APRENDE

Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer: the (NA)^{2}STARS Project

PEPR SCIAM 9 juin 2026

This project has received funding from the European Union's Horizon Europe Euratom Research and Training Programme (EURATOM) under Grant Agreement No: 101164596-APRENDE

European

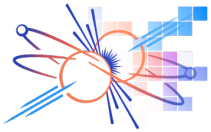
Subatech

Nantes Université

cnrs NUCLÉAIRE & PARTICULES

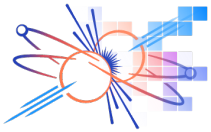
IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)^{2}STARS Project
- Conclusions & Perspectives



APRENDE

- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)^{2}STARS Project
- Conclusions & Perspectives



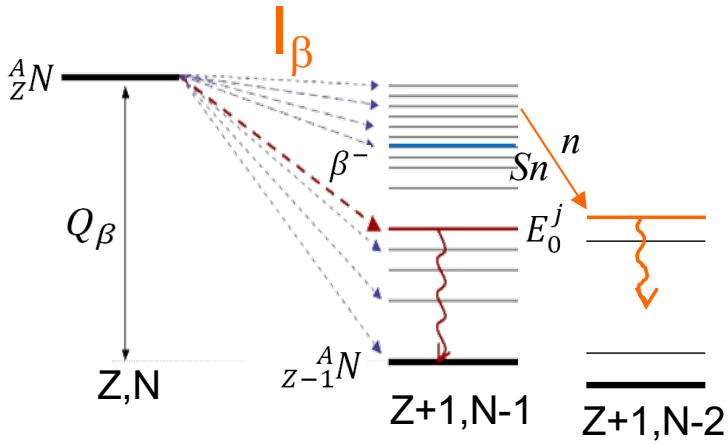
APRENDE

Getting access to the β decay properties

- Gamma-ray spectroscopy:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e $$

$$ \hookrightarrow {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$



- Electron measurement:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} I_{\beta\,fp}{}^{b} \times \underbrace{S_{fp}{}^{b}\left(Z_{fp}, A_{fp}, E_{0\,fp}{}^{b}, E\right)} $$

- Energy spectrum of a b branch of a fission product:

$$ S^{b}_{fp}(p) \propto \underbrace{p^2\left(Q - T_e\right)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{C(Z,p)}_{\text{Shape factor}} \underbrace{\left(1 + \delta(Z,A,p)\right)}_{\text{Subdominant corrections}} $$

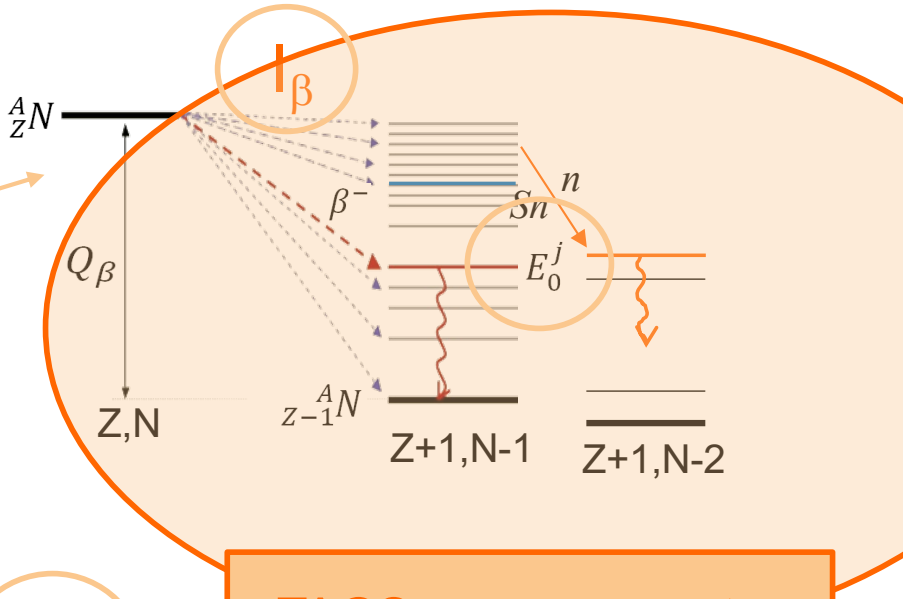
Courtesy M. Estienne

Getting access to the β decay properties

- Gamma-ray spectroscopy:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e $$

$$ {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$



TAGS measurements

- Electron measurement:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} I_{\beta\,fp}{}^{b} \times S_{fp}{}^{b}\left(Z_{fp}, A_{fp}, E_{0\,fp}{}^{b}, E\right) $$

- Energy spectrum of a b branch of a fission product:

$$ S^{b}_{fp}(p) \propto \underbrace{p^2\left(Q - T_e\right)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{C(Z,p)}_{\text{Shape factor}} \underbrace{\left(1 + \delta(Z,A,p)\right)}_{\text{Subdominant corrections}} $$

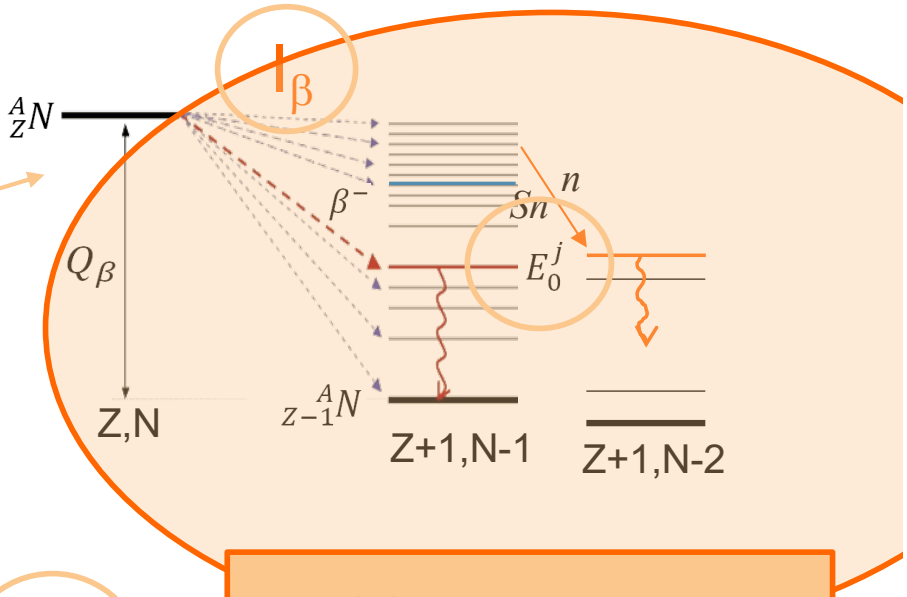
Courtesy M. Estienne

Getting access to the β decay properties

- Gamma-ray spectroscopy:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_e $$

$$ {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$



TAGS measurements

- Electron measurement:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} I_{\beta\,fp}{}^{b} \times S_{fp}{}^{b}\left(Z_{fp}, A_{fp}, E_{0\,fp}{}^{b}, E\right) $$

