Neutrinos, Applications and Nuclear Structure and Astrophysics with Total Absorption G-ray Spectroscopy and the $(NA)^2$STARS Project

GCM Meeting 2022 @ Caen

Collaboration
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Outline

- **Intro: What is/Why the TAGS technique ?**
- **TAS Spectrometers**
- **Physics Cases & Current limitations of the existing TAS**
- **(NA)²STARS**

γ Measurement Caveat

- Before the 90's, conventional detection techniques: high resolution γ-ray spectroscopy
  - ❑ Excellent resolution but efficiency which strongly decreases at high energy
  - ❑ Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daugther nuclei (especially with decay schemes with large Q-values)

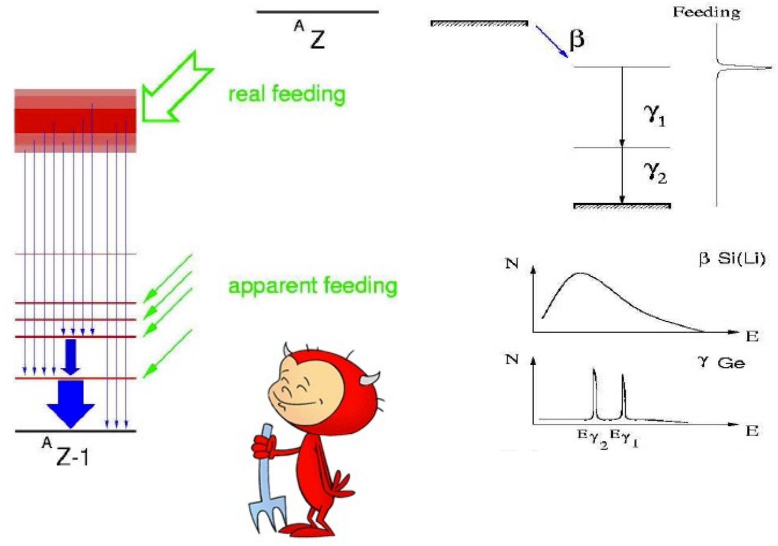
- Incomplete decay schemes: overestimate of the high-energy part of the FP β spectra

- Phenomenon commonly called « pandemonium effect** » by J. C Hardy in 1977

** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

➡ **Strong potential bias in nuclear data bases and all their applications**

Picture from A. Algora



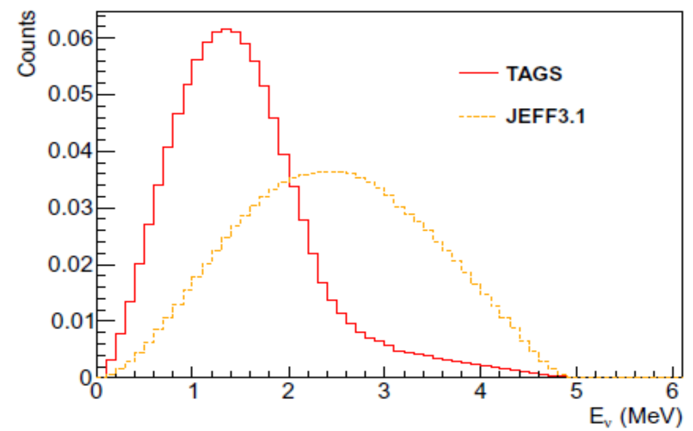
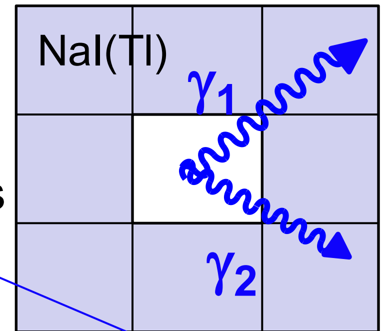
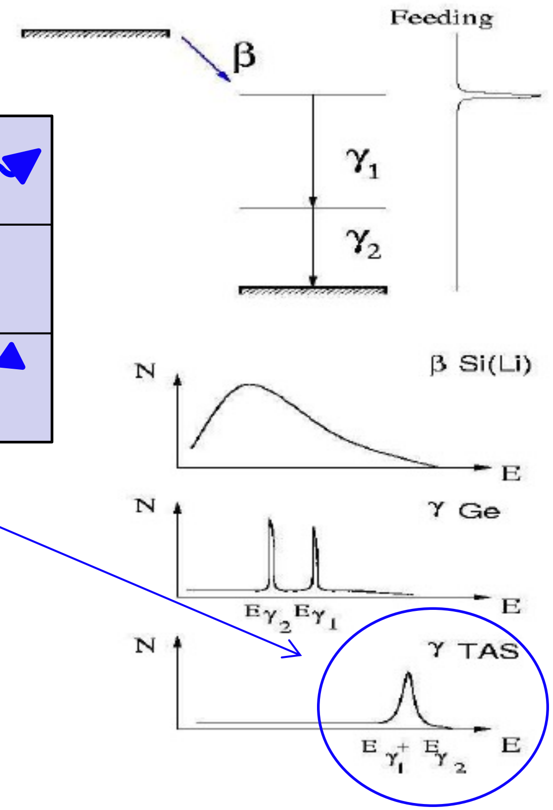


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

TAGS: a Solution to the Pandemonium Effect

- Total absorption γ-ray spectroscopy (TAGS)
  - A TAS is a calorimeter
  - It contains big crystals covering 4π
  - Instead of detecting the individual gamma rays, absorbs the full gamma energy released by the gamma cascades in the β-decay process





- First TAS developed in the 70's but too small detectors to be efficient. Development of the TAGS method efficient and systematic since the 90's (Greenwood & al.)

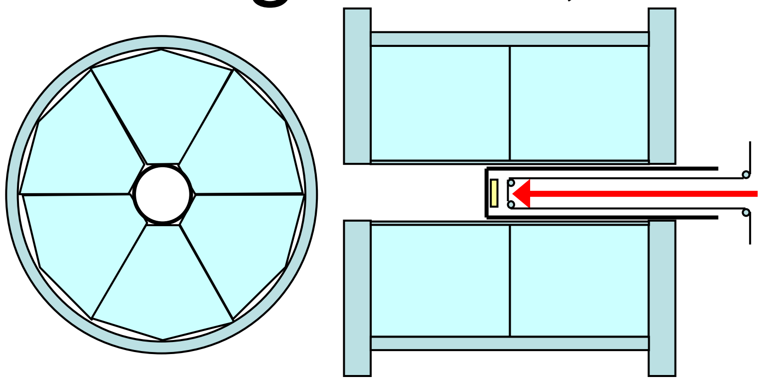
- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution
  - R_{ij} = matrix detector response
  - d_i = measured data
  - Extract f_j the level feeding by deconvolution

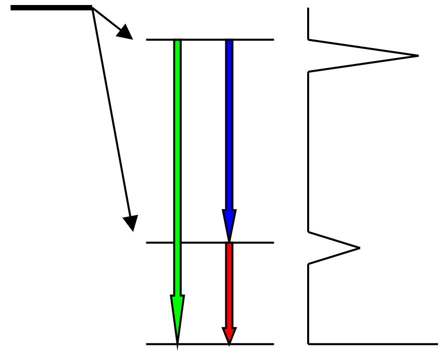
$$d_i = \sum_{j=1}^{m} R_{ij} \, . \, f_j \;\Rightarrow\; I_i = \frac{f_i}{\sum_k f_k}$$

J. L. Tain & D. Cano-Ott, NIMA 571 (2007) 728

Total Absorption γ-ray Spectroscopy (TAGS)

Big cristal, 4π => A TAS is a calorimeter !





Observable:

β-intensity => β-strength:
An ideal TAS would give directly the β-intensity I_β which is linked with the β-strength S_β:

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

Statement of the problem:

$$I_i = \frac{f_i}{\sum_k f_k}$$

Relation between TAS data and the β-intensity distribution:

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

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

Deconvolution (Inverse problem) algorithms

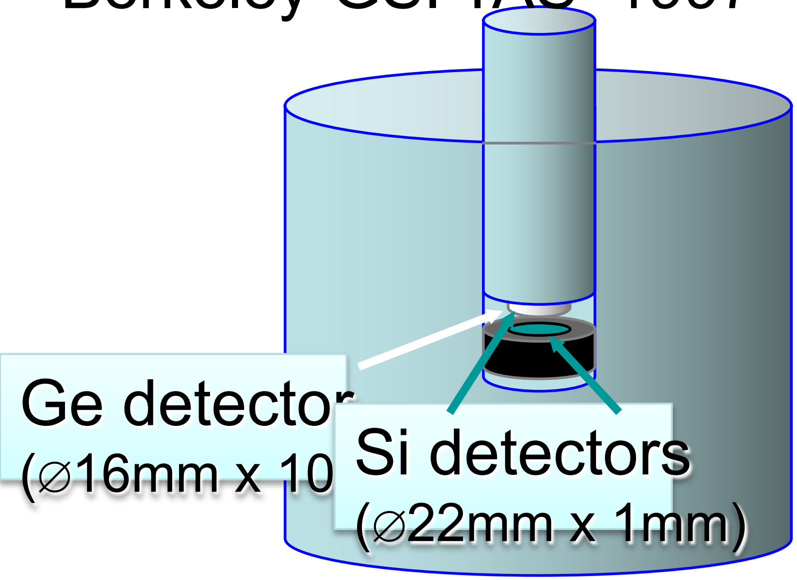
Monte Carlo simulations
+
Nuclear statistical model

- Spectrum must be clean
- Response must be accurately known
- Solution of inverse problem must be stable (requires calorimetry)

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

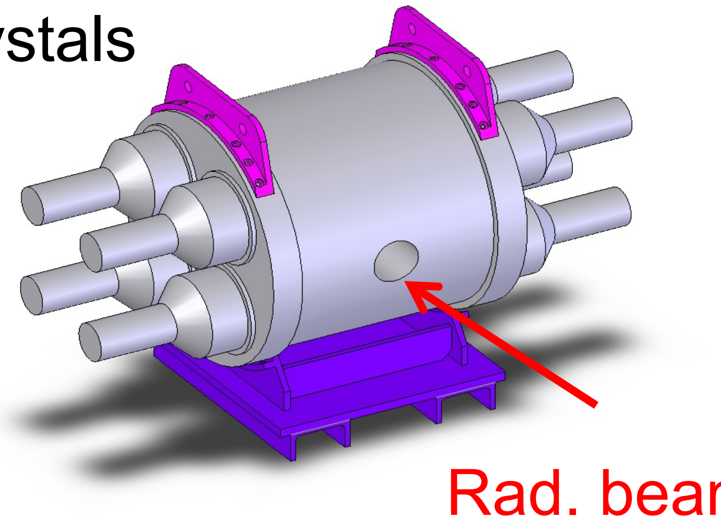
Past and Presently used TAS

Berkeley-GSI TAS 1997

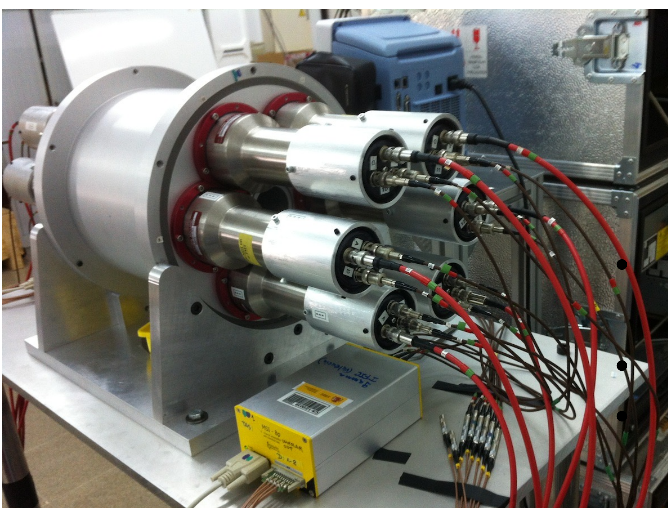


TAS "Lucrecia" @ ISOLDE, CERN

NaI large monocrystals

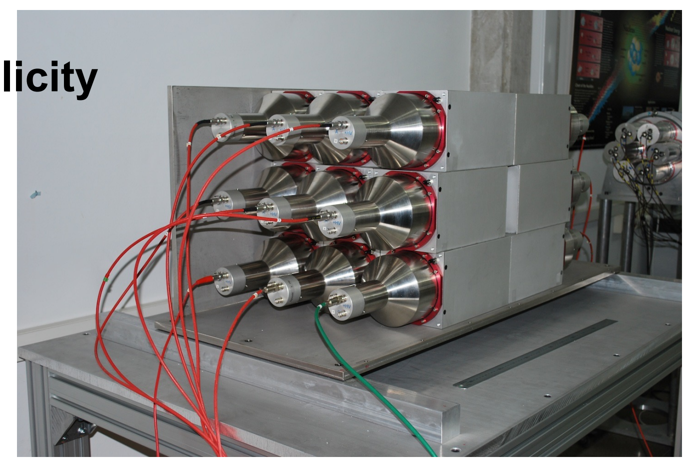


- **Large 18-fold segmented NaI spectrometer**
- **Cascade multiplicity information**



"Rocinante" TAS

- **Compact 12-fold segmented BaF_2 spectrometer**
- **Low neutron sensitivity**
- **Cascade multiplicity information**
- **Good timing**
- **Resolution 10%@1.33MeV**

