β-Decay Total Absorption Gamma-Ray Spectroscopy: Principles and Applications

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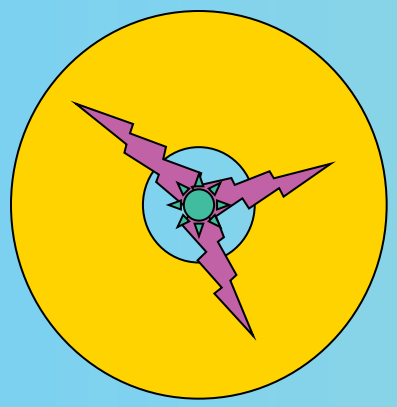
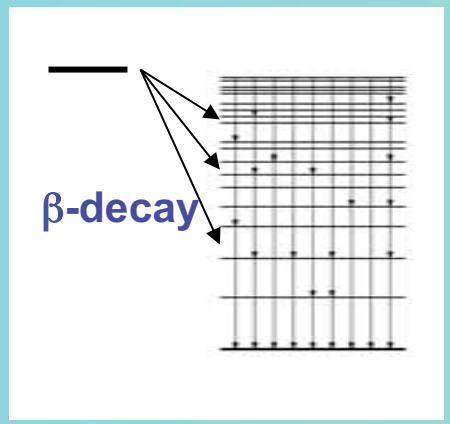
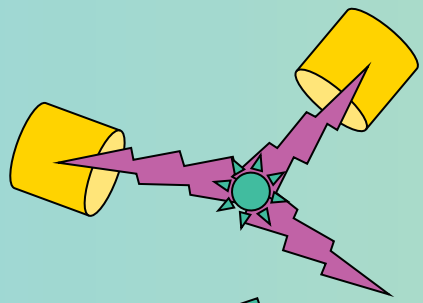
The TAS technique

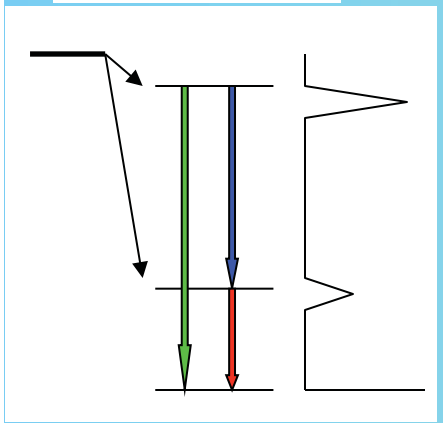
- **T**otal **A**bsorption **S**pectroscopy is the **best** method **to measure** beta **intensities/strengths in β-decay for complex decay schemes**
- Uses **large 4π scintillation detectors**, aims **to detect the full γ-ray cascade** rather than individual γ-rays
- **Avoids the "Pandemonium effect"** (misplacement of β-intensity) of the high resolution spectroscopy



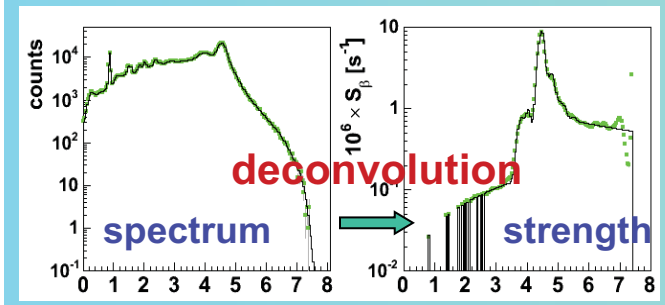


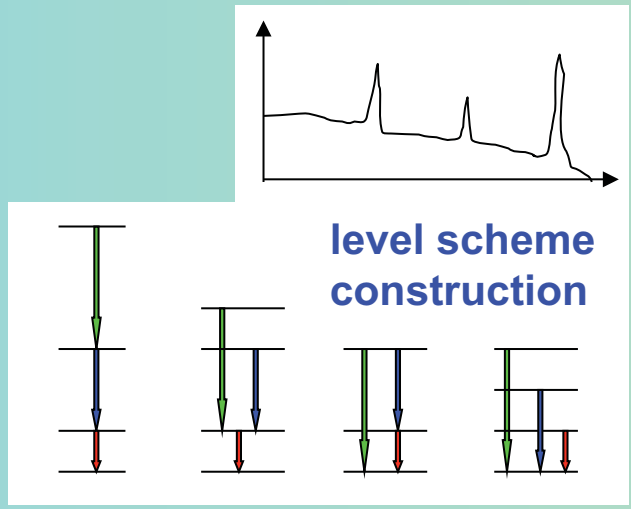


Ideal TAS

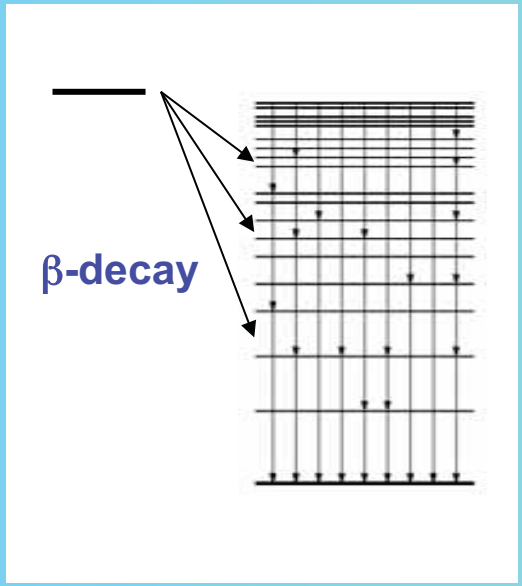


Real TAS: $\mathbf{d} = \mathbf{R} \cdot \mathbf{f}$

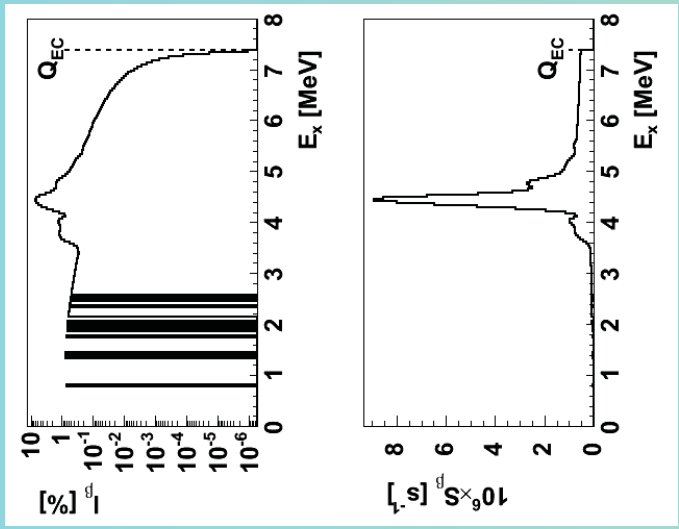




A TAS measures accurately the β-intensity I_β (or β-strength S_β)



INTENSITY STRENGTH



Relation between S_β and I_β:

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

Experimental:
- **Q_β -value**
- **Half-life $T_{1/2}$**
- **Intensity I_β**

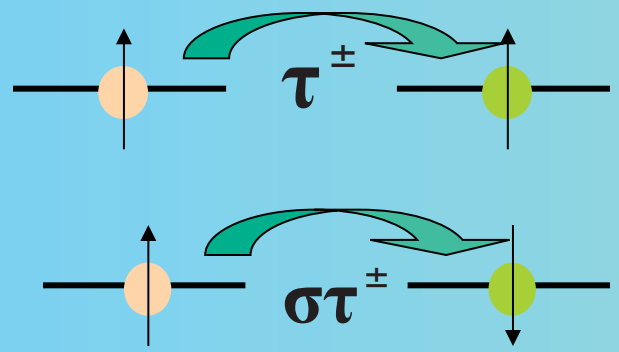
Relation between B and S_β:

$$S_\beta(E_x) = \frac{B_{i\to f}}{D}$$

Theoretical:
- **reduced transition probabilities B [$g_v^2/4\pi$]**

Large level densities: averaged quantities.

• β-decay is a "simple" process which is very sensitive to the nuclear wave function



Fermi / Gamow-Teller:

$$B_{i\to f} = \left|\left\langle \Psi_f \middle| \tau^{\pm} \text{ or } \sigma\tau^{\pm} \middle| \Psi_i \right\rangle\right|^2$$ **(allowed: *l=0*)**

transition probability or strength

• An accurate knowledge of the distribution of the β-decay probability over the daughter-nucleus levels provides information about the structure of nuclei and improves the predictive power of nuclear models as those used in astrophysical process calculations

• The β-intensity distribution largely determines the spectra of emitted particles which is of importance for practical applications notably in the field of nuclear technology

$$\beta^- : {}^A Z \to {}^A(Z+1) + e^- + \bar{\nu}_e$$

$$\beta^+ : {}^A Z \to {}^A(Z-1) + e^+ + \nu_e$$

$$EC: {}^A Z + e^- \to {}^A(Z-1) + \nu_e$$

ISOLDE/OSIRIS TAS:

Duke et al. NP A151 (1970) 609
Hornshoj et al. NP A239 (1975) 15

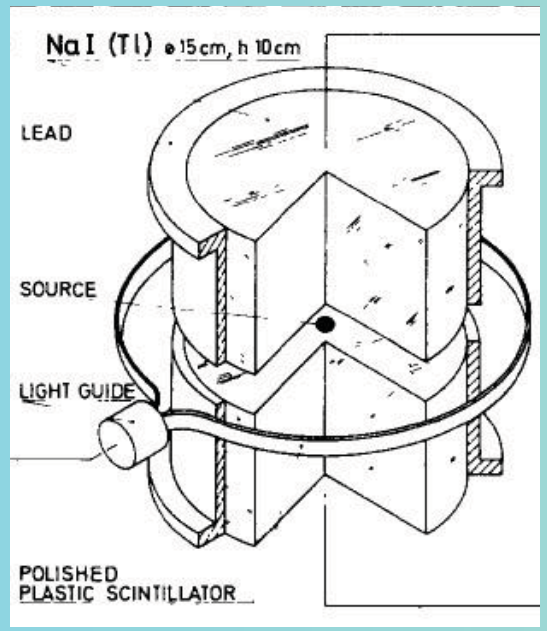
2× Ø15cm×10cm cryst.
+ Plastic scin. ring

