β-strength studies of very neutron-rich nuclei at DESPEC

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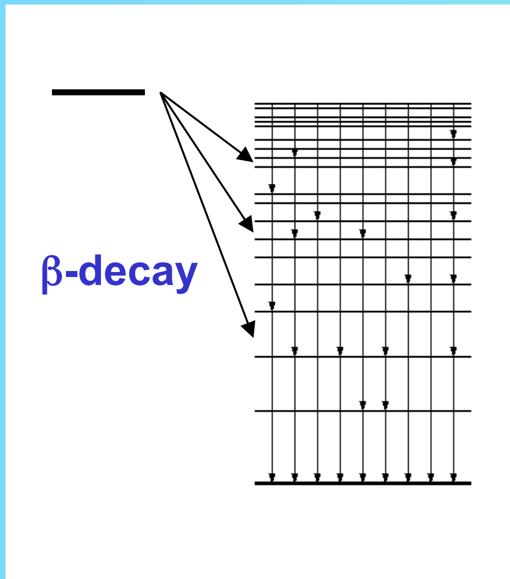
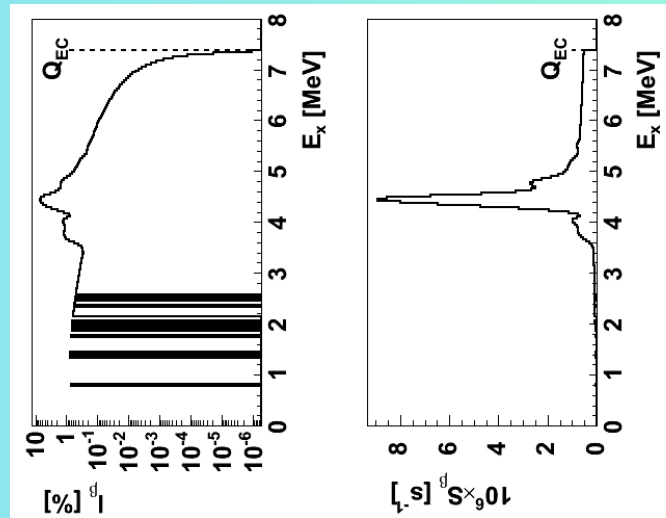
for the BELEN, DTAS and MONSTER Collaborations

- β-decay strength distributions
- Importance for nuclear structure and astrophysics
- First β-delayed neutron measurements
- Future total absorption gamma-ray spectroscopy measurements

β-strength S_β and β-intensity I_β



INTENSITY STRENGTH



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

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

λπ: 0+ Fermi

λπ: 1+ Gamow-Teller

λπ: 0-,1- Non-unique first forbidden

λπ: 2- Unique first forbidden

…

The β-strength measures the nuclear structure dependent part of the decay probability

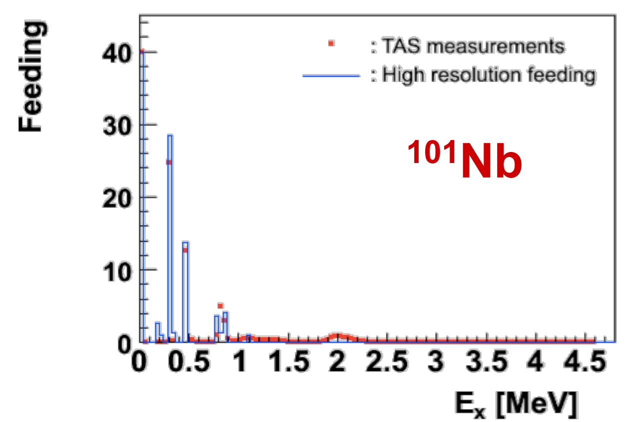
Relation between S_β and I_β:

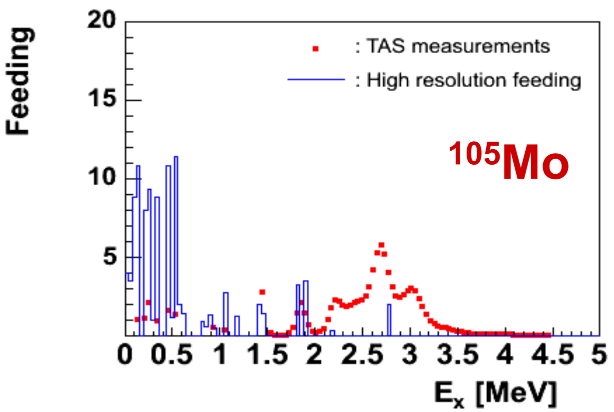
$$S(E_x) = \frac{I(E_x)}{f(Q_\beta - E_x)T_{1/2}} \quad \left[s^{-1}\right]$$

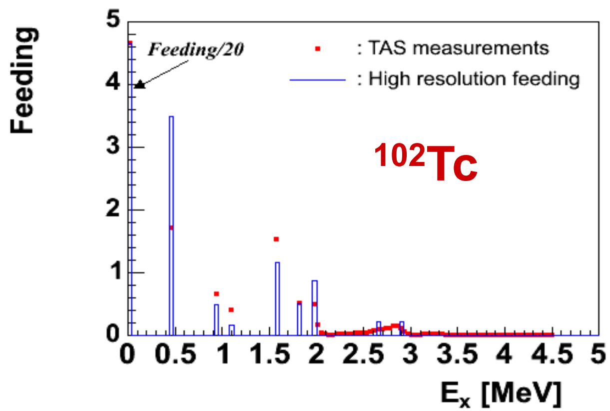
The β-decay probability distribution is very sensitive to nuclear structure

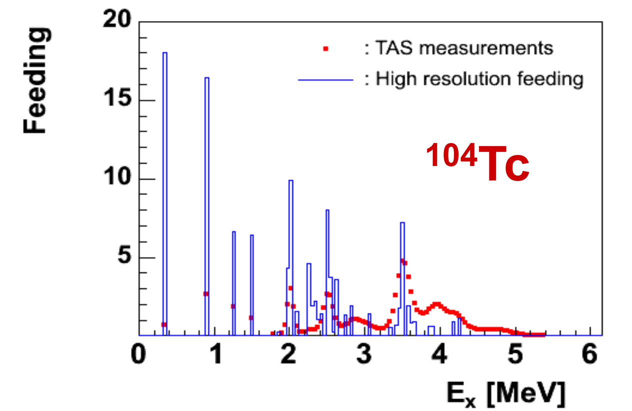
MD. Jordan, PhD Thesis, U. Valencia

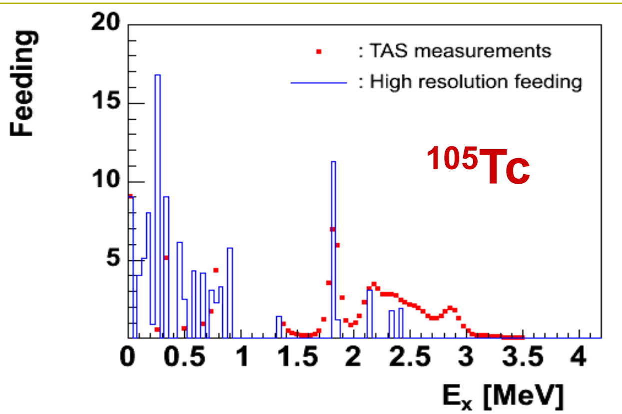
	58		60		62		64		66
	102Ru STABLE 31.55%	103Ru 39.26 D β-: 100.00%	104Ru STABLE 18.62%	105Ru 4.44 H β-: 100.00%	106Ru 373.59 D β-: 100.00%	107Ru 3.75 M β-: 100.00%	108Ru 4.55 M β-: 100.00%	109Ru 34.5 S β-: 100.00%	110Ru 11.6 S β-: 100.00%
43	101Tc 14.22 M β-: 100.00%	102Tc 5.28 S β-: 100.00%	103Tc 54.2 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%	109Tc 0.86 S β-: 100.00% β-n: 0.08%
	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%	108Mo 1.09 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%	107Nb 330 MS β-: 100.00%

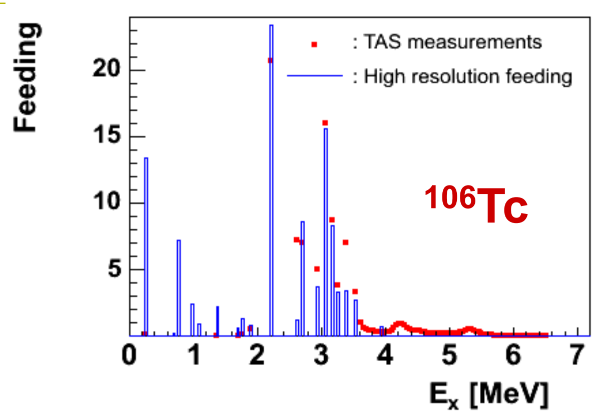


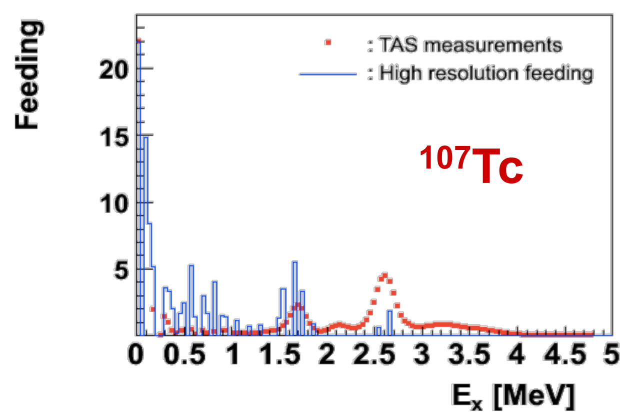




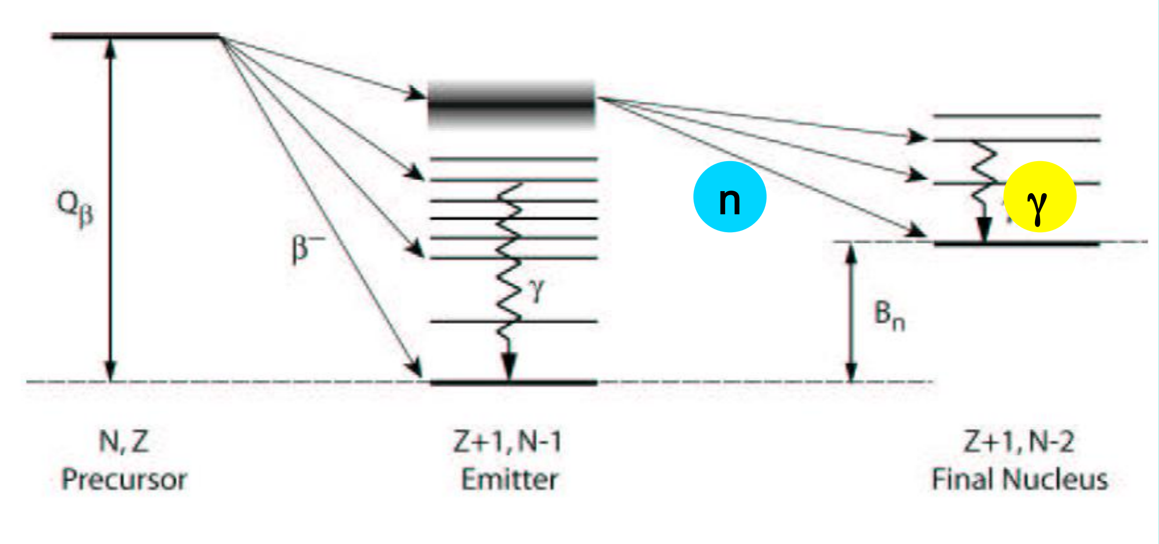






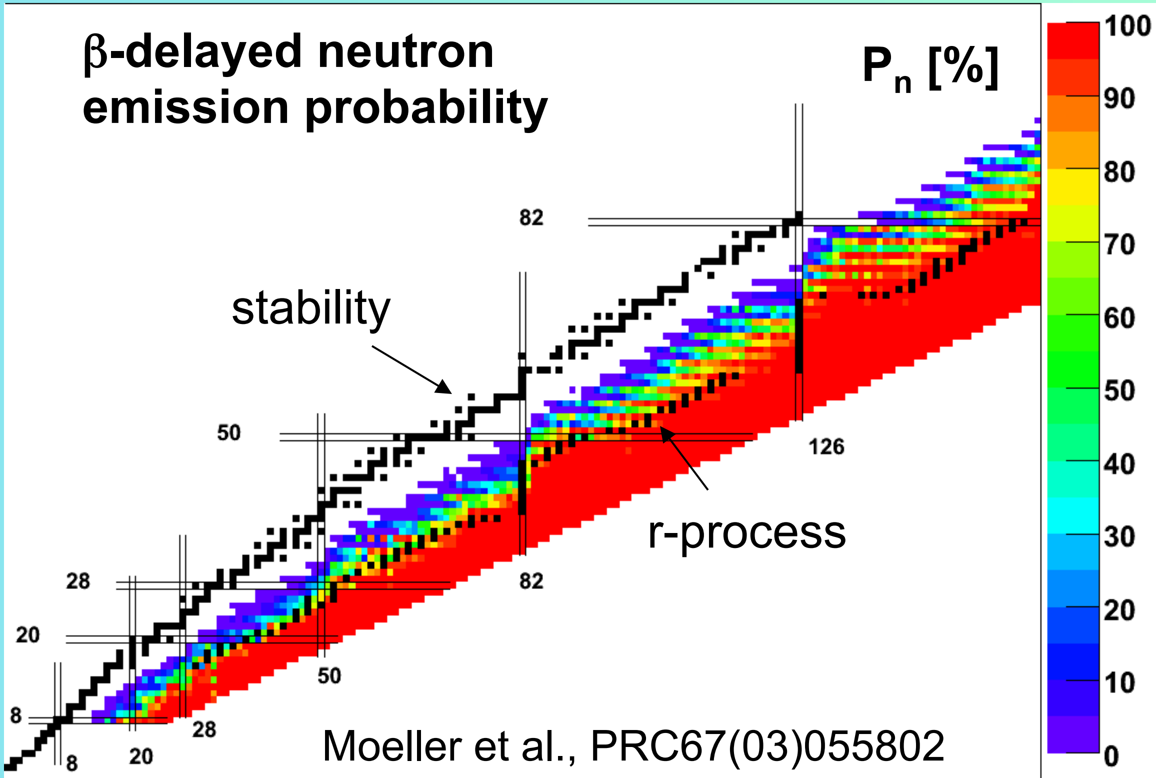


Beta decay of neutron rich nuclei

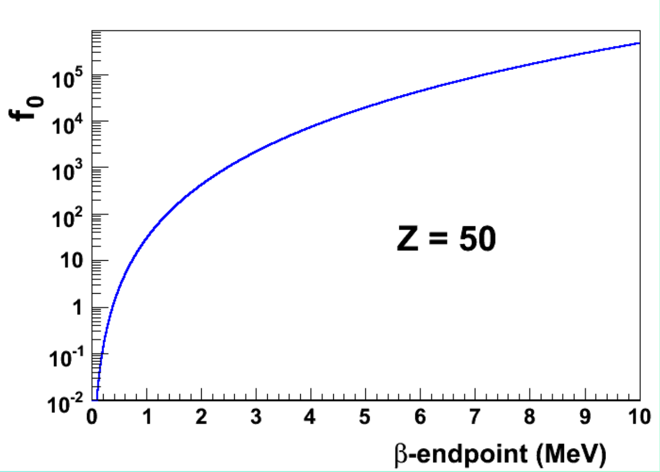


- Far enough from the stability, **β-delayed neutron emission** becomes de dominant decay process

