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

M. Fallot and the (NA)^{2}STARS collaboration

Caen Sept. 2025

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

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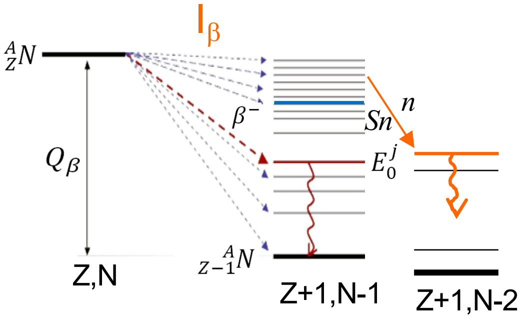
Getting access to the β decay properties

- Gamma-ray spectroscopy:

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

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



- Electron measurement:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} {I_{\beta}}_{fp}^{\ b} \times S_{fp}^{\ b}\left(Z_{fp}, A_{fp}, {E_0}_{fp}^{\ b}, E\right) $$

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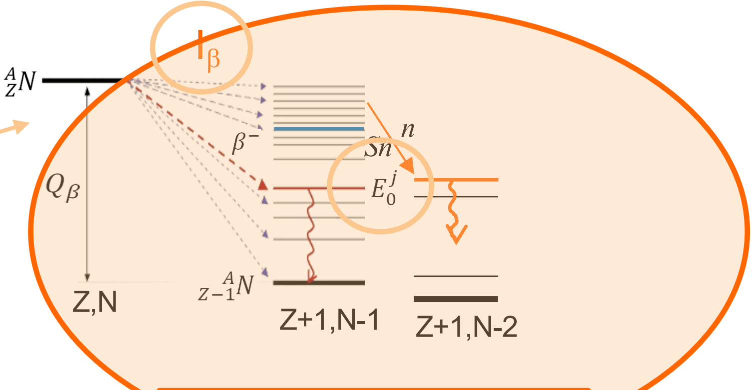

TAGS measurements

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@ this conference:
J. Pépin NSSD ID 206
A. Porta NSSD ID 194
M. Estienne NSSD ID 241

Courtesy M. Estienne

Getting access to the β decay properties

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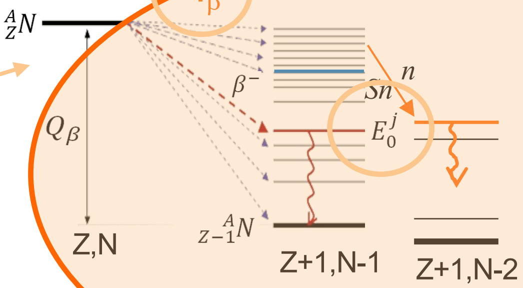

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- Energy spectrum of a b branch of a fission product:

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

eShape measurements

Getting access to the β decay properties

- Gamma-ray spectroscopy:

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

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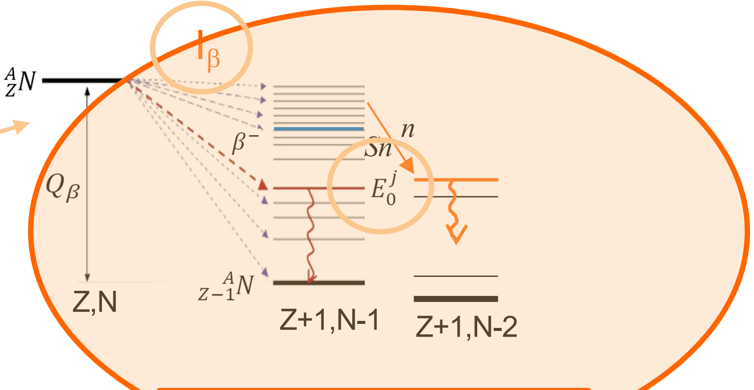

TAGS measurements

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G. Alcala et al. arXiv:2505.05929
Accepted in PRL https://doi.org/10.1103/hyj7-l22h

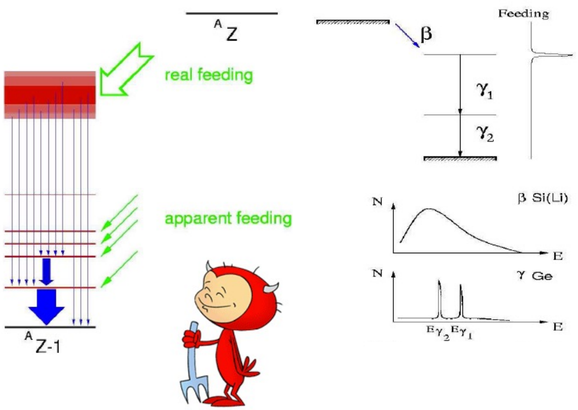
eShape measurements

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)