E_γ = 1 MeV		E_γ = 5 MeV	
ε^P	ε^T	ε^P	ε^T
0.28	0.65	0.15	0.50

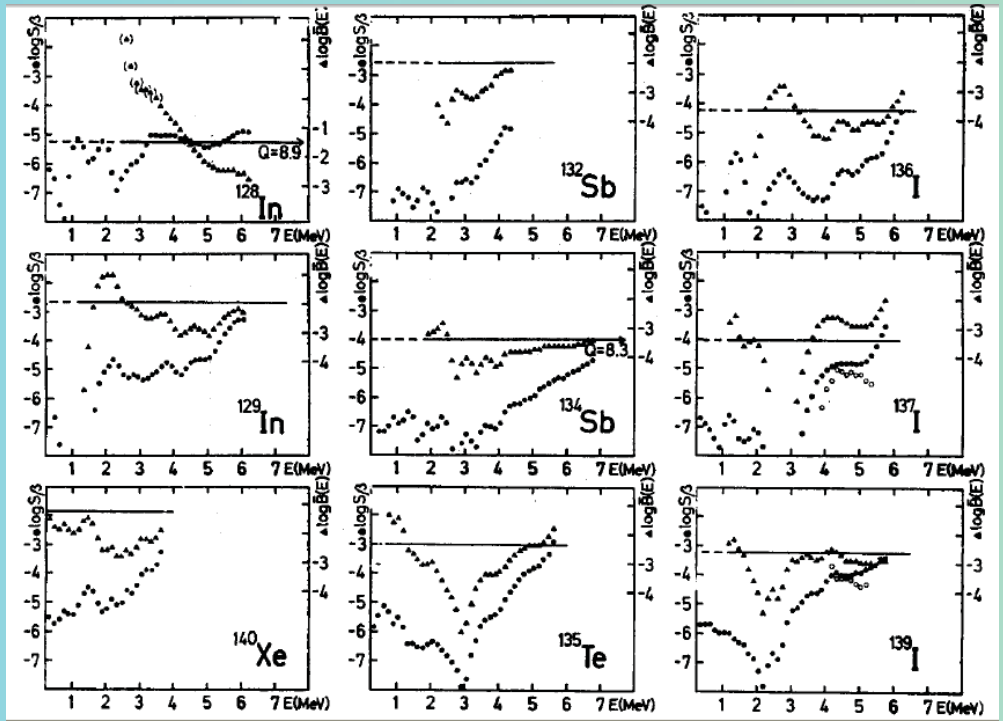
$$\varepsilon_{TAS}^{TOTAL} = 1 - \prod_i \left(1 - \varepsilon_{\gamma i}^{TOTAL}\right)$$

$$\varepsilon_{TAS}^{PEAK} = \prod_i \varepsilon_{\gamma i}^{PEAK}$$

- "Approximate" S_β
- Global properties
- 60 neutron deficient I, Xe, Ir, Pt, Au, Hg, Bi, Po, At, Rn
- 77 fission products



Analysis:
- **γ response from experiment + inter/ extrapolation**
- **nuclear statistical model cascades**
- **Gold-Scofield iterative deconv.**

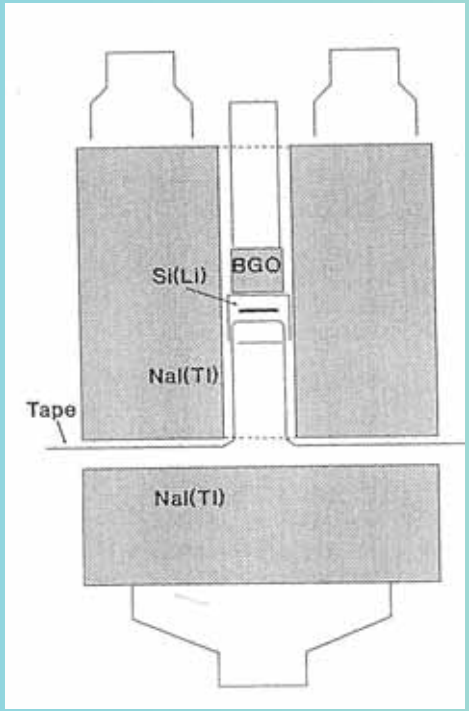


LNPI TAS:

Bykov et al. IAN SSSR 44 (1980) 918

Ø20cm×30cm (2 cryst.) + Si det

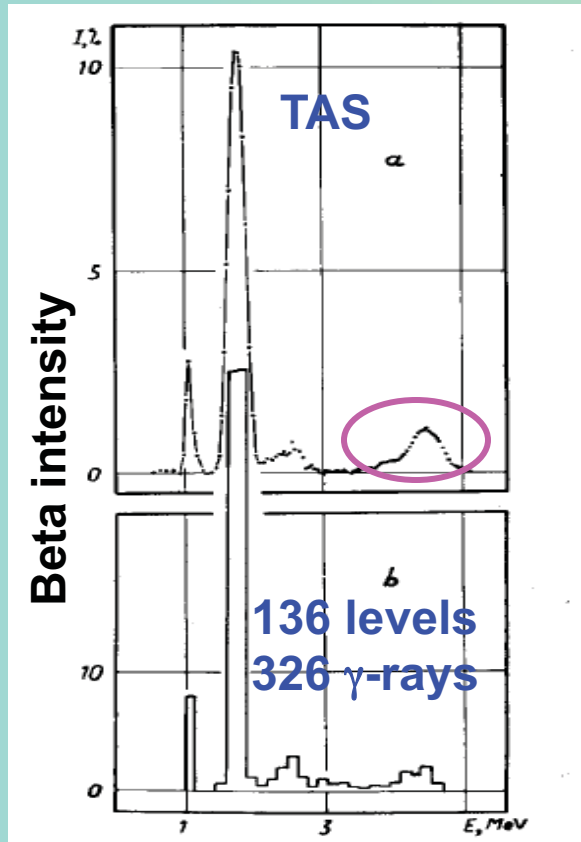
E_γ = 1 MeV		E_γ = 5 MeV	
ε^P	ε^T	ε^P	ε^T
0.44	0.83	0.25	0.68



Analysis:
- **γ and β response from own MC code**
- **cascades by hand**
- **"peel-off" method of deconvolution**

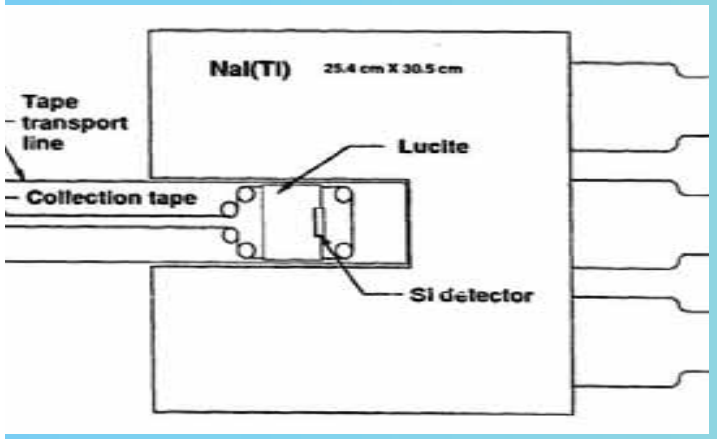
- **Some 50 decays investigated**
- **Nuclear structure effects on S_β**
- **Used also to measure Q_β**
- **Later used at GSI and JYFL**

Alkhazov et al., PLB157, p350: Confirmation of "Pandemonium effect" in 145Gd



INEL TAS:

Greenwood et al. NIM A314 (1992) 514 & A390 (1997) 95

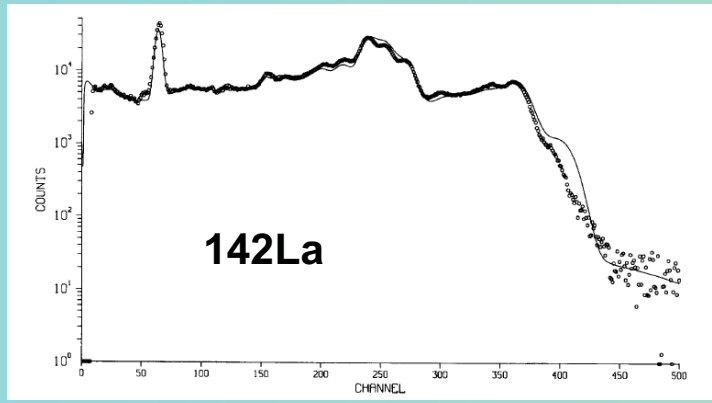


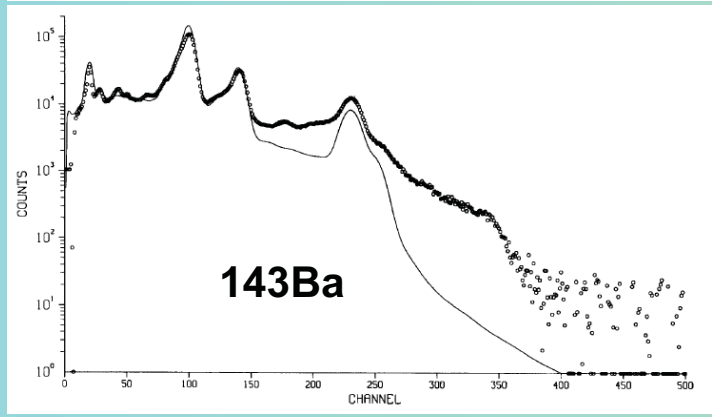
E_γ = 1 MeV		E_γ = 5 MeV	
ε^P	ε^T	ε^P	ε^T
0.64	0.89	0.41	0.76

Analysis:
- **γ and β response from CYLTRAN**
- **cascades by hand**
- **trial-error (no deconvolution)**

Ø25cm×30cm well + Si det.

