V International Conference on Nuclear Structure and Dynamics

NSD2024

Valencia, 27-31 May 2024

Total Absorption γ-ray Spectroscopy (TAGS) measurements at GANIL with STARS

Sonja Orrigo

for the TAS Collaboration (IFIC, Subatech, Surrey, Jyvaskyla, ...)

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

TAGS measurements

- **The TAGS technique**
  - Why it is needed and useful
  - Available Total Absorption Spectrometers (TAS)

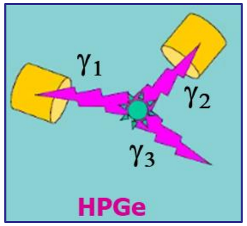
- **The $(NA)^2$STARS project**
  - STARS: 1^{st} device in the World combining spectroscopy and calorimetry
  - 1^{st} experiment with STARS: E891_23 @ GANIL

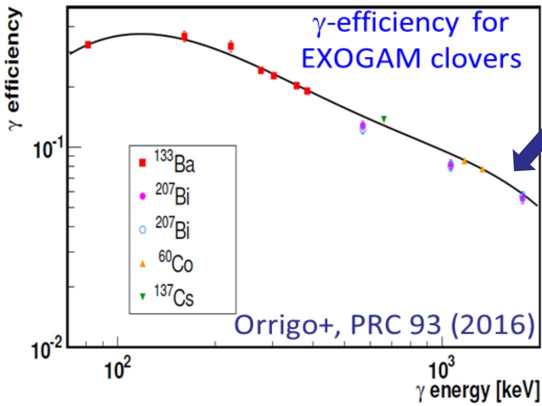
TAGS: to address the Pandemonium effect

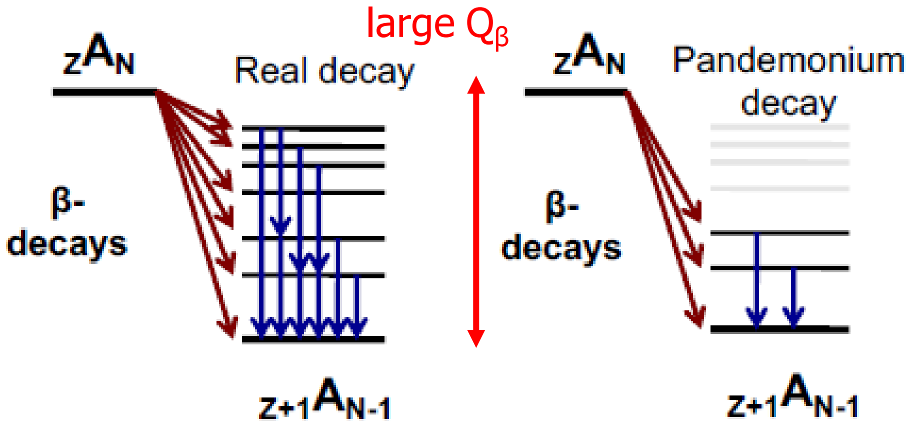
- Conventional β-decay spectroscopy with high-purity Ge detectors (HPGe) is affected by the **Pandemonium** systematic error
  - High-energy γ rays can remain undetected ⇨ missing and wrongly-assigned I_β

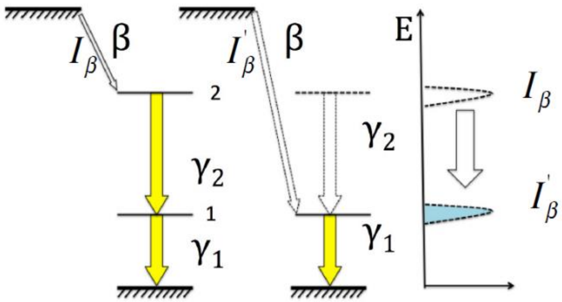
J.C. Hardy+, Phys. Lett. B 71, 307 (1977)