- Energy spectrum of a b branch of a fission product:

$$ S^{b}_{fp}(p) \propto \underbrace{p^2\left(Q - T_e\right)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{C(Z,p)}_{\text{Shape factor}} \underbrace{\left(1 + \delta(Z,A,p)\right)}_{\text{Subdominant corrections}} $$

eShape measurements

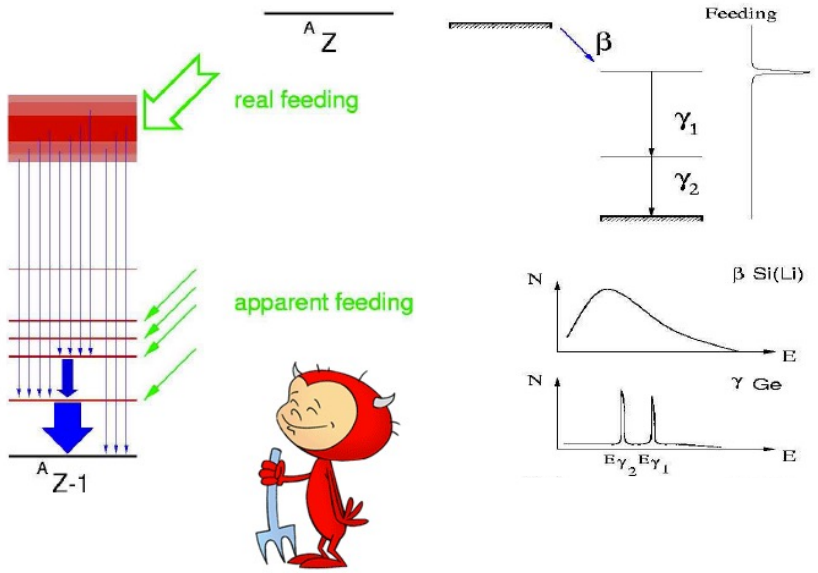
γ Measurement Caveat

- 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



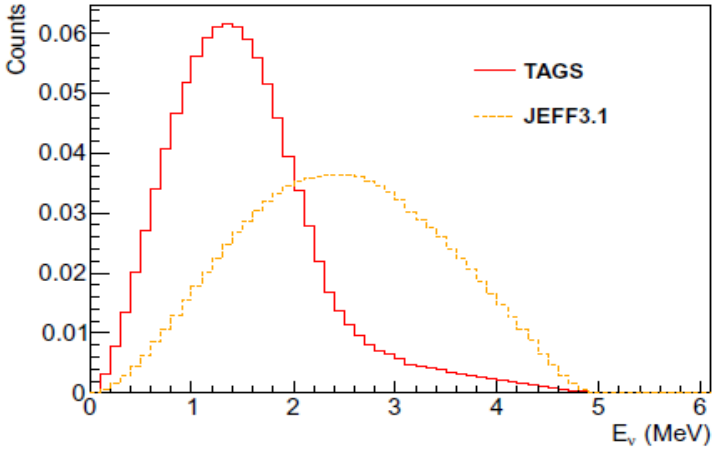
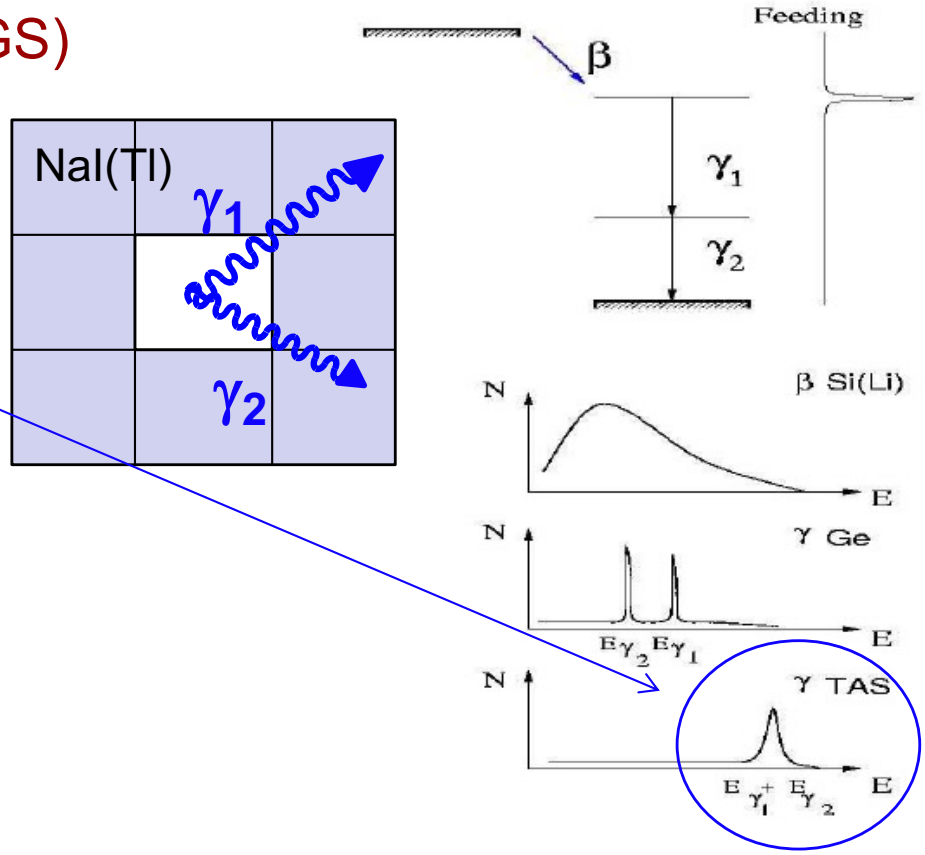


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

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

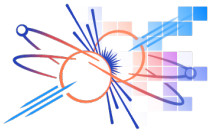


- First TAS developed in the 70's but too small detectors to be efficient. Development of the TAGS method efficient and systematic since the 90's (Greenwood & al.)

- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution
  - R_{ij} = matrix detector response: must be accurately known
  - d_i = measured data: must be clean off contaminants
  - Extract f_j the level feeding by deconvolution: solution of inverse problem must be stable

J. L. Tain & D. Cano-Ott, NIMA 571 (2007) 728
NIM A571 (2007) 719
NIM A430 (1999) 333
NIM A430 (1999) 488

- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)^{2}STARS Project
- Conclusions & Perspectives



APRENDE

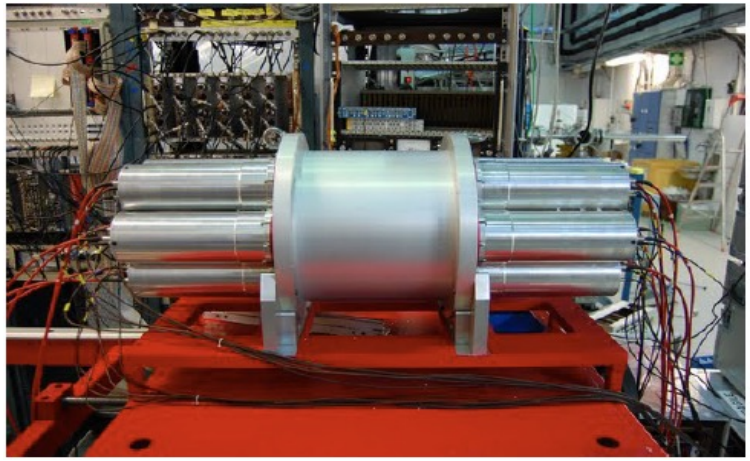
TAGS @IGISOL Jyväskylä in 2009, 2014 and 2022

- IGISOL@Jyväskylä:
  - ❑ Proton induced fission ion-guide source
  - ❑ Mass separator magnet
  - ❑ Double Penning trap system to clean the beams
- 2 (segmented) TAS campains :

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)