- **Beta-intensity measured for 48 fission products**
- **Incorporated into ENSDF**
- **They also measured g.s. feed**
- **Now at ANL**



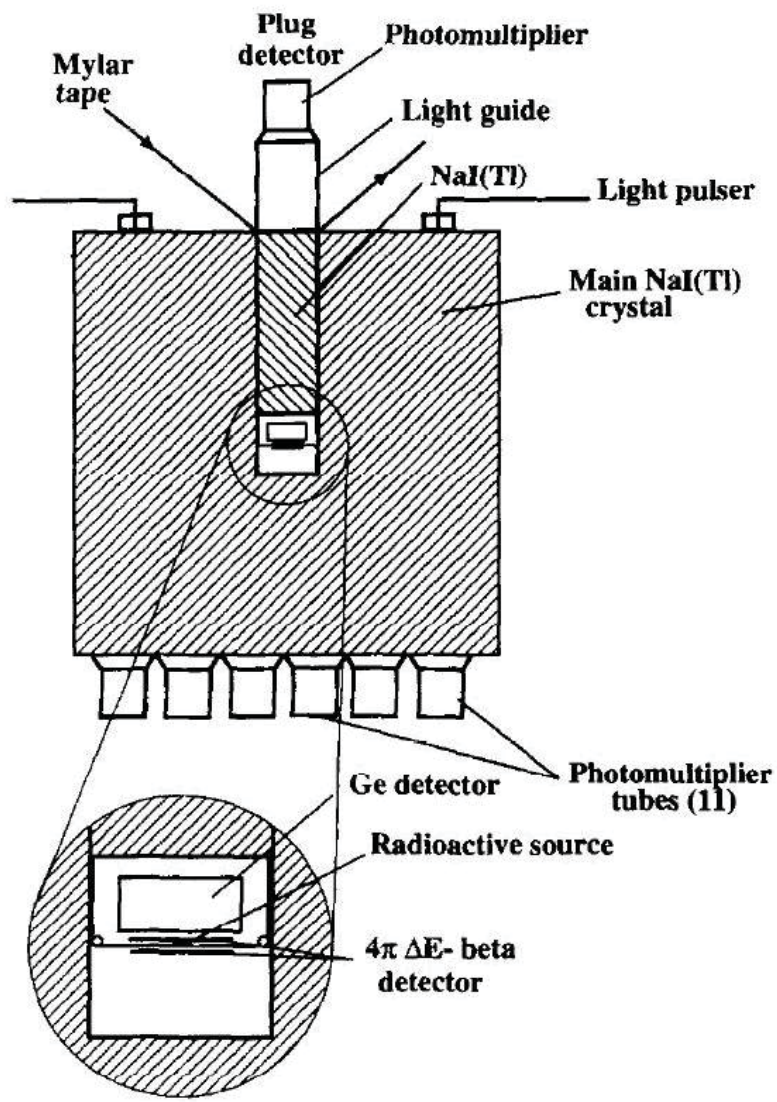


LBL TAS @ GSI:

Karny et al. NIM B126 (1997) 411

Main characteristics

- **true 4π geometry**
- **Ø35cm×35cm NaI well crystal + NaI plug**
- **ancillary detectors:**
  - **Ge detector: X-rays (EC) and γ-rays**
  - **Si detector (β-particles)**
  - **Si telescope (p- and α-particles)**



- **Systematic investigation of GT + strength function in 100Sn (14 nuclei), 146Gd (6 nuclei) and 56Ni (2 nuclei) regions**

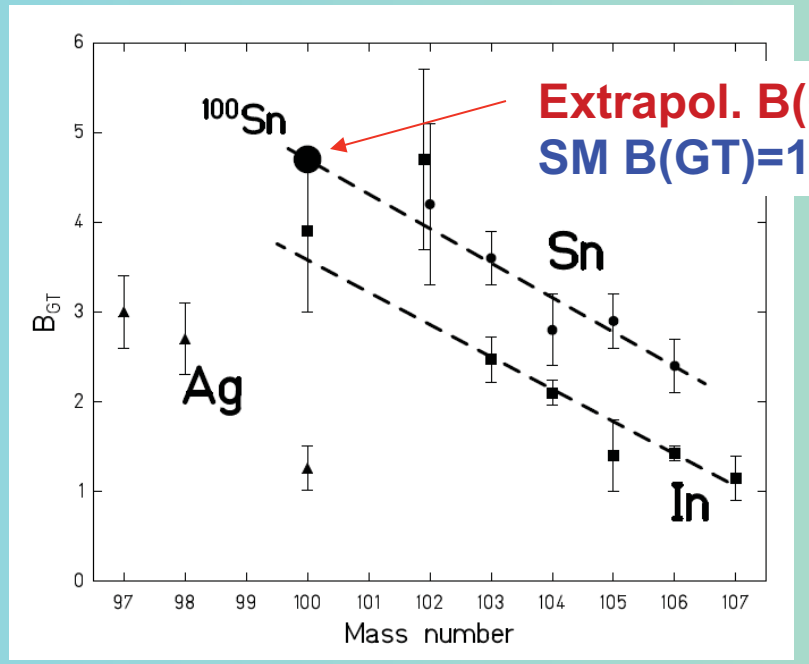
Background is an important source of systematic uncertainty in TAS measurements

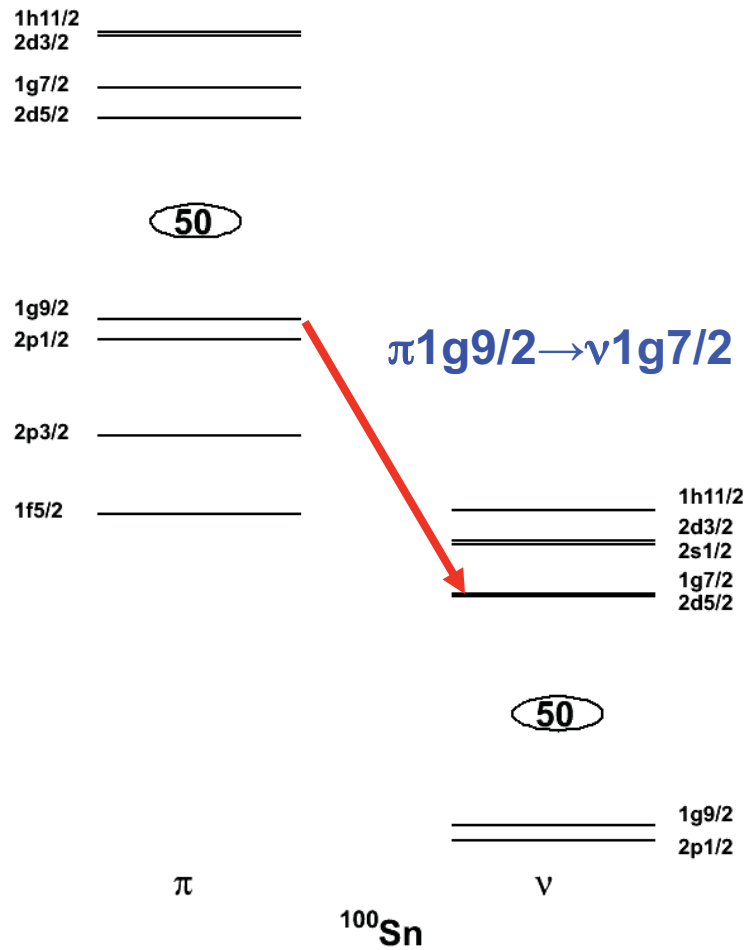
E_γ = 1 MeV		E_γ = 5 MeV	
ε^P	ε^T	ε^P	ε^T
0.65	0.97	0.52	0.89

Gamow-Teller strength around ^{100}Sn

In general the bulk of the β-strength lies outside the Q_β window. Exception: β+/EC for A~150, A~100, N~Z.

Karny et al., EPJ, A25(05)135





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

Relation between TAS data and the β-intensity distribution:

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

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

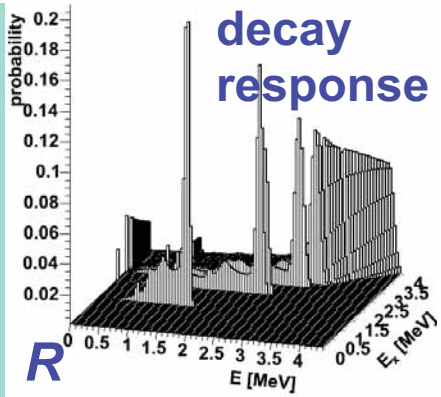
$$I_i = f_i \Big/ \sum_k f_k$$

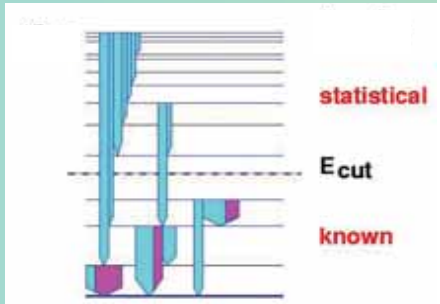
Deconvolution algorithms (inverse problem): EM, ME & LR

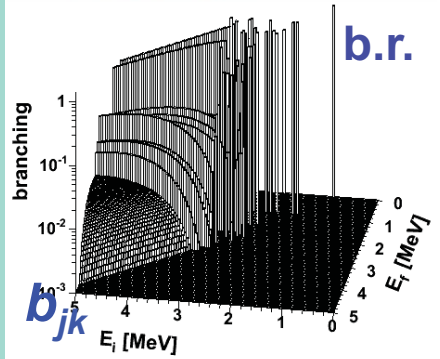
R_j: decay response for level j
b_{jk}: branching ratios j→k, from known level scheme and nuclear statistical model
g_{jk}: γ-ray response j→k, from Monte Carlo simulations

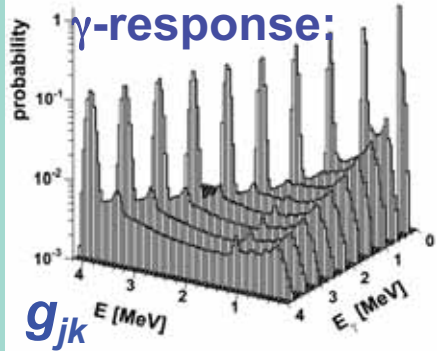
The response should contain also the particle penetration, CE effect, isomer effect, …

NB: The TAS technique is not sensitive to g.s. feed BUT a TAS + β-detector can be used to obtain $I_\beta^{g.s.}$





