QNP 2024

Beta-decay studies with the Total Absorption technique

Sonja Orrigo

EXCELENCIA SEVERO OCHOA

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)

- **Highlights from TAGS measurements**
  - Nuclear structure and nuclear astrophysics:
    nuclear shape, model validation ($T_{1/2}$), n/γ competition
  - Applications: reactor physics, neutrino physics

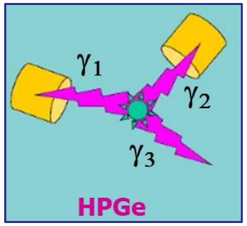
- **The $(NA)^2$STARS project**
  - STARS: 1st device in the World combining spectroscopy and calorimetry
  - 1st experiment with STARS: E891_23 @ GANIL

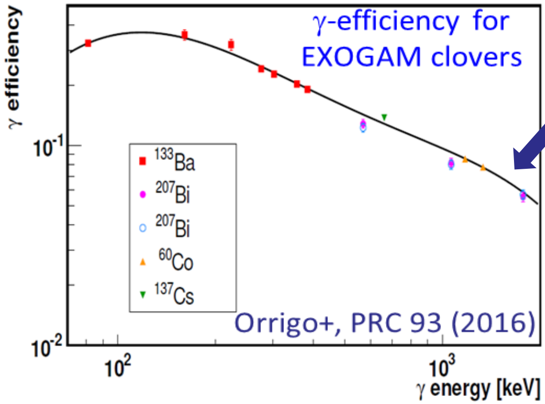
TAGS: to address the Pandemonium effect

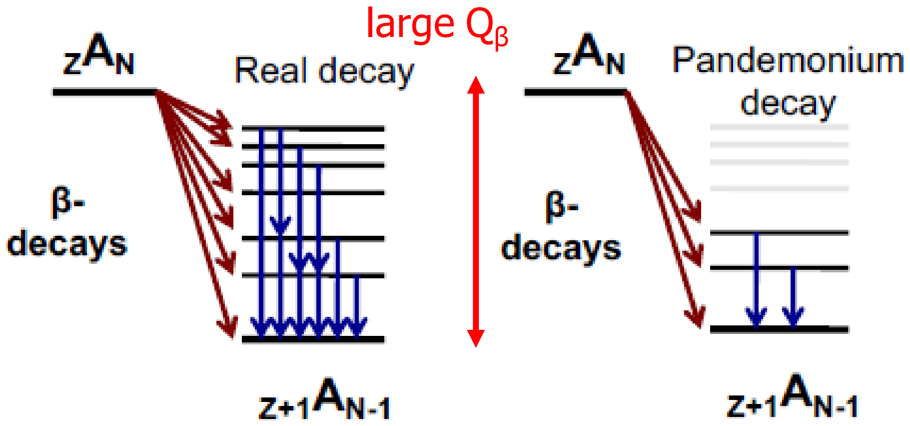
- Conventional β-decay spectroscopy with high-purity Ge detectors (HPGe) is affected by the **Pandemonium** systematic error
  - High-energy γ rays can remain undetected ⇨ missing and wrongly-assigned I_β

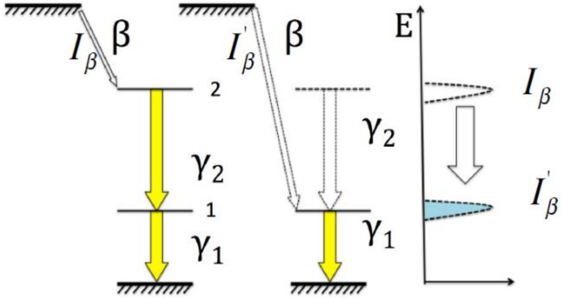
J.C. Hardy+, Phys. Lett. B 71, 307 (1977)

