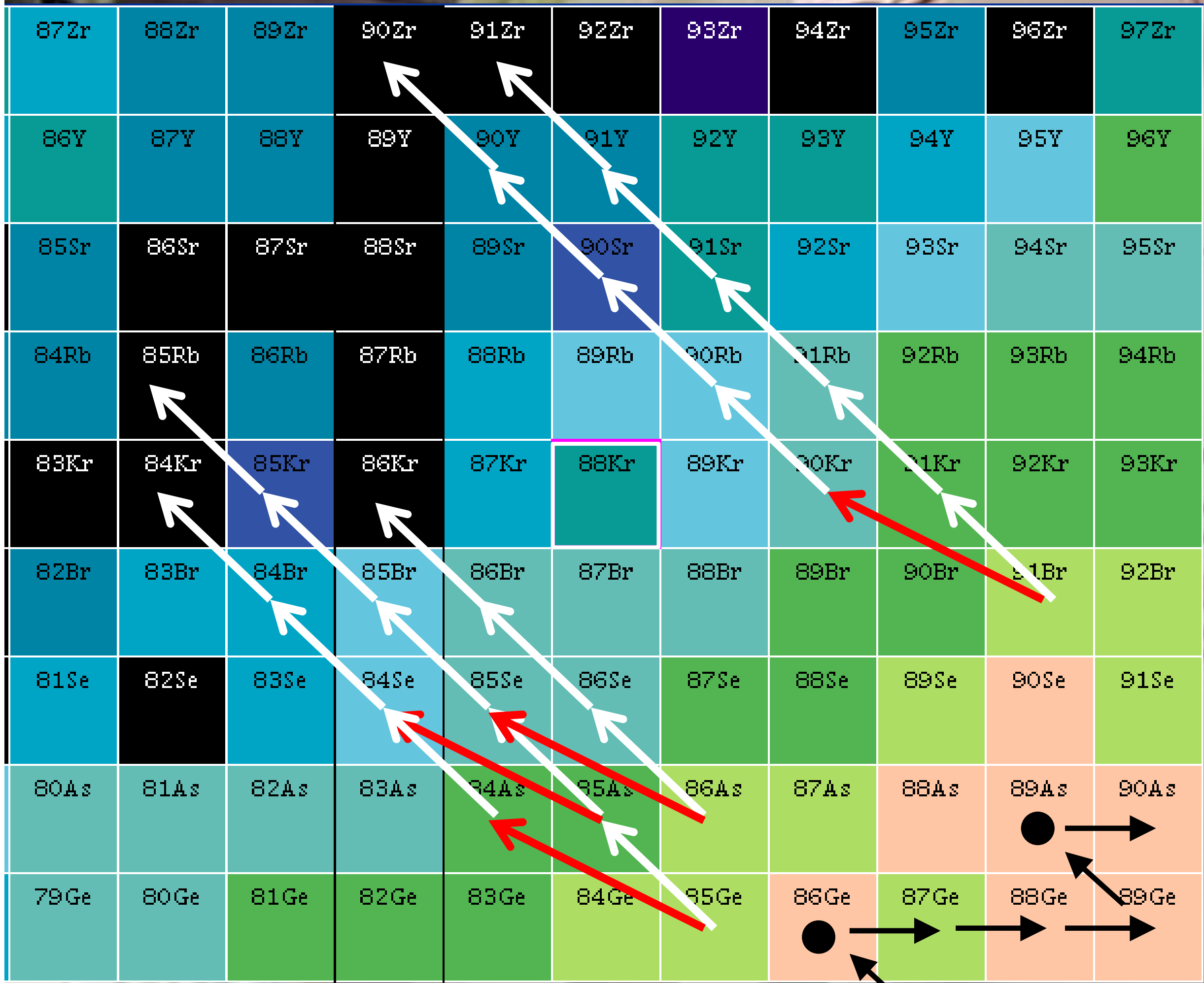




r-process waiting points

$N_n = 10^{23} cm^{-3}$ T=1.5GK

Choice of nuclei for the experiment with BELEN around N=50



^{91}Br

^{86}As

^{85}As

^{85}Ge

Pn (%)	RAS	PKM
91Br	20(3)	31.3(60)
86As	33(4)	26(7)
85As	59.4(24)	55(14)
85Ge	-	14(3)

Contribution to ν_d for thermal fission of ^{235}U:

- **^{91}Br: ~3%**
- **^{85,86}As, ^{85}Ge: ~7%**

RAS: Ruds... ADN... 53 (93)

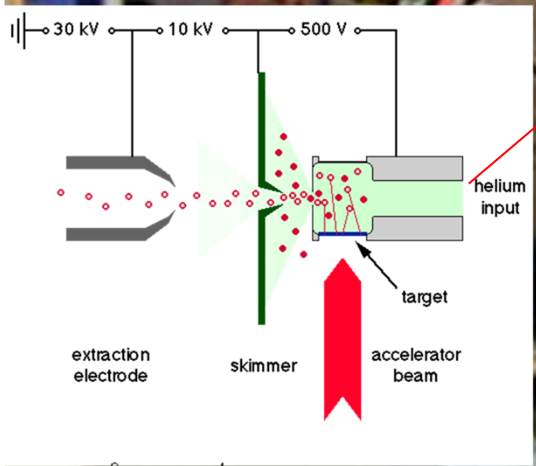
PKM: Pfei... et al. ... NE41... 39

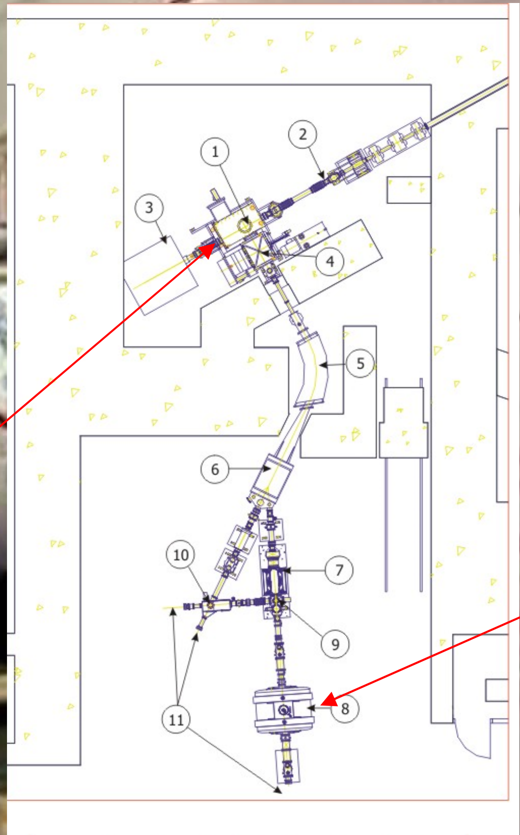
BELEN-20 experiment at JYFL (Jyvaskylä)

JYFL Cyclotron Laboratory @ Univ. Jyväskylä

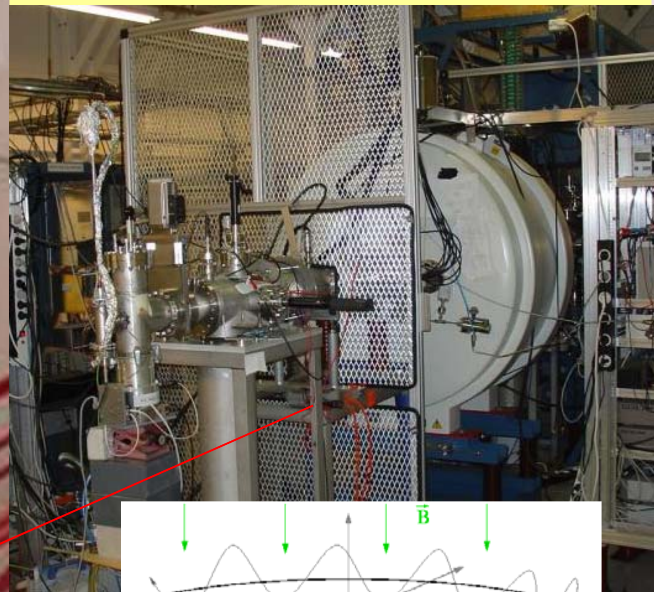
IGISOL separator **+ ion guide** source: refractory elements

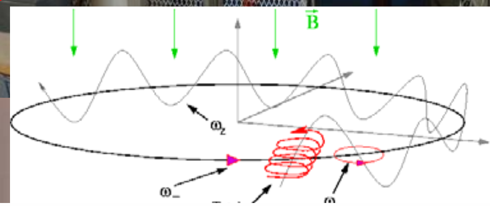
p(25MeV) + Th → FF

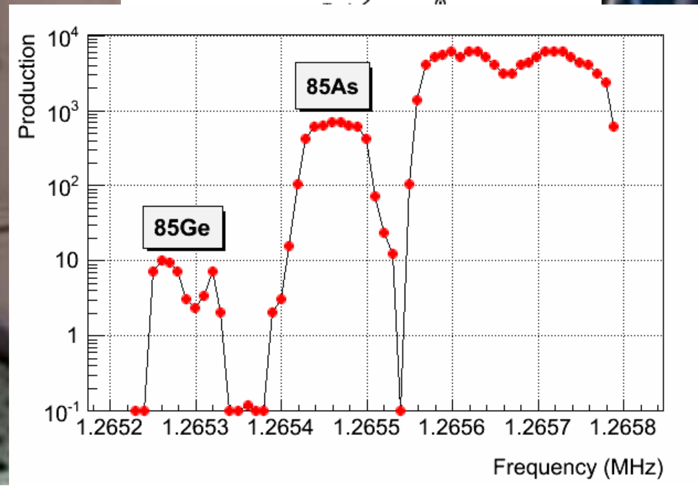




JYFLTRAP Penning trap: isotopic purification



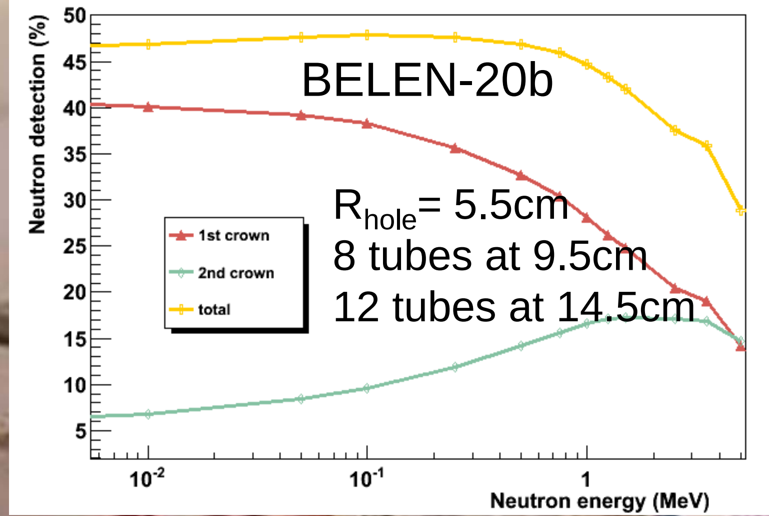




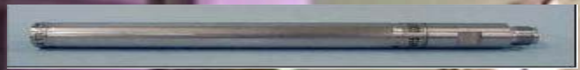
Isotope	Rate (s^{-1})	Isotope	Rate (s^{-1})
^{88}Br	1450	^{85}Ge	6
^{94}Rb	1030	^{85}As	175
^{95}Rb	760	^{86}As	30
^{137}I	100	^{91}Br	80

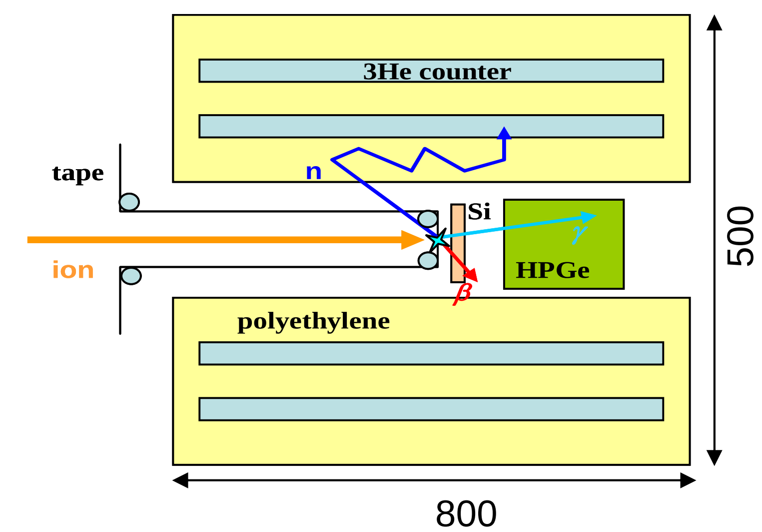
BELEN-20 experiment at JYFL (Jyvaskylä)