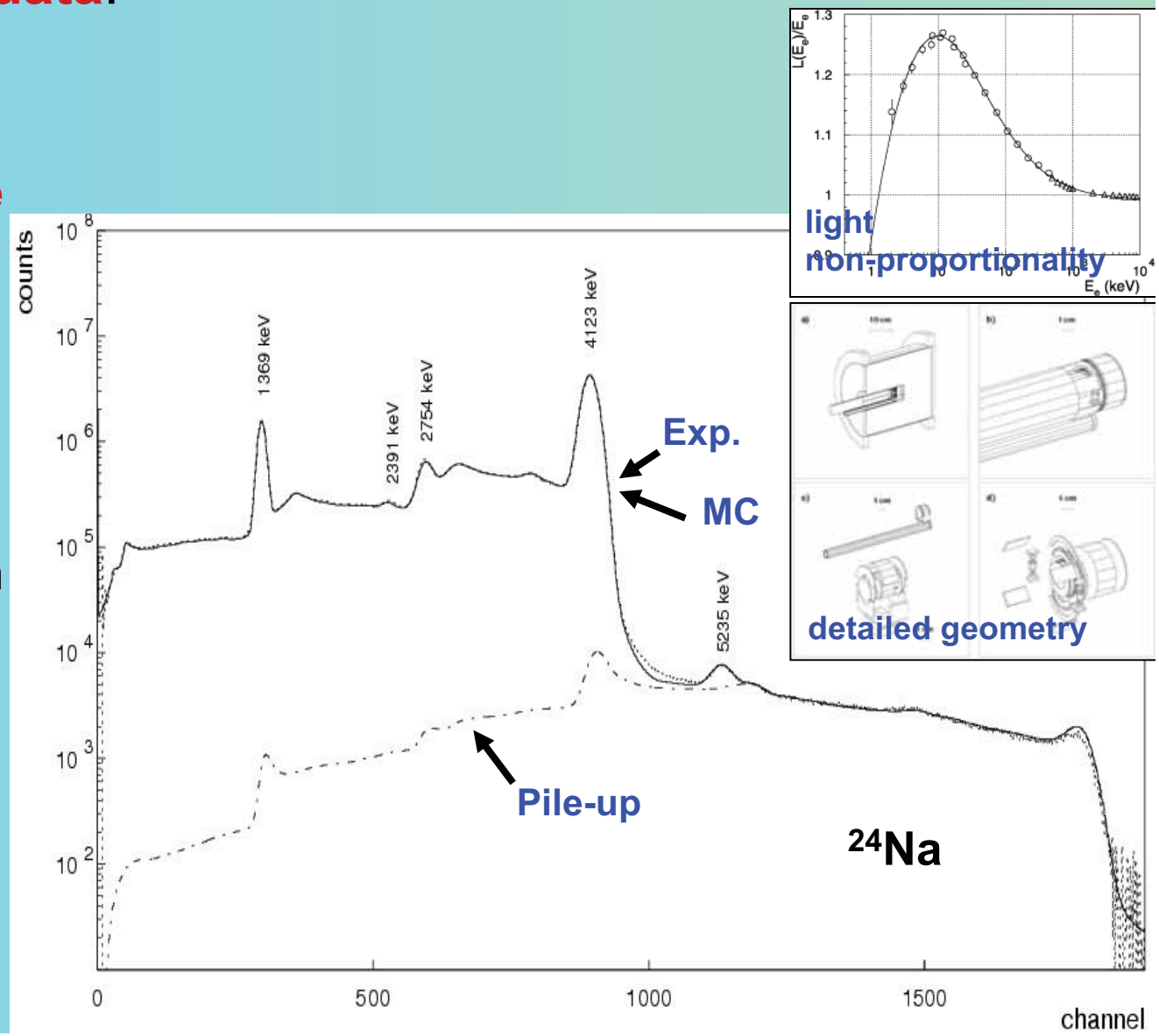




• During the past few years we have undertaken a **systematic investigation of** systematic uncertainties associated with the **analysis of TAS data**:

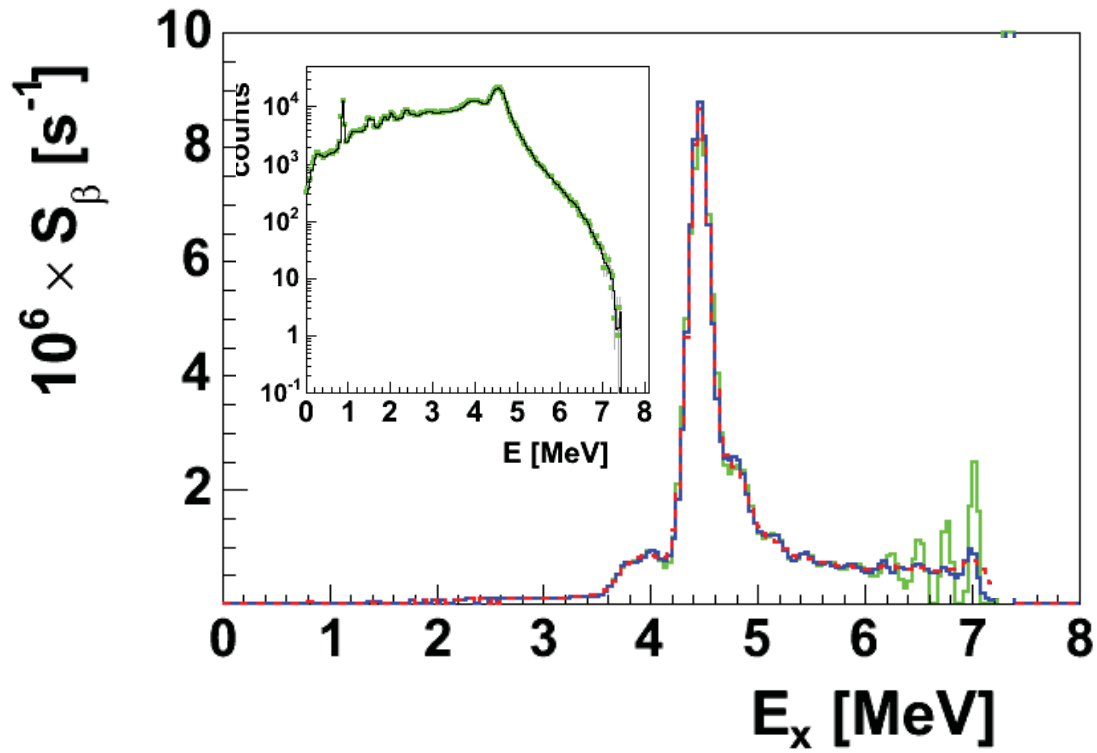
1. Demonstration of the accuracy of **Monte Carlo** simulations to obtain the spectrometer **response** (**Cano et al. NIMA430, p.333)**

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

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

ME method: entropy maximization

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

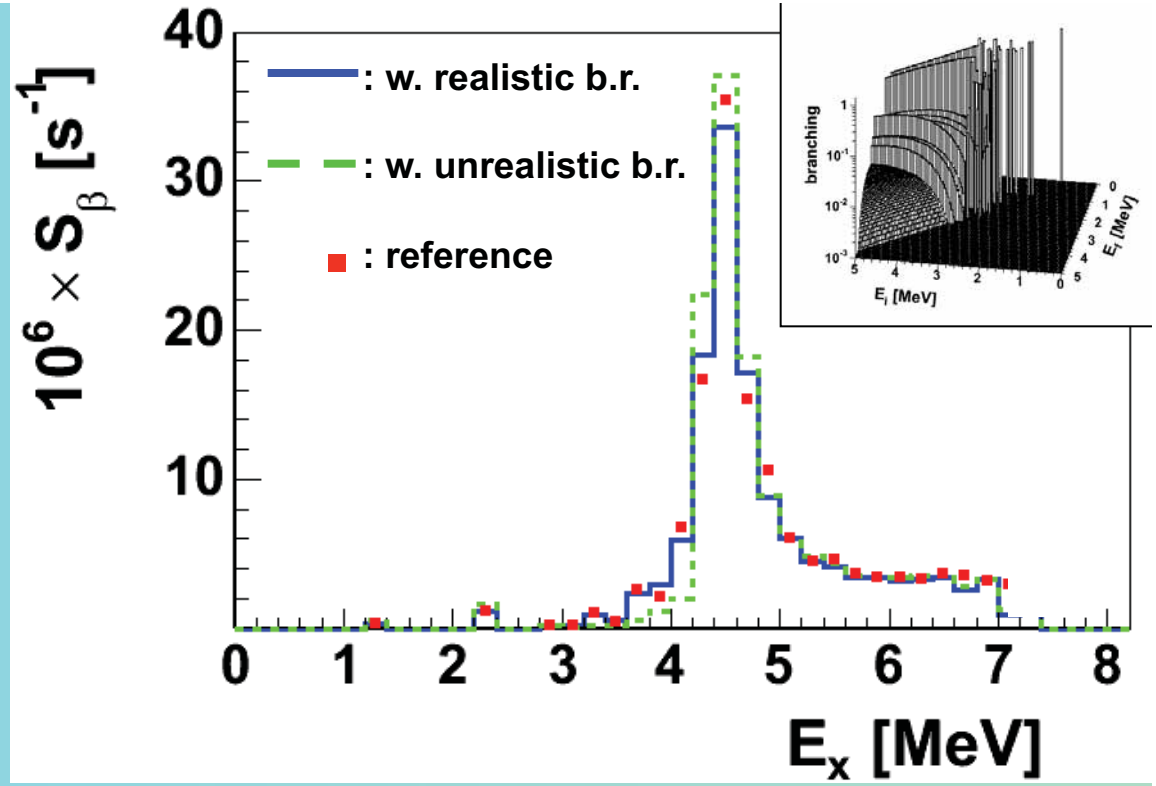
EM method:
Bayes Theorem

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

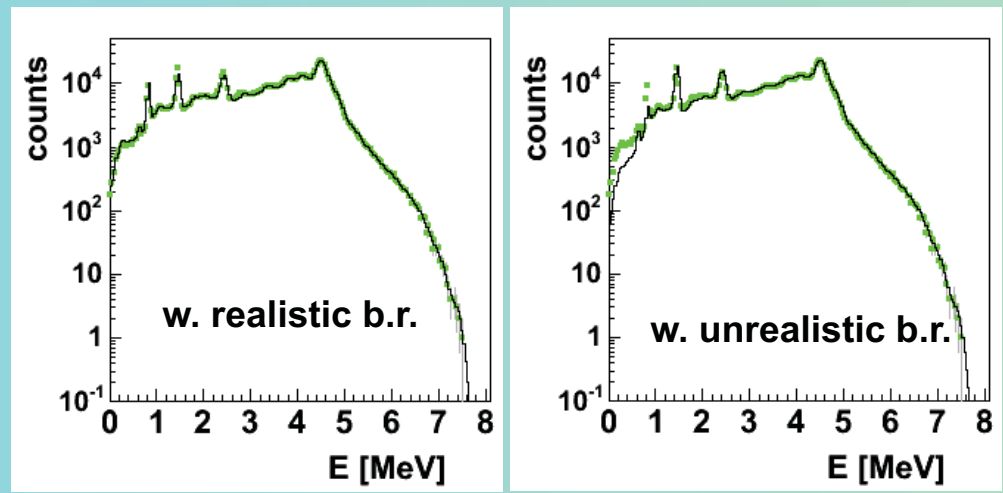
λ: regularization parameter, $\mathbf{B}$: regularization matrix, $\mathbf{V_d}=[1/\sigma_i^2]$: covariance matrix of data