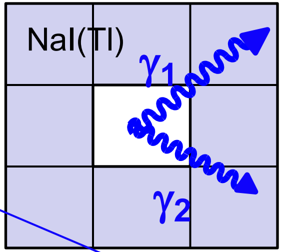
Picture from A. Algora

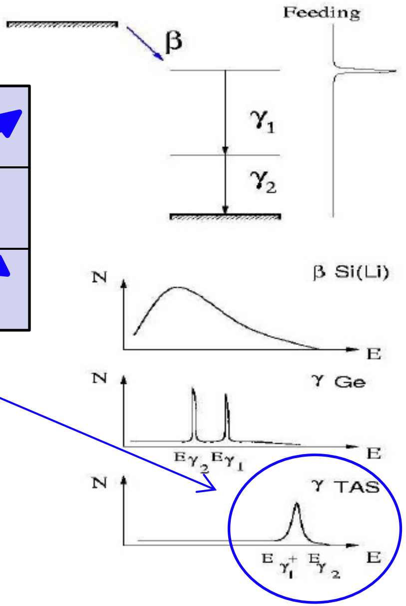


➡ **Strong potential bias in nuclear data bases and all their applications**

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





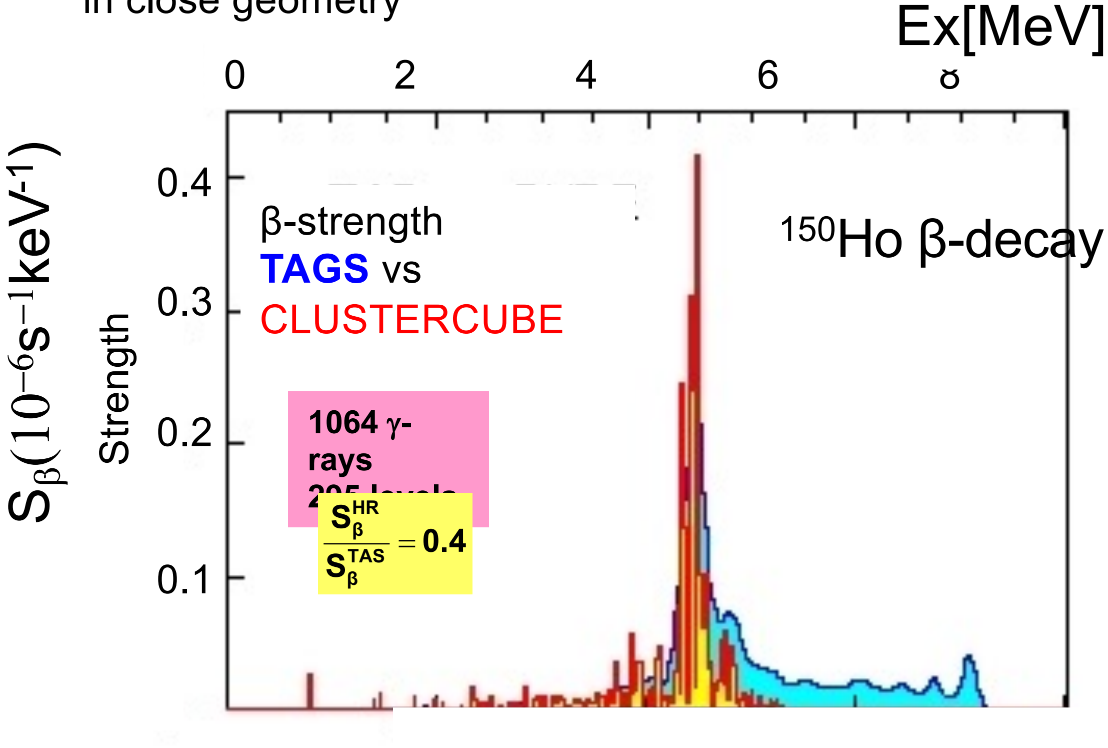
- First TAS developed in the 70's but too small detectors to be efficient. Development of the TAGS method efficient and systematic since the 90's (Greenwood & al.)

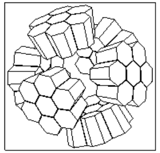
- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution
  - R_{ij} = matrix detector response: must be accurately known
  - d_i = measured data: must be clean off contaminants
  - Extract f_j the level feeding by deconvolution: solution of inverse problem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

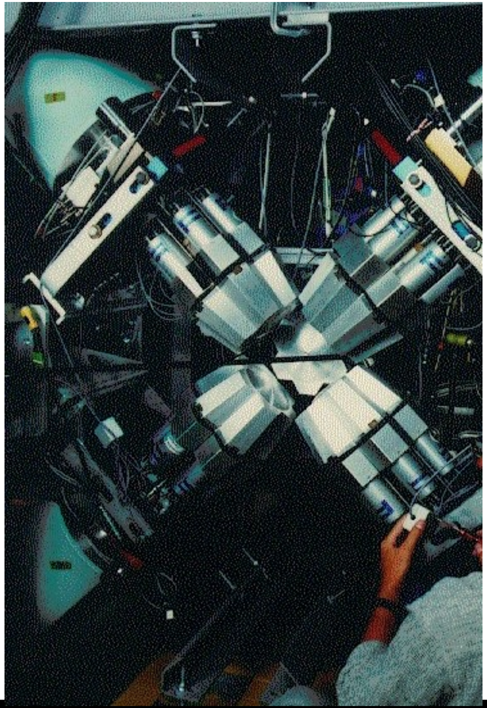
J. L. Tain & D. Cano-Ott, NIMA 571 (2007) 728
NIM A571 (2007) 719
NIM A430 (1999) 333
NIM A430 (1999) 488