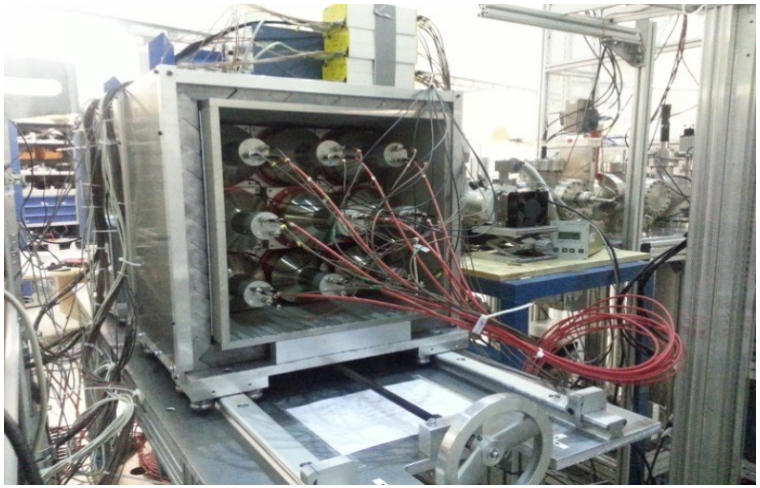
❑ ROCINANTE (IFIC Valencia/Surrey):



- ✓ 12 BaF_2 crystals
- ✓ Compact, γ-multiplicity
- ✓ ε^p=40% @E_γ=5 MeV
- ✓ ΔE=15% @E_γ=0.66 MeV
- ✓ Low n-sensitivity
- ✓ Good timing Δt=1 ns
- ✓ Coupled with a Si detector for β

E. Valencia+, PRC 95 (2017)

❑ DTAS (NUSTAR – DESPEC, IFIC):

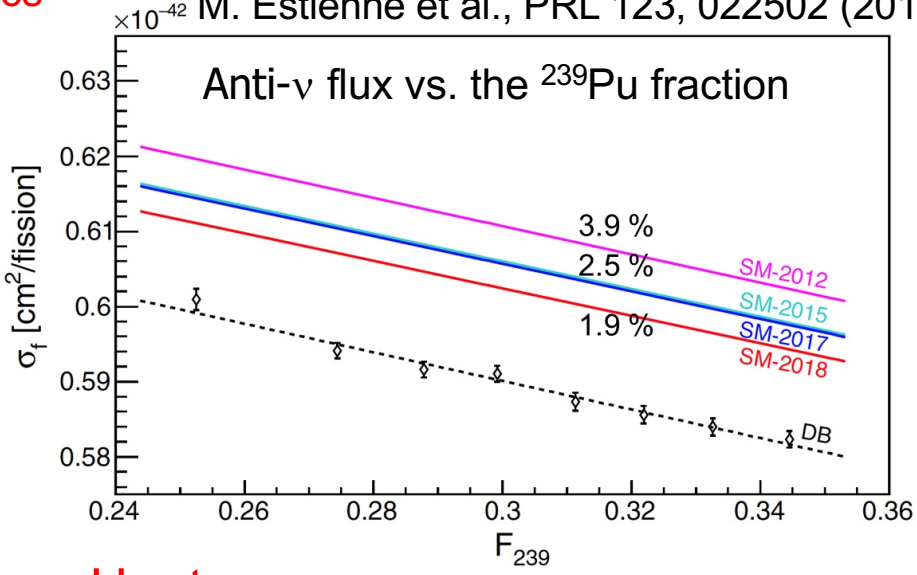


- ✓ 18 NaI(Tl) crystals of 15cm × 15cm × 25 cm
- ✓ Movable, γ-multiplicity
- ✓ ε^p=48% @E_γ=5 MeV
- ✓ ΔE=8% @E_γ=0.66 MeV
- ✓ Moderate n-sensitivity
- ✓ Coupled with a plastic detector

J.L. Tain+, NIM A 803 (2015)

TAGS @IGISOL Jyväskylä in 2009, 2014 and 2022

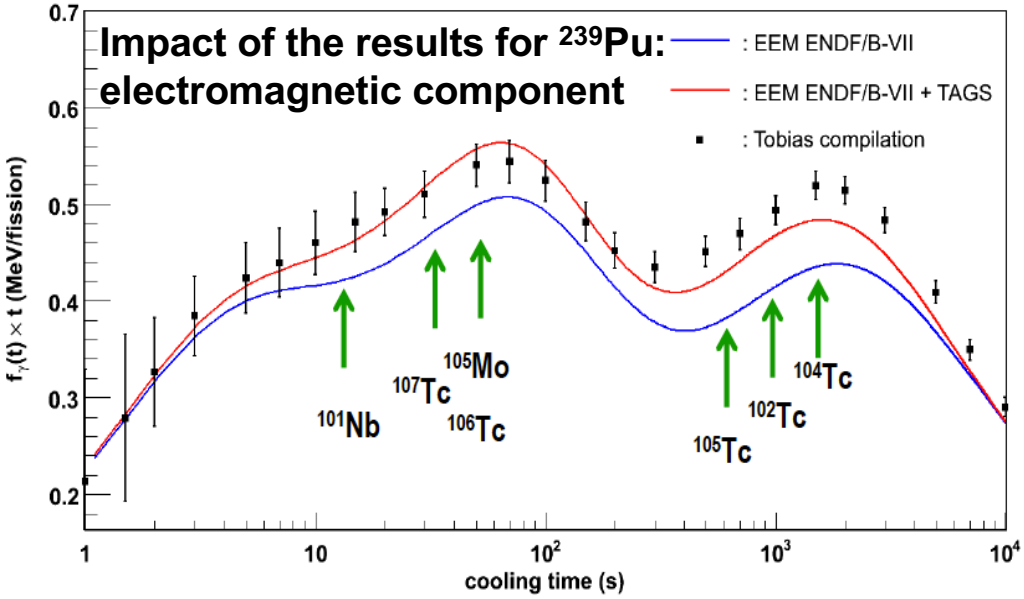
- Neutrino Physics



A.Algora et al. PRL 105, 202501 (2010),
M. Fallot et al. PRL 109, 202504 (2012)
D. Jordan et al. PRC 87, (2013) 044318
A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015)
E. Valencia et al., PRC 95, 024320 (2017)
S. Rice et al. PRC 96 (2017) 014320
V. Guadilla et al. PRL 122, (2019) 042502
V. Guadilla et al. Phys. Rev. C 100, 044305 (2019)
V. Guadilla et al. Phys. Rev. C 106, 014306 (2022)
+ Data vs model in Daya Bay and STEREO recent papers: DB: PRL 130 (2023) 211801, PRL 129 (2022) 041801, STEREO: Nature 613 (2023) 257

- Reactor Decay Heat

A. Nichols et al. Eur. Phys. J. A (2023) **59**: 78
Algora *et al*., PRL 105, 202501 (2010).



- R-process & γ/n competition above Sn

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)

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)

- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)^{2}STARS Project
- Conclusions & Perspectives

APRENDE

(NA)²STARS Project

GOAL: Upgrade of the existent TAS spectrometers **DTAS** and **Rocinante** with **16 $LaBr_3$(Ce) modules** 2"x2"x4"

- **Large efficiency of DTAS/Rocinante + very good energy resolution and timing of $LaBr_3$**
  - ❑ Higher segmentation: γ-γ coincidences, angular correlations, γ-cascade multiplicity
  - ❑ n/γ discrimination through timing
- **Broad physics case:** exotic nuclei further away from stability => nuclear structure and astrophysics on the p-rich (p/γ competition >S_p, p-process, rp-process, SNe…) and n-rich sides (n/γ competition >S_n), decay heat, reactor neutrinos…

