

# Beta decay of very neutron-rich nuclei: delayed neutron emission probabilities

Jose L. Tain ([tain@ific.uv.es](mailto:tain@ific.uv.es))

*Instituto de Fisica Corpuscular (Valencia)*

- $\beta$ -delayed neutron emission
- Importance of  $P_n$  values: nuclear structure, nuclear astrophysics, reactor technology
- Measurement of  $P_n$  values with BELEN
- Future measurements: BRIKEN

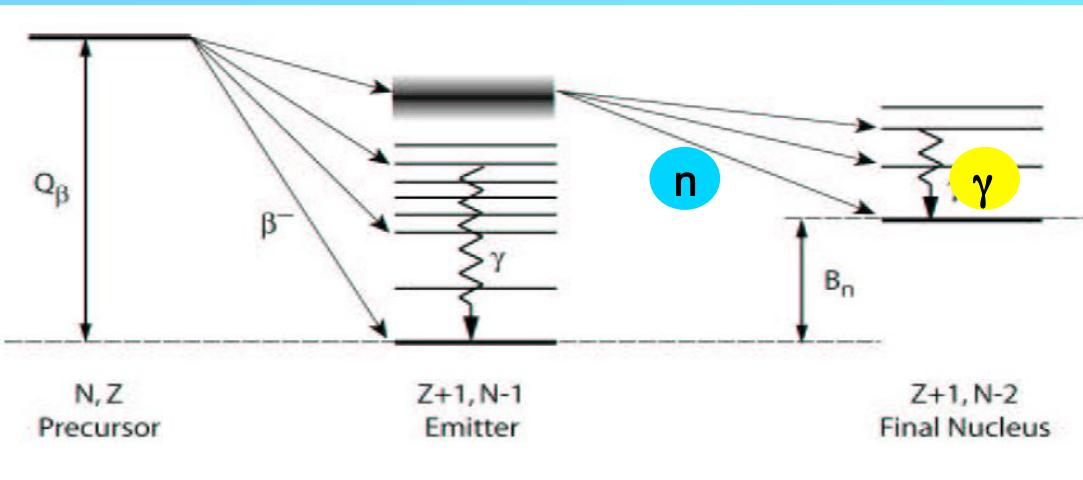


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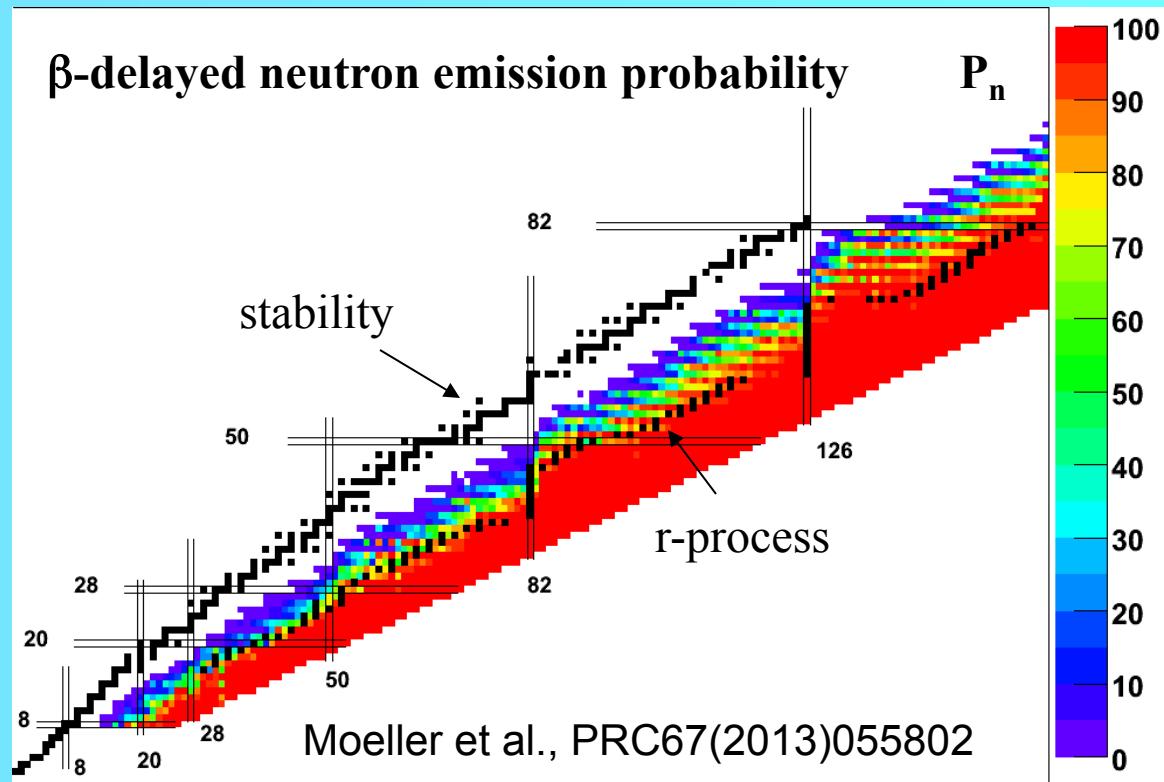


Collective mode studies with  $\beta$ -decay  
Nantes, February 19-20, 2015

# Beta decay of neutron rich nuclei



- For enough neutron rich nuclei  $S_n$  lies below  $Q_\beta$
- If the decay proceeds to states above  $S_n$ , neutron emission dominates over  $\gamma$ -ray de-excitation



# Relation between beta strength and $T_{1/2}$ and $P_n$ values

$$S_\beta(E_x) = \frac{1}{D} \frac{4\pi}{g_V^2} B_{i \rightarrow f}$$

$$B_{i \rightarrow f} = \frac{1}{2J_i + 1} \left| \left\langle f \left| M_{\lambda\pi}^\beta \right| i \right\rangle \right|^2$$