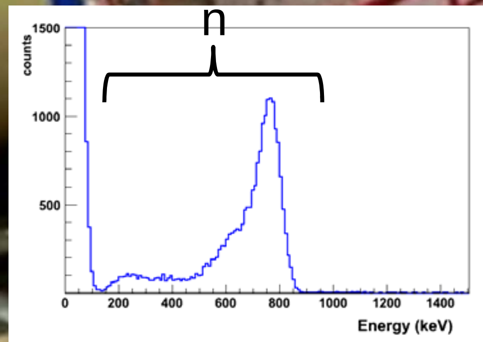
Efficiency up to 48%

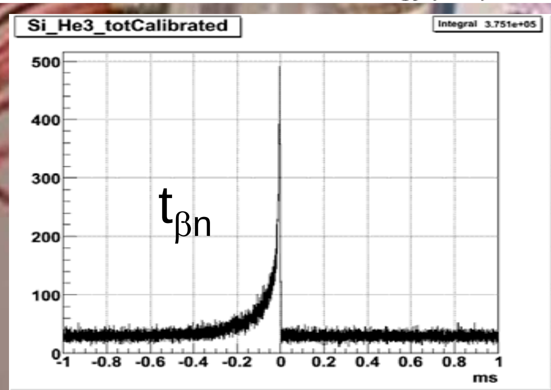


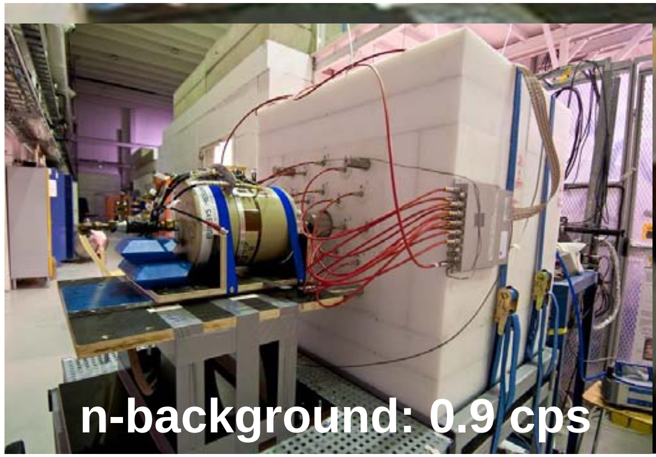
20 ∅2.5cm×60cm 3He tubes @20atm



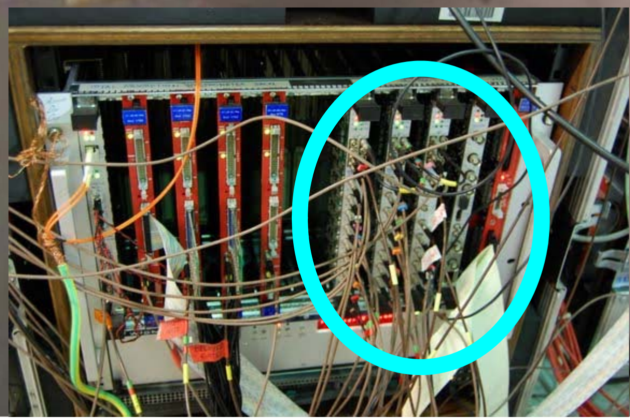








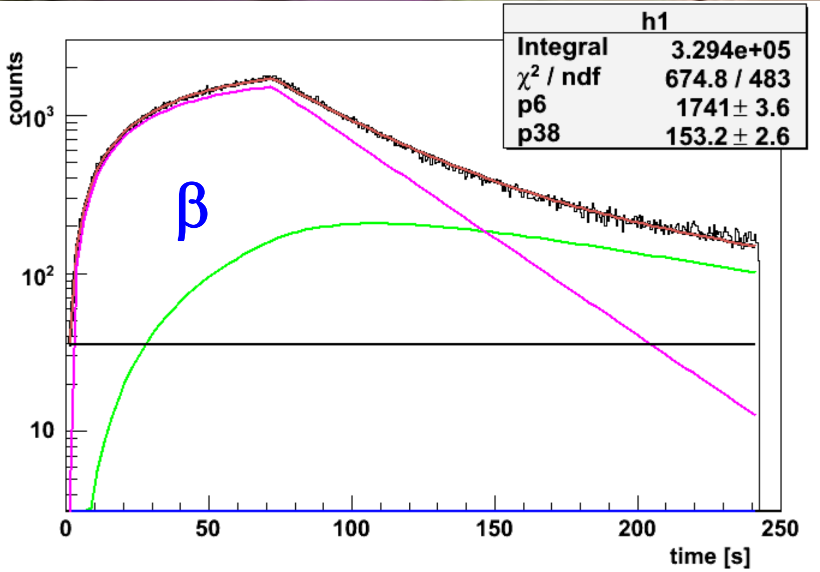
n-background: 0.9 cps

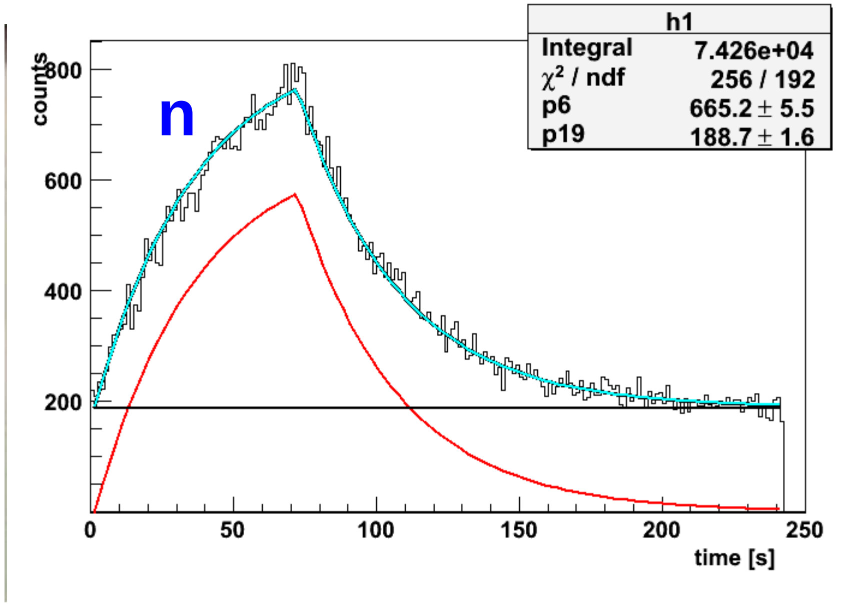


GasificTL:
Self triggered DACQ:
-Time-energy pairs for every neutron or β
-Clean noise separation
-Minimum dead time:<0.5%

Experiment: analysis

^{137}I



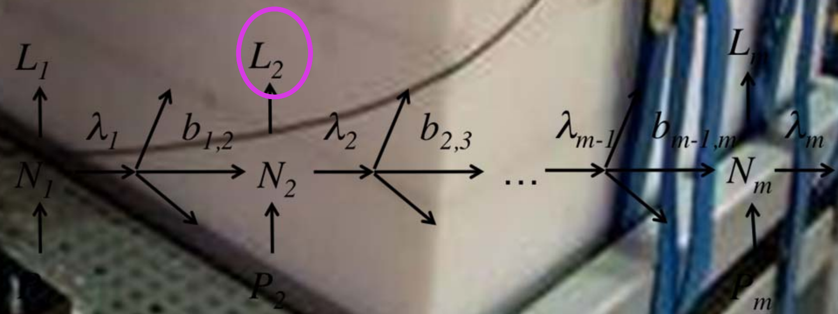


$$P_n = \frac{\varepsilon_\beta}{\varepsilon_n} \frac{N_n}{N_\beta}$$

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

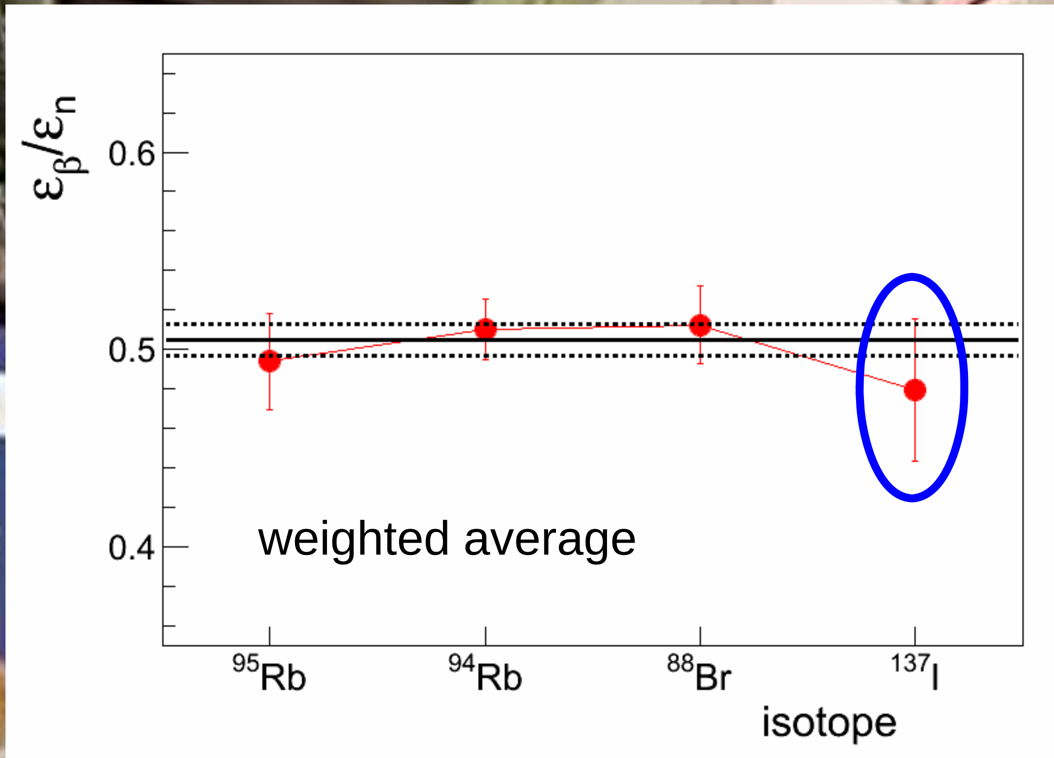
Problem:
- Fit was not good for ^{88,91}Br, ^{137}I
- Their daughters are noble gases: escape from implantation tape

Solution:
- Add a loss term to Bateman equations



Experiment: calibration#

$$\frac{\varepsilon_\beta}{\varepsilon_n} = P_n \frac{N_\beta}{N_n}$$



- Accurate
- Weak dependence of efficiency on neutron energy distribution (verified also by MC simulations)

Preliminary new result for ^{137}I: P_n=7.75(12)%

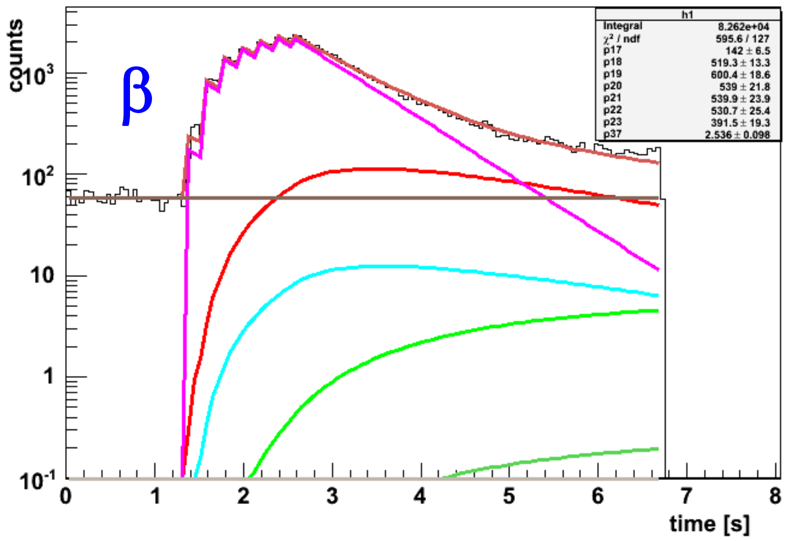
Rudstam et al., ADNDT 53 (93) 1

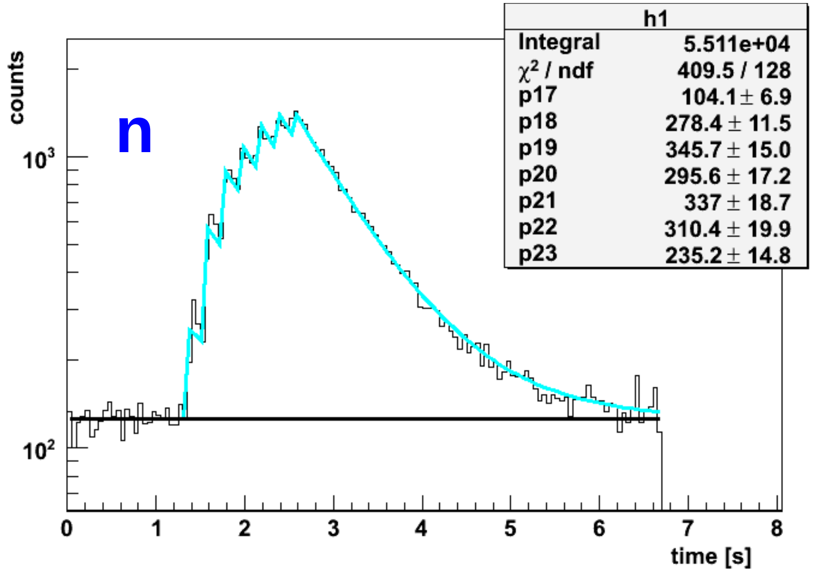
^{137}I	24	3.0(5)	$n-\beta$	ARO64	7.14(23)
		4.7(10)	$n-\beta$	KRA70	
	24.7(2)	8.6(12)	γ^{137}Xe	MAR71	
	24.3(8)	6.6(8)*	*fiss*	SCH72	
	24.8(2)	6.1(8)	$n-\beta$	ASG75	
	24.3	6.7(4)	$n-\beta$	LUN80	
		7.6(8)	*ion*	REE80	
	24.13(12)	7.46(30)	This work		

#: P_n values taken from A[illegible]a et al. IAEA-INDC(NDS)-0599

Preliminary results:

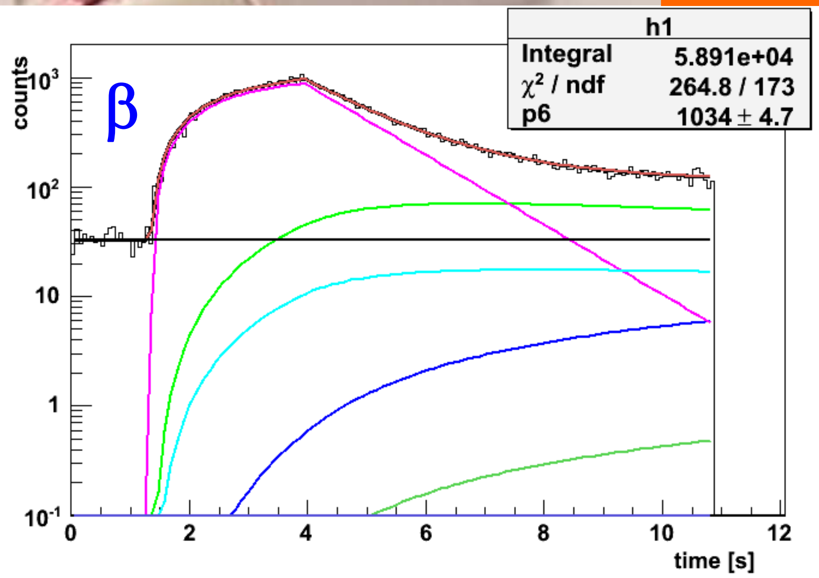
^{91}Br

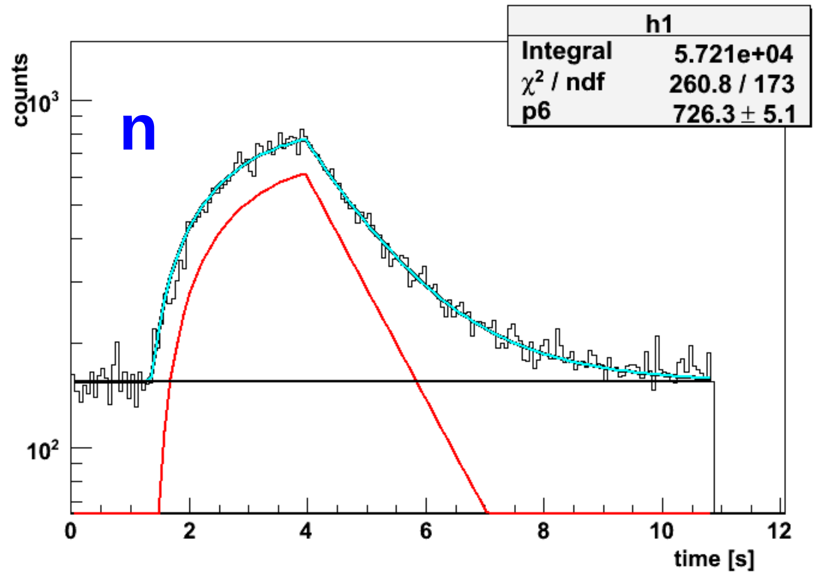




P[illegible] = 2[illegible]5(5)%

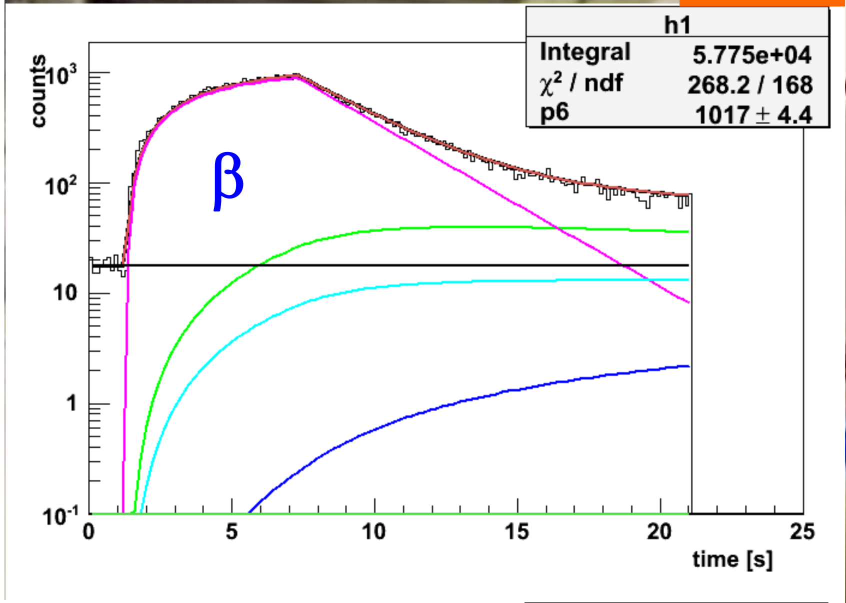
^{86}As

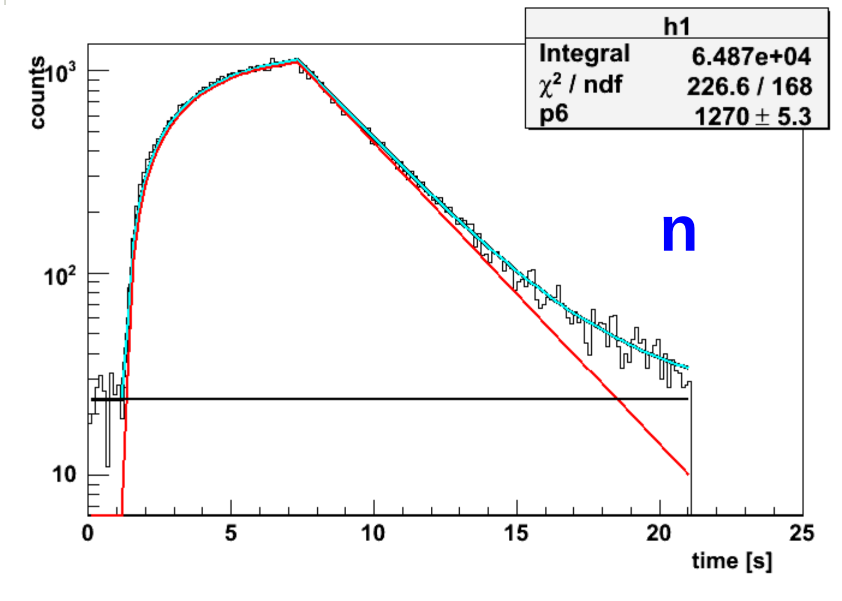




P_n = 35.5(6)%

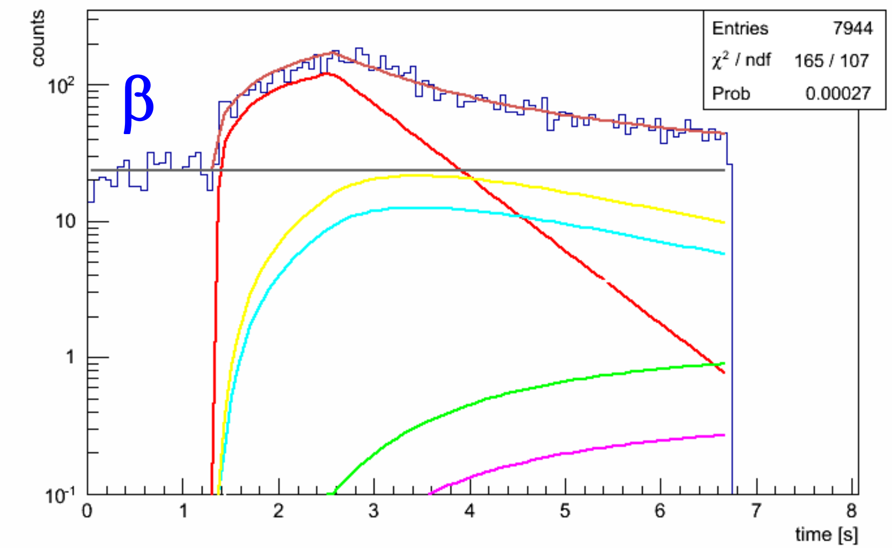
Preliminary results: ^{85}As

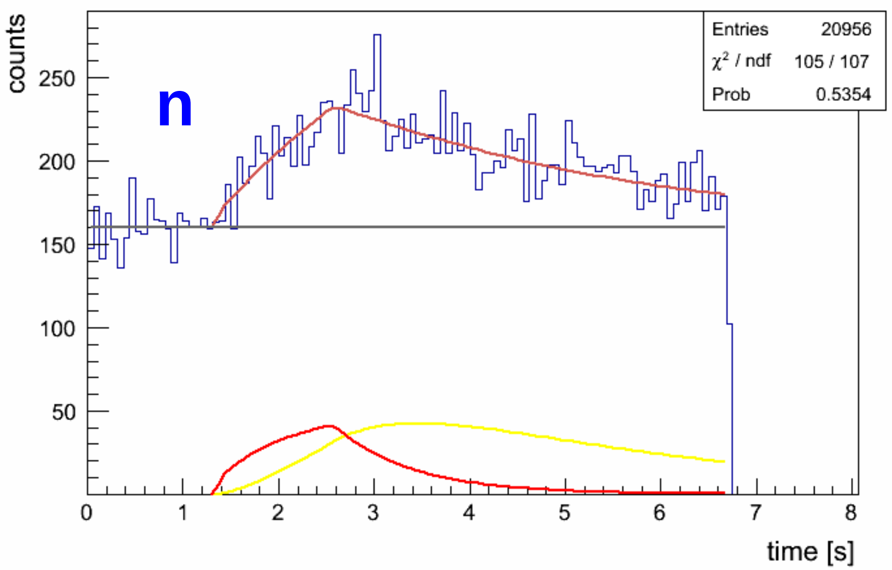




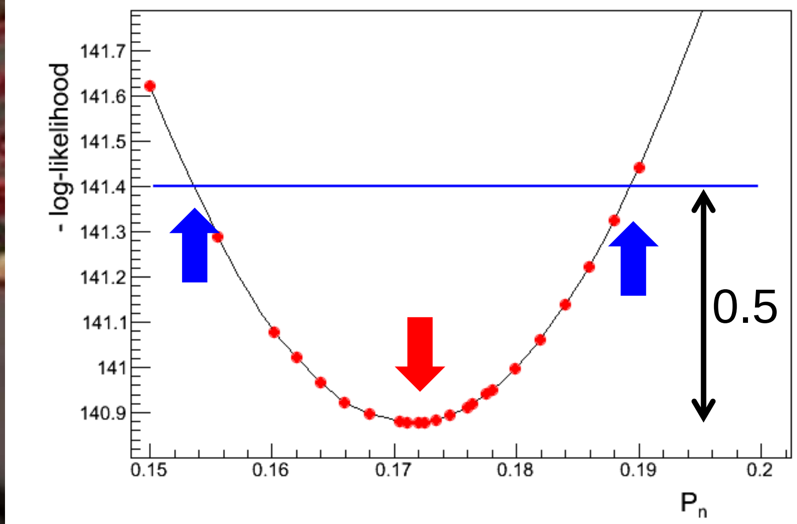
Preliminary uncertainties include only statistical- and efficiency-calibration uncertainties

Results: ^{85}Ge

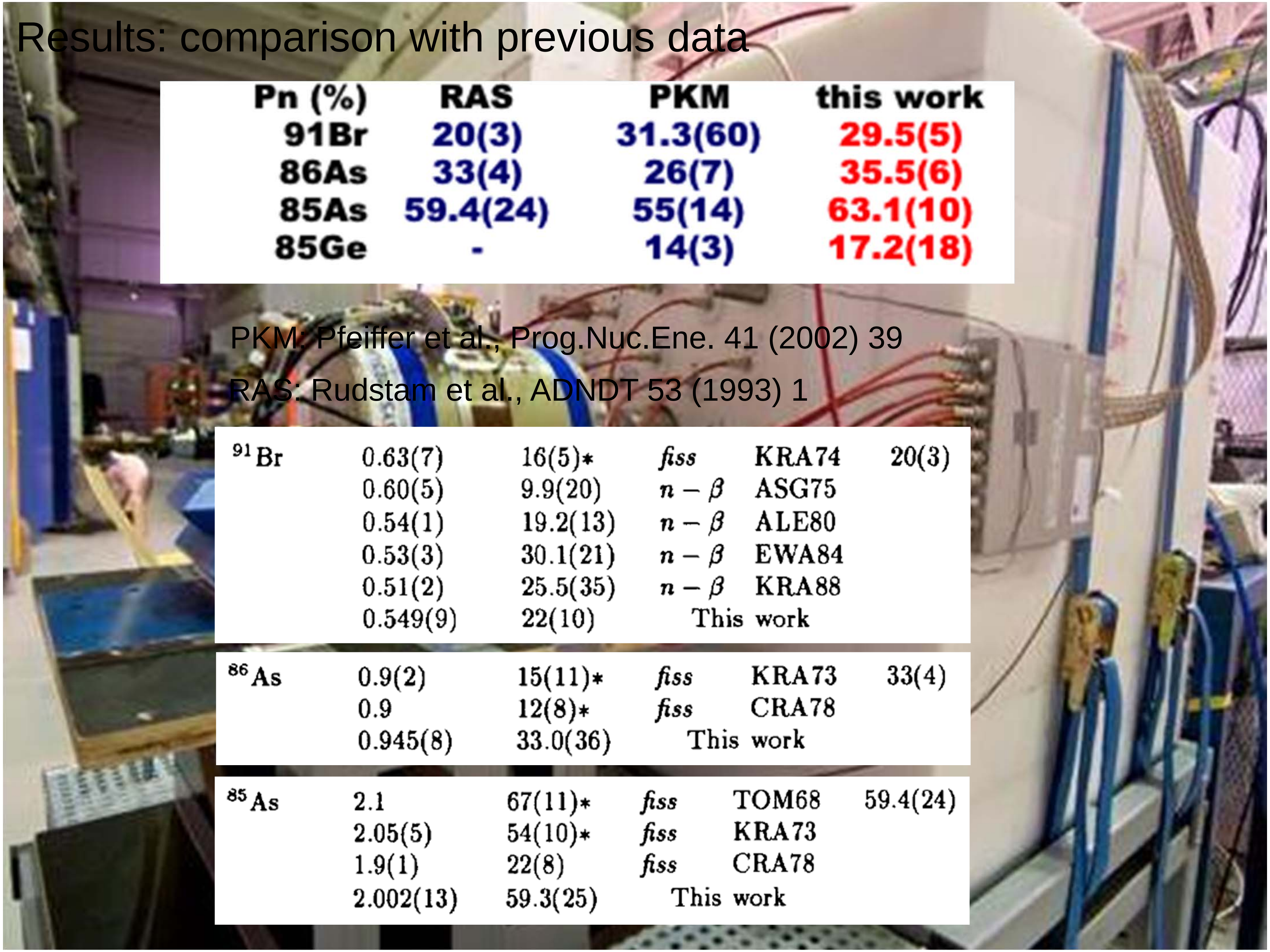




- Low statistics, daughter strong delayed neutron emitter
- Graph of log-likelihood of simultaneous beta and neutron fit for a fixed P_n with production as parameter: value and uncertainty



P_n = 17.2(18)%



Results: comparison with previous data

Pn (%)	RAS	PKM	this work
91Br	20(3)	31.3(60)	29.5(5)
86As	33(4)	26(7)	35.5(6)
85As	59.4(24)	55(14)	63.1(10)
85Ge	-	14(3)	17.2(18)