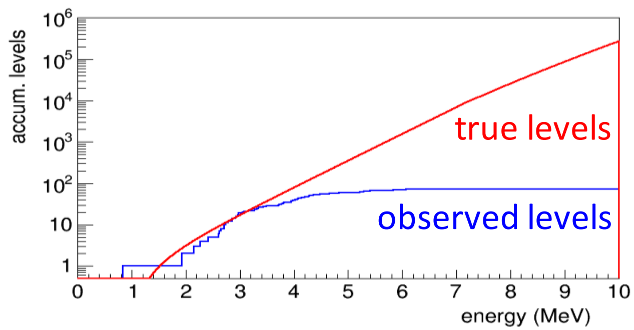
- Exotic nuclei: large Q_β

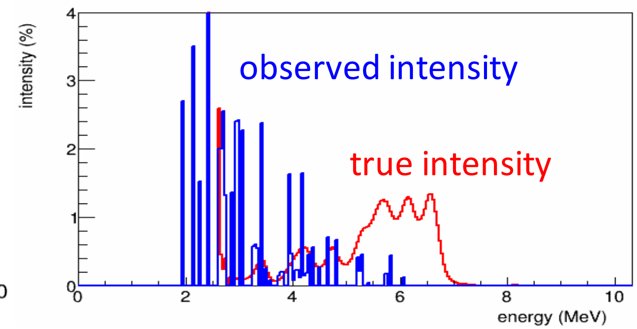








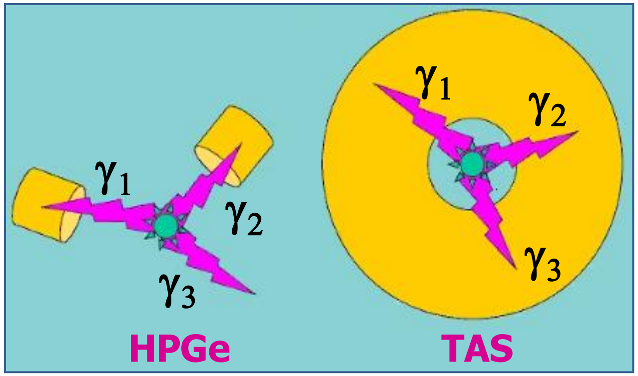


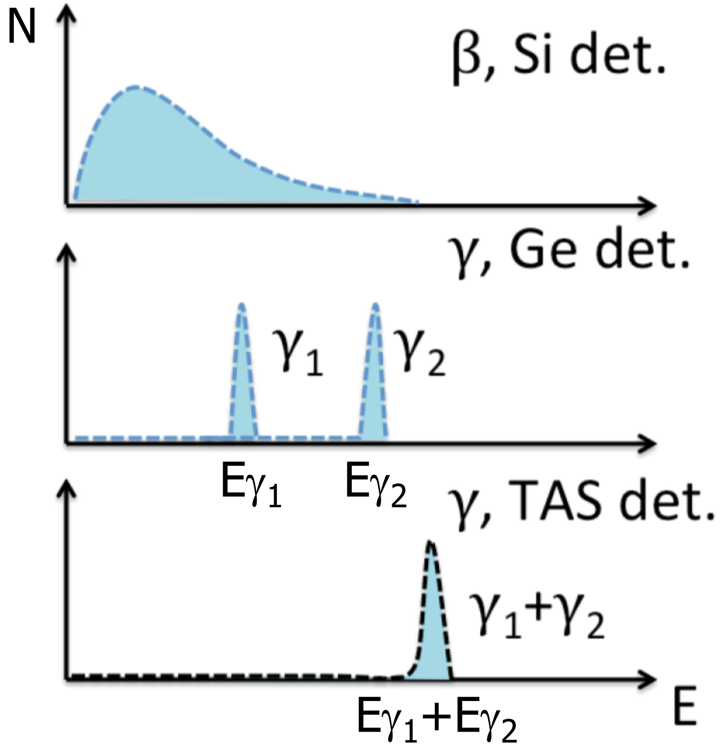


Masking real feeding to low-lying states

The TAGS technique

- **TAGS**: large scintillation crystals of high efficiency acting as **calorimeters**
  - Detection of the full γ-cascade (full energy released in the decay)
- Precise determination of β strength **free of Pandemonium**





β strength

- Fundamental quantity depending on the underlying nuclear structure: nuclear shape
- Provides constrains on theoretical models
  - Complementary to $T_{1/2}$, P_n and masses, all important ingredients in r(rp)-process nucleosynthesis calculations

$$S_b^{exp}(E_x) = \frac{I_b(E_x)}{T_{1/2} f(Q_b - E_x)}$$ ⇐ TAGS

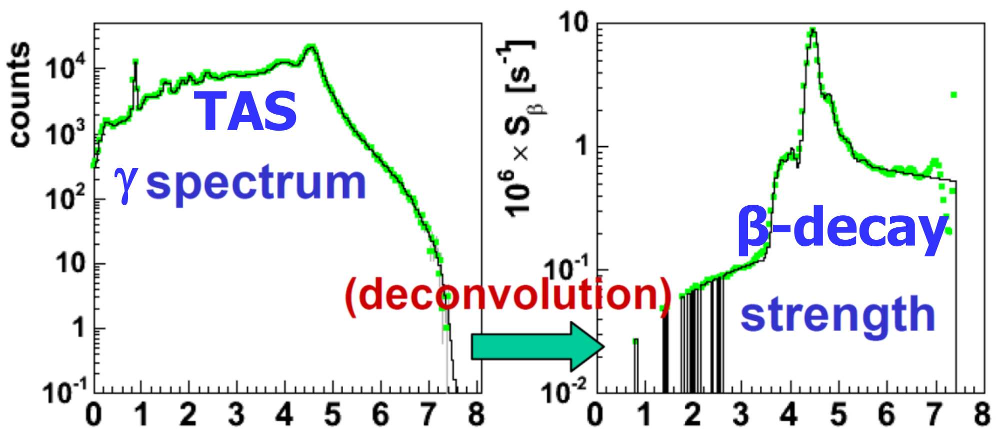
$$S_b^{th}(E_x) = \frac{1}{D}\frac{g_A^2}{g_V^2}\frac{1}{2J_i+1}\left|\left\langle f \left\| M_{l p}^{b} \right\| i \right\rangle\right|^2$$

