A β-Decay Total Absorption Spectrometer for DESPEC

- The TAS technique
- Importance of beta strength distributions
- Status of the project

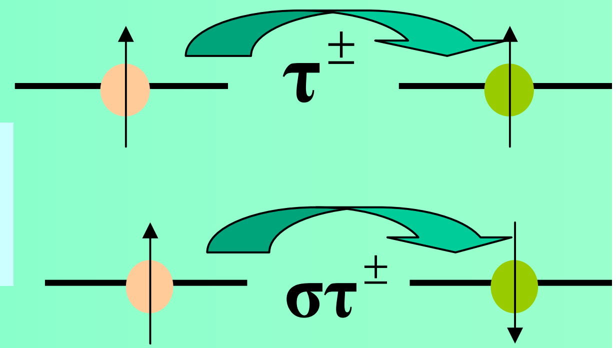
Jose L. Tain @ IFIC-Valencia

PARIS Collaboration Meeting, Krakow, 14 October, 2009

• **Total Absorption Spectroscopy is the best method to measure beta strengths in β-decay for complex decay schemes**

An accurate knowledge of the distribution of the β-decay probability over the daughter-nucleus levels provides information for the understanding of the structure of nuclei of importance on its own or for other fields as astrophysics and nuclear technology

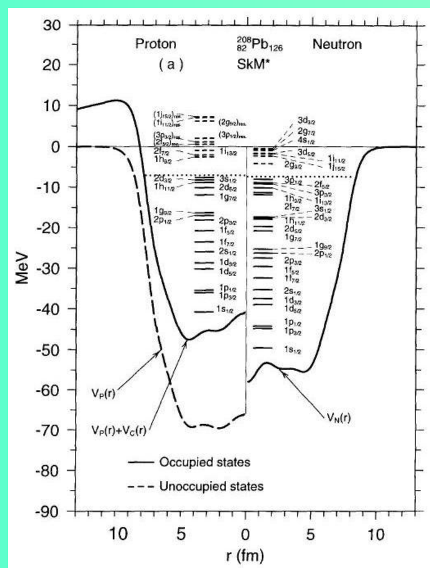
Fermi / Gamow-Teller



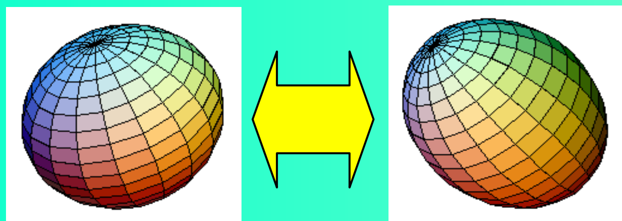
• **Basic process: simple and sensitive to the wave function**

$$S_\beta \propto \left| \left\langle \Psi_f \middle| \tau^\pm \ or\ \sigma\tau^\pm \middle| \Psi_i \right\rangle \right|^2$$

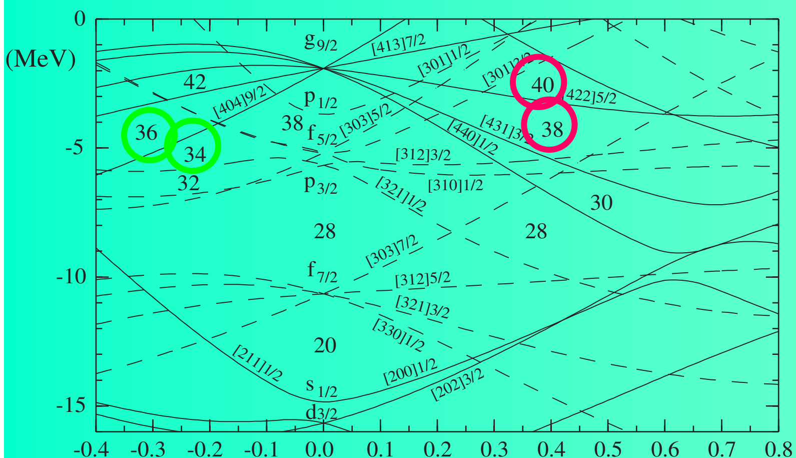
• **In general the bulk of the strength lies outside the Q_β window but the structure inside reveals the nuclear structure**

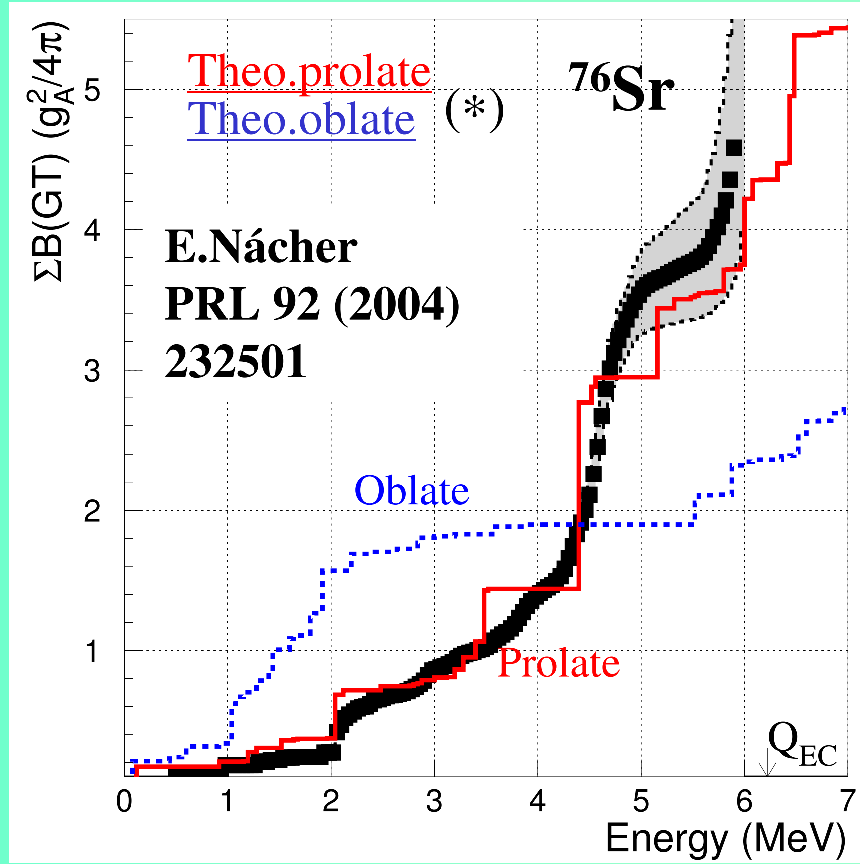


Oblate-prolate competition



N~Z nuclei with A~70-80

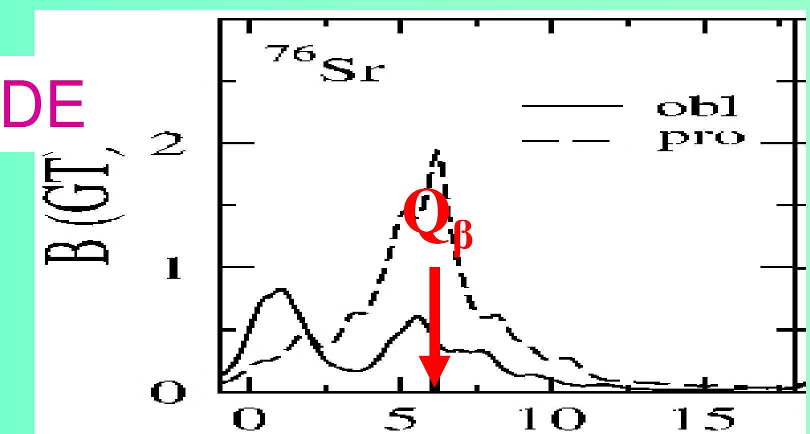




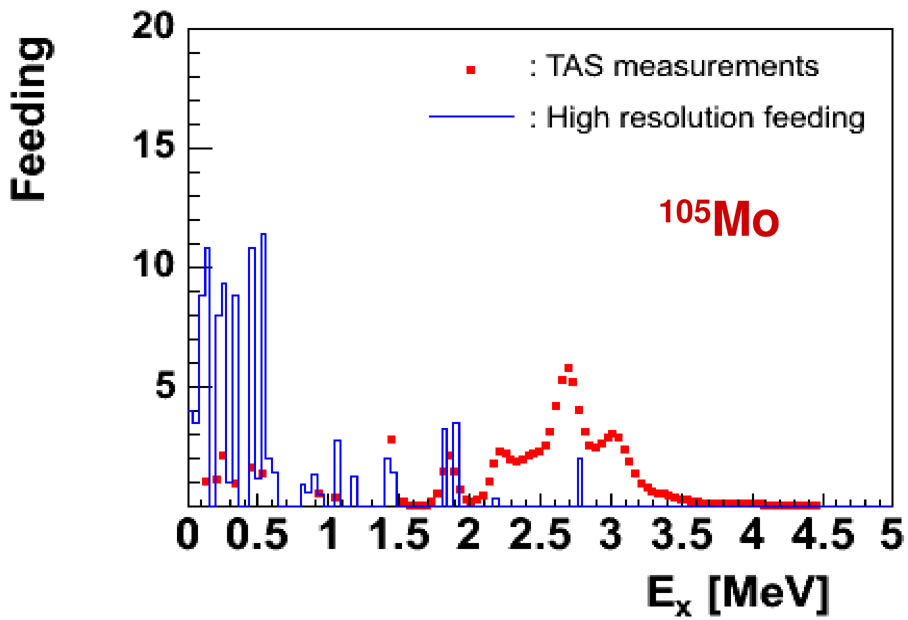
(*) P.Sarriguren et al.NPA 658 (1999)13

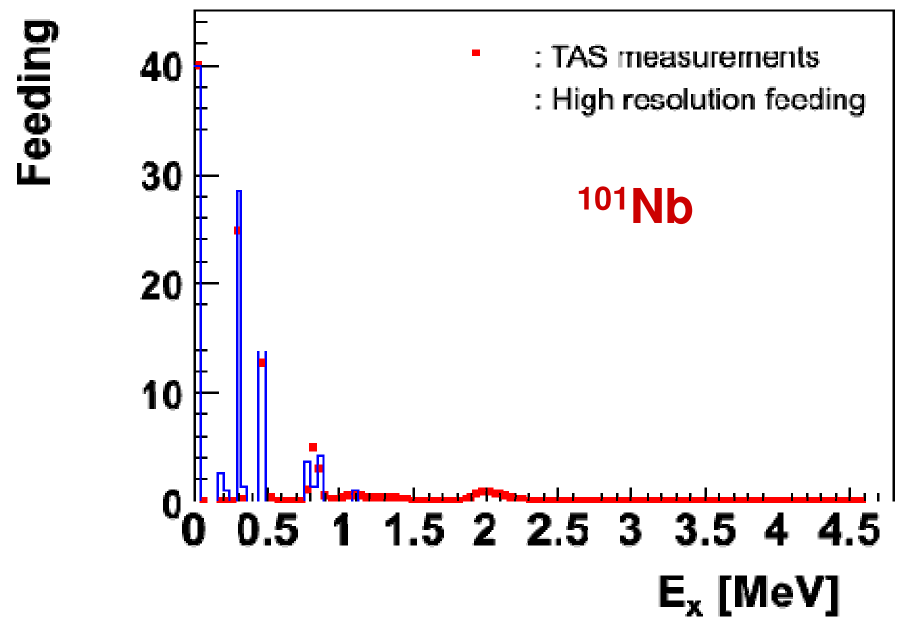
Lucrecia @ ISOLDE

Madrid,
Strasbourg,
Surrey,
Valencia



• **Avoids the "Pandemonium effect"**: misplacement of β-intensity to lower E_x when using **high resolution** (germanium) **spectroscopy**