$\lambda\pi=0+$  : Fermi

$\lambda\pi=1+$  : Gamow-Teller

$\lambda\pi=0-, 1-$  : Non-unique first forbidden

$\lambda\pi=2-$  : Unique first forbidden

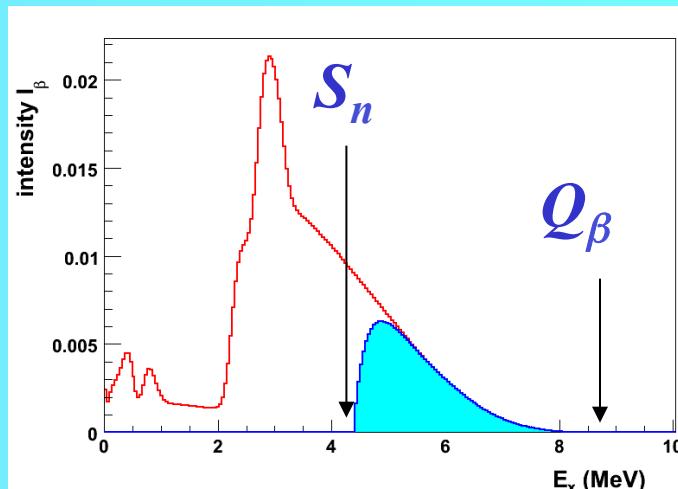
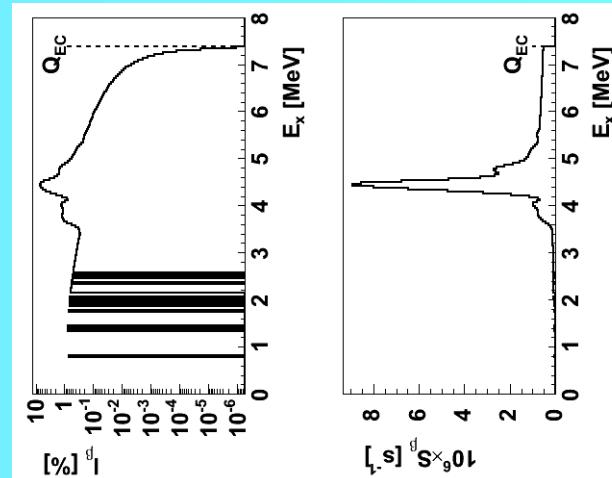
...

$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) dE_x$$

$$P_n = \frac{\int_{S_n}^{Q_\beta} \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} S_\beta(E_x) \cdot f(Q_\beta - E_x) dE_x}{\int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) dE_x}$$

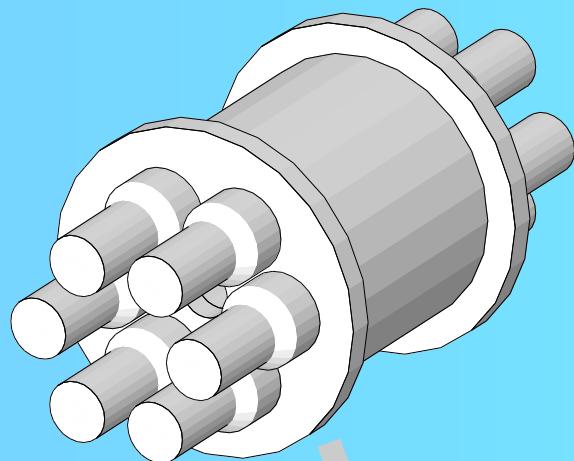
$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x) \cdot T_{1/2}}$$

INTENSITY      STRENGTH

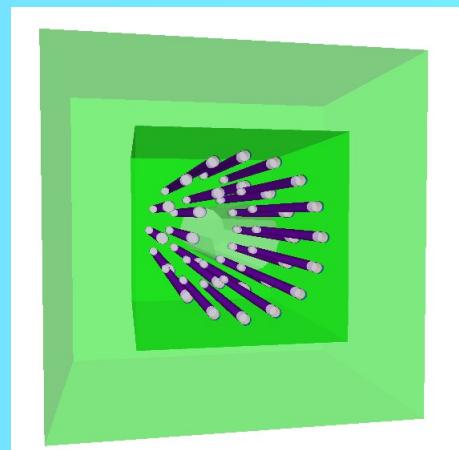


In order to characterize the complete  $\beta$ -strength distribution we are aiming to combine (whenever is feasible) measurements with:

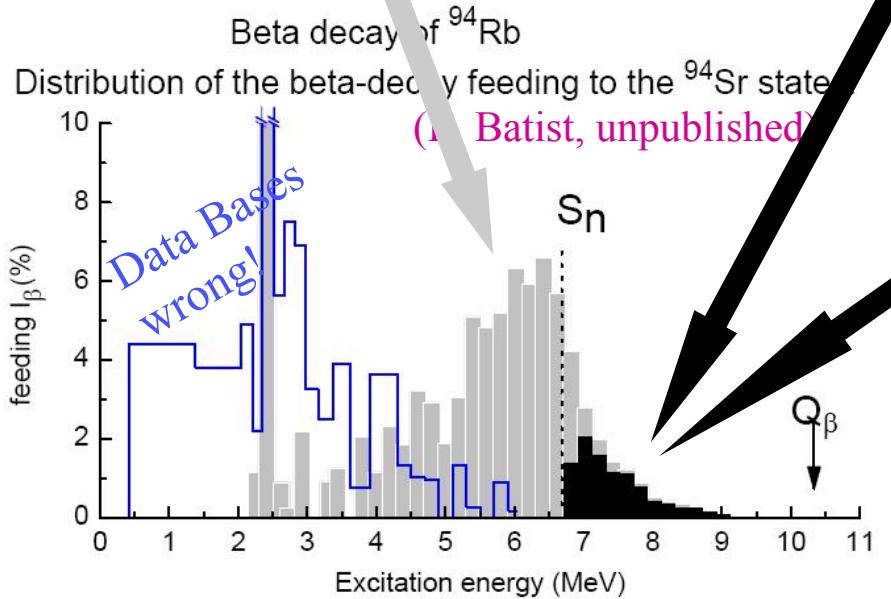
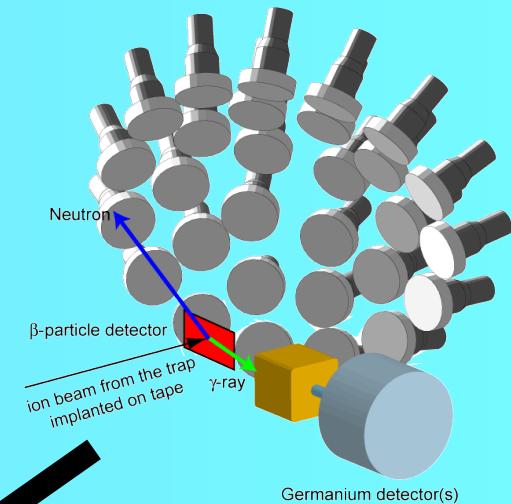
**Total Absorption  $\gamma$ -Ray Spectrometer**



