

### Neutrinos, Applications and Nuclear Structure and Astrophysics with Total Absorption G-ray Spectroscopy and the (NA)<sup>2</sup>STARS Project

### GCM Meeting 2022 @ Caen

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Intro: What is/Why the TAGS technique ?

TAS Spectrometers

@ (NA)<sup>2</sup>

protons Z

Nombre de

Physics Cases & Current limitations of the existing TAS

Nombre de neutrons N >

## 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



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

## TAGS: a Solution to the Pandemonium Effect



- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution <u>m</u>
  - R<sub>ii</sub> = matrix detector response
  - d<sub>i</sub> = measured data
  - Extract f<sub>i</sub> the level feeding by deconvolution





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

## Total Absorption $\gamma$ -ray Spectroscopy (TAGS)

Big cristal,  $4\pi => A$  TAS is a calorimeter !







 $I_i = \frac{J_i}{\sum_{i=1}^{J_i}}$ 

### **Observable:**

β-intensity => β-strength: An ideal TAS would give directly the β-intensity I<sub>β</sub> which is linked with the β-strength S<sub>β</sub>:

$$S_{i} = \frac{I_{i}}{f(Q_{\beta} - E_{i})T_{1/2}} \quad [s^{-1}]$$

Statement of the problem:

Relation between TAS data and the  $\beta$ intensity distribution:

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

Deconvolution (Inverse problem) algorithms

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

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

## Past and Presently used TAS TAS

### TAS "Lucrecia" @ ISOLDE, CERN

Nal large monocrystals

Ge detector (Ø16mm x 10 (Ø22mm x 1mm)

Berkeley-GSI TAS 1997



"Rocinante" TAS

- Large 18-fold segmented Nal spectrometer
- Cascade multiplicity information

Compact 12-fold segmented BaF<sub>2</sub> spectrometer Low neutron sensitivity Cascade multiplicity information Good timing Resolution 10%@1.33MeV



Rad, bear

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DTAS (NUSTAR) +

### **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(TI) scintillator segments. MTAS is designed to perform decay studies with pure beams of neutron-rich nuclei produced in the <sup>238</sup>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.



according to GEANT4 simulations performed by B. C. Rasco (LSU)







g-energy spectrum of <sup>137</sup>Cs activity measured with a single MTAS module. The energy resolution, fwhm(662 keV)  $\sim 7\%$ , 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. \$ 698 K capital + \$ 882 K operations (includes \$ 815 K salaries) = \$ 1580 K Funding: 20/1/15 Funds committed/spent : \$658 K capital and \$512 K operations = \$1270 K

## **Reactor Antineutrinos & Fundamental Physics**

- Measurement of the  $\theta_{13}$  oscillation param by Double Chooz, Daya Bay, Reno
  - □ Independent computation of the anti-v 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 <sup>235</sup>U measured beta spectrum @ILL
- 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

Putting integral beta measurement of <sup>235</sup>U of Scheckenbach *et al.* and sterile neutrinos into question.

AEA.org

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



Nuclear Power Station

#### Near detector Far detector

 Absolute shape comparison of data and prediction: χ<sup>2</sup>/ndf = 41.8/21



## 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** •

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- 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:

$$f(t) = \sum_{i} (\bar{E}_{\beta,i} + \bar{E}_{\gamma,i})\lambda_i N_i(t)$$

$$\beta_{,\gamma} \text{ decay Total decay constant (half-life) and Fission Yield}$$

$$\Rightarrow \text{ Comparisons btw nuclear data & integral measurements show that there remains important discrepancies between data and simulations using different DataBases 
$$\Rightarrow \text{ Pandemonium effect + unknown decay schemes}$$
Nuclear Science NEA/WPEC-25 (2007), Report INDC(NDS)-0577 (2009), Report INDC(NDS)-0676 (2016)$$

## 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
- 2 (segmented) TAS campains :

### ROCINANTE (IFIC Valencia/Surrey):



- ✓ 12 BaF<sub>2</sub> covering  $4\pi$
- ✓ Detection efficiency of a single g ray >80% (up to 10 MeV)
- $\checkmark\,$  Coupled with a Si detector for  $\beta$
- ✓ 7 nuclei (4 delayed neutron emitters) measured (6 for DH and 2 for anti-v)

