Beta delayed neutrons: physics and detection

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1932

Wine: ???

Physics:

Anderson: positron discovery

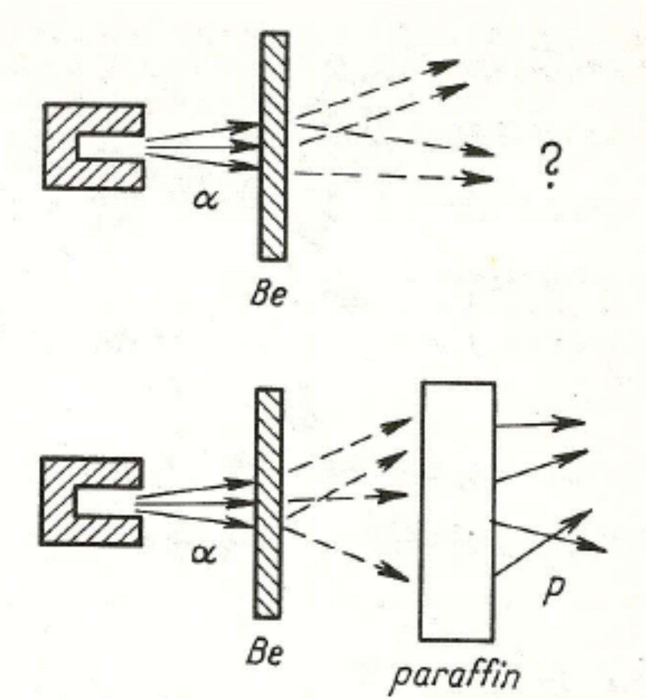
Cockroft and Walton: first reaction with accelerated particles

Chadwick: discovery of the neutron

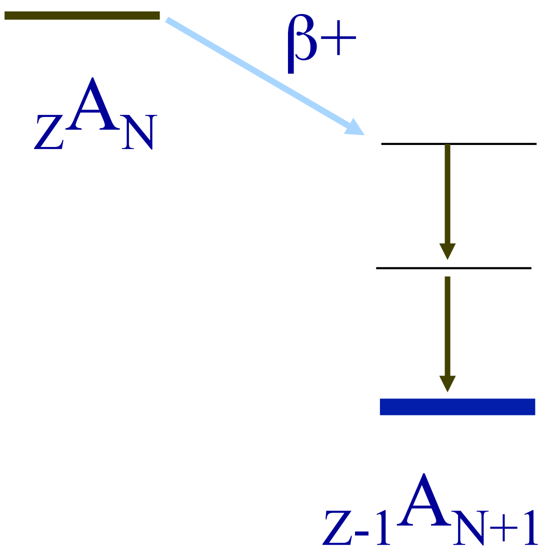
Fermi: first steps in the theory of beta decay

(based on Bothe-Geiger, Joliot-Curie, and his own measurements, it was already predicted by Rutherford in 1920)

Marks the beginning of proton-neutron nuclear model



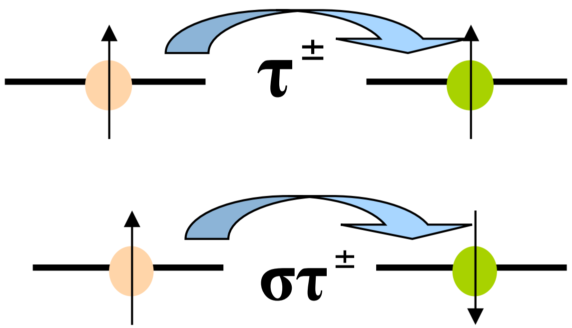
Basic relations and theory of β-decay



$_ZA_N \rightarrow {}_{Z+1}A_{N-1} + e^- + \nu$ for β-

$_ZA_N \rightarrow {}_{Z-1}A_{N+1} + e^+ + \nu$ for β+

$_ZA_N + e^- \rightarrow {}_{Z-1}A_{N+1} + \nu + x_{ray}$ EC



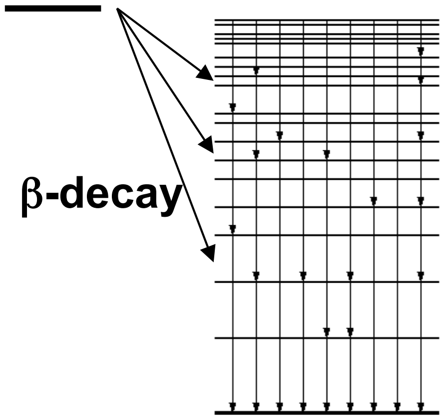
The process is governed by "simple" operators

Fermi / Gamow-Teller:

$$B_{i\rightarrow f} = \left| \left\langle \Psi_f \middle| \tau^{\pm} \ or\ \sigma\tau^{\pm} \middle| \Psi_i \right\rangle \right|^2$$

In principle a good description of ϕ_i and ϕ_f ➡ good B (strength)

Experimental side: feeding /strength distribution



Strength function

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

Beta feeding ($I_\beta(E)$)

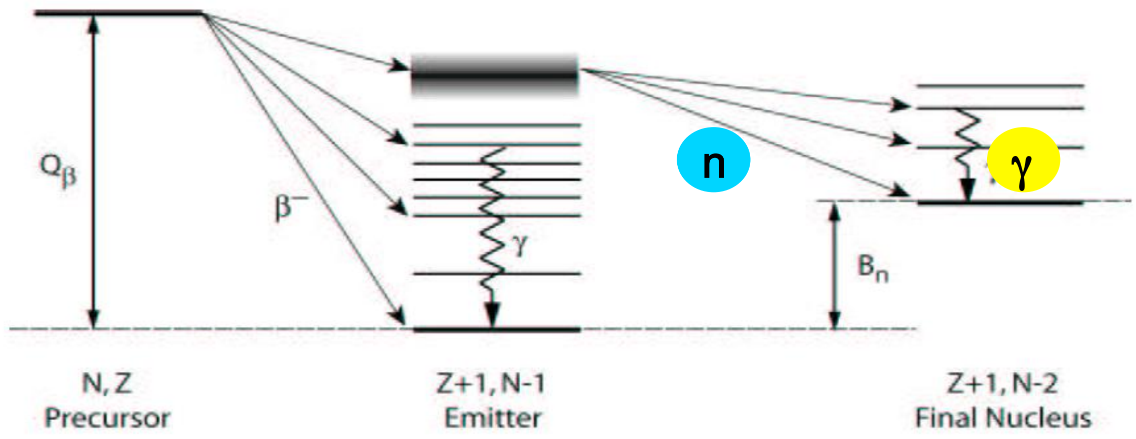
Fermi function ($f(Q_\beta - E)$)

Half life of parent ($T_{1/2}$)

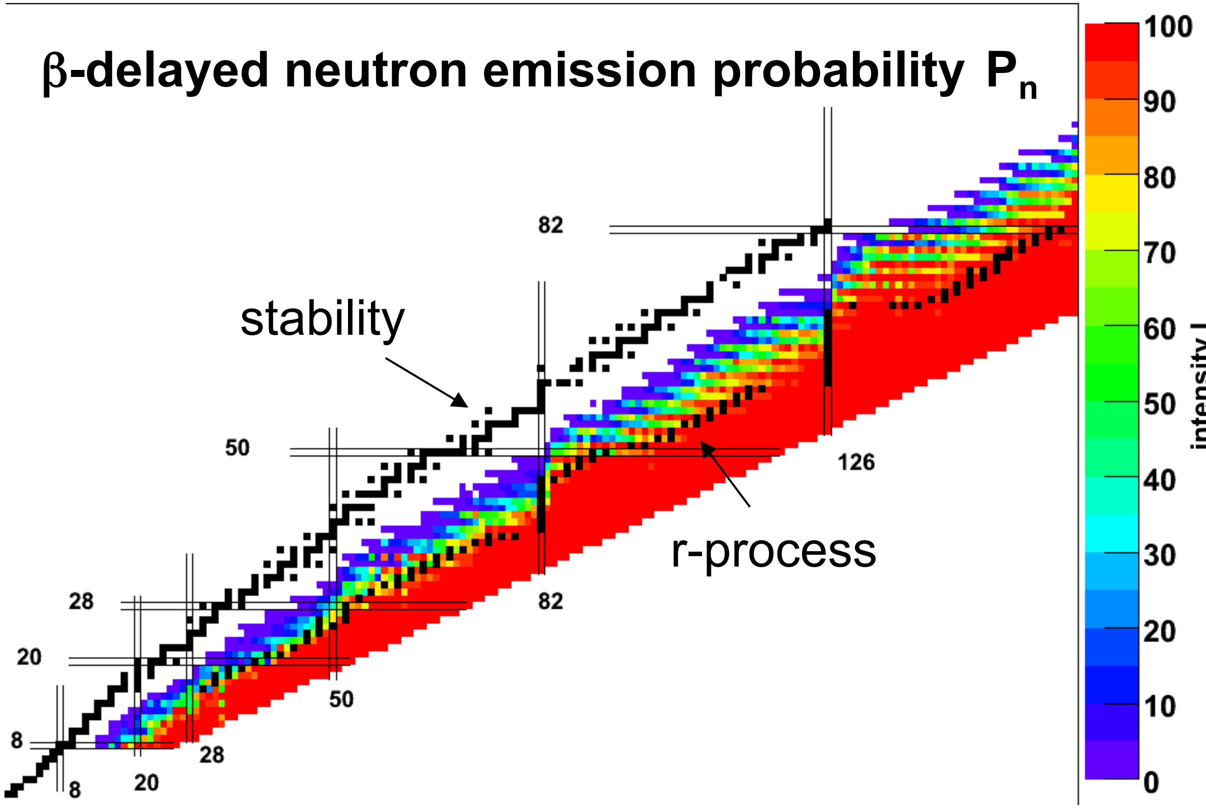
Relationship

$$S_\beta = \frac{1}{6147 \pm 7}\left(\frac{g_A}{g_V}\right)^2 \sum_{E_f \in \Delta E} \frac{1}{\Delta E} B_{i \to f}$$