**$4\pi$  Neutron Counter**



**Neutron Time of Flight Spectrometer**



- TAGS provides data free of “Pandemonium” systematic error
- $4\pi$  n-Counter provides  $P_n$
- n-ToF Array provides the  $E_n$  distribution

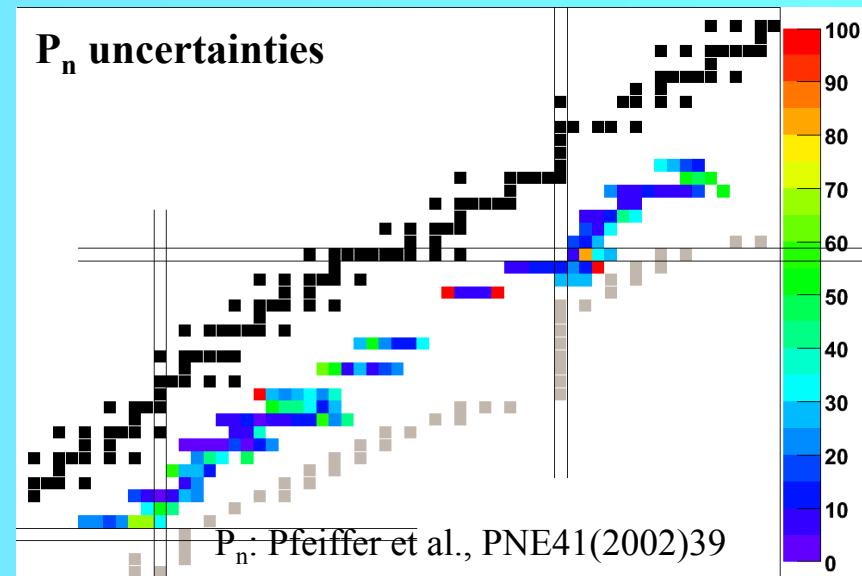
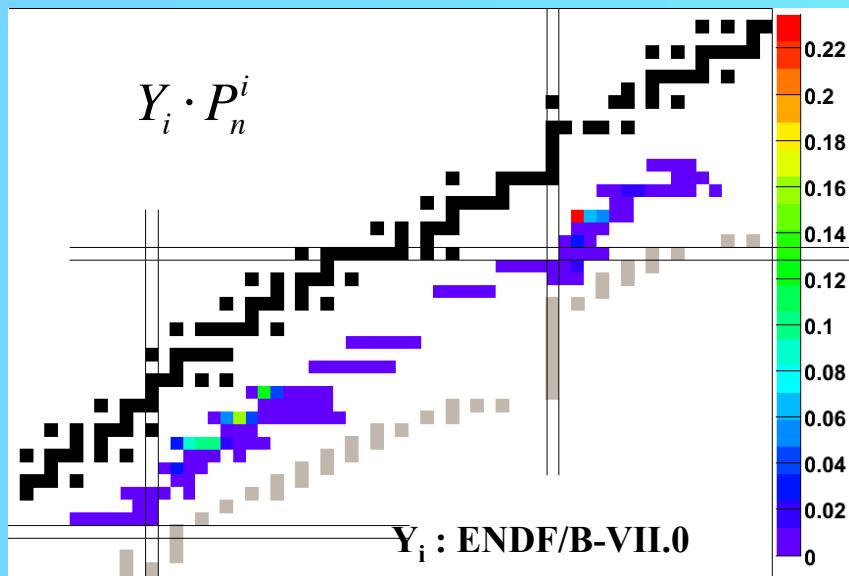
# Motivation: microscopic summation calculations of $\bar{v}_d$

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

Number of delayed neutrons per fission

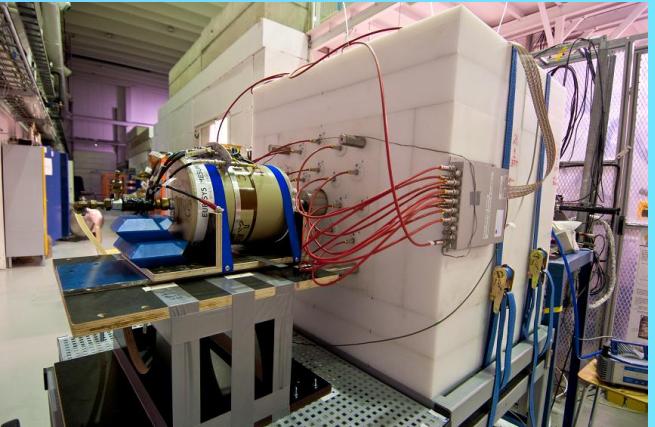
$$\bar{v}_d = \sum_i Y_i \cdot P_n^i$$

Can be used to identify  $P_n$  values that should be revisited



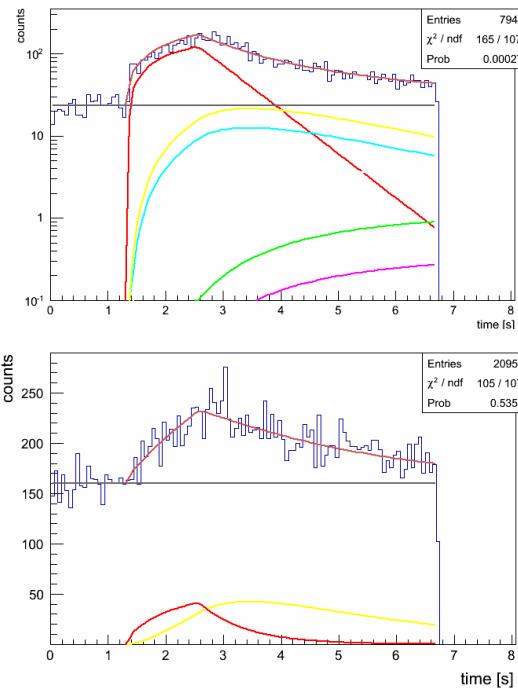
# Experiment (June-2010):