High Resolution & TAGS Complementarity

Six EUROBALL CLUSTER detectors
in close geometry







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

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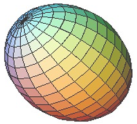
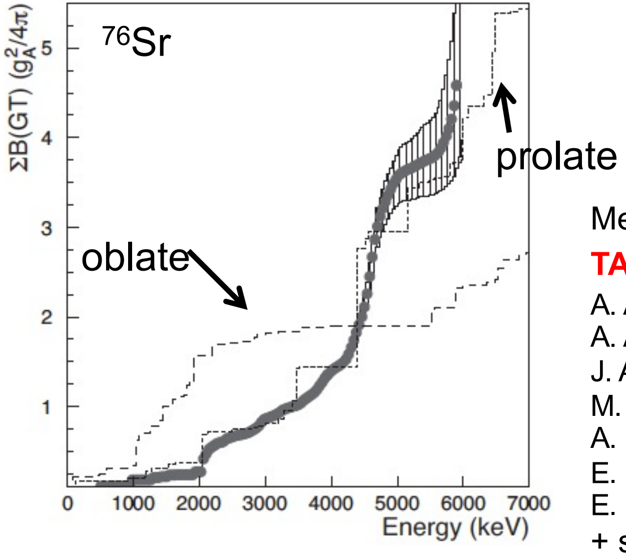
TAGS@ISOLDE

- Useful probe to investigate the **shape of the progenitor state** I. Hamamoto ZPA 353 (1995)
  P. Sarriguren+, NPA 658 (1999)
- Comparison to theor. **QRPA calculations** with different deformations



Very prolate N=Z nucleus



Lucrecia

- ✓ NaI(Tl) single crystal
- ✓ Permanent @ ISOLDE-CERN
- ✓ ε^p=48% @Eγ=5 MeV
- ✓ ΔE=7% @Eγ=0.66 MeV
- ✓ Moderate n-sensitivity

B. Rubio+, JPG NPP 44 (2017)

Method **successfully employed** in many experimental

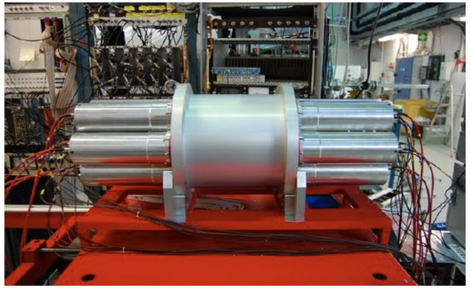
TAGS studies at ISOLDE for 20 years:

A. Algora et al., *Eur. Phys. J. A* **57,** 85 (2021): Review of last decade
A. Algora et al., Phys. Lett. B 819, 136438 (2021)
J. A. Briz et al., Phys. Rev. C 92, 054326 (2015)
M. E. Estévez Aguado et al., Phys. Rev. C 92, 044321 (2015)
A. Pérez-Cerdá et al., Phys. Rev. C 88, 014324 (2013)
E. Nacher et al. Phys. Rev. Lett. 92, 232501 (2004)
E. Poirier et al., Phys. Rev. C 69, 034307 (2004)
+ several experiments in 2023: ^{186}Hg region, r-process, rp-process…

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 :

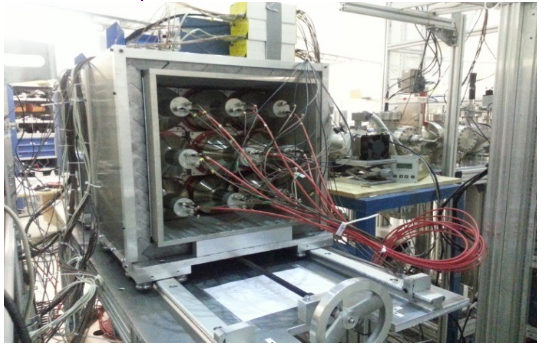
❑ ROCINANTE (IFIC Valencia/Surrey):



E. Valencia+, PRC 95 (2017)

- ✓ 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

❑ DTAS (NUSTAR – DESPEC, IFIC):



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

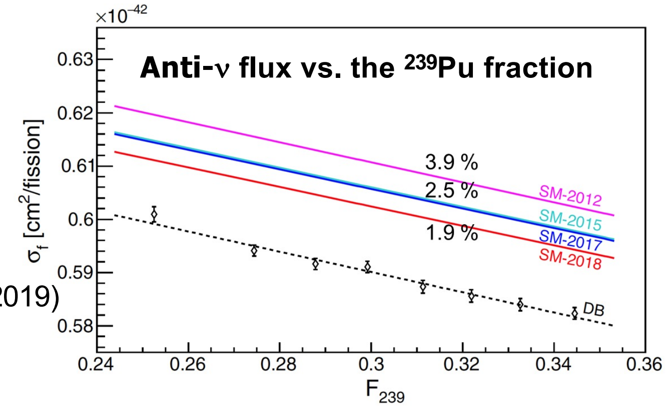
V. Guadilla et al., NIM A (2018)