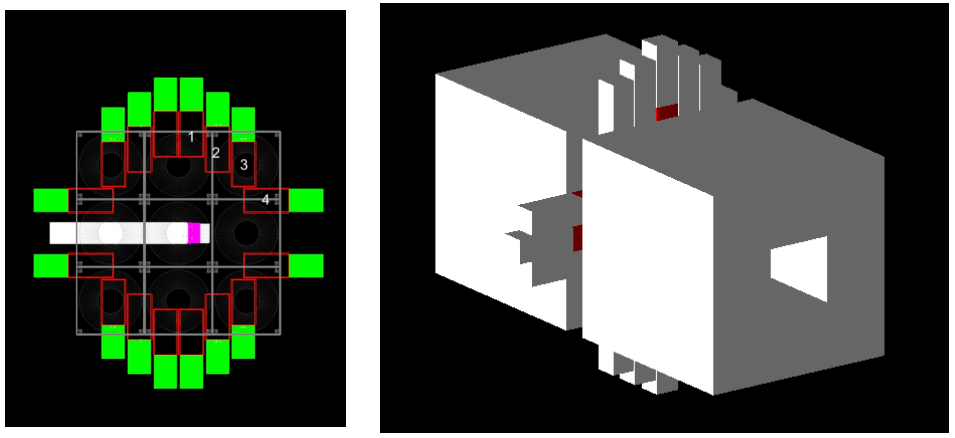
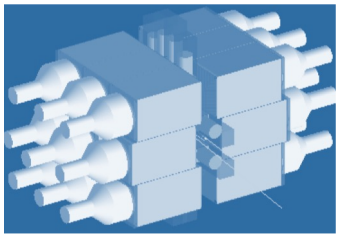


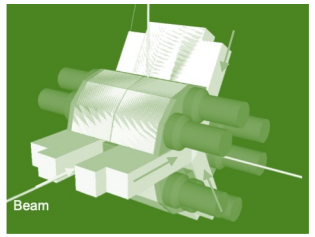
Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

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

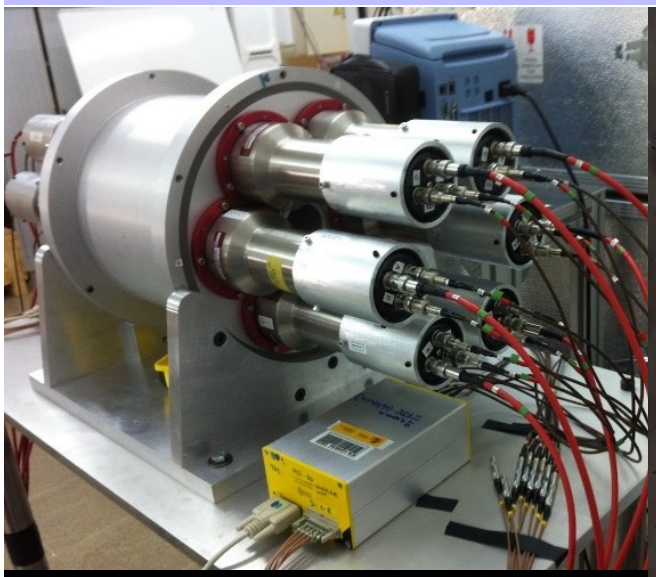


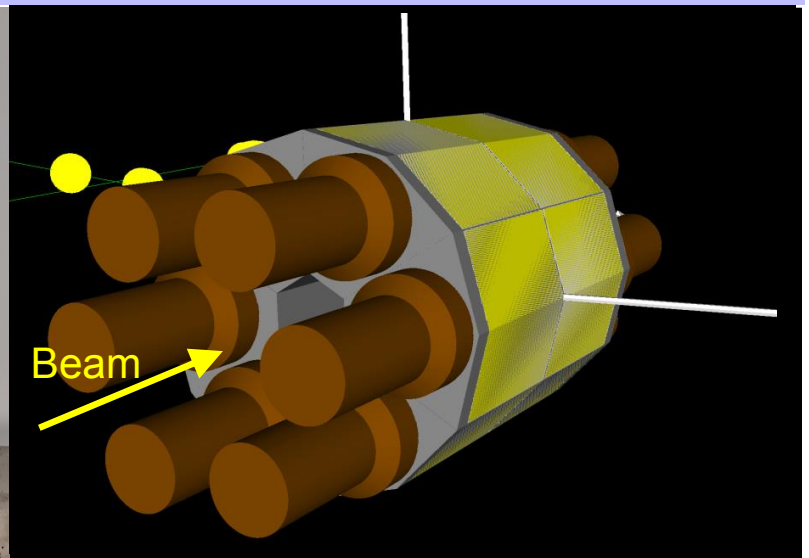
(NA)²STARS Collaboration

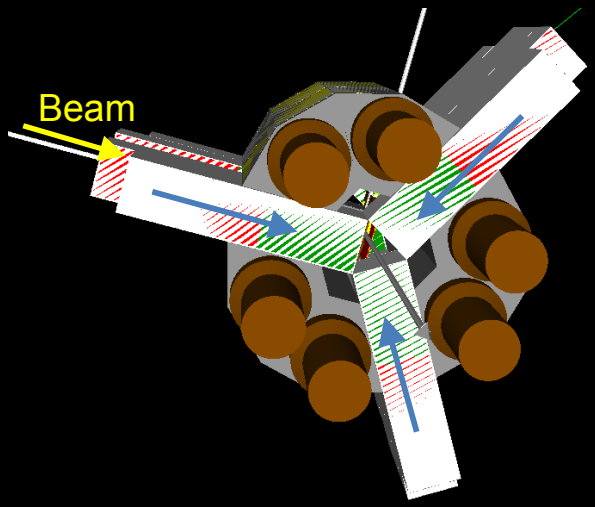


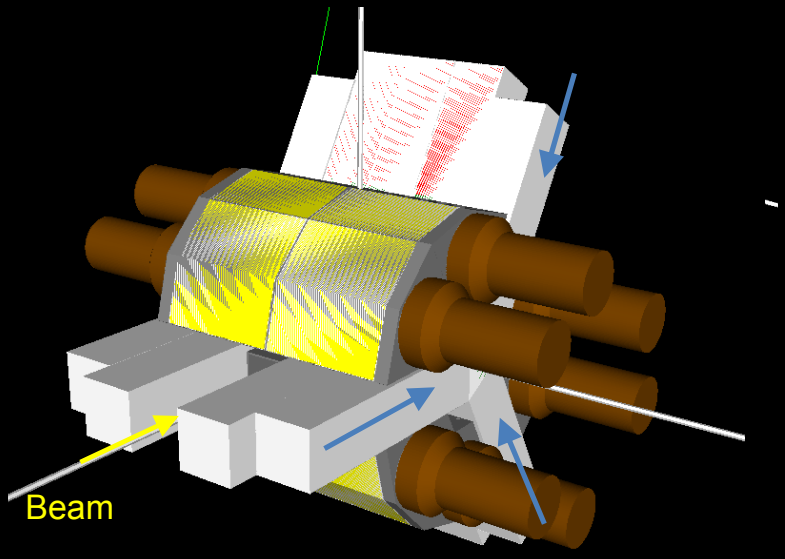
- SUBATECH: E. Bonnet, S. Durand, M. Estienne, M. Fallot, L. Le Floch, J. Pépin, V. Piau, A. Porta
- IFIC Valencia: A. Algora, E. Nacher, S. Orrigo, B. Rubio, J.-L. Tain
- GANIL : J.-C. Thomas, H. Guérin, B. Rebeiro
- CIEMAT Madrid: D. Cano-Ott
- CSIC Madrid: T. Kurtukian Nieto
- IP2I: C. Ducoin, N. Millard-Pinard, O. Stézowski
- Surrey: W. Gelletly, Z. Podolyak
- U. Istanbul: E. Ganioğlu Nutku, L. Şahin Yalçın, M. Yalçınkaya
- U. Huelva: A. M. Benitez-Sanchez
- NPI CAS: A. Cassissa, J. Mrazek, E. Simeckova