## BELEN-20 @JFLTRAP/IGISOL:

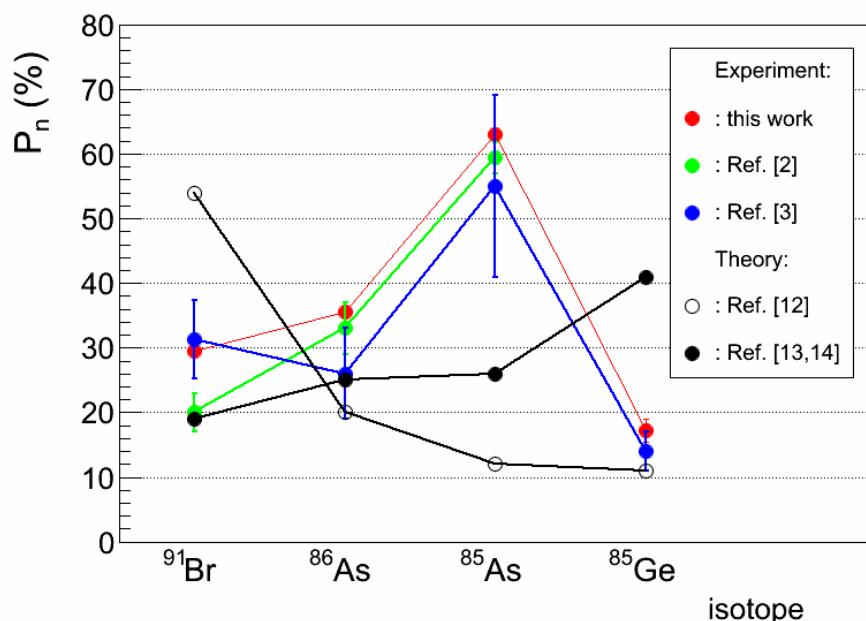
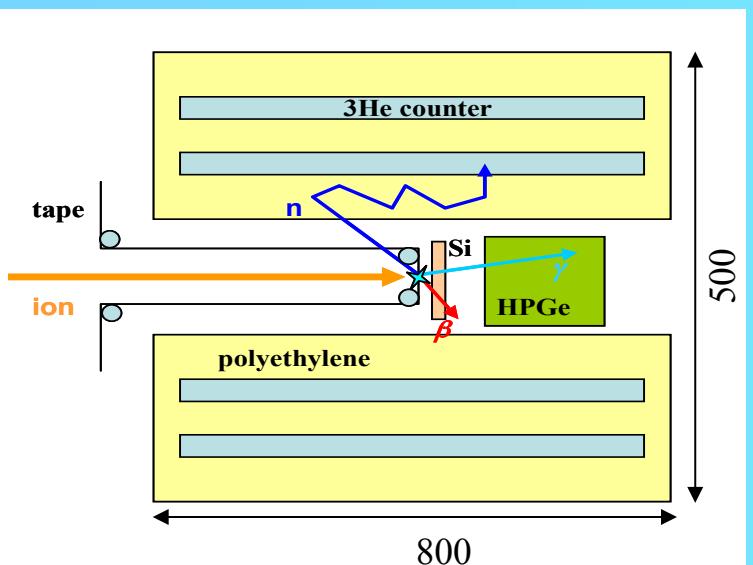


# Analysis:

**85Ge**

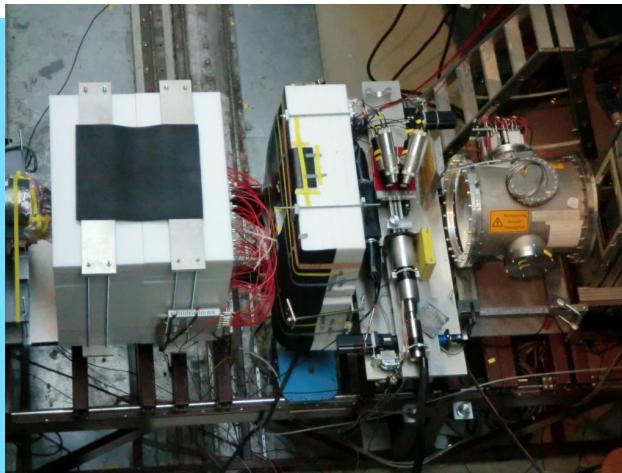
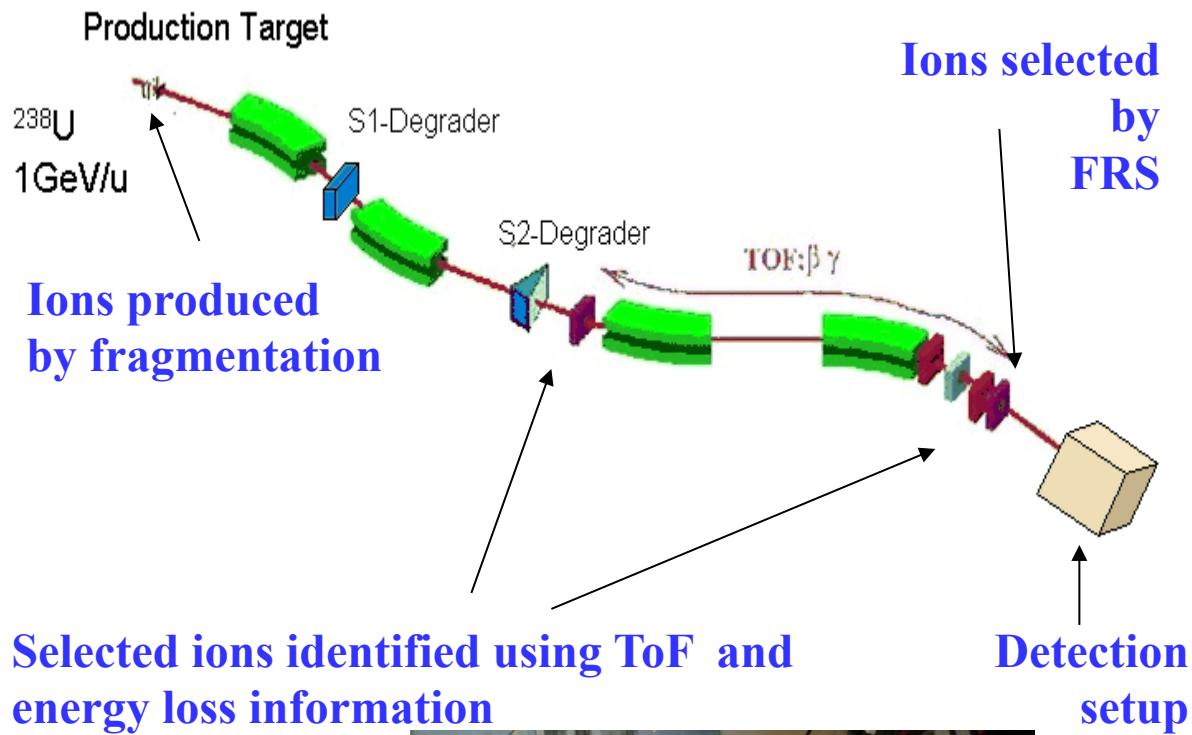