- ✓ 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

TAGS @IGISOL Jyväskylä in 2009, 2014 and 2022

- Neutrino Physics

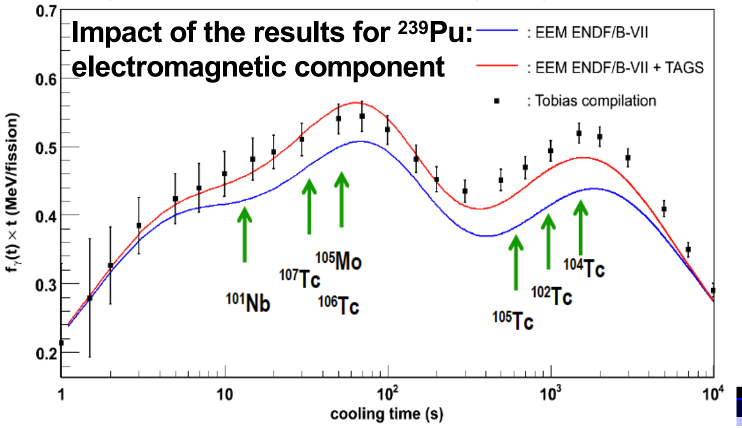
M. Estienne et al., PRL 123, 022502 (2019)



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)

TAGS @IGISOL Jyväskylä in 2009, 2014 and 2022

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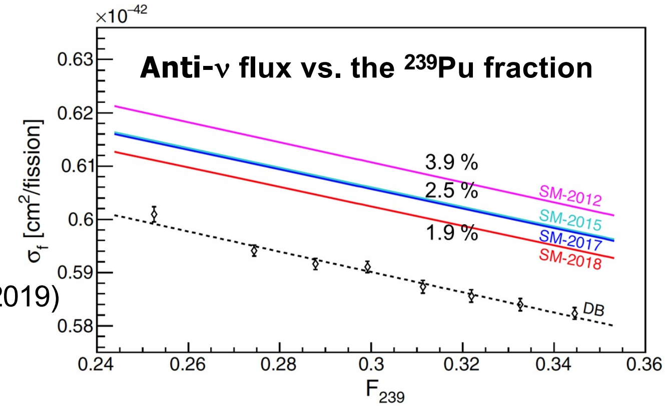
M. Estienne et al., PRL 123, 022502 (2019)



A.Algora et al. PRL 105, 202501 (2010),
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E. Valencia et al., PRC 95, 024320 (2017)
S. Rice et al. PRC 96 (2017) 014320
V. Guadilla et al. PRL 122, (2019) 042502
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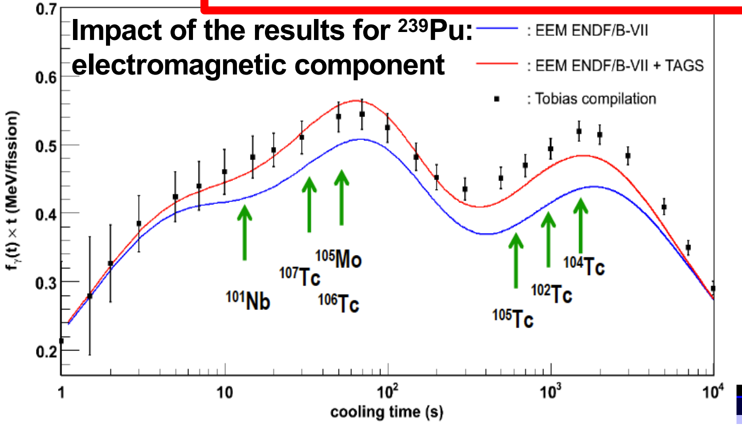
- Reactor Decay Heat

A. Nichols

Algora *et*

See presentations by J. Pépin (ID 206), A. Porta (ID 191), and M. Estienne (ID 241) in the NSSD sessions



Sn

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V. Guadilla et al., Phys. Rev. C 100, 044305 (2019)

DTAS+AIDA @ RIKEN (2019) and GSI (2022)

- 1^{st} experiments with DTAS @ IGISOL (2014): reactor neutrino, DH, n/γ competition
- Successfully commissioned with AIDA @ RIKEN (2019): ^{100}Sn, A. Algora+, NP1412-RIBF130
- DTAS+AIDA @ GSI (2022): n-rich nuclei in the N~126 region, J.L. Tain+, S505 experiment

Courtesy A. Algora

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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 (but are fast).