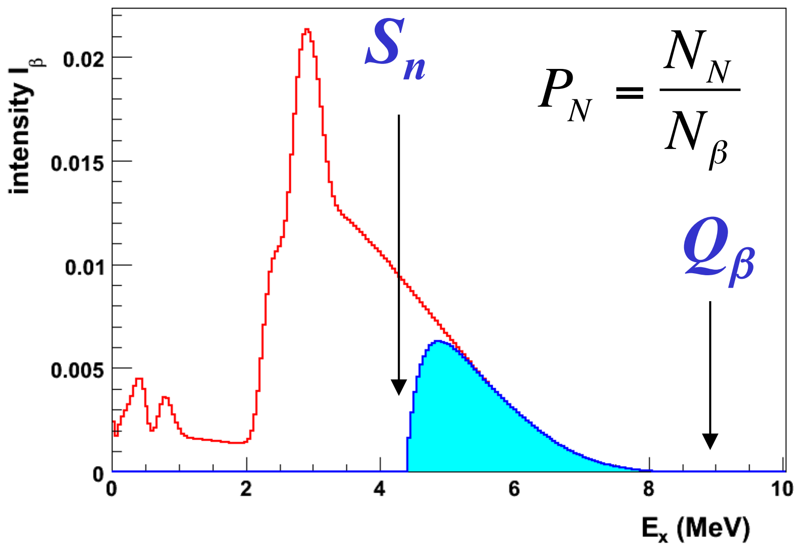
Beta decay in the neutron rich side



If $S_n < Q_\beta$ and the decay proceeds to states above S_n, neutron emission competes and can dominate over γ-ray de-excitation



The process will dominate far from stability on the n-rich side. To have a full picture of the strength …



Beta decay in the neutron rich side

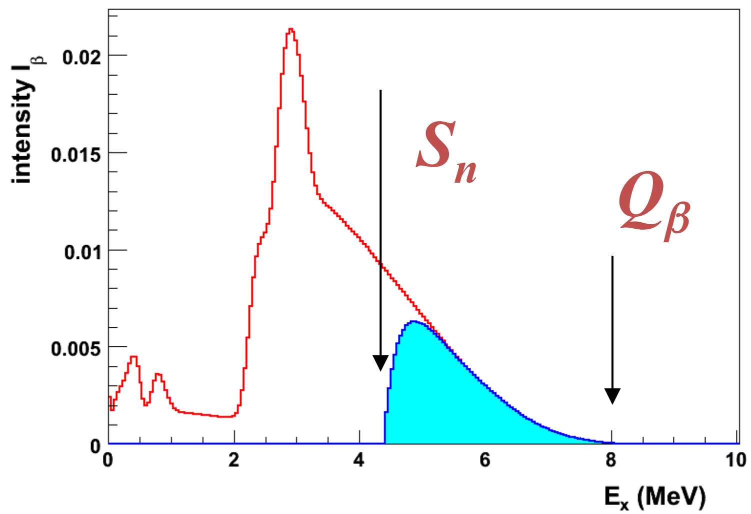
The (inverse of the) half-life $T_{1/2}$ is a weighted average of the β-strength S_β

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

The neutron emission probability P_n measures the fraction of β-strength above the neutron separation energy S_n

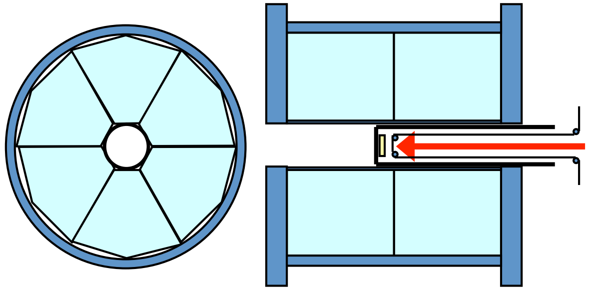
$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) \cdot \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} dE_x}{\int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) dE_x}$$

For n-rich nuclei very far from stability $T_{1/2}$ and P_n will provide (the only) access to nuclear structure information

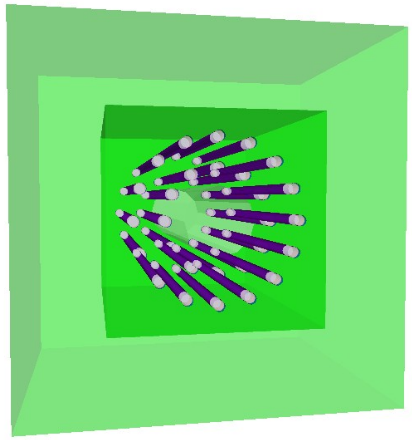


Beta strength measurements: combination of techniques

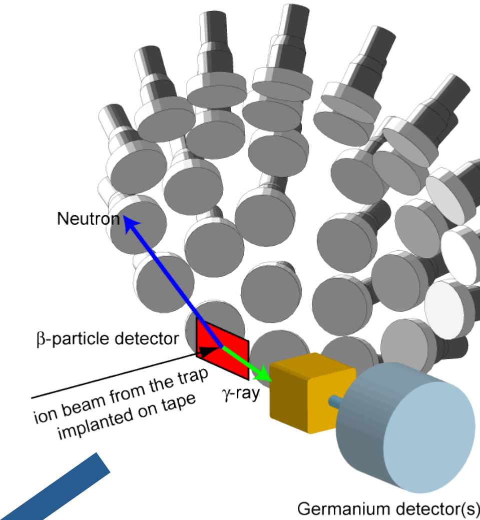
Total Absorption γ-Ray Spectrometer

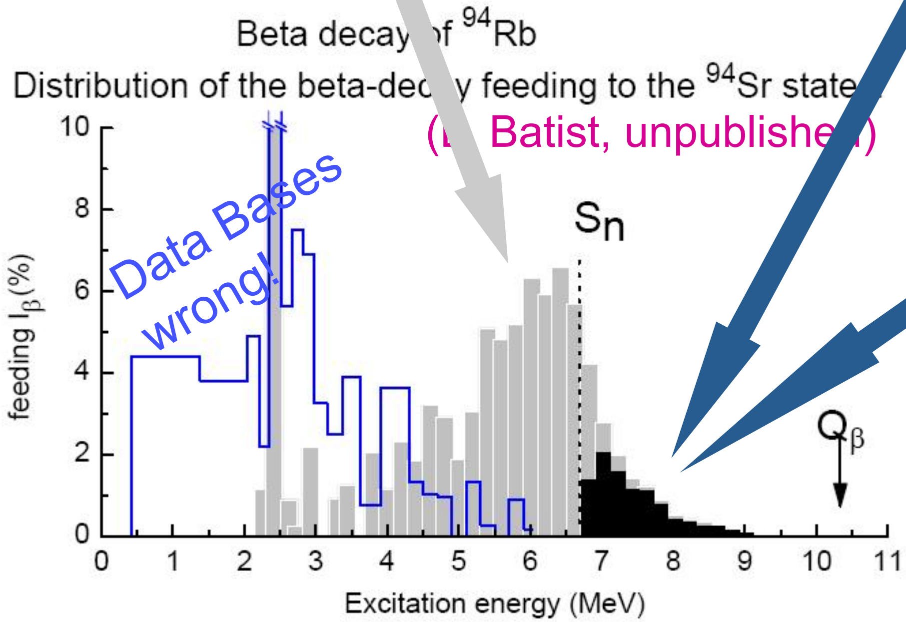


4π Neutron Counter



Neutron Time of Flight Spectrometer



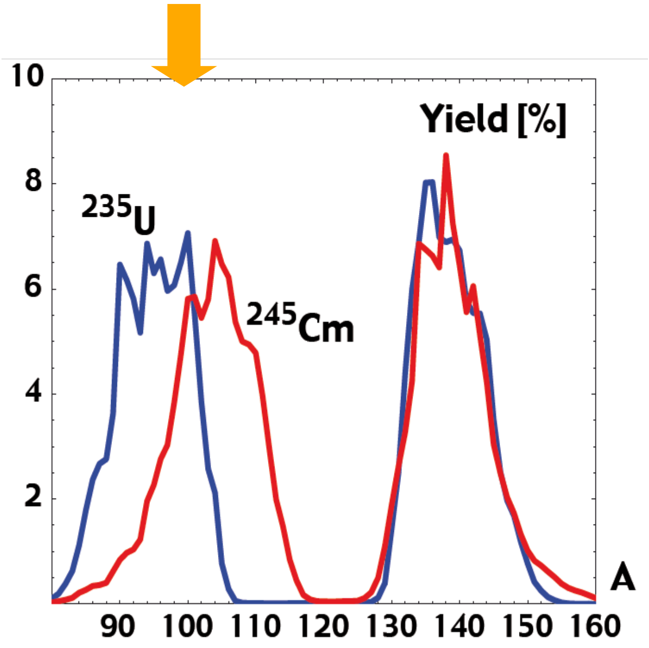


- **TAGS provides data free of "Pandemonium" systematic error**
- **4π n-Counter provides P_n**
- **n-ToF Array provides the E_n distribution**

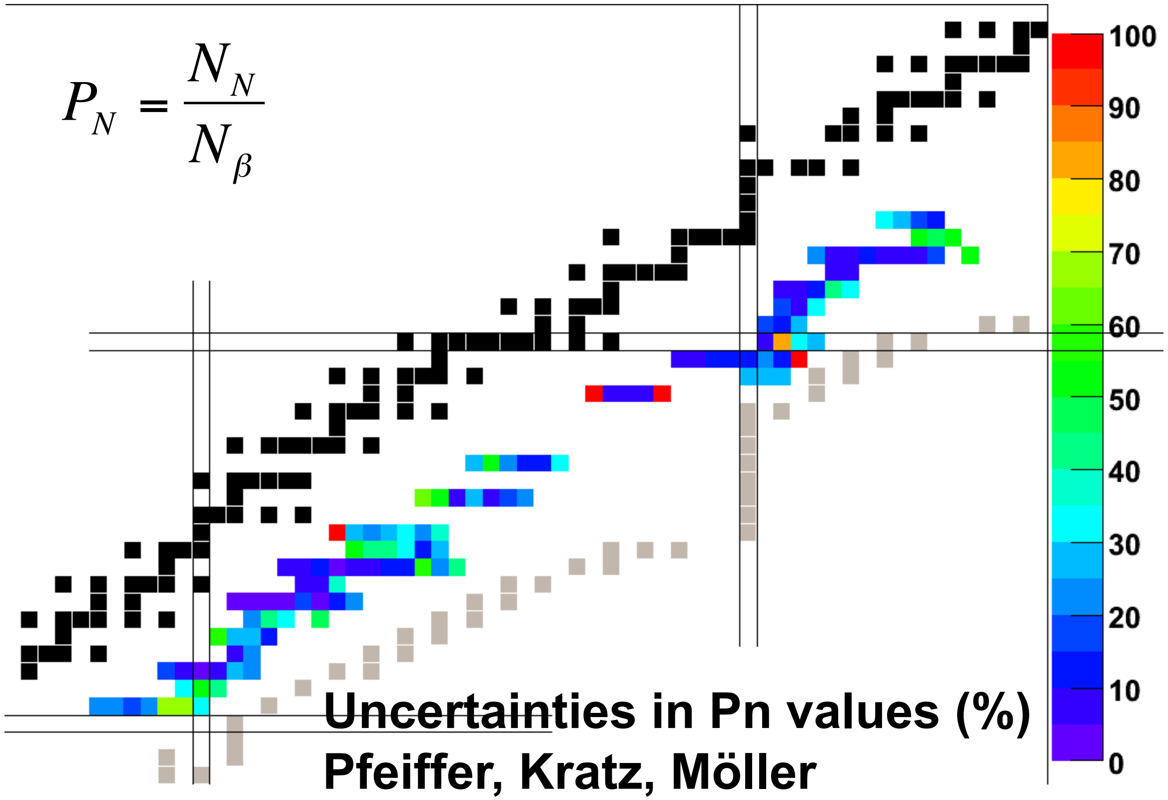
Pn measurements: nuclear structure + reactor technology