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

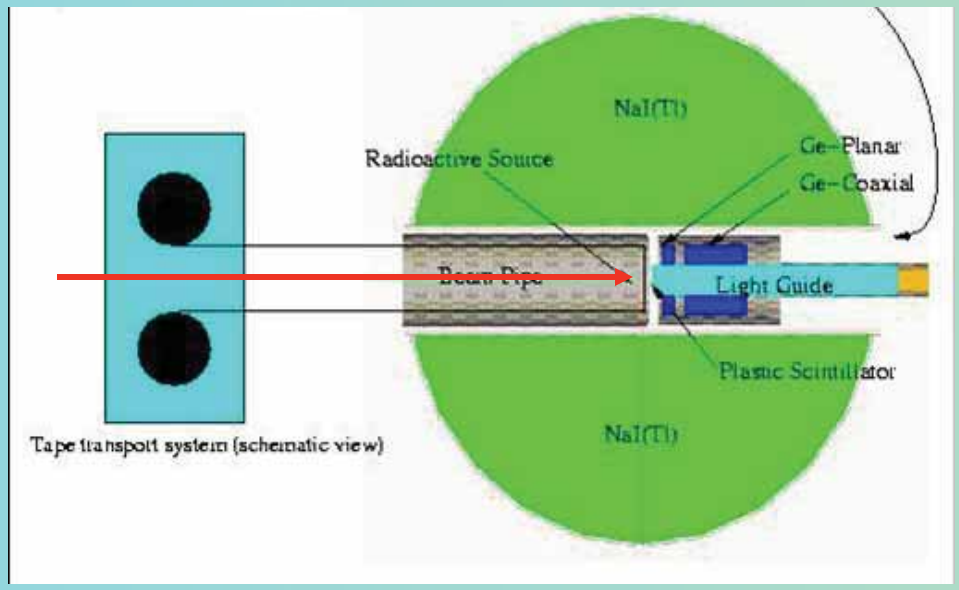
Lucrecia @ ISOLDE:

Rubio et al. JP G31 (2005) S1477

Ø38cm×38cm (tr. hole)
+ Ge det. + Plastic scin.

E_γ = 1 MeV		E_γ = 5 MeV	
ε^P	ε^T	ε^P	ε^T
0.62	0.89	0.44	0.79

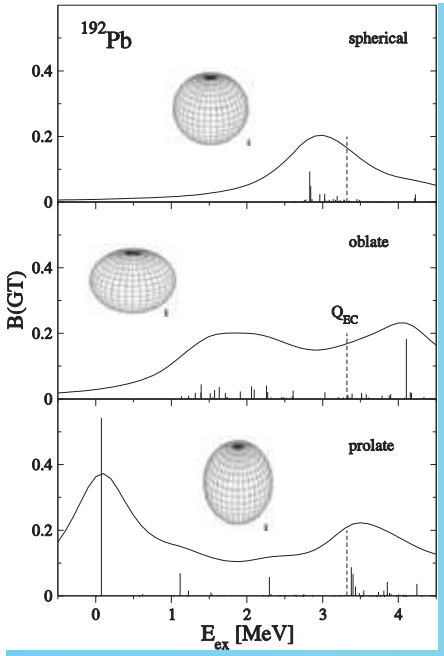
- **Optimized for short $T_{1/2}$: implantation in the center**



- **Nuclear shape and shape coexistence in N~Z Kr, Rb and Sr isotopes**
- **Nuclear shape and shape coexistence in neutron deficient Pb isotopes**

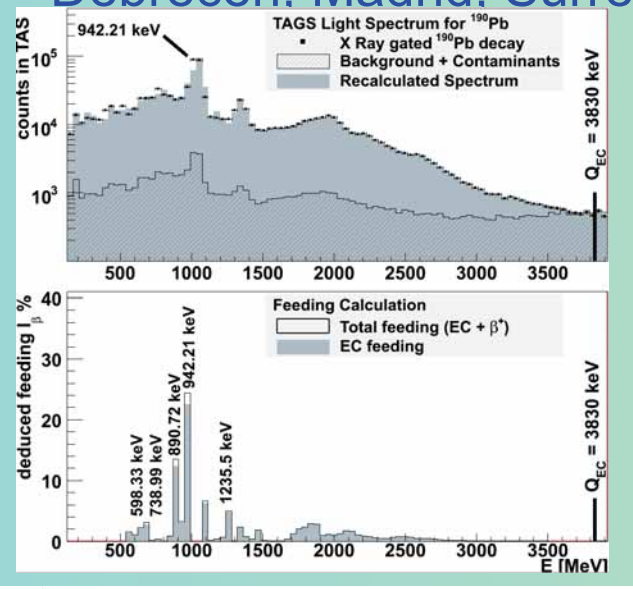
Lucrecia @ ISOLDE

A. Algora et al.: Valencia, Debrecen, Madrid, Surrey

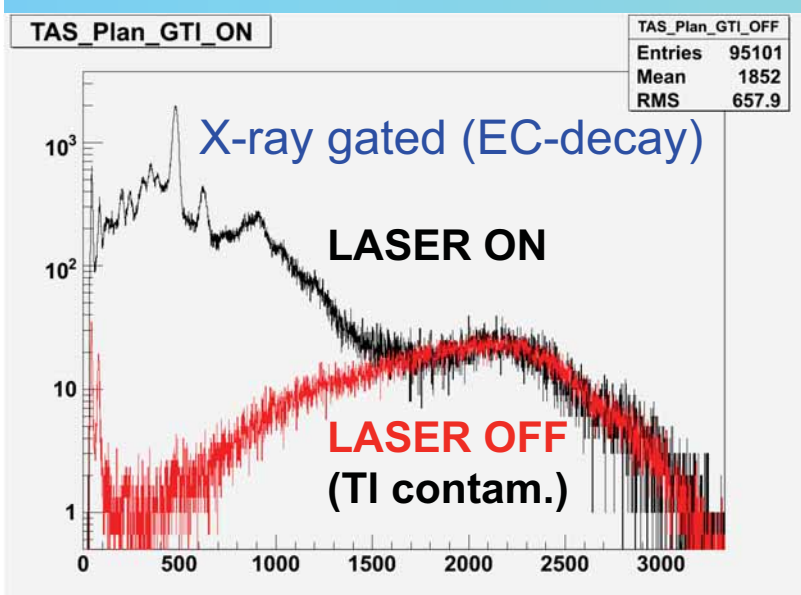


Region of shape coexistence: neutron deficient Pb, Hg, Pt isotopes

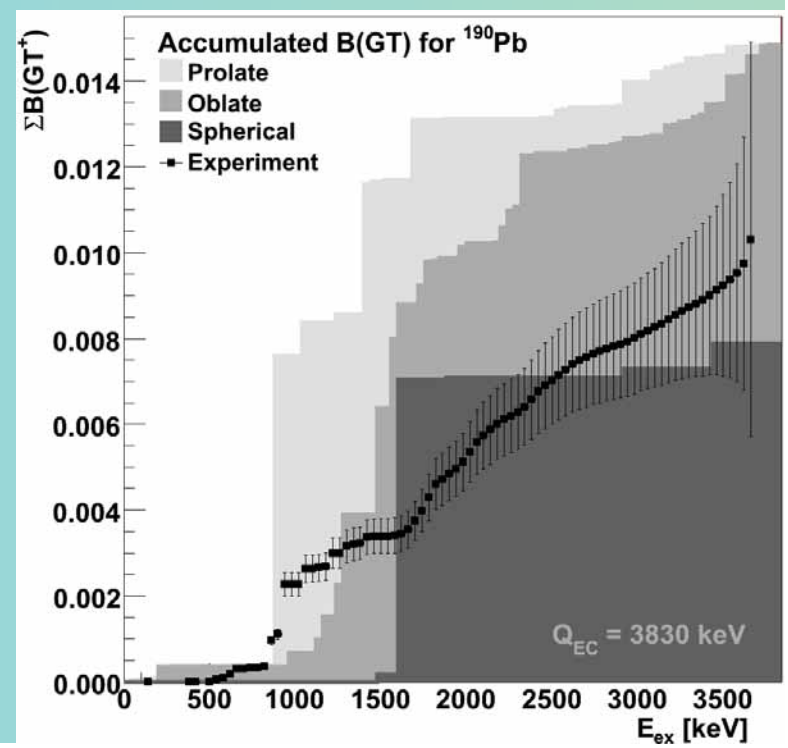
Sarriguren et al., PRC 72, 054317 (2005)