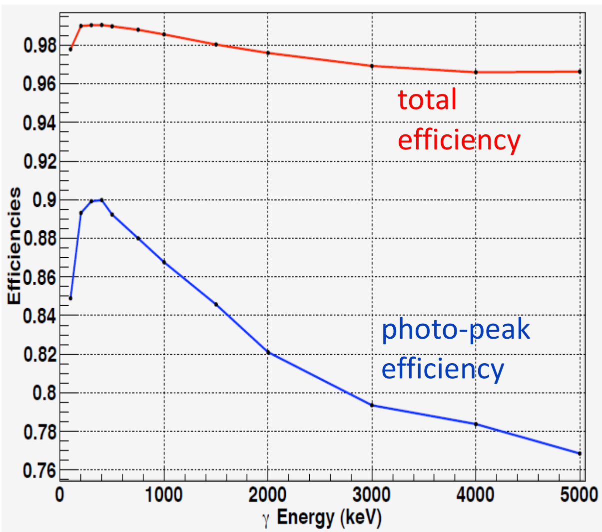


DTAS (NUSTAR) + AIDA DSSSD

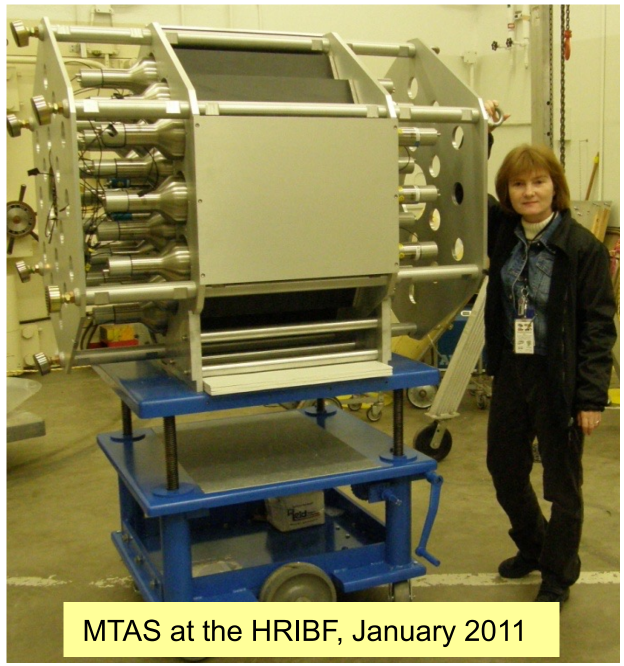
Decay Studies of Fission Products w/ a new Modular Total Absorption Spectrometer (MTAS)

PI's : K. P. Rykaczewski (ORNL) and R.K. Grzywacz (UTK/ORNL)

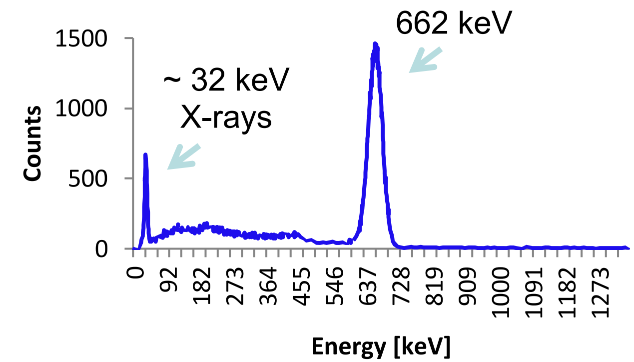
A **Modular Total Absorption Spectrometer (MTAS**) has been constructed from 19 NaI(Tl) scintillator segments. MTAS is designed to perform decay studies with pure beams of neutron-rich nuclei produced in the ^{238}U fission at HRIBF. The total absorption gamma spectra measured with MTAS will be used to derive a true beta-feeding pattern and resulting beta strength function. The studies are important for the verification and development of **the microscopic description of neutron-rich matter** will be performed as well **as applied studies of decay heat released by radioactive nuclei produced in nuclear fuels at power reactors.**



MTAS has superior g-efficiency according to GEANT4 simulations performed by B. C. Rasco (LSU)



MTAS at the HRIBF, January 2011

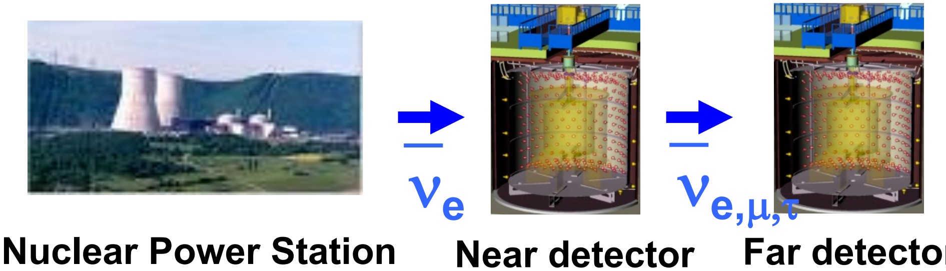


g-energy spectrum of ^{137}Cs activity measured with a single MTAS module.
The energy resolution, fwhm(662 keV) ~ 7%, was found to be better than 8% requested in the detector specifications.

Status: the MTAS has been manufactured at the SGC (Hiram, OH) and delivered to the HRIBF. The tests done using digital electronics show the energy resolution superior to requested specs. Two PhDs were hired full time, one PhD part time.
Funding: \$ 698 K capital + \$ 882 K operations (includes \$ 815 K salaries) = \$ 1580 K
Funds committed/spent : \$ 658 K capital and \$ 512 K operations = \$ 1270 K

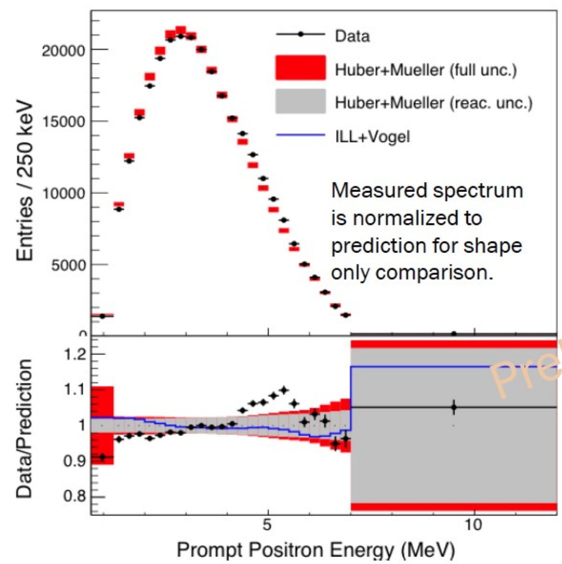
Reactor Antineutrinos & Fundamental Physics

- Measurement of the θ_{13} oscillation param by Double Chooz, Daya Bay, Reno
  - Independent computation of the anti-ν spectra using nuclear DB: conversion method



- Sterile neutrino measurement to explain the "reactor anomaly"
  - 6% deficit of the absolute value of the measured flux compared to the best prediction ILL data
  - Shape anomaly (spectral distorsion) in the full spectrum (btw 4.8-7.3 MeV)
  - Daya Bay PRL points-out a pb in the converted antineutrino spectra from ^{235}U measured beta spectrum @ILL

Absolute shape comparison of data and prediction: $\chi^2/ndf = 41.8/21$



- Next generation reactor neutrino experiments like JUNO or background for other multipurpose experiment

- Reactor Monitoring: prediction of antineutrino emission of future reactor designs rely on nuclear data

IAEA.org International Atomic Energy Agency

➡ Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and sterile neutrinos into question.

➡ Growing interest in Summation Method (SM) to calculate anti-ν spectra, but new measurements needed due to Pandemonium problem

Reactor Decay Heat (DH)

- **Definition:** following the shut-down of the chain reaction in a reactor, **the nuclear fuel continues to release energy called decay heat.**
- Evaluation of the **reactor safety** as well as **various economic aspects** of nuclear power
- **Emitters: essentially made up of FP and actinides**
  - ❑ DH: residual power of **6-12% of the nominal power** of the reactor just after its shut-down

- Estimate through **the only predictive method** for future reactors: **the « summation method »**

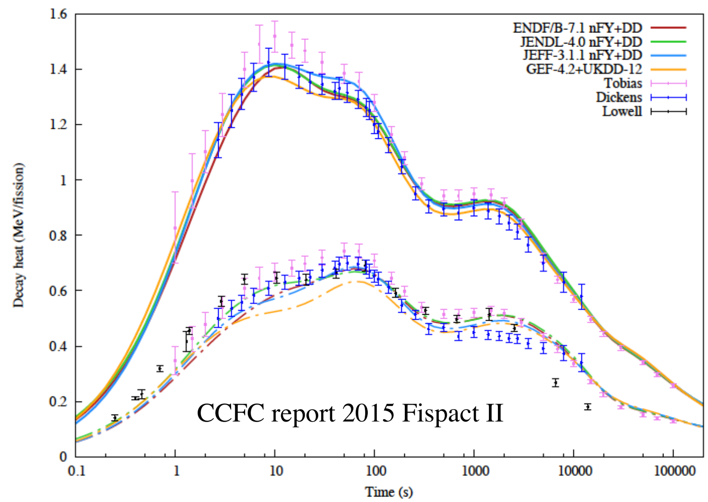
⇒ Summation of all the fission product and actinide contributions:

$$\mathbf{f}(t) = \sum_i (\bar{E}_{\beta,i} + \bar{E}_{\gamma,i})\boldsymbol{\lambda}_i \mathbf{N}_i(t)$$

β,γ decay — Total decay constant (half-life) and Fission Yield

⇒ **Comparisons btw nuclear data & integral measurements show that there remains important discrepancies between data and simulations using different DataBases**

⇒ **Pandemonium effect + unknown decay schemes**



Figur **Total (solid) and gamma (dashed) decay heat from thermal pulse on ^{235}U**

Nuclear Science NEA/WPEC-25 (2007), Report INDC(NDS)-0577 (2009), Report INDC(NDS-0551, Report INDC(NDS)-0676 (2016)

2 TAGS Campains at IGISOL Jyväskylä in 2009 and 2014

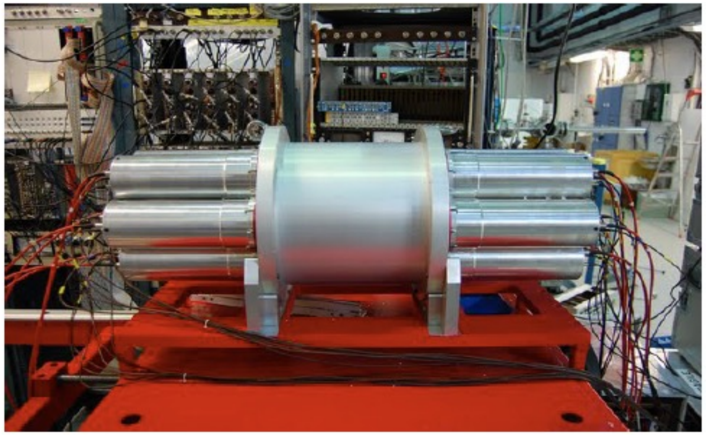
- IGISOL@Jyväskylä:
  - ❑ Proton induced fission ion-guide source
  - ❑ Mass separator magnet
  - ❑ Double Penning trap system to clean the beams

B. Rubio, J. L. Tain, A. Algora et al., Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013)

- 2 (segmented) TAS campains :

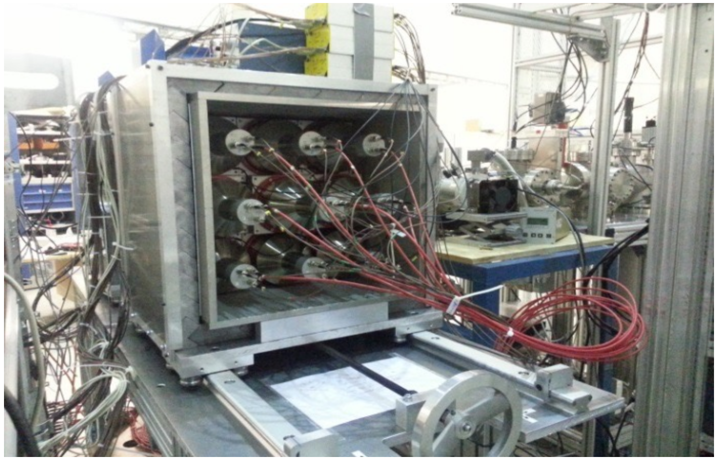
J.L. Tain et al., NIMA 803 (2015) 36
V. Guadilla et al., submitted to NIMA (2018)

❑ ROCINANTE (IFIC Valencia/Surrey):



- ✓ 12 BaF_2 covering 4π
- ✓ Detection efficiency of a single g ray >80% (up to 10 MeV)
- ✓ Coupled with a Si detector for β
- ✓ 7 nuclei (4 delayed neutron emitters) measured (6 for DH and 2 for anti-ν)

❑ DTAS (IFIC Valencia):



- ✓ 18 NaI(Tl) crystals of 15cm × 15cm × 25 cm
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- ✓ Coupled with plastic scintillator for β
- ✓ 12 nuclei for anti-ν measured & 11 for DH

30 Measured Nuclei

- 2014 campain (23 nuclei): Table from IAEA Report INDC(NDS) 0676 (2015)