At FAIR both γ-ray spectroscopy and neutron spectroscopy will be required to study the β-strength



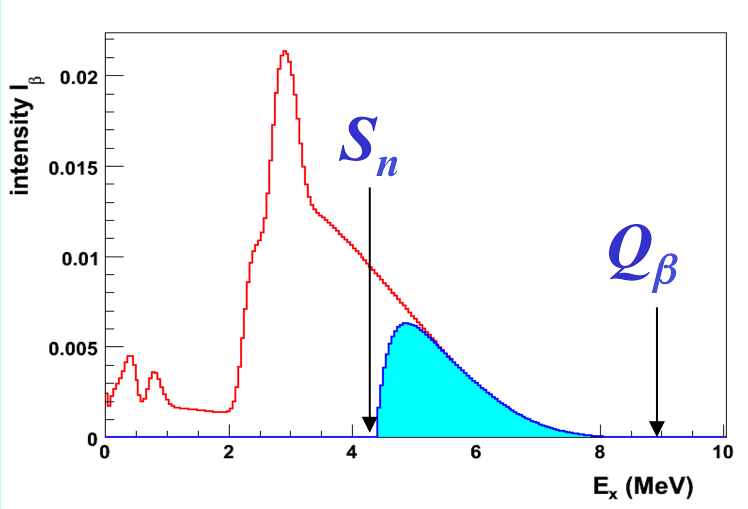
• The (inverse of the) half-life $T_{1/2}$ is a weighted average of the β-strength S_β



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

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

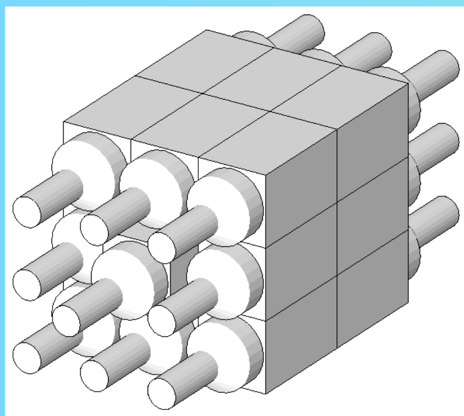
$$P_n = T_{1/2} \times \int_{S_n}^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) \cdot \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} dE_x$$



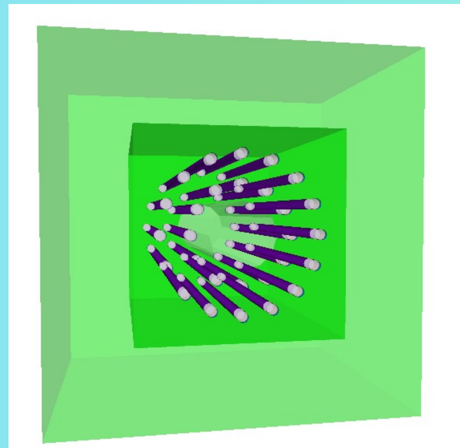
• For n-rich nuclei very far from stability $T_{1/2}$ and P_n provide (the only) access to nuclear structure information

At DESPEC one or more of the following instruments will be used to study β-strength distributions:

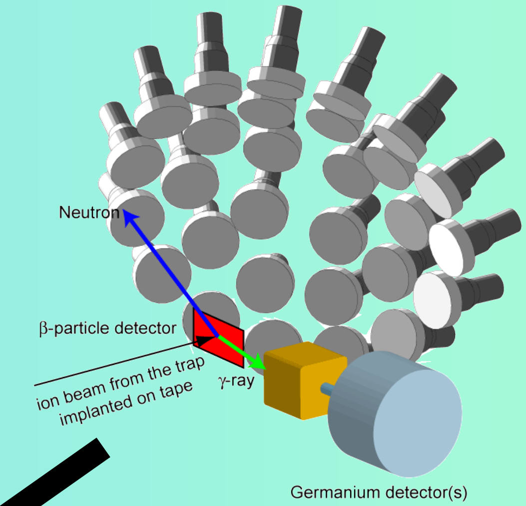
Total Absorption γ-Ray Spectrometer: DTAS

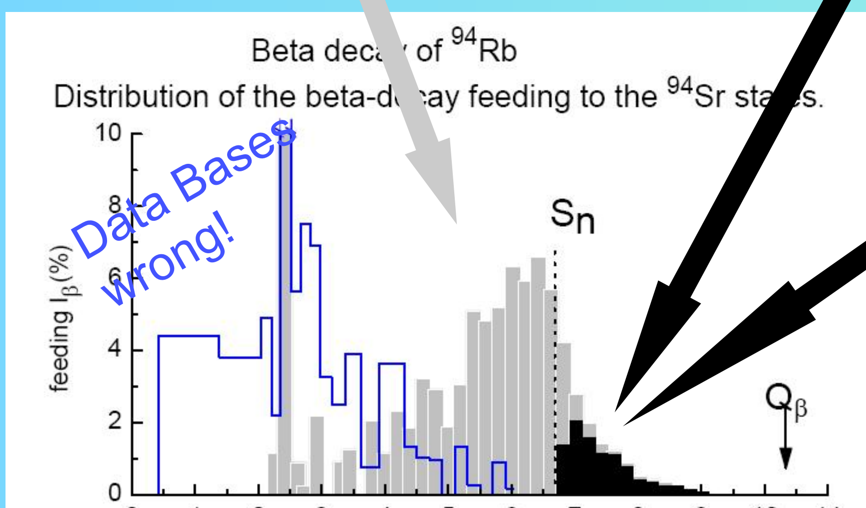


4π Neutron Counter: BELEN



Neutron Time of Flight Spectrometer: MONSTER

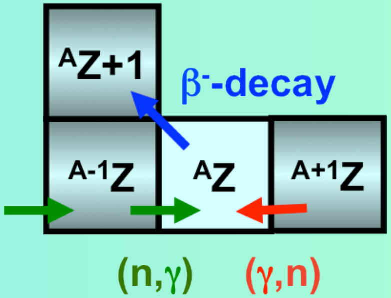


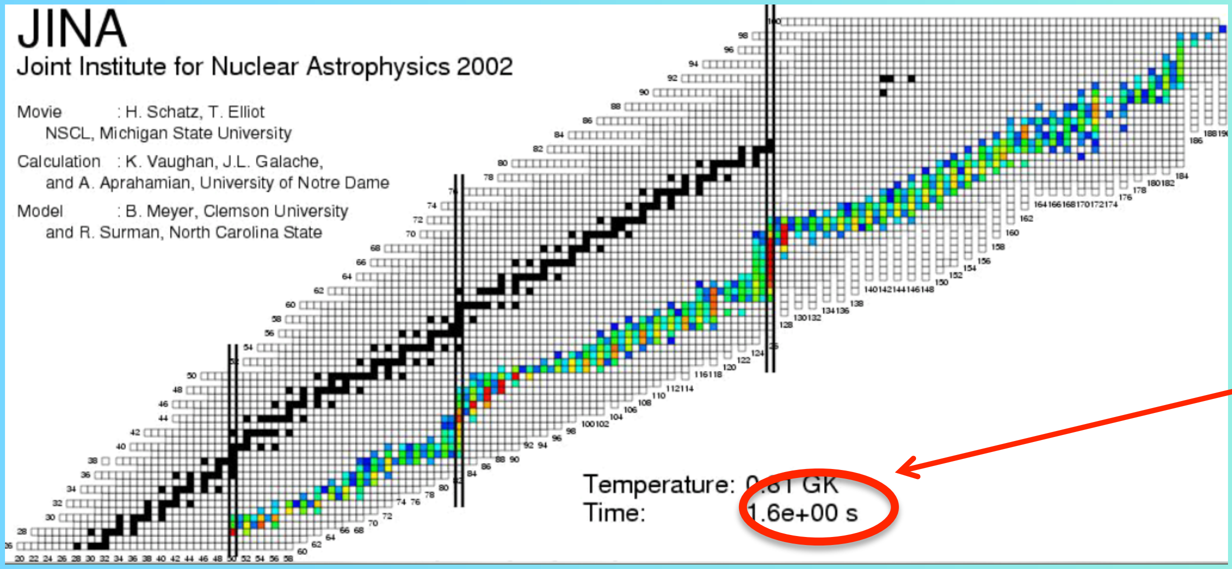


(L. Batist, unpublished)

- DTAS provides data free of systematic errors
- BELEN provides P_n
- MONSTER provides the E_n and the strength above S_n

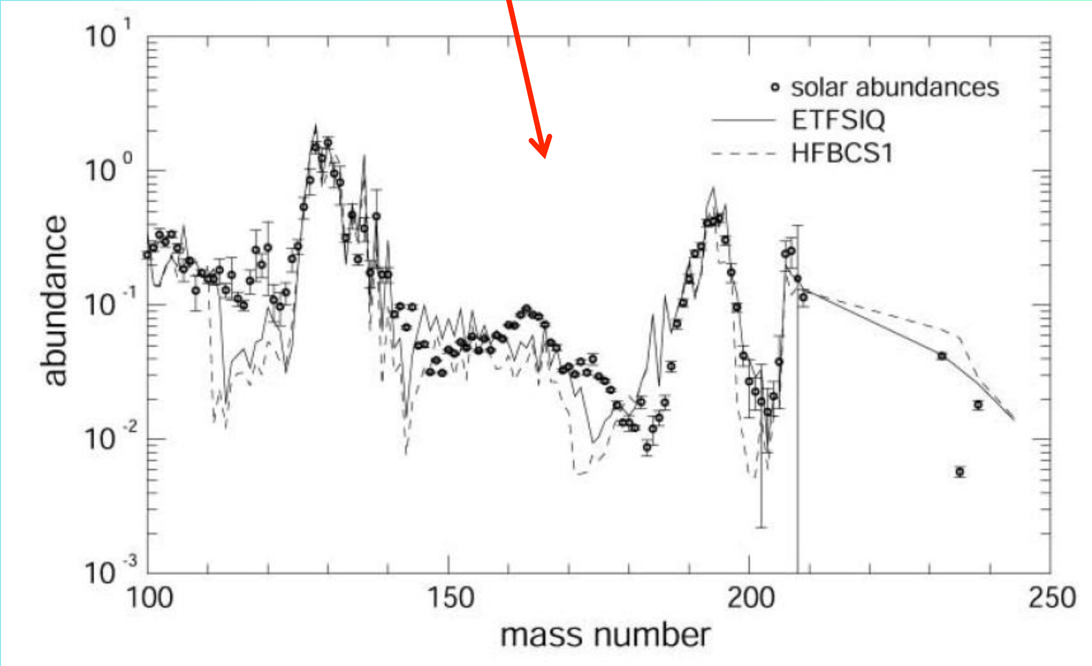
Rapid neutron capture astrophysical process





$T_{1/2}$ **and** P_n **values are required for r-process calculations:**

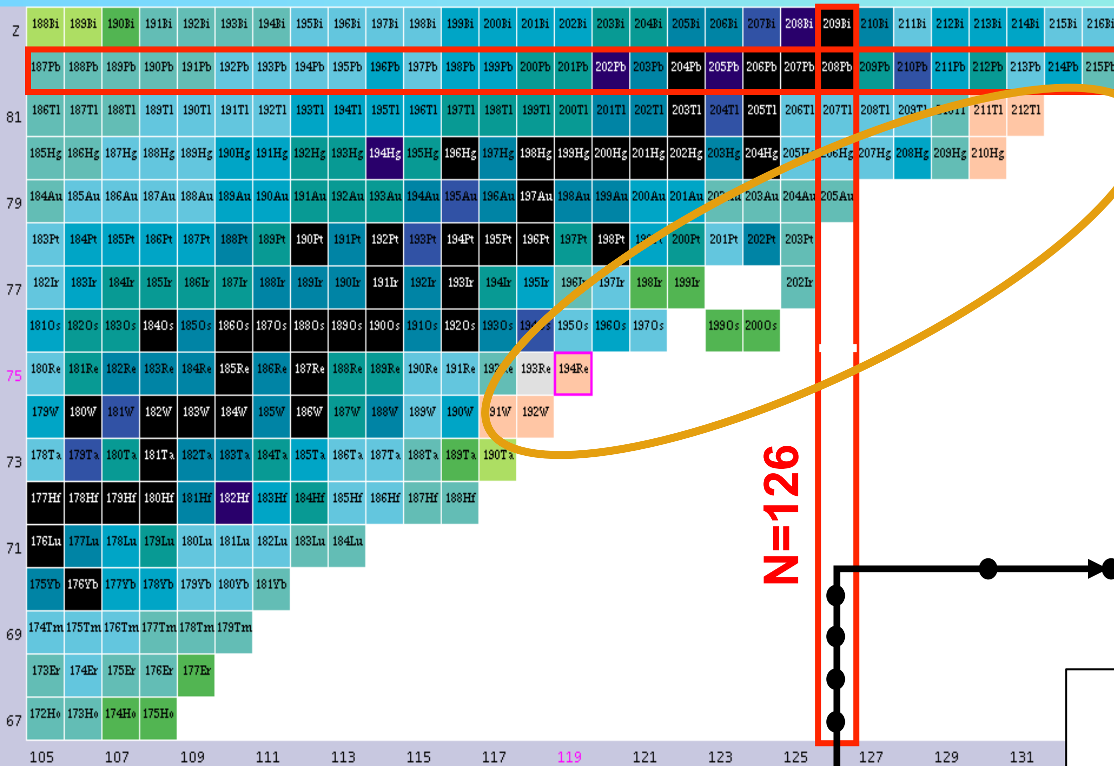
- **speed of the process**
- **final abundance distribution**