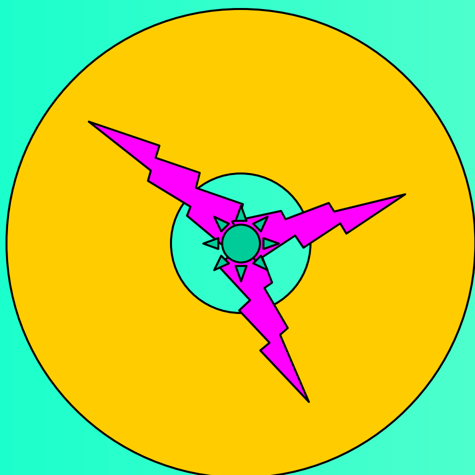


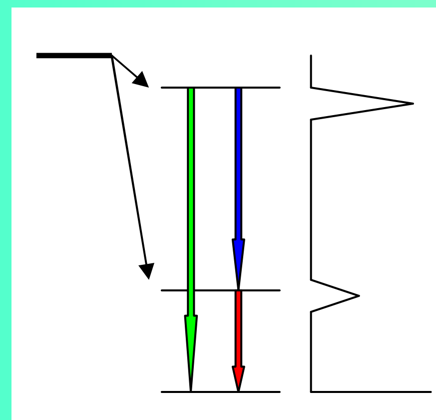


Pandemonium effect is due to:
- **Fragmentation of the intensity (large level densities)**
- **Limited efficiency of Ge detectors**

Is likely to happen when the level density is large but ultimately depends on nuclear structure

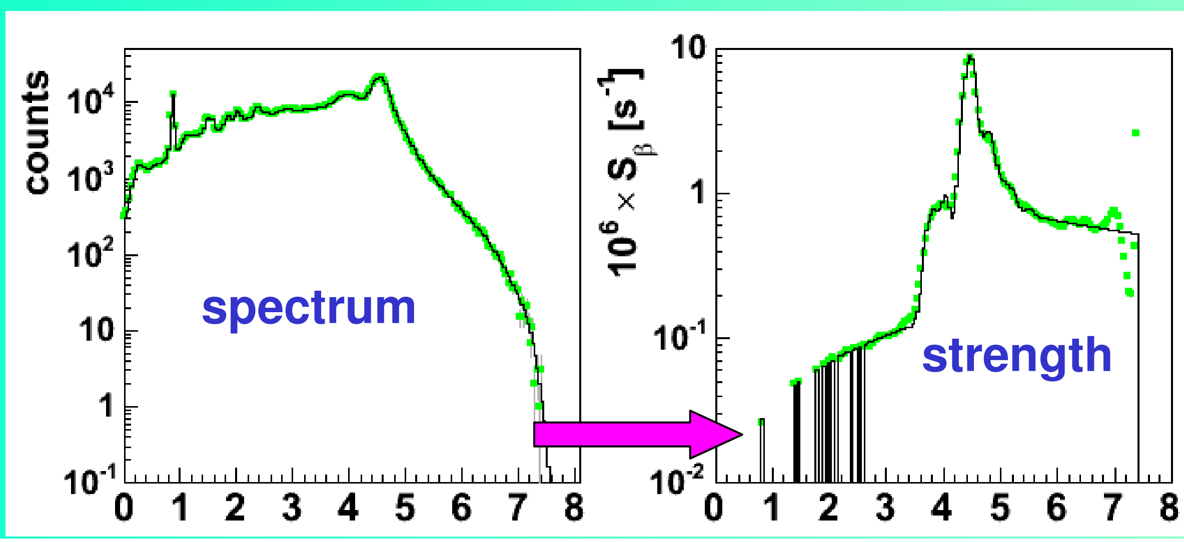
- Uses **large 4π scintillation detectors**, aiming **to detect the full γ-ray cascade** rather than individual γ-rays





An ideal TAS would give directly the β-intensity I_β

$$S_i = \frac{I_i}{f(Q_\beta - E_i)T_{1/2}} \quad \left[s^{-1}\right]$$



Deconvolution with spectrometer response to decay

$$\mathbf{f} = \text{"}\mathbf{R}^{-1} \cdot \mathbf{d}\text{"}$$

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

Response from MC simulations and nuclear statistical model

How do we extract the β-intensity (strength) from TAS spectra?

Relation between TAS data and the β-intensity distribution:

$$d_i = \sum_j R_{ij} f_j$$

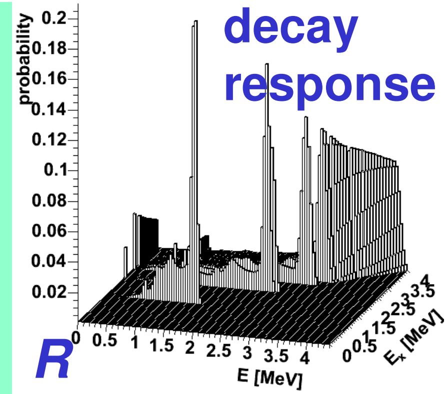
$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

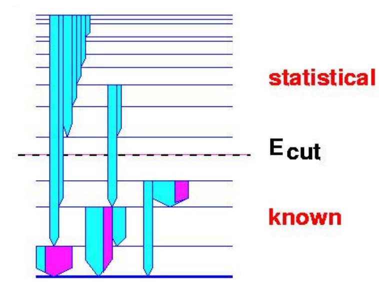
$$I_i = f_i \Big/ \sum_k f_k$$

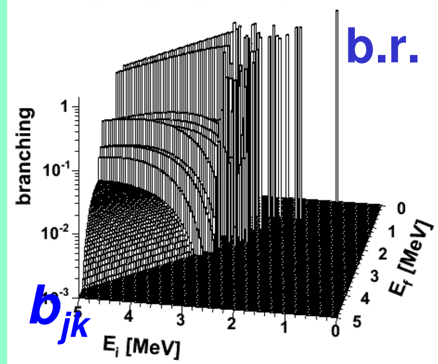
Deconvolution algorithms (inverse problem): EM, ME & LR

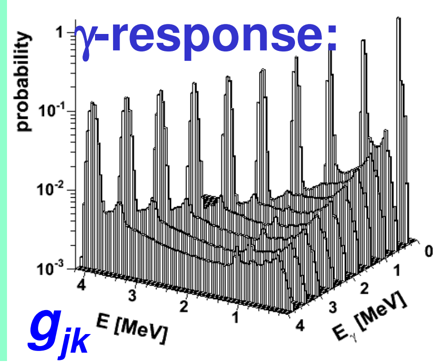
R_j: decay response for level j
b_{jk}: branching ratios j→k, from known level scheme and nuclear statistical model
g_{jk}: γ-ray response j→k, from Monte Carlo simulations

(the response may contain also the β-penetration, CE effect, isomer effect, …)









- **Accurate beta intensity** distribution measurements have also **applications in nuclear technology** …

Improvement of reactor decay heat calculations based on evaluated data

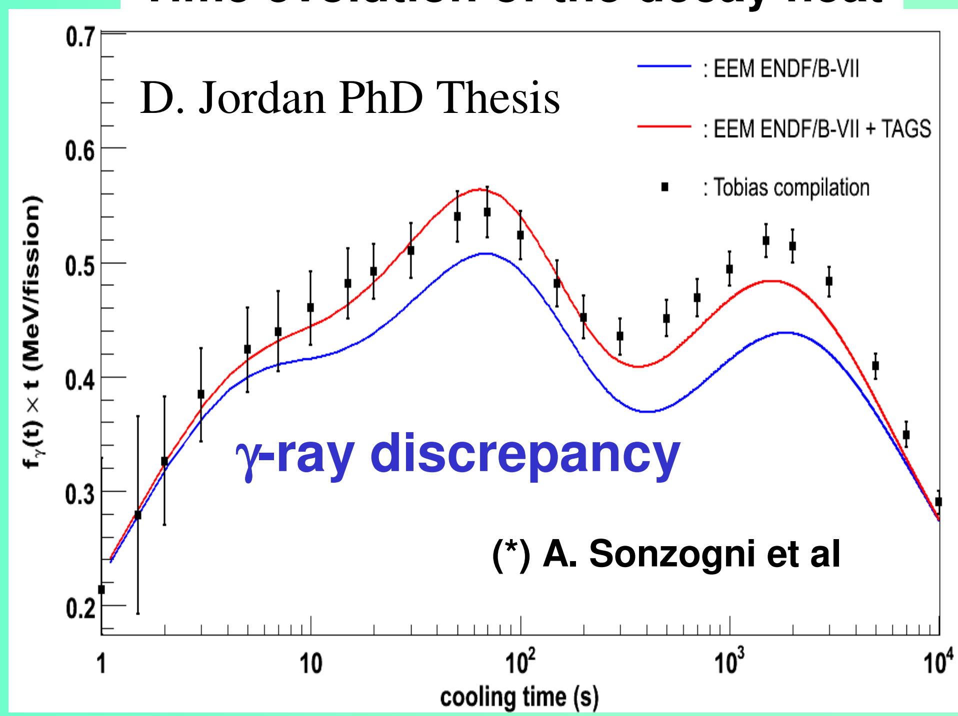
$$H(t)=\sum_{i=1}^{n} N_i(t)\frac{ln2}{T^i_{1/2}}\int_0^{Q^i_\beta}\overbrace{I^i_\beta(E_x)\underbrace{\left[E_x+\hat{E}_\beta(E_x)\right]}_{\langle E_\beta\rangle}}^{\langle E_\gamma\rangle}dE_x$$

IGISOL + JFLTRAP @Jyvaskyla

Valencia, Jyvaskyla, Debrecen, Gatchina, Surrey

	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%	105Ru 4.44 H β-: 100.00%	106Ru 373.59 D β-: 100.00%	107Ru 3.75 M β-: 100.00%	108Ru 4.55 M β-: 100.00%	109Ru 34.5 S β-: 100.00%
43	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 S β-: 100.00%	104Tc 18.3 M β-: 100.00%	105Tc 7.6 M β-: 100.00%	106Tc 35.6 S β-: 100.00%	107Tc 21.2 S β-: 100.00%	108Tc 5.17 S β-: 100.00%
	100Mo 0.78E+19 Y 9.63% 2β-: 100.00%	101Mo 14.61 M β-: 100.00%	102Mo 11.3 M β-: 100.00%	103Mo 67.5 S β-: 100.00%	104Mo 60 S β-: 100.00%	105Mo 35.6 S β-: 100.00%	106Mo 8.4 S β-: 100.00%	107Mo 3.5 S β-: 100.00%
41	99Nb 15.0 S β-: 100.00%	100Nb 1.5 S β-: 100.00%	101Nb 7.1 S β-: 100.00%	102Nb 4.3 S β-: 100.00%	103Nb 1.5 S β-: 100.00%	104Nb 4.9 S β-: 100.00% β-n: 0.06%	105Nb 2.95 S β-: 100.00% β-n: 1.70%	106Nb 1.02 S β-: 100.00% β-n: 4.50%
	58		60		62		64	