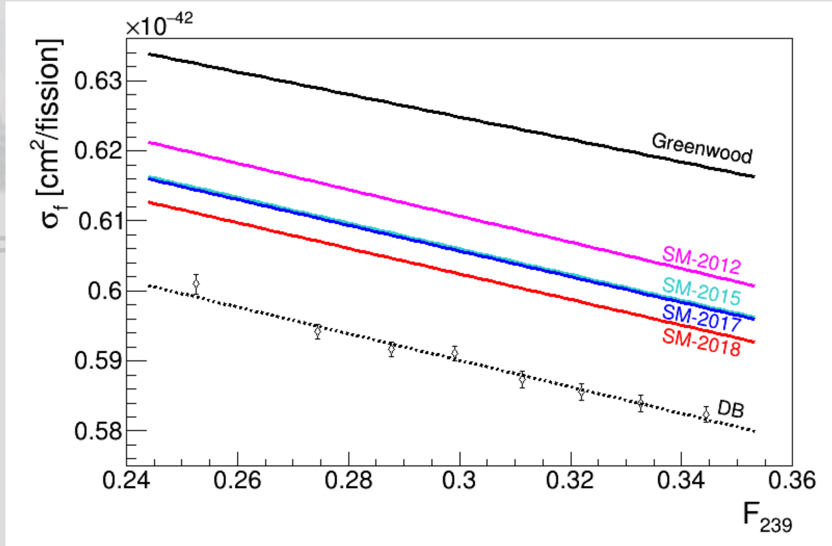
Nuclide	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$	Nuclide	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$
^{95}Rb	1	2		^{102m}Nb	-	1	-
^{95}Sr	-	-	1	^{103}Tc	1	2	-
^{95}Y	-	-	1	^{103}Mo	1	2	-
^{96gs}Y	2	2	1	^{108}Tc	-	-	-
^{96m}Y	-	1	-	^{108}Mo	-	-	-
^{99}Y	-	-	1	^{137}Xe	1	3	-
^{99}Zr	2	1	-	^{138}Xe	-	1	-
^{98gs}Nb	1	1	1	^{137}I	1	2	1
^{98m}Nb	-	-	-	^{138}I	-	-	2
^{100gs}Nb	1	1	1	^{140}Cs	-	-	1
^{100m}Nb	-	1	-	^{142}Cs	3	-	1
^{102gs}Nb	2	2	1				

V. Guadilla's PhD thesis (9 nuclei Valencia)
L. Le Meur's PhD thesis and J. – A. Briz-Monago's Postdoc (3 nuclei Subatech)
V. Guadilla's Postdoc (5 nuclei Subatech)
A.Beloeuvre's PhD (1 nucleus Subatech, waiting for planned TAGS experiment@Jyväskylä)

Reactor Antineutrinos & Fundamental Physics

- **TAGS results from the last decade have improved the quality of the predictions for reactor antineutrinos reaching the best agreement with the Daya Bay** ones obtained so far with a model, leaving little room for the RAA, **provided that the correction of more Pandemonium data should reduce this discrepancy**

- **Shape anomaly unexplained**



M. Estienne et al. PRL 123, (2019) 022502.
Algora et al., *Eur. Phys. J. A* **57**, 85 (2021).

⇒ **Several Focusses for Future:**

⇒ above 4.5 MeV « shape anomaly », shorter-lived nuclei ($T_{1/2}$ from hours-minutes to a few tens of ms), mostly in the light fission products, a few in the heavy ones

⇒ Isomer decays play a major role in the high energy part of the spectrum

⇒ Need for more precise predictions for short times after fission: shorter-lived nuclei (CNNS experiments)

⇒ Better understanding of the antineutrino spectra for the future neutrino exp. (ex. JUNO-TAO)

Reactor Decay Heat (DH)

- **TAGS results from the last decade have improved the quality of the predictions for reactor decay heat**
- Still some Pandemonium candidates in the priority lists
- Still unexplained discrepancies especially for ^{235}U thermal fission pulse
- Still need improved predictions for future reactor designs & fuels
- Need to better control uncertainties on decay heat at short times

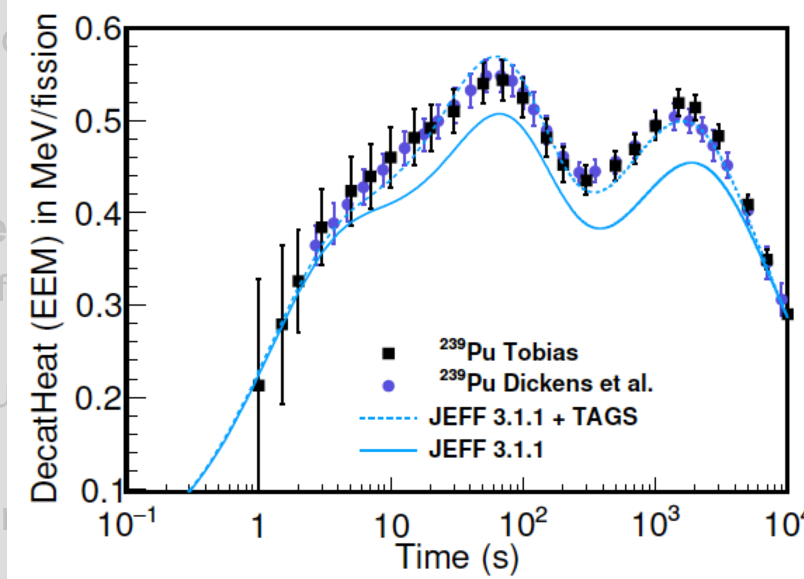


Fig. 13. Impact of the inclusion of the total absorption measurements performed for 13 decays (^{86,87,88}Br, ^{91,91,94}Rb, ^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc) published in Refs. [7,8,24,62,67] in the gamma component of the decay heat calculations for ^{239}Pu.

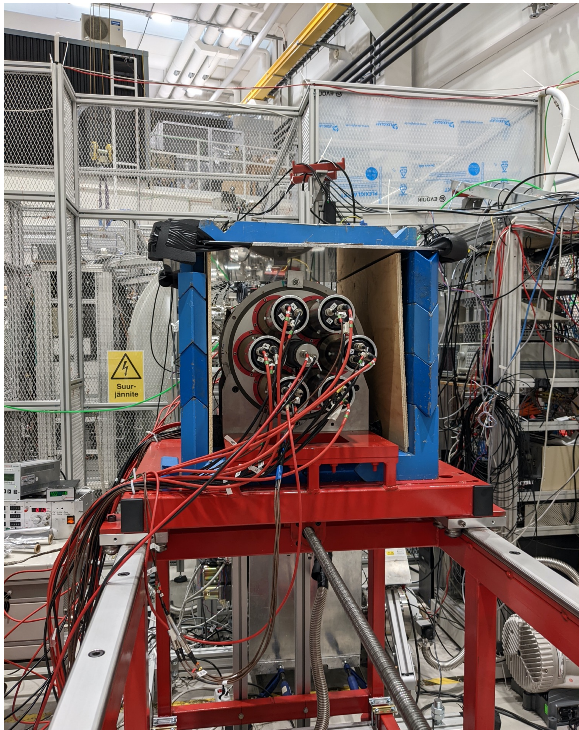
Algora et al., *Eur. Phys. J. A* **57,** 85 (2021).
Calc. By L. Giot (Subatech)

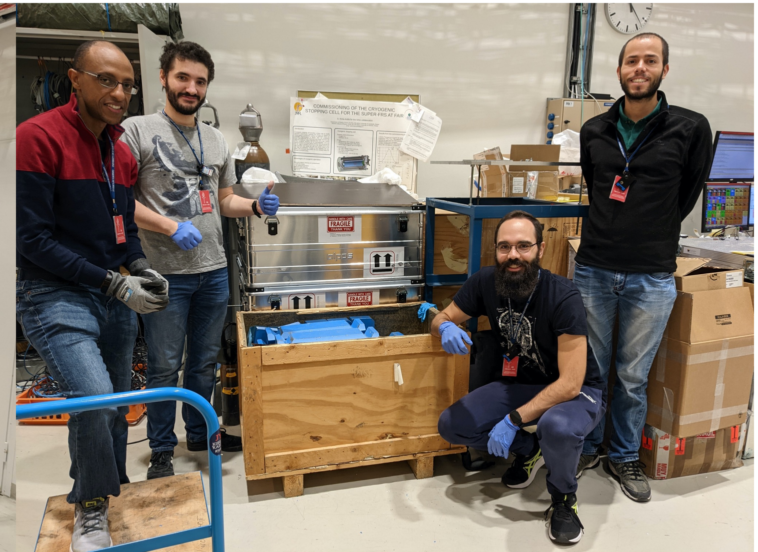
⇒ **Several Focusses for Future:**

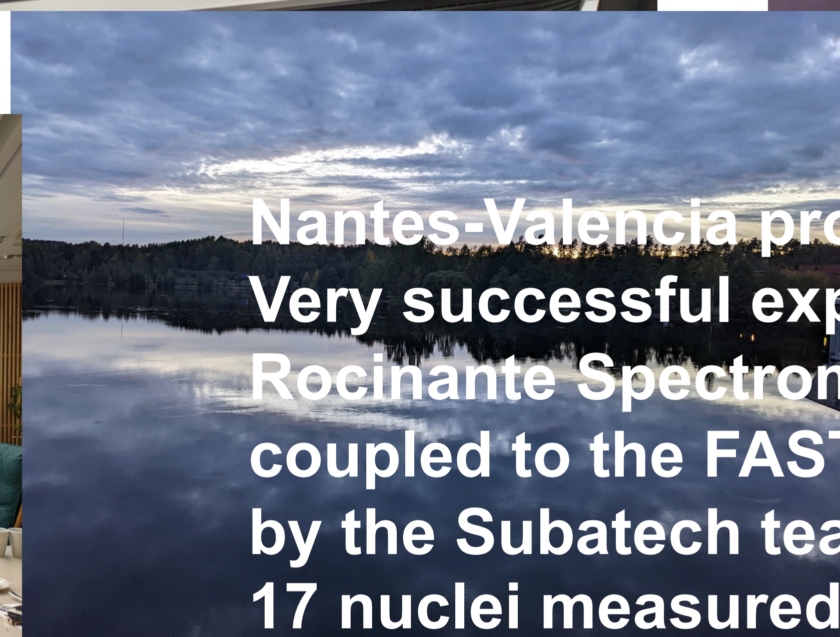
⇒ Focus on shorter-lived contributors: already existing lists (IAEA reports)

⇒ new lists to be established for innovative reactor designs (on-going)

New TAGS Campaign @ Jyväskylä 2022



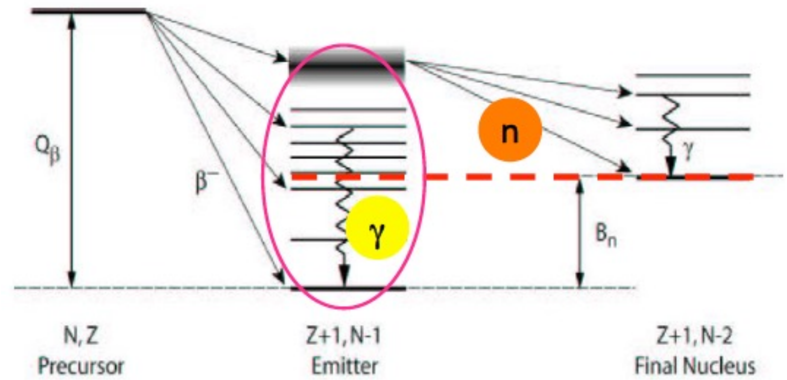


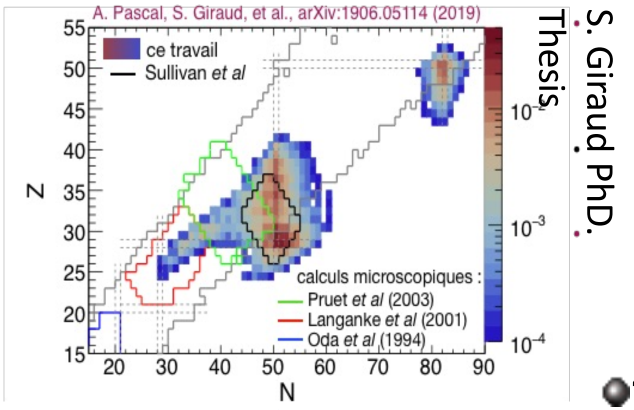


Nantes-Valencia proposal,
Very successful experiment,
Rocinante Spectrometer
coupled to the FASTER DAQ
by the Subatech team
17 nuclei measured with TAGS

TAGS experiments for nuclear astrophysics

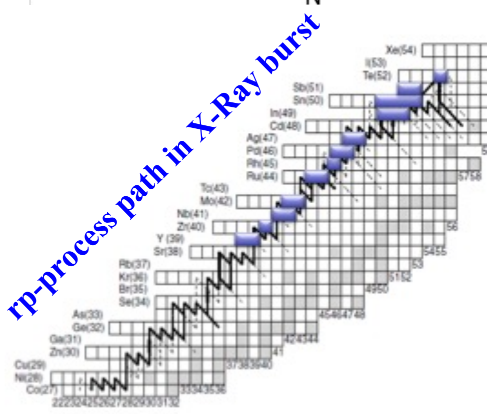
- **R-process:**
  - β-decay of delayed neutron emitters as a "surrogate" of the (n,γ) reaction: **enhanced Γγ measured in some nuclei impacting (n,γ) cross sections => general trend ?**
  - Probe the presence **of low-lying collective modes with β-decay** as it impacts the r-process paths





- **Core-collapse SNe:** Study the electron capture properties of targetted nuclei which play an important role in core-collapse supernovae