$\Rightarrow$ **Natural improvement of the existing TAS: combine efficiency, energy resolution, segmentation and timing !**

- Physics cases:

$\Rightarrow$ **Antineutrino, Decay Heat, Nuclear Structure & Astrophysics on n-rich side:** towards **shorter-lived contributors =>** n-richer nuclei => large Q-values, β-n branch = n contamination and knowledge of Pn + less nuclear structure knowledge on decay daughters

$\Rightarrow$ **Nuclear Structure & Astrophysics on n-deficient side: more exotic** means less nuclear structure knowledge on decay daughters, large Q-values, β-delayed particle emission

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⇒ **Nuclear Structure & Astrophysics on n-deficient side: more exotic** means less nuclear structure knowledge on decay daughters, large Q-values, β-delayed particle emission **efficiency, better energy resolution, potential angular correlations**

(NA)^{2}STARS 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…

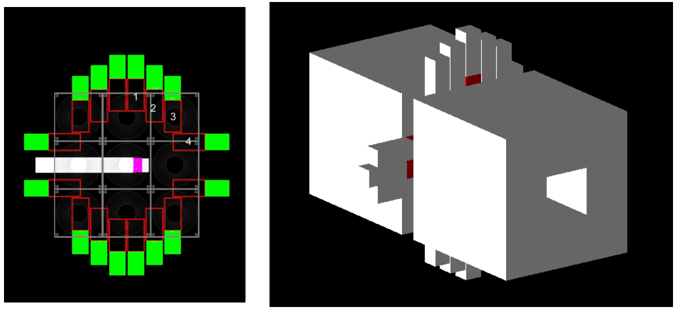
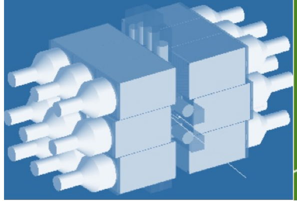


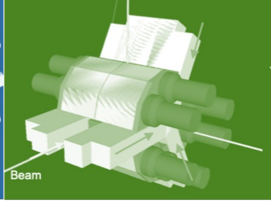
Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

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

$(NA)^2$STARS Collaboration





- SUBATECH: E. Bonnet, S. Durand, M. Estienne, M. Fallot, S. Nandi, N. Payan, 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. Ribeiro
- 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

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],

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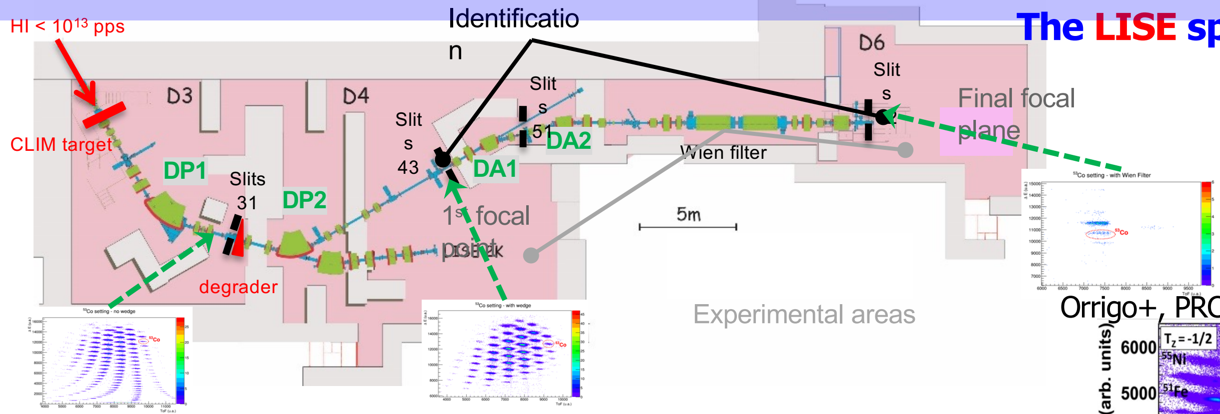
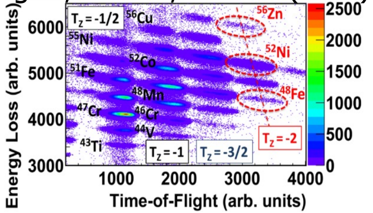
[19] Univ. Istanbul, Turkey
[20] Univ. Warsaw, Poland
[21] LPCCAEN, France
[22] NPI CAS, Czech Republic
[23] CCHEN, Santiago, Chile
[24] NIPNE, Romania

$(NA)^2$STARS Experimental setup @ GANIL

The LISE spectrometer

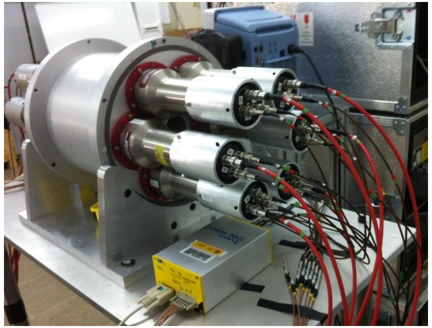


Origrigo+, PRC 93, 044336 (2016)

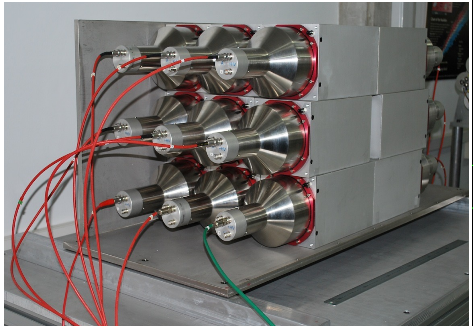


- **New DSSSD (GANIL)** **1 mm-thick, 40x40 mm^2**
- **Rocinante (refurbished) or DTAS + 16 $LaBr_3$ crystals**