- **Beta decay can provide the first insight in nuclear structure of exotic nuclei. Testing ground for nuclear models (Terra Incognita)**
- **The neutron emission probability P_n determines the delayed neutron fraction β_{eff} : reactor kinetics. More accurate measurements will improve summation calculations for Gen IV reactors with MA containing fuel**

Fission Fragment distribution

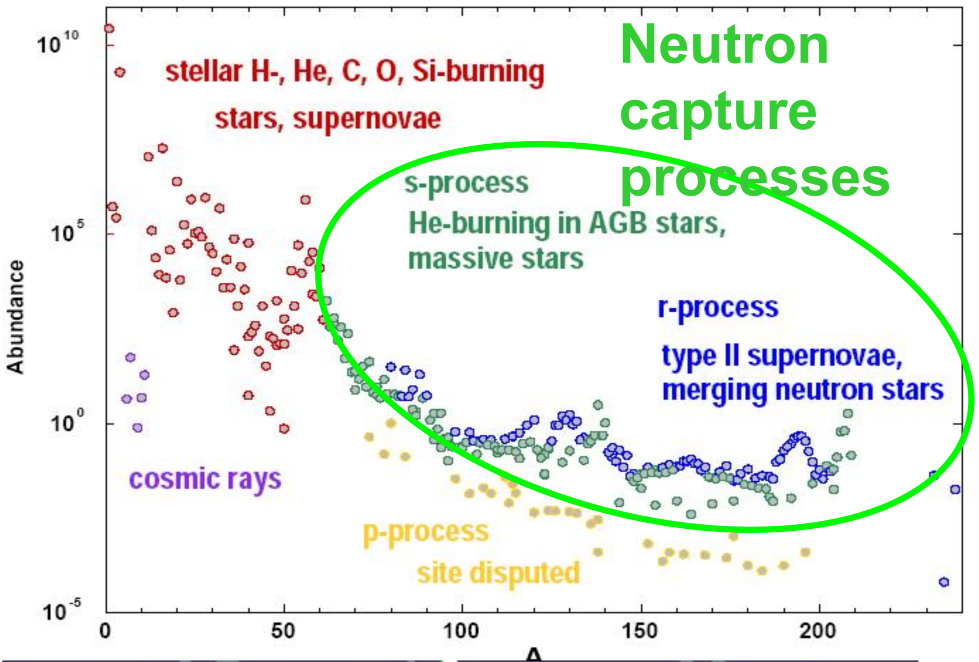


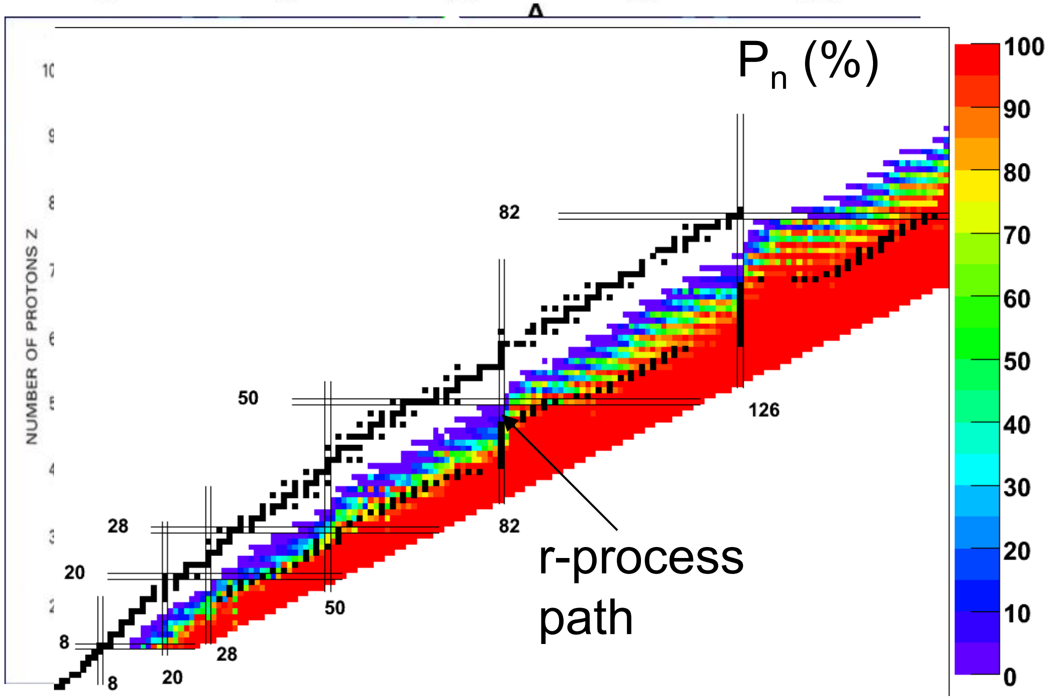
Courtesy of J.L.Tain



Uncertainties in Pn values (%)
Pfeiffer, Kratz, Möller

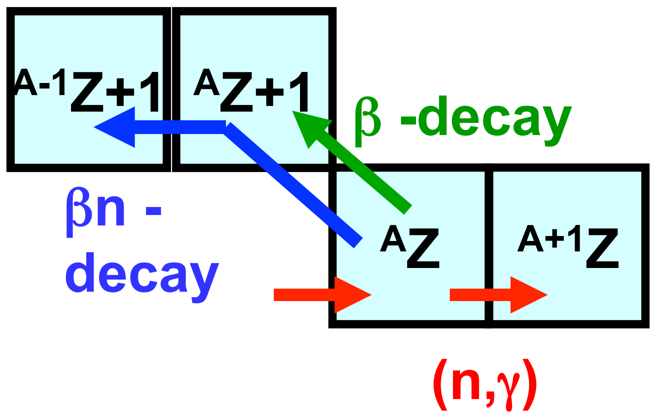
Astrophysics application: the r-process





Pn values play a key role in the understanding of the r-process

r-process: a short and very high neutron-flux produces very neutron rich nuclei in a short time, which then decay to stability. Key for the understanding of the abundance of elements



- The β-decay half-life determines the speed of the process and conforms the abundance distribution
- The delayed neutron emission probability shapes the abundance distribution

(Fernando, Rebecca talks)

Neutron detectors ultra-quick guide

Modest developments in the last 40 years compared to other detector systems

Gas detectors: mainly based on the $^{3}He(n,p)$, $^{10}B\ (n,a)$, $^{1}H(n,p)$ and (n,fission) reactions

Liquid organic scintillators: based on the $^{1}H(n,p)$ reaction. Still one of the preferred options for building large neutron spectrometers when pulse shape discrimination is required

Solid organic scintillators: based on the $^{1}H(n,p)$ and are one of the preferred options for building large neutron spectrometers when pulse shape discrimination is not required, (favourable neutron signal to γ-ray background)

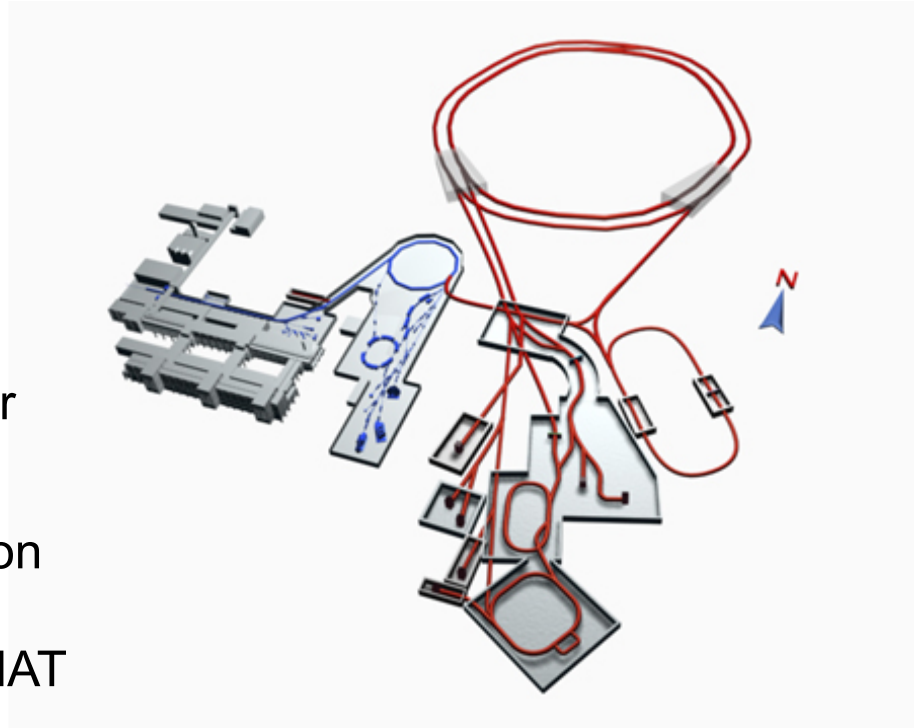
Organic scintillators loaded with neutron converters: rely on the $^{1}H(n,p)$ which moderates the neutron energy after a few collisions and trigger a different (n, charged particle) or (n,γ) reaction in the dopant.

Solid inorganic scintillators, etc.