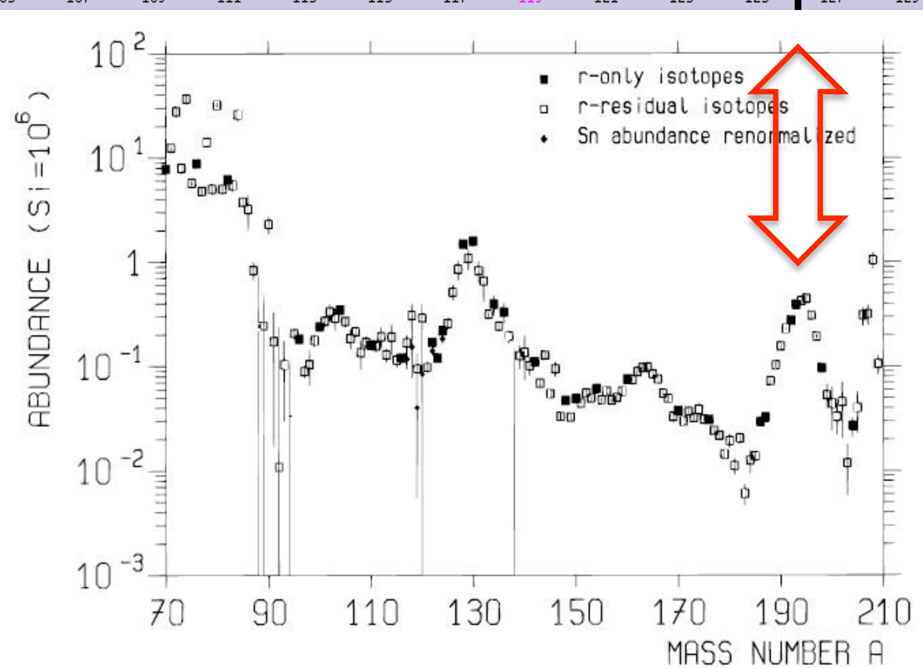


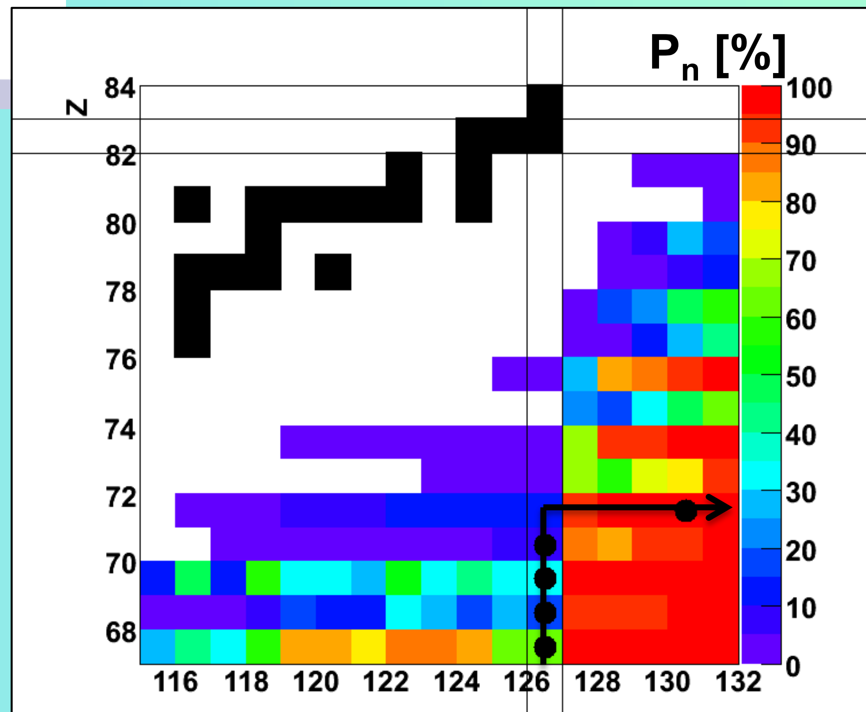
For most of the nuclei involved $T_{1/2}$ **and** P_n **have to be obtained from β-strength theoretical calculations**

The region close the r-process 3rd peak:

- r-process calculations beyond the 3rd peak
- Actinide production and U/Th cosmo-chronometers
- Contribution to Pb/Bi: s-process termination path

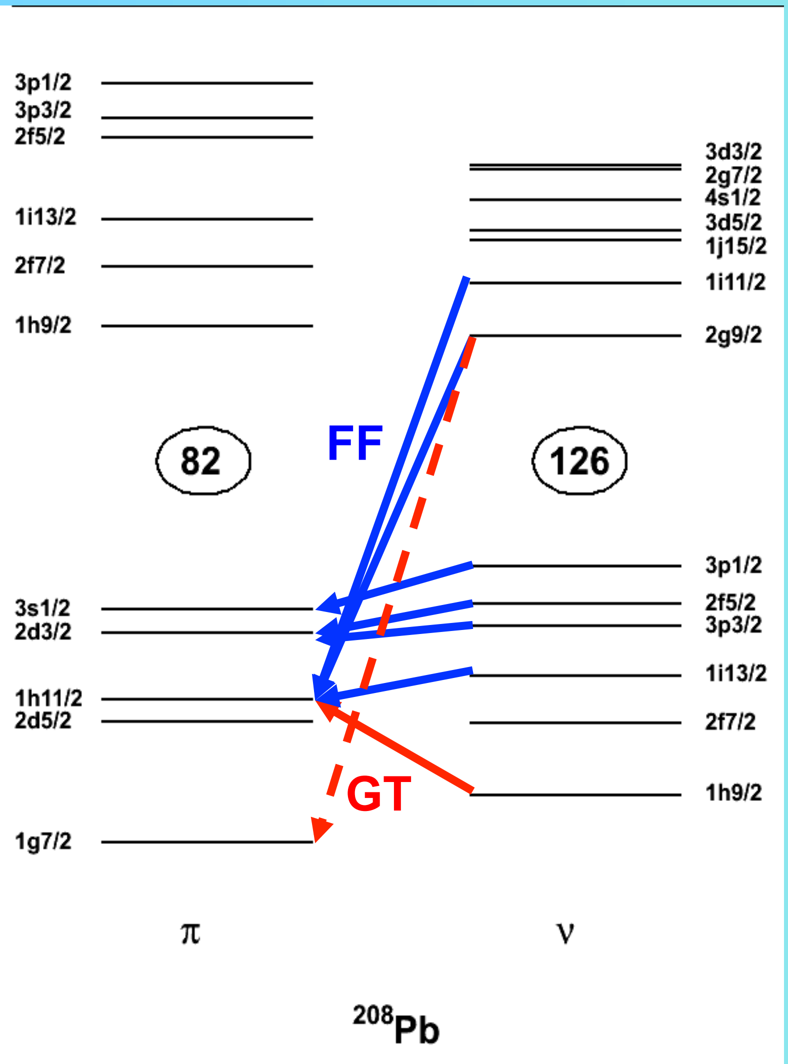




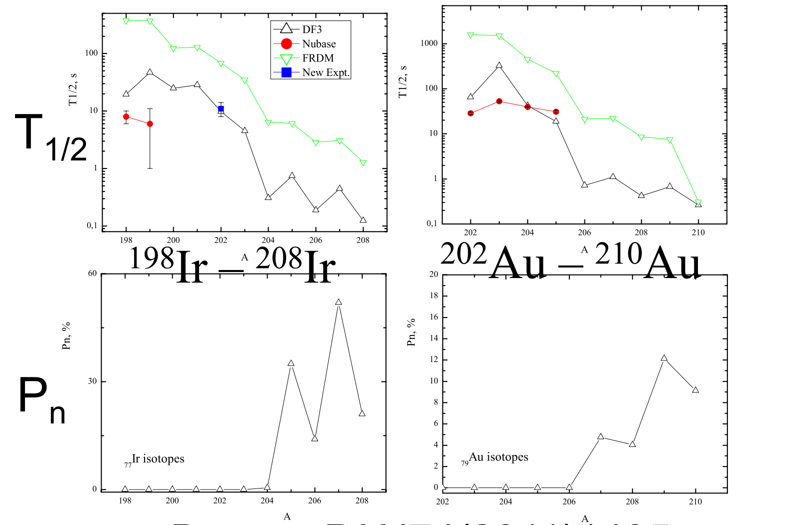


Moeller et al., PRC67(03)055802

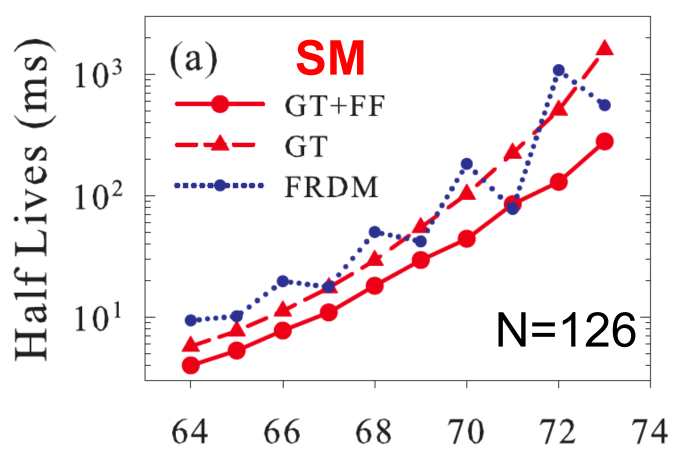
First-forbidden transitions play a dominant role in this region



In general FF far-of-stability produce a shortening of half-lives: Moeller, PRC67(2003)055802