The TAGS technique

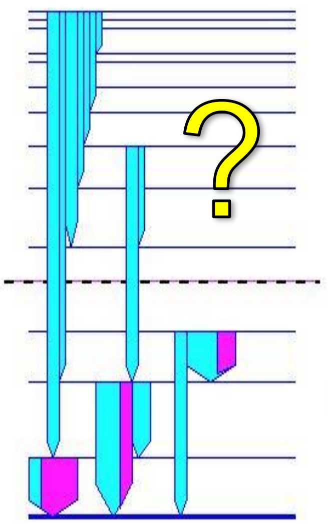
- A **TAGS deconvolution algorithm** is used to solve the linear inverse problem to extract the feeding intensities $I_\beta(E_x)$
  (d_i = measured data, R_{ij} = matrix detector response, f_j = level feeding I_β)

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

- Response R_{ij} by Monte Carlo with knowledge of level energies E_x and γ-branchings b_γ



Reproduce the data in χ^2 or M.L. sense



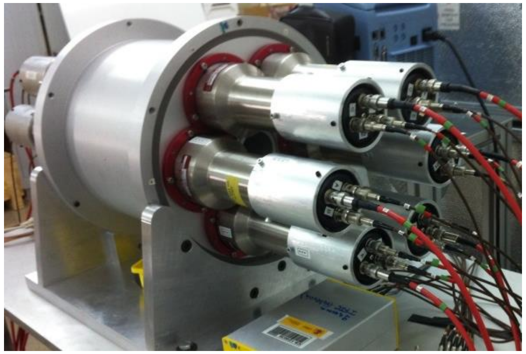
Nuclear statistical model

E_{cut}

Known level scheme from HPGe exp.

Cano+, NIMA 430(1999)333
Tain-Cano, NIMA 571(2007)719, 571(2007)728

Total Absorption Spectrometers (TAS)



Lucrecia

- NaI(Tl) single crystal
- Permanent @ ISOLDE-CERN
- ε^p=48% @E_γ=5 MeV
- ΔE=7% @E_γ=0.66 MeV
- Moderate n-sensitivity
- Widely used in the last 20 years
- @ ISOLDE

B. Rubio+, JPG NPP 44 (2017)

Rocinante

- 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
- @ IGISOL

E. Valencia+, PRC 95 (2017)

DTAS

- 18 NaI(Tl) crystals
- Movable, γ-multiplicity
- ε^p=48% @E_γ=5 MeV
- ΔE=8% @E_γ=0.66 MeV
- Moderate n-sensitivity
- @ IGISOL, RIKEN, GSI

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

Many experiments performed at international facilities

Nuclear structure and astrophysics, applications in decay heat and reactor neutrino anomaly

Total Absorption Spectrometers (TAS)

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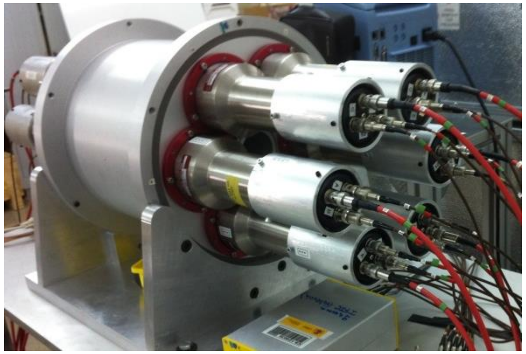

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Nuclear structure and astrophysics, applications in decay heat and reactor neutrino anomaly

Talk by Gustavo Alcalá & poster by Julien Pépin

The (NA)^{2}STARS project

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

Subatech (M. Fallot), IFIC Valencia, IP2I Lyon, GANIL, Nucl. Phys. Inst. of the Czech Academy of Sciences (NPI CAS), CIEMAT Madrid, Univ. of Surrey (UK), IEM CSIC Madrid

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

STARS

- 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
- Unprecedented combination of spectroscopic and calorimetric studies

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BROAD PHYSICS CASE:

exotic nuclei further away from stability, nuclear structure and astrophysics on the p-rich (p/γ competition >S_p) and n-rich sides (n/γ competition >S_n), decay heat, reactor neutrino anomaly

- Endorsed by the GANIL Scientific Council in 01/2023 ($LaBr_3$ crystals co-funded by GANIL)
- 05/2024: **Fully funded** (period: 2024 – 2028, ready for DESIR by 2028)
- 2 TAS ⇨ Large impact: measurements at different facilities