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

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

### DTAS (IFIC Valencia):



- ✓ 18 NaI(TI) crystals of 15cm × 15cm × 25 cm
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- $\checkmark\,$  Coupled with plastic scintillator for  $\beta$
- $\checkmark\,$  12 nuclei for anti-v measured & 11 for DH

## **30 Measured Nuclei**

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

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

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## **Reactor Antineutrinos & Fundamental Physics**

- Measurement of the  $\theta_{13}$  oscillation param by 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
- s obtained so far with a model, leaving little Nuclear
  - room for the RAA, provided that the
  - correction of more Pandemonium data should reduce this discrepancy
  - Shape anomaly unexplained
- ⇒ Several Focusses for Future:



- $\Rightarrow$  above 4.5 MeV « shape anomaly », shorter-lived nuclei (T<sub>1/2</sub> from hours-minutes to a
- few tens of ms), mostly in the light fission products, a few in the heavy ones
  - $\Rightarrow$  Isomer decays play a major role in the high energy part of the spectrum
    - $\Rightarrow$  Need for more precise predictions for short times after fission: shorter-lived nuclei (CNNS experiments)
    - $\Rightarrow$  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 actinide priority lists residual power of 6-12% of the nominal power of
- Still unexplained discrepancies especially for <sup>235</sup>U thermal fission pulse he only predictive method for full
- Still need improved predictions for future reactor designs & fuels of all the fission product and actinide col
- Need to better control uncertainties on decay heat at short times

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





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

⇒ Comparisons btw nuclear data & integral measurements show that there remains important

- ⇒ Several Focusses for Future: simulations using
  - $\Rightarrow$  Focus on shorter-lived contributors: already existing lists (IAEA reports)

 $\Rightarrow$  new lists to be established for innovative reactor designs (on-going)

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

heat from thermal pulse on <sup>235</sup>U

### 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

Giraud PhD





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

•<sup>44</sup>Ti production rate: probes the innermost shells of the SN explosion: measure the  $\gamma$  emission from unbound proton states in key nuclei to constrain reaction rates playing a role in the <sup>44</sup>Ti abundance (« surrogate method » )

- Measure the **beta strength of rp-process waiting points**
- P-process: measure (p, $\gamma$ ) and ( $\alpha$ , $\gamma$ ) 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 © 2017. The American Astronomical Society. All rights reserved. https://doi.org/10.3847/2041-8213/aa9059



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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