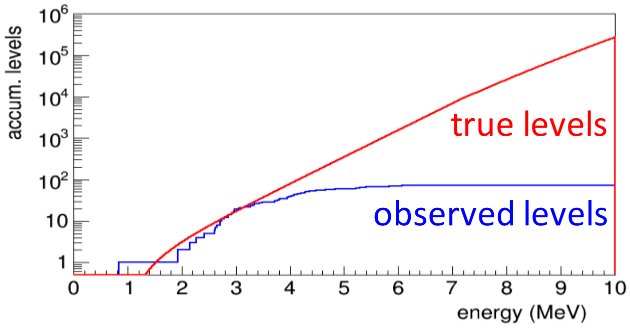
- Exotic nuclei: large Q_β

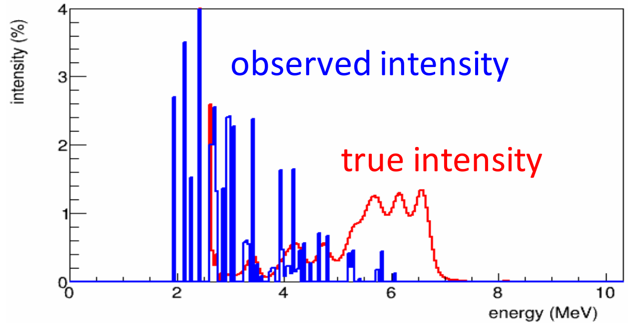








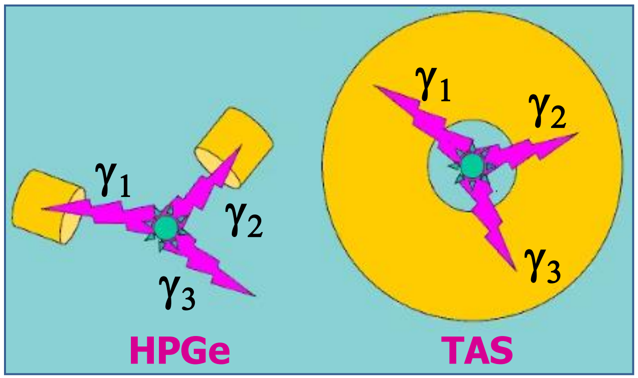


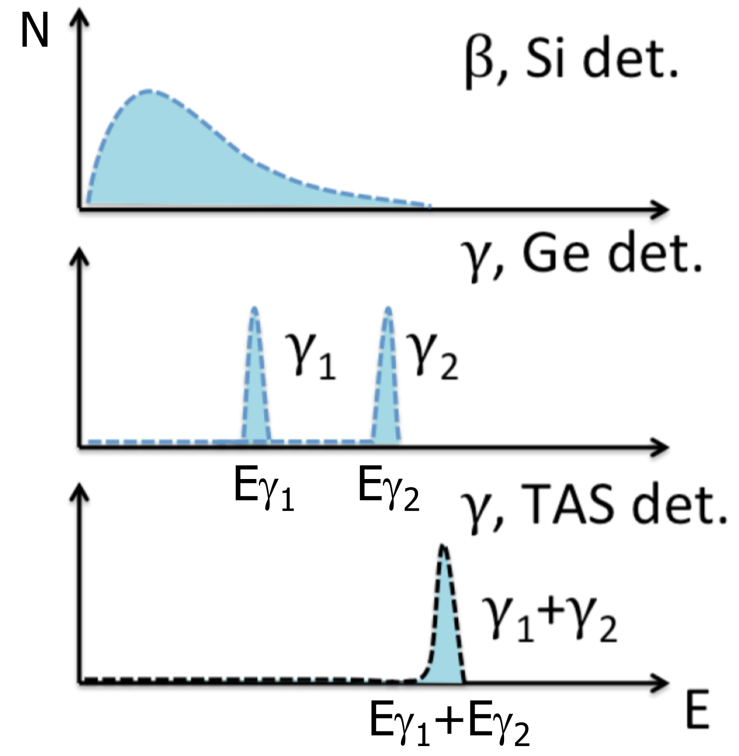


Masking real feeding to low-lying states

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

$$S_{\beta}^{\exp}(E_x) = \frac{I_{\beta}(E_x)}{T_{1/2} f(Q_{\beta} - E_x)}$$

← **TAGS**

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

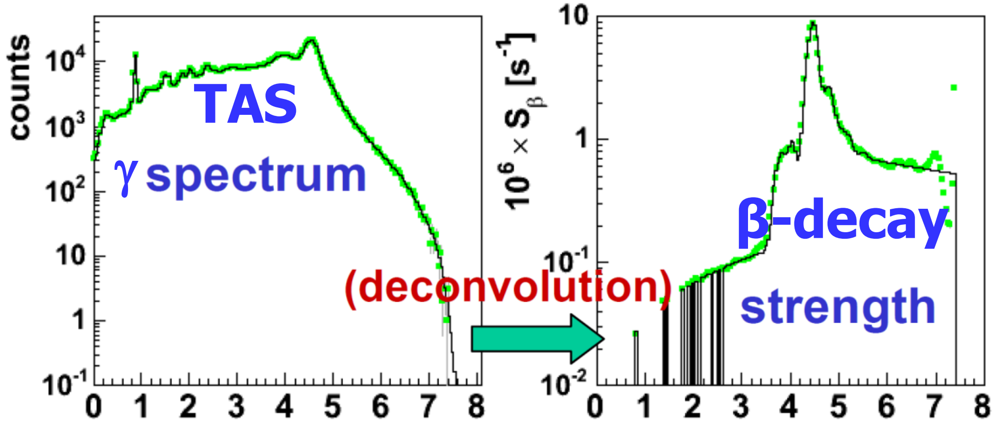
The TAGS technique

- A **TAGS deconvolution algorithm** is used to solve the linear inverse problem to extract the feeding intensities $I_\beta(E_x)$

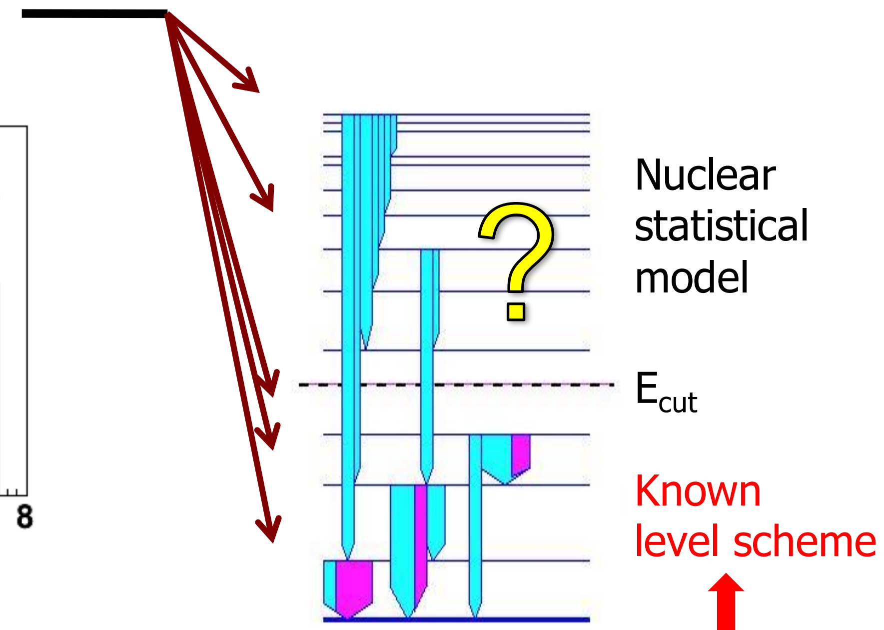
  (d_i = measured data, R_{ij} = matrix detector response, f_j = level feeding I_β)