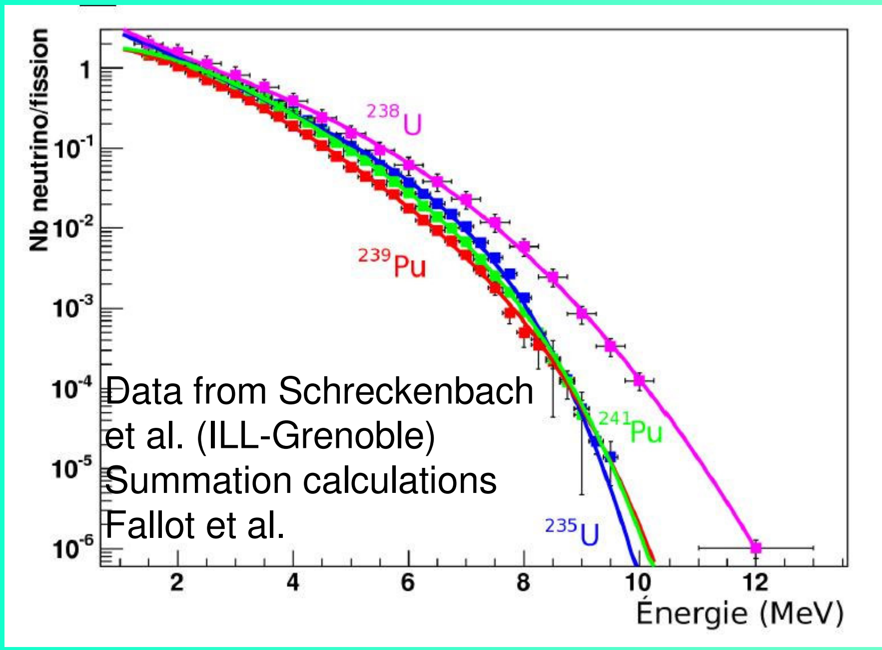
Time evolution of the decay heat

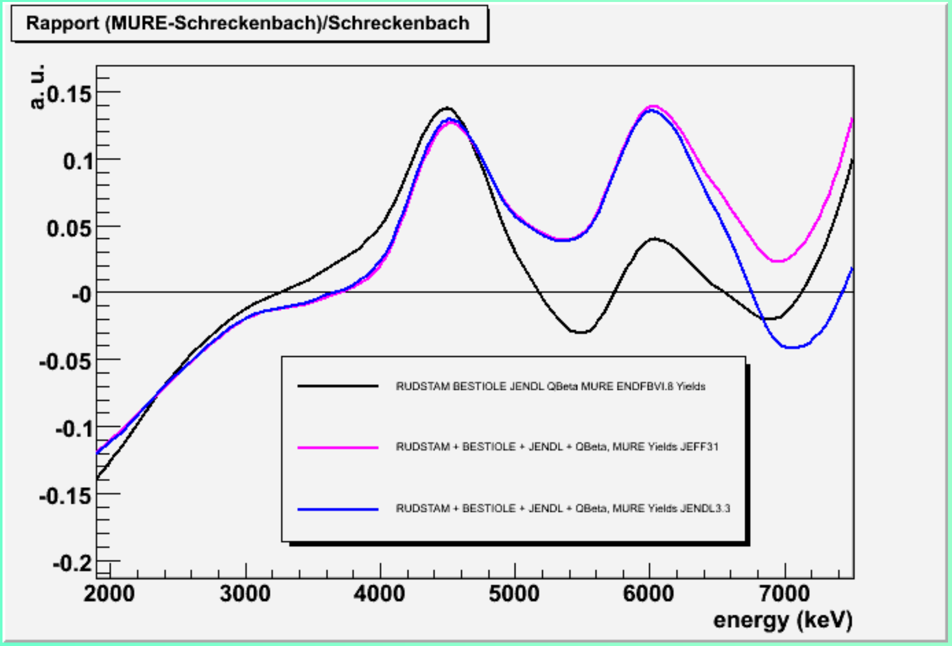


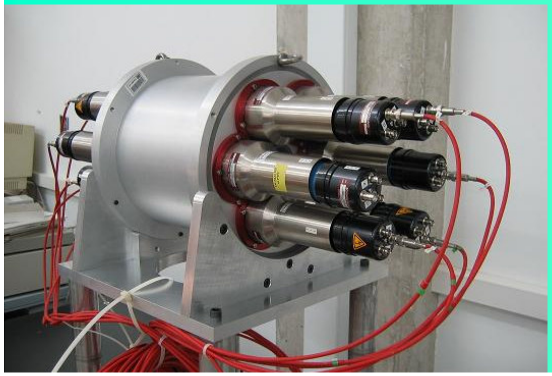
… and applications in fundamental physics

Reactor neutrino spectrum: neutrino oscillations and homeland security

How well known is the reactor anti-neutrino spectrum?



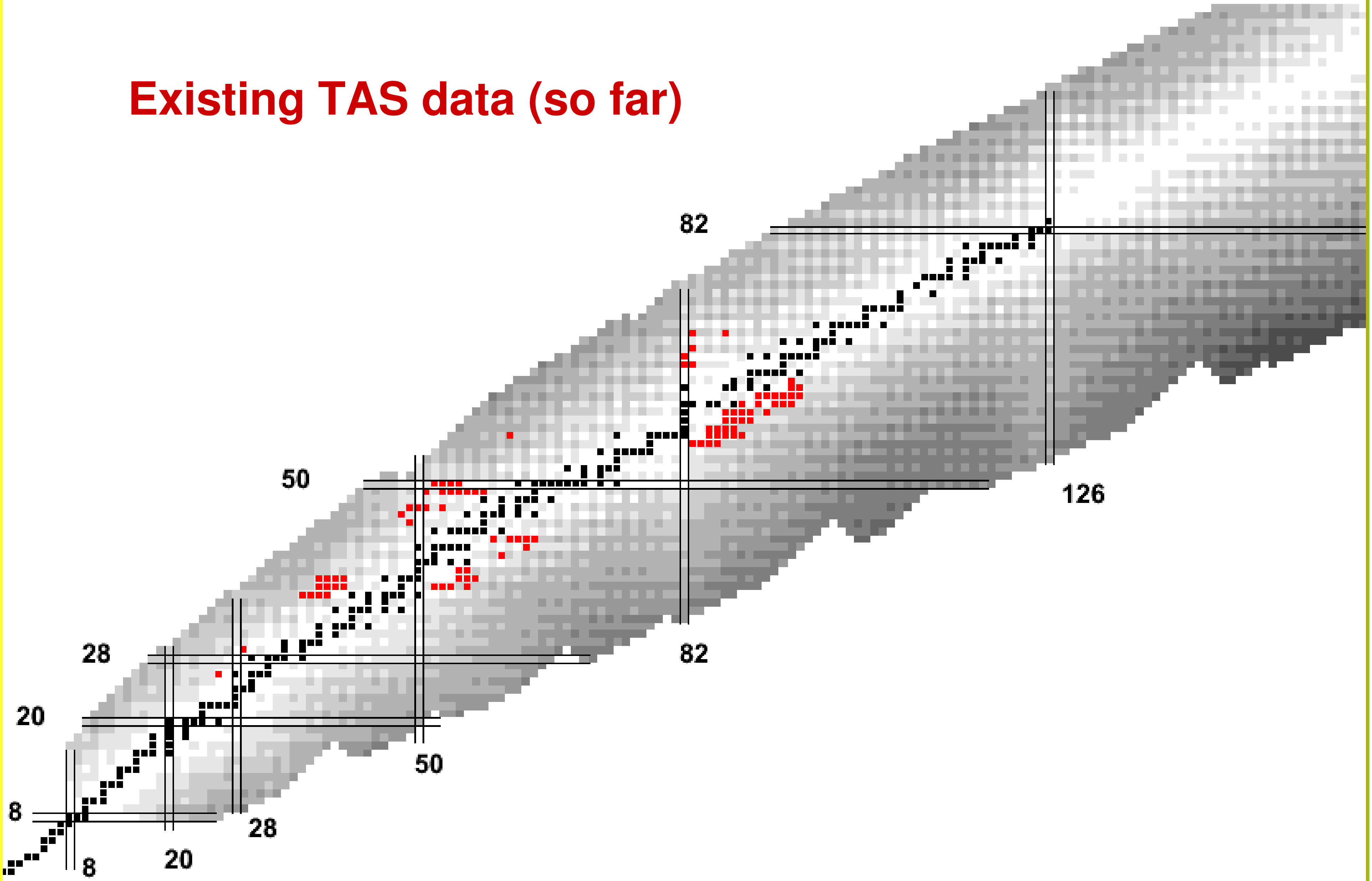




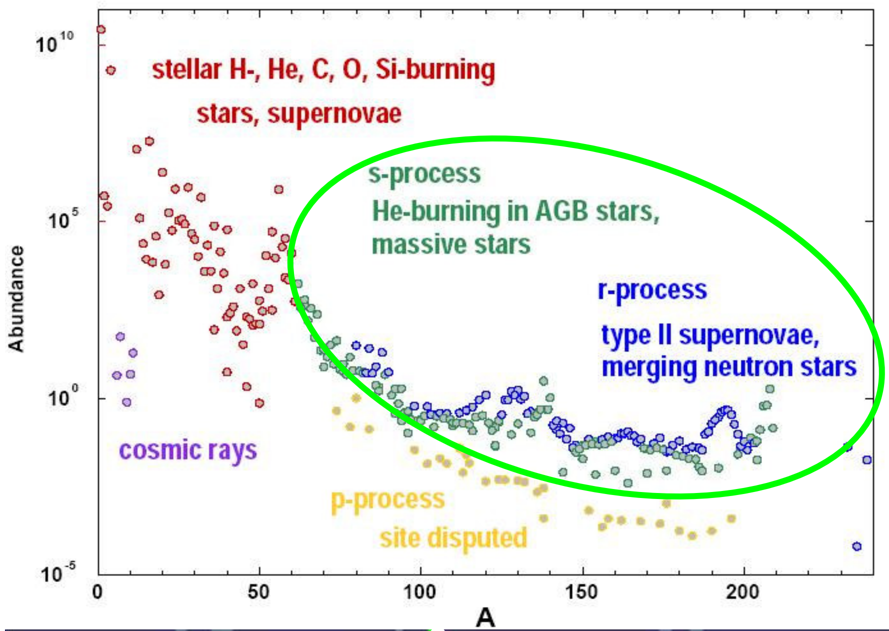
Nantes, Valencia, Jyvaskyla, Surrey

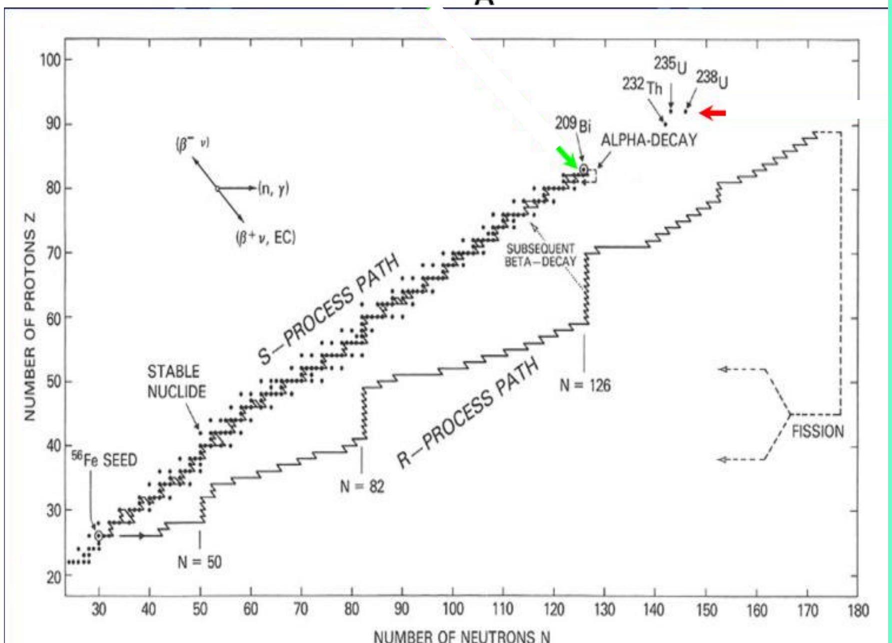
- **Proposal for measurement at JYFL:**
- **Penning trap & precision trap to separate isotopes and isomers**
- **^{92,93}Rb, ^{95}Sr, ^{96}Y, ^{99}Y, ^{100m,100}Y, ^{100m}Nb, ^{100}Nb, ^{138}I and ^{142}Cs**