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3a 7.8 010 5 940 0.4	*0.44 135 2497 135 2497 2497 2497 2497 2497 2497 2497 2497	84 Ba 235 m 235 m CS 19 s 19 s 19 s 19 s 19 s 19 s 10 s 10 s 10 s 10 s 10 s 10 s 10 s 10	1366 27 Se 8 137 11232 136 12.16 d 12.16 d 12.16 d 12.16 d 12.16 d 13.7 13.5 13.6 13.6 13.6 13.6 13.7 13.6 13.6 13.7 13.6 13.6 13.7 13.6 13.6 13.7 13.6 13.6 13.7 13.6 13.6 13.7 13.7 13.6 13.7 13.6 13.7 13.6 13.7 13.6 13.7 13.6 13.7 13.6 13.7 13.6 13.5 13.6 13.5 13.6 13.5 15.5 1	5 Βα 7 • 0.4 • 0.	se a 138 1.6988 1.6988 1.6988 1.6988 1.6988 1.6988 1.6988 1.698	8 8 9 7 18 9 1 19 19 19 19 19 19 19 19	See 3a 13 3.06 4. 5, 1142 5, 1142	87 39 m 21) 38 22.m 38 38 37 n 40 1 1 1 1 1 1 1 1 1 1 1 1 1	Se 88           Ba 140           12.75 d           7.75 d           7.6           Cs 139           9.3 m           7.42           728.627           421           Xe 138           14.1 m           256 454           7786, 2016	β         2           β         2           1         1           β         2           344         C           ψ         6.02           ψ         6.02           ψ         5.02           φ         5.02           ψ         5.02	<b>30 89</b> <b>a</b> 141 <b>b</b> 3m <b>b</b> 30. <b>b</b> 304. <b>c</b> 130 <b>b</b> 337 <b>5</b> <b>b</b> 6. <b>c</b> 139 <b>39</b> . <b>7 5</b> <b>0</b> . <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b> <b>139</b>	Se 90           Ba 142           10.6 m           07 1.0.20           255.1204           895           Cs 141           24.94 s           17 52           18, 562, 1194           59           10.6 m           7 52           13.6 s           17 2.6           1006, 1454           915, 622	р Se 91 Ba 143 14.5 s 0 <sup>-</sup> 4.2. 7.211, 700, 36 1011. Cs 142 1.684 s 0 <sup>-</sup> 7.3. 7.360, 1326 967. ра Xe 141 1.72 s 0 <sup>-</sup> 6.2. у же, 119 106. ра	an south and sou	Ba 144 11.5 s 57 24.2 s 1104.4 30 s 57 388 Cs 143 157 388 196,212 306 196,212 306 1972,657,588 1972,657,588	4 173 3 2 508
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3a 7.8 010 5 8 0.4 0.4 0.4	+ 0.44 135 2-99 2-99 2-99 2-99 2-99 2-99 2-99 2-9	84 Ba 2.55 m 19 e 19 e 15.3 m 1,527 1,127	136 137 137 137 136 136 136 136 137 138 135 135 135 135 135 135 136 137 138 138 138 137 138 137 138 137 138 138 138 138 137 138 138 138 138 138 138 138 138	5 5 8 8 7 0.4' C( 3) 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28- 7 (28-	a 138 1.698 a 138 1.698 a 137 0.05 a 5, 12 0 4 + 0.07 a + 0.07 a + 0.07 a + 0.07 a + 0.07 a 136 .8573 a 135 .61 h 5, 22, 0 1458	B     B     S	Se 13 ia 14 ia	87         μ           39         μ           π         μ           π         π           88         μ           220         π           10         1           10         1           37         1           37         1           36         5           56         5           57         5	Se         86           Ba 140         12.75 d           12.75 d         537.30,163           305         106           CS 139         9.3 m           9.3 m         9.3 m           9.42         1200,627           1421         Xe 138           14.1 m         1258 4.34           1758 4.34         14.1 m           1758 4.34         14.2 m           1758 4.34         1768,2018           1137         24.2 s           5.0         12.8 601           10.32 9.46         0.34 9.46	β         8           β <sup>+</sup> 2         γ 190           344         C           φ <sup>+</sup> 5.7         γ 600           γ 720         1201           X0         3           φ <sup>+</sup> 5.7         219           γ 5002         2175           1         5           γ 5002         200	30         830           a 141         8.30           b 304         277           s 140         8.30           63.7 s         5.62           s 