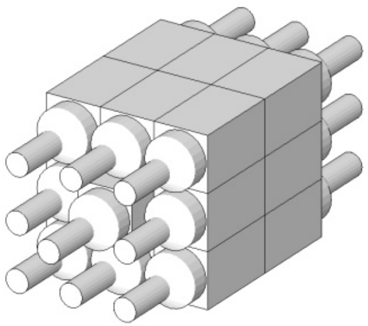
There are new materials coming out, but for the moment small in sizes

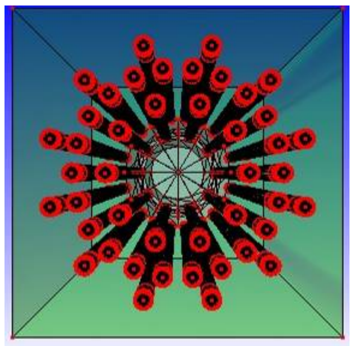
Detector developments for FAIR

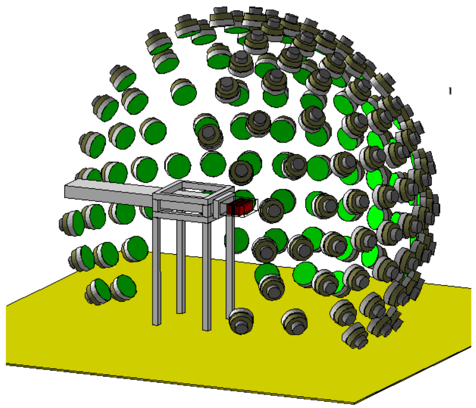
Our group is heavily involved in the development of instrumentation for the DESPEC (DEcay SPECtroscopy) experiment of FAIR. The most relevant contributions are presently related to:



- A modular Total Absorption Spectrometer (IFIC, Valencia, responsibility)
- A modular TOF neutron detector based on cells of BC501A liquid scintillator material (MOdular Neutron SpectromeTER) (CIEMAT resposability)
- A 4π neutron detector (Beta dELayEd Neutron detector) (UPC responsibility)

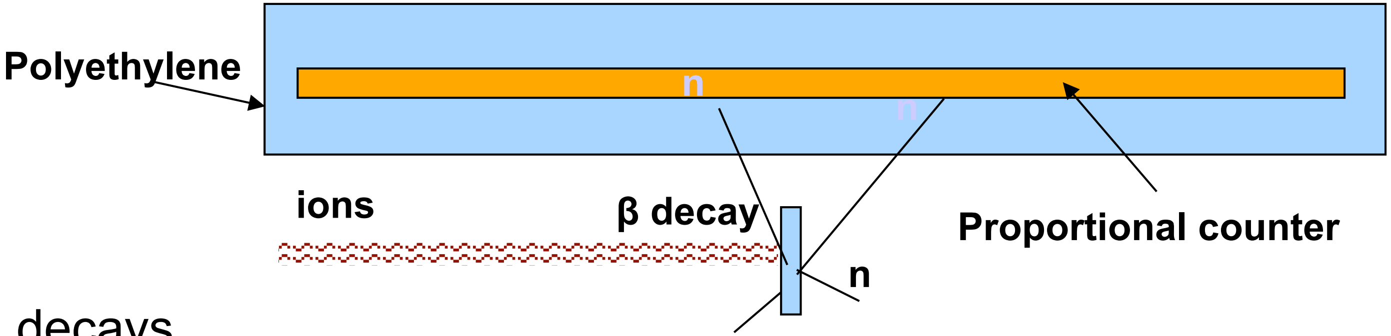






Pn integral measurements

$$P_N = \frac{N_n}{N_\beta}$$



N_n is the number of beta decays going through neutron emission

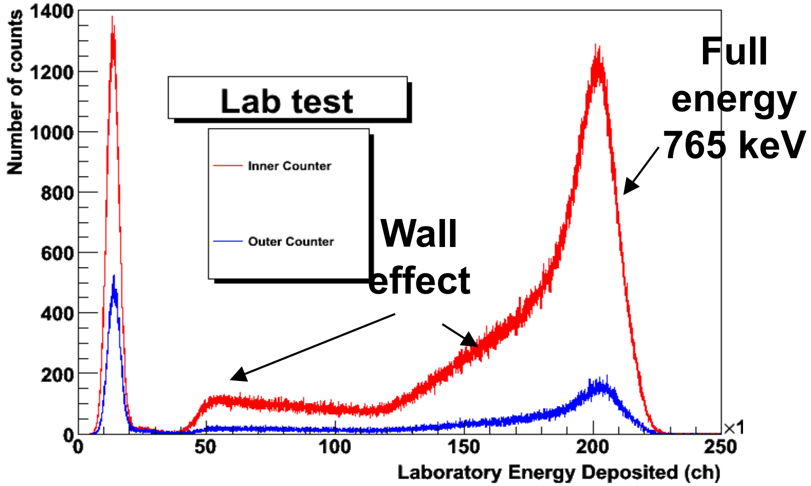
N_β is the number of decays

$$n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 765\ keV$$

$$n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He + 0.48\ \gamma + 2.3\ MeV$$

Some key issues concerning the technique:

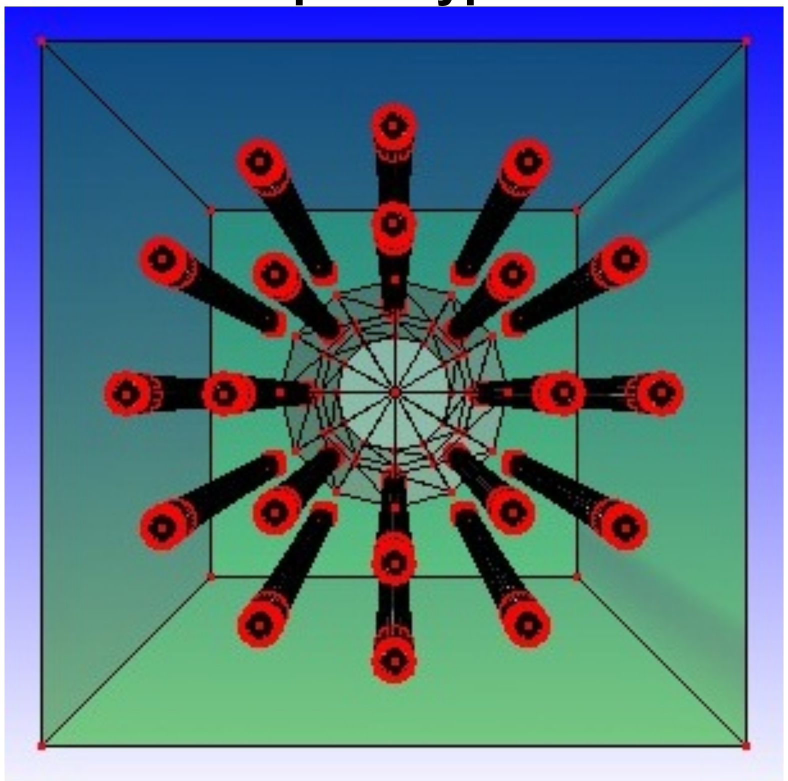
- Moderation of the neutrons is required
- Calorimeter like measurements
- Purity of the sources, background issues
- Efficiency of the detectors
- The efficiency curve of the detector should be as flat as possible (no dependence on the E of the neutrons up to the highest possible energy)

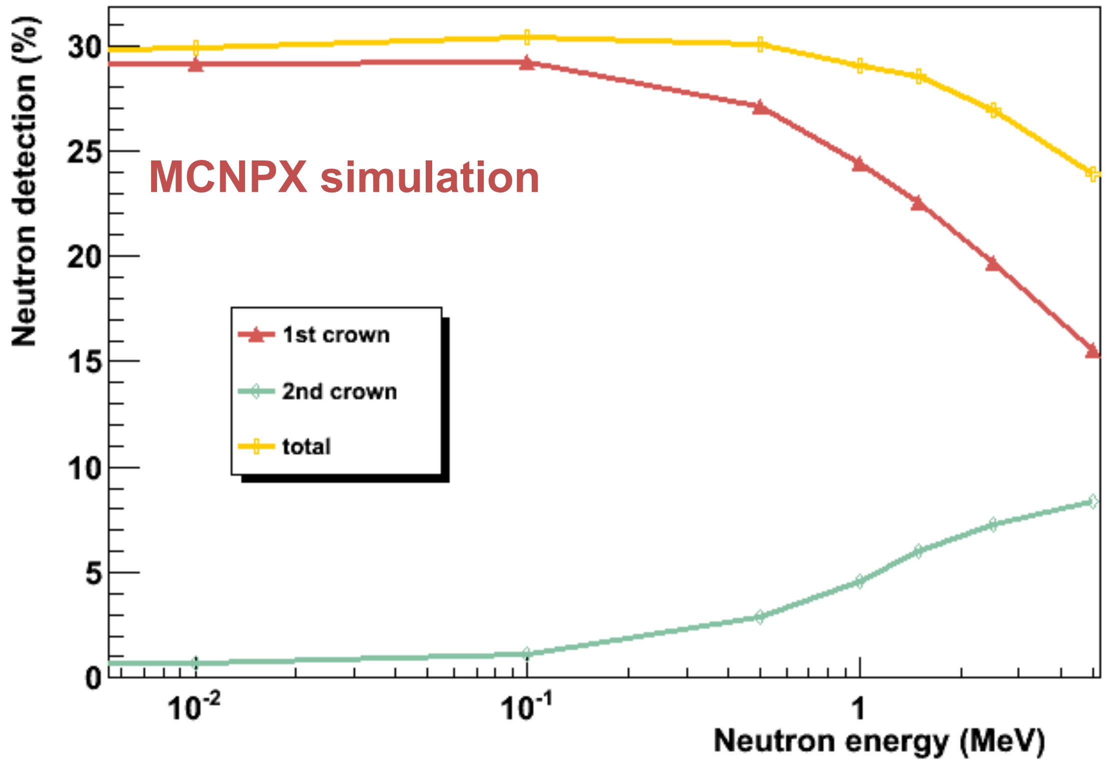


Examples: “Krat’s long counter”, NERO, 3Hen

Pn measurements at Jyväskylä: the BELEN-20 detector

Detector consists of two crowns of (8+12) ^{3}He detectors embedded in a polyethylene matrix with total dimensions 90x90x80 cm^3 and a r=5 cm beam hole. First prototype of the detector we are developing for DESPEC (FAIR)