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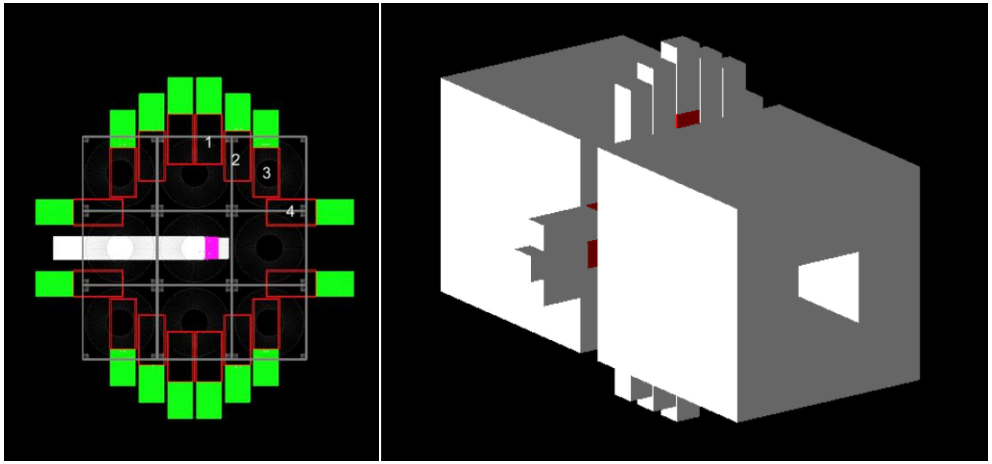
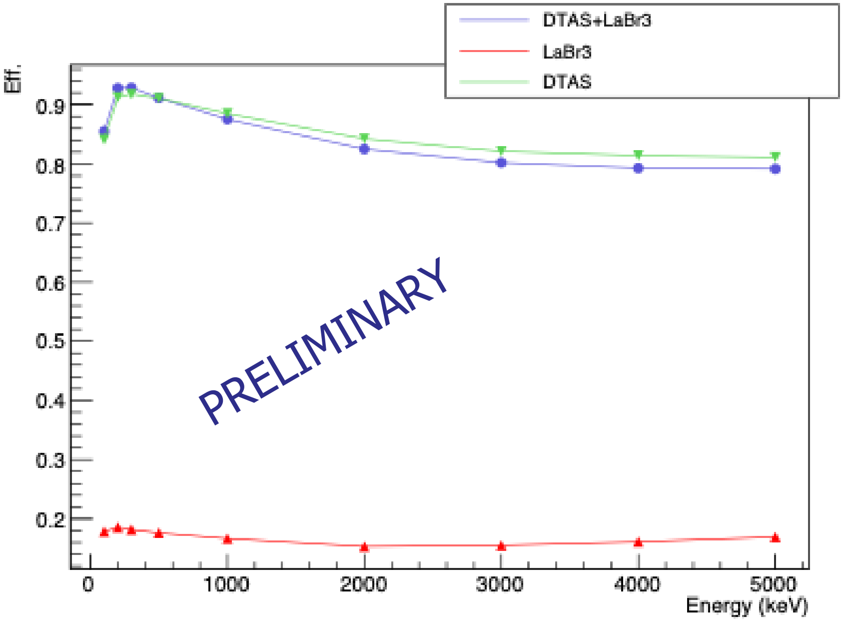
STARS

- Already 8 $LaBr_3$ crystals among partners, performances tests ongoing



View of possible arrangement of the 16 $LaBr_3$:Ce (red) in the middle of the NaI crystals of DTAS (grey) with a central hole to accommodate the beam tube and the β detector (pink) (courtesy A. Beloeuvre)



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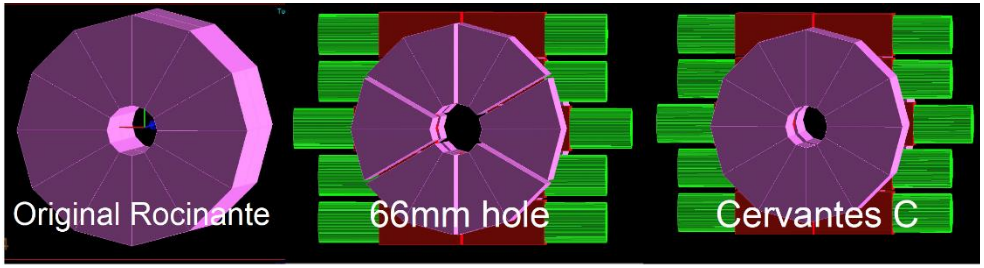
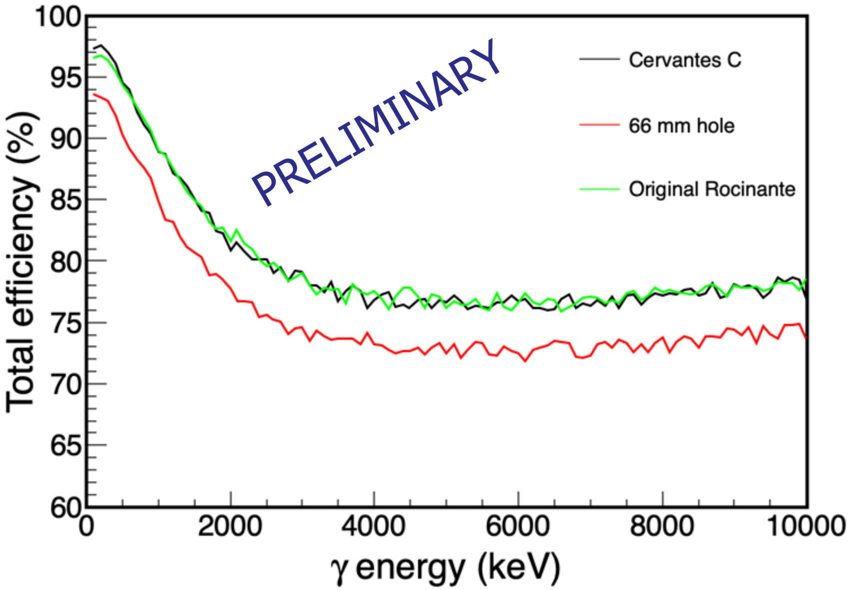
Rocinante: refurbishment in progress