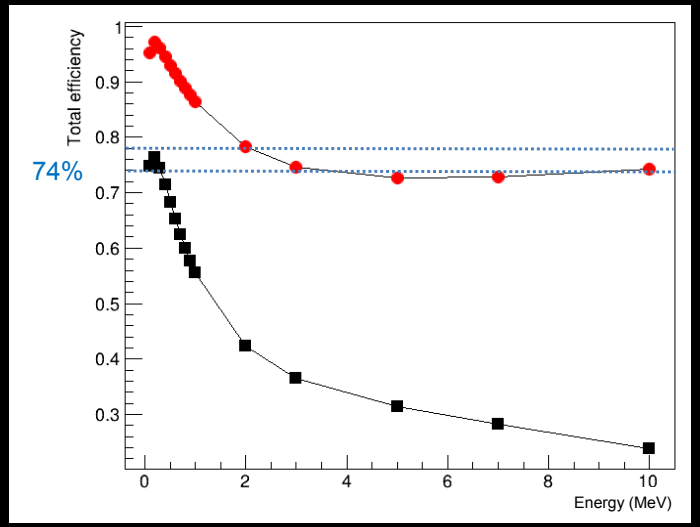
The (NA)²STARS project











GANIL laboratoire commun CEA/DRF SPIRAL2 CNRS/IN2P3

PROPOSAL E891_23

GANIL PAC 14/11/2023

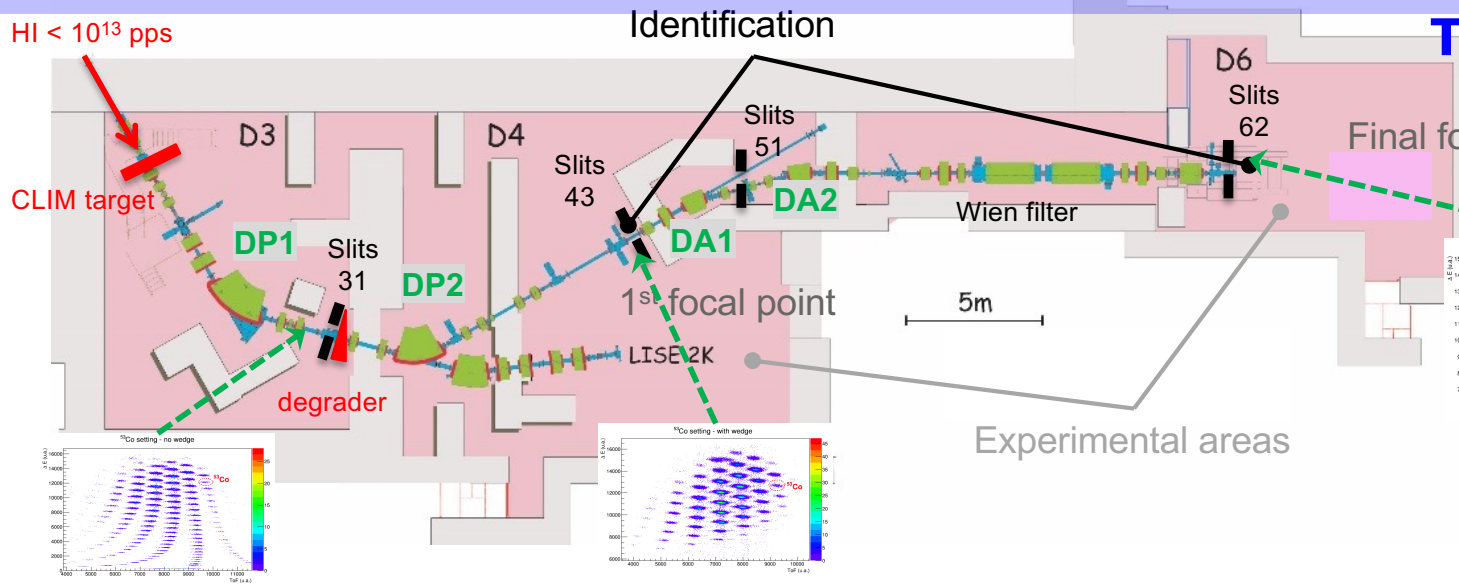
Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

Spokespersons: M. Fallot[1], S. E. A. Orrigo[2], A. M. Sánchez Benítez[3],

B. Rubio[2], A. Algora[2,4], J.-C. Thomas[5], W. Gelletly[6], B. Blank[7], L. Acosta[8], J. Agramunt[2], P. Aguilera[9], O. Aktas[5], G. Alcala[2], P. Ascher[7], D. Atanasov[7], B. Bastin[5], A. Beloeuvre[1], E. Bonnet[1], S. Bouvier[1], M. J. G. Borge[10], J. A. Briz[11], A. Cadiou[1], D. Cano Ott[12], G. de Angelis[13], G. de France[5], Q. Delignac[7], F. de Oliveira Santos[5], N. de Séréville[14], C. Ducoin[15], J. Dueñas[3], M. Estienne[1], A. Fantina[7], M. Flayol[7], C. Fonseca[2], C. Fougeres[16], L. M. Fraile[11], H. Fujita[17], Y. Fujita[17], D. Galaviz[18], E. Ganioglu[19], F. G. Barba[18], M. Gerbaux[7], J. Giovinazzo[7], D. Godos[8], S. Grevy[7], V. Guadilla[20], F. Gulminelli[21], F. Hammache[14], J. Mrázek[22], O. Kamalou[5], T. Kurtukian-Nieto[10], I. Martel[3], N. Millard-Pinard[15], F. Molina[23], E. Nacher[2], S. Nandi[1], S. Parra[2], J. Pépin[1], J. Piot[5], Z. Podolyak[6], A. Porta[1], B. M. Rebeiro[5], P. Regan[6], D. Rodriguez[2], O. Sorlin[5], C. Soto[15], O. Stezowski[15], C. Stodel[5], J. L. Tain[2], O. Tengblad[10], P. Teubig[18], L. Trache[24]

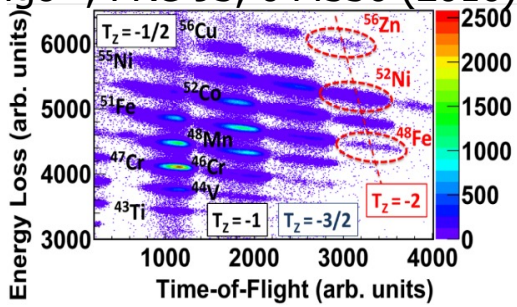
[1] *Subatech, Nantes, France*
[2] *IFIC-CSIC, Valencia, Spain*
[3] *UHU, Spain*
[4] *Atomki, Debrecen, Hungary*
[5] *GANIL Caen, France*
[6] *Univ. Surrey, UK*
[7] *IP2I, Bordeaux, France*
[8] *Instituto de Física-UNAM, Mexico*
[9] *Univ. Padova and INFN, Italy*
[10] *IEM-CSIC, Spain*
[11] *UCM Madrid, Spain*
[12] *CIEMAT, Spain*
[13] *LNL-INFN, Italy*
[14] *IJCLab, Orsay, France*
[15] *IP2I, Lyon, France*
[16] *ARGONNE, USA*
[17] *RCNP Osaka, Japan*
[18] *LIP-Lisboa, Portugal*
[19] *Univ. Istanbul, Turkey*
[20] *Univ. Warsaw, Poland*
[21] *LPCCAEN, France*
[22] *NPI CAS, Czech Republic*
[23] *CCHEN, Santiago, Chile*
[24] *NIPNE, Romania*