PKM: Pfeiffer et al., Prog.Nuc.Ene. 41 (2002) 39

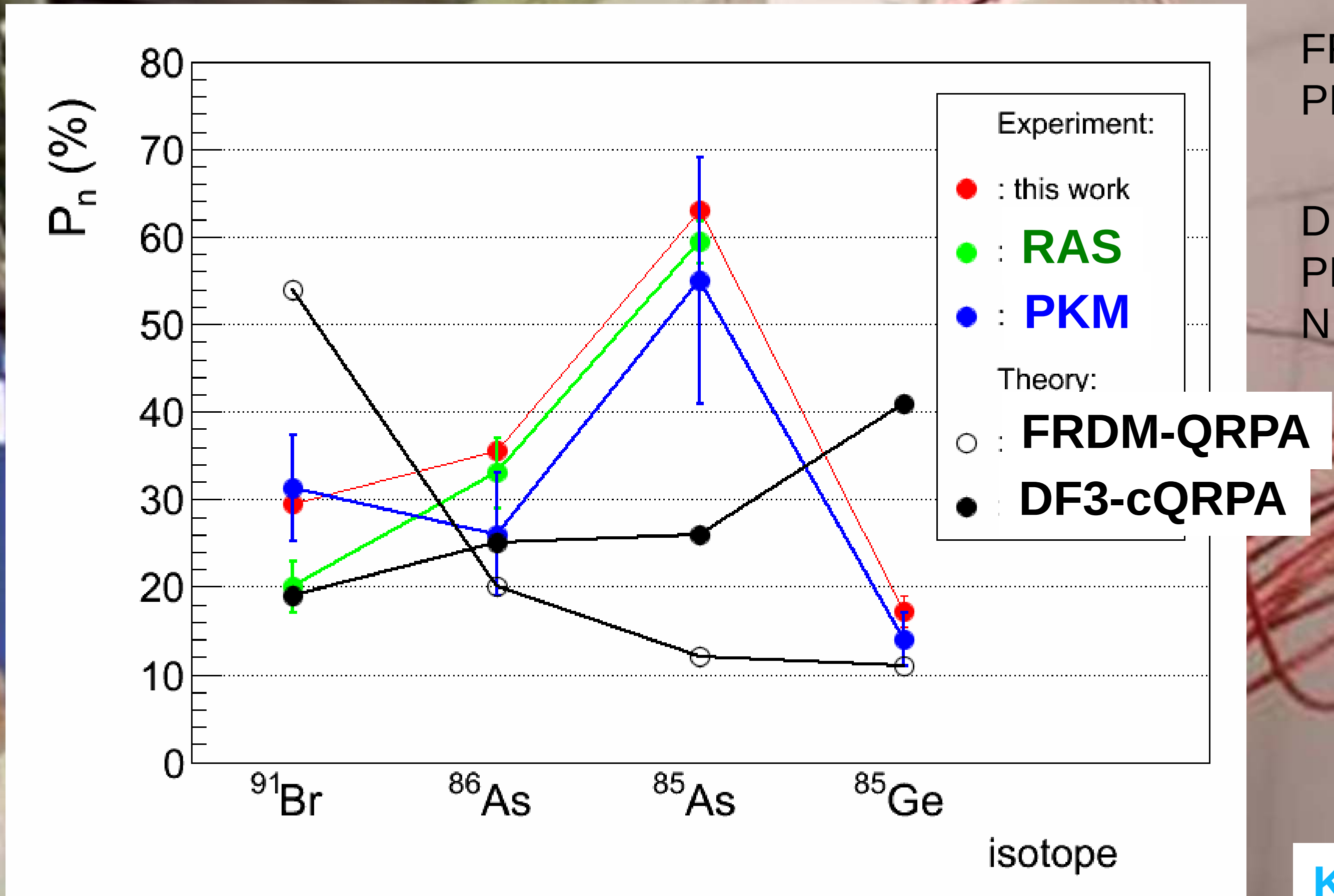
RAS: Rudstam et al., ADNDT 53 (1993) 1

^{91}Br	0.63(7)	16(5)*	*fiss*	KRA74	20(3)
	0.60(5)	9.9(20)	$n-\beta$	ASG75	
	0.54(1)	19.2(13)	$n-\beta$	ALE80	
	0.53(3)	30.1(21)	$n-\beta$	EWA84	
	0.51(2)	25.5(35)	$n-\beta$	KRA88	
	0.549(9)	22(10)	This work		

^{86}As	0.9(2)	15(11)*	*fiss*	KRA73	33(4)
	0.9	12(8)*	*fiss*	CRA78	
	0.945(8)	33.0(36)	This work		

^{85}As	2.1	67(11)*	*fiss*	TOM68	59.4(24)
	2.05(5)	54(10)*	*fiss*	KRA73	
	1.9(1)	22(8)	*fiss*	CRA78	
	2.002(13)	59.3(25)	This work		

Results: comparison with theoretical estimates



FRDM-QRPA: Moeller et al., PRC67(03)55802

DF3-cQRPA: Borzov, PRC71(05)65801, NPA777(06)445

Both calculations reproduce $T_{1/2}$ within a factor 2

…and empirical formulas

Pn (%)	this work	PKM	MSJABS
91Br	29.5(5)	12.1	27.0
86As	35.5(6)	9.3	33.2
85As	63.1(10)	7.9	36.3
85Ge	17.2(18)	4.3	9.8

Kratz-Hermann formula:

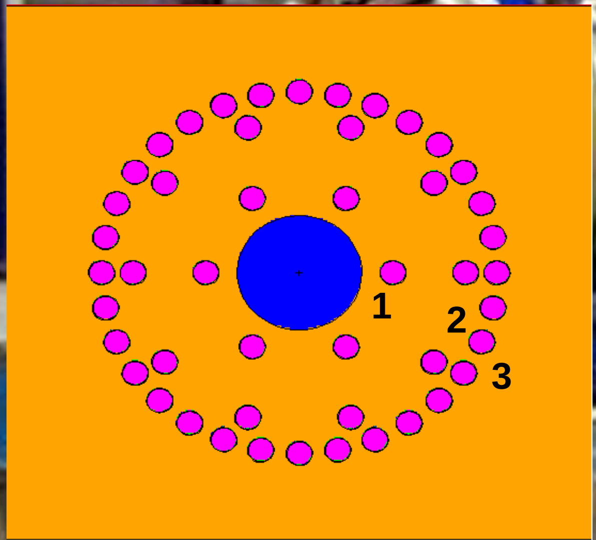
$$P_n = a\left(\frac{Q_\beta - S_n}{Q_\beta - C}\right)^b$$

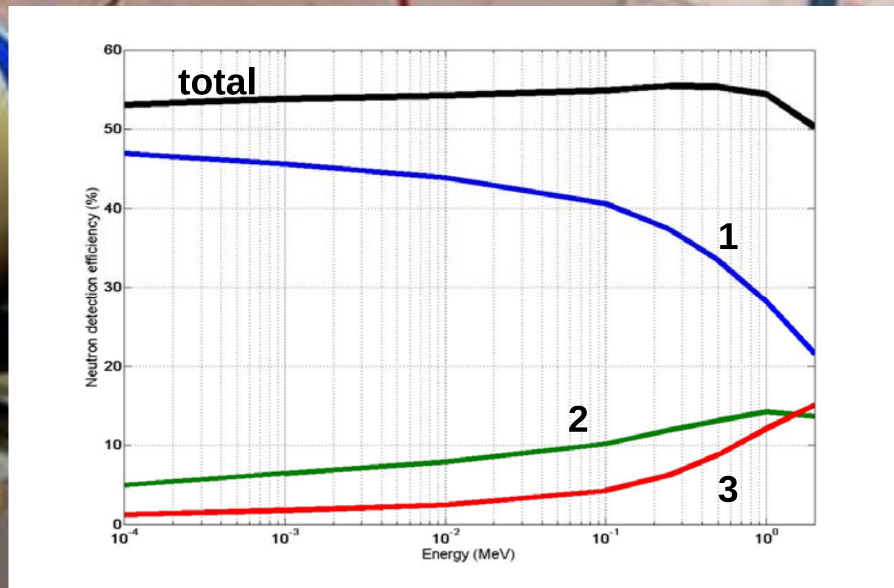
McCutchan et al PRC86(12):

$$\frac{P_n}{T_{1/2}} = a\left(Q_\beta - S_n\right)^b$$

Conclusion & Perspective of BELEN@JYFL:

- **New accurate P_n measurements have been performed for (^{137}I), ^{91}Br ,^{86,85}As, ^{85}Ge which had relatively large uncertainties are important contributors to the delayed neutron fraction in reactors, to the first abundance peak of the r-process and sensitive to the nuclear structure for Z>28, N>50**

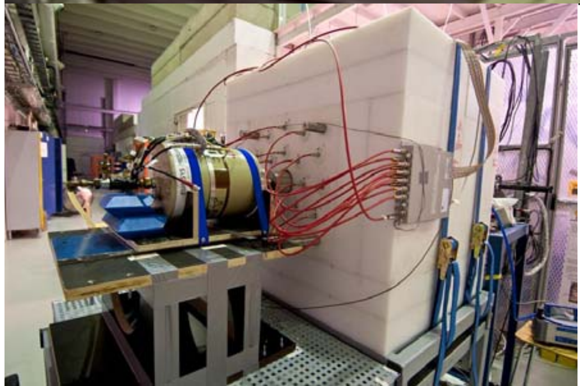




- New experiments at JYFL in 2013 on one (J.L. Tain et al) and two-neutron emitters (R. Dillmann et al.)
- IAEA-CRP has been launched on beta-delayed neutron emission

http://www-nds.iaea.org/beta-delayed-neutron/

Beta dELayEd Neutron detector - **BELEN**



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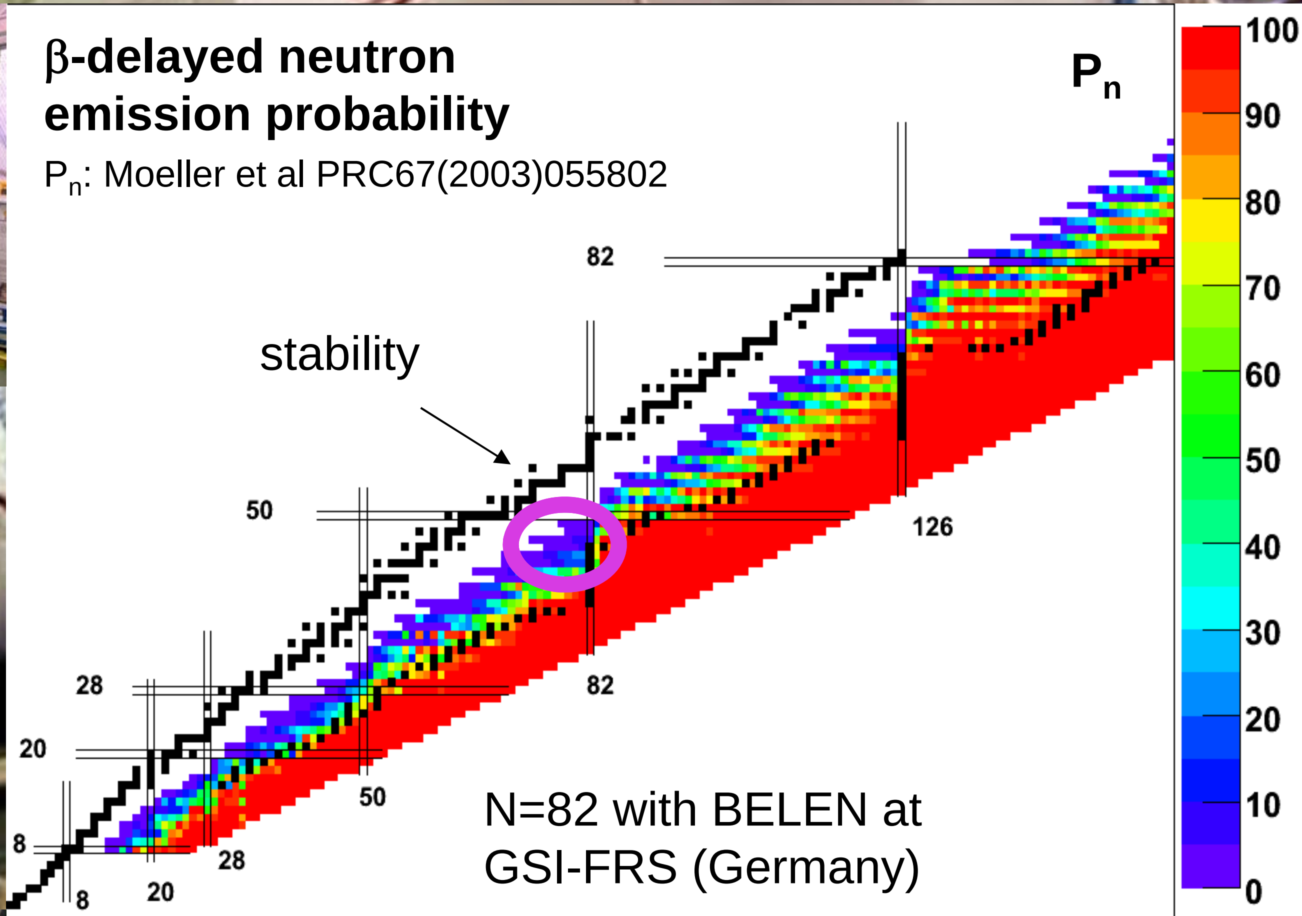
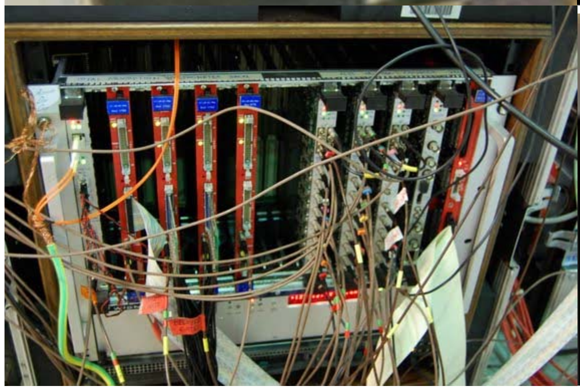
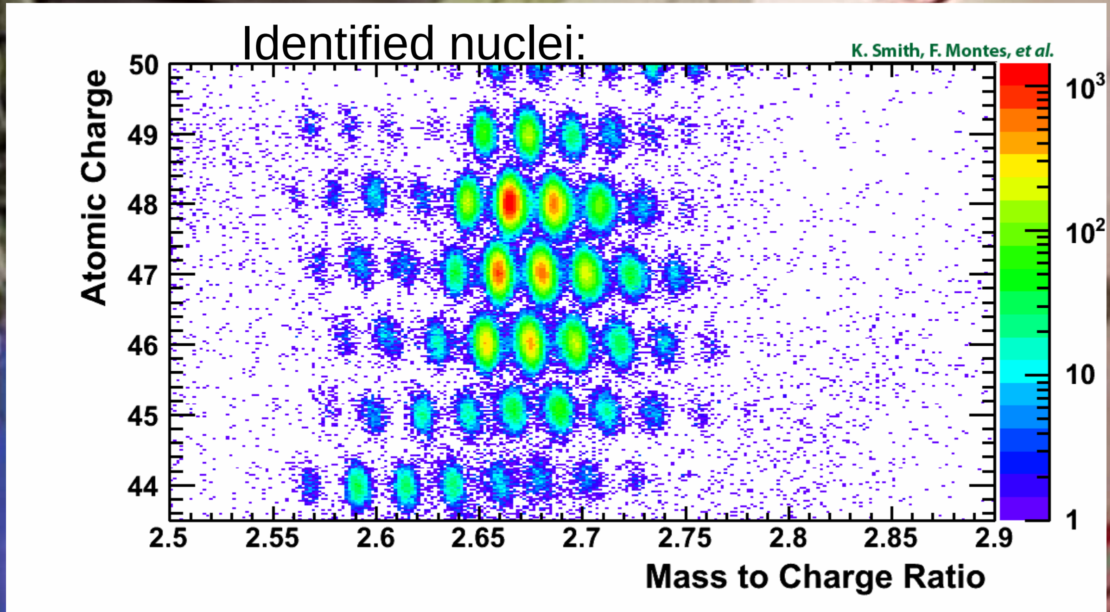
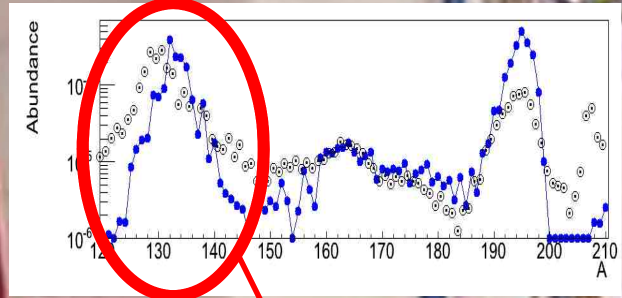
- Perspective