View of possible arrangement of the 16 $LaBr_3$:Ce (red) in the middle of the BaF_2 crystals of Rocinante (purple) with a central hole for the beam tube and β detector (internship K. Dewyspelaere)



PROPOSAL E891_23

Approved by GANIL PAC (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]

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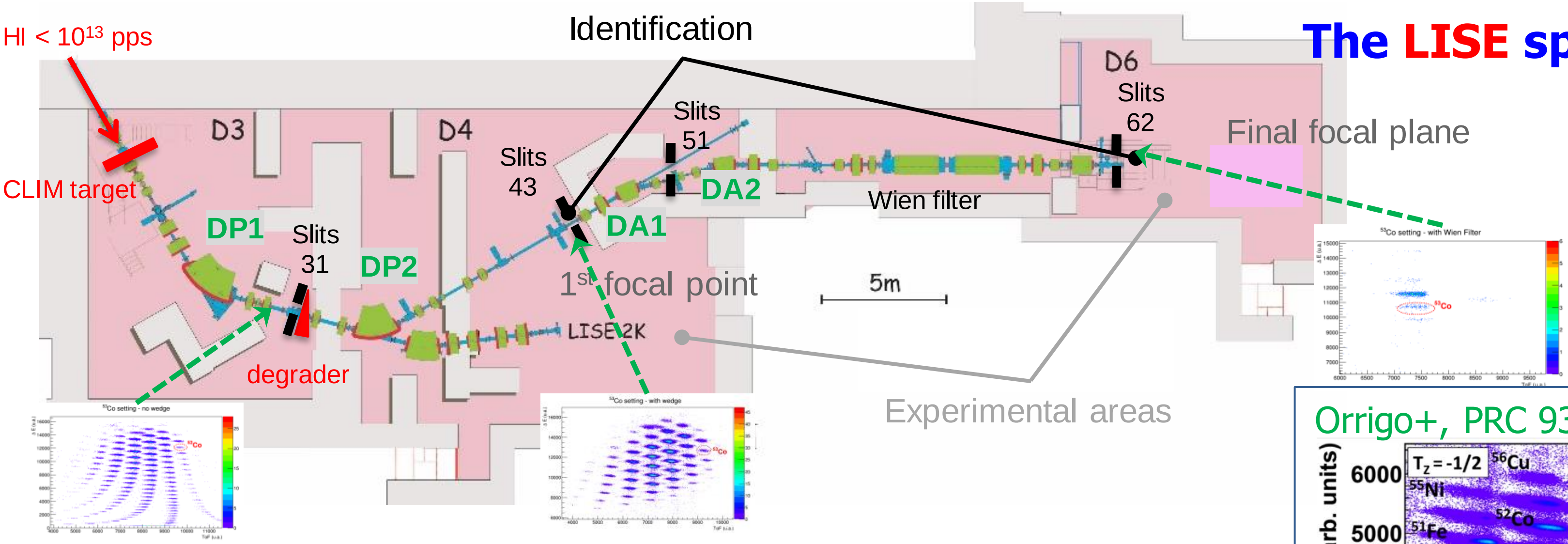
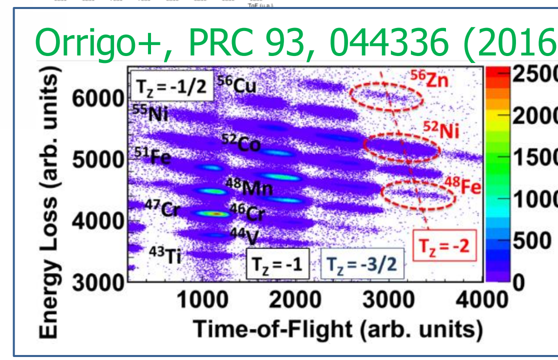
[3] UHU, Spain
[4] Atomki, Debrecen, Hungary
[5] GANIL Caen, France
[6] Univ. Surrey, UK
[7] IP2I, Bordeaux, France
[8] Instituto de Física-UNAM, Mexico
[9] Univ. Padova and INFN, Italy
[10] IEM-CSIC, Spain
[11] UCM Madrid, Spain
[12] CIEMAT, Spain
[13] LNL-INFN, Italy
[14] IJCLab, Orsay, France
[15] 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