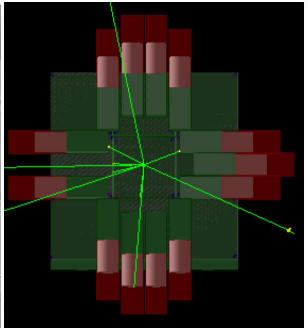
Rocinante



DTAS



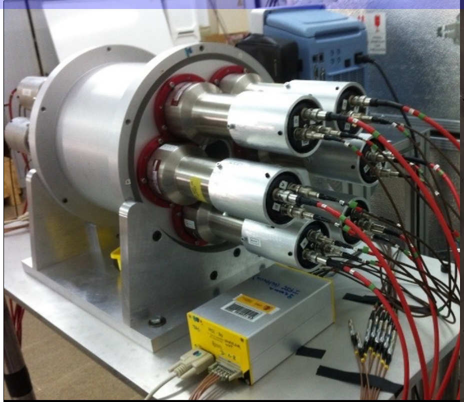
+ $LaBr_3$ modules

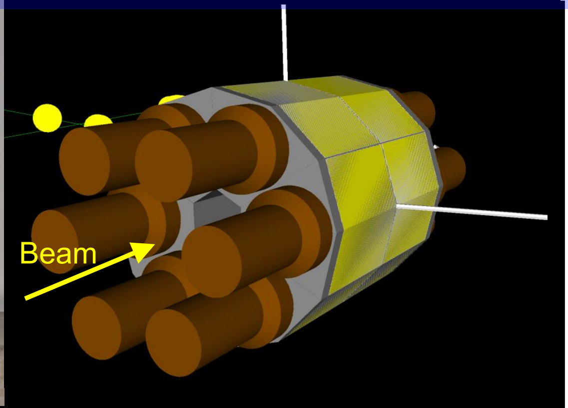


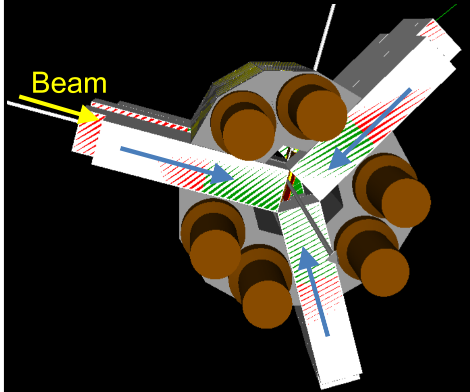
+ New DSSSD

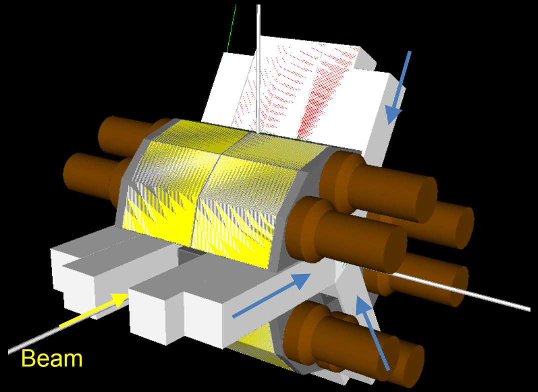
STARS

The $(NA)^2$STARS project









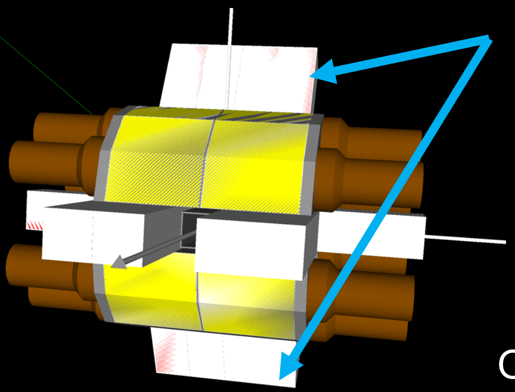
BaF_2: ρ= 4.893 g/cm^3, τ_{decay}= 0.6 and 620ns, energy resolution ~10 %@1332 keV