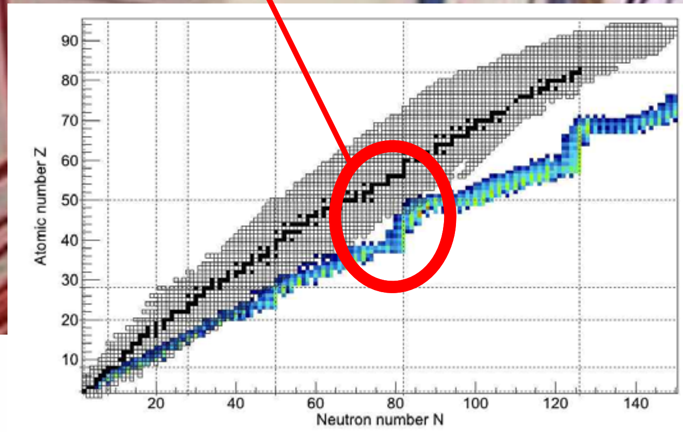


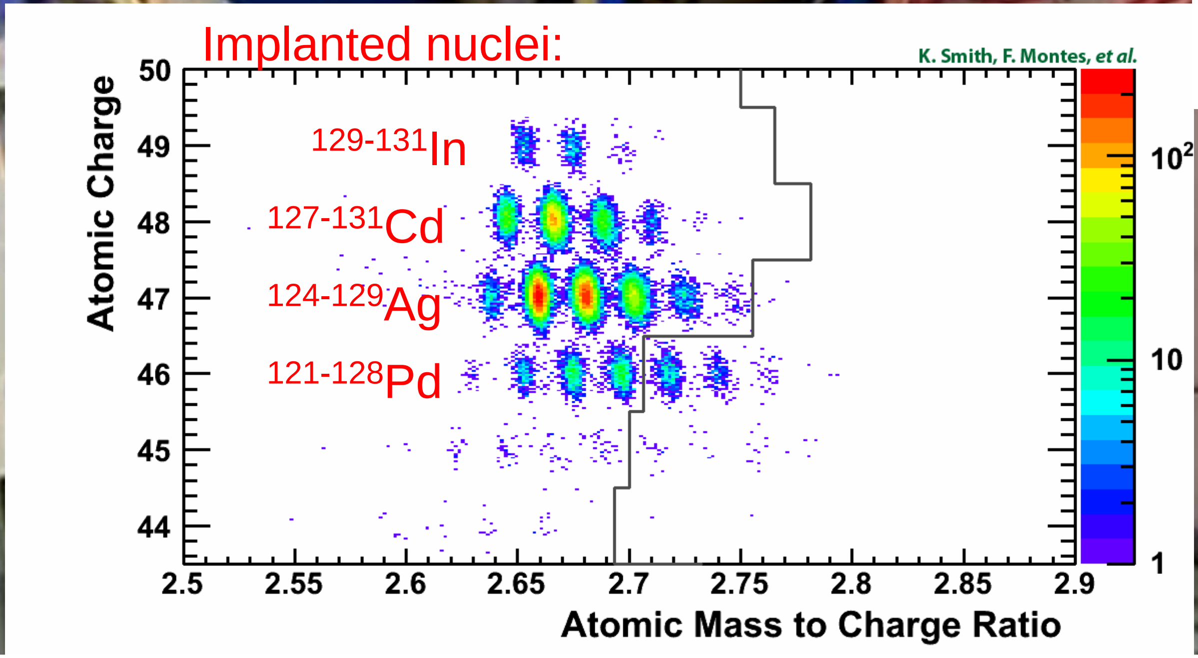


BELEN@S323 Experiment: GSI FRS (F. Montes et al.)



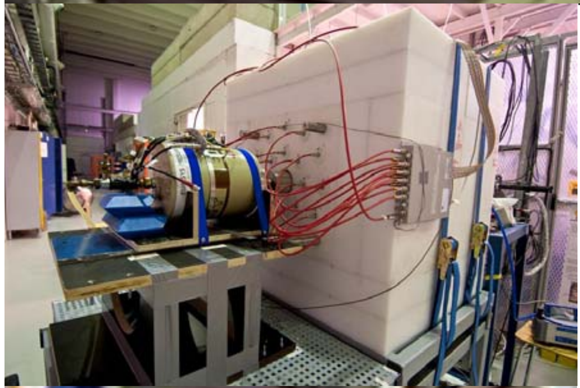




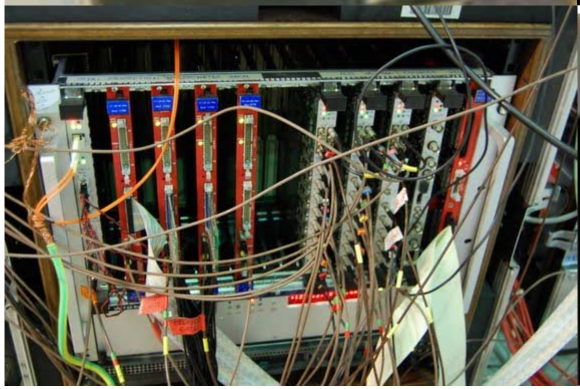


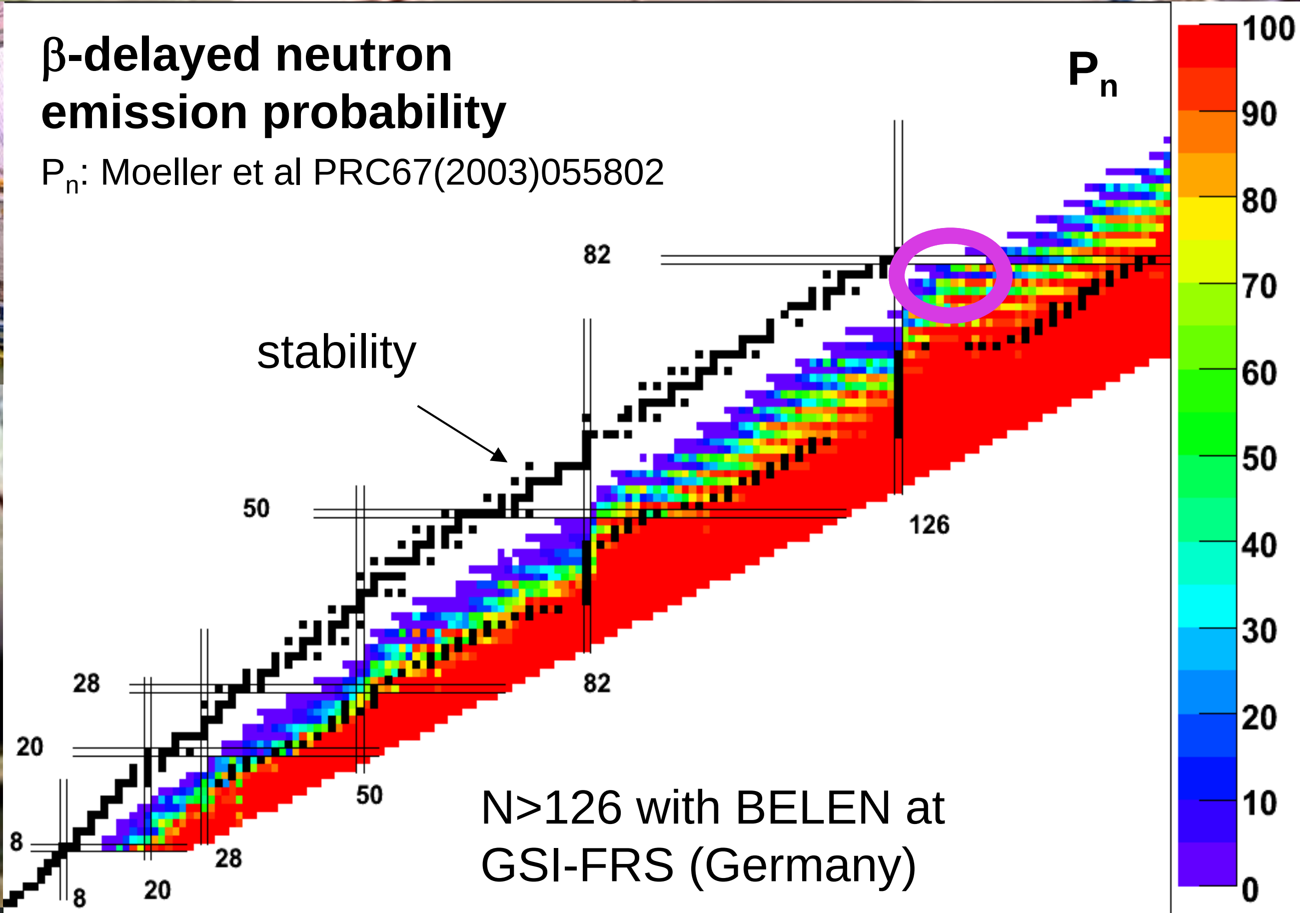
Analysis is in progress, part of the PhD Thesis of K. Smith (NSCL-MSU).

Beta dELayEd Neutron detector - **BELEN**



- Motivation
- Experiment
- Data analysis
- Preliminary results
- Perspective



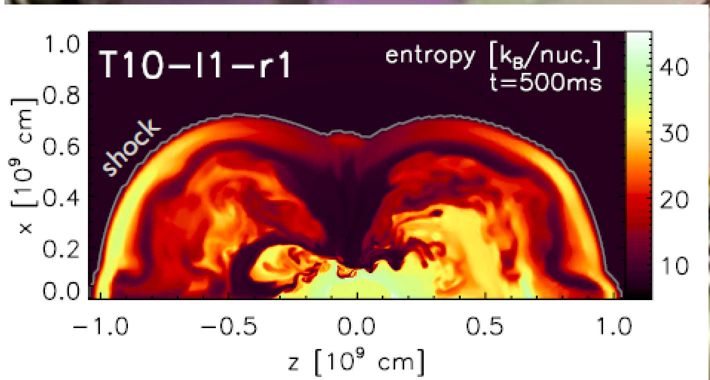


Preliminary results:

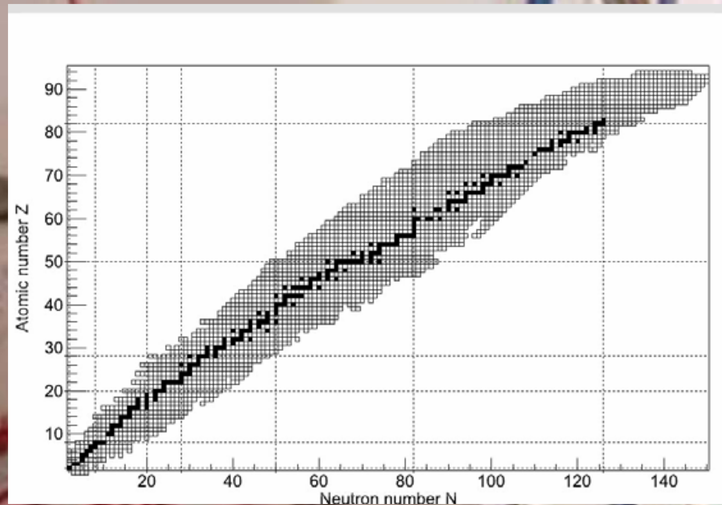
- Nuclei in the Cosmos XII, Cairns, Australia, 2012
- Nuclear Data for Science and Technology, NY, USA, 2013

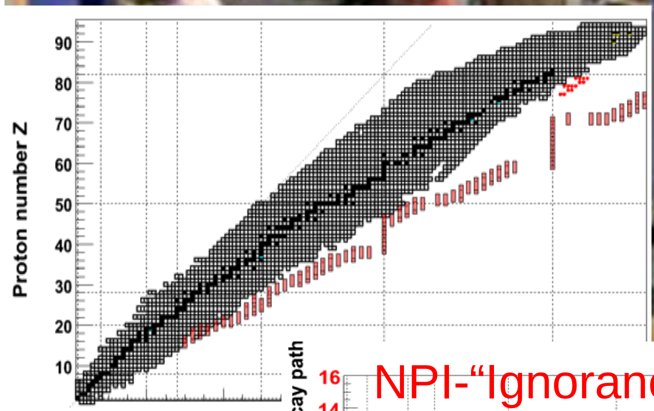
Decay measurements around the third r-process peak

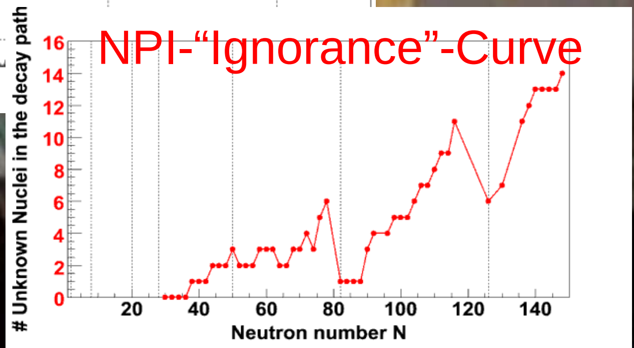
- Explosive nucleosynthesis and the r-process around the third abundance peak

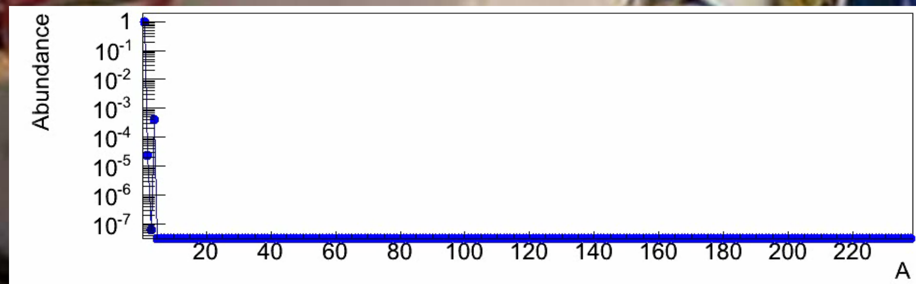


State of the art SNe simulations (e.g. A. Arcones, et al.) do NOT yield the termo-conditions (entropy) for the reproduction of the third r-process peak → SNe are not the r-process environment?