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

- 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



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

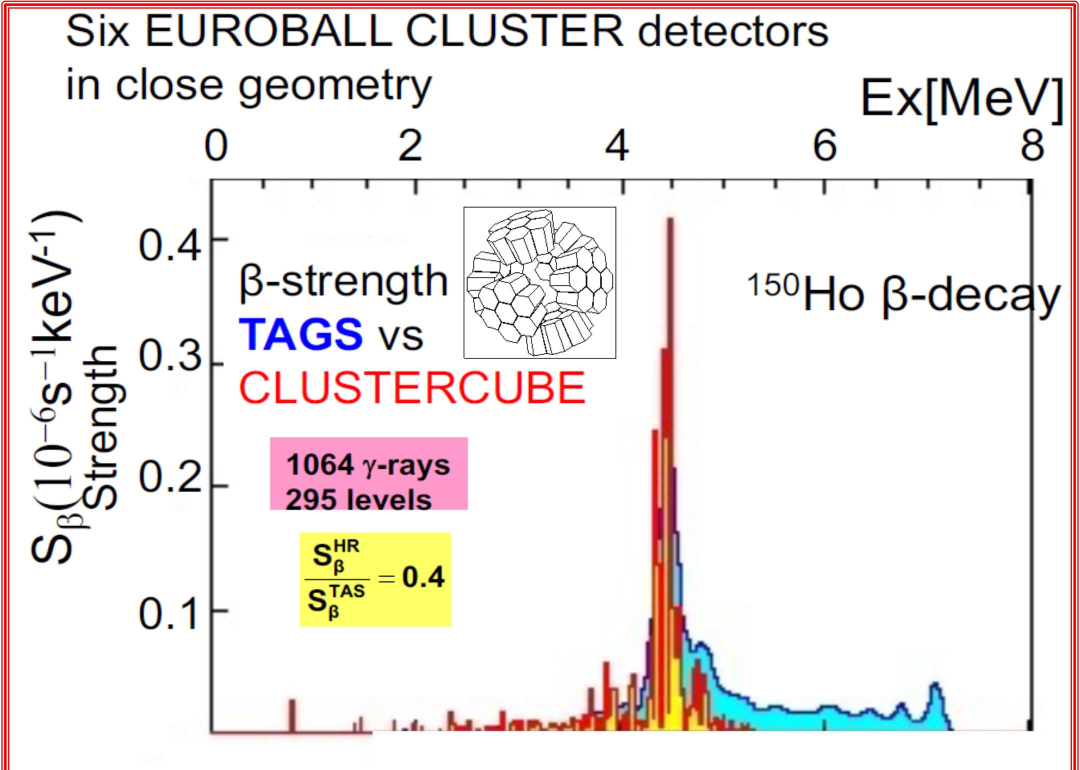
Excellent knowledge at low E_x from HPGe exps.: **complementary**

The TAGS technique

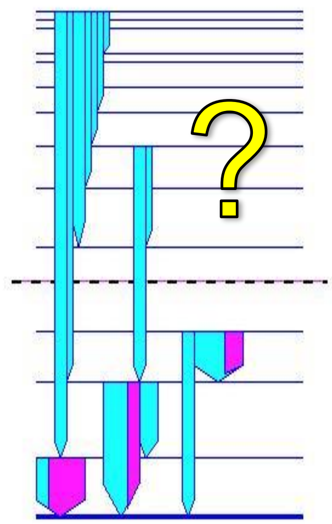
- A **TAGS deconvolution algorithm** is used to solve the linear inverse problem to extract the feeding intensities $I_\beta(E_x)$
  (d_i = measured data, R_{ij} = matrix detector response, f_j = level feeding I_β)

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

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

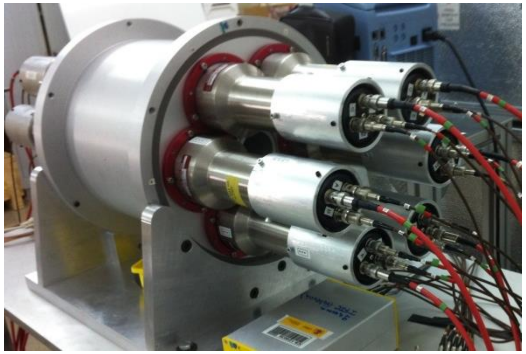


A. Algora, B. Rubio et al PRC 50 (2002)



Excellent knowledge at low E_x from HPGe exps.: **complementary**

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 by TAS Collaboration at international facilities

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

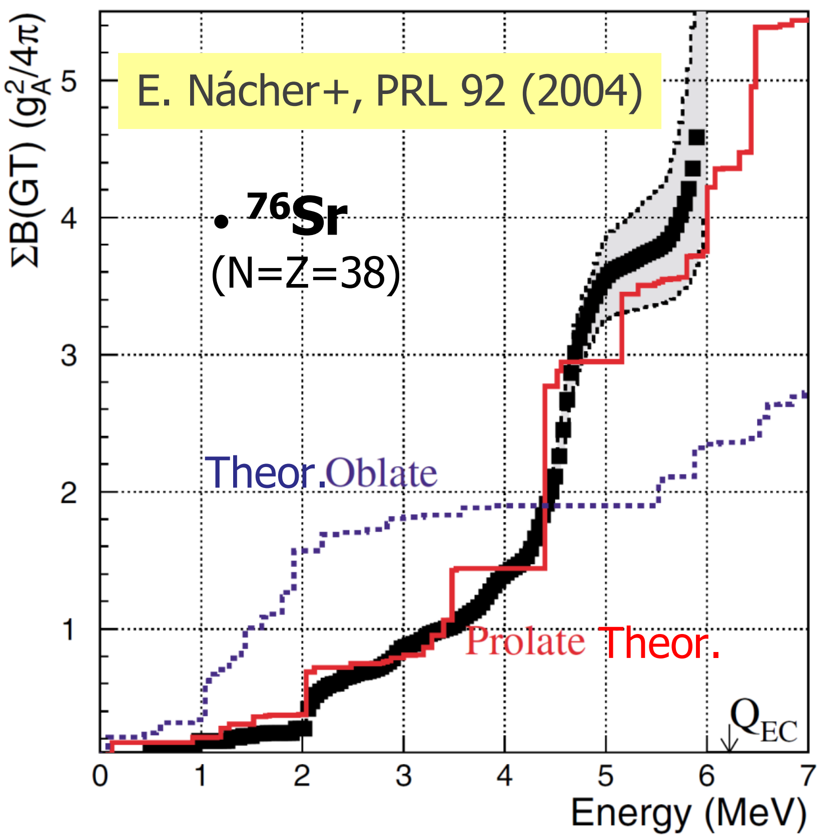
Nuclear shape from β-strength distribution