140         8.39           63.7 s         5.62           909         9.39.7 s           0         5.297           138         5.4 s           5.45         484	Se 90           Ba 142           10.6 m           p 1.0.20           y255.1204           895           Cs 141           24.94 5           p 5.2           p 6           V265.1204           905           Cs 141           24.94 5           p 5.2           P 26           y 806.1454           1315.622           I 139           2.29 s           623           97           97           97           97           97           97           97           97           97           97           97           98           97           97           97           97           97           97           97           97           97           97           97           97           97           97           97.	Seg 91           Ba 143 14.5 s           p <sup>-</sup> 4.2. 7.211, 790, 96 1011.           Cs 142 1.684 s p <sup>+</sup> 7.3. 7.360, 1326 967.           y 360, 1326 967.           y #00, 119 108 pn           I 140 0.86 s y 377, 458 807.	an and an	Ba 144 11.5 s 57.24.2.9. 104.430, 1 157.388 Cs 143 1.78 s 196.212 306. 1.78 s 196.212 306. 196.212 1.23 s 57.20.057, 657, 658, 658, 658, 658, 658, 658, 658, 658	10 5 173 3 2 508 387
3a 7.8 010 35 8 0.4 0.4 0.4	136 354 • 0.44 135 2.19 <sup>1</sup> a 5.03 134 337 • 0.28 33 20318 57 • 0.28 33 20318 57 • 0.28 33 20318 57 • 0.28 33 20318 57 • 0.28 132 • 0.28 •	84 Ba 235 m 5 002 CS 19 4 T 5.3 m 5.3 m 5.	See 8 137 136 137 136 136 136 135 135 135 135 135 135 135 135	- 0.4 5 Baa 7 - 0.4 3 β - 0.2 3 ( β - 0.2 8 - 0.2 1 6 β - 1.5 -	135 135 137 1698 1698 1698 137 138 137 136 8573 135 151 135 1458 134	8 8 8 8 8 9 1 1 1 1 1 1 1 1 1 1 1 1 1	Sie 13 3.a 13 3.a 13 3.a 13 6. [142 25 13 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	87 39 m (1) 33 33 33 30 30 30 30 30 30 30	Ke         88           Ba         140           12.75 d         1.6.           537, 30, 163         300           537, 30, 163         300           116         Cs         139           9.3 m         1.4.         1.4.           1742         1275, 627         1421           Xe         138         14.1 m           258.84.0.         1218, 621.6.         1.137           24.2 s         5.0         1218, 601           14.2 s         1.5.         1.5.           15.8 4.0.         1.2.         1.137           24.2 s         5.0         1.2.           14.1 m         1.2.         1.2.           14.2 s         5.0         1.2.           15.8 4.0.         1.3.         1.3.           16.9 7.0.032         0.48         1.3.	μπ           Bi           1           B <sup>2</sup> γ 1900           344.           C           μ <sup>2</sup> 602           γ 1900           γ 1201           X0           γ 1201           X0           γ 1201           X0           γ 590           γ 590           γ 590           T           γ 590           T	<b>30 89</b> <b>a</b> 141 <b>b</b> 3m <b>b</b> 3.0 <b>a</b> 141 <b>b</b> 3m <b>b</b> 3.0 <b>a</b> 141 <b>b</b> 3m <b>b</b> 3.0 <b>b</b> 3.0 <b>c</b> 140 <b>b</b> 3.7 s <b>b</b> 6.2 <b>c</b> 139 <b>b</b> 3.9 <b>c</b> 139 <b>b</b> 3.9 <b>c</b> 139 <b>b</b> 3.5 s <b>c</b> 4.8 s	Se 90 Ba 142 10.6 m of 10.20. 1255.1204 985 Cs 141 24.94 s f 52. 48,562,1194 589 h Xe 140 13.6 s of 2.6. 7006,1434 1315,622 I 139 - 2.29 s - 6.3. 528,571,589 37 n Te 138	Se 91 Se 91 Ba 143 14.5 s 07-42 7211, 750, 38 1011. Cs 142 1.684 s 17-7.3. 7360, 1326 967. 762. 760, 1325 967. 1140 0.886 s 77-7. 80 1140 0.886 s 77-7. 80 Te 139	10 10 10 10 10 10 10 10 10 10 10 10 10 1	Ba 144 11.55 57.24,29 104,490 157,388 CS 143 1785 59. 196,232 006. 176,232 006. 172,057, 197,2057, 198,232 006. 1141 0.43 s 57.2057, 199,2057,2057, 199,2057,2057,2057,2057,2057,2057,2057,2057	4 173 3 2 508 2 508