# Results:

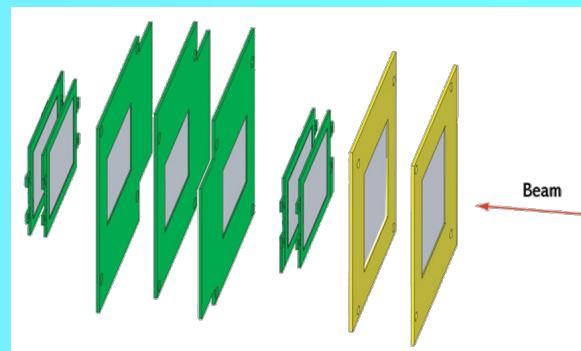


# Experiment (August-2011):

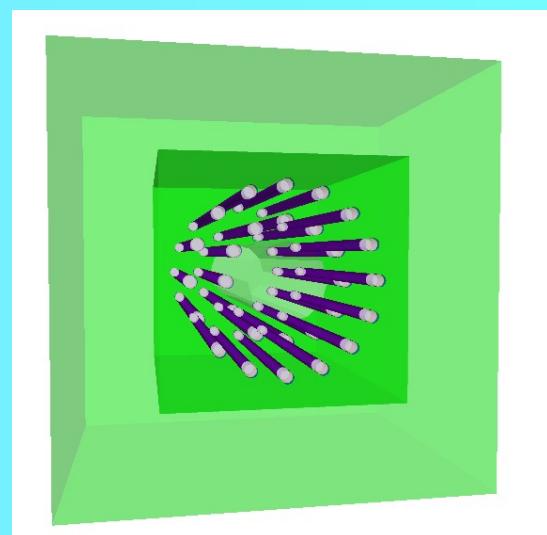
**BELEN-30 @FRS-GSI:**

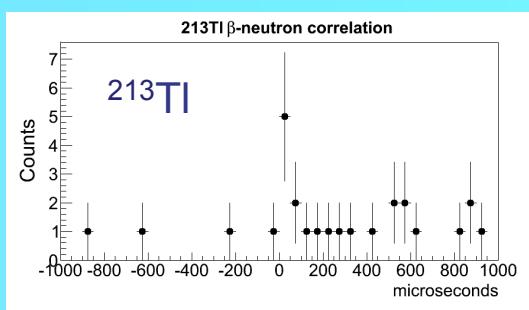
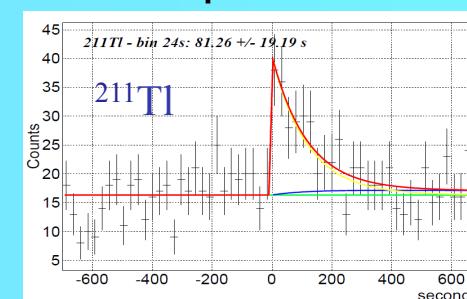
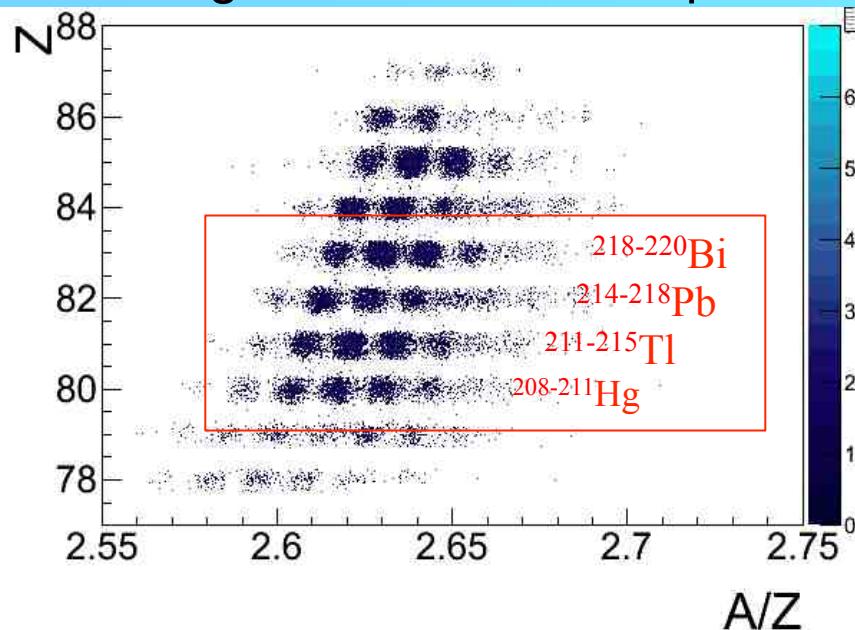
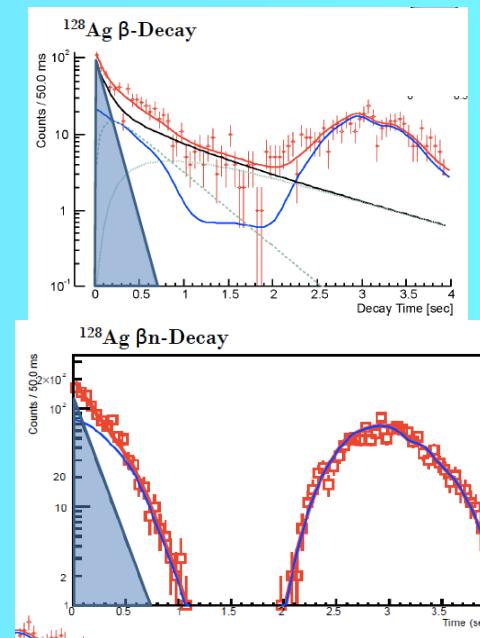
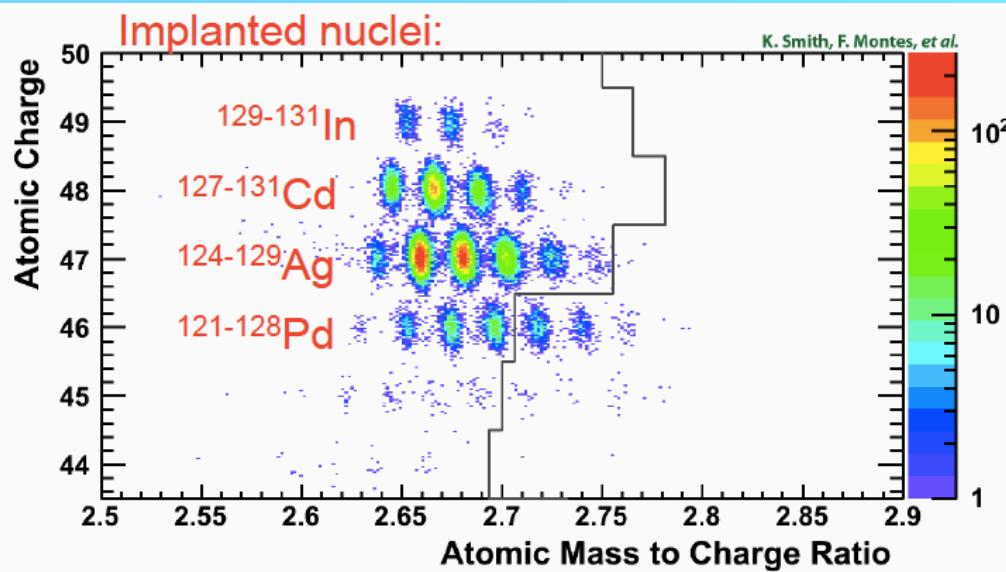