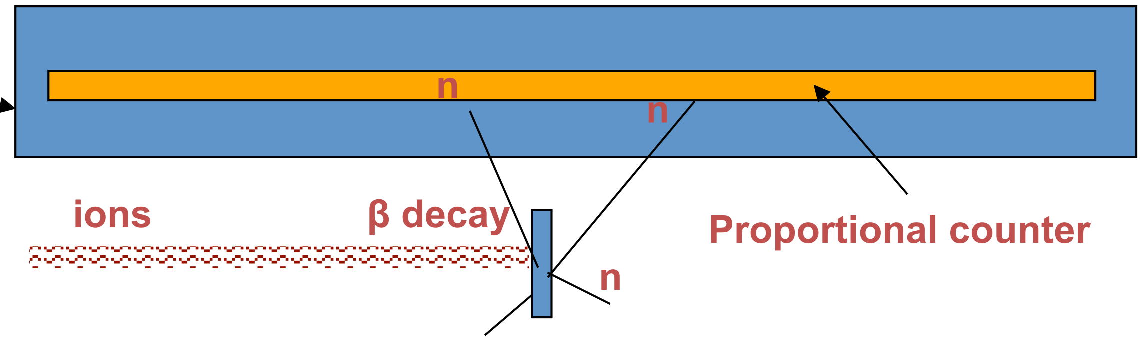




$^3He + n \rightarrow {}^3H + {}^1H + 765$ keV

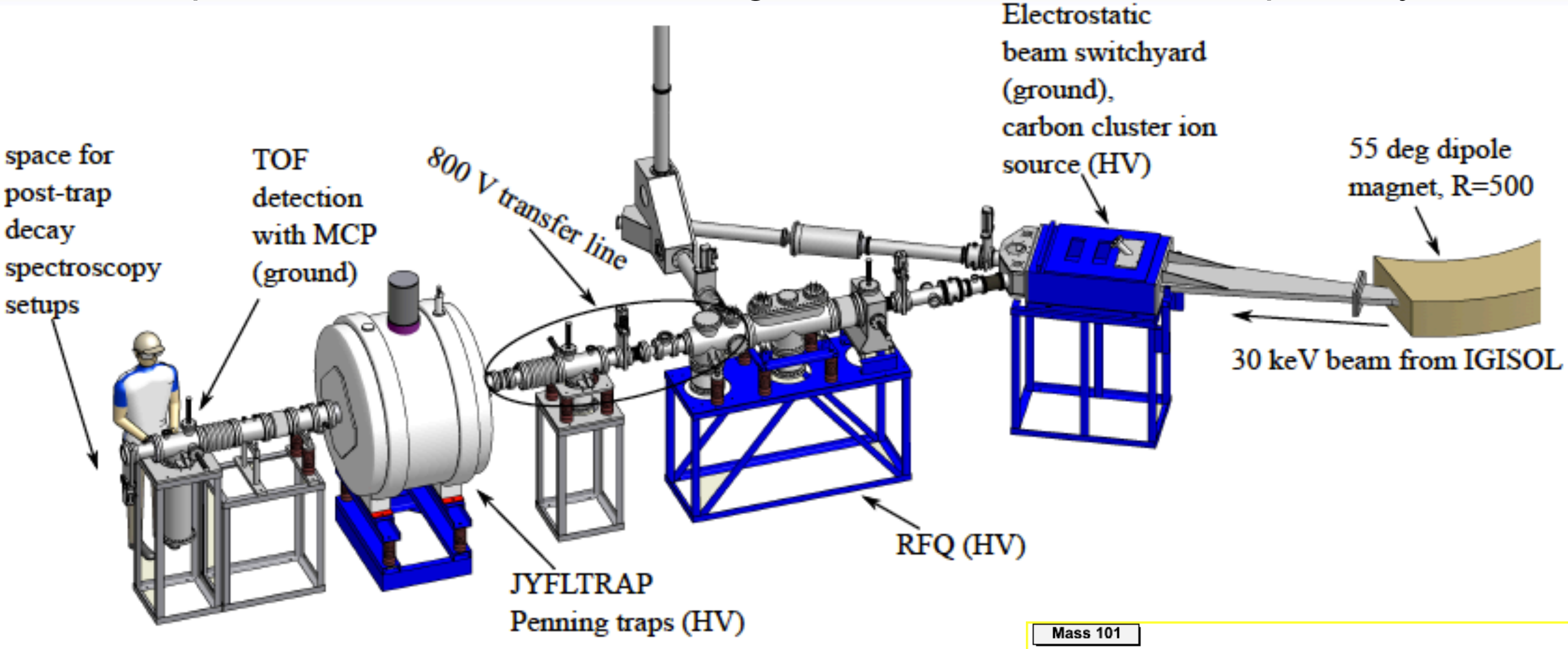
Tubes of 60 cm length

20 Atm preasure



Why JYFL for the tests/measurements?

The main reasons are the chemical insensitivity (ion guide technique), high purity by means of purification of the beam using the JYFLTRAP and acceptable yields!



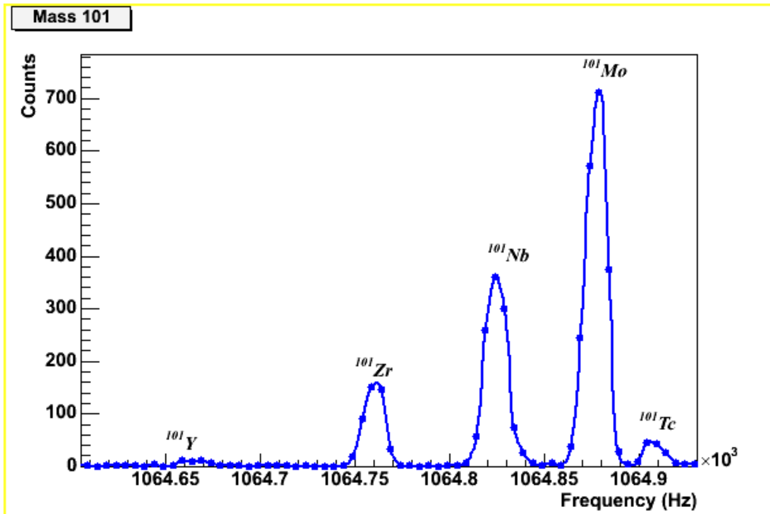
ISOLDE(CERN)

GPS $\frac{M}{\Delta M} = 2400$

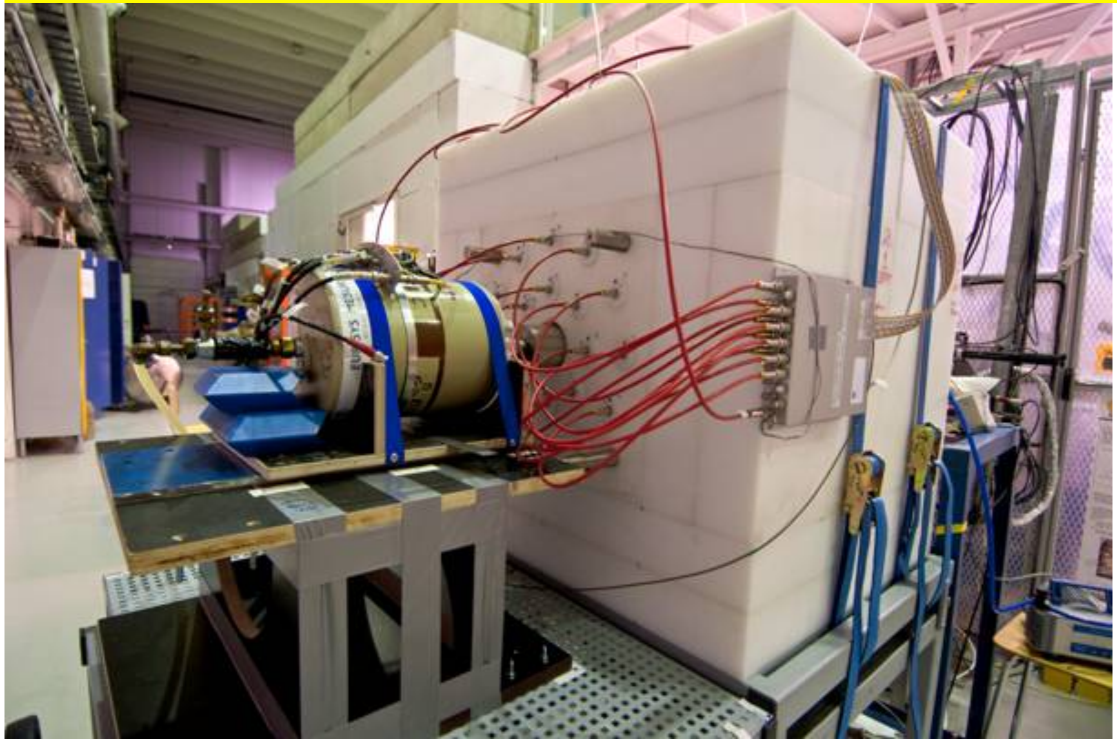
HRS $\frac{M}{\Delta M} = 5000$

Isobar spectrum of A=101 fission products measured at spectroscopy setup

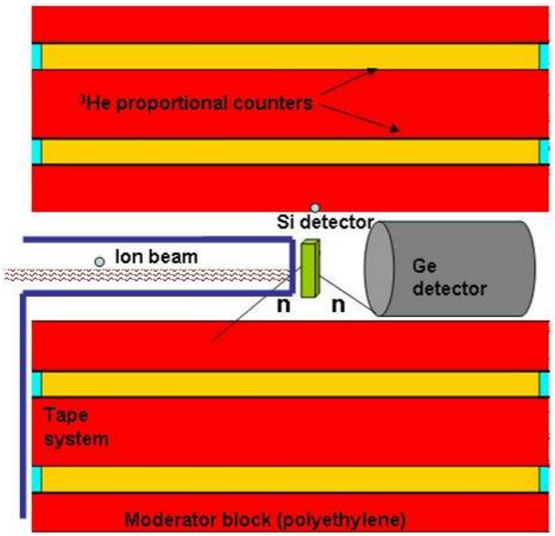
$$\frac{M}{\Delta M} = 10^4 - 10^6$$



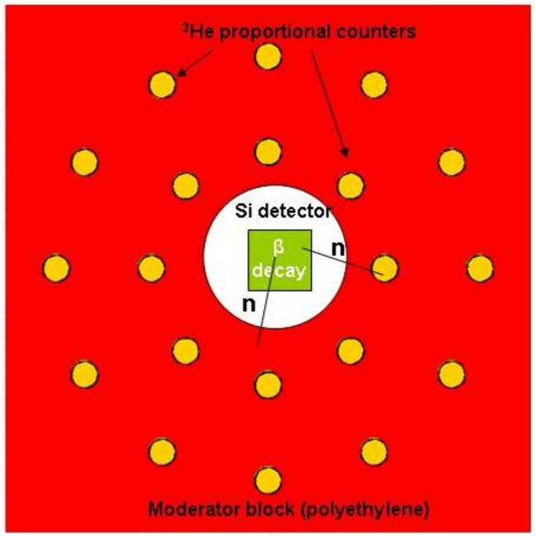
First BELEN-20 measurements: IGISOL+JYFLTRAP