Existing TAS data (so far)



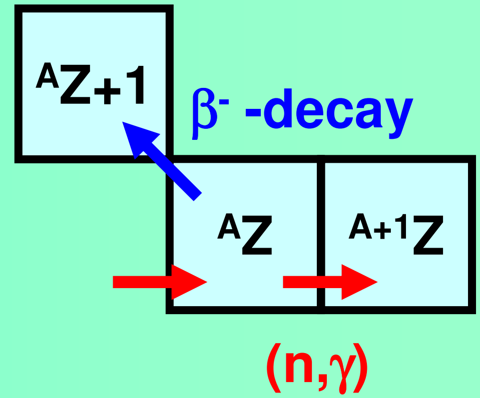
Neutron capture is the source of elements heavier than iron





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

The **interplay** between **β-decay** and **(n,γ)** determine the isotopic abundances



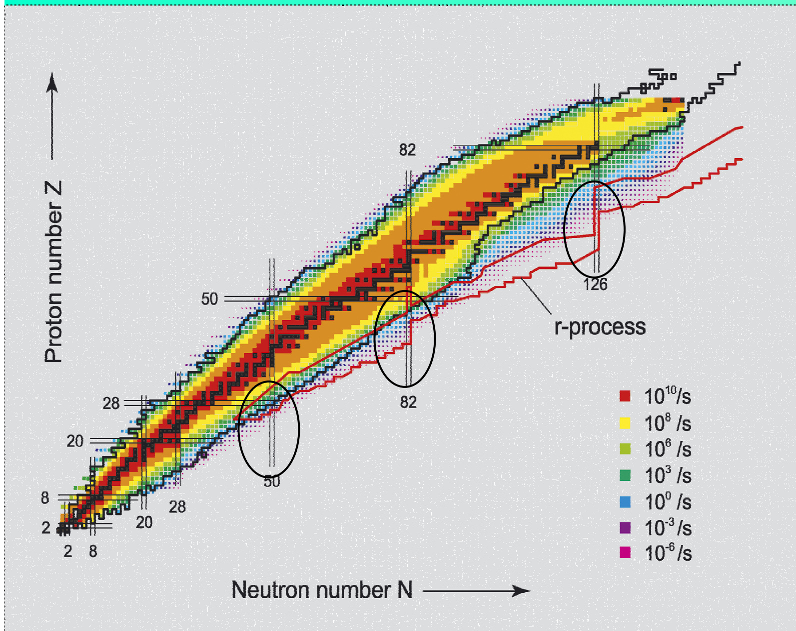
- For the **r-process** (very far from stability) the relevant quantity is $T_{1/2}$ (mostly theoretical)

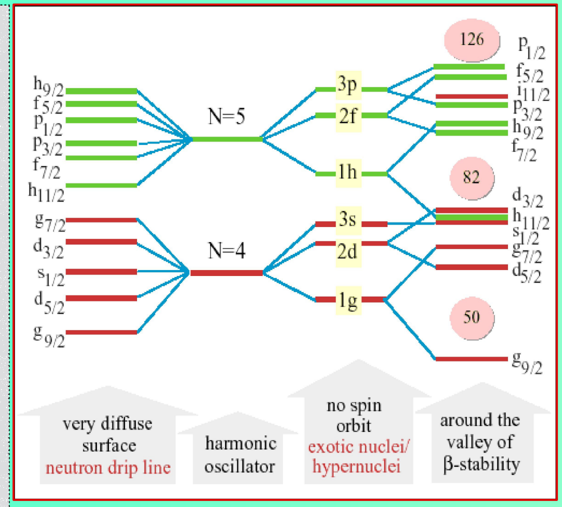
☞ trimming of the codes to reproduce S_β

Improving the predictive power of theoretical calculations

A related but more general nuclear structure question:

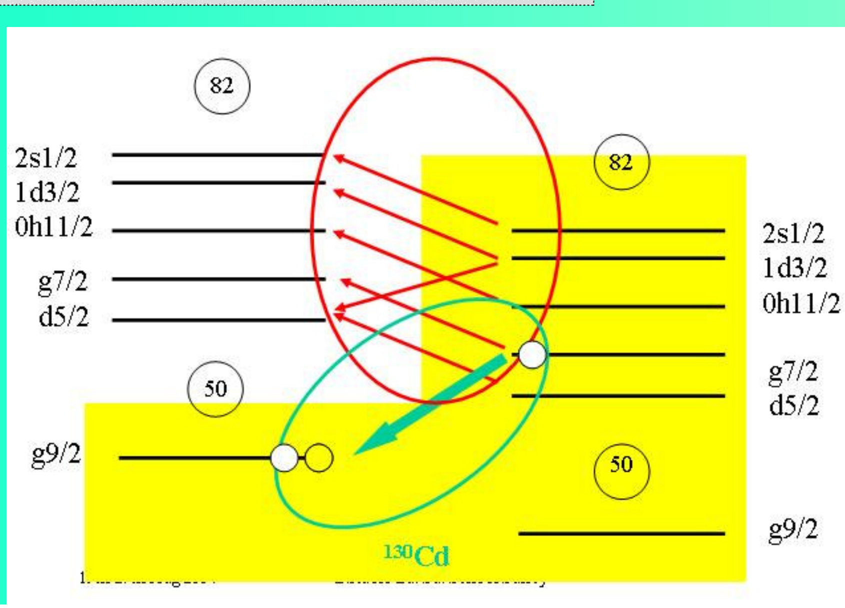
Is the shell structure altered at extreme isospin values?

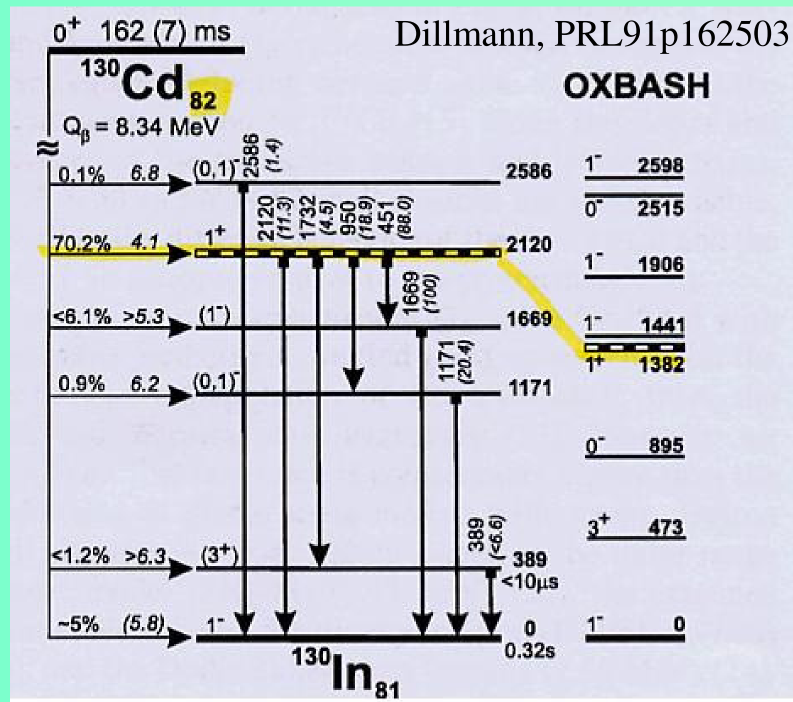




N=82 shell closure

The ^{130}Cd β-decay case: unplaced or missing strength

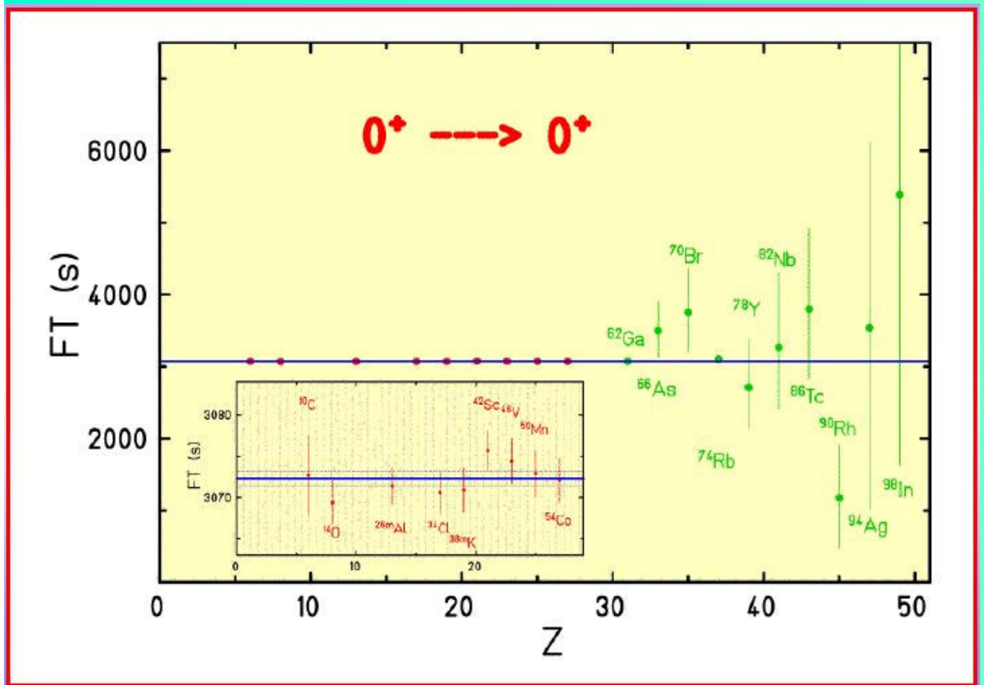




Test of the CVC hypothesis and unitarity of CKM matrix

Super-allowed $0^+ \rightarrow 0^+$ β-decay

$$ft = \frac{T_{1/2} \cdot f(Q_{EC})}{I_\beta}$$



$$Ft = ft(1+\delta_R')(1-\delta_C+\delta_{NS})$$

$$= \frac{K}{g_V^2(1+\Delta_R)\langle M_F \rangle^2}$$

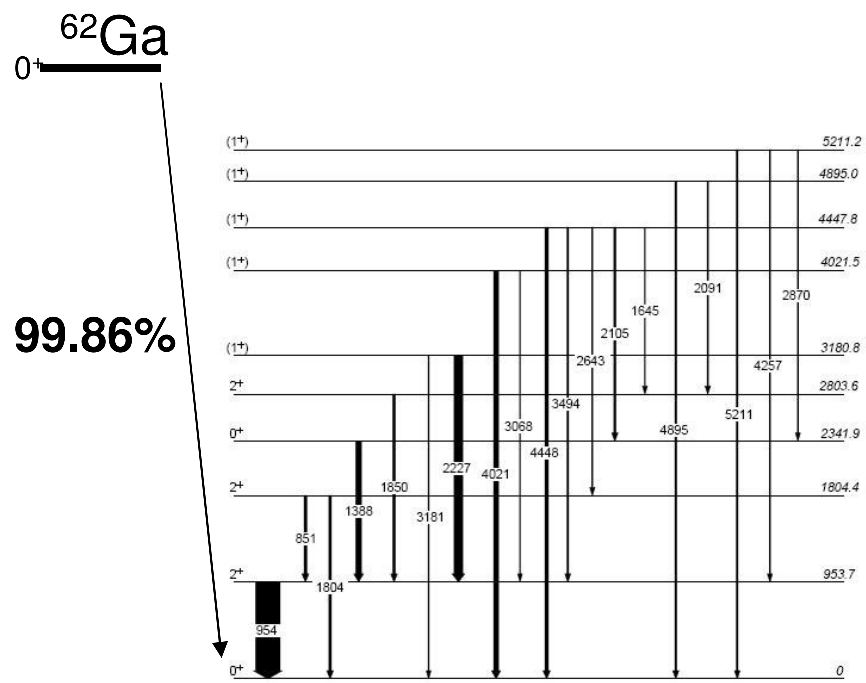
N=Z odd-odd nuclei:

^{62}Ga, ^{66}As, ^{70}Br, …, ^{94}Ag

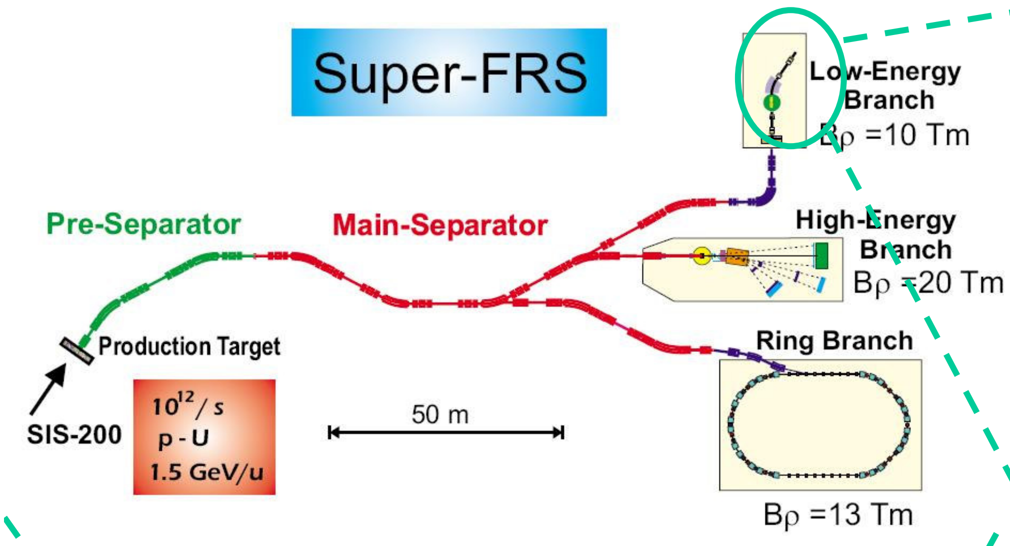
Use of TAS to detect high lying weak GT branches

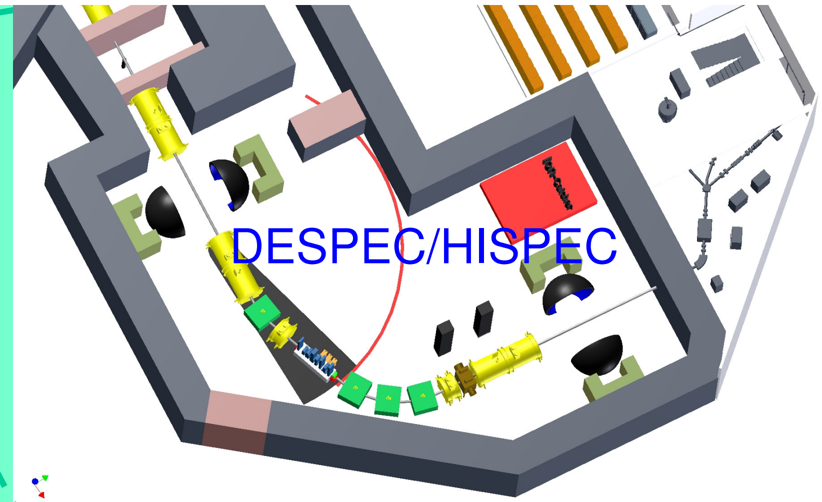
Hardy & Towner PRL88p252501

Precision of 10^{-3} !



Hyland, PRL97, 102501 ^{62}Zn

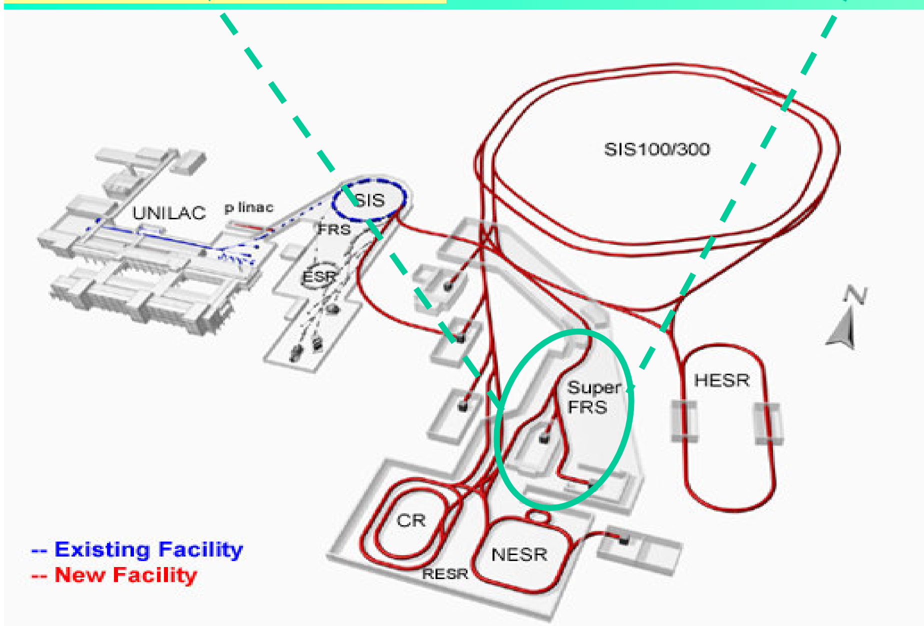




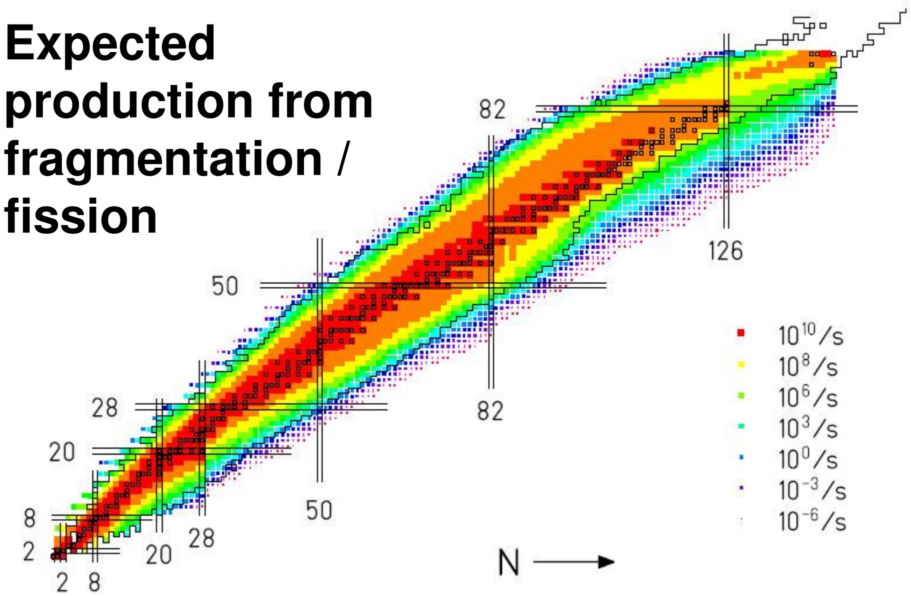
Facility for Antiproton and Ion Research

TAS for DESPEC experiment of the NUSTAR collaboration

Valencia, Madrid, Gatchina, Darmstadt, Debrecen, St. Petersburg, Surrey



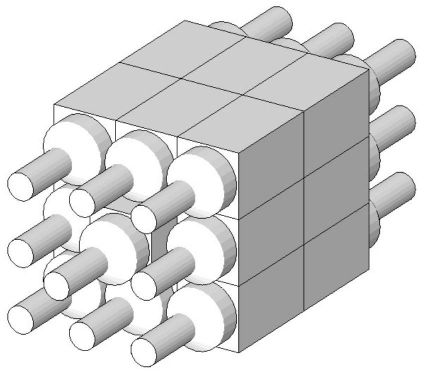
Expected production from fragmentation / fission



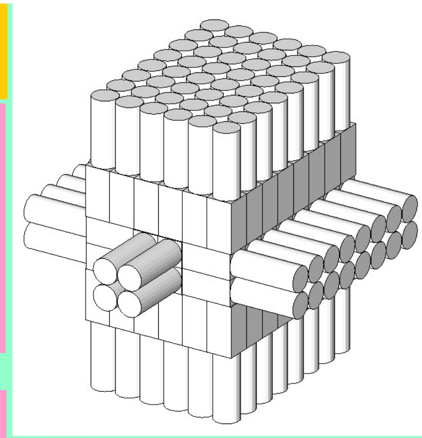
DESPEC TAS design choices

16 + 1 modules:
15×15×25 cm³ **NaI(Tl)**
+ 5” PMT (50% light col.)
V= 95 L, M= 351 kg

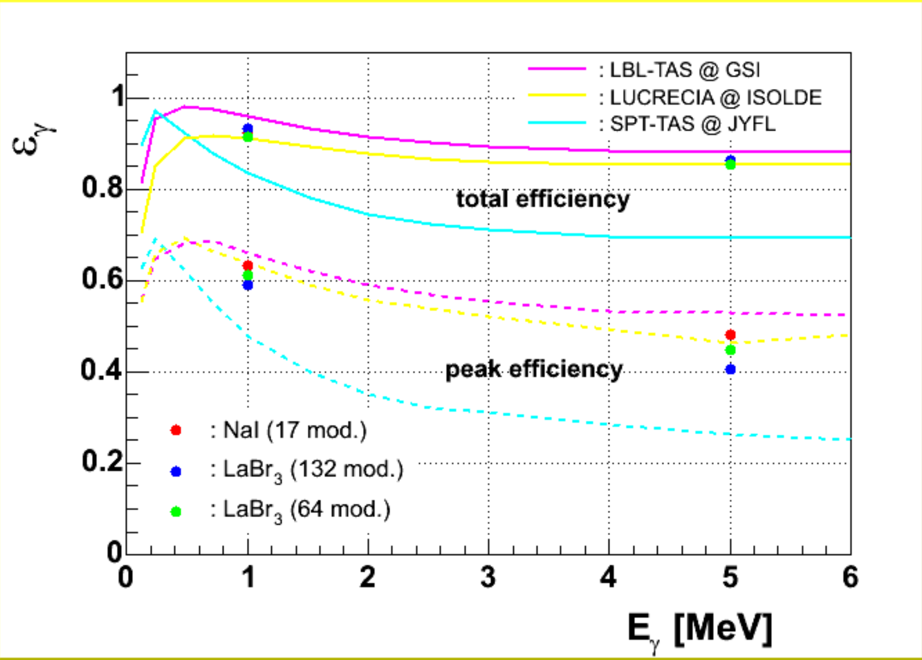
ΔE/E ~ 5%
(@1.3MeV)
Δt ~ 2 ns
τ ~ 230ns



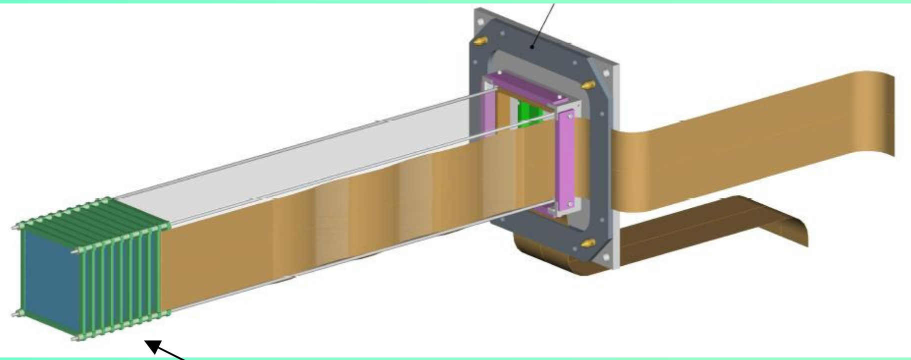
128 + 4 modules:
5.5×5.5×11 cm³ **$LaBr_3$:Ce**
+ 2” PMT (60% light col.)
V= 44 L, M= 223 kg