- **^{44}Ti production rate**: probes the **innermost shells** of the SN explosion: measure the γ emission from unbound proton states in key nuclei to constrain reaction rates playing a role in the ^{44}Ti abundance (« surrogate method »)

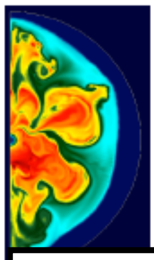


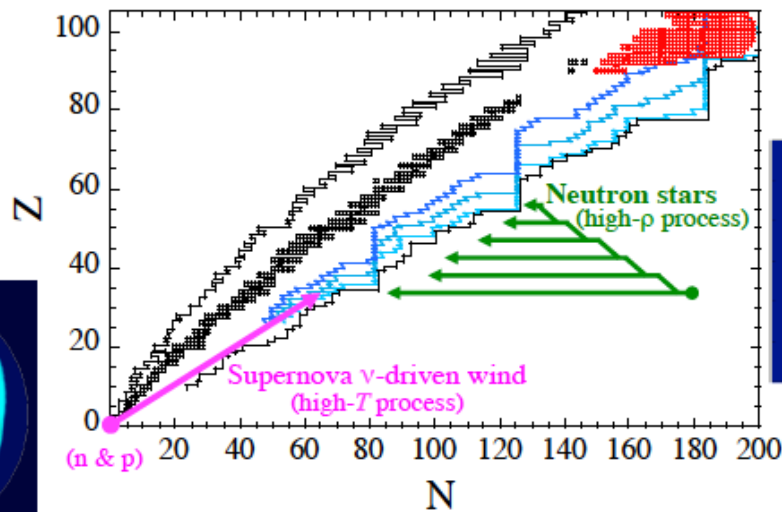
- Measure the **beta strength of rp-process waiting points**

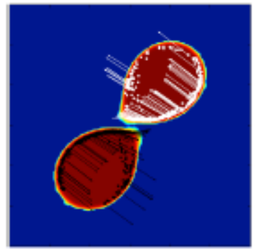
- **P-process: measure (p,γ) and (α,γ) key cross-sections**

R-Process

one of the still unsolved puzzles in nuclear astrophysics
… the r-process site remains unknown ...



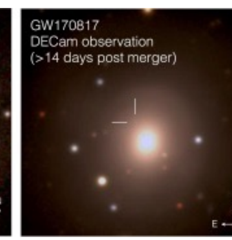




Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as
one of the top 11 questions in Physics and Astronomy
("Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century": 2003, National research council of the national academies, USA)

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L16 (7pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa9059

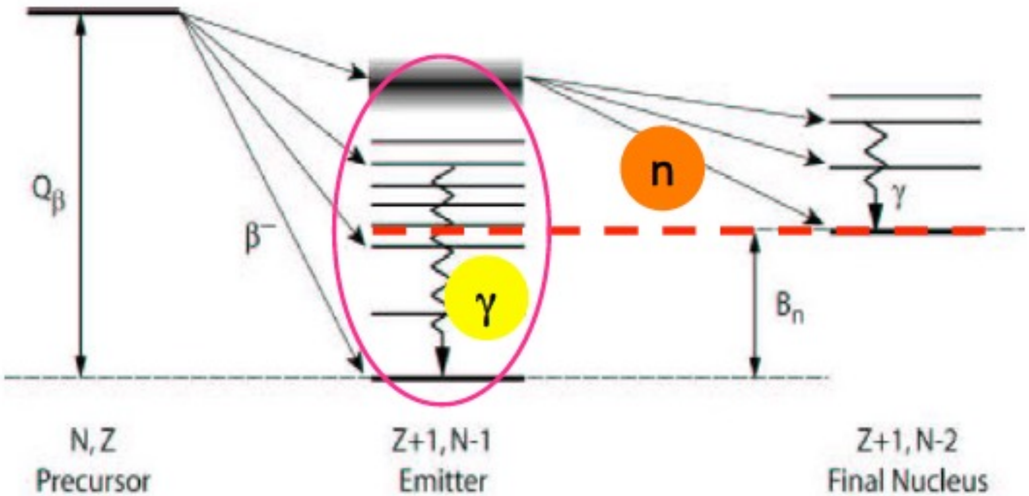
The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera

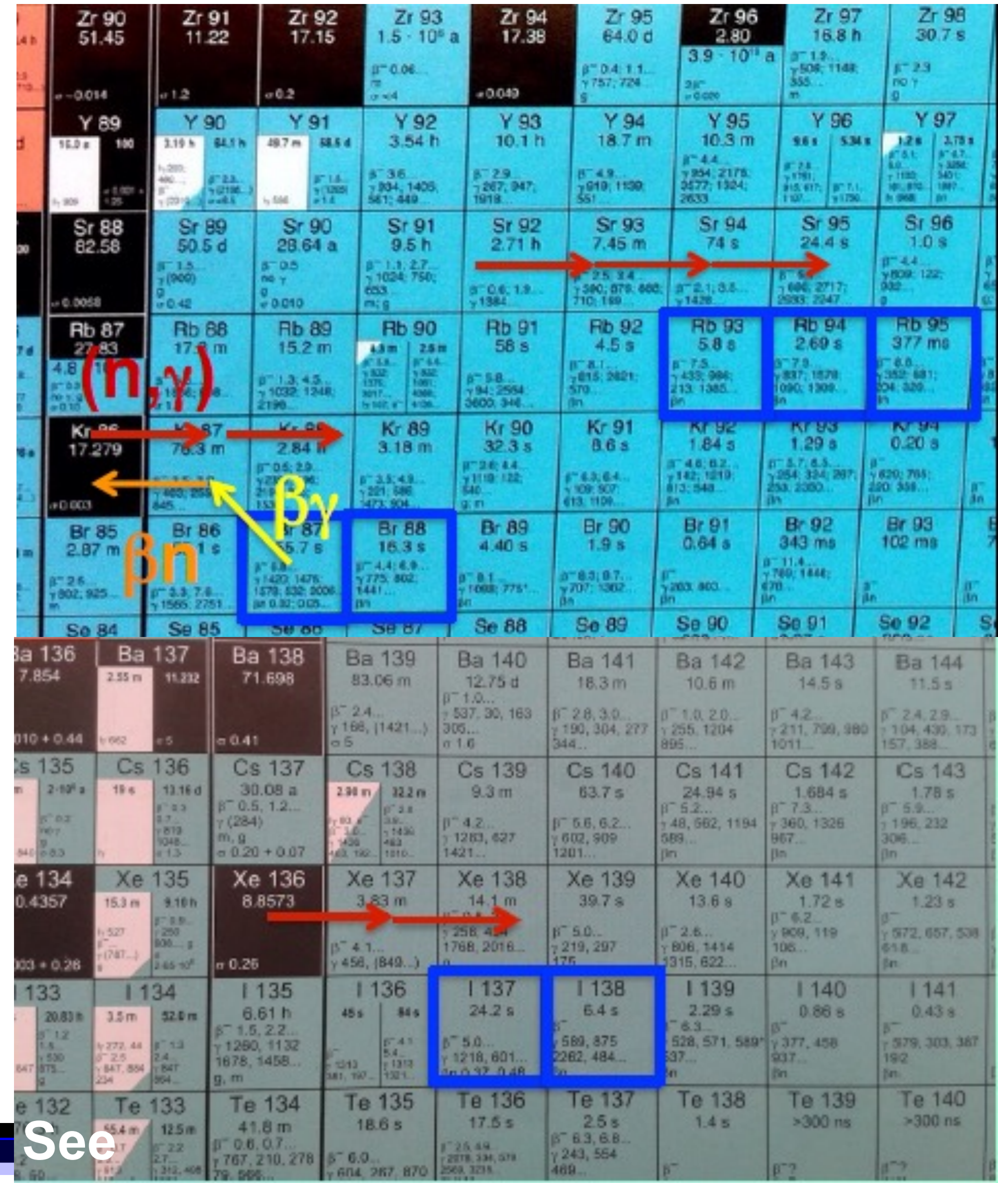


Kilonova predicted by astronuclear physicists Metzger et al. in 2010 !!!

« Both the light curves and spectra closely **resemble predictions for a 'kilonova' a transient powered by radioactive decay of heavy nuclei and isotopes synthesized through the r-process in the merger ejecta**. This is the **first clear demonstration that r-process nucleosynthesis occurs in neutron star binary mergers,** and although this is a single event, the inferred ejecta mass and event rate suggest that such mergers could be the dominant r-process site. »

Total Absorption Spectroscopy of β-delayed neutron emitters





Isotope	P_n (%)	S_n (MeV)	Q_β (MeV)
^{87}Br	2.60(4)	5.5152(3)	6.818(3)
^{88}Br	6.58(18)	7.054(3)	8.975(4)
^{93}Rb	1.39(7)	5.290(9)	7.466(9)
^{94}Rb	10.18(24)	6.828(10)	10.281(8)
^{95}Rb	8.7(3)	4.348(7)	9.228(21)
^{137}I	7.14(23)	4.0256(1)	6.027(9)
^{138}I	5.56(22)	5.660(3)	7.992(7)

β-decay of delayed neutron emitters as a "surrogate" of the (n,γ) reaction

J.L. Tain et al., PRL 115, 062502 (2015)

E. Valencia et al., Phys. Rev. C 95, 024320 (2017).
V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

Table 7. P_γ obtained from our measurements [24, 25] in comparison with the Pn values of the decays. P_γ is defined as the gamma emission probability above the S_n value (in analogy to P_n). The values are given in % (see the text for more details).

Isotope	$P_\gamma(TAGS)$	P_n
^{87}Br	$3.50^{+0.49}_{-0.40}$	2.60(4)
^{88}Br	$1.59^{+0.27}_{-0.22}$	6.4(6)
^{94}Rb	$0.53^{+0.33}_{-0.22}$	10.18(24)
^{95}Rb	$2.92^{+0.97}_{-0.83}$	8.7(3)
^{137}I	$9.25^{+1.84}_{-2.23}$	7.14(23)

^{94}Rb: γ-ray branching one order of magnitude higher than H-F calculation with standard parameters.

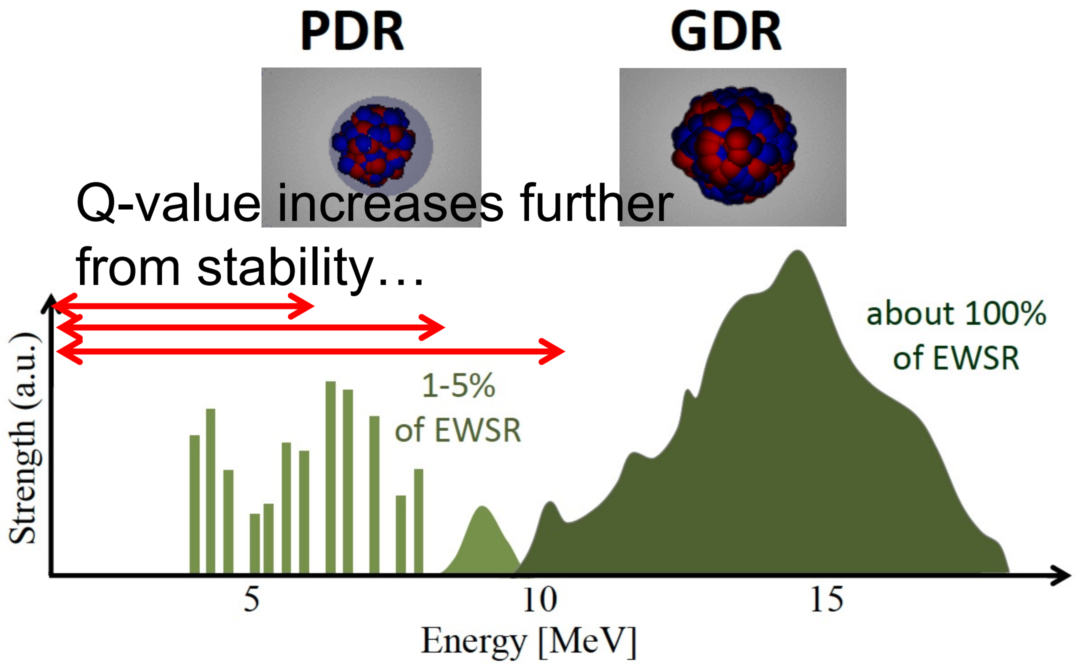
⇒**Such an enhancement of Γγ will have a similar effect on the (n,γ) cross section: impact on r-process abundance**

⇒ Experiment done using the Total Absorption γ-ray Spectroscopy (TAGS) technique (calorimetry), the most suited for detection of high energy gamma rays

⇒ **Very interesting as (n,γ) reaction rates are very hard to measure on such exotic nuclei**

Low-lying Collective Modes

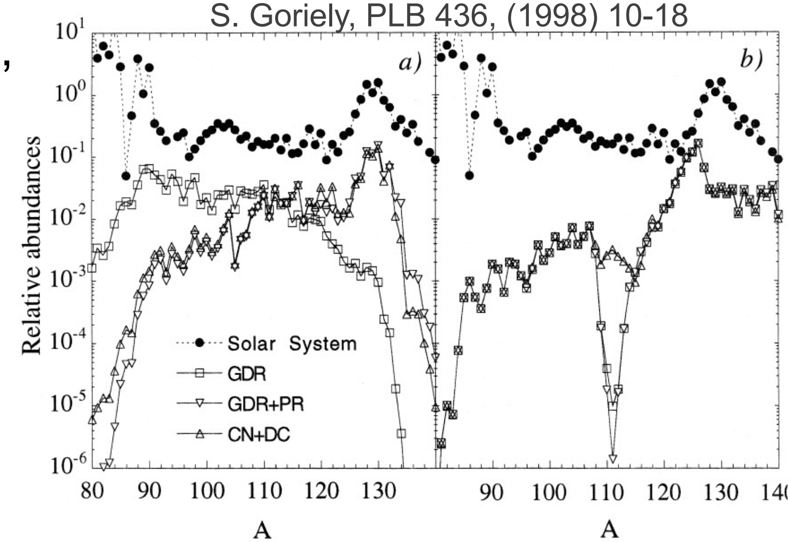
Q-value increases further from stability…



Credit: Casey Reed, Penn State Uni.