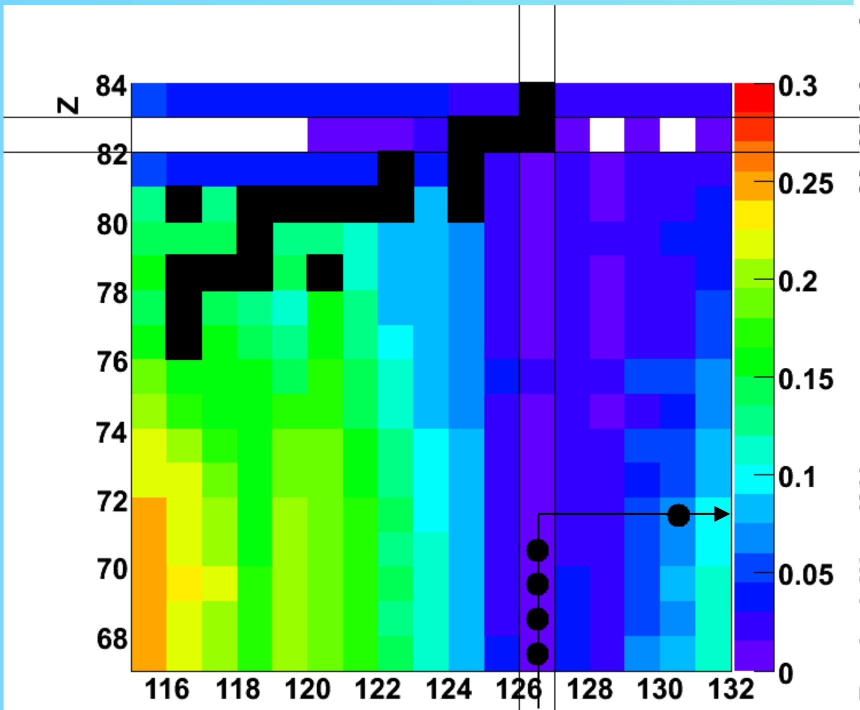
Borzov, PAN74(2011)1435



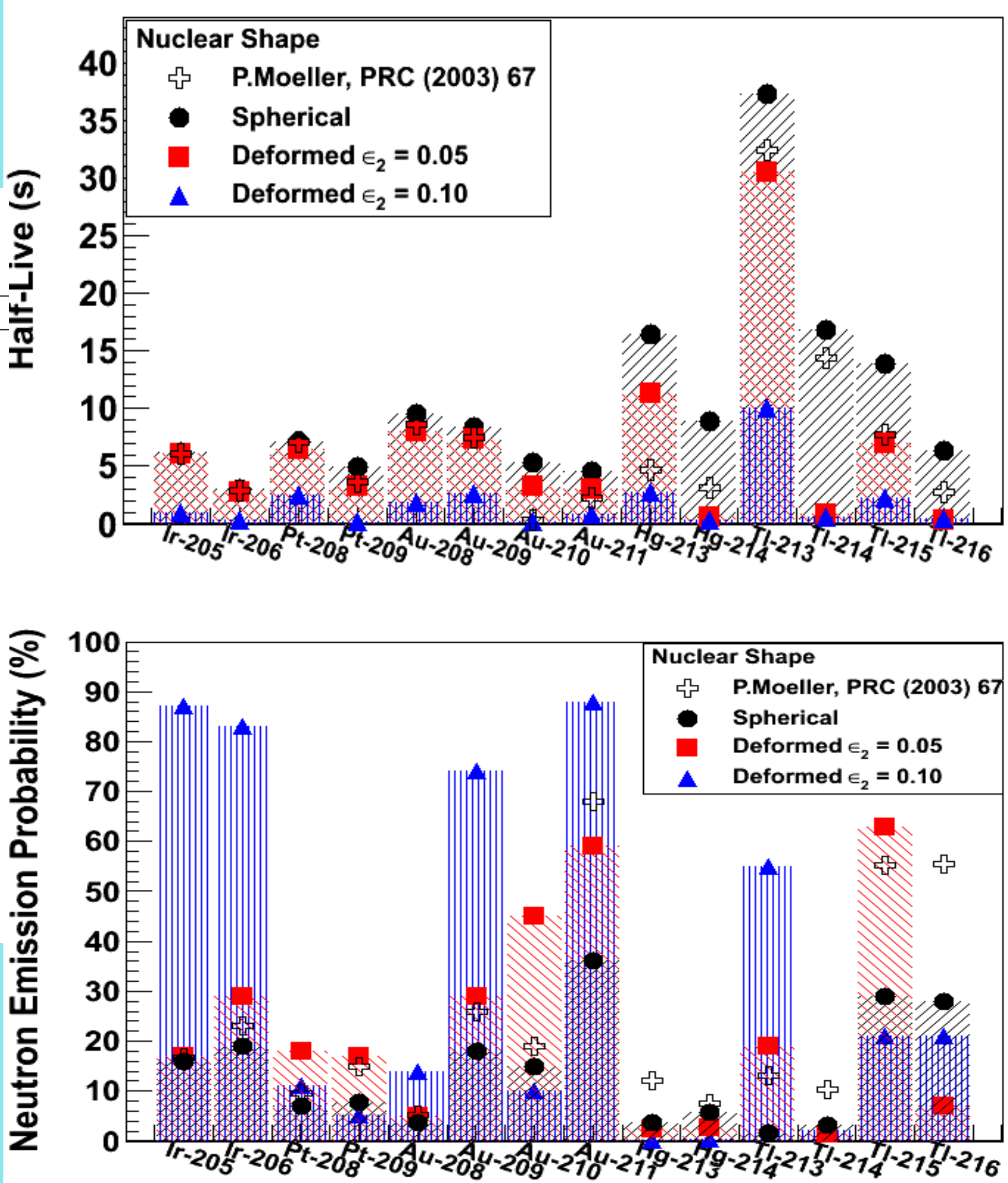
Suzuki, PRC85(2012)015802

Considerable differences between calculations

Further to consider: influence of deformation



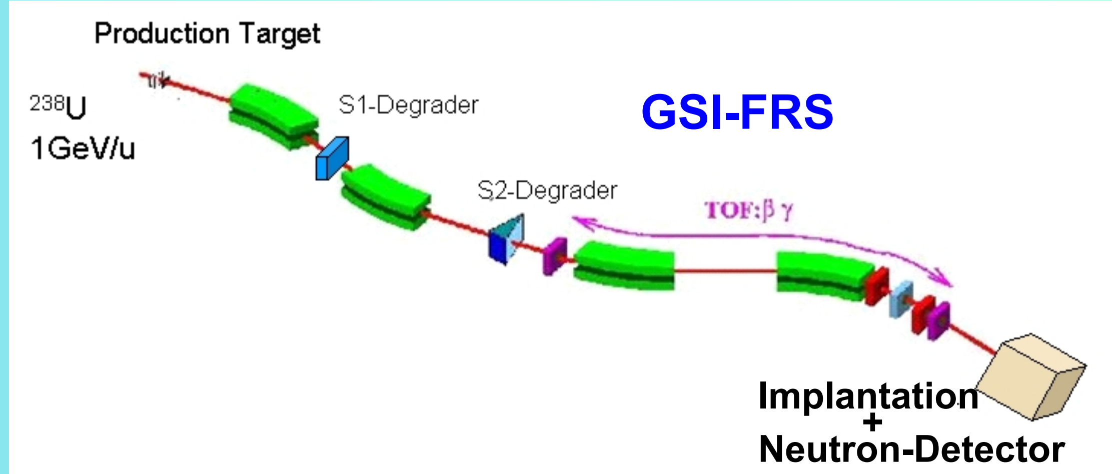
Moeller et al., ADNDT59(95)185



Experimental data needed!

S410: Measurement of β-delayed neutrons around the 3rd r-process peak (C. Domingo et al.)

September 2011

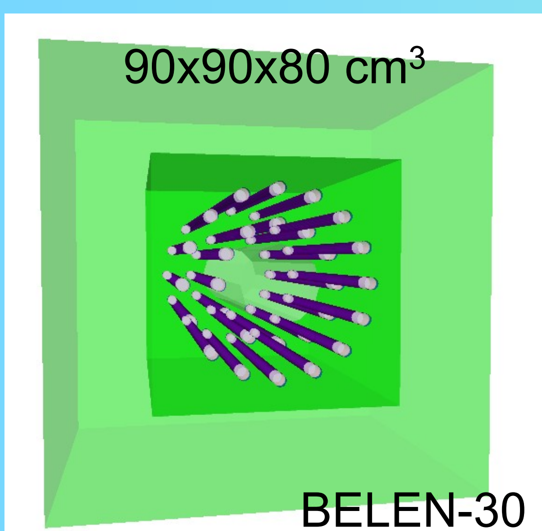


BEta deLayEd Neutron detector

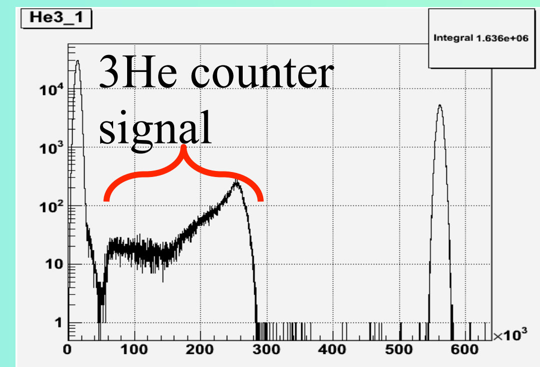
(UPC, IFIC, GSI/Giessen)

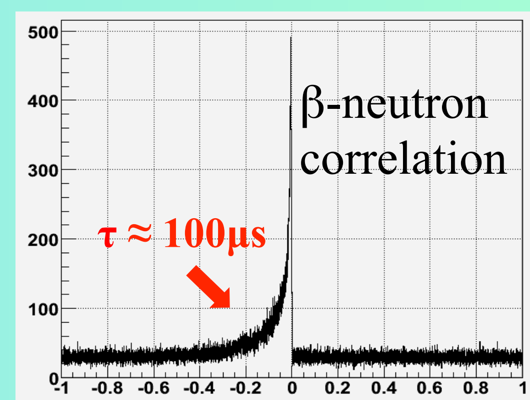
⃠2.5cmx60cm high-pressure ^{3}He tubes in a polyethylene moderation matrix

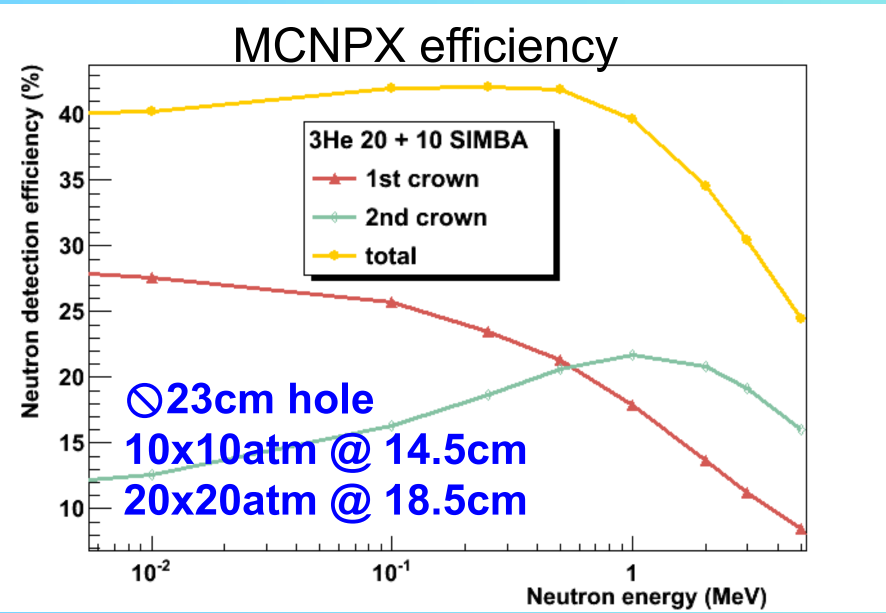
- High selectivity
- Large efficiency
- Some energy dependence
- Long moderation times



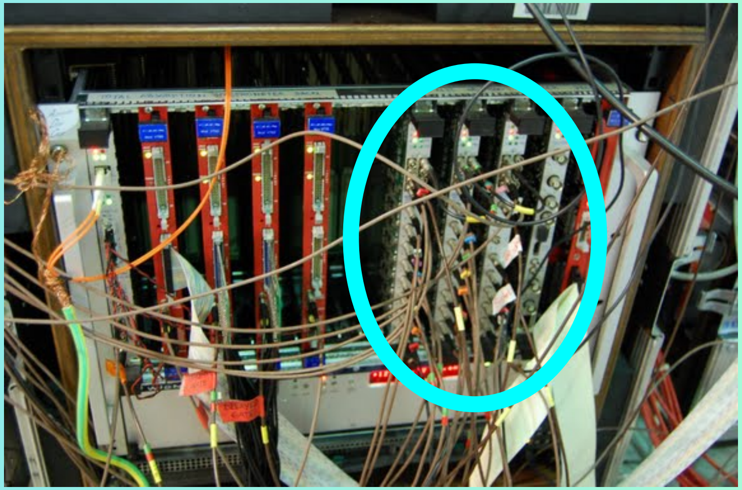
$$P_n = \frac{1}{\varepsilon_n} \frac{N_{\beta n}}{N_\beta}$$





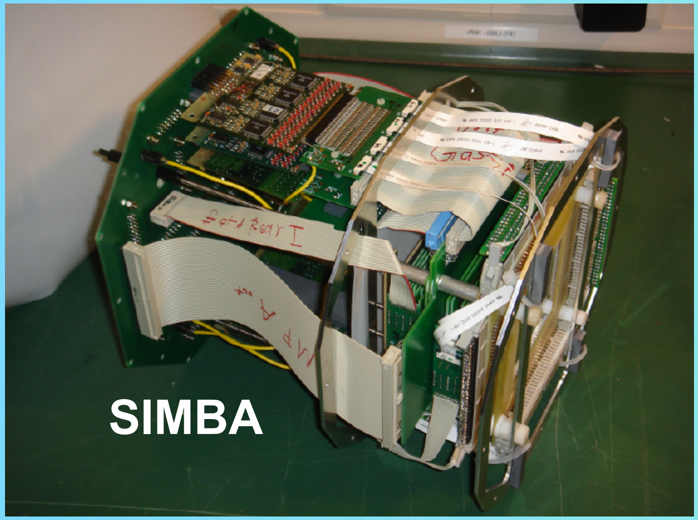


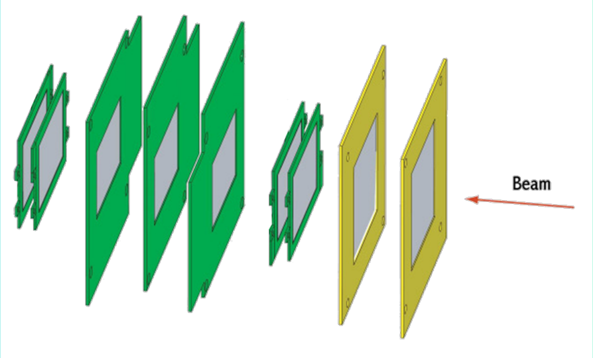
Self-triggered digital acquisition system integrated into MBS



Silicon IMplantation detector and Beta Absorber

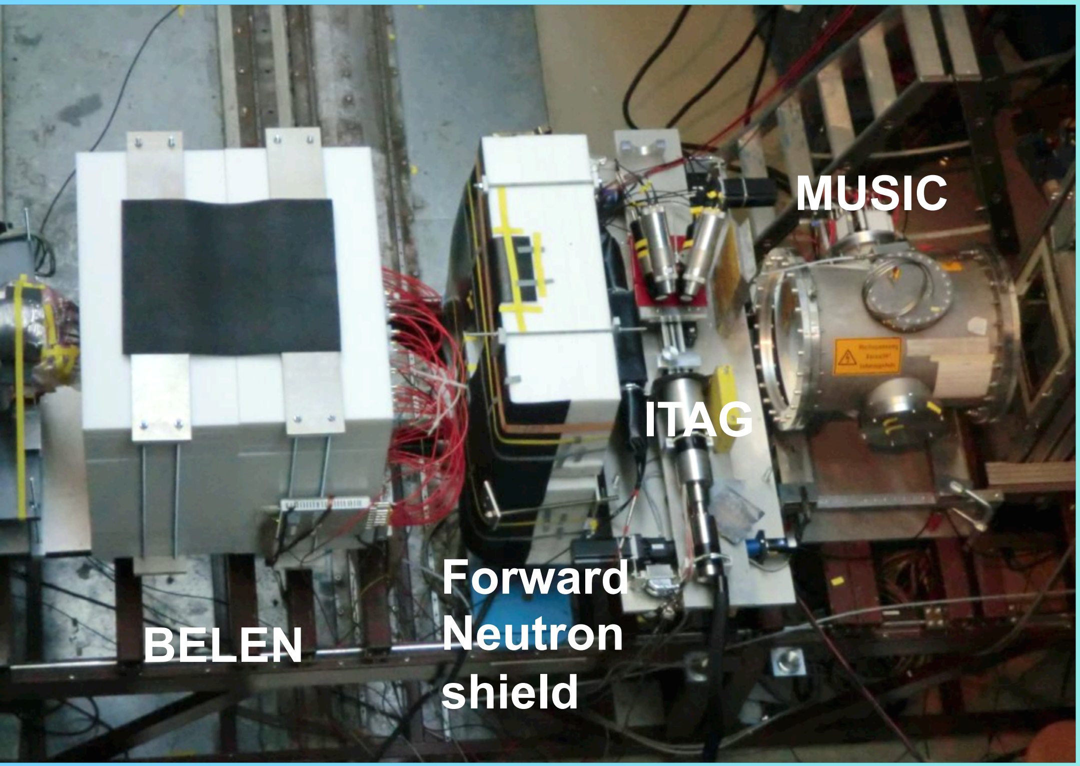
(TUM)