ΔE/E ~ 2%?
(@1.3MeV)
Δt ≤1 ns
τ ~ 26/160ns

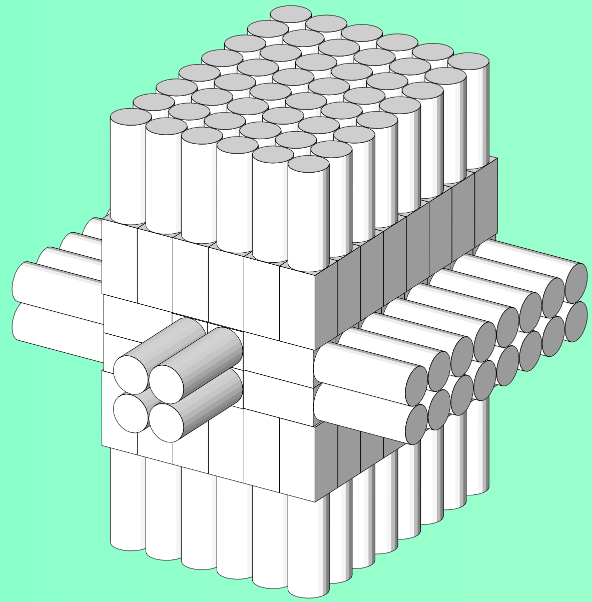


AIDA implantation setup



Stack of DSSSD

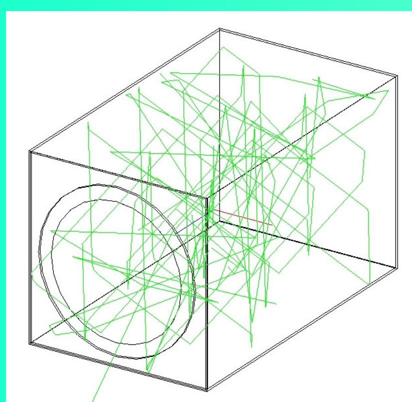
The $LaBr_3$ case (prototype module):

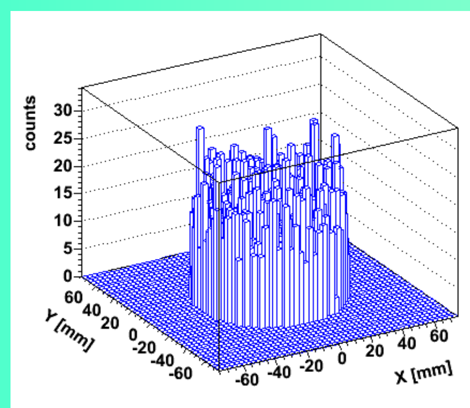


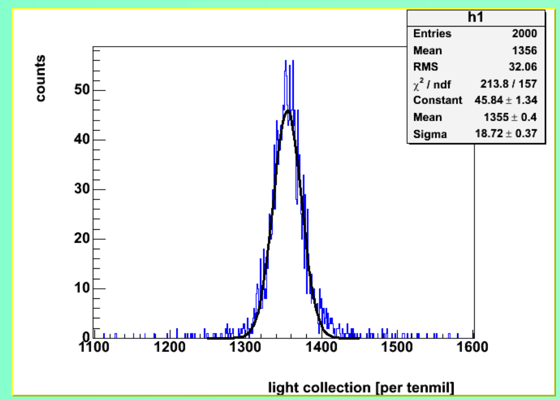
In discussion with Saint-Gobain Crystals:

- Energy resolution
- Dead material (housing/reflector/assembly)
- PMT´s, stabilization
- Mechanical construction
- Cost and delivery

In parallel MC simulation of performance:







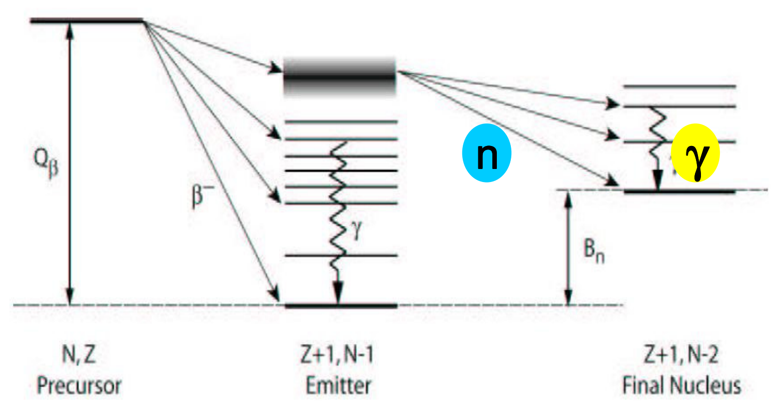
It can be converted into a low-resolution high-efficiency γ-ray array complementary/alternative to a Ge array

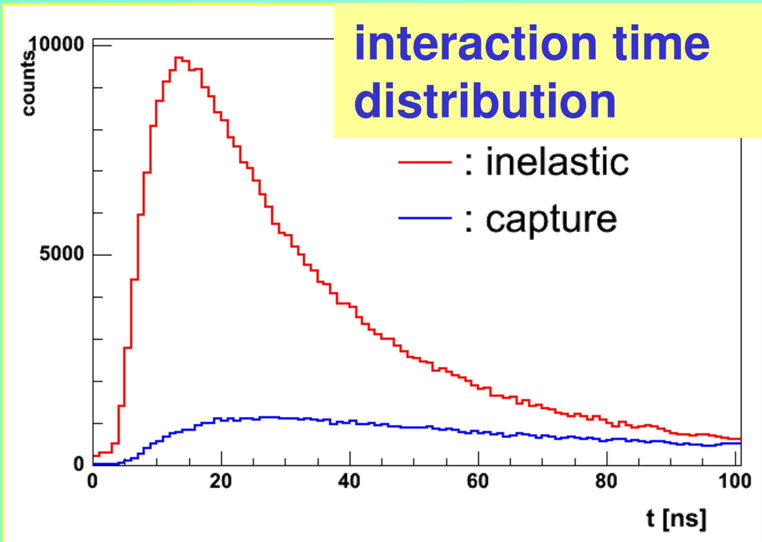
Neutron sensitivity

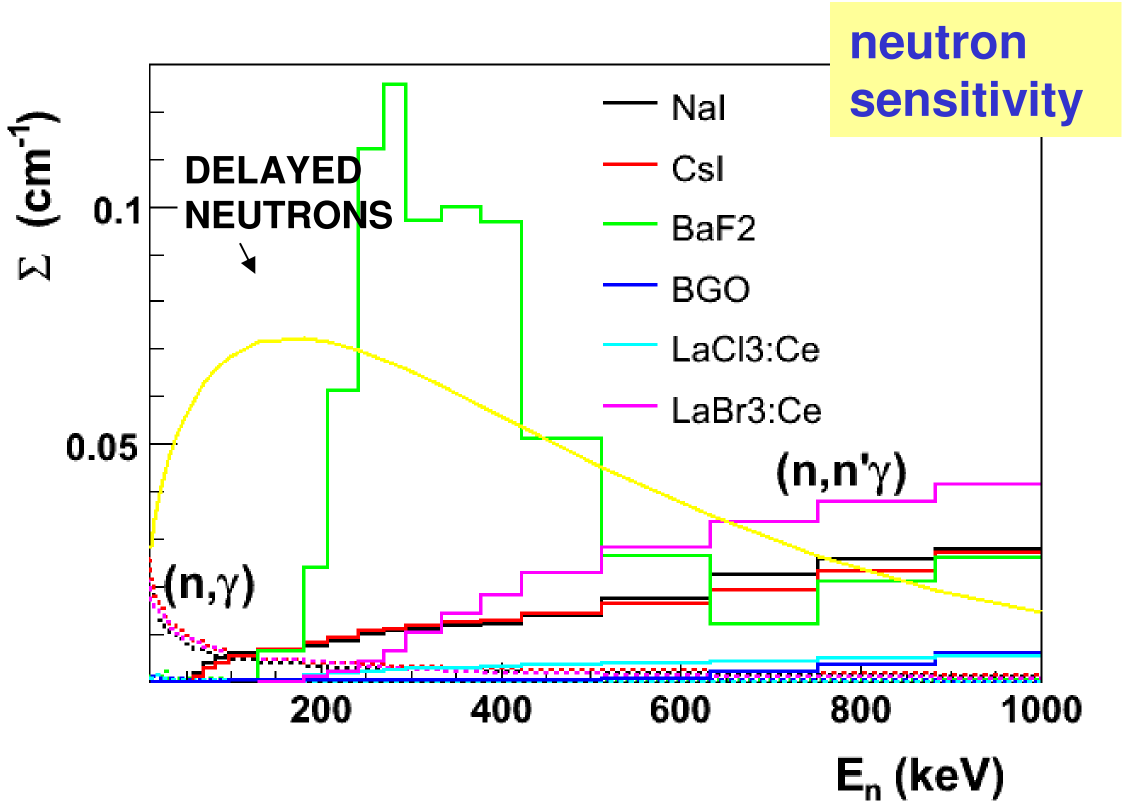
(The case of delayed neutron emitters)

• Monte Carlo simulations: ☞
MSc Thesis (D. Jordan, U. Valencia)

• n detection probability: NaI= 40% , BaF_2=60%
• Discrimination through timing (Δt < 5ns)