- Studying collective modes in exotic nuclei is a challenge, use the β-decay as a probe for low-lying collective modes in the daughter nucleus would allow to:
  - ❑ Go further from the stability than using reactions
    - ➢ a real opportunity to study their presence systematically when spins/parities are favorable
  - ❑ Complement other techniques such as (g,g'), (a,a'), etc…
  - ❑ Get almost background free data

S. Goriely, PLB 436, (1998) 10-18



Cross section measurements for p-process nucleosynthesis

Scientific motivation

p-nuclei = rare, stable proton-rich isotopes
~ 35 nuclei from 74Se to 196Hg

Produced in **explosive nucleosynthesis** (supernovae)

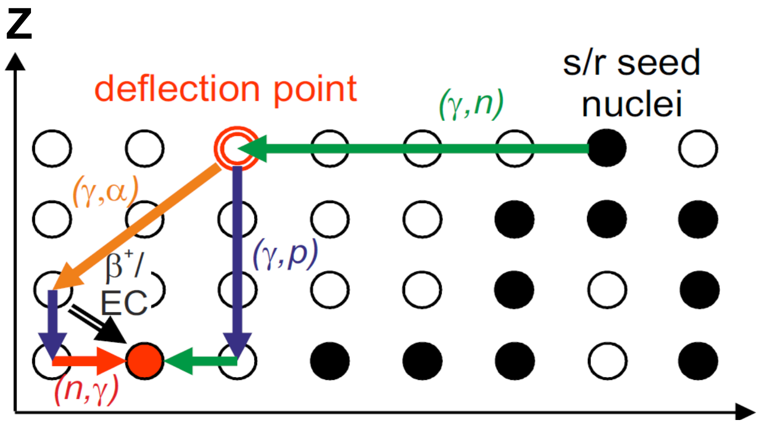
Reaction network :
~ 2000 nuclei (mostly exotic), 20 000 reactions
Reaction cross sections from **statistical model**

Experimental data needed
to constrain the **statistical parameters**
(optical potentials, level densities, gamma strength)

Photo-disintegrations (γ,n), (γ,p), (γ,α)
Radiative captures (p,γ), (α,γ)

Astrophysical energy range :
deep below Coulomb barrier
challenge of very low cross sections (below 1 μb)

Crab nebula (SN remnant)



Extract of typical p-process reaction network, from Rauscher 2013

Cross section measurements for p-process nucleosynthesis

Experimental project for gamma-summing at NFS

***p-process collaboration** in France : IP2I-Lyon, GANIL, LPC-Caen, IJCLab, Subatech, IPHC,*
in Europe : Demokritos, Universities of Bruxelles (ULB), Jyväskylä, Huelva, Surrey, Lisbon, and beyond : iThemba

Objective : use **high-intensity beams to access low cross sections**
for radiative captures (p,γ), (α,γ) at astrophysical energy

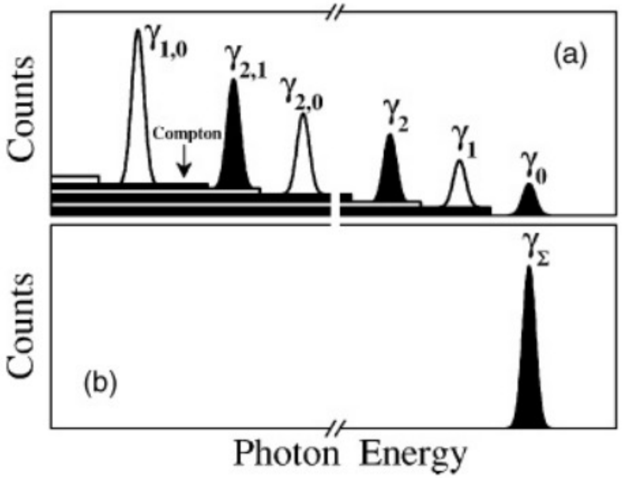
Required beams : **protons** 1-3 MeV, **alphas** 8-12 MeV

Measurement techniques :
- **activation** when allowed by lifetime of reaction product
- in many cases, **in-beam** measurements are needed :
gamma angular distribution (spectrometers)
or **gamma summing** (calorimeter)

New approach for in-beam measurements :
Gamma summing with **segmented calorimeter**
=> information on gamma cascade **multiplicity**
=> better knowledge of **sum peak efficiency**

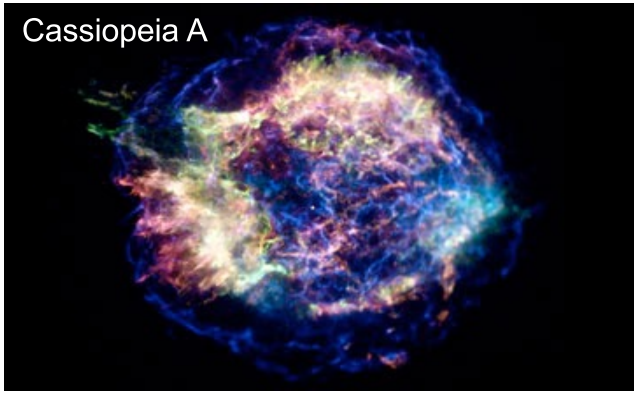
Needs concerning **targets :**
- **manufacturing of thin targets of enriched isotopes in mass range A ~ 100-200**
- solutions for **sustaining high intensity beams**

γ-summing, from Spyrou+ 2007



Study of core-collapse supernovae

masses around ^{78}Ni (JYFL)



Credit: NASA

Core-Collapse Supernovae simulation :
One of the BIG astro challenges

Present best 3D hydro simulations do not yet produce satisfactory CCSN explosion **=> Microphysics is essential !**

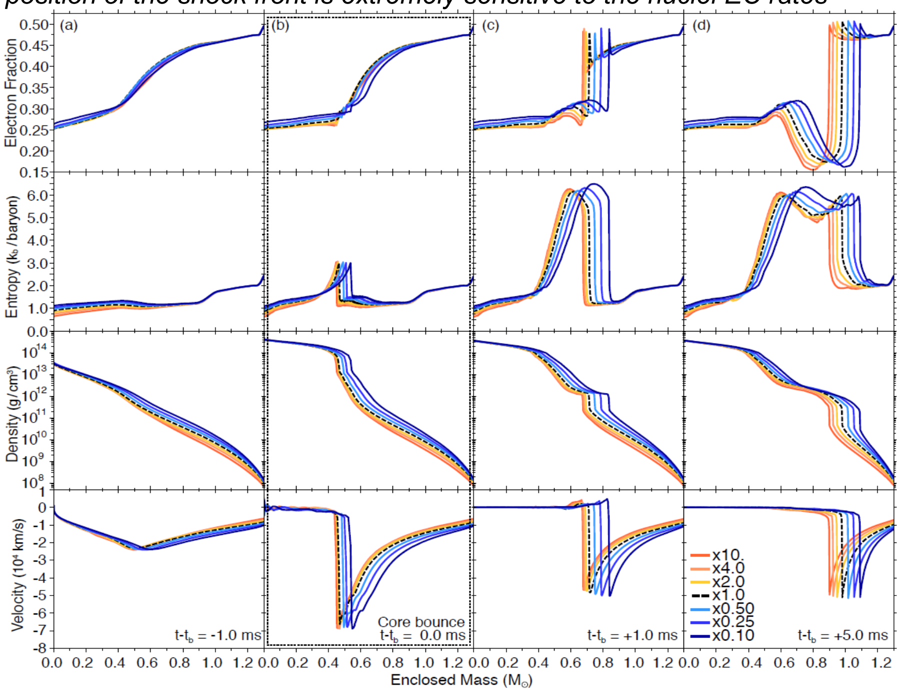
Key observables

- **EC rates : GT response** (β-decay, charge exchange)
- **Nuclear mass**
- **EoS**

Key regions of the nuclear chart

- **Around ^{78}Ni (N=50)**
- **Around ^{128}Pd (N=82)**

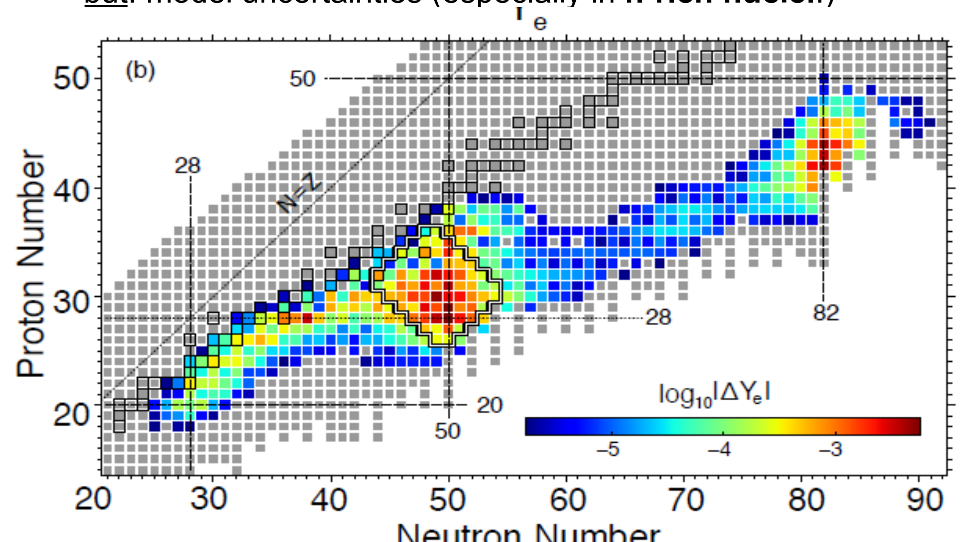
position of the shock front is extremely sensitive to the nuclei EC rates



Sullivan *et al.* ArXiV:1508.0734

Electron-capture rates

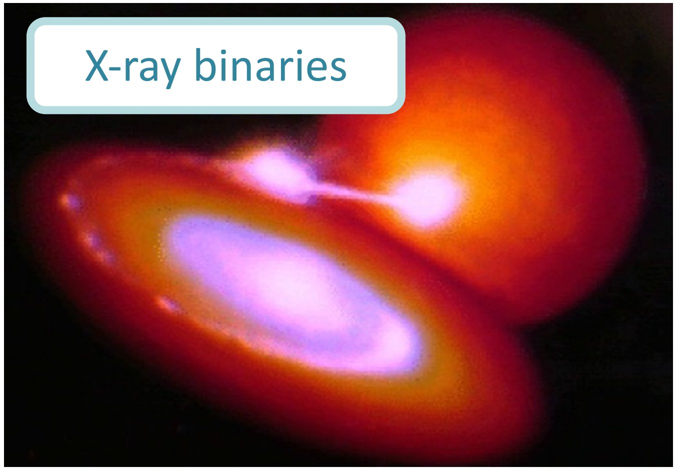
- EC : crucial all along the life of a star *(particularly in massive stars → CCSN!)*
- <u>but</u>: model uncertainties (especially in **n-rich nuclei**!)

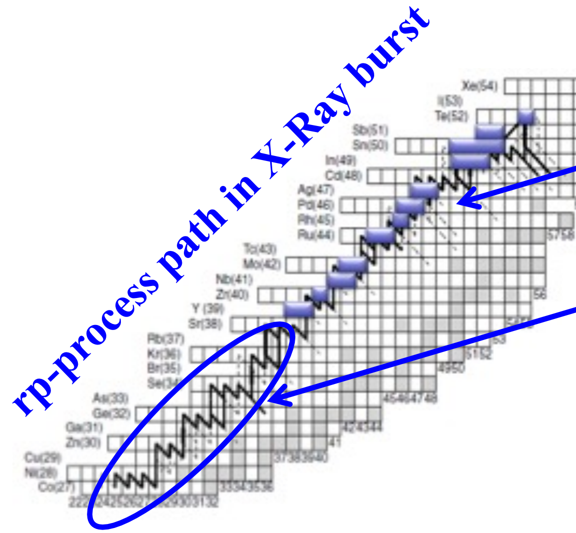


Sullivan *et al.* ArXiV:1508.0734

B. Bastin, A. Kankainen (experiment) / F. Gulminelli, A. Fantina (theory) et al.

Rp-process





S^3-LEB (Z<=54)

Complementarity of SPIRAL1 beams below ^{78}Y

Sequence of rapid proton captures and β+ decays near the proton dripline

Some complementary measurements to the existing proposals and LoI @ ISOLDE and Riken could be proposed for the rp-process

@SPIRAL1 + S^3-LEB(DESIR): S^3 will provide access to the most exotic nuclei + refractory elements

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

^{44}Ti Nucleosynthesis

Quest for resonances in the reaction $^{45}V(p,\gamma)^{46}Cr$

Proposal resonant elastic scattering 2007 : F. De Oliveira, M. Fallot et al. Proposal E773 : Á. M. Sánchez Benítez, J.-C. Thomas et al.