Decay measurements around the third r-process peak

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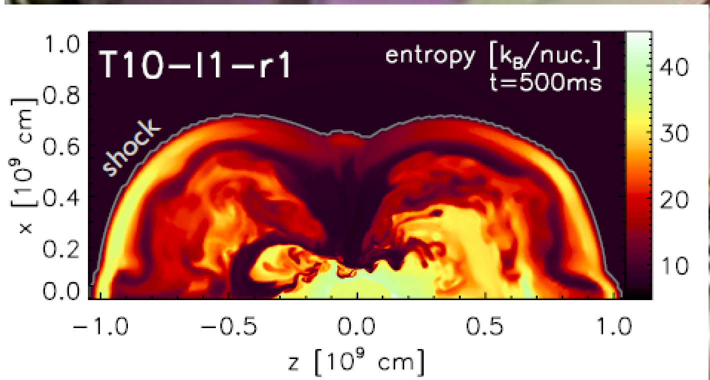

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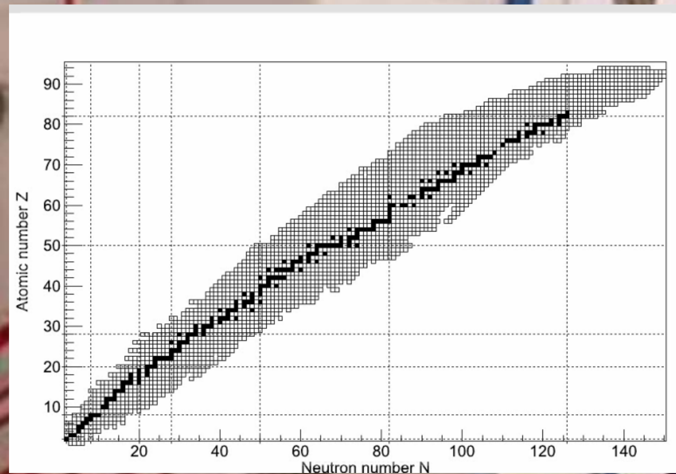

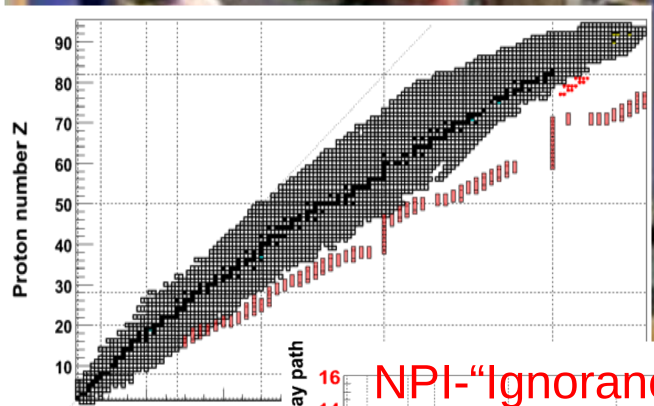

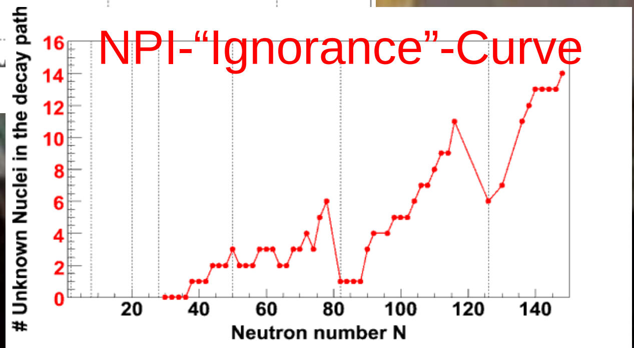

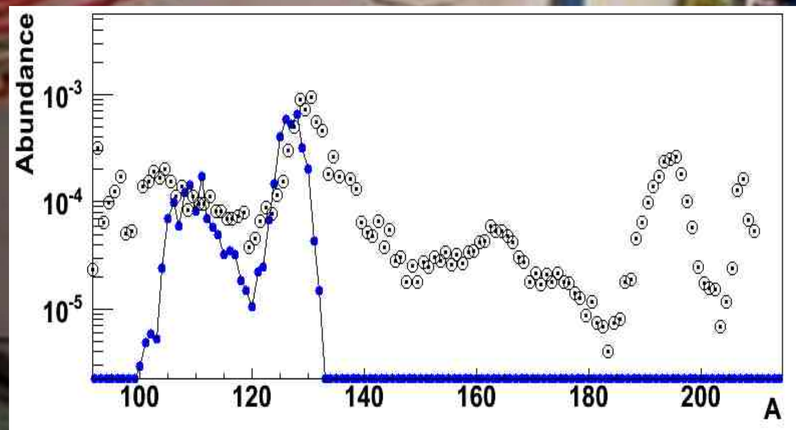

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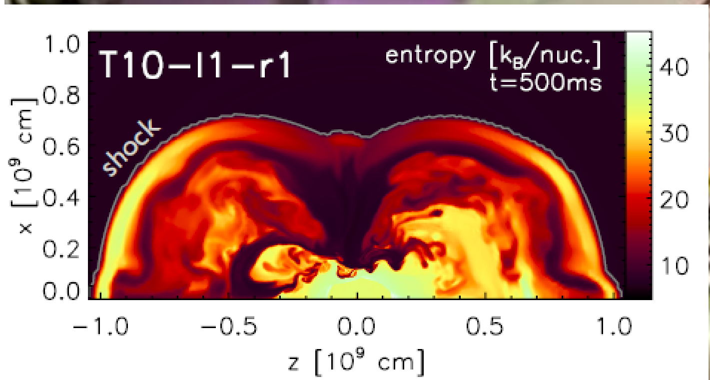

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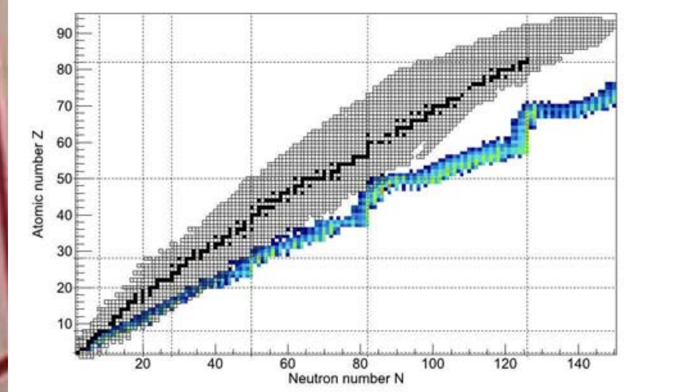
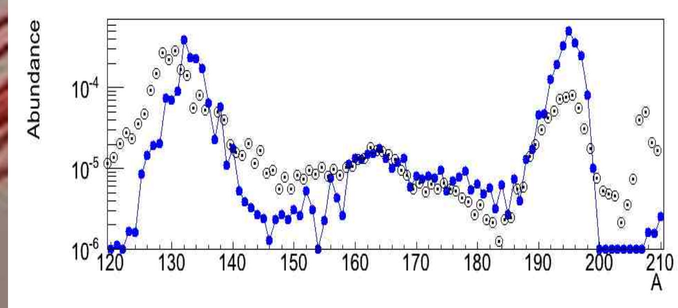
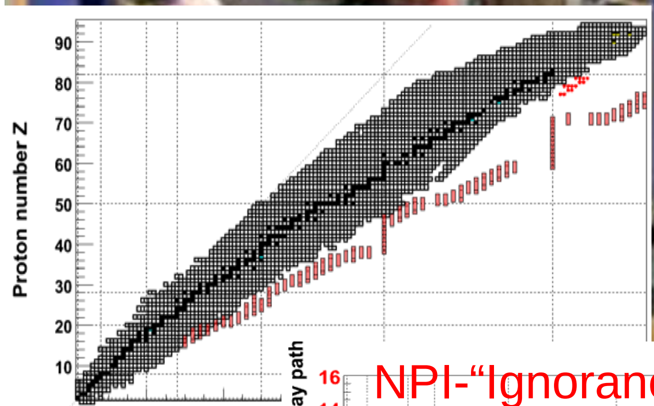
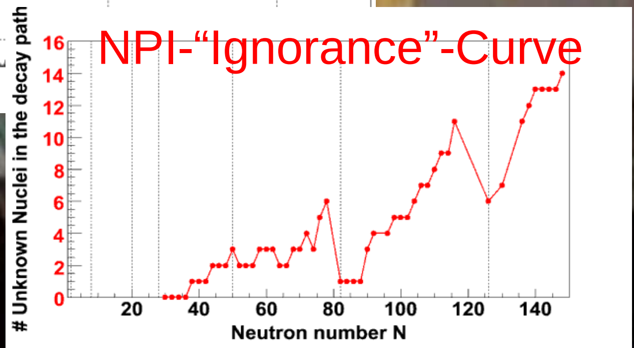


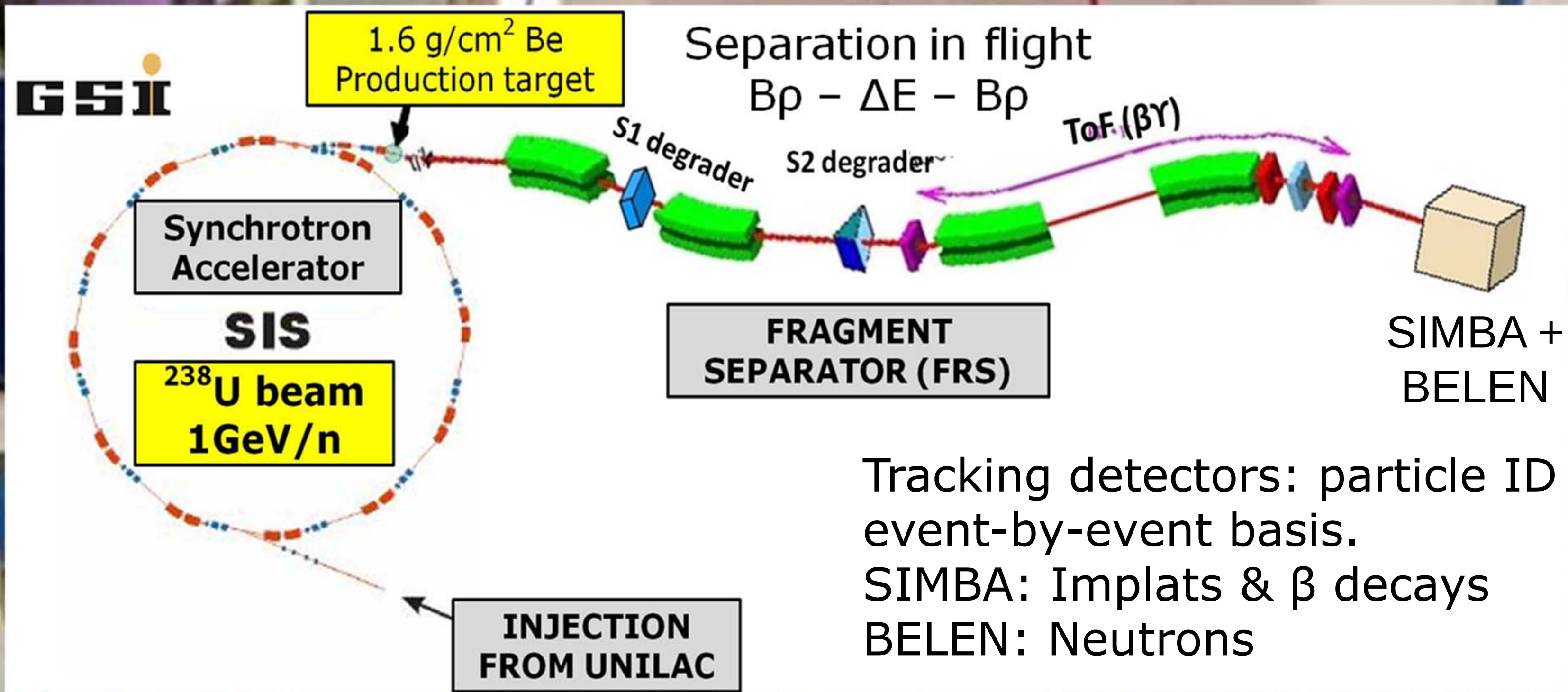






BELEN @ RIB of GSI, N>126
Experimental set-up

Large intensity ($2x10^9$ ions/pulse) & high-energy (1 GeV/u) for ^{238}U beams

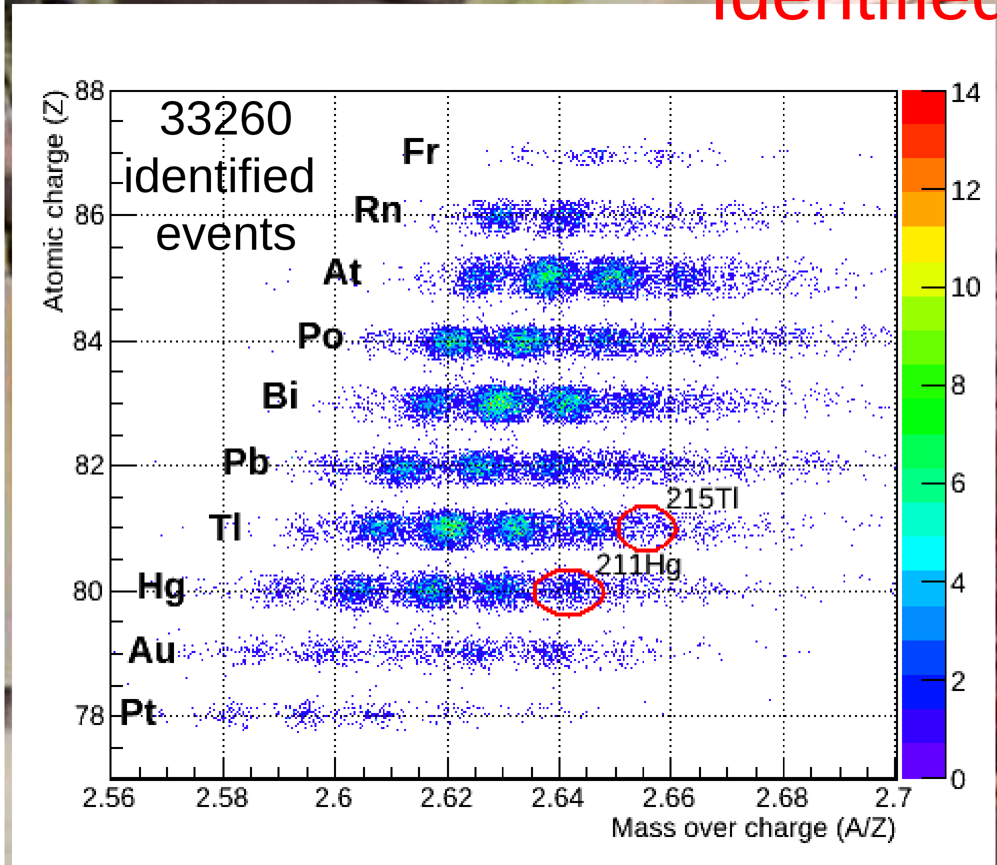


Tracking detectors: particle ID on an event-by-event basis.
SIMBA: Implats & β decays
BELEN: Neutrons

The detection system is based on a stack of SSSD- and DSSD-detectors for measuring ion-implants and beta-decays (SIMBA). Implants-region was surrounded by the 4π neutron detector BELEN.

Experiment with BELEN @ RIB of GSI, N>126

Identified Nuclei



This identification information should allow us to estimate **fragmentation cross-sections** for ^{238}U at 1 GeV/u.