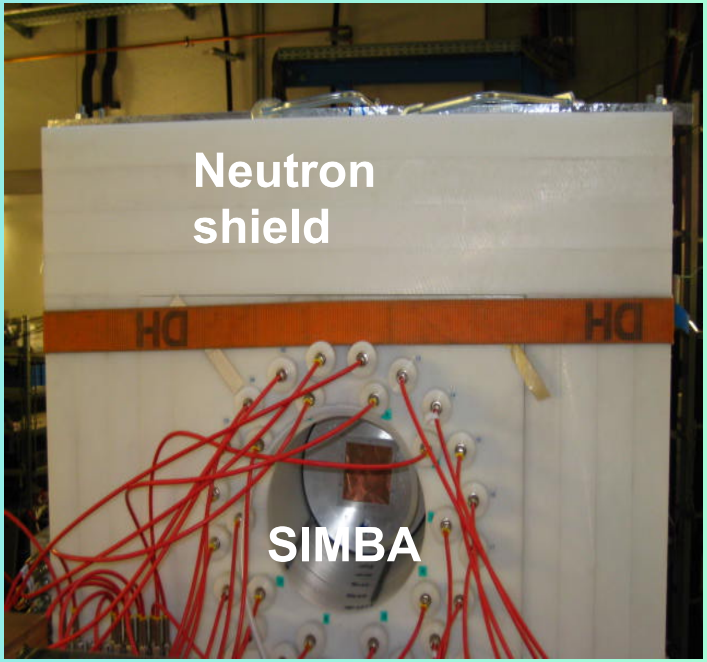


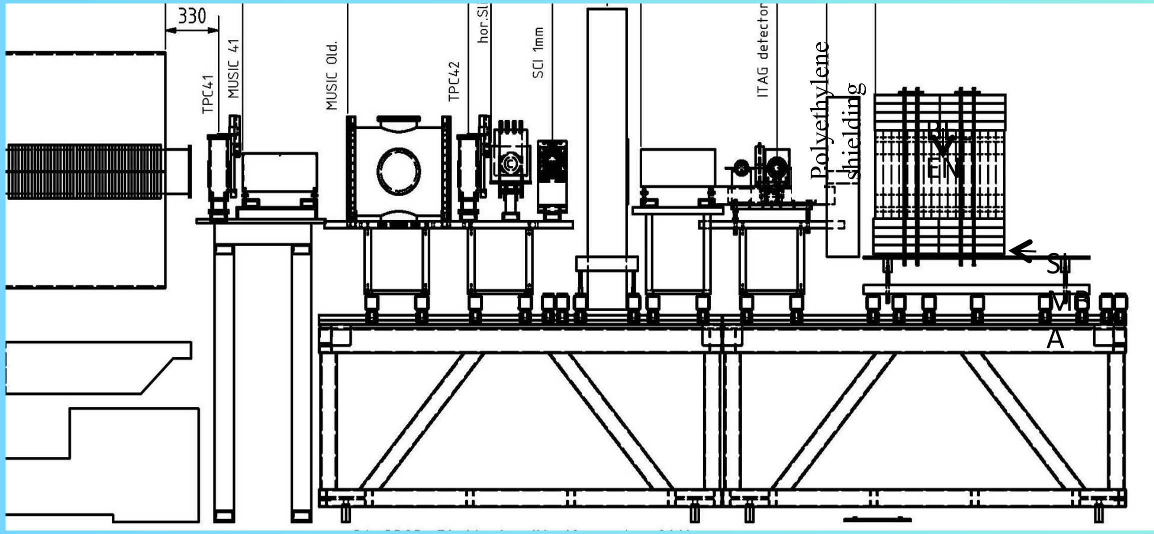


- 2×SSD (6cm×6cm×0.3mm) **X-Y**
- 2×SSD (6cm×4cm×1mm) **β-absorber**
- 3×DSD (6cm×4cm×0.7mm) **implant**
- 2×SSD (6cm×6cm×1mm) **β-absorber**

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



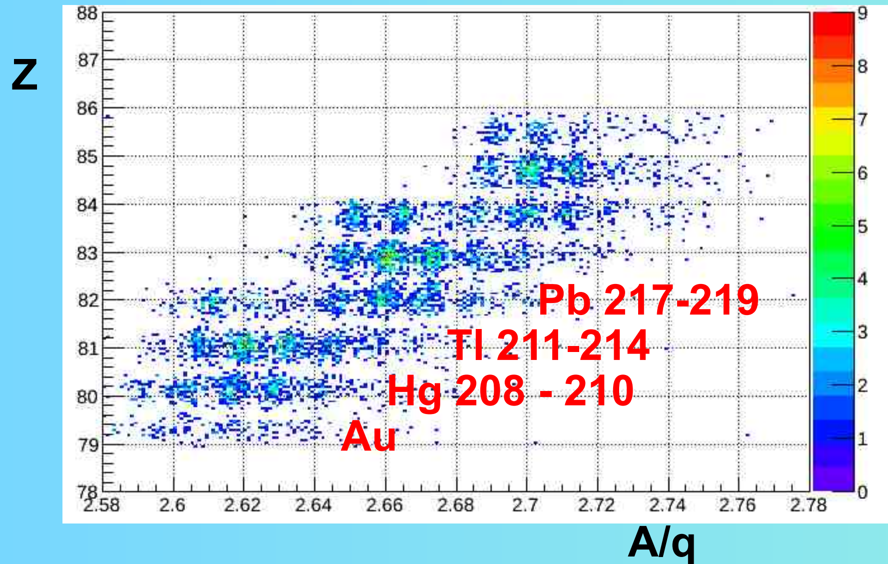




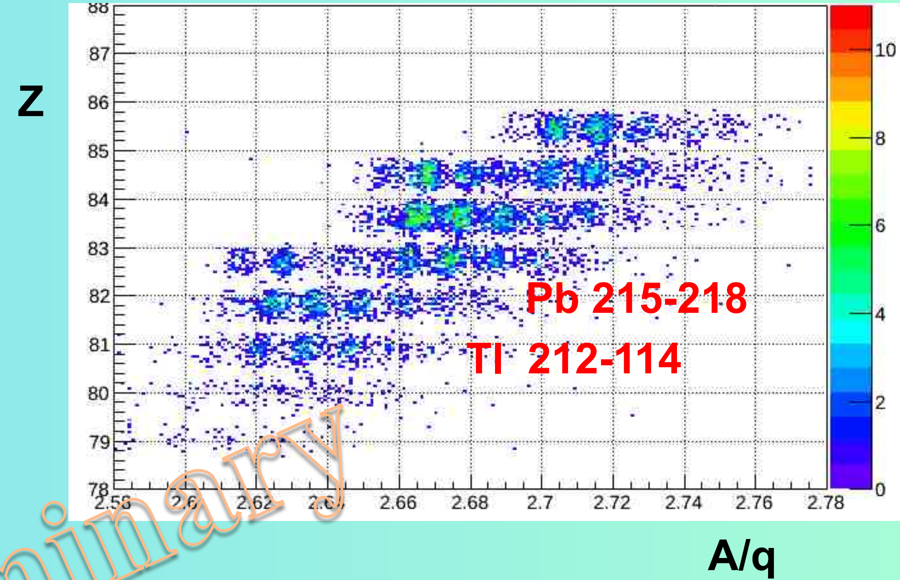
^{238}U + Be
1 GeV/u
1-2x10^{9} pps

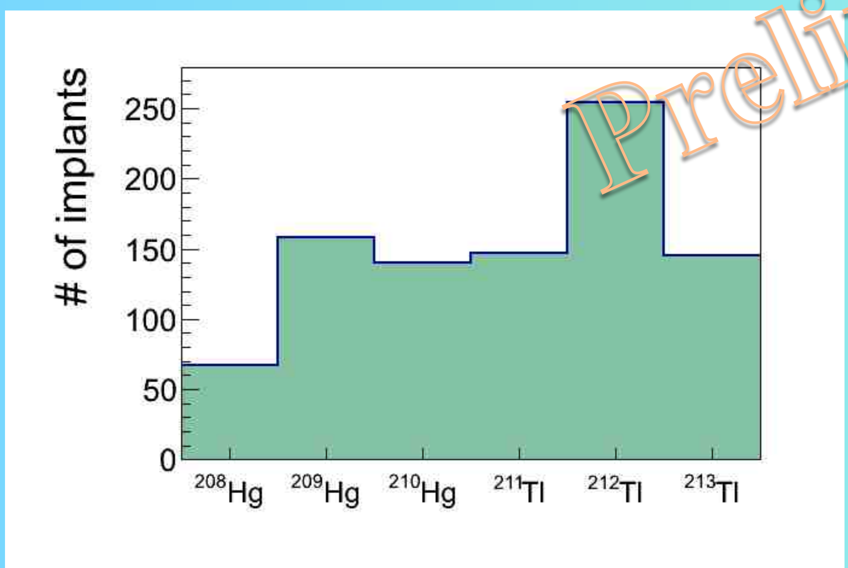
(S323: Beta-decay of very neutron rich Rd, Pd, Ag isotopes including the waiting point 128Pd (F. Montes et al.) was carried with the same set-up in the same run**)**

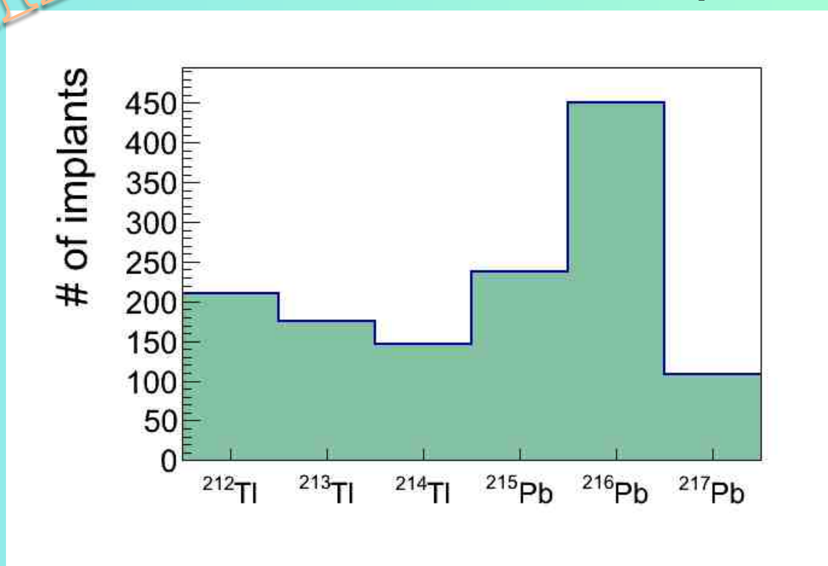
^{211}Hg setting (all statistics)



^{215}Tl setting (half statistics)

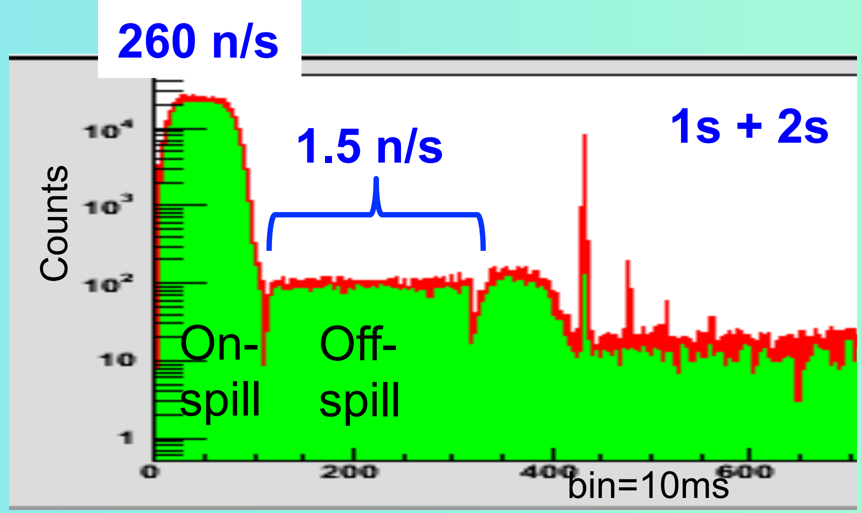


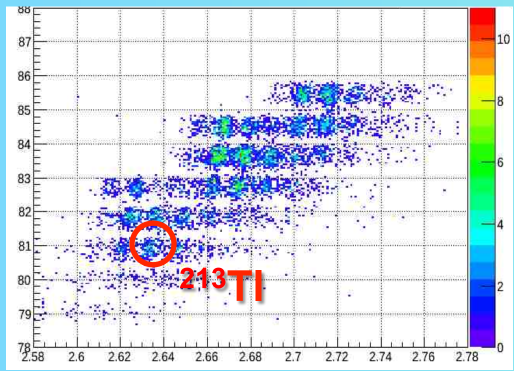


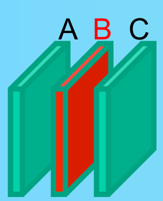


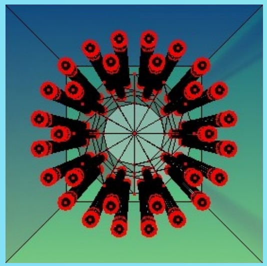
(Preliminary analysis by R. Caballero & C. Domingo)

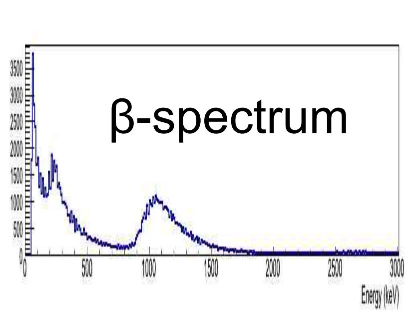
Beta- delayed neutrons have been identified in spite of the large beam-induced neutron background!