Experimental setup @ GANIL

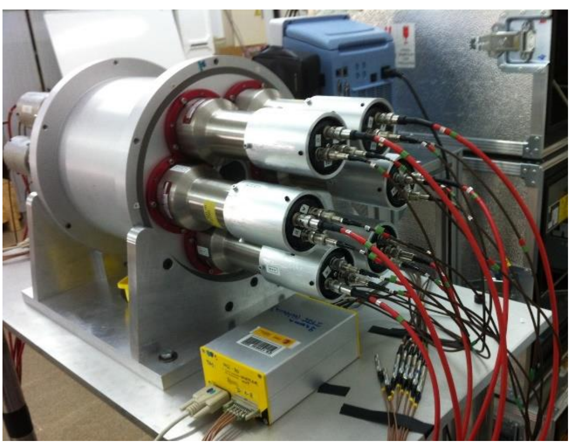
The LISE spectrometer



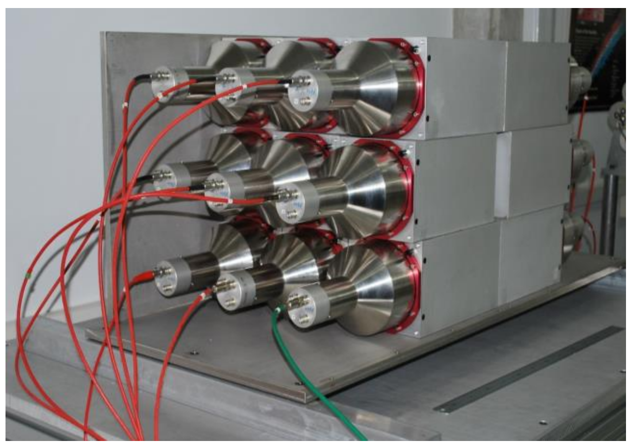


- New DSSSD (GANIL) 1 mm-thick, 40x40 mm^2
- 13 $LaBr_3$ crystals expected (already 8)

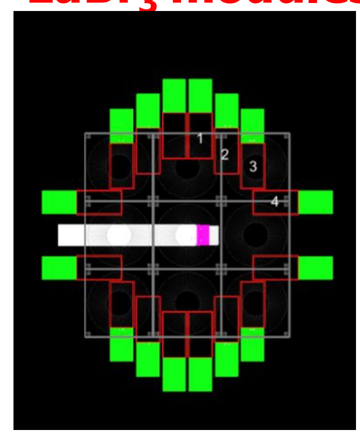
Rocinante



DTAS



+ $LaBr_3$ modules



STARS

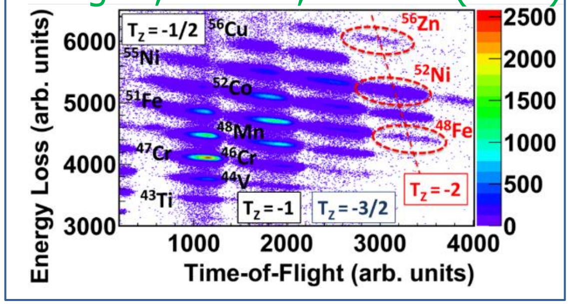
PROPOSAL E891_23

Approved by GANIL PAC (11/2023)

Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

- 1st experiment with **STARS**
- Measure the β-decay properties of several p-rich nuclei in the Cr-Zn region of great interest for:

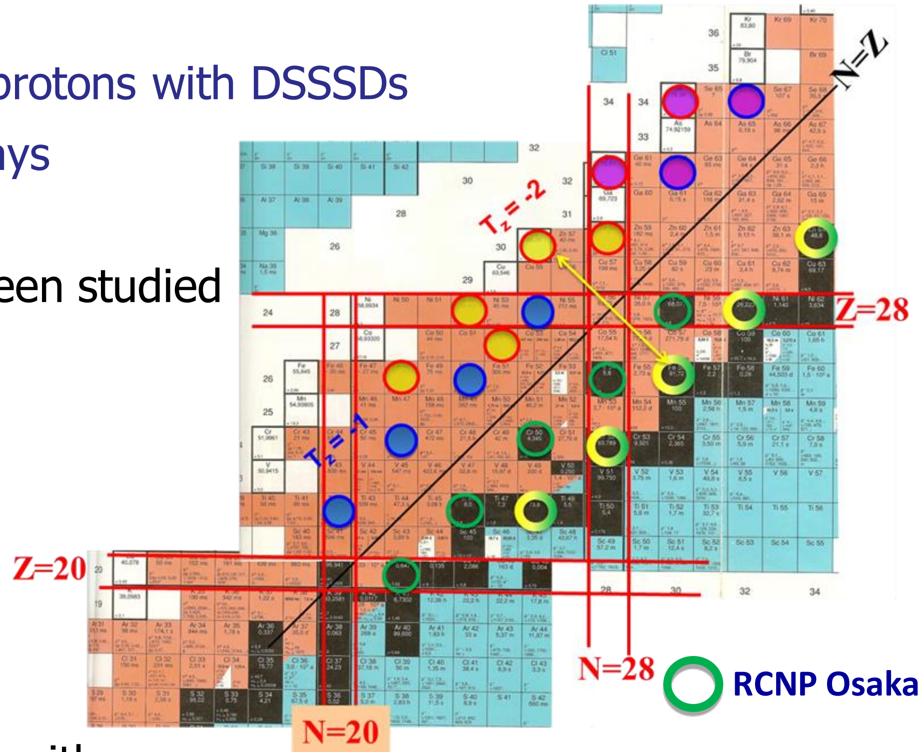
Orrigo+, PRC 93, 044336 (2016)