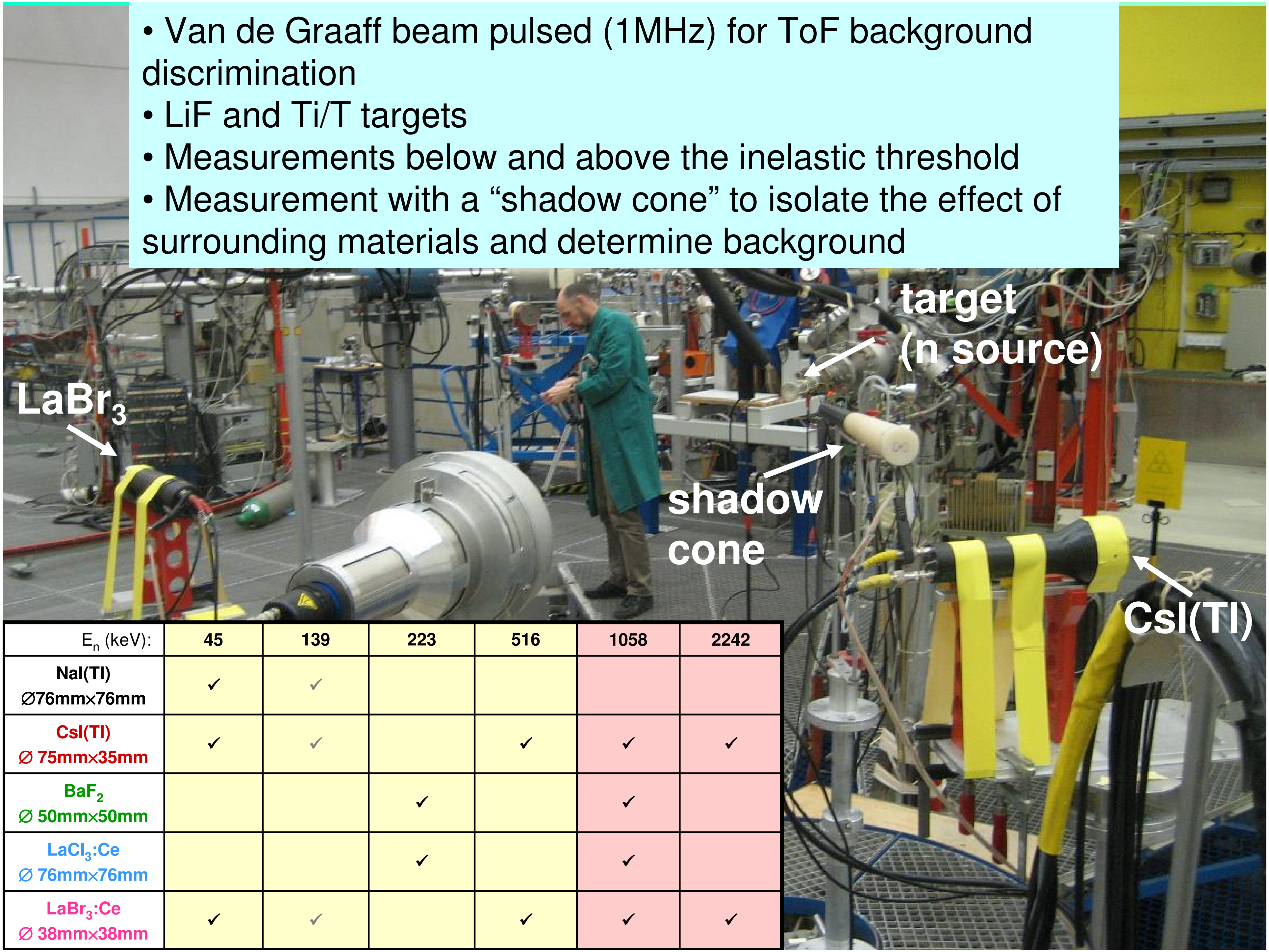




Validation of MC simulations through experimental tests:

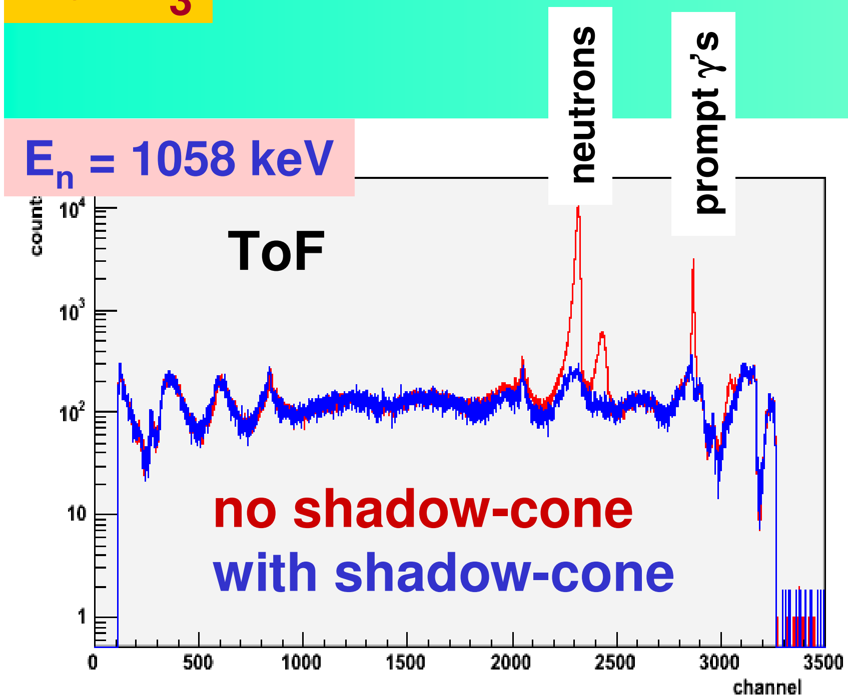
• **March, 9-13**
@ PTB-Braunschweig

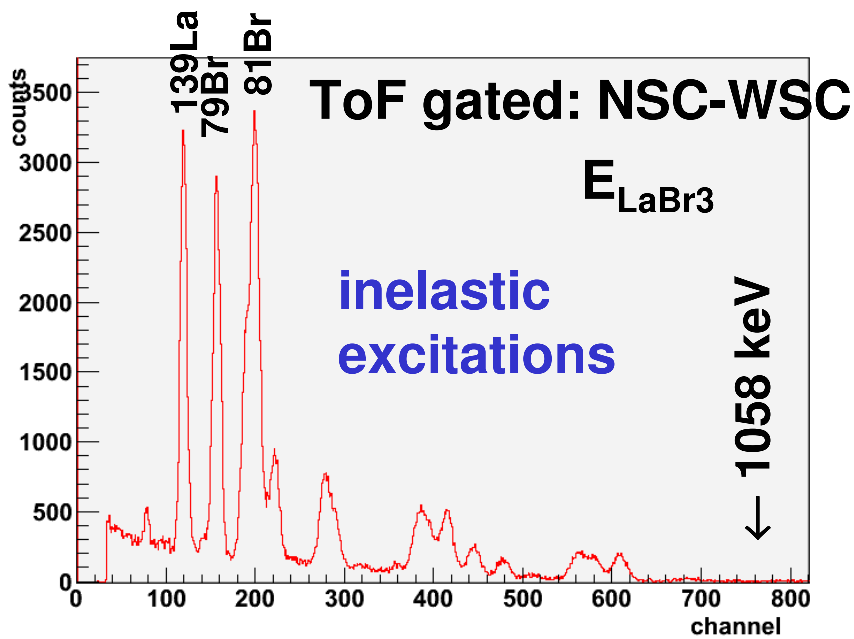
- Van de Graaff beam pulsed (1MHz) for ToF background discrimination
- LiF and Ti/T targets
- Measurements below and above the inelastic threshold
- Measurement with a “shadow cone” to isolate the effect of surrounding materials and determine background



E_n (keV):	45	139	223	516	1058	2242
NaI(Tl) ∅76mm×76mm	✓	✓				
CsI(Tl) ∅ 75mm×35mm	✓	✓		✓	✓	✓
BaF_2 ∅ 50mm×50mm			✓		✓	
$LaCl_3$:Ce ∅ 76mm×76mm			✓		✓	
$LaBr_3$:Ce ∅ 38mm×38mm	✓	✓		✓	✓	✓

$LaBr_3$



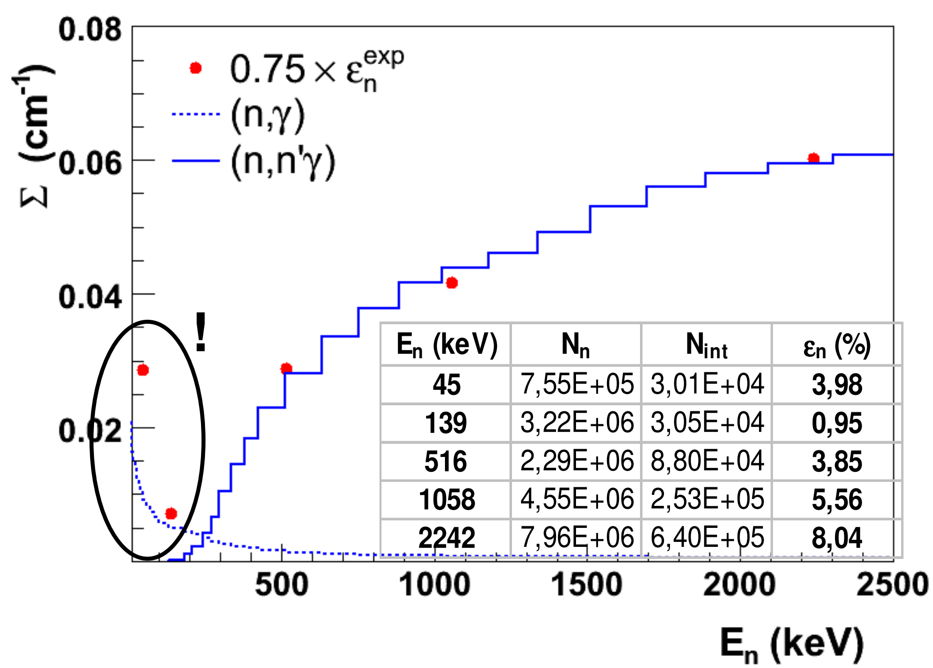


RESULTS:

- The result is only meaningful in comparison with MC simulations

MC simulations:

- need neutron reaction data for intervening isotopes: G4 missing information → new tool (CIEMAT)
- need proper γ-cascade generation:
capture: new model (IFIC)
inelastic: to be developed



E_n (keV)	N_n	N_{int}	ε_n (%)
45	7,55E+05	3,01E+04	3,98
139	3,22E+06	3,05E+04	0,95
516	2,29E+06	8,80E+04	3,85
1058	4,55E+06	2,53E+05	5,56
2242	7,96E+06	6,40E+05	8,04

THANK YOU!

Requirements for reliable TAS result

From the analysis point of view:

- **Response must be accurately known**:
  - → for all particles emitted: e-/e+, γ-ray, …
  - → response should depend "weakly" on de-excitation branching ratios
- **Solution of inverse problem must be stable**

NIM A430 (1999) 333
NIM A430 (1999) 488
NIM A571 (2007) 719
NIM A571 (2007) 728

From the experimental point of view:

Spectrum must be clean:

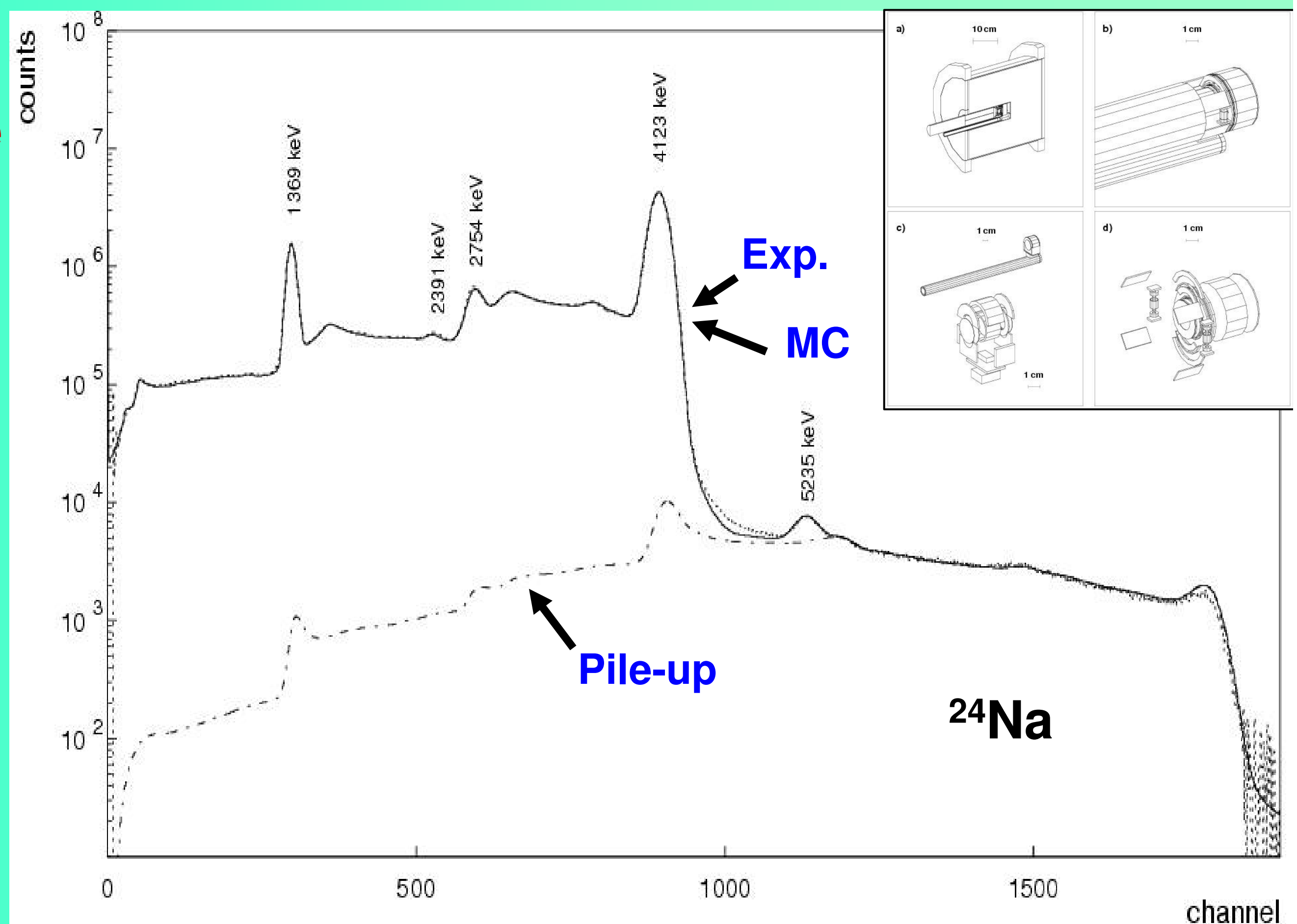
→ eliminate background and contaminations

- Production: clean (mass separators, traps, laser selective sources) or ion-per-ion identification
- Control of daughter activity
- Background reduction / measurement
- Spectrometer: highly efficient
- Spectrometer: good resolution
- Use of ancillary detectors

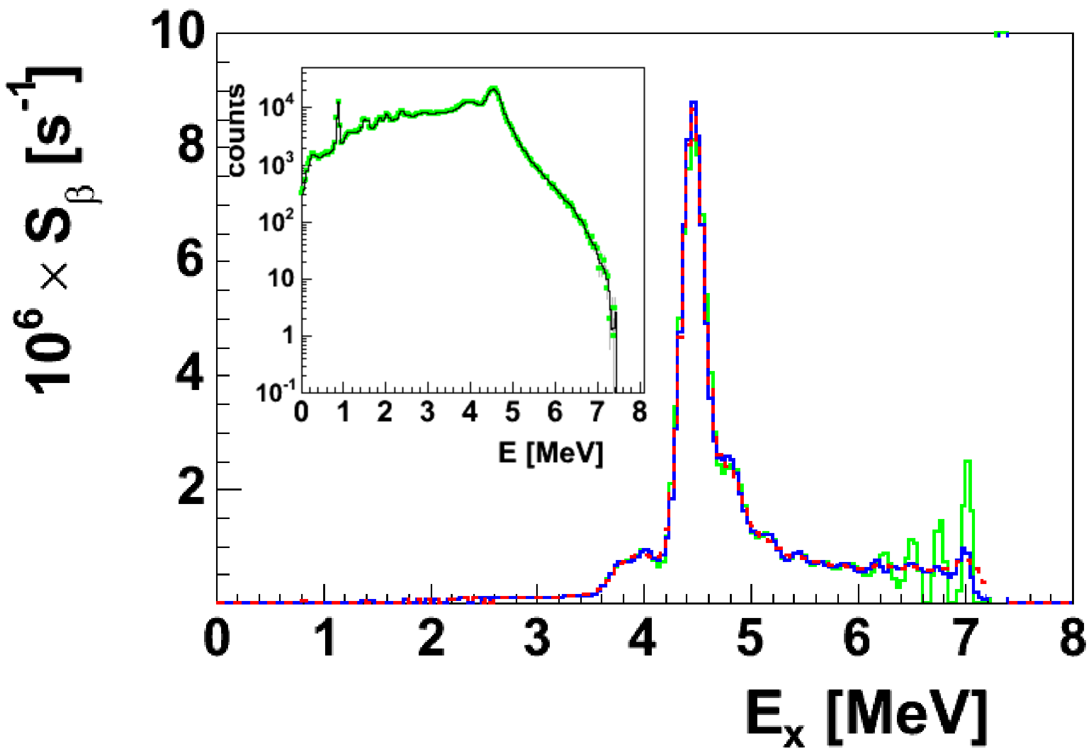
• During the past few years we have undertaken a **systematic investigation of** systematic uncertainties associated with the **analysis of TAS data**:

1. Demonstration of the accuracy of **Monte Carlo** simulations to obtain the spectrometer **response** (**Cano et al. NIMA430, p.333)**

2. Accurate calculation of pulse pile-up which constitutes an intrinsic background close to the end point **(Cano et al. NIMA430, p.488)**



3. Investigation of the adequacy of several **algorithms** for the solution of the TAS inverse problem **(Tain et al., NIMA 571, 728)**



LINEAR REGULARIZATION ☹
MAXIMUM ENTROPY ☺
EXPECTATION-MAXIMIZATION ☺

Result insensitive to algorithm parameters: λ, $\mathbf{B}$, $f^{(0)}$, n_{iter}, …

The two (three) algorithms agree within few %

LR method:
polynomial smoothing

$$\mathbf{f} = \left(\mathbf{R}^{\mathrm{T}} \cdot \mathbf{V}_{\mathbf{d}}^{-1} \cdot \mathbf{R} + \lambda \mathbf{B}^{\mathrm{T}} \cdot \mathbf{B}\right)^{-1} \cdot \mathbf{R}^{\mathrm{T}} \cdot \mathbf{V}_{\mathbf{d}}^{-1} \cdot \mathbf{d}$$

ME method:
entropy maximization

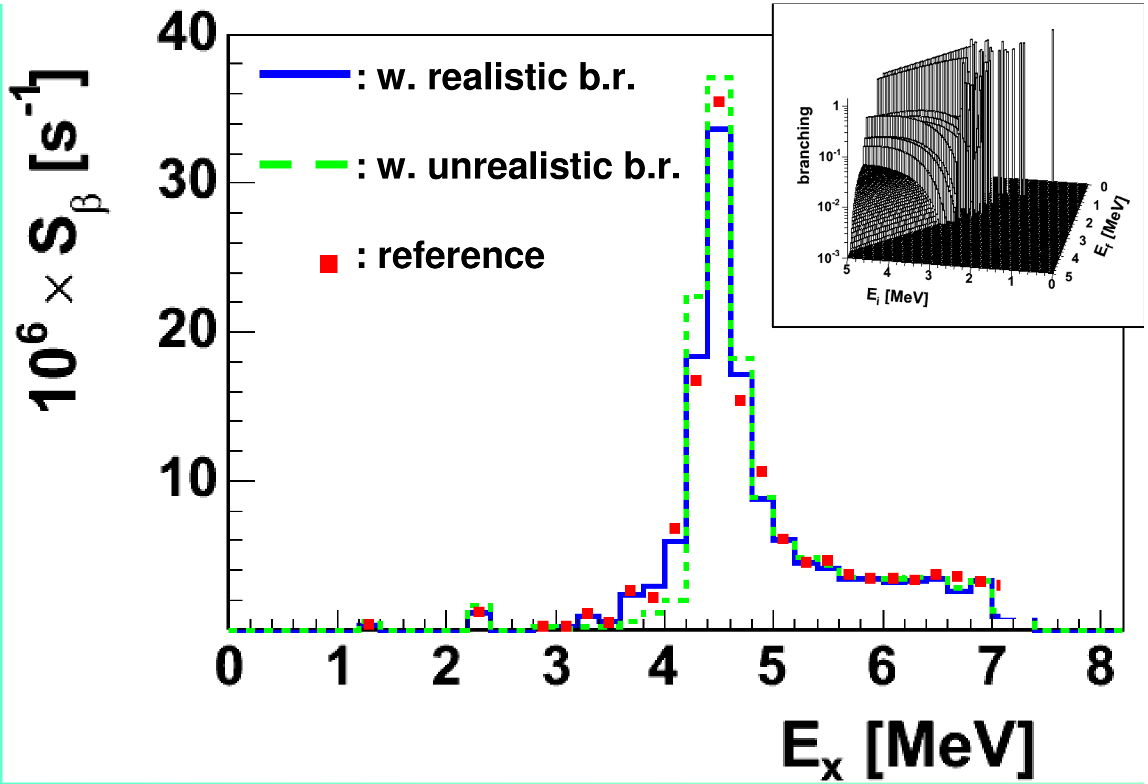
$$f_j^{(s+1)} = f_j^{(s)} \exp\left(\frac{2}{\lambda} \sum_i \frac{R_{ij}}{\sigma_i^2}\left(d_i - \sum_k R_{ik} f_k^{(s)}\right)\right)$$

EM method:
Bayes Theorem

$$f_j^{(s+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} f_j^{(s)} d_i}{\sum_k R_{ik} f_k^{(s)}}$$

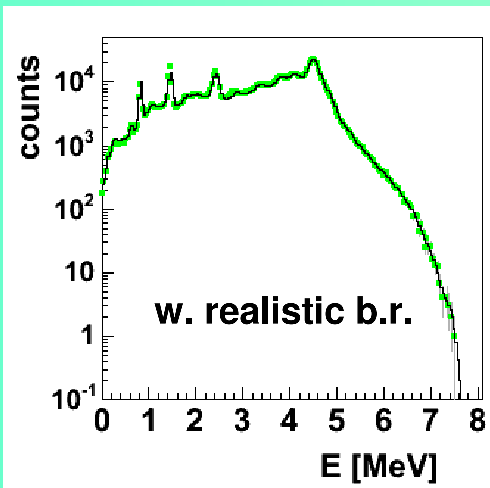
λ: regularization parameter, $\mathbf{B}$: regularization matrix, $\mathbf{V_d}=[1/\sigma_i^2]$: covariance matrix of data

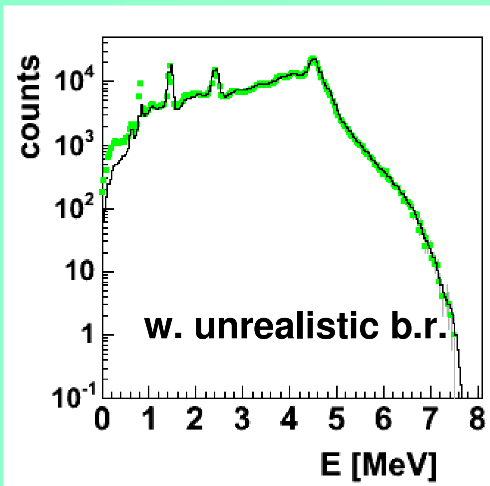
4. Investigation of the dependency of the result on the **assumption** about the cascade **branching ratios** **(Tain et al., NIMA 571, 719)**



Needs to know the true branching ratios and intensity → use statistical nuclear model to create decay of fictitious nucleus

S_β at high energies (level densities) and ΣS_β is rather insensitive to b.r.





Rebinning of:

$$\mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

introduces non-negligible effect