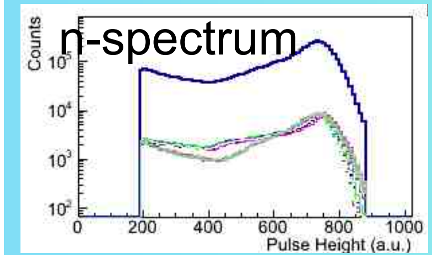


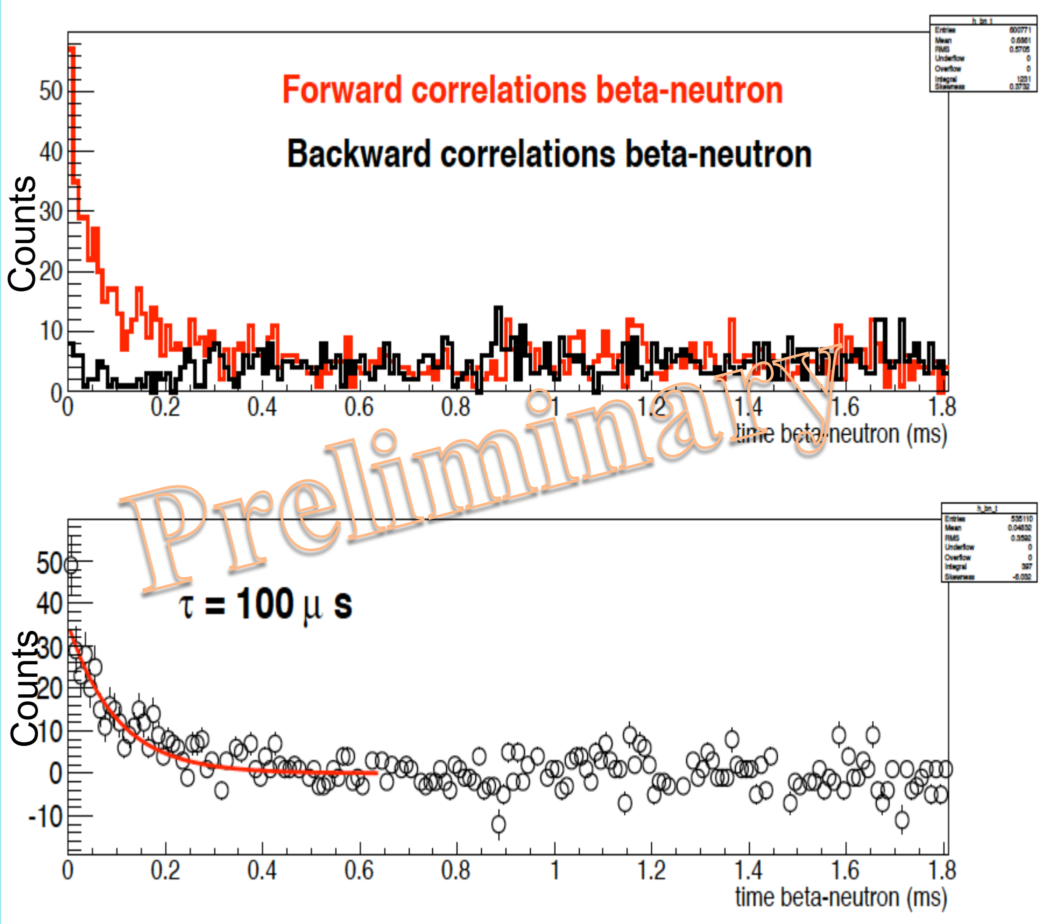






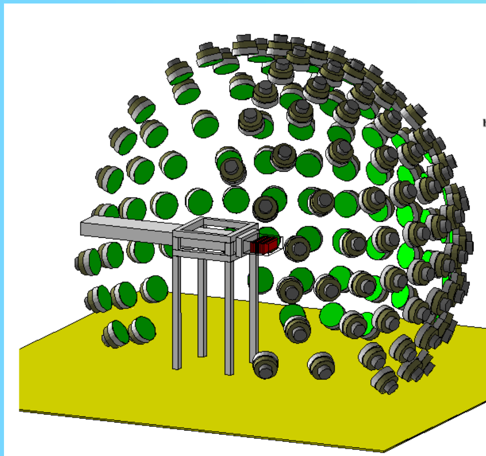




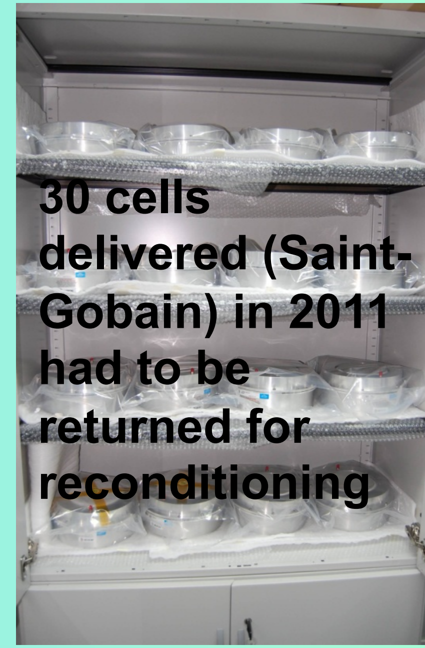


MOdular Neutron SpectromeTER

(CIEMAT,VECC,JYFL,IFIC)

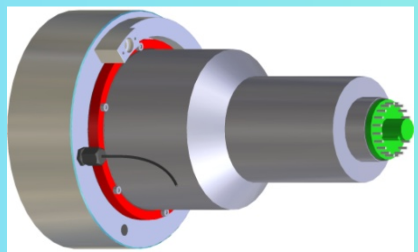


200 detectors, 10cm radius		ΔE/E @ 1 MeV	
TOF length (m)	Geometric efficiency	1ns	4ns
2	12.5%	3.5%	6.0%
3	5.6%	2.5%	4.2%

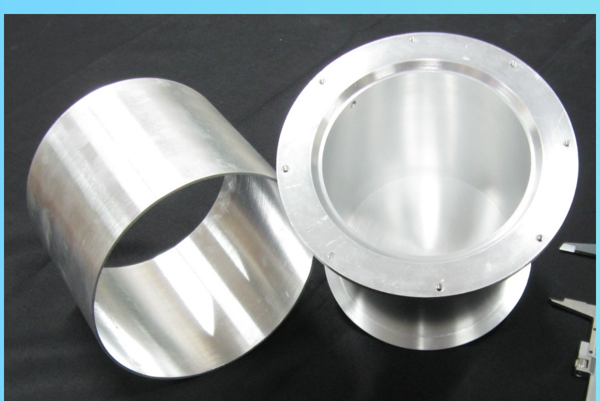


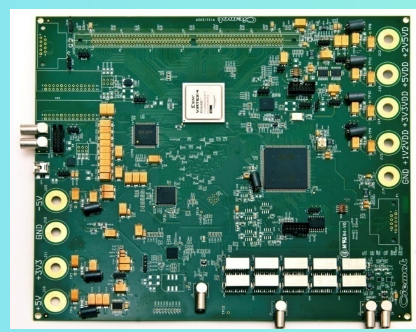
30 cells delivered (Saint-Gobain) in 2011 had to be returned for reconditioning

200 x BC501A modules
⦸20cmx5cm cell
5”PMT R4144

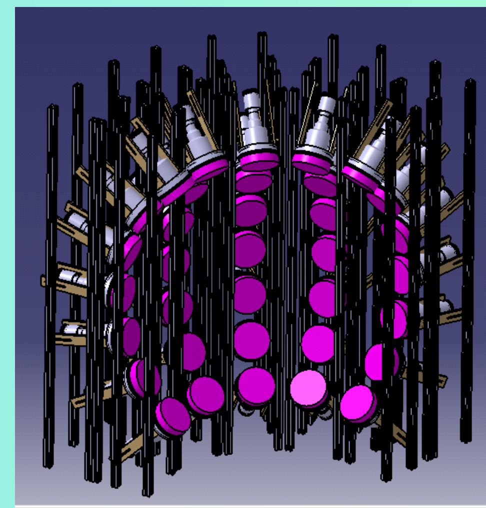


Production of prototypes for further cells started at VECC

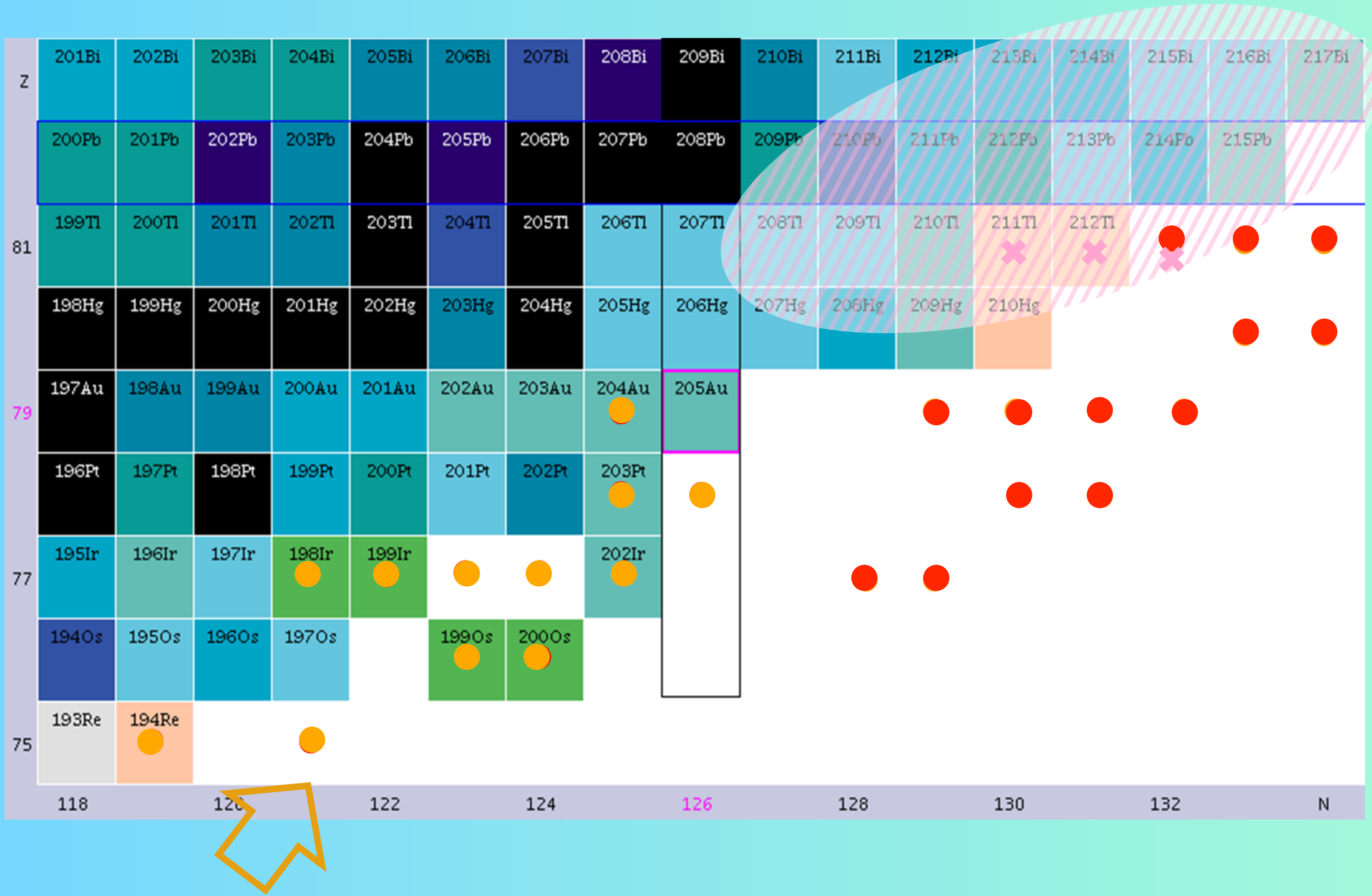




Dedicated digitizers: 14bit-1Gs/s under production (CIEMAT)



- **30 cell demonstrator**
- **ready by the end 2012**
- **commissioning at JYFL**

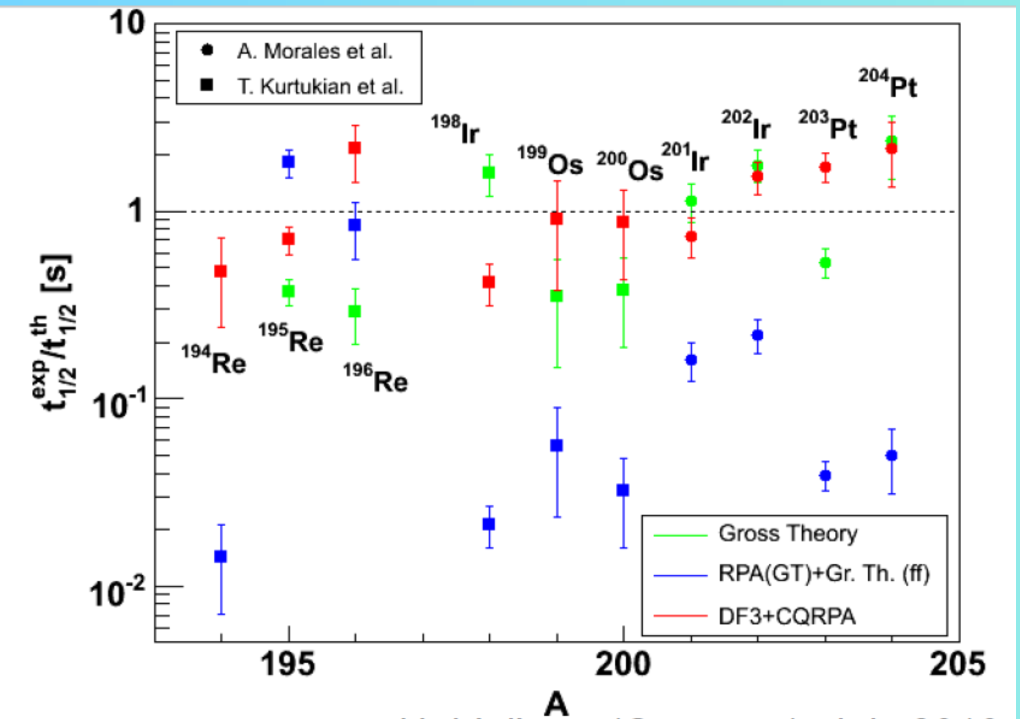


C. Domingo-Pardo et al., Experiment S410

J. Benlliure et al., NIC XI, Heidelberg, 2011

J.J. Valiente et al., Experiment S350, this conf.

Experimental $T_{1/2}$ seems to favor some models but here there is no neutron emission to check!