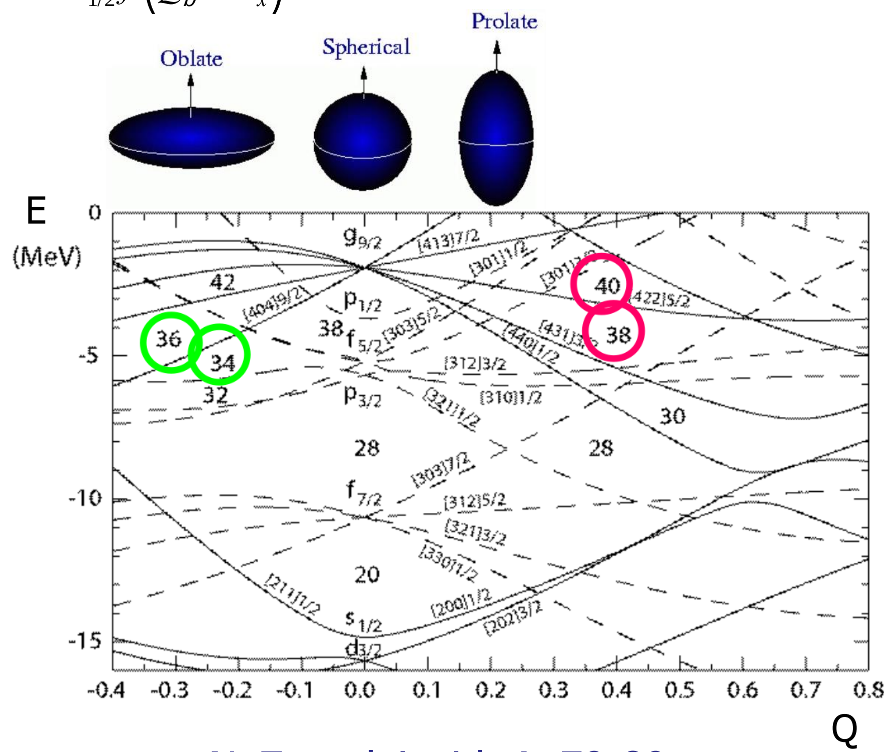
- Fundamental quantity depending on the underlying nuclear structure
- Useful probe to investigate the **shape of the progenitor state**
- Comparison to theor. **QRPA calculations** with different deformations
  - The pattern depends on the shape of the parent nucleus

I. Hamamoto ZPA 353 (1995)

P. Sarriguren+, NPA 658 (1999)

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





N~Z nuclei with A~70-80

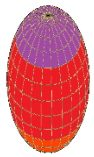
Nuclear shape from β-strength distribution

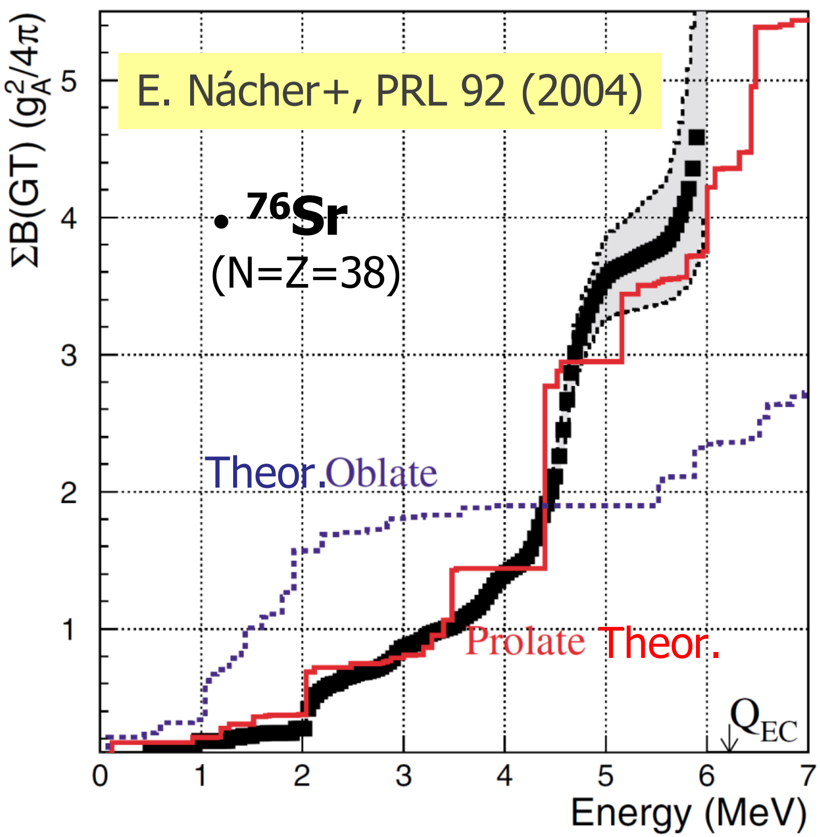
- Useful probe to investigate the **shape of the progenitor state**
- Comparison to theor. **QRPA calculations** with different deformations

I. Hamamoto ZPA 353 (1995)

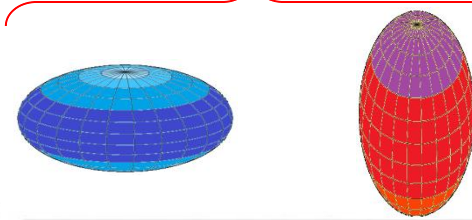
P. Sarriguren+, NPA 658 (1999)