Ions implanted and their  $\beta$ -decay measured in a stack of DSSDs: SIMBA(TUM)



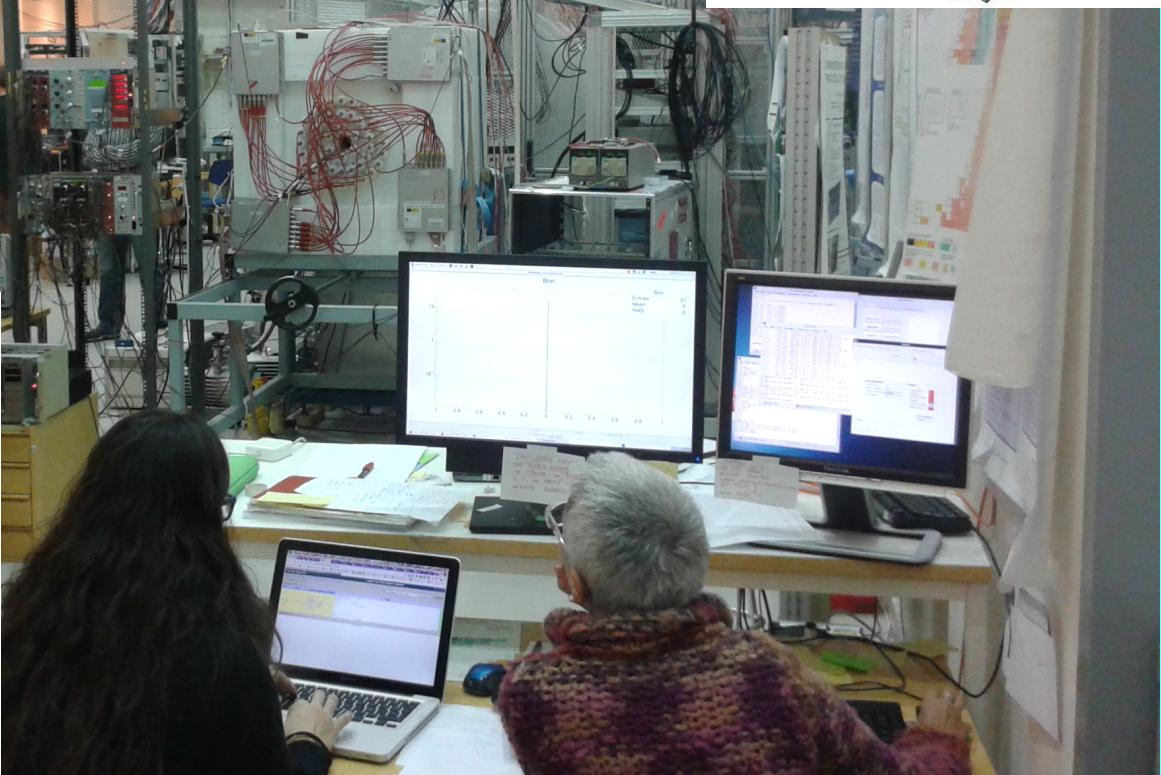
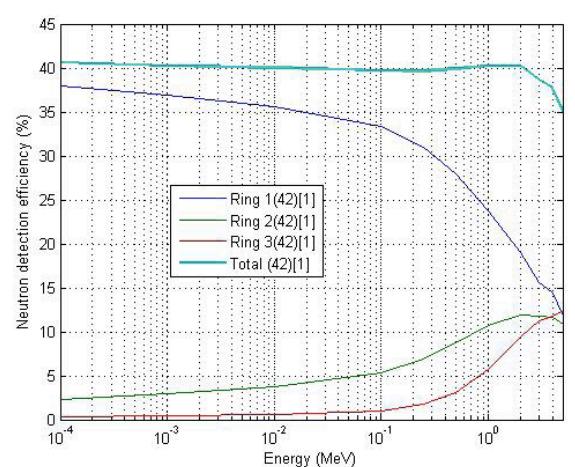
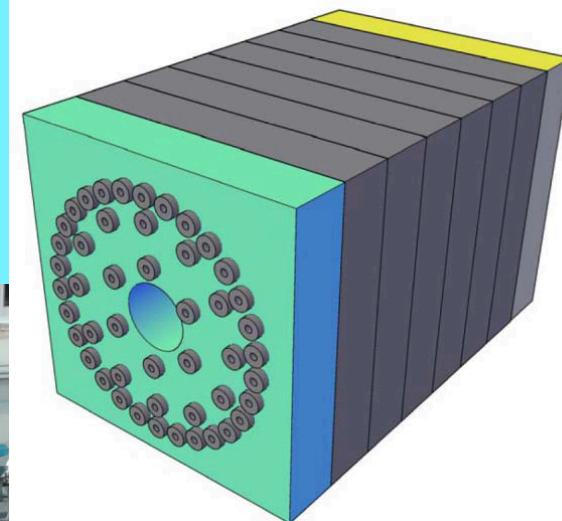
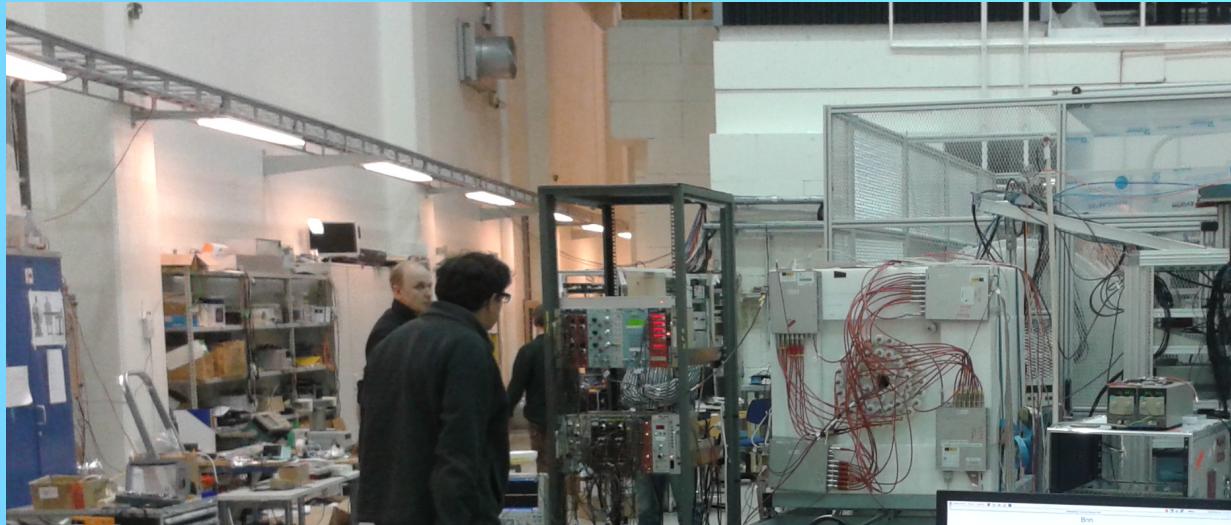
Neutrons detected with BELEN-30