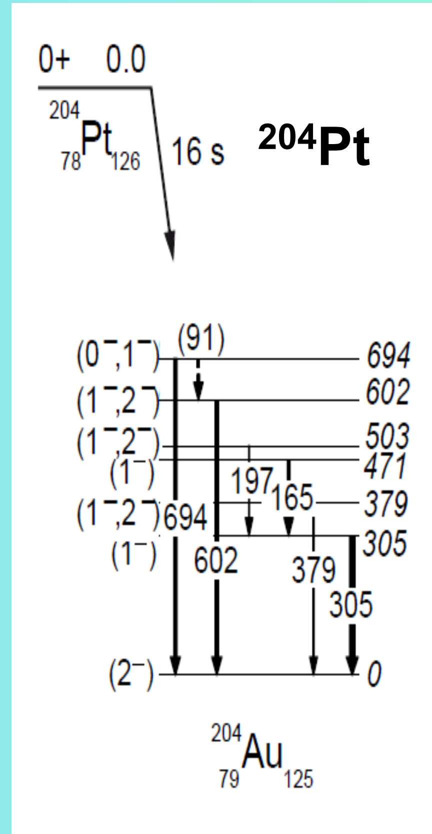


208Pb (1GeV/u)
+
Be (2.5g/cm2)

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

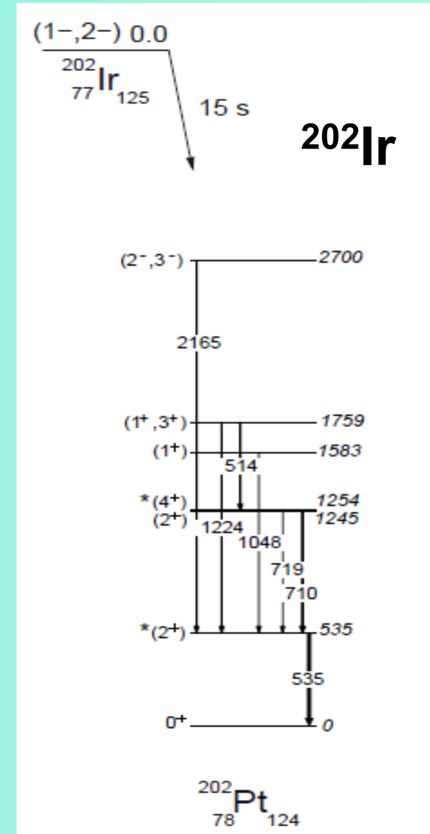
STATISTICS:

3×10^4 ions



Q_β = 2.3 MeV (SY)
$N^{lev}=2.7\times10^3$

8×10^3 ions



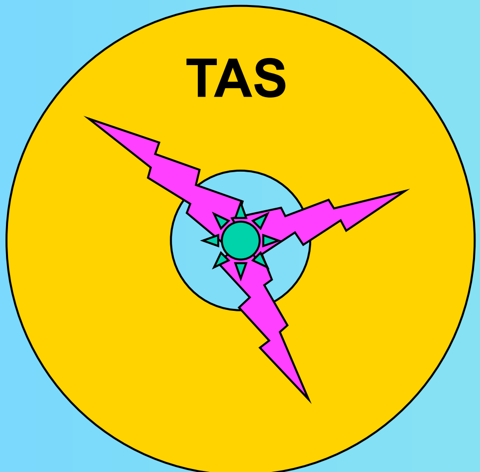
Q_β = 5.4 MeV (SY)
$N^{lev}=4.1\times10^4$

- **Region accessible for TAS with enough statistics**

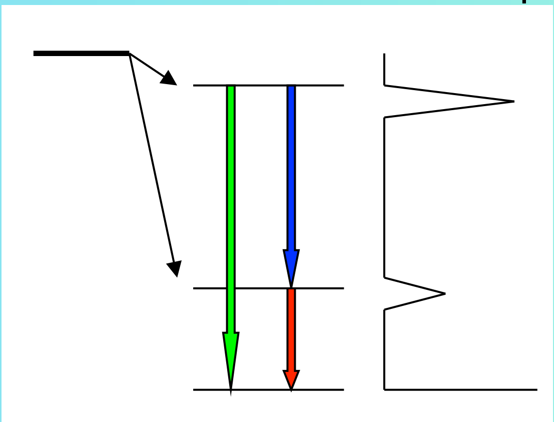
(^{204}Au, ^{204,203}Pt, ^{201}Ir,…)

Total Absorption Gamma-ray Spectroscopy:

- 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



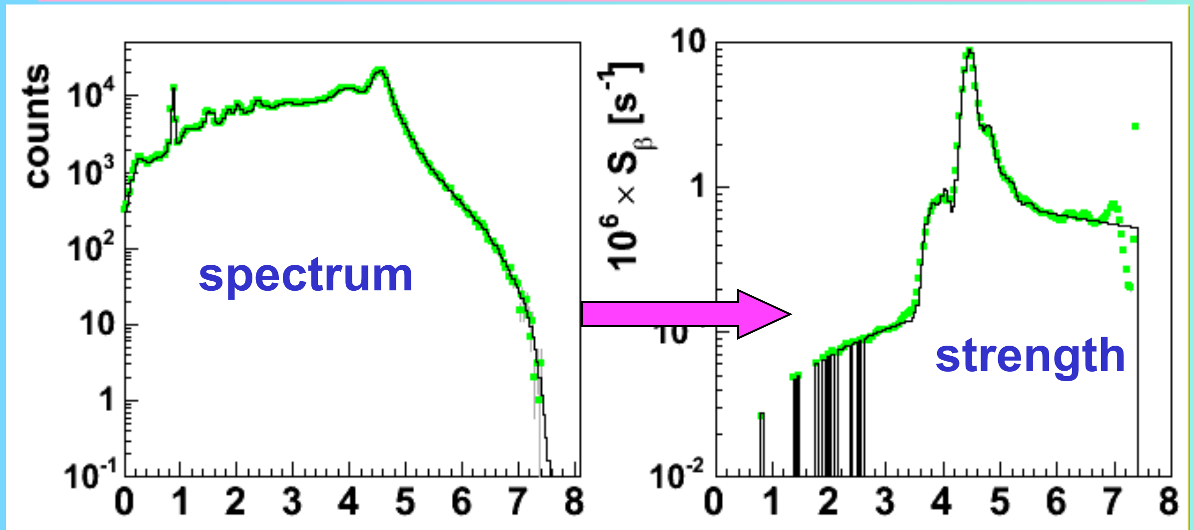
Real TAS response depends weakly on de-excitation path

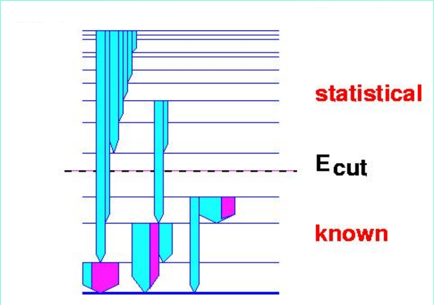
Response from MC simulations and nuclear statistical model

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

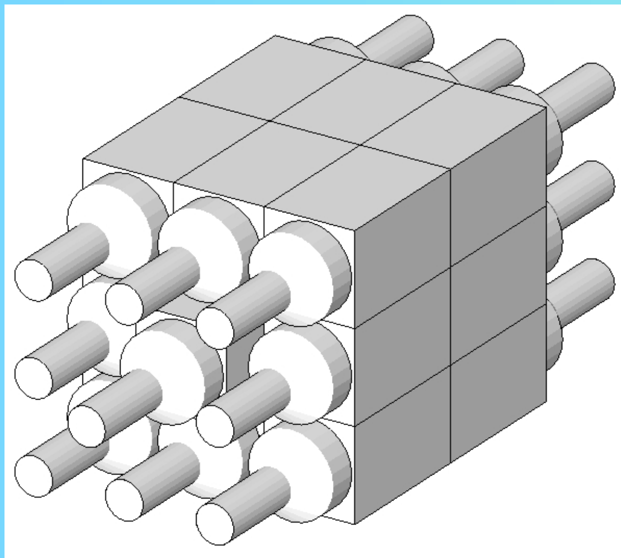
$$\mathbf{R}_j = \sum_{k=0}^{j-1} b_{jk} \mathbf{g}_{jk} \otimes \mathbf{R}_k$$

Deconvolution with the TAS response to decay



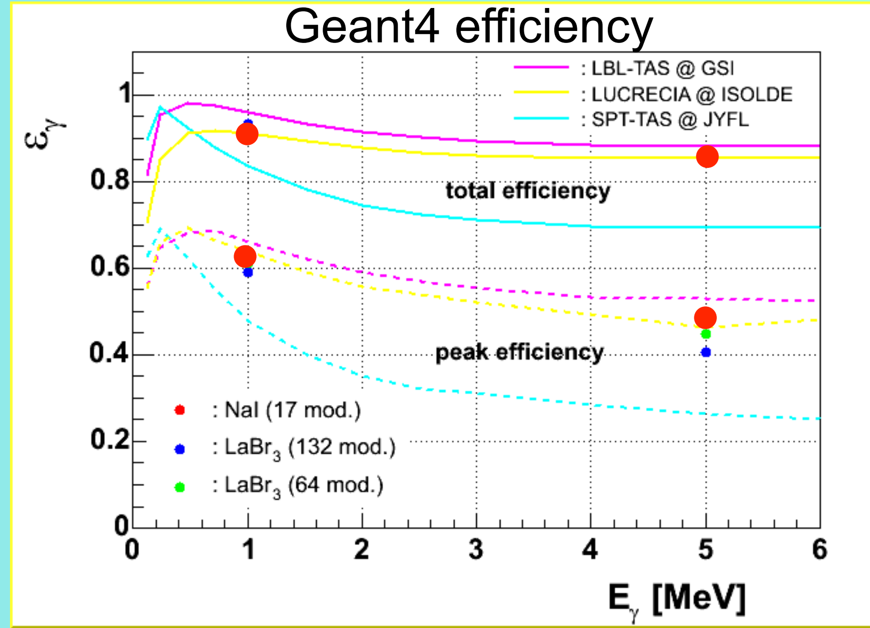


β-Decay Total Absorption Spectrometer



16 × NaI(Tl) crystals:

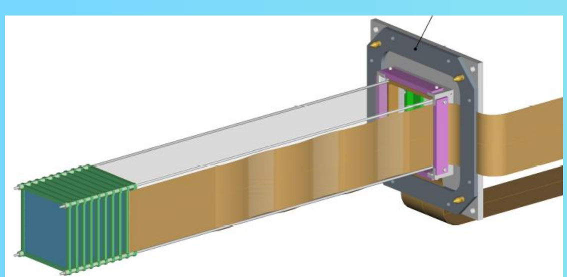
- $15 \times 15 \times 25$ cm^3
- Minimum dead-material
- 5” PMT: ETL9390



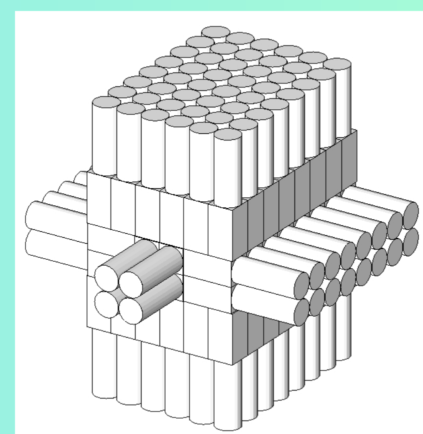
Good efficiency

➔ **Cascade multiplicity information**

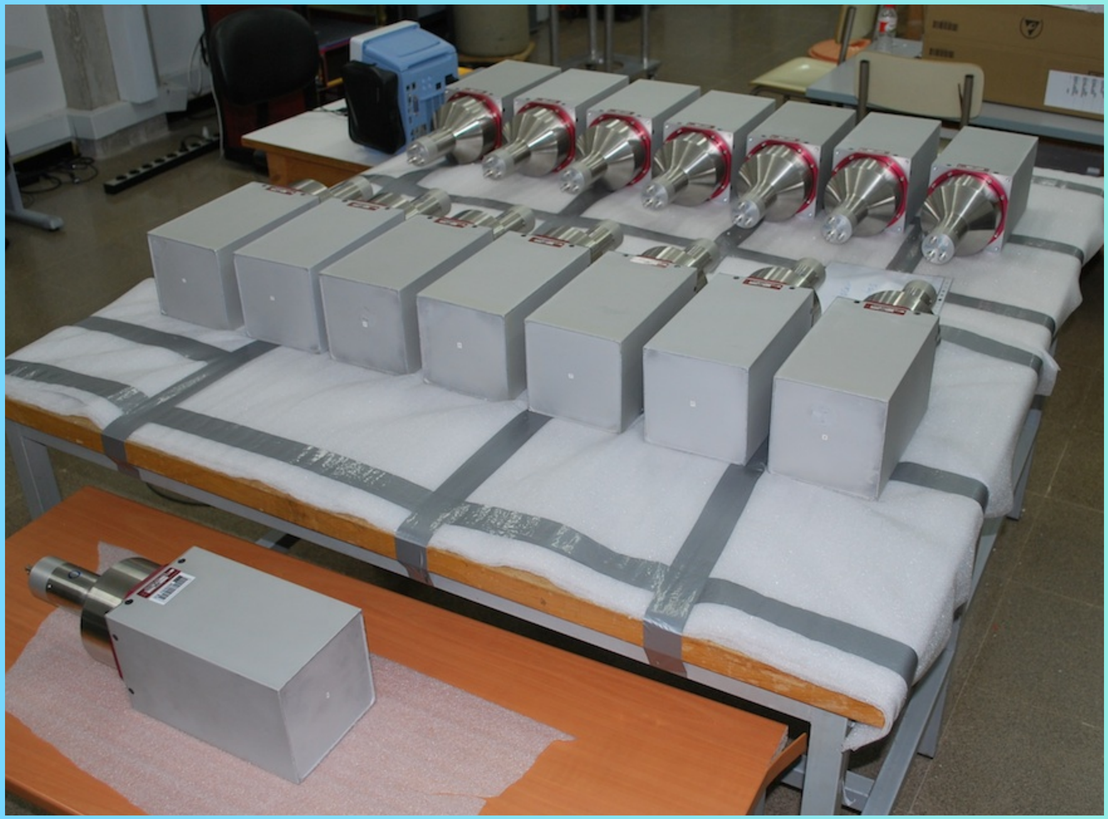
Designed to be coupled to AIDA implantation detector

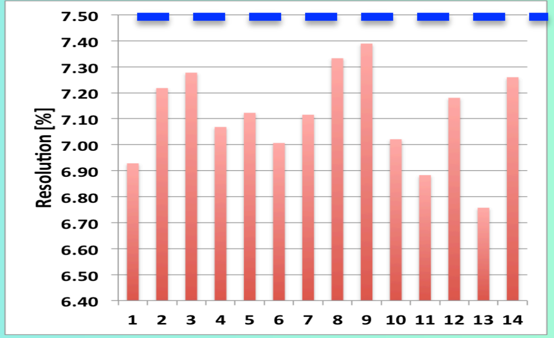


A design with 128 × $5.5 \times 5.5 \times 11$cm3 $LaBr_3$:Ce crystals was discarded because of cost

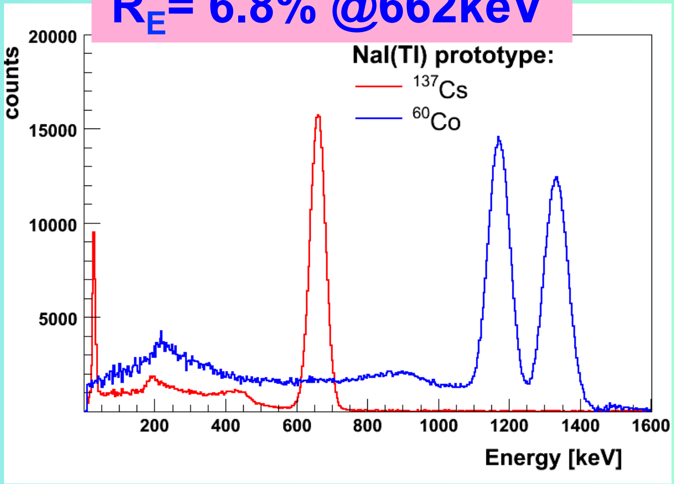


14 detector modules just delivered!