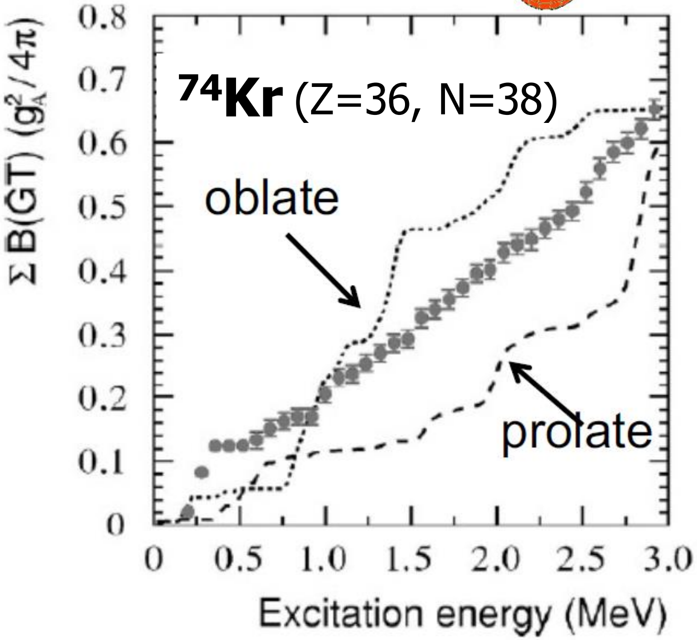
^{76}Sr clearly prolate





^{74}Kr, shape admixture





E. Poirier+, PRC 69(2004)

Nuclear shape from β-strength distribution

- Method **successfully employed** in many experimental **TAGS studies at ISOLDE**
- **Recently extended to treat shape mixing**
  - Mixing oblate and prolate configurations independently in parent and daughter

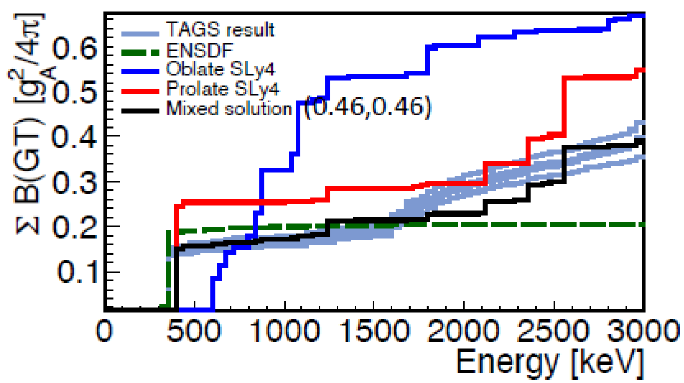
$$\varphi_{parent} = \lambda|oblate\rangle + \sqrt{1-\lambda^2}\,|prolate\rangle$$

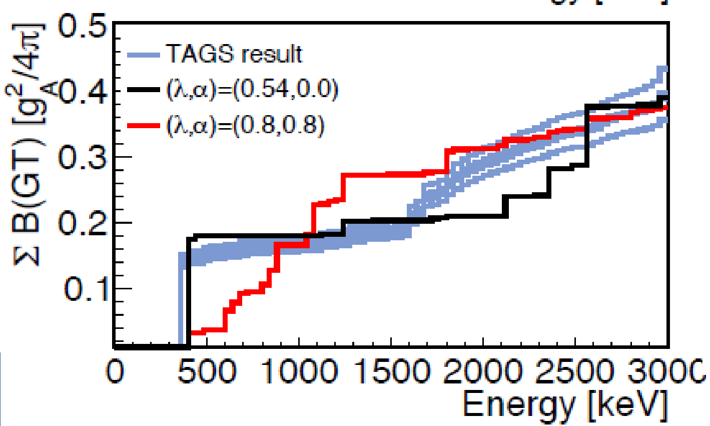
$$\phi_{daugther} = \alpha|oblate\rangle + \sqrt{1-\alpha^2}\,|prolate\rangle$$

$$GT_{decay} = \alpha^2\lambda^2 GT_{oblate} + (1-\alpha^2)(1-\lambda^2)GT_{prolate} + \dots$$

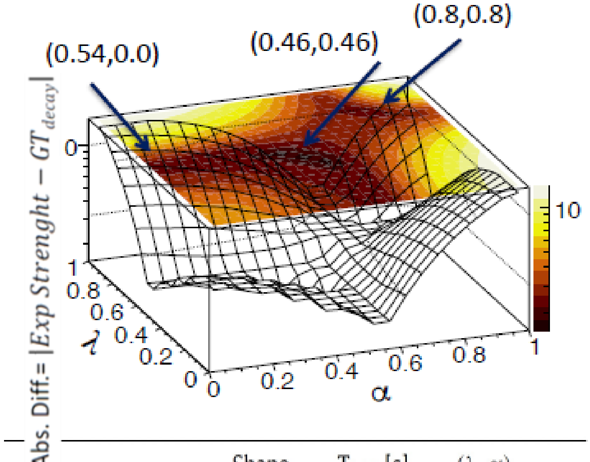
A. Algora+, PLB 819 (2021)

ISOLDE exp. IS539:
β decay of ^{186}Hg





Minima in the surface (λ, α)



	Shape	$T_{1/2}$ [s]	(λ, α)
QRPA-SLy4 model	prolate	60.0	(0.0, 0.0)
	oblate	47.9	(1.0, 1.0)
	mixed	89.1	(0.46, 0.46)
	mixed	84.5	(0.54, 0.0)
	mixed	93.4	(0.80, 0.80)
Experiment		82.3(36)	

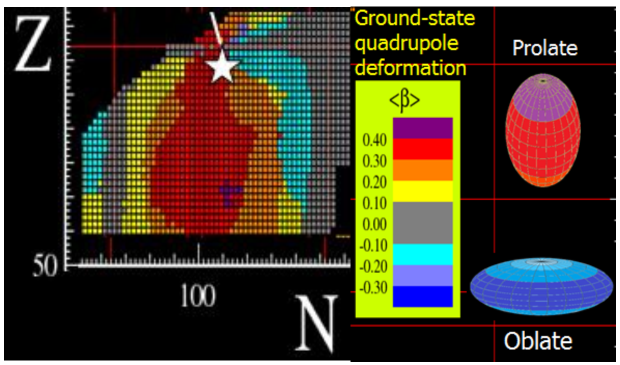
Algora et al. , PLB **819**, 136438 (2021)

Nuclear shape from β-strength distribution

IS707 @ ISOLDE-CERN

β-strength of ^{183,185,187}Hg

- Beamtime in 2023 @ ISOLDE
- Shape transitional region around A~186: oblate / prolate competition