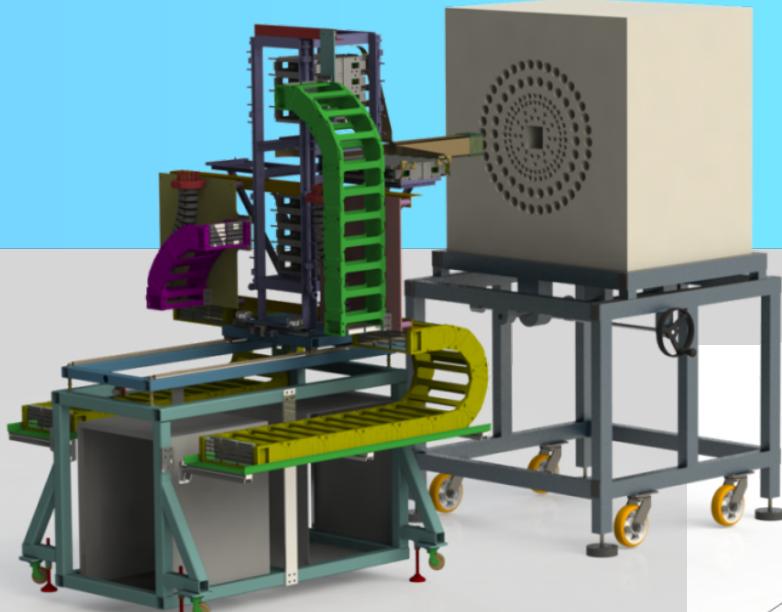
Very difficult measurements but we obtain  $P_n$  values for a handful of isotopes

# Latest measurements (Nov. 2014): BELEN-48 @JFLTRAP/IGISOL-IV:



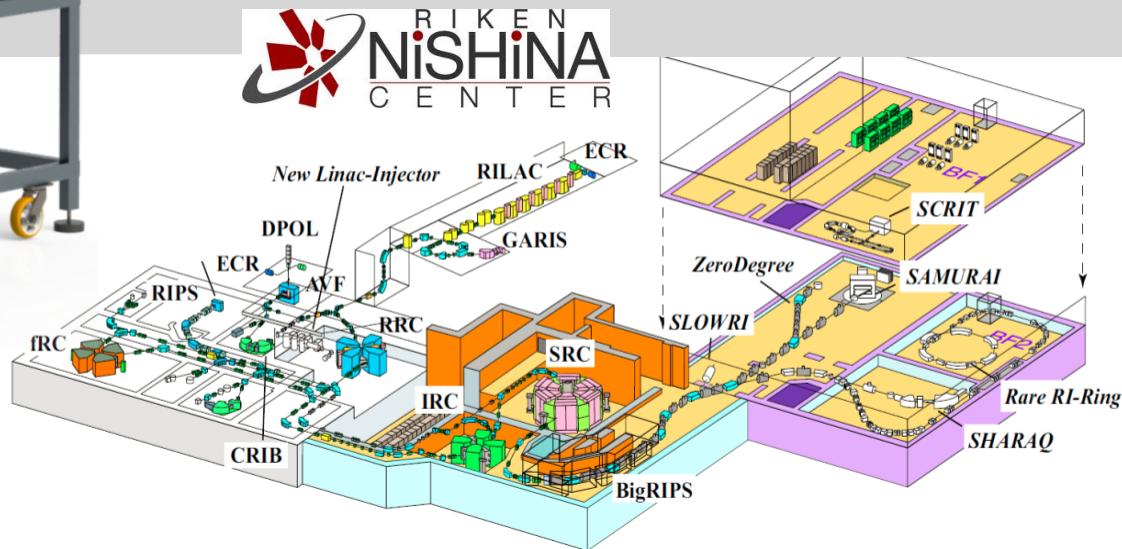
Isotopes: **98,98mY, 99Y, 138Te, 138,139,140I, 135,137Sb**