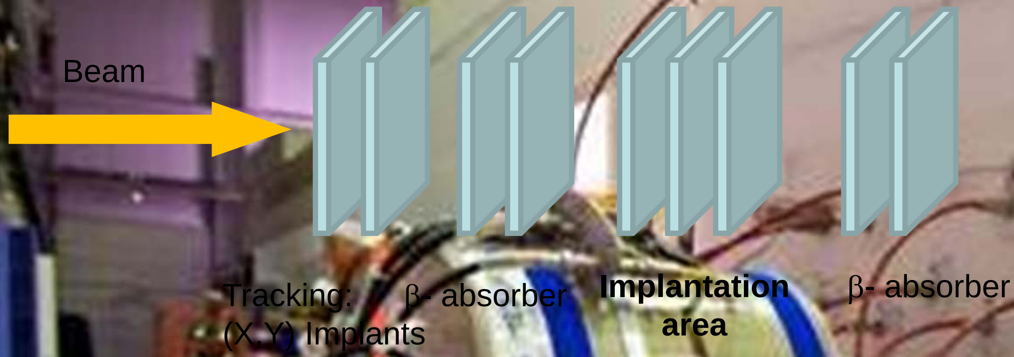
The results will be compared versus the CSs reported in *PRC82 (2010), H.Alvarez-Pol, et al.*, which represent the only experimental information available so far.

Isomer tagging was used for Z identification and two centred settings on ^{211}Hg and ^{215}Tl were measured during 4.5 days. The implantation area was optimized for Hg and Tl region where good resolution has been obtained.

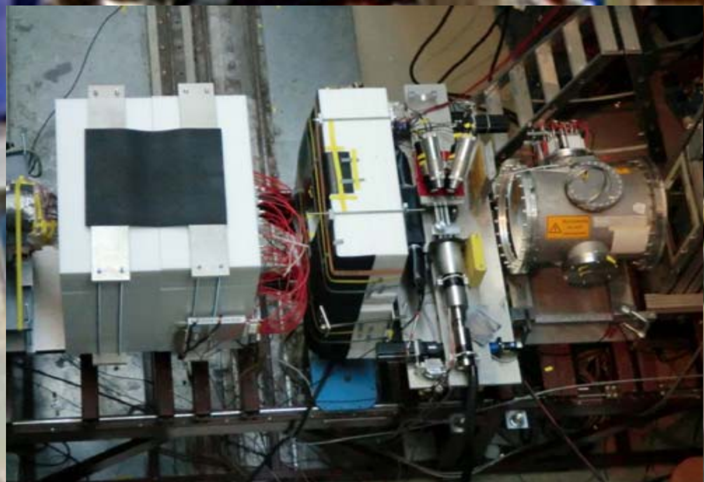
Experiment with BELEN @ RIB of GSI, N>126

Experimental set-up

Detection system: SIMBA & BELEN detector



PhD thesis C. Hinke, TUM (2010) **Diploma thesis K. Steiger, TUM (2009)**

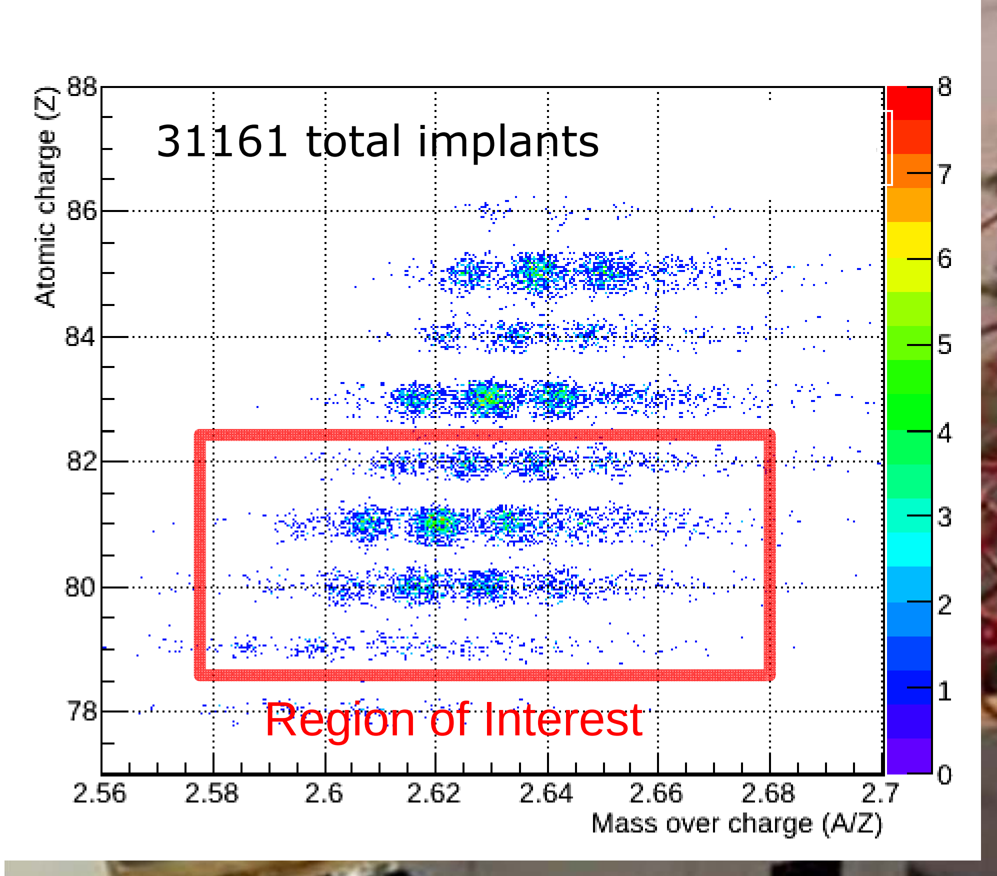


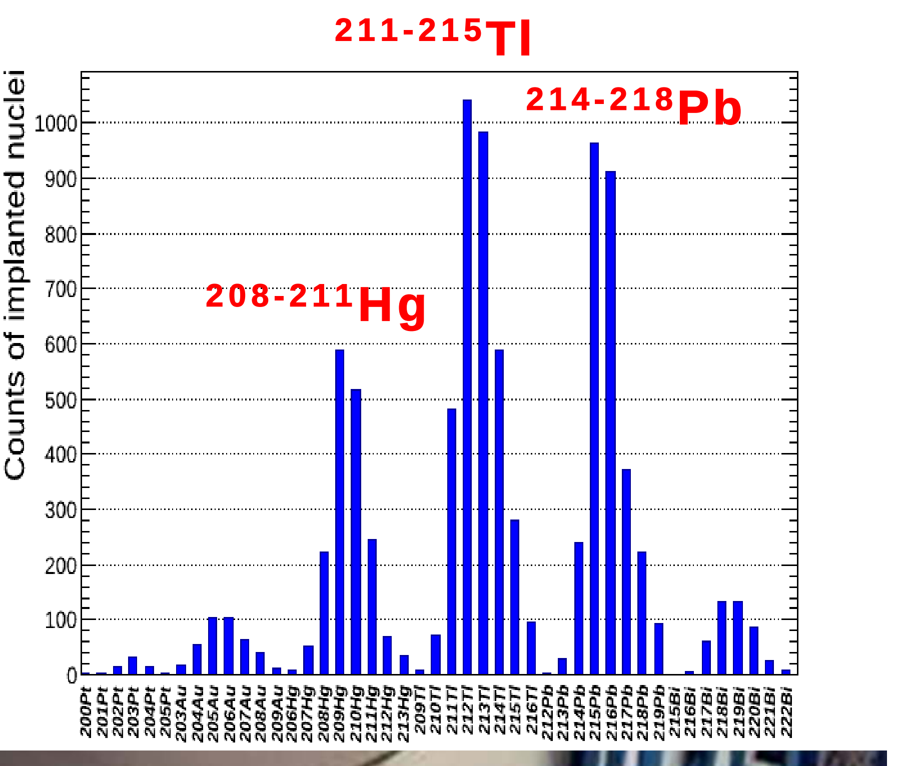
BELEN efficiency 40(2)% (checked experimentally)

The Beta dElayEd Neutron (BELEN) detector, based in ^{3}He counters embedded in a polyethylene matrix located around Silicon IMplantation Beta Absorber (SIMBA).

Experiment with BELEN @ RIB of GSI, N>126

Identified and Implanted Nuclei

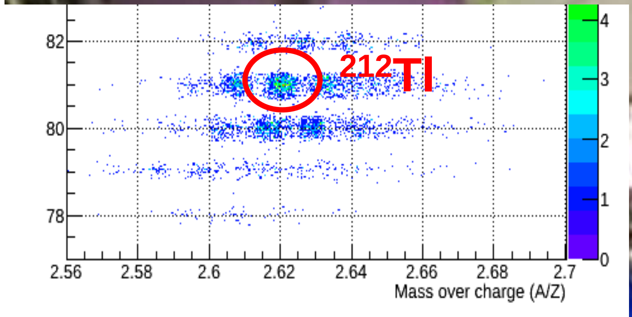




Implantation in the highly segmented layers of SIMBA detector DSSD area.

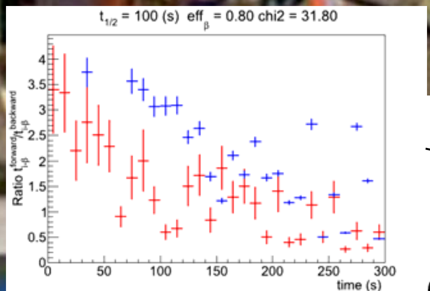
Experiment with BELEN @ RIB of GSI, N>126

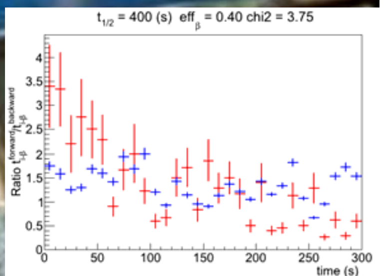
Analysis method to determine half lives: ^{212}Tl

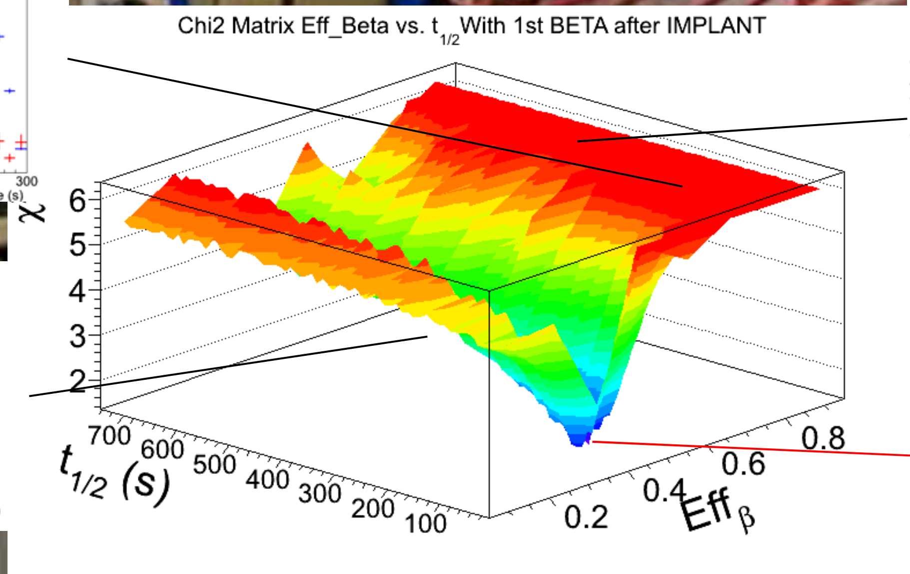


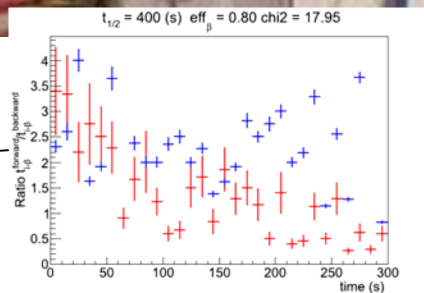
As first approach, we apply the method developed at USC for long half-lives in complex background environments (*NIM-A-589 (2008),T.Kurtukian*).
Basically, the method consists of comparing implant-beta time-correlation spectra (actually the ratios forward/backward) for several values of the unknown quantities: beta efficiencies and half-lives, for certain (known) rates of implantation and beta-decay events.

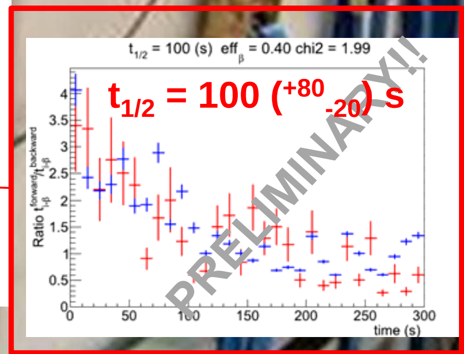
Ref. Value from G.Benzoni et al. PLB 715 (2012) $\mathbf{t_{1/2} = 96\ (^{+42}_{-38})\ s}$









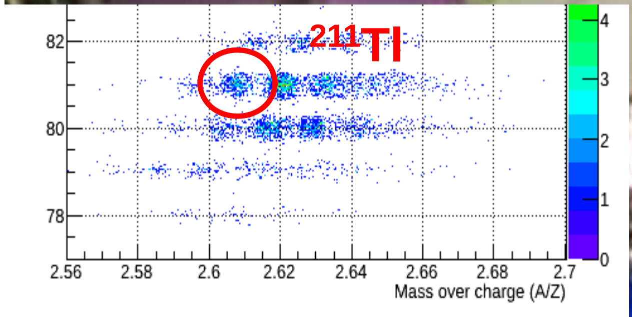


RED: experimental ratios forward-backward

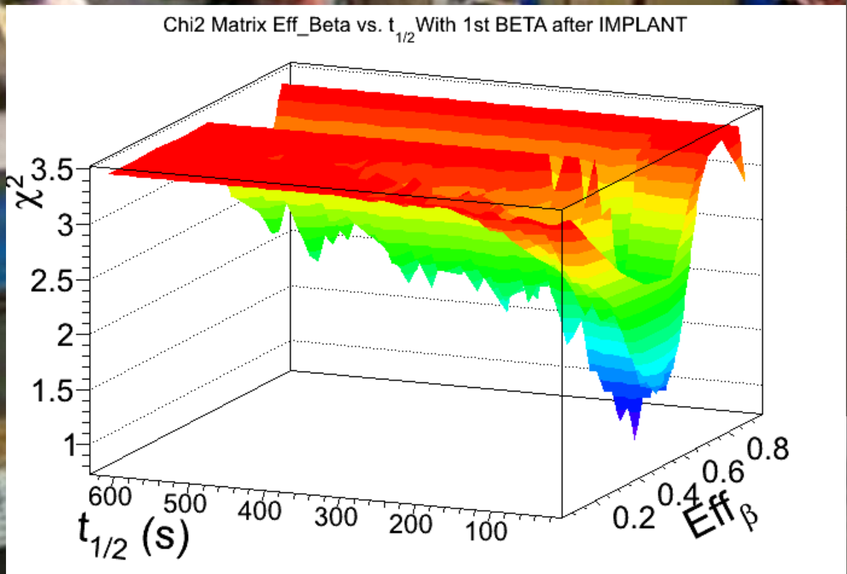
BLUE: simulated ratios for different half lives and silicon efficiencies