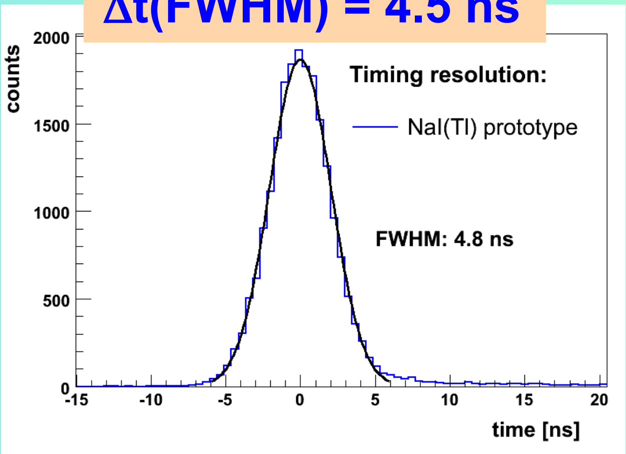




R_E= 6.8% @662keV



Δt(FWHM) = 4.5 ns



Full spectrometer assembled plus electronics ready by the end of the year

Conclusions:

- **First experiments with BELEN have been performed at the FRS to investigate β-delayed neutron emission close to ^{132}Sn and ^{208}Pb (2nd and 3rd r-process abundance peak). JINR is joining with additional 40 counters**
- **The DTAS spectrometer will be ready by the end of 2012 for commissioning and awaiting for a PRESPEC stopped beam campaign**
- **A 30 cell prototype of MONSTER will be ready at the end of 2012 for commissioning and awaiting for a PRESPEC stopped beam campaign**

BELEN Collaboration: UPC-Barcelona, IFIC-Valencia, GSI-Darmstadt/U. Giessen, CIEMAT-Madrid, JINR-Dubna

DTAS Collaboration: IFIC-Valencia, U. Surrey, CIEMAT-Madrid, JYFL-Jyvaskyla, PNPI-Gatchina

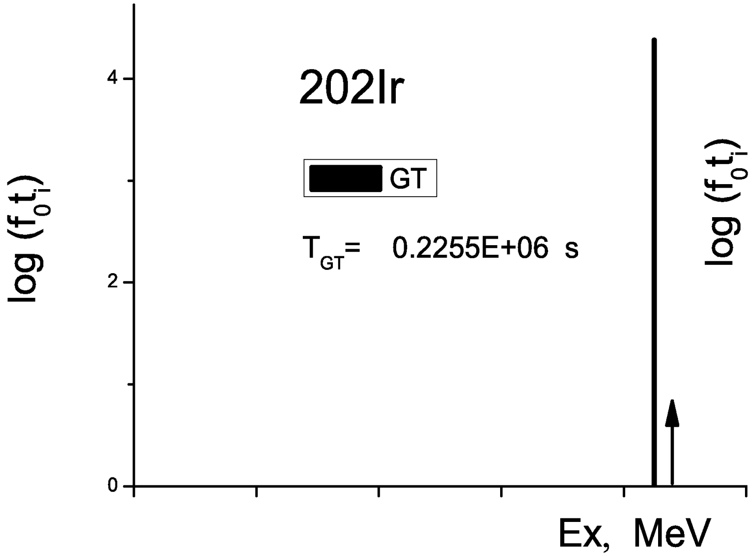
MONSTER Collaboration: CIEMAT-Madrid, VECC-Kalkatta, JYFL-Jyvaskyla, IFIC-Valencia

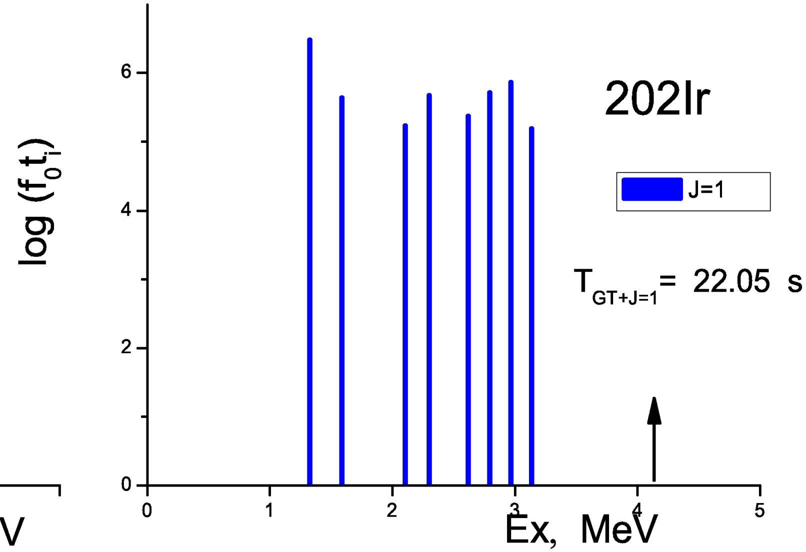
S410:

R.Caballero-Folch[1], J.Agramunt[2], A.Algora[2], F.Ameil[3], Y.Ayyad[4], J.Benlliure[4], M.Bowry[5], F.Calviño[1], D.Cano-Ott[6], T.Davinson[7], I.Dillmann[8,3], C.Domingo-Pardo[2], A.Estrade[3], A.Evdokimov[8,3], T.Faestermann[9], F.Farinon[3], D.Galaviz-Redondo[10], A.García-Rios[6], H.Geissel[3], W.Gelletly[5], R.Gernhuser[9], M.B.Gómez-Hornillos[1], C.Guerrero[11], M.Heil[3], C.Hinke[9], R.Knöbel[3], I.Kojouharov[3], J.Kurcewicz[3], N.Kurz[3], Y.Litvinov[3], L.Maier[9], J.Marganiec[3], M.Marta[3,8], T.Martinez[6], F.Montes[12], I.Mukha[3], D.R.Napoli[13], Ch.Nociforo[3], C.Paradela[4], S.Pietri[3], Z.Podolyák[5], A.Prochazka[3], S.Rice[5], A.Riego[1], B.Rubio[2], H.Schaffner[3], Ch.Scheidenberger[8,3], K.Smith[14,15], E.Sokol[16], K.Steiger[9], B.Sun[3], J.L.Taín[2], M.Takechi[3], D.Testov[17,16], H.Weick[3], E.Wilson[5], J.Winfield[3], R.Wood[5] and P.Woods[7]

[1]Universitat Politècnica de Catalunya, Barcelona, Spain; [2]Institut de Física Corpuscular, València, Spain; [3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany; [4]Universidad de Santiago de Compostela, Spain; [5]Department of Physics, University of Surrey, Guildford GU27XH, UK; [6]CIEMAT, Madrid, Spain; [7]School of Physics and Astronomy, University of Edinburgh, UK; [8]II. Physikalisches Institut, Justus-Liebig Universität Giessen, Germany; [9]Department of Physics E12, Technische Universität München, Germany; [10]CFNUL, Centro de Fisica Nuclear da Universidade de Lisboa, Portugal; [11]CERN; [12]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan, USA; [13]Laboratory Nazionali di Legnaro, INFN, Italy; [14]Department of Physics, University of Notre Dame, South Bend, Indiana, USA; [15]Joint Institute for Nuclear Astrophysics, University of Notre Dame, South Bend, Indiana, USA; [16]Flerov Laboratory, Joint Institute for Nuclear Research, Dubna, Russia; [17]IPN Orsay, France

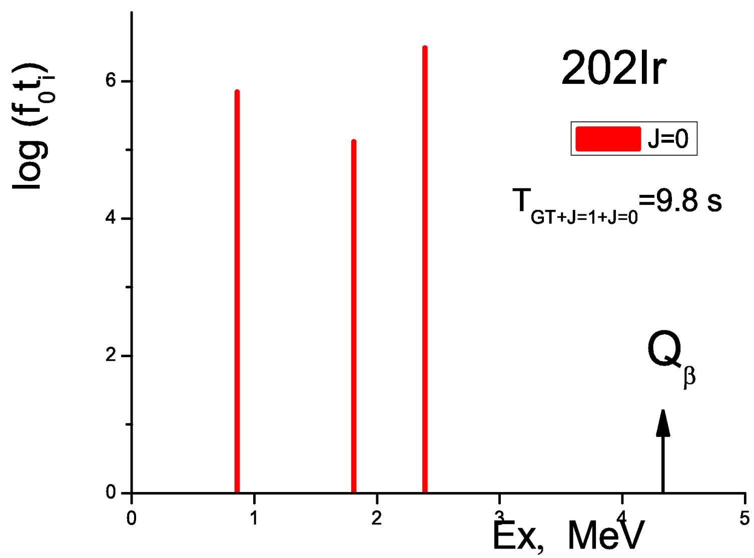
THANK YOU!

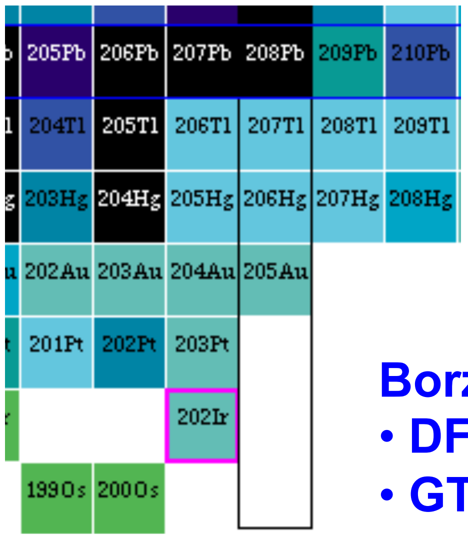




^{202}Ir

(Z=77, N=125)





Borzov, Phys.At.Nucl. (2011)

- **DF+QRPA**
- **GT + FF (microscopic)**
- **no deformation**

Q_β = 5.4 MeV (SY)

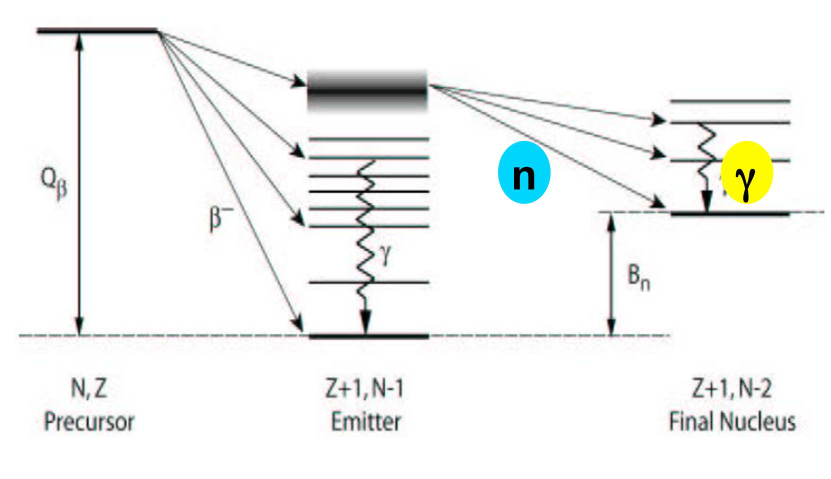
Expected number of levels: $N^{lev}=4.1\times10^4$

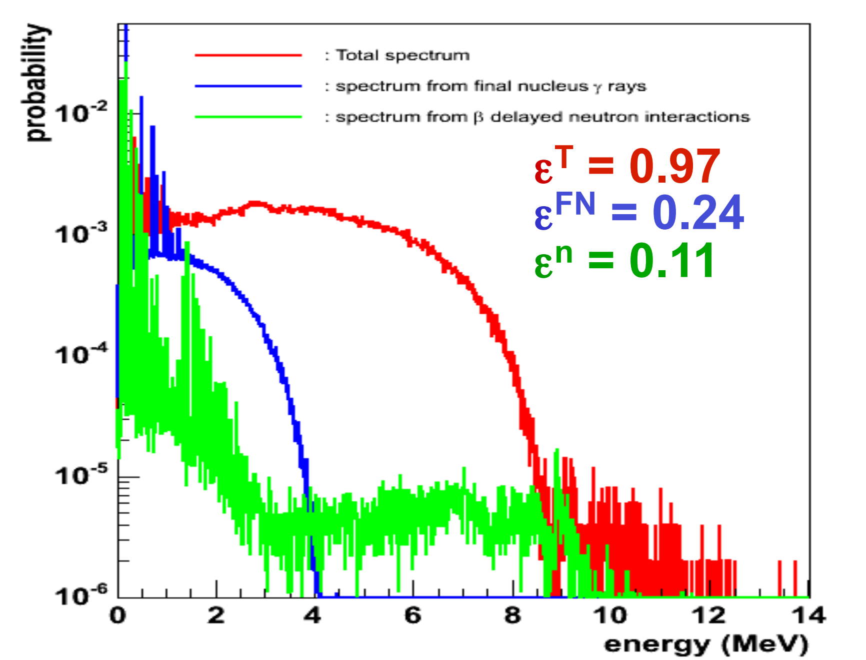
Goriely et al. PRC78(08) 064307

TAS neutron sensitivity

(The case of delayed neutron emitters)

^{147}Cs Q_β=9.2MeV, S_n=4.5MeV , P_n= 27.5%





MC Simulations: M.D. Jordan