TABLE 5

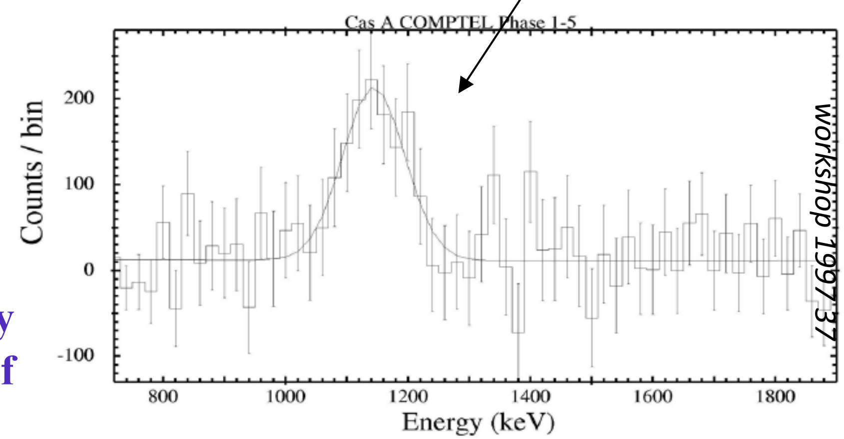
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

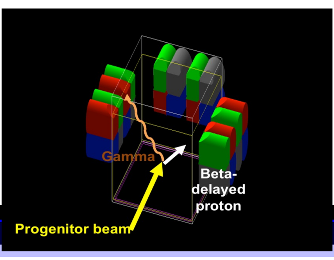
[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\text{Ti})$ near the standard reaction rates.

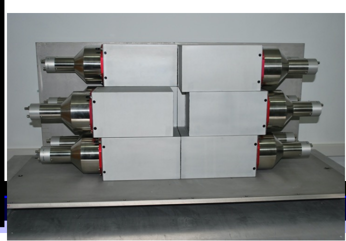
- ^{44}Ti is produced in type II supernovae (SN II) mechanism: α-rich freeze-out. Shock-wave after core-collapse reaches the α-rich region in the cooling phase, $1 < T_9 < 5$
- ^{44}Ti ($T_{1/2}$= 59 y) is a cosmic gamma ray emitter (67.9, 78.4, 1157 keV). Observed by COMPTEL and INTEGRAL satellites
- **^{44}Ti ejecta is a sensitive probe for core-collapse models**
- ^{44}Ti main responsible for ^{44}Ca solar system abund.

Abundance of produced ^{44}Ti is **very sensitive to the reaction rate of ^{45}V(p,γ) (not known exp.)**



Iyudin et al. 2nd INTEGRAL workshop 1997 37





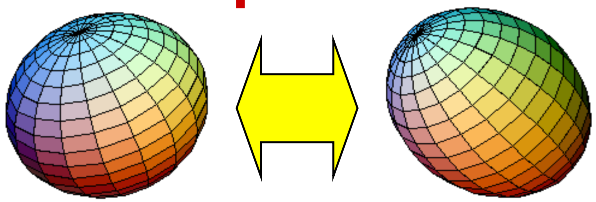
Spectroscopy of key nuclei in astrophysics:

Experimental approaches: TAGS technique to measure the γ-rays emitted above the p emission threshold, constraining then the (p, γ) cross-section @ LISE/GANIL, and then with Spiral1/S^3

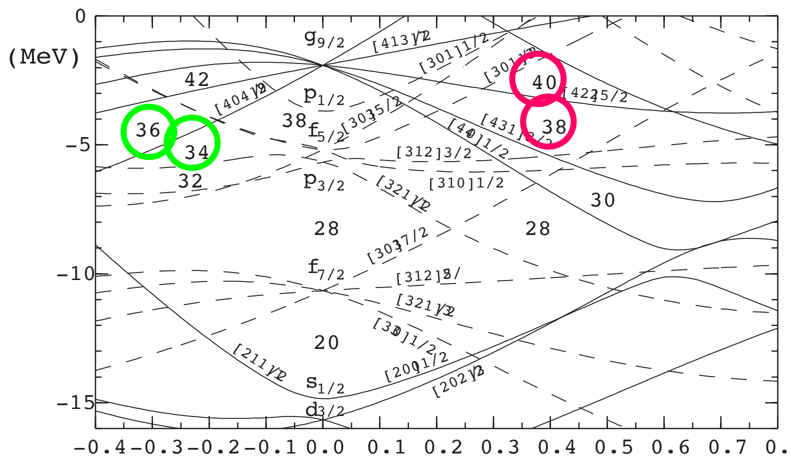
Beta-delayed proton emission studied with ACTAR TPC & EXOGAM

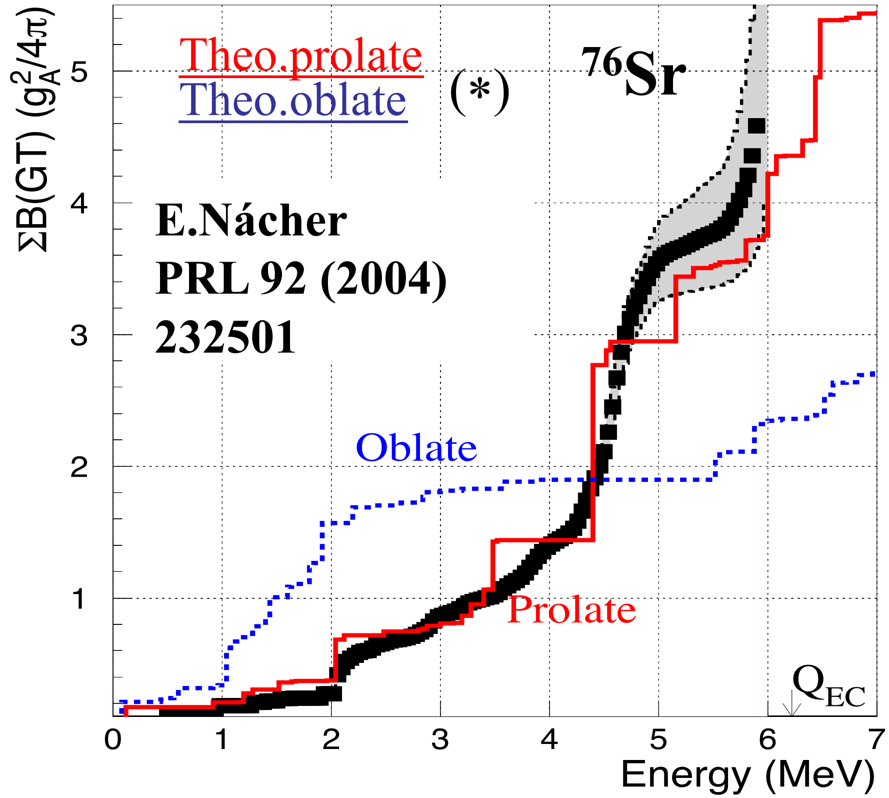
TAGS & B(GT)

Oblate-prolate competition



N~Z nuclei with A~70-80

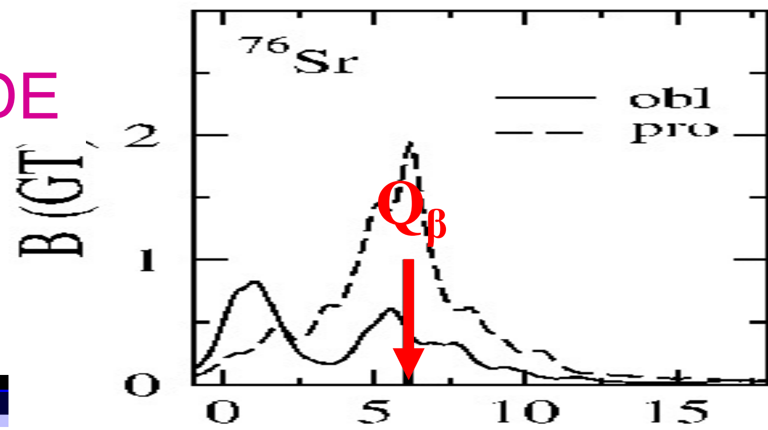




(*) P.Sarriguren et al.NPA 658 (1999)13

Lucrecia @ ISOLDE

Madrid,
Strasbourg,
Surrey,
Valencia



TAGS & B(GT)

- Recent summary of results from the last decade(s): Algora et al., *Eur. Phys. J. A* **57,** 85 (2021).
- On the n-rich side and on the n-deficient side

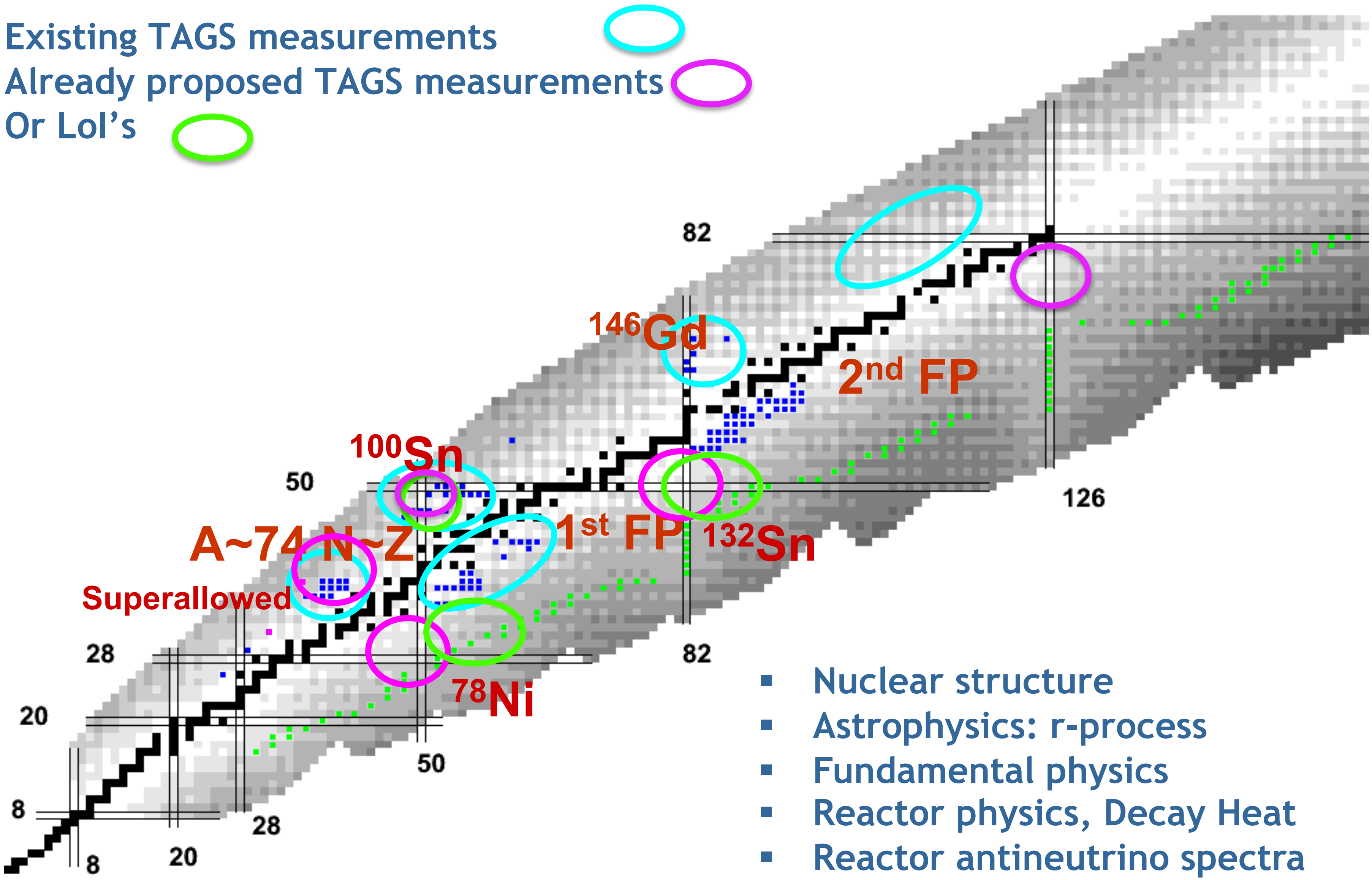
Beta Decay and the N = 82 Waiting Point nuclei

Beta strength measurements around the doubly-magic neutron-rich ^{78}Ni

Beta strength measurements in the ^{100}Sn region

A. Algora, **B. Rubio, J.L. Taín**, J. Agramunt, C. Domingo, S. Origo
IFIC-CSIC Valencia, Spain
B. Gomez-Hornillos, F. Calviño, G. Cortes
INTE-DFEN-UPC, Barcelona, Spain
D. Cano-Ott, T. Martinez
CIEMAT Madrid, Spain
W. Gelletly, Z. Podolyak, P. H. Regan
Univ. of Surrey, Guildford, UK
T. Kurtukian-Nieto, B. Blank
CENBG, Bordeaux, France
L. Caceres
GANIL, France
A. Jungclaus
IEM-CSIC Madrid Spain
Y. Fujita
Osaka University, Japan

Outlooks



- Nuclear structure
- Astrophysics: r-process
- Fundamental physics
- Reactor physics, Decay Heat
- Reactor antineutrino spectra

TAGS experimental challenges

TAGS technique needs some minimal knowledge on the daughter nuclei.
NaI crystals are very sensitive to neutrons.
BaF_2 are less sensitive but have a poor energy resolution.