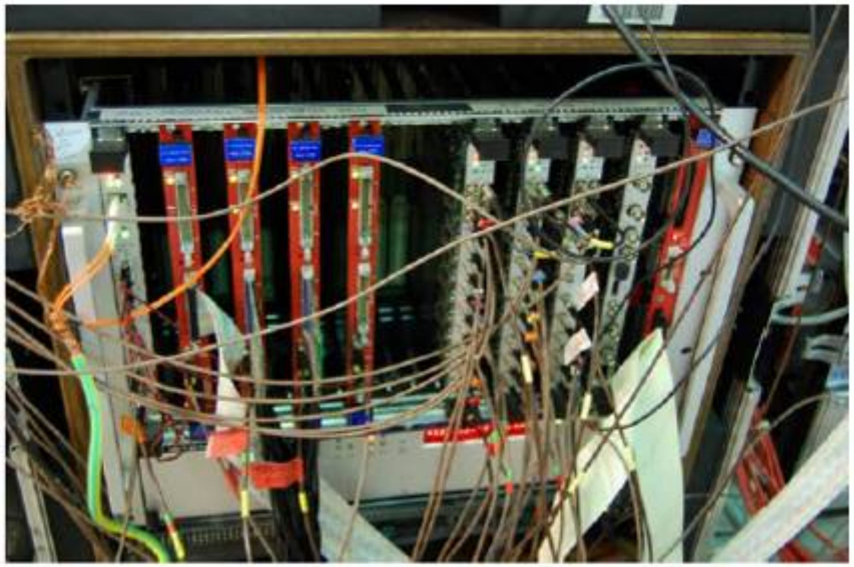
- First measurement: decay of ^{88}Br, ^{94,95}Rb, ^{138}I, (^{138}Te)
- Trap assisted spectroscopy
- Goal: measure Pn of cases that are important for the calibration of the detector, for decay heat and for testing nuclear models. The cases with A~ 90 are relatively close to the r-process path.
- Triggerless DACQ developed in Valencia (minimum dead-time, time-stamping, flexibility for time correlations)

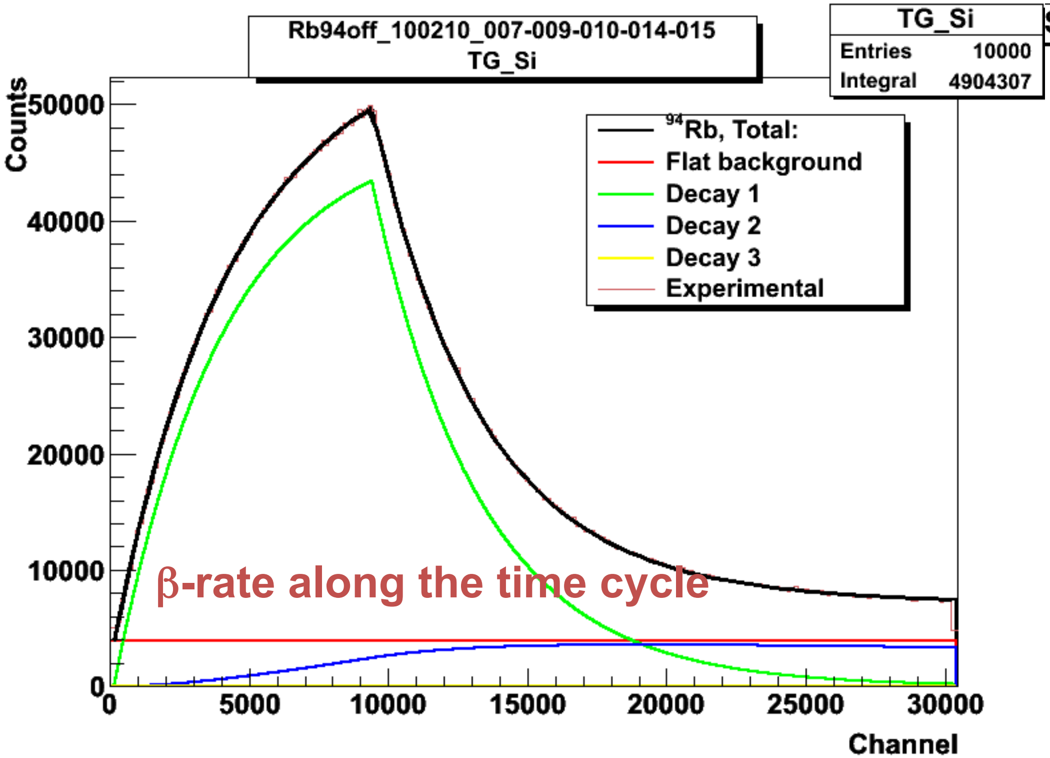


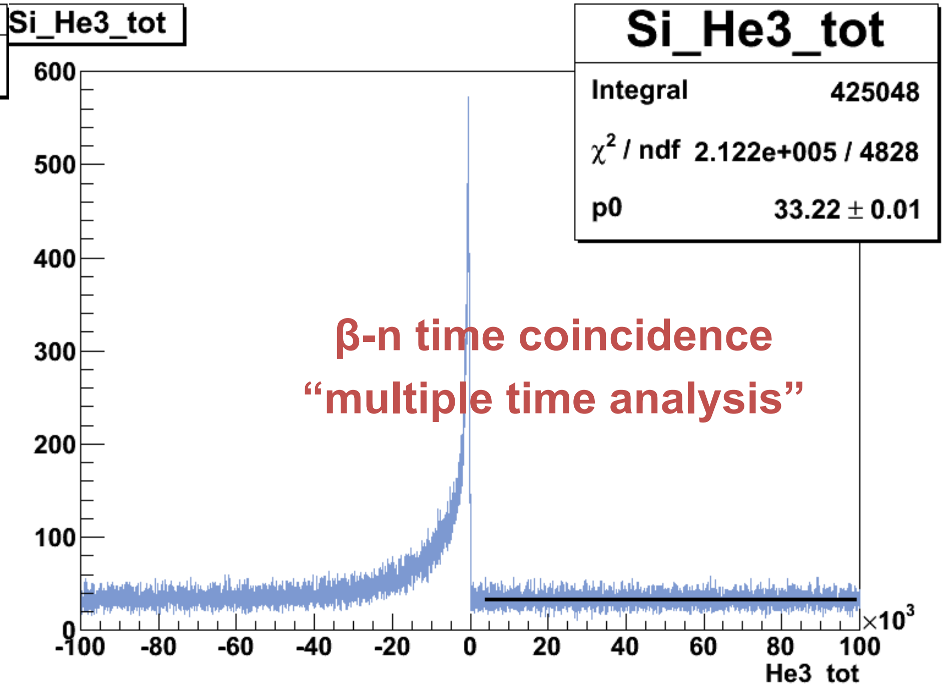
Side view



Front view







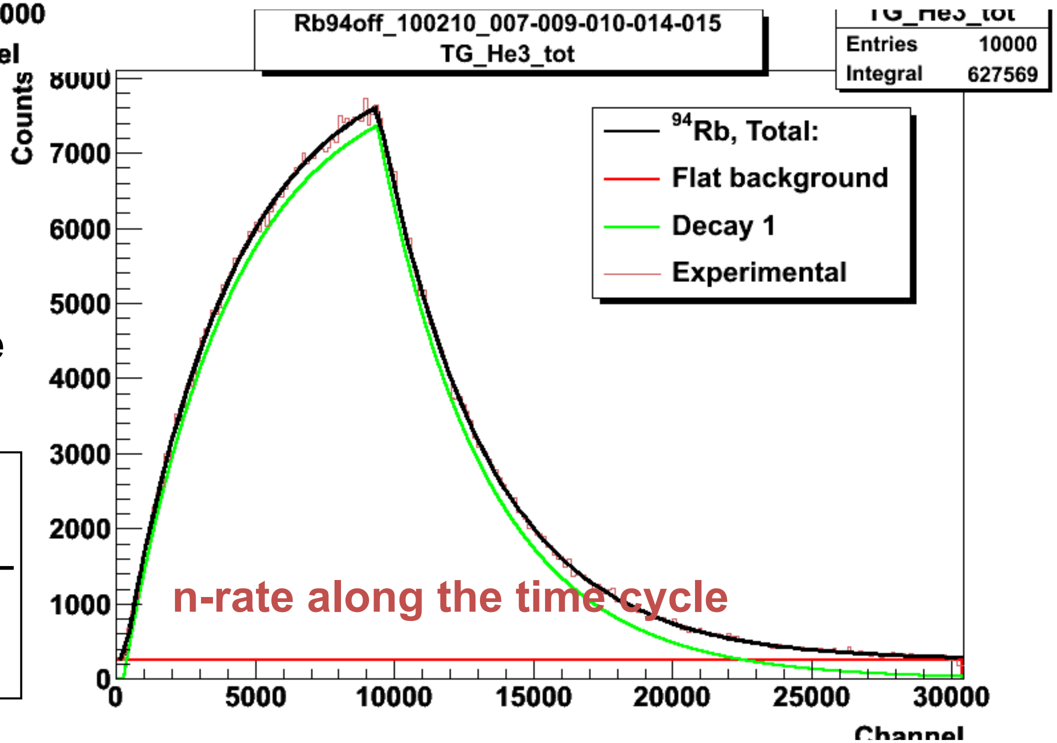
Decay&grow fits using Bateman equations.

Cycle

Ions were implanted on tape for $3T_{1/2}$ and left decay for $7T_{1/2}$. then remove the activity

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

$$P_N = \frac{\varepsilon_\beta}{\varepsilon_N}\frac{N_N}{N_\beta}$$



First results

The P_n values of ^{88}Br and ^{95}Rb were used as references to calculate the efficiency of BELEN-20. The average efficiency for BELEN-20 is (27.1±0.8) %.

Isotope	ε_n	unc
^{88}Br	0.276	0.007
^{95}Rb	0.266	0.008

Using the above average efficiency, the P_n for ^{94}Rb and ^{138}I were calculated and they are in good agreement with values from previous work.

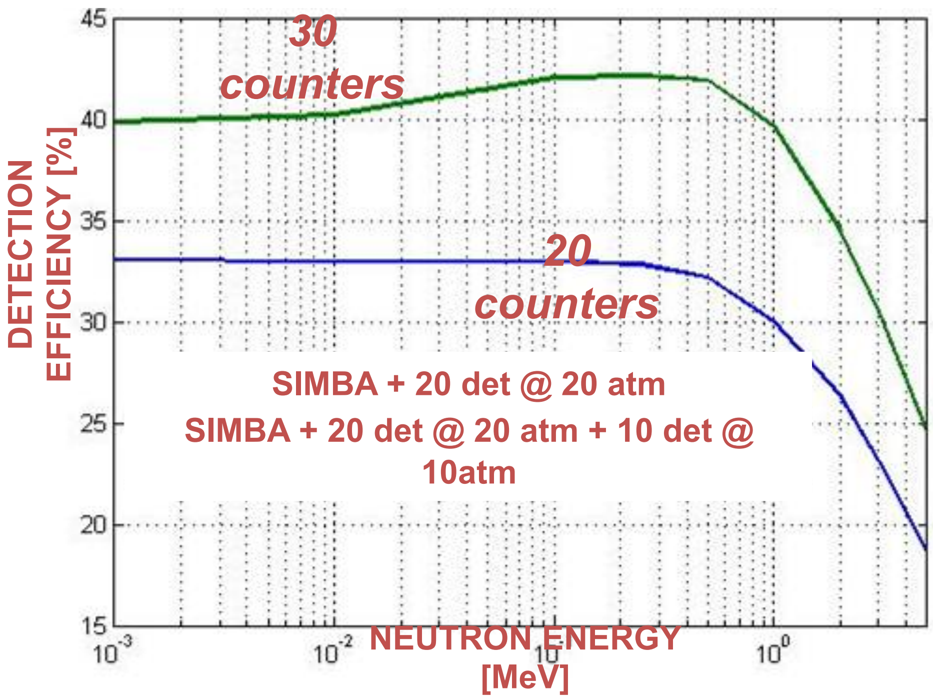
Isotope	P_n (%)	Unc.	Author
^{94}Rb	10.28	0.31	This work
	10.01	0.23	Rudstam
	9.1	0.11	Pfeiffer
^{138}I	5.32	0.20	This work
	5.46	0.18	Rudstam
	5.17	0.36	Pfeiffer