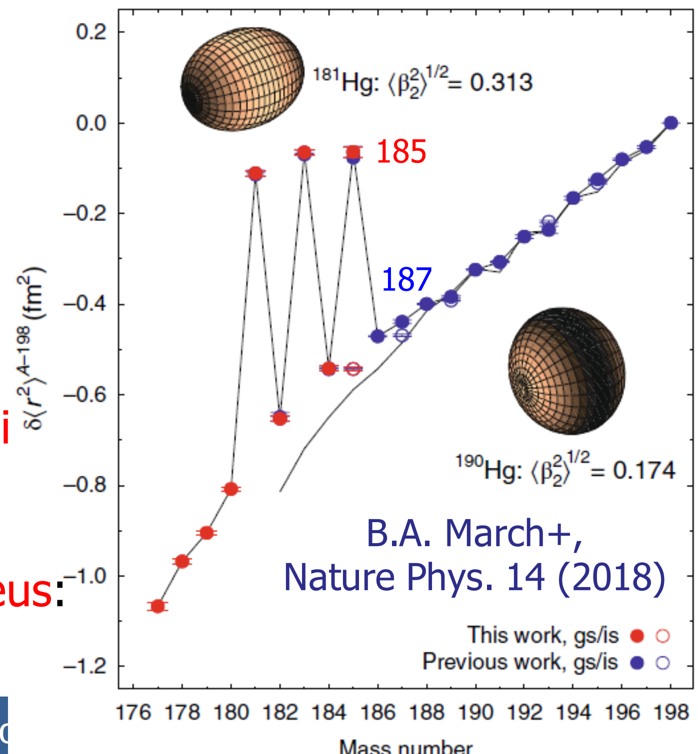
CERN-INTC-2021-056 / INTC-P-617
28/09/2021

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Total absorption beta decay studies around ^{186}Hg

Spokespersons: Alejandro Algora (Alejandro.Algora@ific.uv.es) Sonja E. A. Orrigo (Sonja.Orrigo@ific.uv.es) Luis Mario Fraile (lmfraile@ucm.es)

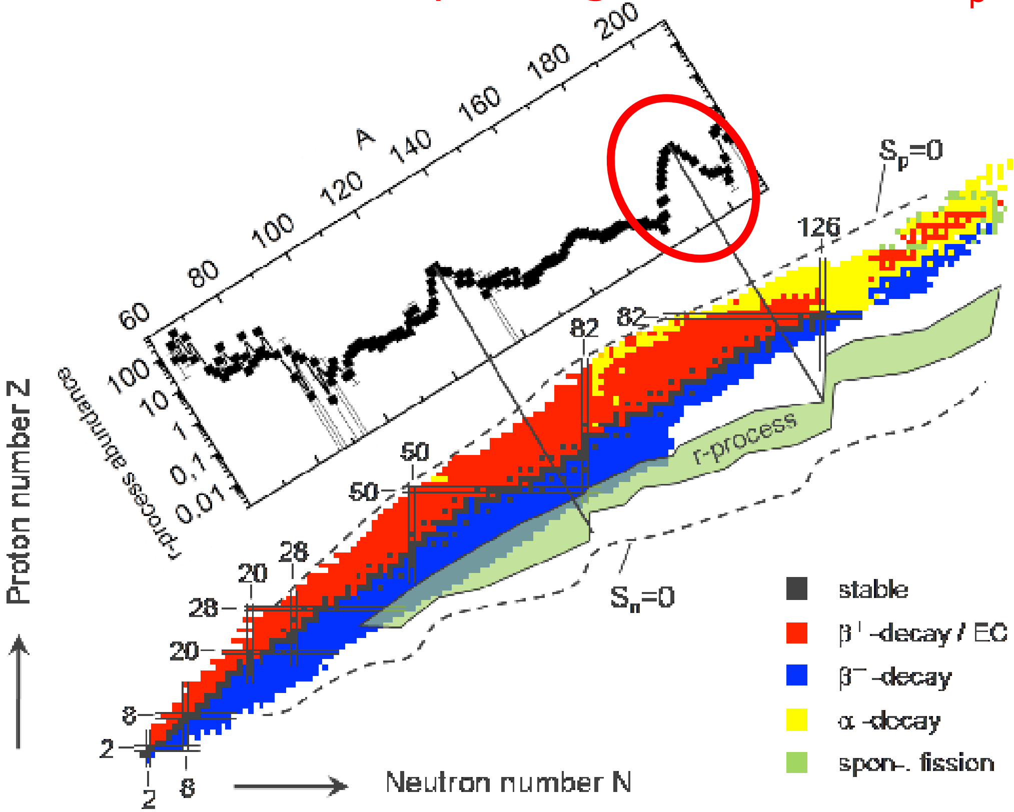


Hg isotopes

- Staggered change in the mean-square charge radii conventionally associated with shape changes
- Strong discontinuity 187 vs. 185 and lighter ones
- Different nuclear shapes expected in a same nucleus: g.s. and $13/2^{+}$ isomeric state **1st time!**

Model validation: $T_{1/2}$ discrepancies and β-strength

- r-process abundance simulations depend on nuclear physics inputs
  - Half-lives $T_{1/2}$
  - n-emission probabilities P_n
- Lack of nuclear data for n-rich nuclei, especially for A>180 (3rd peak)
  - Global β-strength calculations across the nuclear chart provide theoretical β-strength distributions S_β from which to extract $T_{1/2}$ and P_n



$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\, dE_x$$

$$P_n = T_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma^n(E_x)}{\Gamma^{tot}(E_x)} S_\beta(E_x)\cdot f(Q_\beta - E_x)\cdot dE_x$$

$$S_b^{th}(E_x) = \frac{1}{D}\frac{g_A^2}{g_V^2}\frac{1}{2J_i+1}\left|\left\langle f \left\| M^b_{lp} \right\| i \right\rangle\right|^2$$