⇒ Antineutrino, Decay Heat, R-process: **shorter-lived contributors**

⇒ **Shorter-lived nuclei means:** n-richer nuclei => β-n branch = n contamination and knowledge of Pn, less nuclear structure knowledge on decay daughters

⇒ **On the n-deficient side: more exotic** means less nuclear structure knowledge on decay daughters

⇒ **P-process**: TAGS = γ-summing technique, actual limitations come from the **uncertainty on the sum peak**

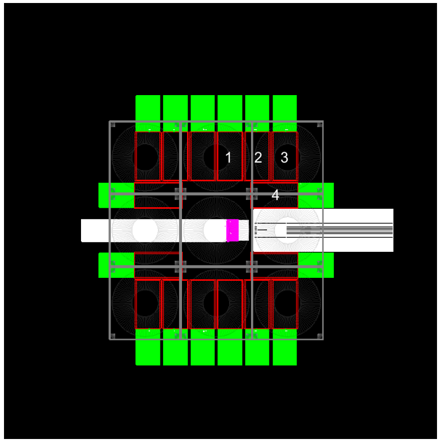
$(NA)^2$STARS Project

- **Addition of 16 2" x 2" x 4" $LaBr_3$:Ce modules between the two halves of the DTAS**

⇒ **large efficiency combined with the very good energy resolution and timing** of the $LaBr_3$: solution to the study of more exotic nuclei with the TAGS technique, n/γ discrimination with TOF

⇒ higher segmentation: **γ-γ coincidences and angular correlations of specific γ-ray cascades: study of more exotic nuclei or cross-section measurements**.

⇒ **knowledge of γ-cascade multiplicity = good control of the uncertainty on the sum peak efficiency**



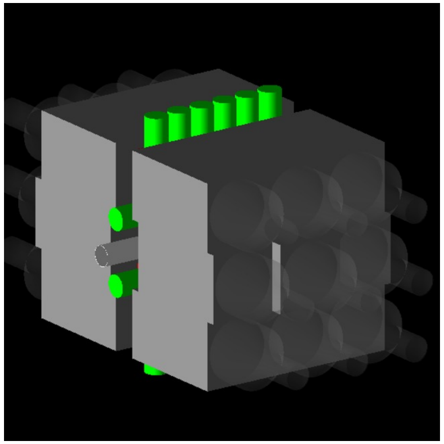


Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

⇒ Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer:

A combination of calorimetric and spectroscopic tools for beta decay and in-beam measurements

(NA)²STARS Project

- **Upgrade of the DTAS detector with 16 $LaBr_3$**
- Already **7** crystals among partners
- **Large impact**: **GANIL, DESIR,** RIKEN, Jyväskylä, ISOLDE, FAIR, …
- **Large Physics Case**: n-rich and n-deficient nuclei, further away from stability
- **Improved energy resolution of $LaBr_3$**
- **n/γ discrimination with TOF**
- **Higher segmentation: possible γ,γ correlation studies**

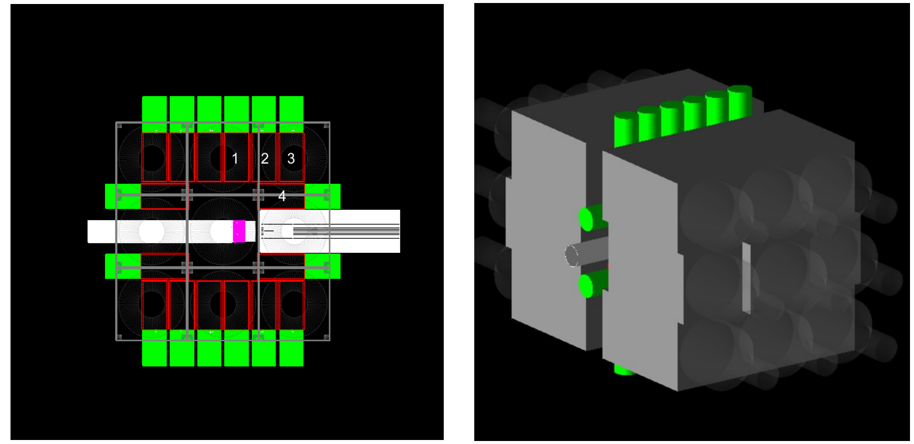


Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

An unprecedented Combination of calorimetric and spectroscopic tools for beta decay and in-beam measurements

⇒ The $LaBr_3$ ring could also be used to complement experimental setups. A test on the **Falstaff experiment @ NFS with 2 LaBr3 modules** from Subatech will be performed @ GANIL next weeks

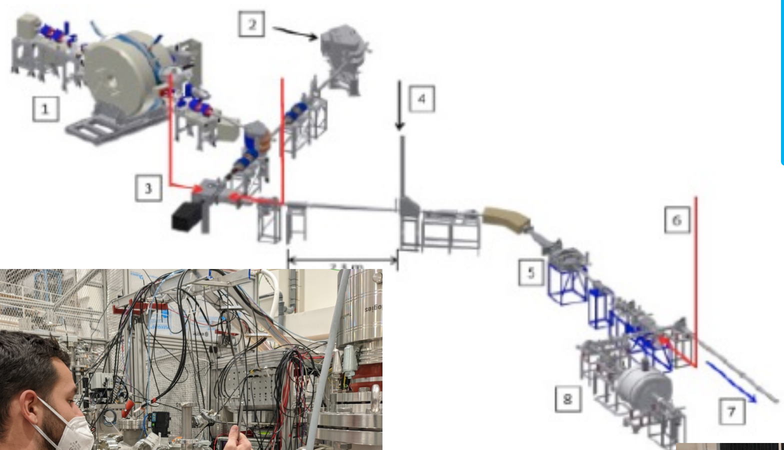
Conclusion and Outlooks

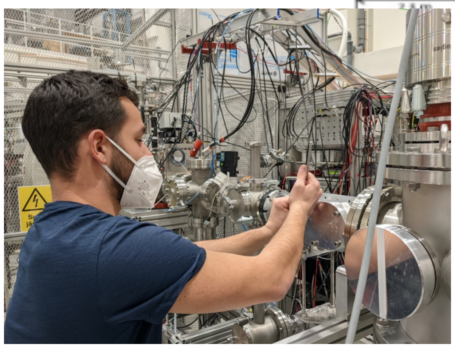
- TAGS experiments are complementary to high-resolution γ-ray spectroscopy
- Particularly well adapted to measure high energy γ-rays and B(GT) avoiding the Pandemonium effect
- The TAGS collaboration in Europe has a large physics program spanning both n-rich and n-deficient nuclei, performed presently at IGISOL Jyväskylä, ISOLDE Cern, GSI and Riken
- Part of this program could be performed at GANIL in the future: existing LoIs @ DESIR + new experiments that could be proposed in the near future on the above-described physics cases
- The $(NA)^2$STARS project would allow studying more exotic nuclei with the TAGS technique and make in-beam measurements of key cross-sections for astrophysics with the γ-summing method

E-Shape (Nantes-Valencia-Surrey) 2022

- : **E-Shape campaign @IGISOL (Jyväskylä) in Jan. 2022:**

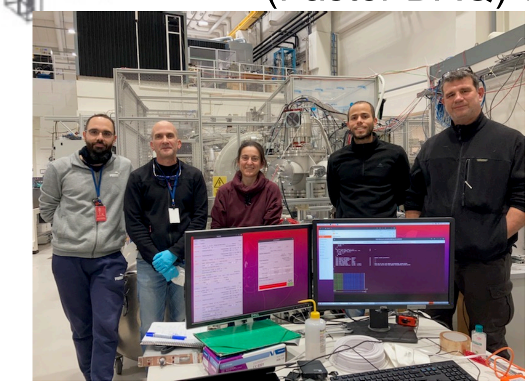
E-Shape Motivations: measure electron spectral shapes from First-Forbidden β-decays for Reactor Antineutrinos and Nuclear Structure and Astrophysics

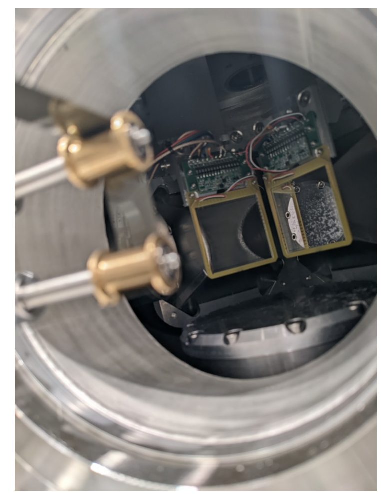




2 PhD students:
G. Alcala (Valencia) and A. Beloeuvre (Nantes)

Huge technical involvement by Subatech (Technical Services and SEN team): Mechanics + Electronics (Faster DAQ) very successful





Coming Next: 1 E-Shape experiment@ Jyväskylä in 2023 (1 PhD funding)

TAGS COLLABORATION

IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, V. Guadilla, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt

SUBATECH Nantes: A. Beloeuvre, J.A. Briz, M. Fallot, V. Guadilla, A. Porta, A.-A. Zakari-Issoufou, M. Estienne,_T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyvaskyla: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber

CIEMAT Madrid: T. Martinez, L.M. Fraile, V. Vedia, E. Nacher

IPN Orsay: M. Lebois, J. Wilson

BNL New-York: A. Sonzogni

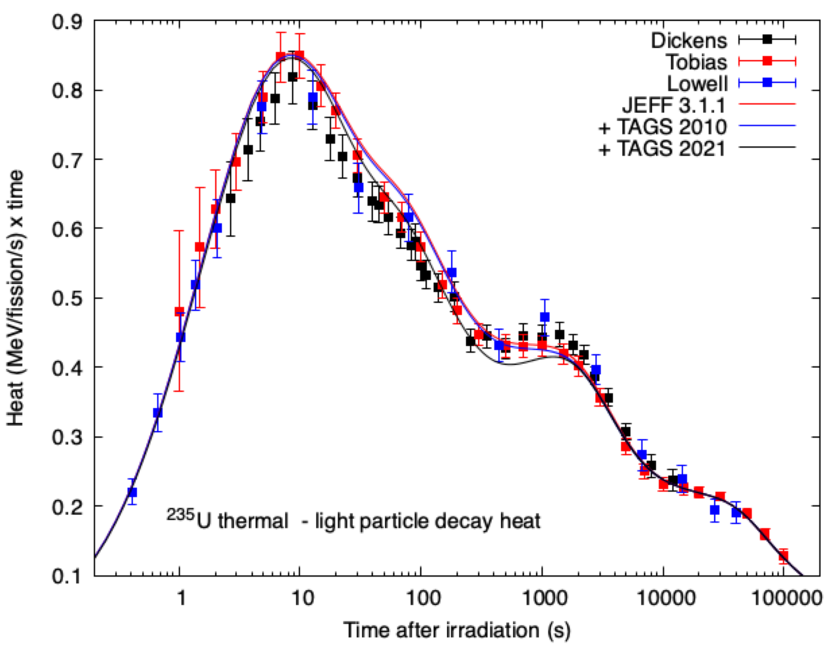
Istanbul Univ.: E. Ganioglu

Special thanks to the young researchers working in the project:
A. Beloeuvre, R. Kean, L. Le Meur, J.A. Briz, V. Guadilla, J. Pépin, E. Valencia, S. Rice, A. -A. Zakari-Issoufou
Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Cormon, A. Cucoanes, M. Estienne, M. Fallot, L. Giot, A. Porta, T. Shiba, …are acknowledged

THANK YOU

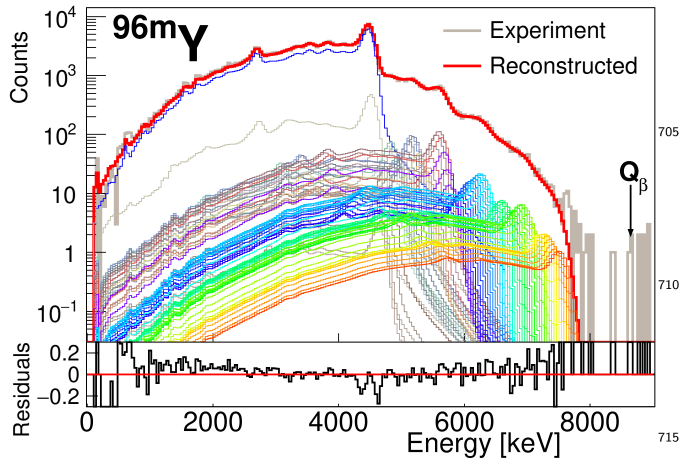
Recent Results

On-going paper with the IAEA: calculation of impact of all published TAGS data (including Europe and US)

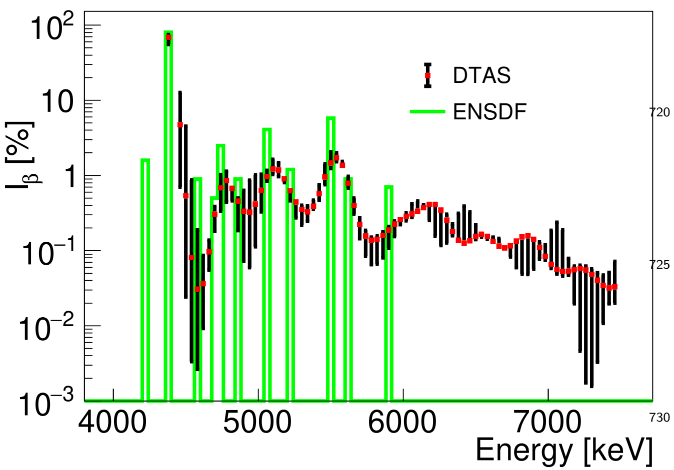


Total Absorption γ-ray Spectroscopy of the β decays of ^{96gs,m}Y,

V. Guadilla et al. Phys. Rev. C 106, 014306 (2022)



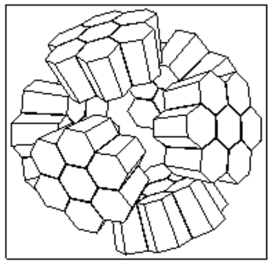
^{96gs}Y (0^-) priority 1 for Antineutrinos
^{96m}Y (8^+) priority 1 for Decay Heat for Th/U fuel