(NA)²STARS Experimental setup @ GANIL



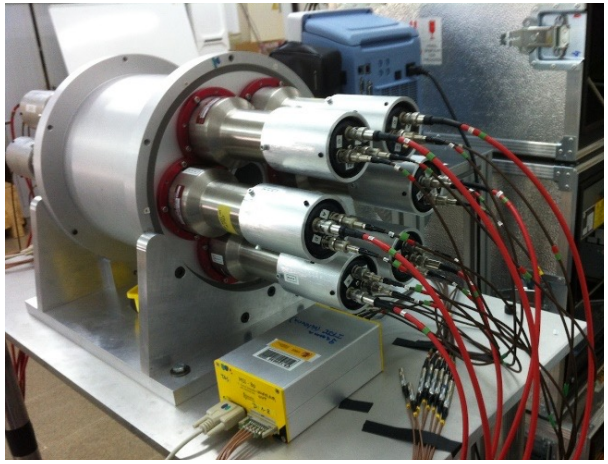
The LISE spectrometer

Orrigo+, PRC 93, 044336 (2016)

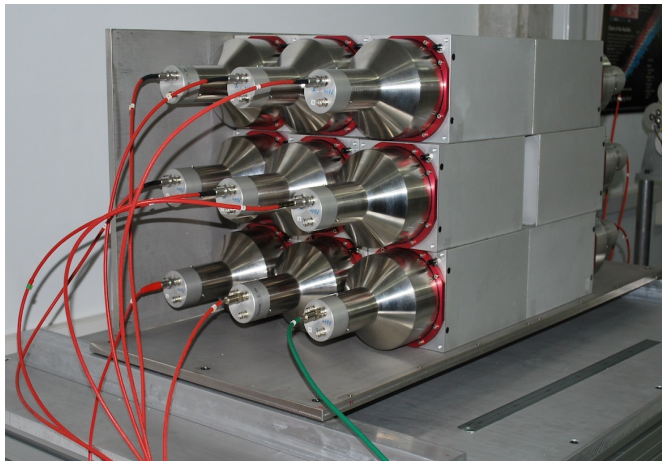


- **New DSSSD (GANIL) 1 mm-thick, 40x40 mm²**
- **Rocinante (refurbished) or DTAS + 16 $LaBr_3$ crystals**