Measurement (Nov. 08)
using RILIS of ^{192,190,188}Pb



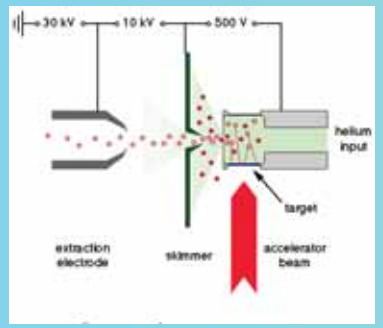
E. Estevez, PhD Thesis

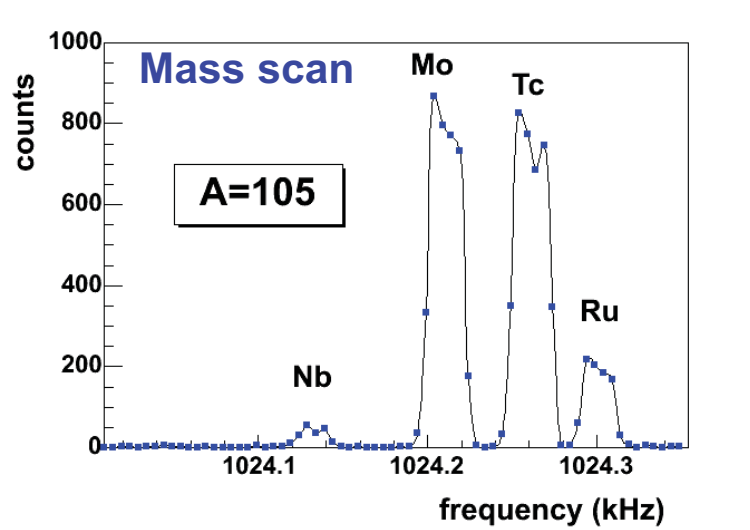


IGISOL separator + ion guide source: refractory elements

TAS measurements @ Univ. Jyvaskyla

JYFLTRAP Penning trap: isotopic purification

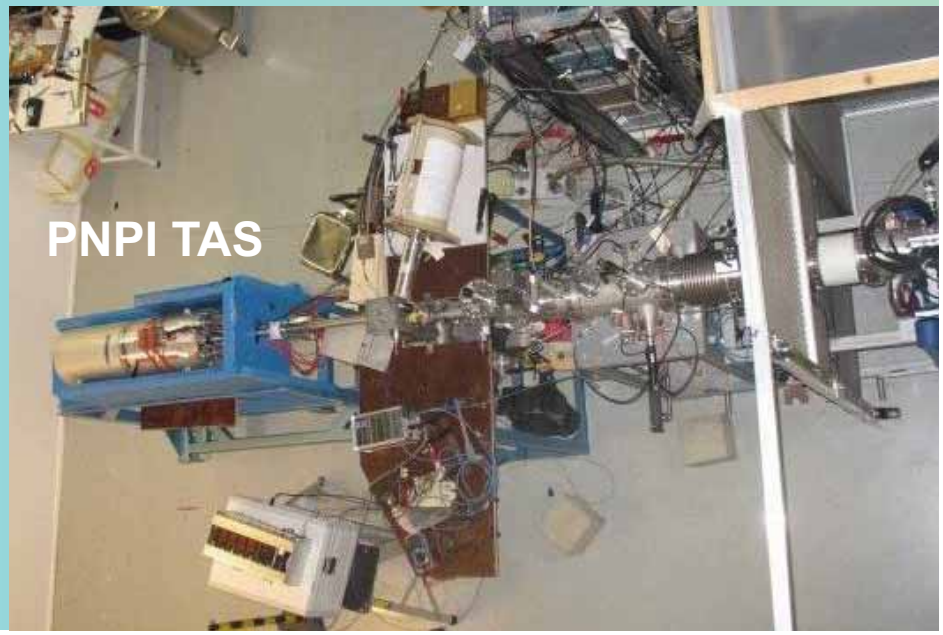




Measurement of Nb, Mo and Tc isotopes for Reactor Decay Heat

Valencia, Jyvaskyla, Debrecen, Gatchina, Surrey

45	103Rh STABLE 100%	104Rh 42.3 S β-: 99.55% ε: 0.45%	105Rh 35.36 H β-: 100.00%	106Rh 29.80 S β-: 100.00%	107Rh 21.7 M β-: 100.00%	108Rh 16.8 S β-: 100.00%	109Rh 80 S β-: 100.00%	110Rh 28.5 S β-: 100.00%
	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	



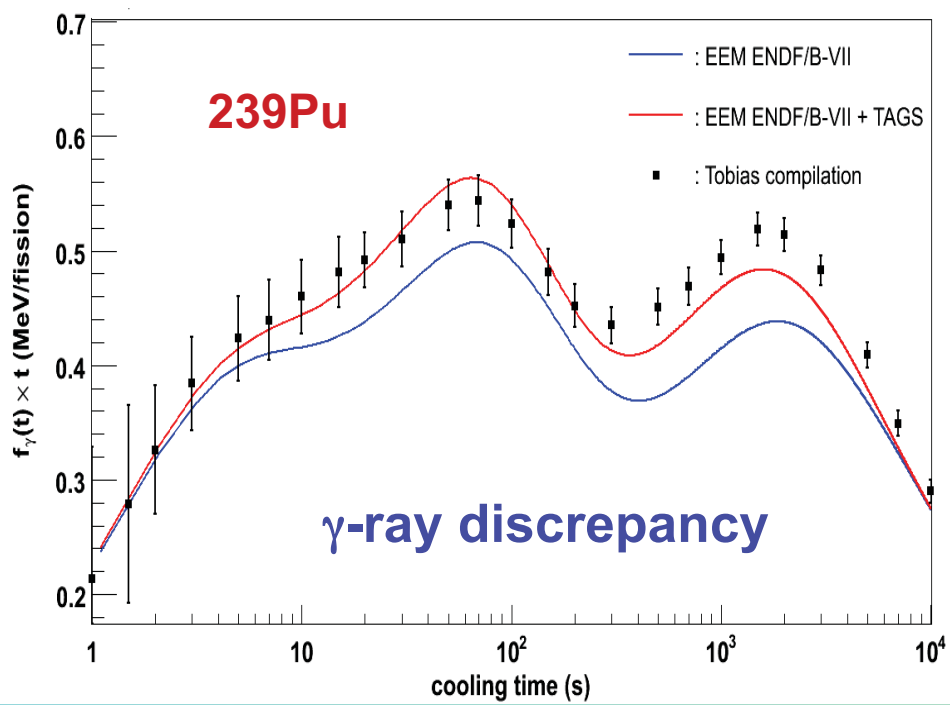
Improvement of reactor decay heat calculations based on evaluated data

$$H(t) = \sum_{i=1}^{n} N_i(t) \frac{ln2}{T_{1/2}^{i}} \int_{0}^{Q_\beta^i} I_\beta^i(E_x)\left[\overbrace{E_x}^{\langle E_\gamma \rangle} + \underbrace{\hat{E}_\beta(E_x)}_{\langle E_\beta \rangle}\right] dE_x$$

- Yoshida et al. JNST36,135: 102,104,105Tc
- WPEC-SG25: priority list

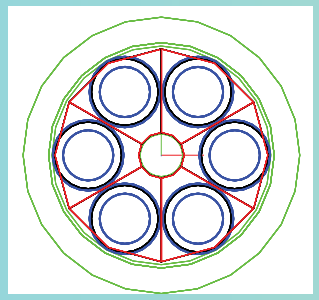
Isotope	Emiss.	TAS [keV]	ENDF/BVII [keV]	Diff. [keV]
^{101}Nb (7.1 s)	beta	1797 (133)	1966 (307)	-169
	gamma	445 (279)	270 (22)	175
^{102}Tc (5.28 s)	beta	1935 (11)	1945 (16)	-10
	gamma	106 (23)	81 (5)	25
^{104}Tc (1098 s)	beta	**931 (10)**	**1595 (75)**	**-664**
	gamma	**3229 (24)**	**1890 (31)**	**1339**
^{105}Tc (456 s)	beta	**764 (81)**	**1310 (205)**	**-546**
	gamma	**1825 (174)**	**665 (19)**	**1160**
^{105}Mo (35.6 s)	beta	**1076 (43)**	**1922 (122)**	**-846**
	gamma	**2347 (91)**	**552 (24)**	**1795**
^{106}Tc (35.6 s)	beta	**1457 (30)**	**1906 (67)**	**-449**
	gamma	**3132 (70)**	**2191 (51)**	**941**
^{107}Tc (21.2 s)	beta	**1276 (212)**	**2054 (254)**	**-778**
	gamma	**1795 (450)**	**515 (11)**	**1280**

D. Jordan, PhD Thesis
A. Algora et al. PRL105, 202501



Decay-heat calculation
A. Sonzogni et al

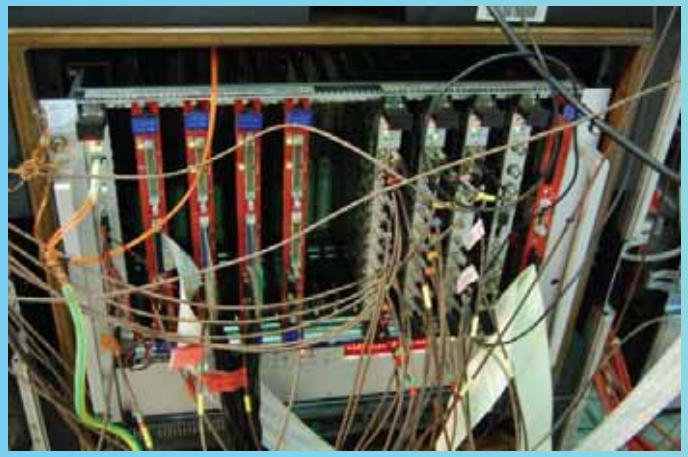
New segmented BaF_2 TAS (Surrey-Valencia)

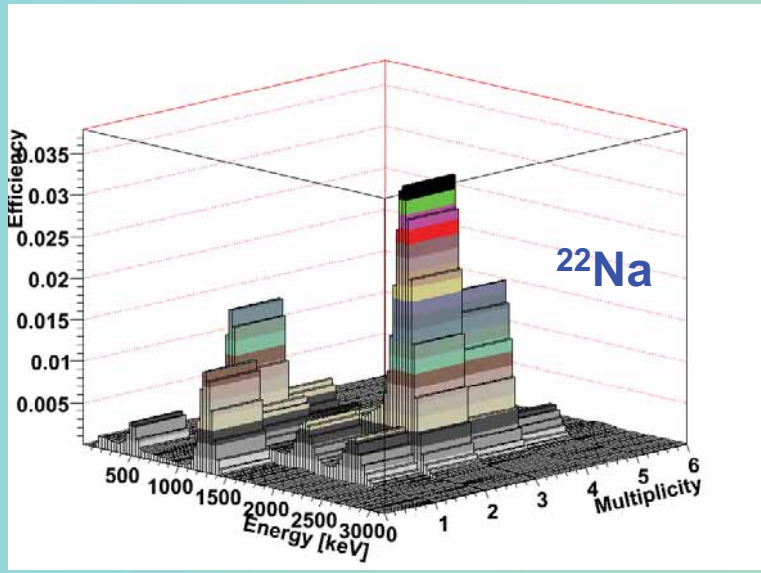


12× BaF2 crystals / 3" Q-PMT

- Compact design: for easy transportation
- Segmented spectrometer: for cascade multiplicity determination