  - Nuclear structure: β-decay of selected T_z=-2 nuclei (^{44}Cr, ^{48}Fe, ^{52}Ni, ^{56}Zn)
    - To study isospin symmetry free of Pandemonium
  - Nuclear astrophysics: β-decay of ^{46}Mn and ^{48}Mn
    - To constrain reaction rates of interest for the ^{44}Ti nucleosynthesis
      - $^{45}V(p,\gamma)^{46}Cr$ and $^{47}V(p,\gamma)^{48}Cr$

Nuclear Structure: β-decay of selected T_z=-2 nuclei

- During last decade we have performed a systematic study of the **β decay of proton-rich nuclei**
  - Detection of β-particles and β-delayed protons with DSSSDs
  - β-delayed γ-rays detected by HPGe arrays



- Rich spectroscopic info, many cases have been studied
  - Orrigo+, PRL 112, 222501 (2014)
  - Molina+, PRC 91, 014301 (2015)
  - Orrigo+, PRC 93, 044336 (2016)
  - Orrigo+, PRC 94, 044315 (2016)
  - Kucuk, Orrigo+, EPJA 53, 134 (2017)
  - Orrigo+, PRC 103, 014324 (2021)

- β-decay data is enriched by the comparison with complementary **CE reactions** on the stable mirror target
  - Y. Fujita, B. Rubio, W. Gelletly, PPNP 66, 549 (2011)
  - H. Fujita+, PRC 88, 054329 (2013)
  - E. Ganioglu+, PRC 93, 064326 (2016)

Primary beams for RIBs production:

GANIL
e556: ^{64}Zn @79 AMeV
e556a: ^{58}Ni @75 AMeV

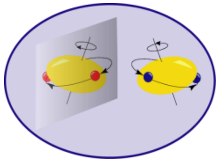
GSI
^{58}Ni @680 AMeV

RIKEN
^{78}Kr @345 AMeV

Nuclear Structure: β-decay of selected T_z=-2 nuclei

Isospin symmetry in mirror nuclei

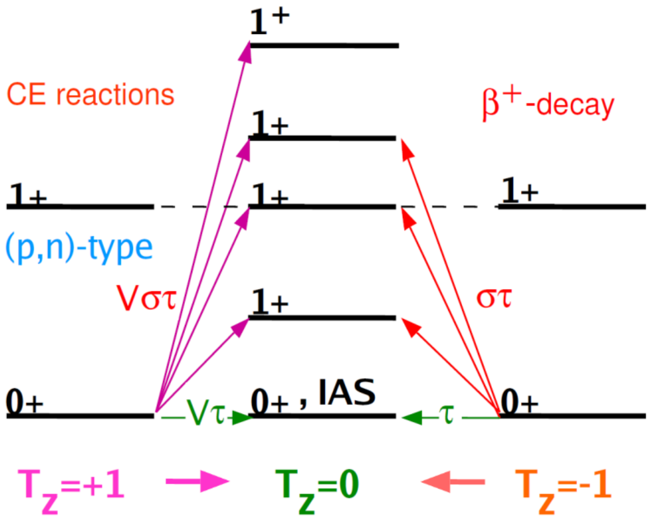
- Mirror **Fermi** and **Gamow Teller** transitions are expected to have the same strength
- What can we learn from the comparison?
  - Investigate **isospin symmetry** in mirror nuclei
  - Improve our knowledge of **GT transitions** close to the proton drip-line and along the **rp-process pathway**