### β-decay of delayed neutron emitters as a "surrogate" of the

### $(n,\gamma)$ 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.**  $P_{\gamma}$  obtained from our measurements [24,25] in comparison with the Pn values of the decays.  $P_{\gamma}$  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	$P_{\gamma}(TAGS)$	$P_n$
${}^{87}{ m Br}$ ${}^{88}{ m Br}$ ${}^{94}{ m Rb}$ ${}^{95}{ m Rb}$ ${}^{137}{ m I}$	$\begin{array}{r} 3.50\substack{+0.49\\-0.40}\\ 1.59\substack{+0.27\\-0.22}\\ 0.53\substack{+0.33\\-0.22}\\ 2.92\substack{+0.97\\-0.83}\\ 9.25\substack{+1.84\\-2.23}\end{array}$	$2.60(4) \\ 6.4(6) \\ 10.18(24) \\ 8.7(3) \\ 7.14(23)$

<sup>94</sup>Rb: γ-ray branching one order of magnitude higher than H-F calculation with standard parameters.

 $\Rightarrow$ Such an enhancement of  $\Gamma\gamma$  will have a similar effect on the (n, $\gamma$ ) cross section: impact on r-process abundance

- $\Rightarrow$  Experiment done using the Total Absorption  $\gamma$ -ray Spectroscopy (TAGS) technique (calorimetry), the most suited for detection of high energy gamma rays
- $\Rightarrow$  Very interesting as (n, $\gamma$ ) reaction rates are very hard to measure on such exotic nuclei

## Low-lying Collective Modes





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



#### **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 ( $\gamma$ ,n), ( $\gamma$ ,p), ( $\gamma$ , $\alpha$ ) Radiative captures (p, $\gamma$ ), ( $\alpha$ , $\gamma$ )

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

### Courtesy of C. Ducoin, O. Stezowski



Crab nebula (SN remnant)



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

#### 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  $(p, \gamma)$ ,  $(\alpha, \gamma)$  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

#### Courtesy of C. Ducoin, O. Stezowski



## Study of core-collapse supernovae

### masses around <sup>78</sup>Ni (JYFL)

### 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

Spiidi.

nun CEA/DRE

- Around <sup>78</sup>Ni (N=50)
- Around <sup>128</sup>Pd (N=82)

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

#### 0.50 (a) S0.45-٠ to 0.40 Ē0.35 Ē0.30 <u>8</u>0.25 0.20 Sullivan 0.15 6.0 uo 5.0 4.0 50θţ 30 20 al. Number Number ArXiV:1508.0734 0.0 10<sup>14</sup> ູ 10<sup>18</sup> ພັງ10<sup>18</sup> <sup>101</sup> Deusity 10<sup>10</sup> 10<sup>9</sup> Proton 30 10<sup>8</sup> (s) -1 w -2 Core bounce $t-t_{=} -1.0 \text{ ms}$ $t-t_{=}+50 \text{ ms}$ <u>x0 10</u> 30 0.0 0.2 0.4 0.6 0.8 1.0 1.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 Enclosed Mass (Mo B. Bastin, A. Kankainen (experiment) /

### **Electron-capture rates**

 EC : crucial all along the life of a star (particularly in massive stars → CCSN!)







## Rp-process





Sequence of rapid proton captures and  $\beta$ + 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<sup>3</sup>-LEB(DESIR): S<sup>3</sup> will provide access to the most exotic nuclei + refractory elements



## <sup>44</sup>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.

TABLE 5		
Order of Importations Produce $^{44}$ Ti at $\eta = 0$	NCE OF JCING a	• <sup>44</sup> Ti is produ mechanism:
Reaction	Slope	reaches the
$^{44}\text{Ti}(\alpha, p)^{47}\text{V}\dots$	-0.394	• $^{44}\text{Ti}(\text{T}_{1/2}=5)$
$^{45}V(p, \gamma)^{46}Cr$	-0.361	Observed by
${}^{57}Co(p, n)^{57}Ni$ ${}^{36}Ar(\alpha, p)^{39}K$	+0.137 +0.102 +0.037	• <sup>44</sup> Ti ejecta
$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$ $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	-0.024 -0.017	for core-co
${}^{57}\text{Ni}(p, \gamma){}^{58}\text{Cu} \dots$ ${}^{58}\text{Cu}(p, \gamma){}^{59}\text{Zn} \dots$	+ 0.013 + 0.011	• <sup>44</sup> Ti main r
$^{36}$ Ar( $\alpha$ , $\gamma$ ) $^{40}$ Ca $^{44}$ Ti( $p$ , $\gamma$ ) $^{45}$ V	+0.008 -0.005	solar system
${}^{57}$ Co( $p, \gamma$ ) ${}^{58}$ Ni ${}^{57}$ Ni( $n, \gamma$ ) ${}^{58}$ Cu	+0.002 + 0.002	Abundance of
${}^{54}$ Fe( $\alpha$ , <i>n</i> ) ${}^{57}$ Ni ${}^{40}$ Ca( $\alpha$ , <i>p</i> ) ${}^{43}$ Sc	+0.002 -0.002	sensitive to

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

#### Thomas et al.

- <sup>44</sup>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,  $1 < T_9 < 5$
- <sup>44</sup>Ti ( $T_{1/2}$ = 59 y) is a cosmic gamma ray emitter (67.9, 78.4, 1157 keV). Observed by COMPTEL and INTEGRAL satellites
- <sup>44</sup>Ti ejecta is a sensitive probe for core-collapse models
- <sup>44</sup>Ti main responsible for <sup>44</sup>Ca solar system abund.