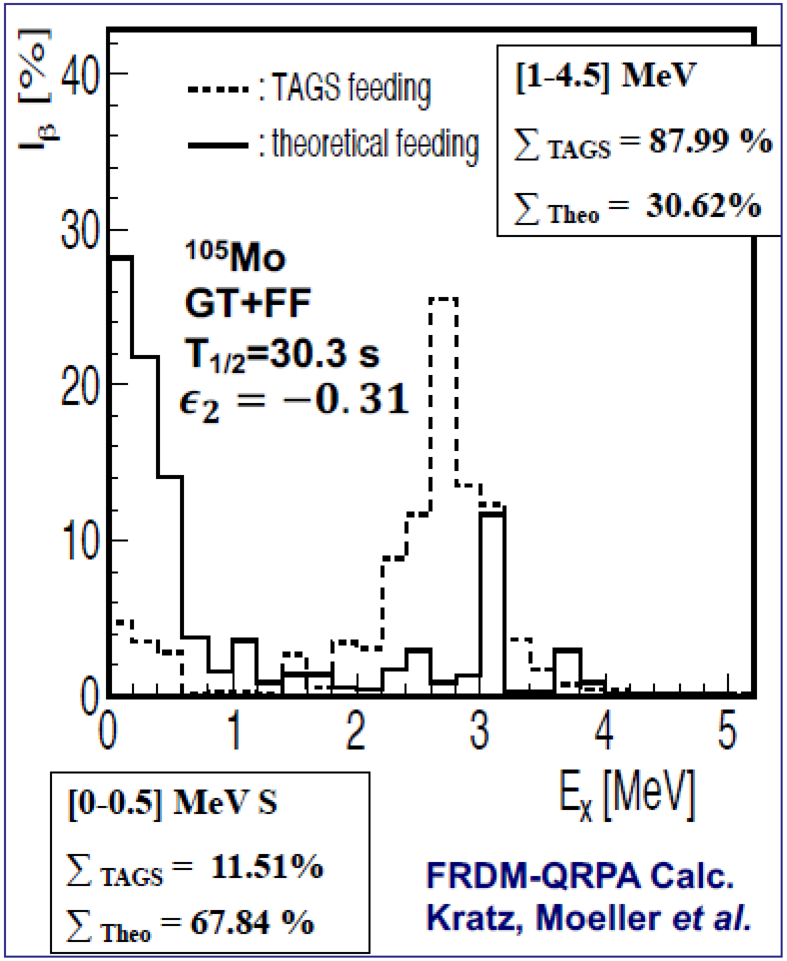
$$S_b^{\exp}(E_x) = \frac{I_b(E_x)}{T_{1/2} f(Q_b - E_x)}$$

TAGS

Model validation: $T_{1/2}$ discrepancies and β-strength

- The reason for the discrepancies is that $T_{1/2}$ (integral quantity) is not uniquely related to the β-strength distribution

  ⇒ needs for measurements of β-strength across the nuclear chart



$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x)\, dE_x$$

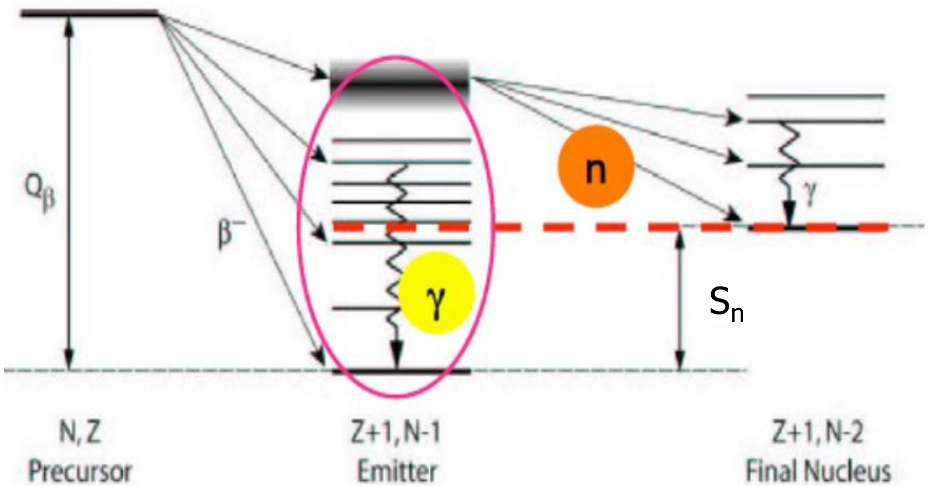
Decay of ^{105}Mo

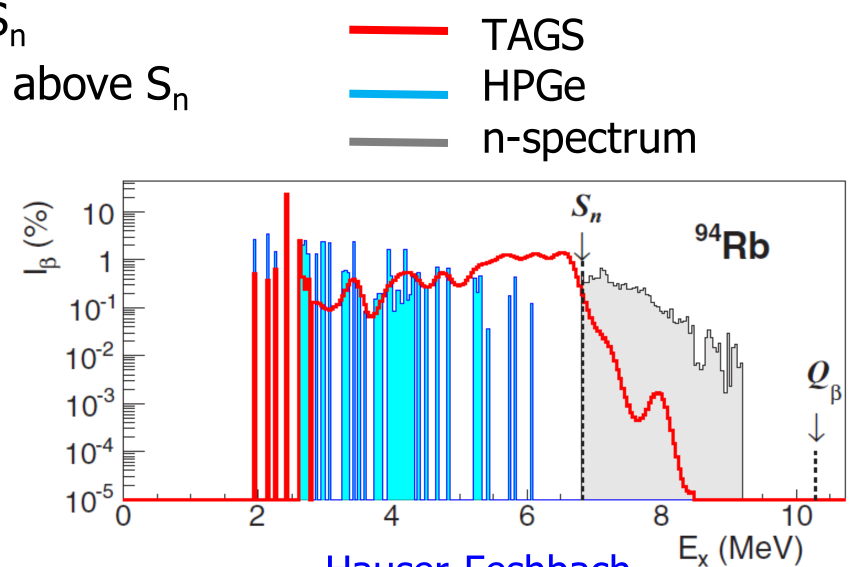
- Experiment: $T_{1/2}$ = 35.6(16) s
  A. Algora+, PRL 105 (2010)

- Theory: $T_{1/2}$ = 30.3 s
  P. Moeller+, PRC 67 (2003)
  FRDM-QRPA
  GT + First Forbidden
  Deformation (ε_2=0.31)