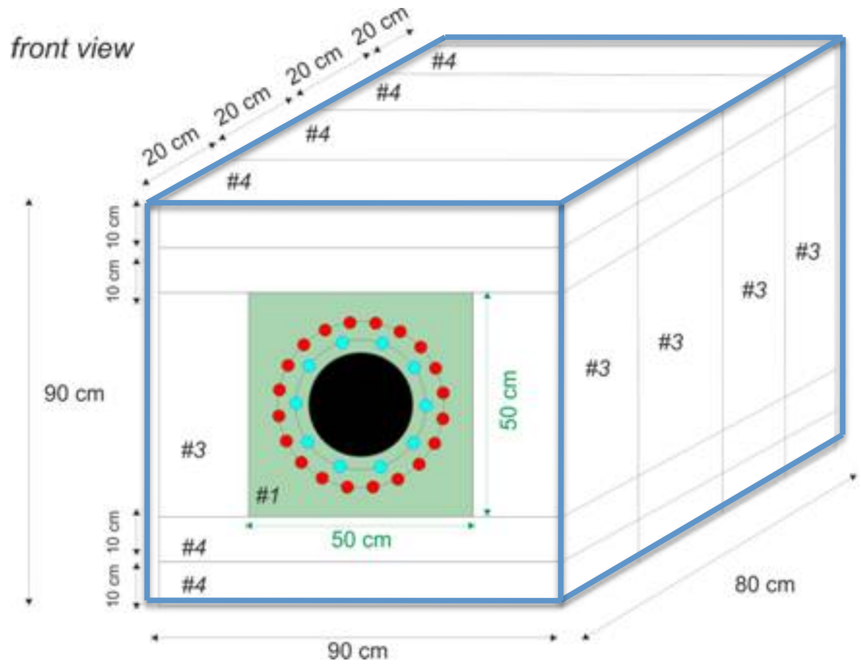
Courtesy of M. B. Gomez

BELEN-30 at GSI Fragment Separator (FRS)

Two proposals approved at FRS-GSI will use the BELEN detector in 2011

- **S323 *"Beta-decay of very neutron-rich Rh, Pd, Ag nuclei including the r-process waiting point ^{128}Pd".* F. Montes et al.**
- **S410 *"Beta-decay measurements of new isotopes near the third r-process peak".* C. Domingo et al. ($^{213-218}$Tl, ^{213,214,216}Hg, $^{208-213}$Au, ^{205,206}Ir isotopes)**



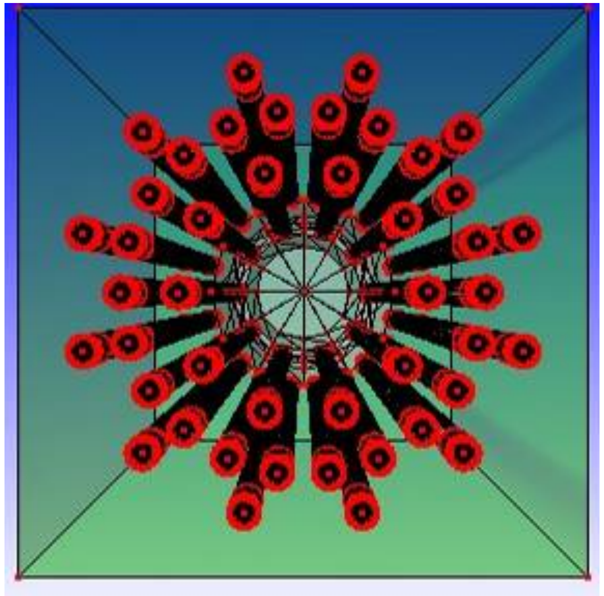


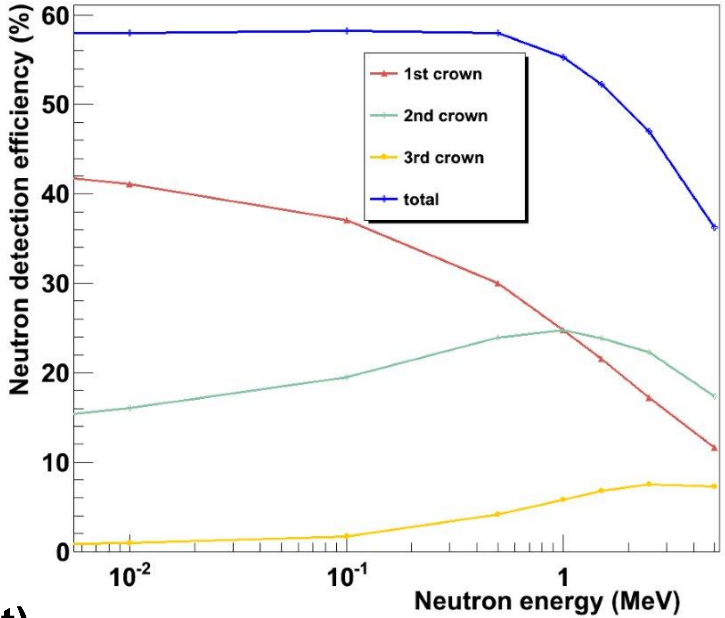
20 ^{3}He counters (20 atm) +
10 ^{3}He counters (10 atm)

Intermediate status
„BELEN-30“ (2011)

BELEN progression

• The original planned neutron detector for DESPEC consists of 44 ^{3}He counters arranged in 3 crowns. To be combined with AIDA, but …





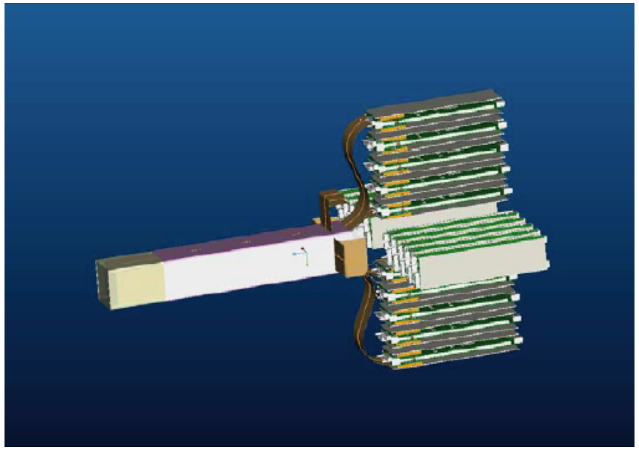
40 counters @ 10 atm UPC (refurbishment)

10 counters @ 10 atm GSI

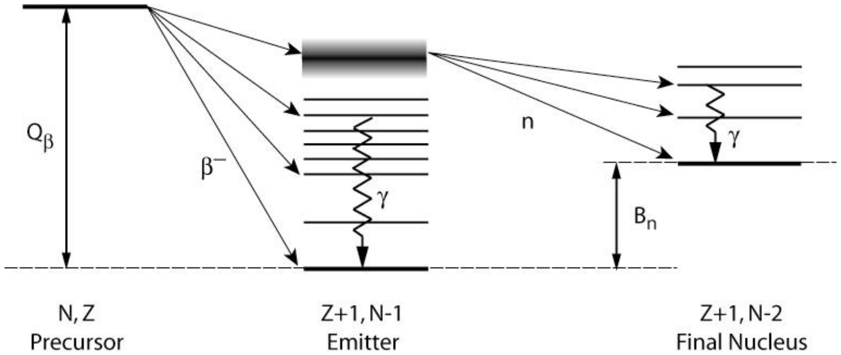
60 counters @ 4 atm JINR

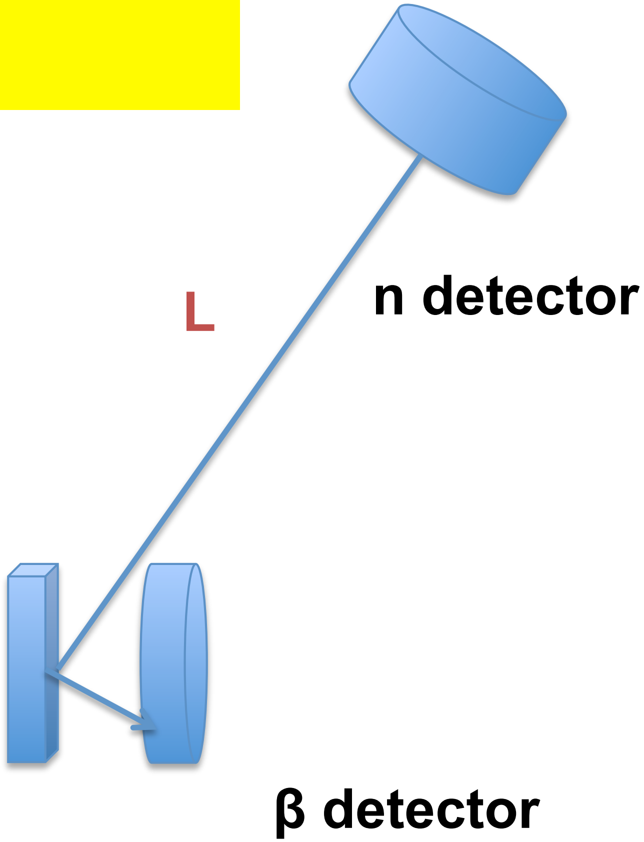
The final detector BELEN for DESPEC (FAIR) will have 110 counters.

BELEN: 0, 20, 30, (44), 110



TOF technique





$$E_n = \frac{1}{2} M_n V^2 = \frac{1}{2} M_n \frac{L^2}{t^2}$$

Energy Resolution

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

Some key issues concerning the detection technique:

- **dL depends on the thickness of the detector (trade off between intrinsic eff. and resolution)**
- **dt depends on the timing properties of the detectors**
- **Need to differentiate the gamma pulses from the neutron ones (pulse shape)**
- **Solid angle coverage (coupled with other detectors)**
- **Cross-talk between detectors**
- **Combined with Pn measurements can provide the full strength distribution**

Examples: TONNERRE, DESCANT, etc.