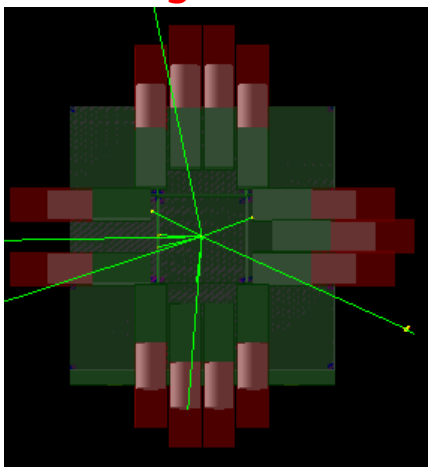
Rocinante



DTAS

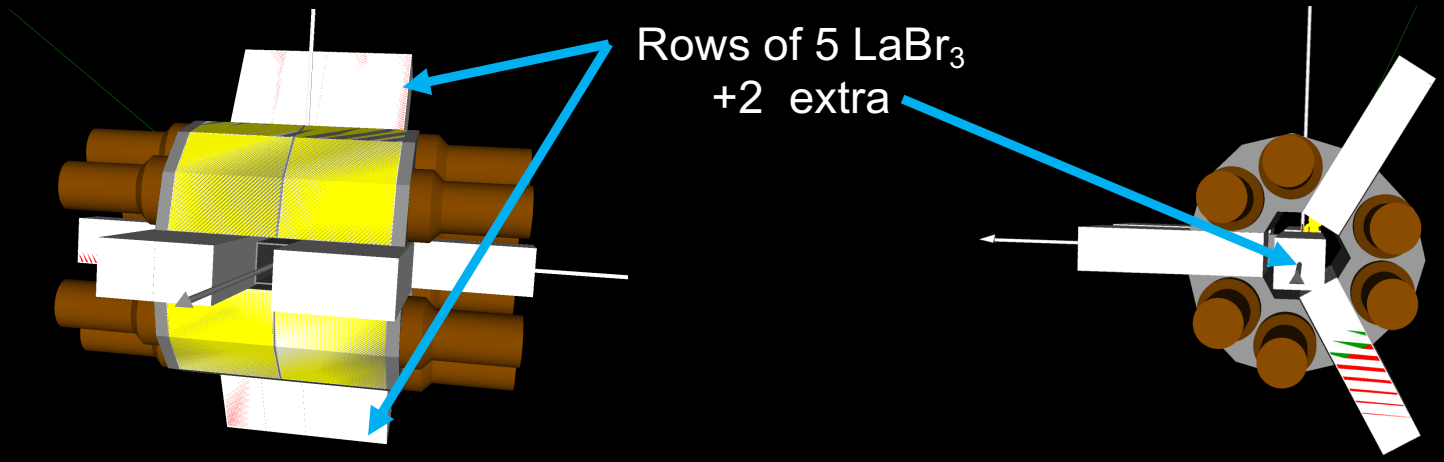


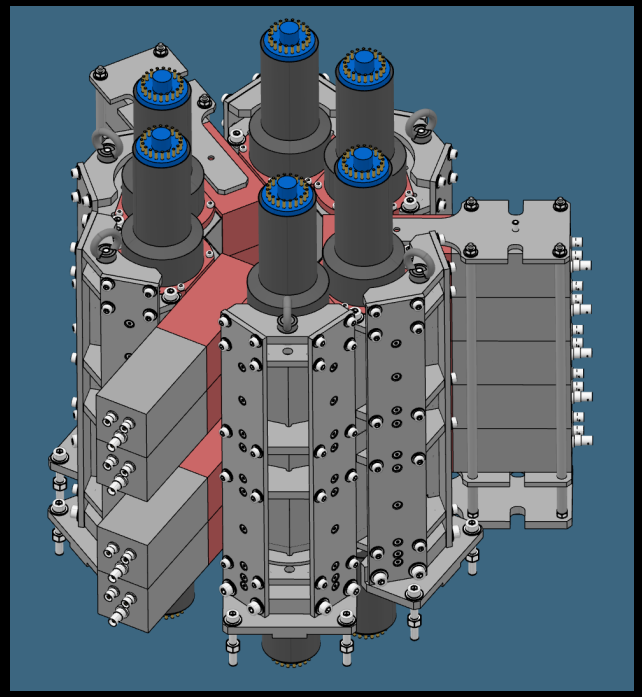
+ $LaBr_3$ modules + New DSSSD

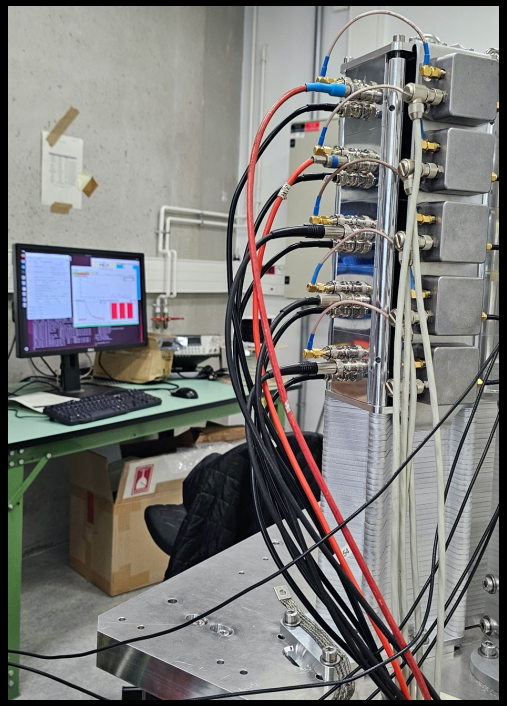


STARS

The (NA)²STARS project

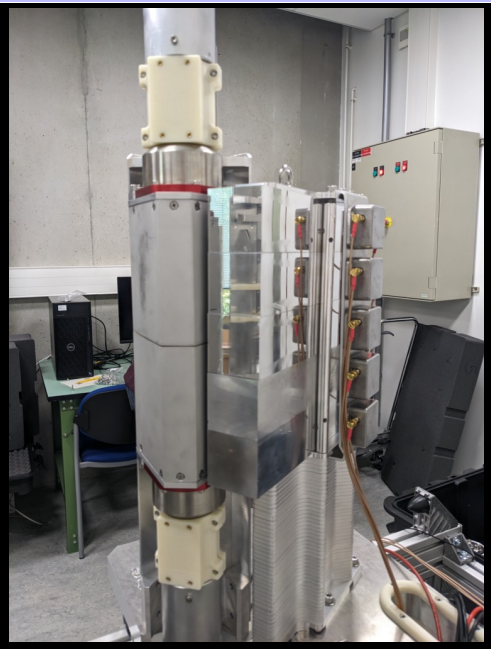




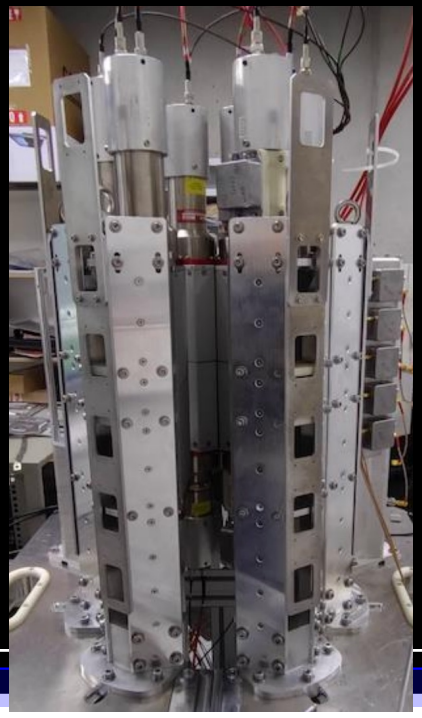
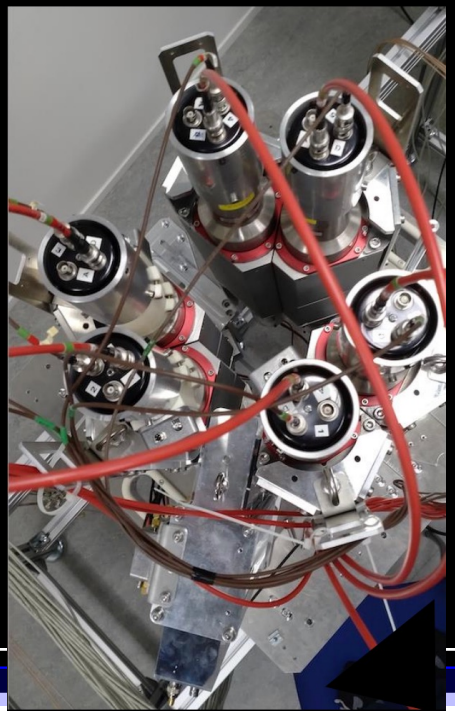