Abundance of produced <sup>44</sup>Ti is very sensitive to the reaction rate of  ${}^{45}V(p,\gamma)$  (not known exp.)



### Spectroscopy of key nuclei in astrophysics:

Experimental approaches: TAGS technique to measure the  $\gamma$ -rays emitted above the p emission threshold, constraining then the (p,  $\gamma$ ) cross-section @ LISE/GANIL, and then with Spiral1/S<sup>3</sup>

Beta-delayed proton emission studied with ACTAR TPC & EXOGAM

## TAGS & B(GT)



## TAGS & B(GT)

### Oblate-prolate

- 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 PRL 92 (2004)





**E.Nácher** 

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





### Lol, day-one-experiments Jan 2011

### Beta Decay and the N = 82 Waiting Point nuclei

Beta strength measurements around the doubly-magic neutron-rich <sup>78</sup>Ni



### Beta strength measurements in the <sup>100</sup>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 20/1/15 Y. Fuiita

#### Courtesy Berta Rubio

-Osaka University, Japan

### **Outlooks**



## TAGS experimental challenges

TAGS technique needs some minimal knowledge on the daughter nuclei. Nal crystals are very sensitive to neutrons. BaF<sub>2</sub> are less sensitive but have a poor energy resolution.

- ⇒ Antineutrino, Decay Heat, R-process: shorter-lived contributors
- $\Rightarrow$  Shorter-lived nuclei means: n-richer nuclei =>  $\beta$ -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
- $\Rightarrow$  **P-process**: TAGS =  $\gamma$ -summing technique, actual limitations come from the uncertainty on the sum peak

in the <sup>44</sup>Ti abundance (« surrogate method » )

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

P-process: measure (p,g) and (a,g) key cross-sections

### (NA)<sup>2</sup>STARS Project

- Addition of 16 2" x 2" x 4" LaBr<sub>3</sub>:Ce modules between the two halves of the DTAS
- ⇒ large efficiency combined with the very good energy resolution and timing of the LaBr<sub>3</sub> : solution to the study of more exotic nuclei with the TAGS technique,  $n/\gamma$  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 inbeam measurements

### Collaboration: Subatech – IP2I - IFIC Valencia – CIEMAT Madrid

### (NA)<sup>2</sup>STARS Project

- Upgrade of the DTAS detector with 16 LaBr<sub>3</sub>
- 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<sub>3</sub>
- $\circ$  n/ $\gamma$  discrimination with TOF
- Higher segmentation: possible  $\gamma$ , $\gamma$  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<sub>3</sub> 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

### **Collaboration: Subatech – IP2I - IFIC Valencia – CIEMAT MAdrid**

## **Conclusion and Outlooks**

- TAGS experiments are complementary to high-resolution  $\gamma$ -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 Lols
   @ DESIR + new experiments that could be proposed in the near future on the above-described physics cases
- The (NA)<sup>2</sup>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:



G. Alcala (Valencia) and A. Beloeuvre (Nantes)

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

> 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

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

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 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 $\gamma$ -ray Spectroscopy of the $\beta$ decays of ${}^{96gs,m}Y$ ,

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



## THE HIGH RESOLUTION METHOD

### Six EUROBALL CLUSTER detector in close geo







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## Experimental setup at Jyväskylä (142Cs, 99Y, 138I, 96,96mY)



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



- DTAS = 18 crystals of NaI(TI)
  - ~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
- $\rightarrow$  Mass resolution of  $\delta m/m \sim 10^{\text{-6}}$
- → A very pure beam is needed

L. Le Meur's PhD