The DESPEC Modular Neutron SpectrometeTER (MONSTER)

The construction of the cells will be shared between **Spain** (CIEMAT, IFIC), **India** (VECC), **Finland** (Univ. of Jyvaskyla), **Sweden** (Univ. of Uppsala).

-Cell design fixed.

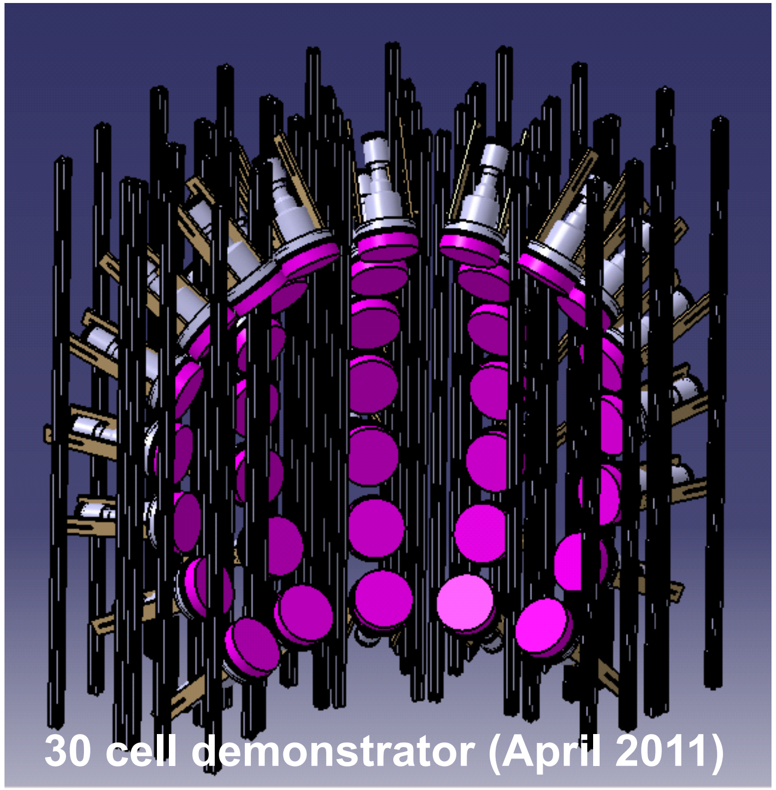
-30 cell demonstrator funded and being presently assembled at CIEMAT

-50 further cells will be made by VECC (India).

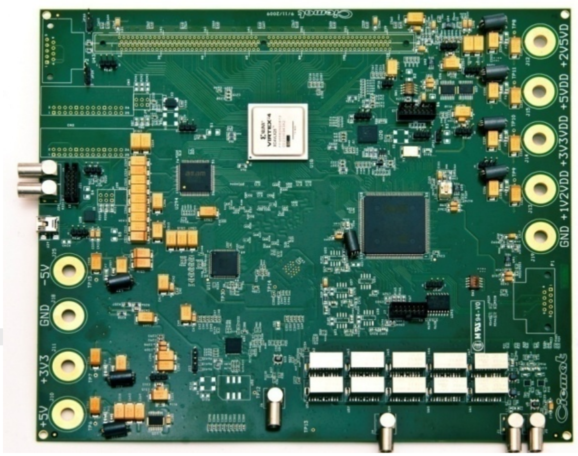
-Accepted test combined with AIDA (PRESPEC Umbrella proposal at FRS (GSI))

-Accepted experiments at JYFL (new IGISOL facility)

-Synergies with SPIRAL-2 (with LPC–Caen for the DESIR facility, LNL- Legnaro for the NEDA project)



New high performance digitiser boards for MONSTER and γ-ray detectors based on inorganic scintillators : 12/14 bit & 1 GHz



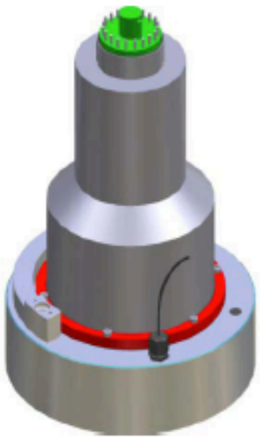
courtesy of D. Cano-Ott,

The DESPEC MOdular Neutron SpectromeTER

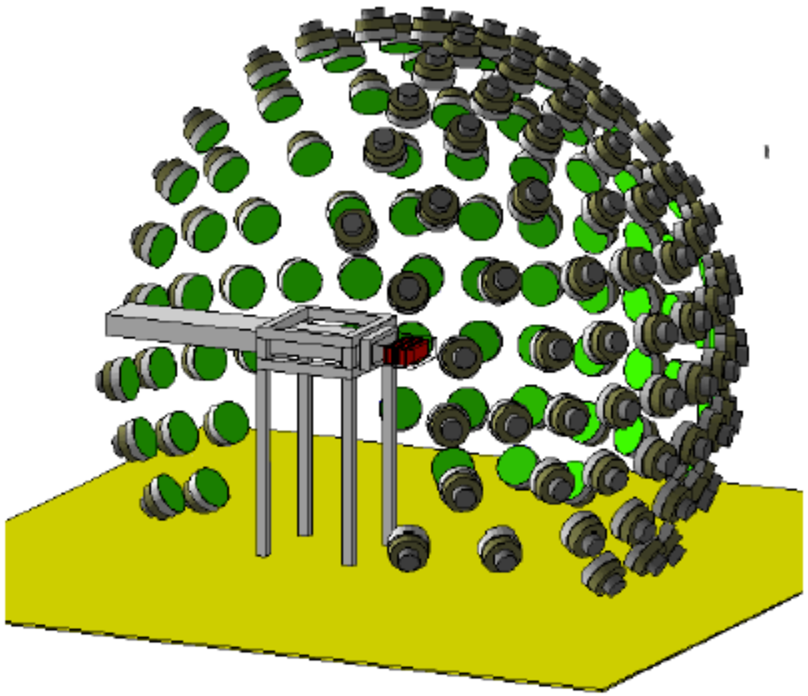
- Cylindrical cell of 20 x 5 cm filled with BC501A/EJ301
- Reasonable intrinsic efficiency (~50% @ 1MeV)
- Energy threshold ~ 30 keVee (E_n ~100 keV)
- Reasonable energy resolution < 10% up to 5 MeV:
- Good neutron timing ~1ns
- Good β timing: < 4ns
- Reasonable flight path 2-3 m TOF
- Good total efficiency: 150 – 200 detectors

200 detectors, 10cm radius		ΔE/E @ 1 MeV	
TOF distance (m)	Geometric efficiency	1ns	4ns
2	12.5%	3.5%	6.0%
3	5.6%	2.5%	4.2%

Design similar to other projects (DESIR @ SPIRAL II)



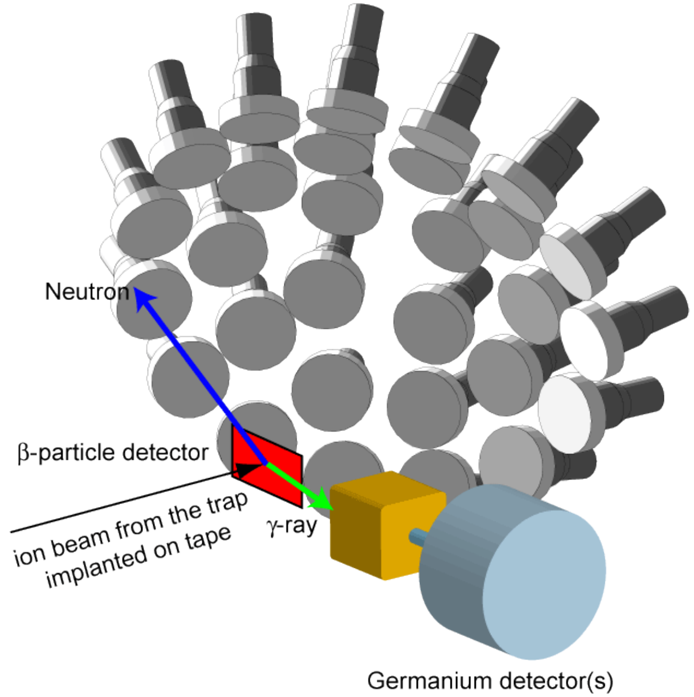
Ø=20cm
L=5cm

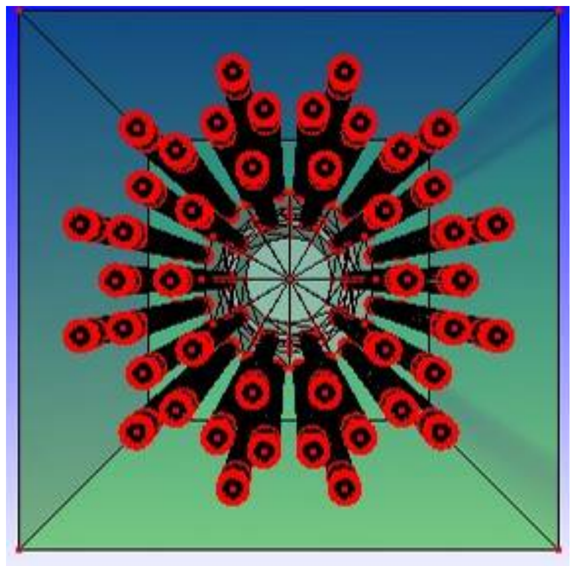


Courtesy of D. Cano

Future measurements at Jyväskylä: TOF and 4π

- We still have to do a complementary measurement of ^{88}Br,^{94,95}Rb, and ^{137}I using a prototype of the MONSTER detector (Mini TOF) array developed for DESPEC (FAIR). The prototype array will consist of 30 cells (BC501A liquid scintillator)
- New proposal accepted for the study of beta delayed neutron emission of some Ge, As, Y isotopes. This is relevant for summation calculations of generation IV reactors (first proposal, but some will follow, 4π measurement)
- We have in mind also new measurements relevant for the r-process and nuclear structure





Conclusions

• We have just started a complementary program to our TAS measurements in the neutron rich side which is based on 4π neutron detector and the TOF technique (beginning of the learning curve!).

•The detector development is mainly related to the FAIR facility, but we will exploit the developed prototypes in other facilities, mainly in Jyväskyla, GSI (and later FAIR), ALTO (and later SPIRAL2).

• Our research will address topics of conventional nuclear structure, applications to reactor technology, and astrophysics

• After yesterday's talk of N. D. Scielzo, I though that my talk was completely obsolete, but this is not the only new breakthrough. Purity of the beams, digital electronics, time stamping and "old proved detector techniques" can still provide new results.

Collaboration

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CIEMAT, Spain
UPC, Spain
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MTA ATOMKI, Hungary
JNIR, Russia
LPC, France
IFIC, Spain
VECC, India
Univ. of Uppsala, Sweden

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THANK YOU