To be continued…

The (NA)²STARS project

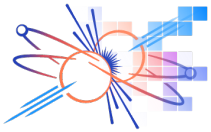




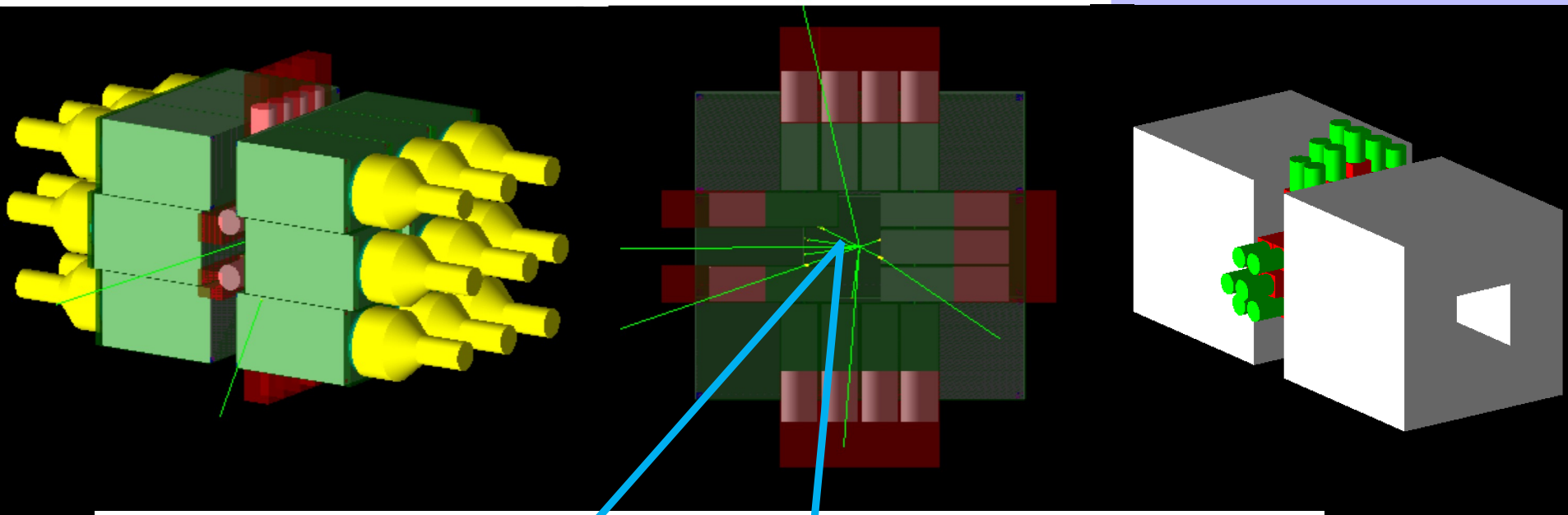
To be continued…

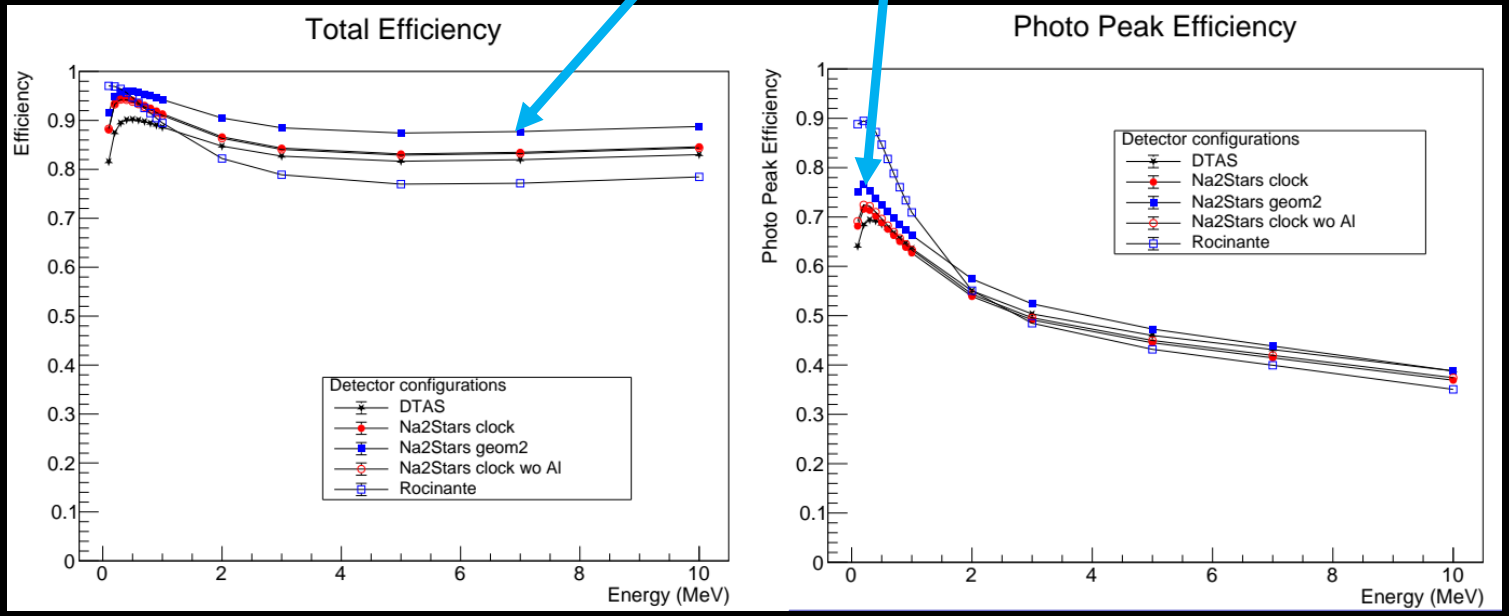
- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)²STARS Project
- Conclusions & Perspectives



APRENDE

The (NA)²STARS project

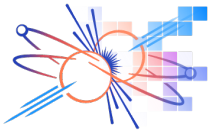




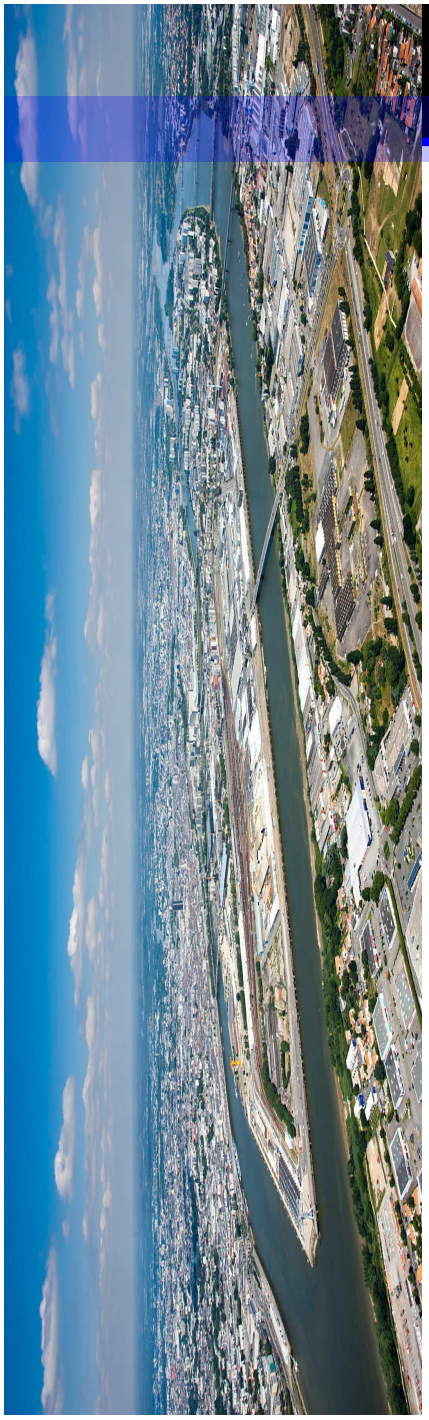
The (NA)²STARS project in the PEPR

- Scientific Objectives: beta decay properties of Fission Products (reactor safety, reactor monitoring, …) free of Pandemonium effect with the TAGS technique
- Deliverable: a new TASpectrometer available for measuring more FP decay data (from priority lists in IAEA papers and reports)
- Upgrade of the existing spectrometers: (NA)^{2}STARS
- STARS version mixing $LaBr_3$ and BaF_2 nearly there (commissioning July 26)
- In the context of the PEPR: next stage = build the STARS mixing $LaBr_3$ and NaI detectors
- 1 experiment accepted in Jyväskylä, planned in 2027: new TAGS campaign on Fission Products with the STARS
- Manpower:
  - Personnel chercheurs permanents en h.m. sur le projet : ~ 1.5 etp et ~10 h.m. / an d' Ingénieurs – techniciens de Subatech impliqués sur 5 ans
  - Démarrage d'un post-doctorat en juillet 26 sur R&D (NA)^{2}STARS

- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- (NA)^{2}STARS Project
- Conclusions & Perspectives



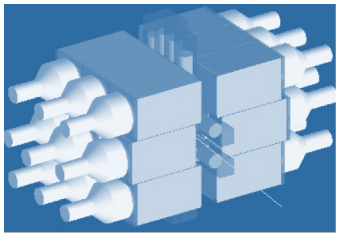
APRENDE

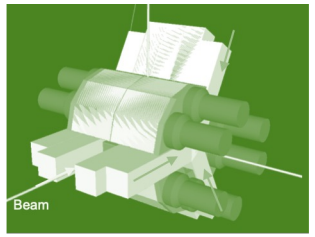


Conclusions & Perspectives

- 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
- The **STARS** will ally efficiency with improved energy resolution, timing, increased segmentation, **commissioning in GANIL July 2026**
- **A new proposal has been accepted to the PAC of Jyväskylä in Dec. 25 on fission products (to be performed in 2027-28)**
- **The PEPR will allow to build the next stage of the STARS mixing NaI and $LaBr_3$ detectors**
- **Goal:** to have **an upgraded TAS** most of the time available **to measure more decay data on FP on a long term scale**

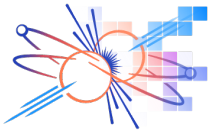
THANK YOU





- SUBATECH: E. Bonnet, S. Durand, M. Estienne, M. Fallot, L. Le Floch, J. Pépin, V. Piau, A. Porta
- IFIC Valencia: A. Algora, E. Nacher, S. Orrigo, B. Rubio, J.-L. Tain
- GANIL : J.-C. Thomas, H. Guérin, B. Rebeiro
- CIEMAT Madrid: D. Cano-Ott
- CSIC Madrid: T. Kurtukian Nieto
- IP2I: C. Ducoin, N. Millard-Pinard, O. Stézowski
- Surrey: W. Gelletly, Z. Podolyak
- U. Istanbul: E. Ganioğlu Nutku, L. Şahin Yalçın, M. Yalçınkaya
- U. Huelva: A. M. Benitez-Sanchez
- NPI CAS: A. Cassissa, J. Mrazek, E. Simeckova

THE END



APRENDE