$LaBr_3$: ρ=5.08 g/cm^3, τ_{decay}=17 ns, energy resolution ~3 %@662 keV

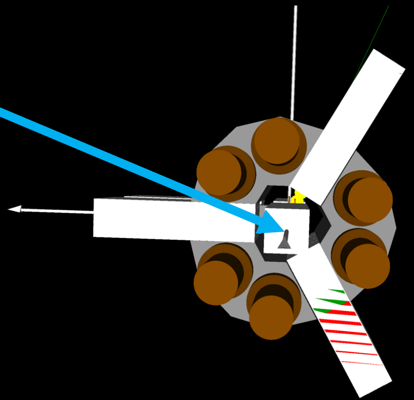
On-going work…

Pictures A. Algora & Simulations M. Estienne

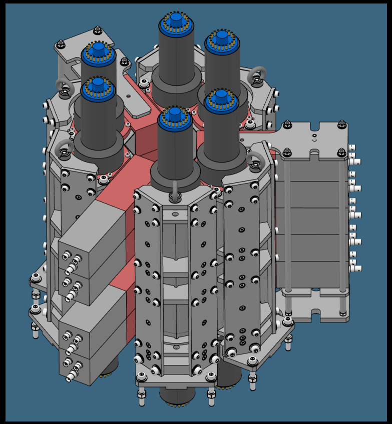
The $(NA)^2$STARS project

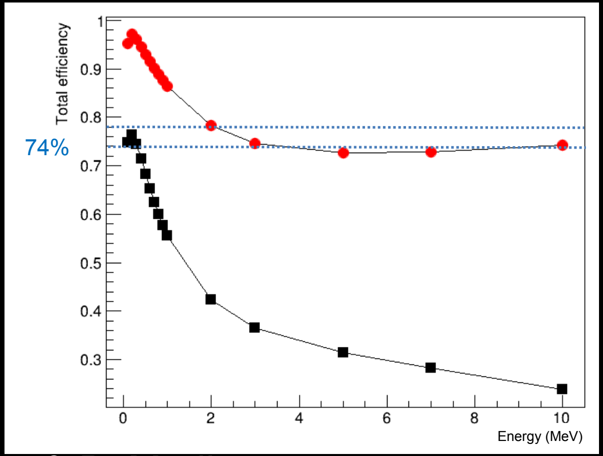


Rows of 4 $LaBr_3$
+2 extra



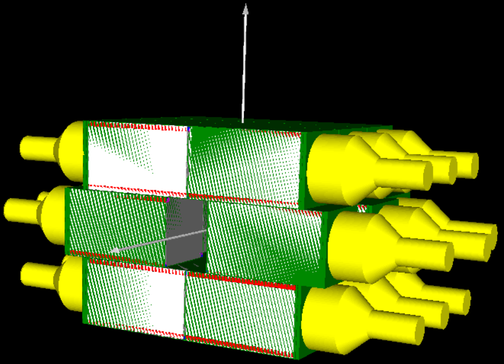
On-going work…





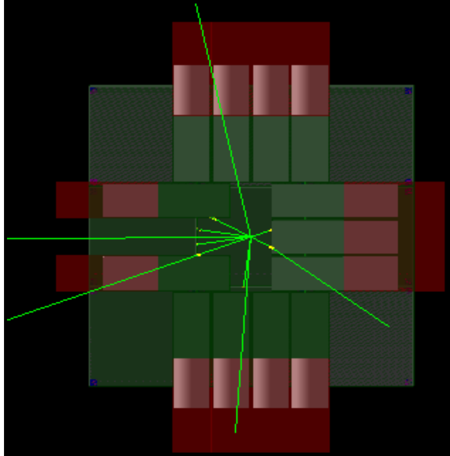
Mechanical Drawings: J.-S. Stutzmann & B. Madiot