- Online/offline gain matching using contaminant α-peaks



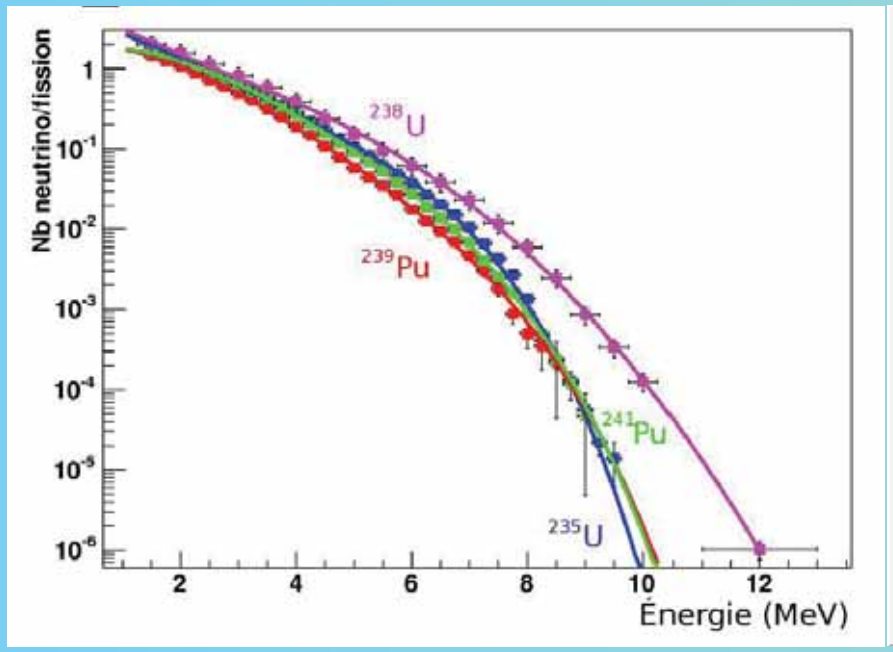


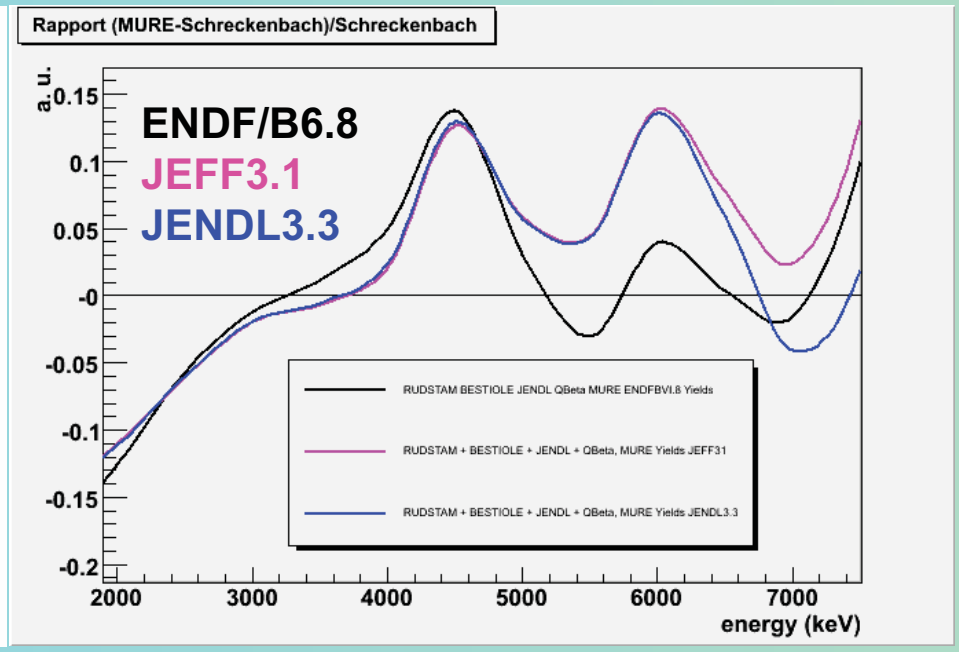
- "Conventional" electronics (V785, V775, V792) being substituted by "digital" electronics (SIS3302)

- Good timing: for β-delayed neutron discrimination

Reactor neutrino spectrum: neutrino oscillations and homeland security

How well known is the reactor anti-neutrino spectrum?

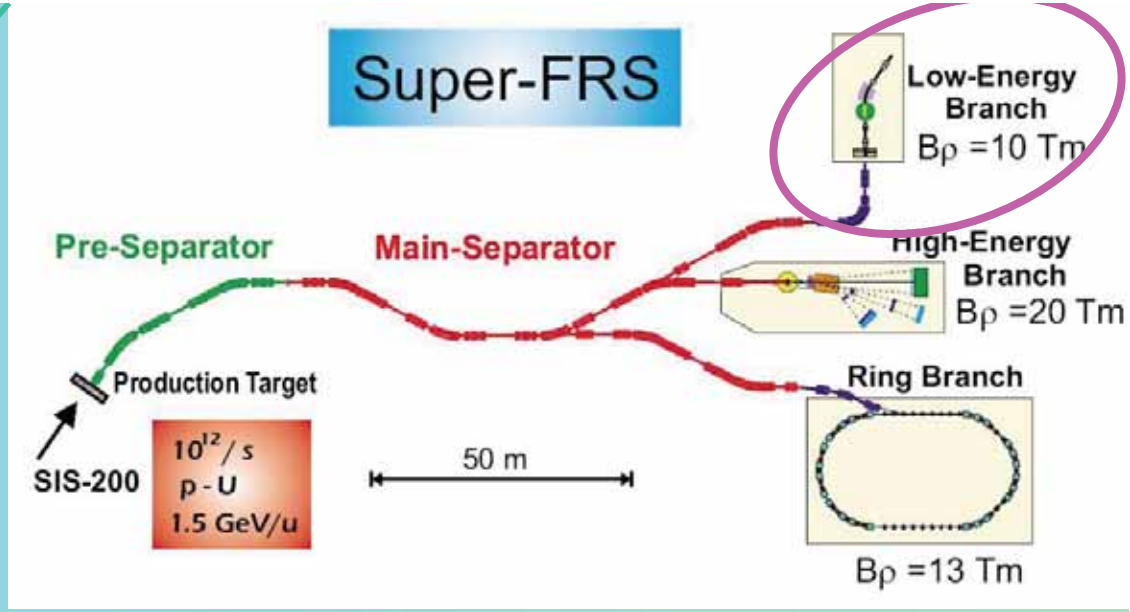




Data from Schreckenbach et al. (ILL-Grenoble)
Summation calculations Fallot et al. (Subatech-Nantes)

First measurement at IGISOL-JFLTRAP: November 2009

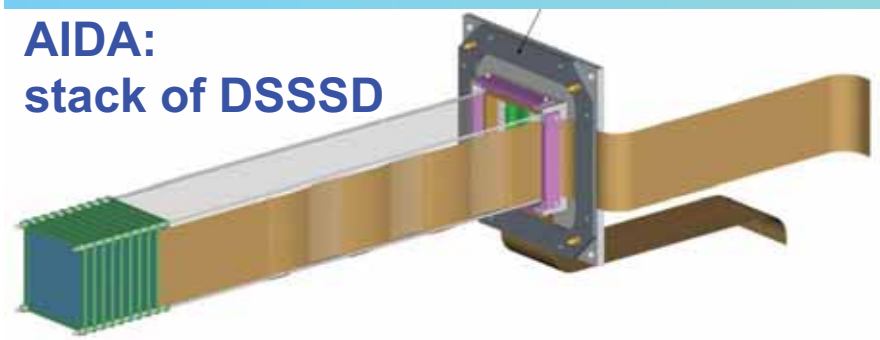
Nantes, Valencia, Jyvaskyla, Surrey



NUSTAR collaboration: DESPEC experiment

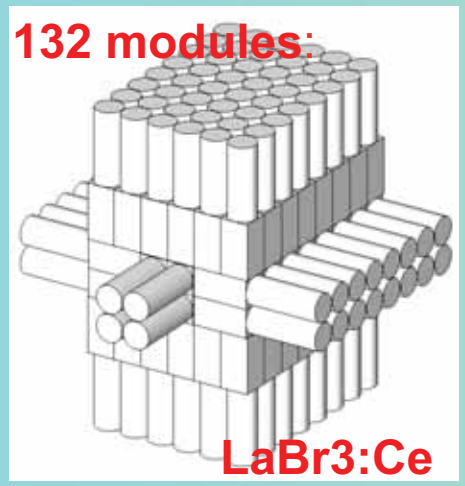
High energy ions (fragmentation, fission, …) separated and identified with the Super-FRS and implanted in an active stopper

AIDA: stack of DSSSD

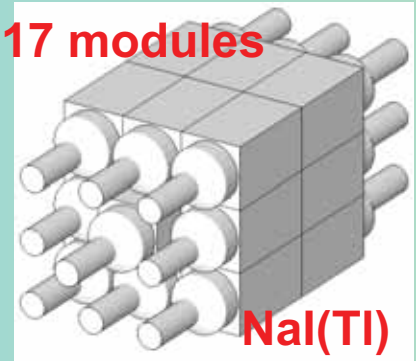


New TAS development

132 modules:



17 modules



Valencia, Madrid, Gatchina, Darmstadt, Debrecen, Jyvaskyla, Surrey

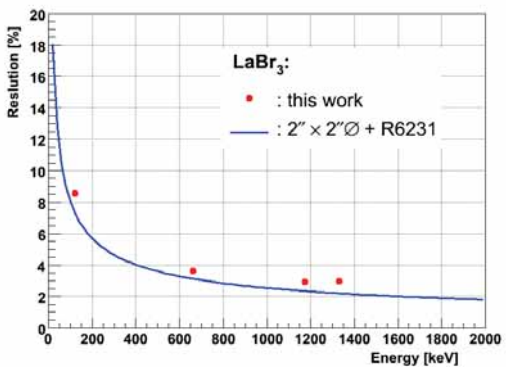
$LaBr_3$:Ce Prototype

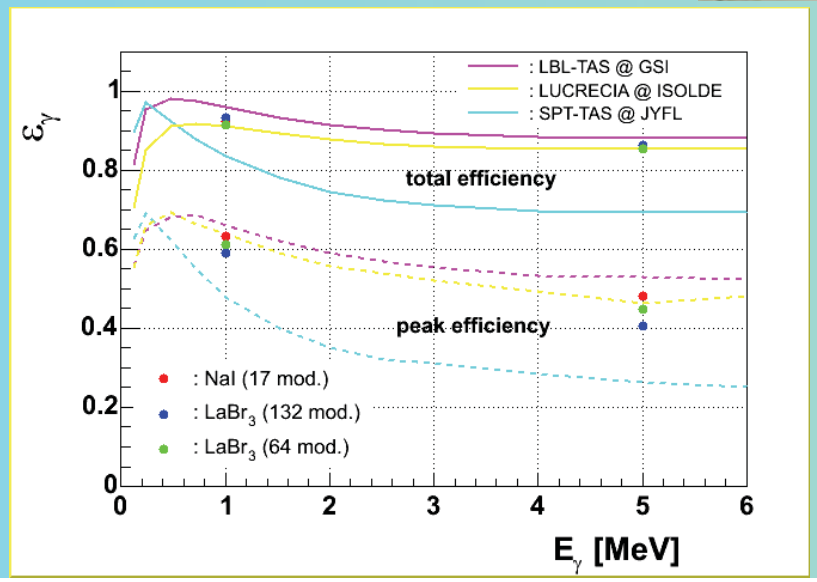
Saint-Gobain:

- **Crystal: 55×55×110 mm^3**
- **Teflon + damping: 2.25 mm**
- **Aluminum canning: 0.5 mm**
- **PMT: R6236 & R6231 (Hamam.)**

R_E= 3.7% @662keV

Δt(FWHM) = 1.0 ns

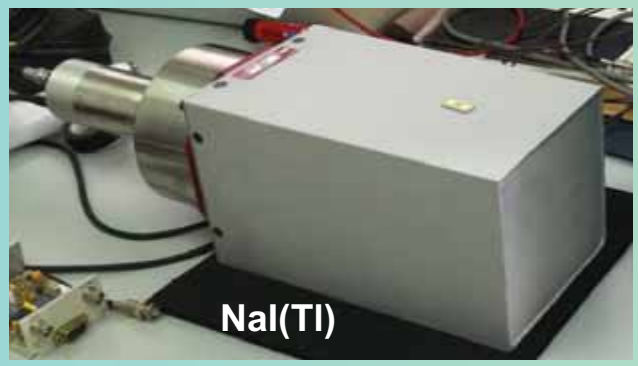




NaI(Tl) Prototype

Scionix:

- **Crystal: 150×150×250 mm^3**
- **Teflon reflector + damping: 1 mm**
- **Aluminum canning: 1 mm (reinforcement on edges)**
- **PMT: ETL9390**



R_E= 6.8% @662keV

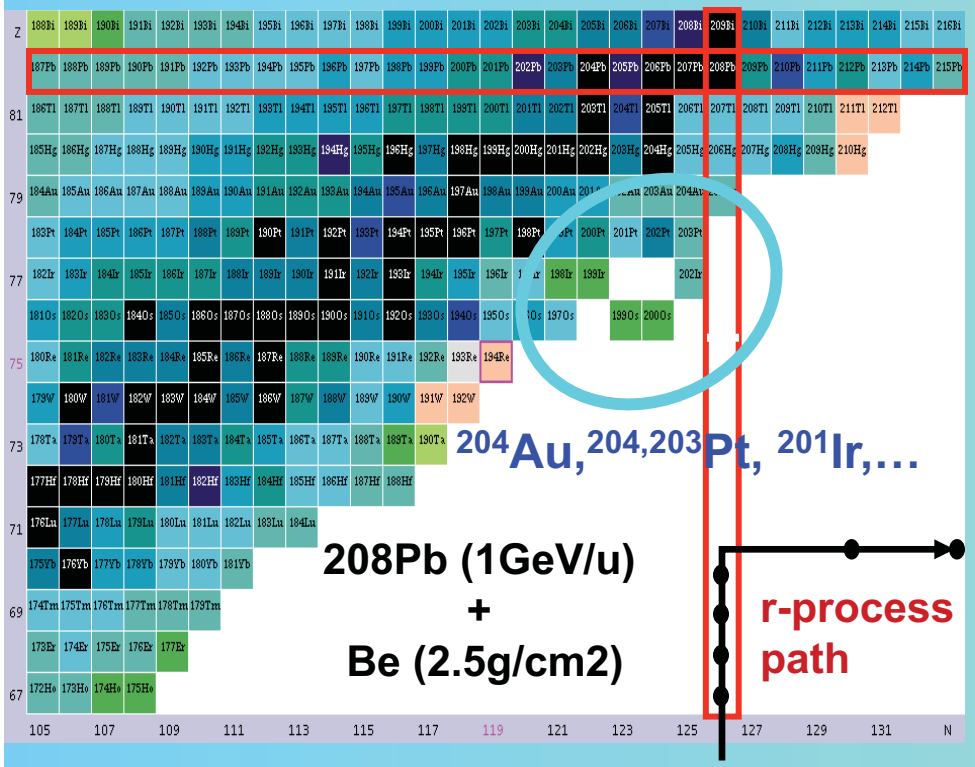
Δt(FWHM) = 4.5 ns

- **NaI(Tl) assembly under construction**
- **Ready by October**

Beta strength measurements near to the 3rd r-process peak

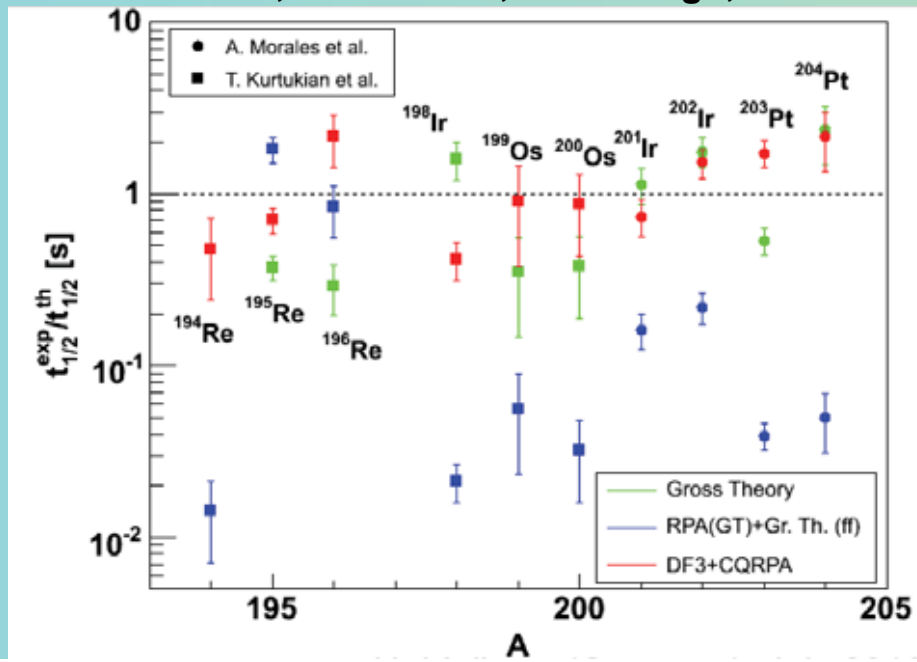
(South-west of ^{208}Pb)

Valencia-Darmstadt-Gatchina-Madrid-Santiago-Surrey…



- **Test/improve the prediction capability of theoretical models of β-strength distributions ($\rightarrow T_{1/2}, P_n$)**
- **Decay dominated by FF transitions**
- **Largely unexplored but "unique" accessible at GSI**

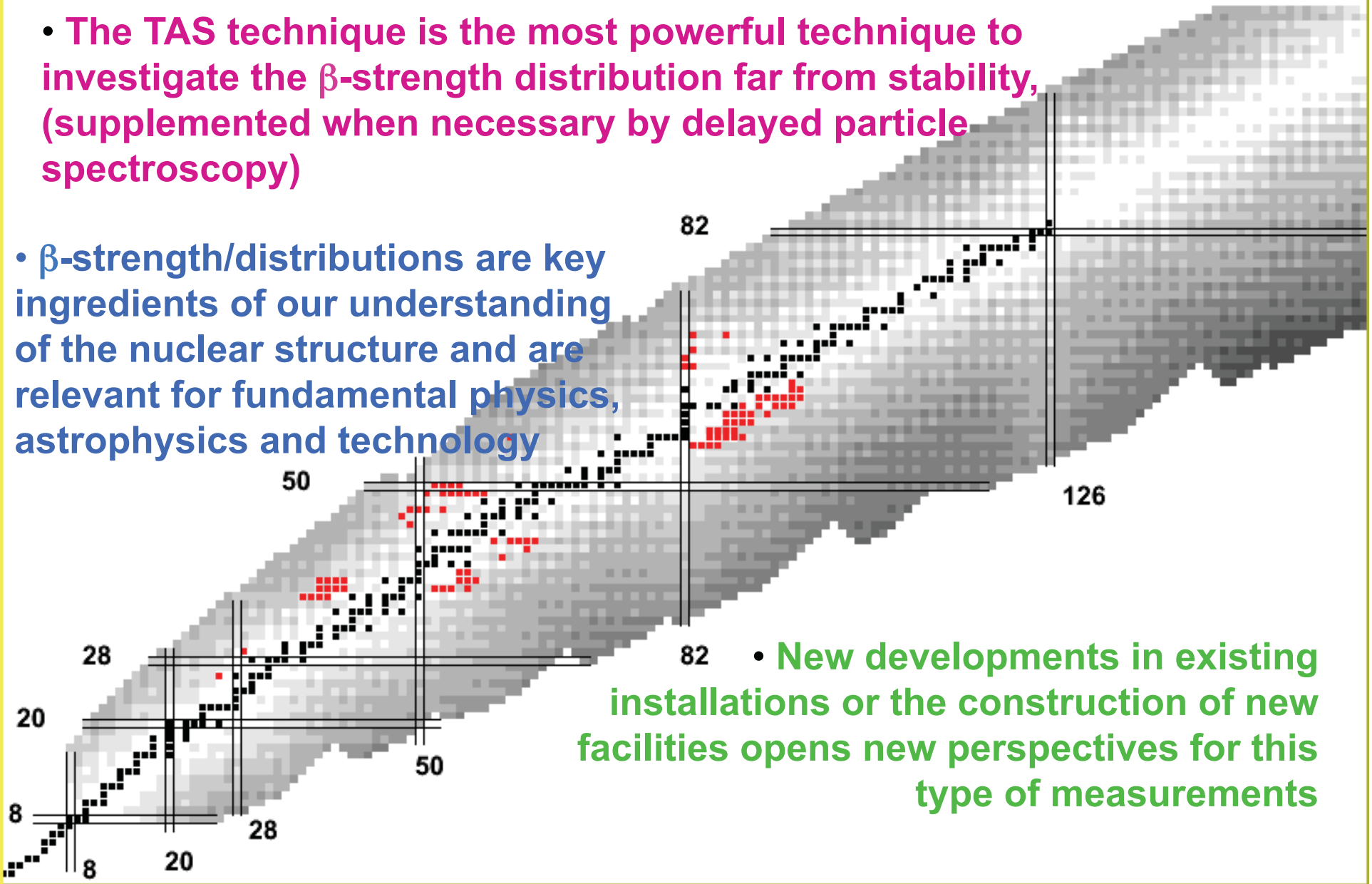
- **T. Kurtukian et al., NPA827 (2009) 687c**
- **A.I. Morales, PhD Thesis, U. Santiago, 2011**



Conclusions:

- **The TAS technique is the most powerful technique to investigate the β-strength distribution far from stability, (supplemented when necessary by delayed particle spectroscopy)**

- **β-strength/distributions are key ingredients of our understanding of the nuclear structure and are relevant for fundamental physics, astrophysics and technology**



- **New developments in existing installations or the construction of new facilities opens new perspectives for this type of measurements**

Some of the people involved until now:

CIEMAT Madrid: D. Cano-Ott, …
GSI Darmstadt: R. Kirchner, E. Roeckl, …
IEM Madrid: M.J.G. Borge, O. Tengblad, …
IFIC Valencia: A. Agramunt, A. Algora, D. Jordan, E. Estevez, E. Nacher, B. Rubio, J.L. Tain, …
INR Debrecen: A. Krasznahorkay, M. Csatlos, …
IRES Strasbourg: P. Lessagne, C. Miehe, E. Poirier, …
PNPI St. Petersburg: L. Batist, V. Wittmann, …
U. Jyvaskyla: J. Aysto, T. Eronnen, A. Jokinen, J. Rissanen, …
U. Surrey: W. Gelletly, P. Regan, …
U. Warsaw: M. Karny, K. Rykacezky, …

THANK YOU!