# The BRIKEN Project

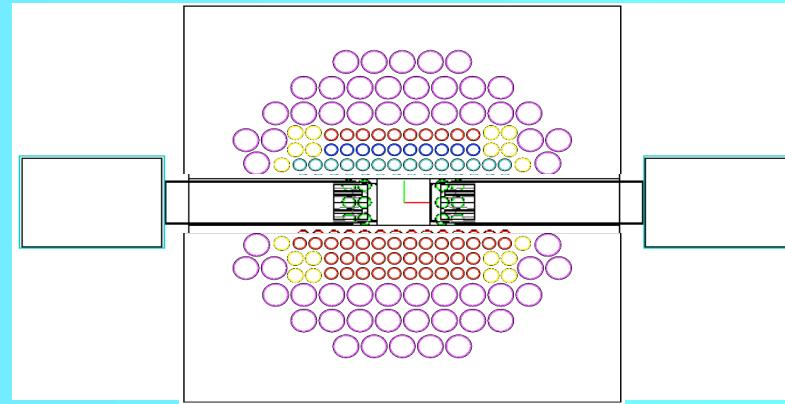
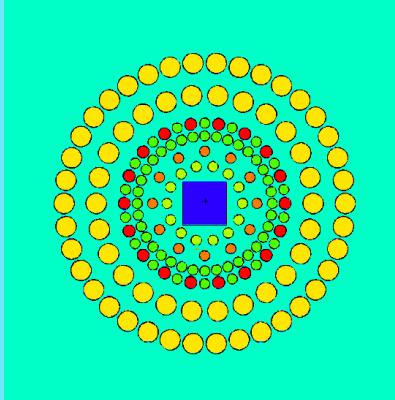


- 20 institutions
- 50 participants

- The largest moderated neutron detector
- The AIDA implantation detector
- BigRIPS spectrometer

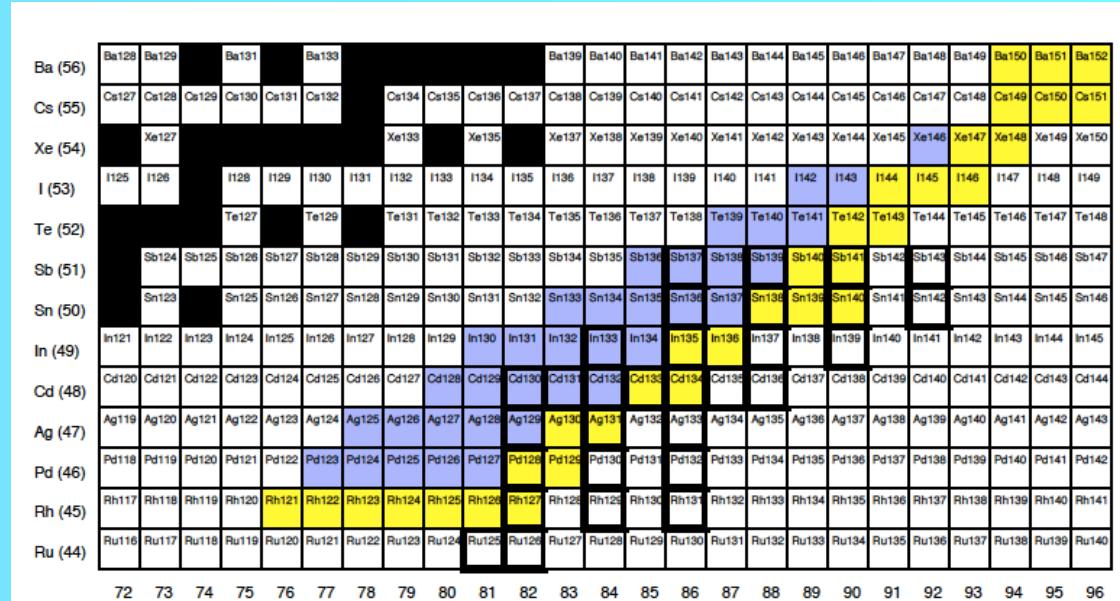


- About 172  $^3\text{He}$  tubes (ORNL, UPC, GSI, JINR, RIKEN) + triggerless DACQ (IFIC)



- A. Estrade, G. Lorusso, F. Montes: “Measurement of beta-delayed neutron emission probabilities relevant to the  $A = 130$  r-process abundance peak”
- K. P. Rykaczewski, J. L. Tain, R. K. Grzywacz, I. Dillmann : “Measurements of new beta-delayed neutron emission properties around doubly-magic  $^{78}\text{Ni}$ ”

Se					2.7%	0.83%	3.8%	3.2%	10%	0%
As			12% 0%	20% 0%	37% 0%	32% 2.2%	76% 1.3%	28% 2.6%	89% 3.2%	45% 39%
Ge			10% 0%	11% 0%	24% 0%	31% 4.6%	49% 0.5%	9.9% 1.2%	74% 3.1%	43% 19%
Ga	5% 0%	9% 0%	59% 0%	27% 15%	61% 10%	21% 44%	69% 13%	35% 41%	70% 19%	20% 47%
Zn	6% 0%	13% 0%	45% 0%	29% 21%	49% 13%	28% 9%	64% 5%	46% 27%		
Cu	11% 0%	25% 0%	44% 13%	62% 21%	29% 57%	46% 31%	13% 64%	24% 43%		
Ni Z=28	25% 0%	39% 0%	62% 5%	64% 14%	20% 57%	37% 22%				
Co	26% 6%	69% 7%	41% 25%	67% 16%	1% 73%					
	<b>N=50</b>									
	52	54	56	58						



## Conclusions:

- Measurements of  $P_n$  values can give information (otherwise inaccessible) on  $\beta$ -strength distribution on exotic n-rich nuclei close to the end of the decay energy window
- The BELEN detector has been used successfully to improve our knowledge on  $P_n$  values of fission products and also on  $A=200$  nuclei
- Extension of this type of measurements to new facilities are ongoing

**THANK YOU!**