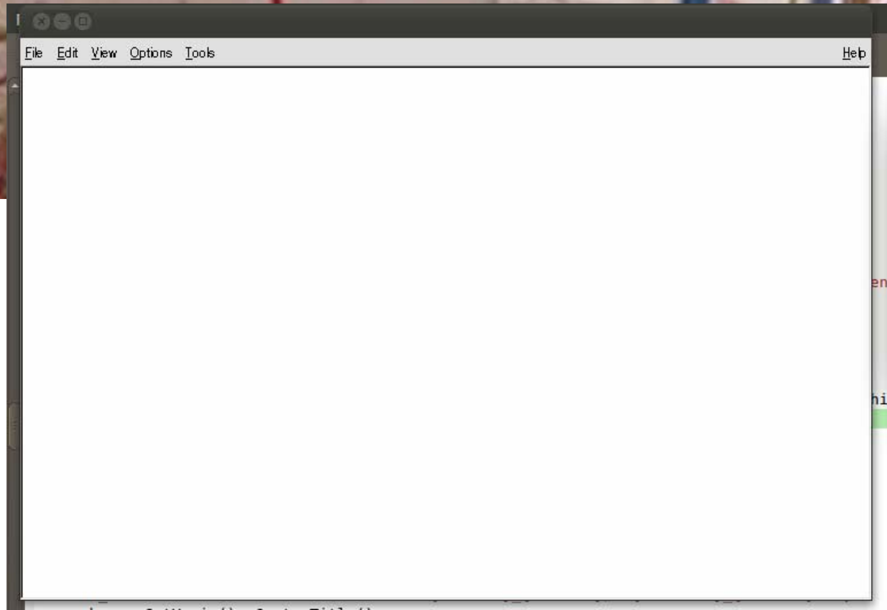
Experiment with BELEN @ RIB of GSI, N>126

Analysis method to determine half lives: ^{211}Tl



Ref. Value from G.Benzoni et al. PLB 715 (2012) $t_{1/2} = 88\ (^{+46}_{-29})$ s

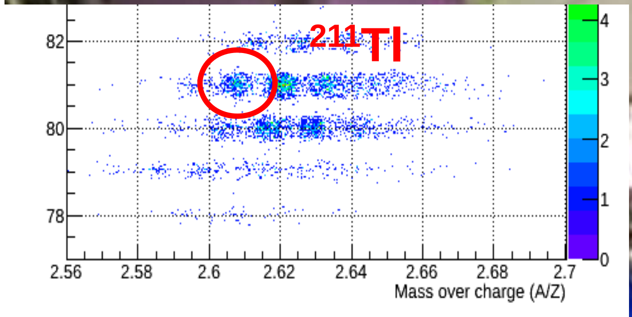




RED: experimental ratios
BLUE: simulated ratios

Experiment with BELEN @ RIB of GSI, N>126

Analysis method to determine half lives: ^{211}Tl



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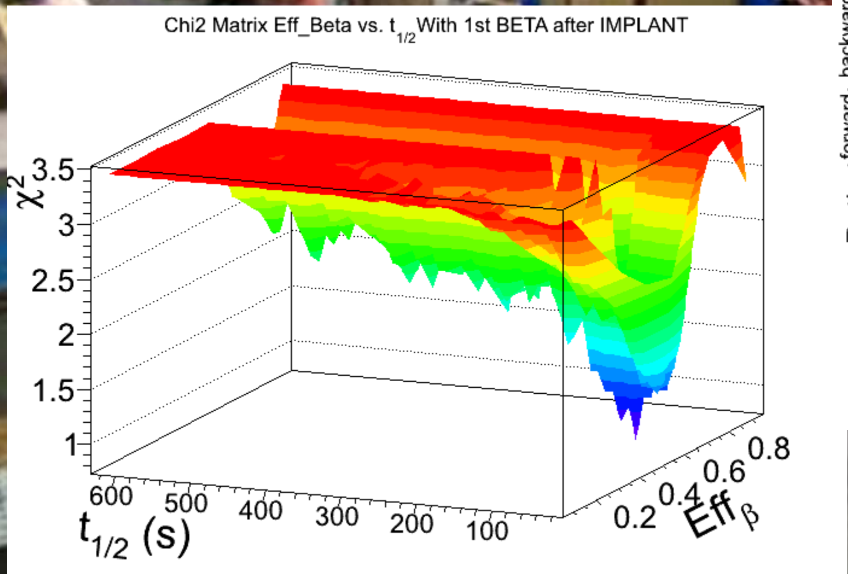

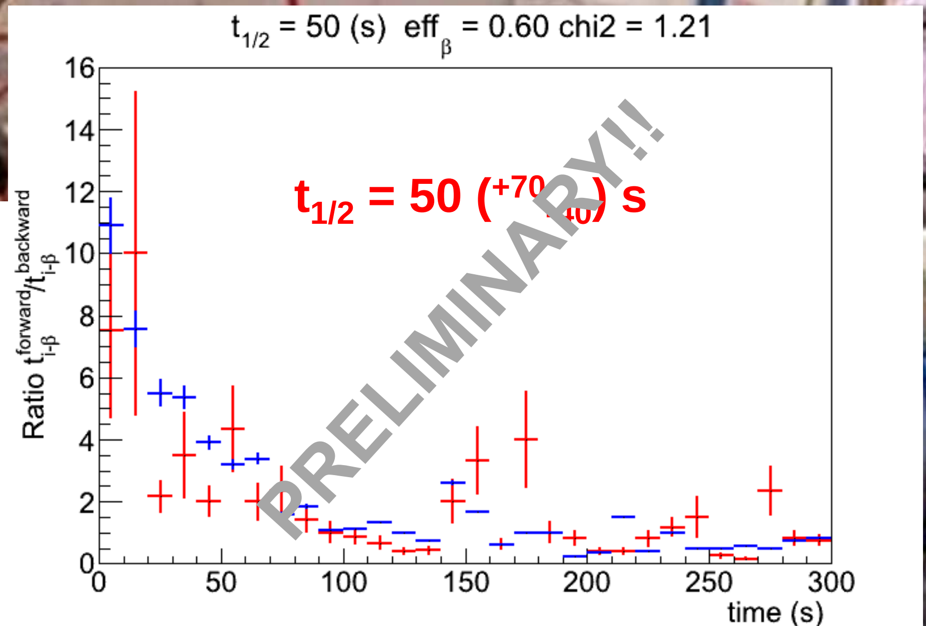

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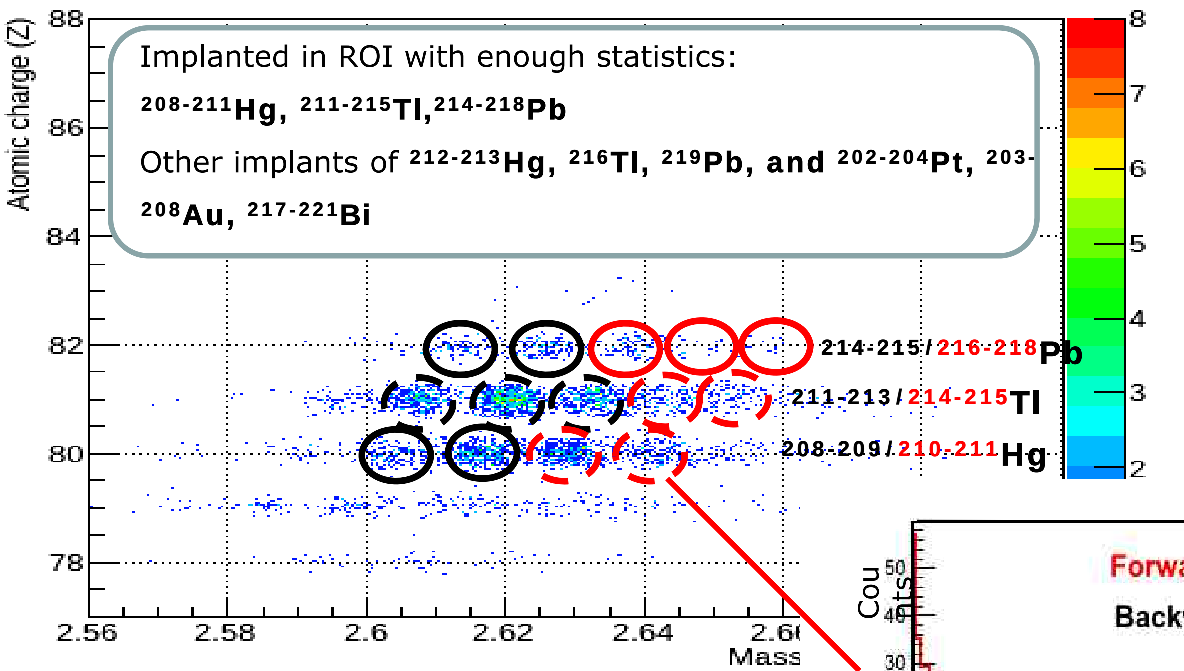
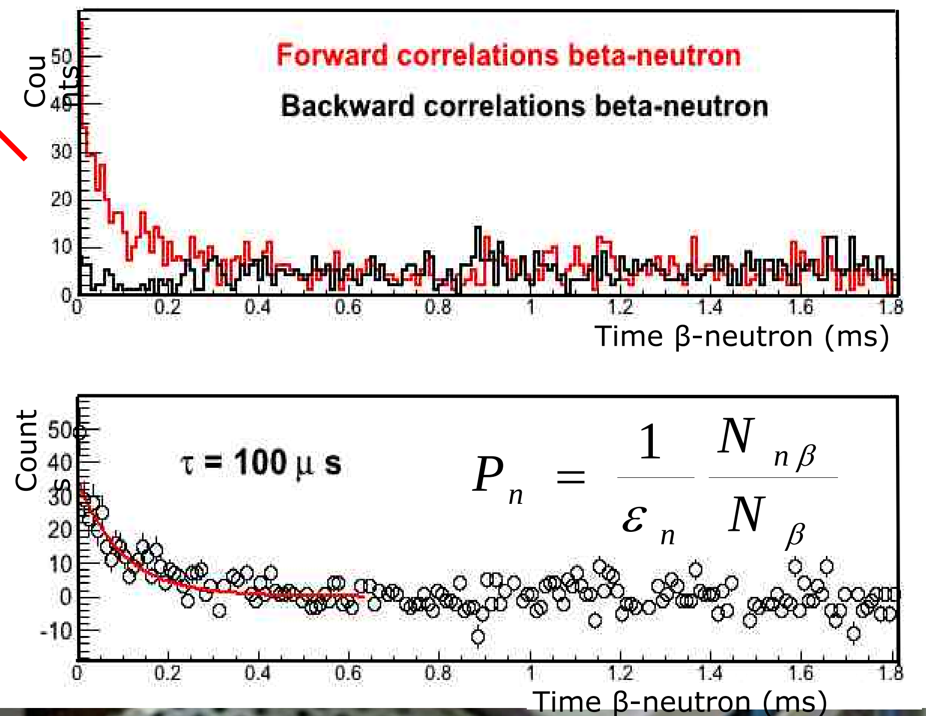
Experiment with BELEN @ RIB of GSI, N>126

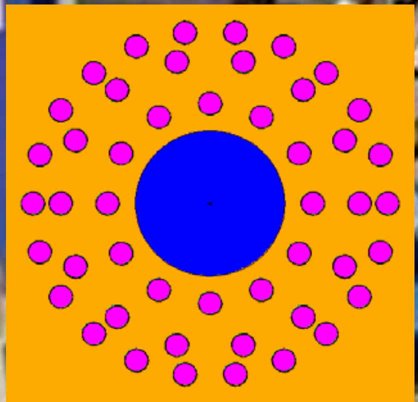


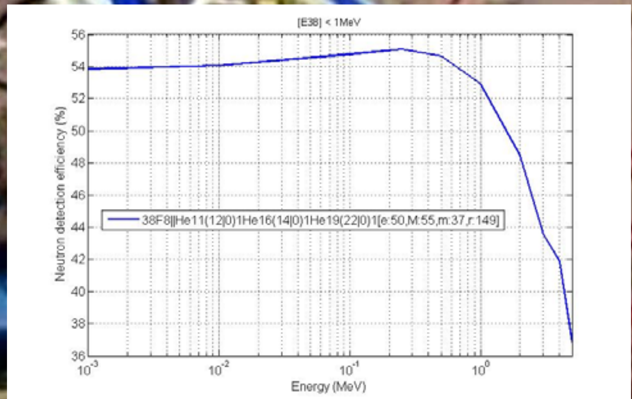
Analysis is in progress, part of the PhD Thesis of R. Caballero-Folch. (UPC-BCN)



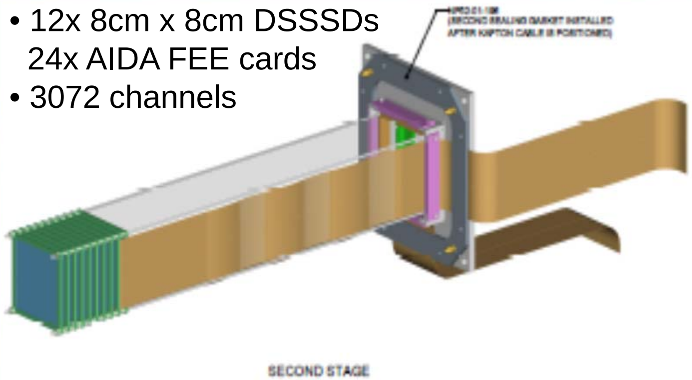
Future Plans, BRIKEN Campaign: BELEN @ RIKEN

- Until FAIR becomes operational (2017-2018), we plan to keep measuring with BELEN at GSI-FRS, at JYFL, and at RIKEN.
- A 1st Workshop on Opportunities with BELEN at RIKEN (BRIKEN) was made in Valencia (Spain), on 17-18/XII/2012.
- The plan is to combine BELEN with the Advanced Implantation Detector Array (AIDA) developed by Edinburgh – Liverpool – STFC DL & RAL.





- 12x 8cm x 8cm DSSSDs
  24x AIDA FEE cards
- 3072 channels



- Already many interesting physics cases discussed at the 1st BRIKEN workshop:
  - Combined measurement of masses, half-lives and neutron branchings (Univ. of Edinburgh, UK)
  - Measurement of multiple neutron emitters around N=50 and N=82 (GSI, Germany)
  - Neutron emission by fission fragments for improved ν_d calculations for reactor technologies and safety (CIEMAT, Spain).
  - Nuclear astrophysics: understanding the origin of the REP (A=135) (IFIC, Spain)
  - Nuclear astrophysics: [illegible] for the 2nd r-process abundance peak (NSCL-MSU, USA).
- Many more proposals are co[illegible] for the BRIKEN campaign… and more new ideas are welcome!