Mirror symmetry

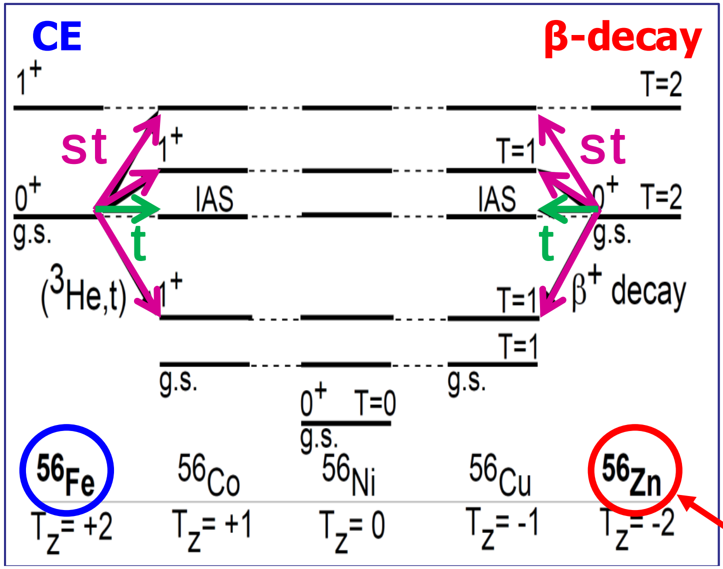
$$^{A}_{Z}X_{N} \qquad ^{A}_{N}Y_{Z}$$

The T=1 isospin multiplet: the final state is identical

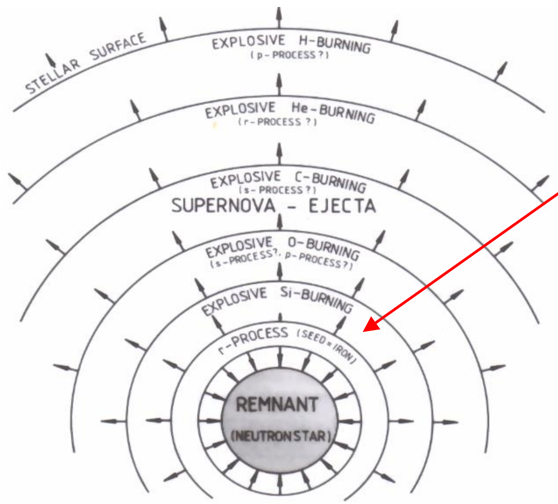


Y. Fujita, B. Rubio, W. Gelletly, PPNP 66, 549 (2011)

The T=2 isospin multiplet: the final nucleus is not identical



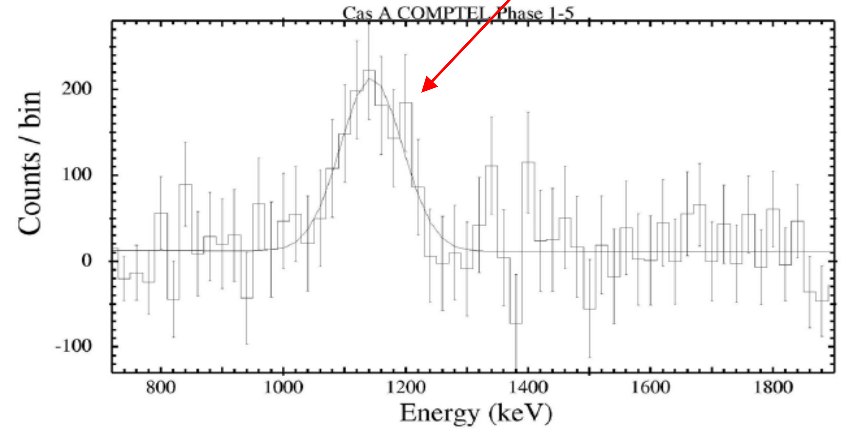
Orrigo+, PRL 112, 222501 (2014)



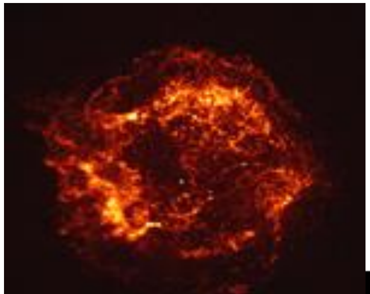
- ^{44}Ti is produced in type II supernovae (SN II)
  - Mechanism: α-rich freeze-out. Shock-wave after core-collapse reaches the α-rich region in the cooling phase, $1 < T_9 < 5$
- ^{44}Ti ($T_{1/2}$= 59 y) is a cosmic γ-ray emitter (67.9, 78.4, 1157 keV)
  - Observed by COMPTEL and INTEGRAL satellite-based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

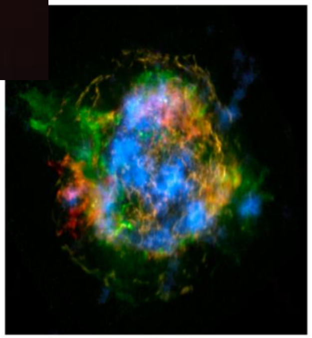
  ^{44}Ti → ^{44}Sc → ^{44}Ca

- ^{44}Ti production rate is a sensitive probe for core-collapse models



Iyudin et al. 2nd INTEGRAL workshop 1997 37


CHANDRA : Cas. A



A. Arcones et al. / Progress in Particle and Nuclear Physics 94 (2017) 1–67

"The amount and distribution of ^{44}Ti can be used to probe the innermost boundary between material falling back and being ejected, once nuclear physics uncertainties are addressed"

Cassiopeia A remnant
X-ray data from NUSTAR image (^{44}Ti in blue)

Outlook

- **TAGS measurements**
  - Perfect tool to measure high-energy γ-rays and β-strength without Pandemonium
  - Complementary to high-resolution γ-ray spectroscopy
- **(NA)²STARS project:** the new **STARS** spectrometer
  - 1st TAS worldwide combining high efficiency with high resolution and timing as well as increased segmentation
  - 1st experiment already approved @ GANIL
  - Broad physics case spanning both n-rich/deficient nuclei and applications
  - Large impact: GANIL, DESIR, RIKEN, IGISOL, FAIR, …

Thank you for your attention!