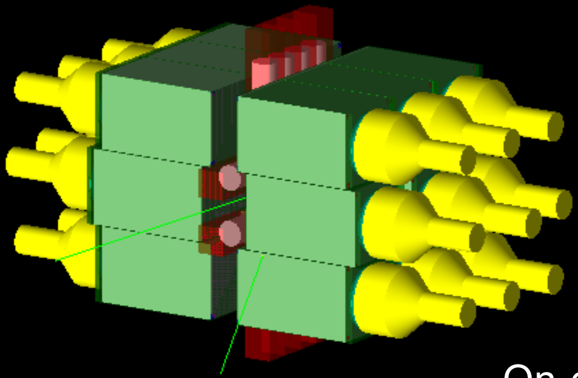
The $(NA)^2$STARS project



NaI: ρ=3.67 g/cm^3, τ_{decay}=230 ns, energy resolution ~7 %@662 keV

$LaBr_3$: ρ=5.08 g/cm^3, τ_{decay}=17 ns, energy resolution ~3 %@662 keV

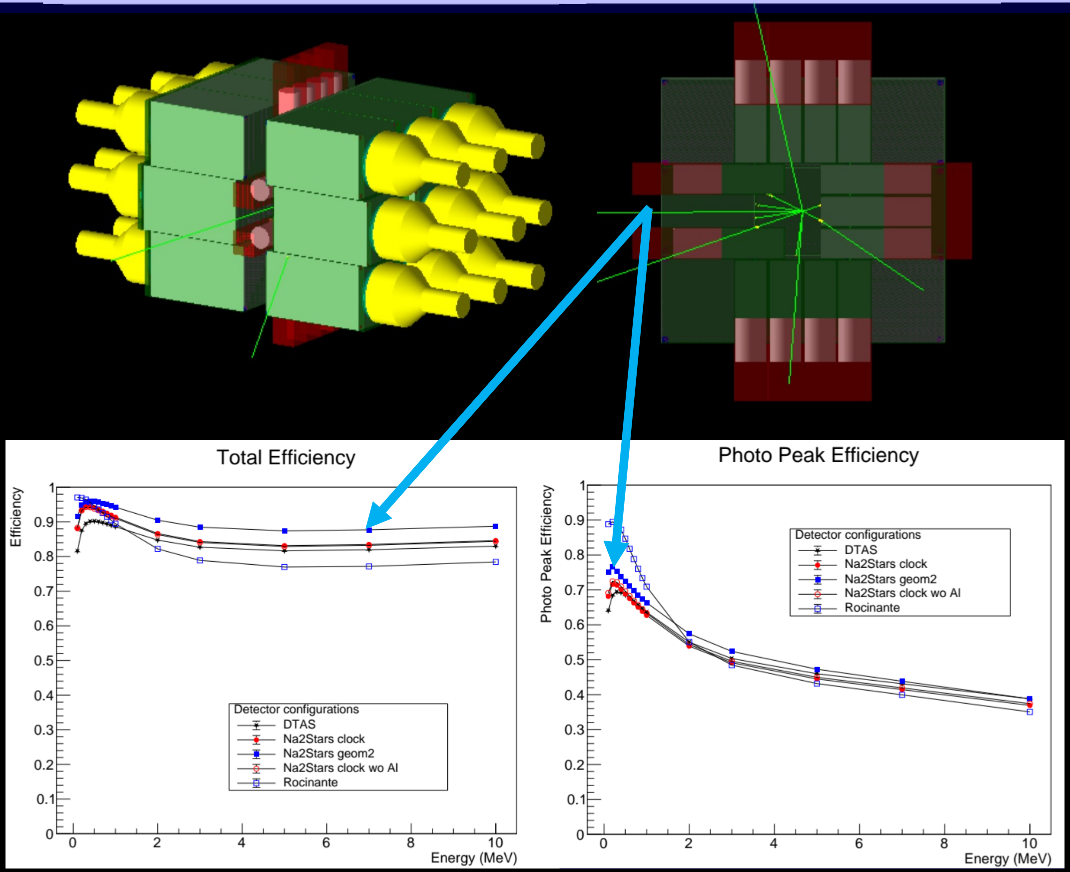




On-going work…

Picture A. Algora & Simulations M. Estienne, A. Porta

The $(NA)^2$STARS project



On-going work…

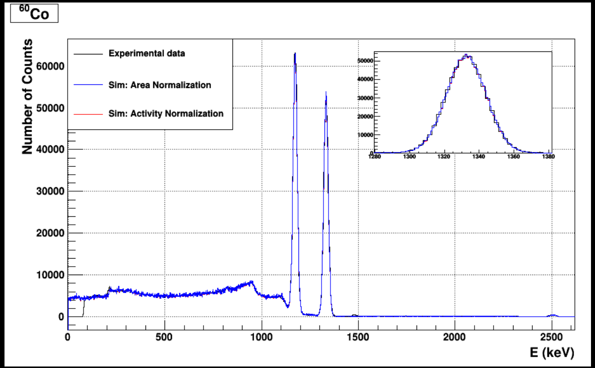
Simulations E. Lancien, M. Estienne & A. Porta

Subatech

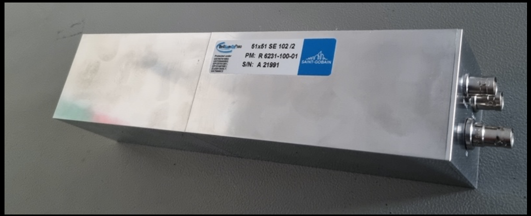
The (NA)²STARS project

- R&D on-going also on DSSSD det. @ GANIL
- Electronics & DAQs, @ GANIL and Subatech (S. Bouvier, H. Guérin, B. Rebeiro, J.-C. Thomas et al.)
- First individual module tests by CIEMAT and IFIC, design based on design studies performed for DESPEC TAS (DTAS)
- New tests on-going @Subatech (V. Piau et al., M1 & M2 internship students: N. Payan, O. Chettir, N. Trimech)

FASTER



Courtesy D. Cano-Ott

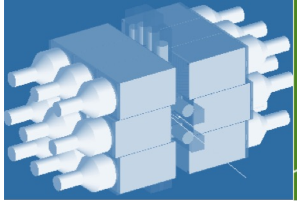


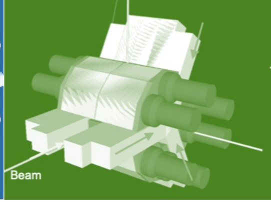
- Intro: What is/Why the TAGS technique ?
- Total Absorption Spectrometers & Experiments
- $(NA)^2$STARS Project
- Conclusions & Perspectives

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 $(NA)^2$STARS project will allow studying more exotic nuclei with the TAGS technique
- The STARS will be the first TAS worldwide allying efficiency with improved energy resolution, timing, increased segmentation
- Part of this program will be performed at GANIL in the future: starting @ LISE in early 2026 (new proposals foreseen at Jyväskylä, GSI, Riken…)

THANK YOU





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- GANIL : J.-C. Thomas, H. Guérin, B. Ribeiro
- CIEMAT Madrid: D. Cano-Ott
- CSIC Madrid: T. Kurtukian Nieto
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- Surrey: W. Gelletly, Z. Podolyak
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- NPI CAS: A. Cassissa, J. Mrazek, E. Simeckova

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