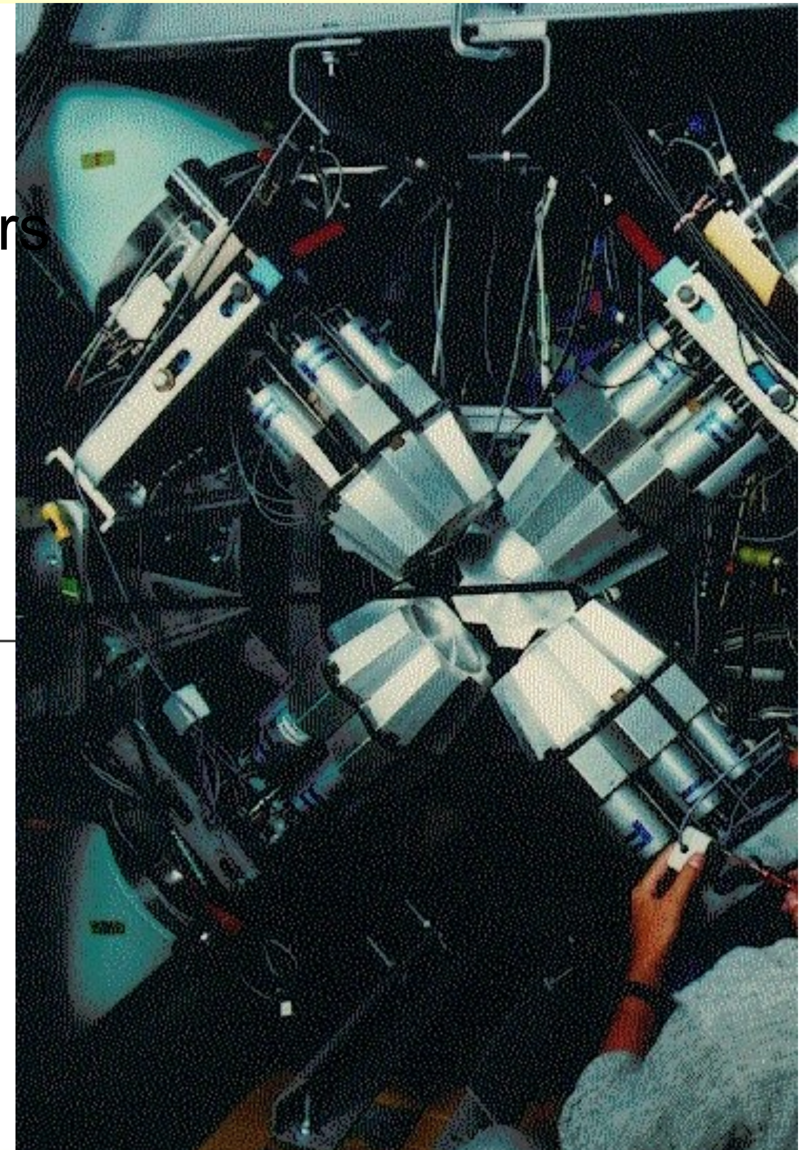


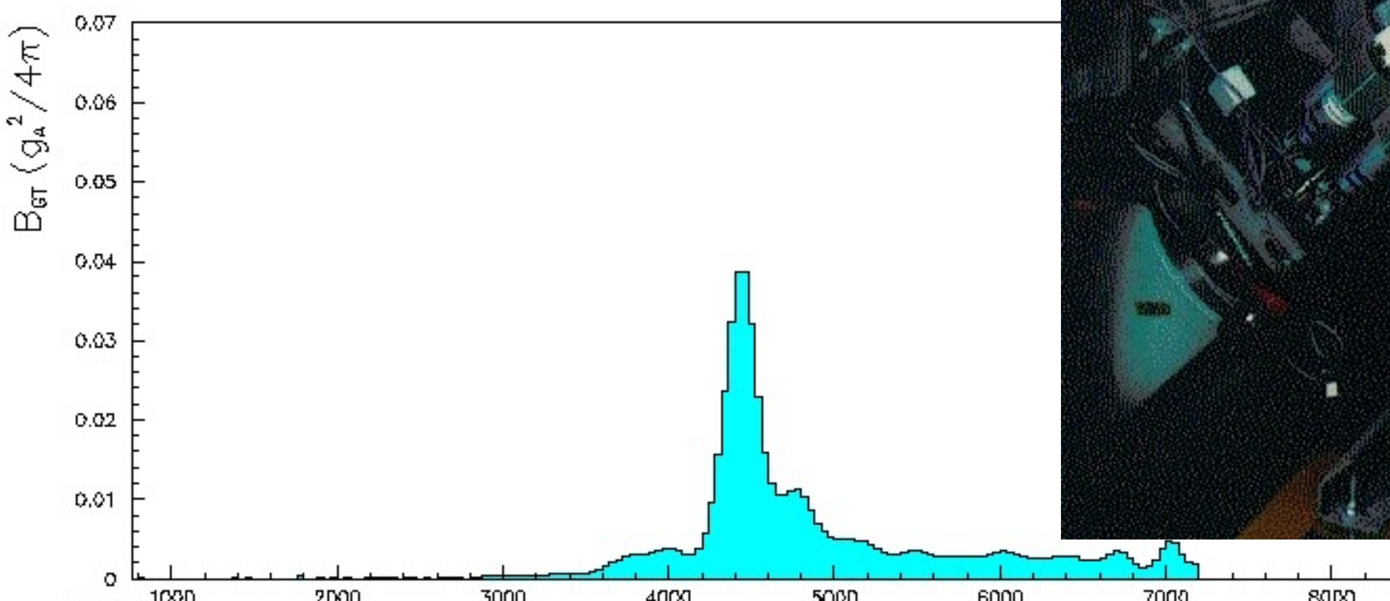
⇒ **Clear Pandemonium effect in the ^{96m}Y**

THE HIGH RESOLUTION METHOD

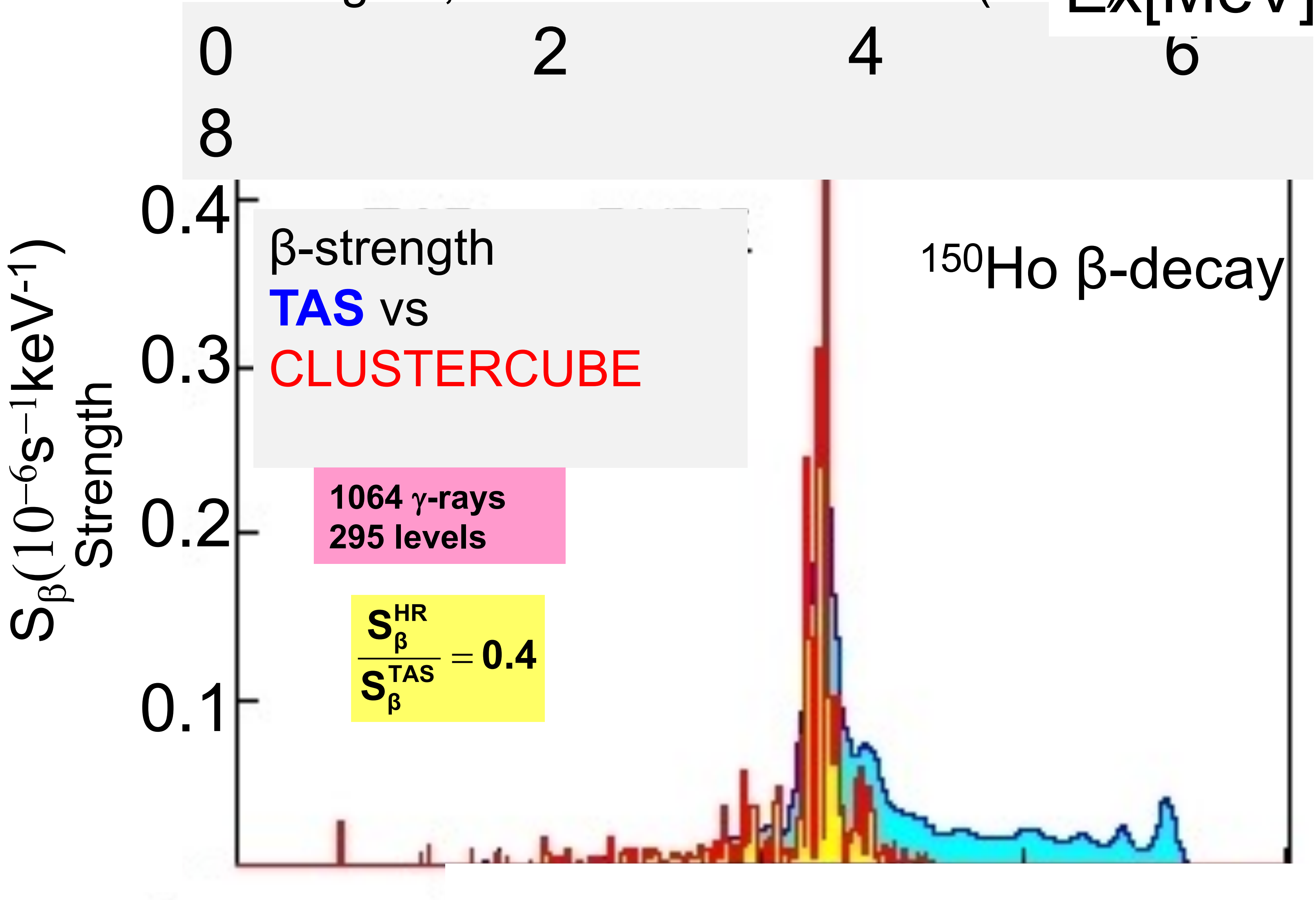
Six EUROBALL CLUSTER detectors
in close geo



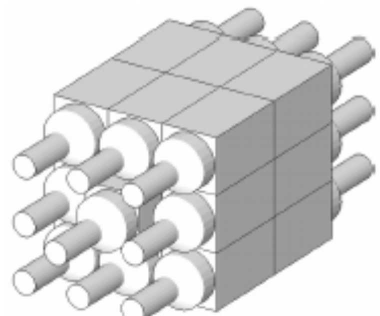




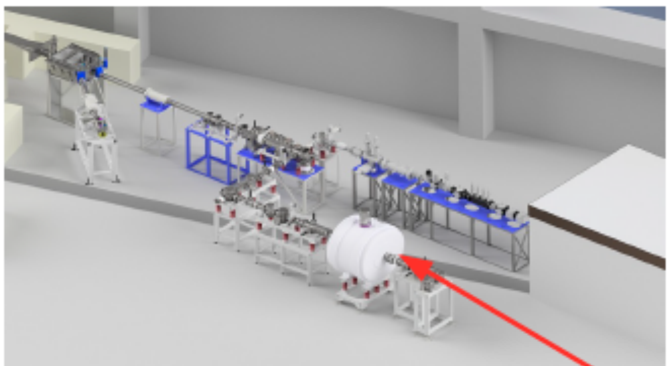
A. Algora, B. Rubio et al PRC 50 (2002)



Experimental setup at Jyväskylä (^{142}Cs, ^{99}Y, ^{138}I, ^{96,96m}Y)



V. Guadilla et al., Nucl. Instrum. Methods B 376 (2016), p. 334



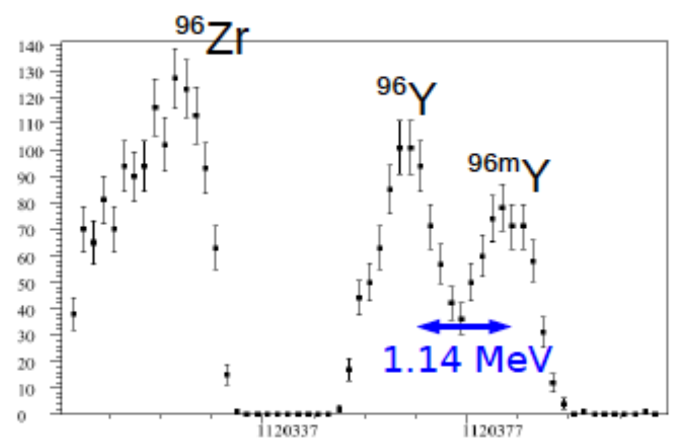
- DTAS = 18 crystals of NaI(Tl)
  - ~90% efficiency for a 1 MeV gamma
  - ΔE/E ~ 5% at 1.3 MeV
- β detector = plastic detector
  - In coincidence with γ → suppression of the background
  - 30% detection efficiency
- HPGe detector
  - Allow identification of possible contaminants coming from the decay chain

Why Jyväskylä IGISOL-4 facility ?

→ Because of the JYFLTRAP, a double Penning Trap

→ Mass resolution of δm/m ~ 10^{-6}

→ A very pure beam is needed



L. Le Meur's PhD