β-delayed neutron/γ competition by TAGS

- Few known cases of n/γ competition from n-unbound states (n typically dominant)
- TAGS technique to study γ-ray emission above S_n
- Surprisingly large γ-ray branching was observed above S_n





- **^{94}Rb**: γ-branching ×10 larger than H.-F. calc.
  ⇨ ×10 enhancement in Γ_γ / Γ_n ⇨ σ(n,γ)

$$\frac{I_{\beta\gamma}}{I_{\beta\gamma}+I_{\beta n}} \Leftrightarrow \left\langle \frac{\Gamma_\gamma}{\Gamma_\gamma+\Gamma_n} \right\rangle$$

J.L. Tain+, PRL 115 (2015)
E. Valencia+, PRC 95 (2017)
V. Guadilla+, PRC 100 (2019)

$$P_n = T_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma^n(E_x)}{\Gamma^{tot}(E_x)} S_\beta(E_x) \cdot f(Q_\beta - E_x) \cdot dE_x$$

Hauser-Feshbach

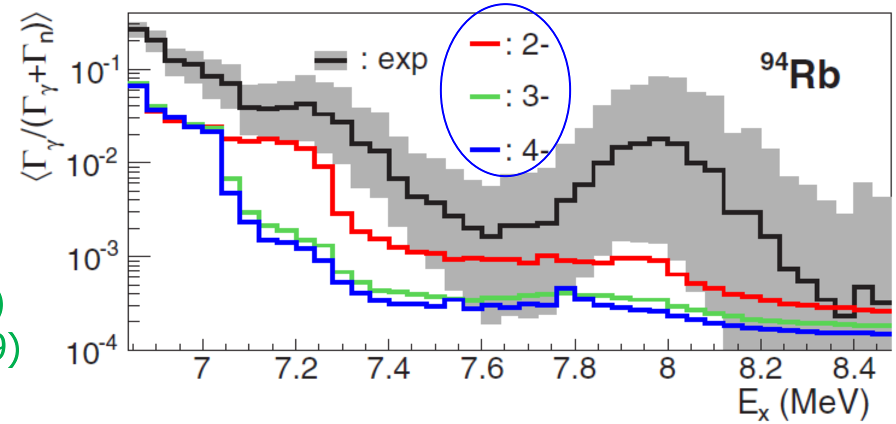


FIG. 12. Average γ to total width from experiment (black line) and calculated for the three spin-parity groups populated in allowed decay (red, green, blue). The gray-shaded area around the experiment indicates the sensitivity to systematic effects. See text for details.

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

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

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

The (NA)²STARS project

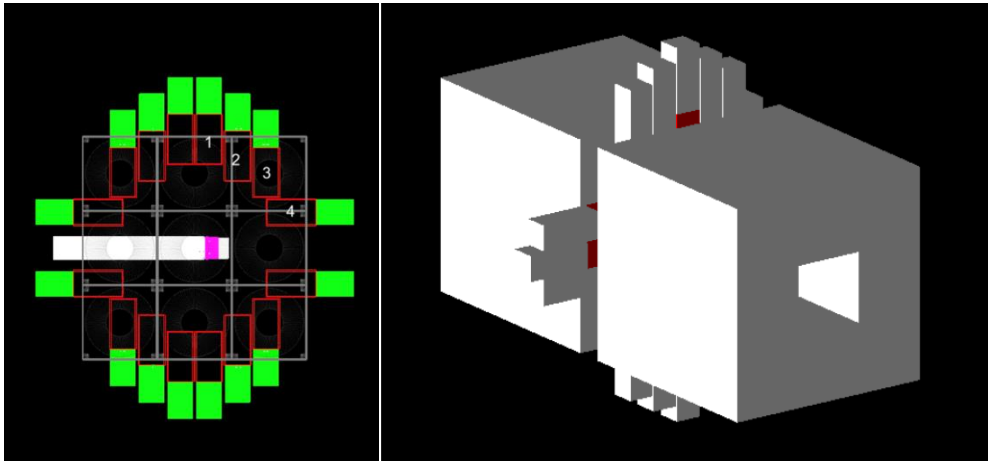
Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with a higher Resolution Spectrometer

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

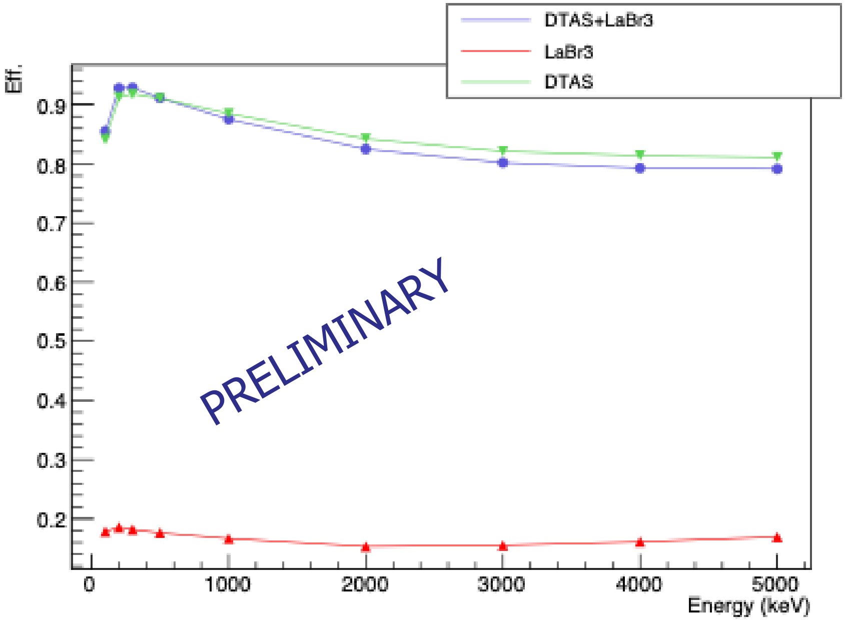
GOAL: Upgrade of the existent TAS spectrometers **DTAS** and **Rocinante** with **16 $LaBr_3$(Ce) modules** 2″x2″x4″

STARS

- 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)



The $(NA)^2$STARS project

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

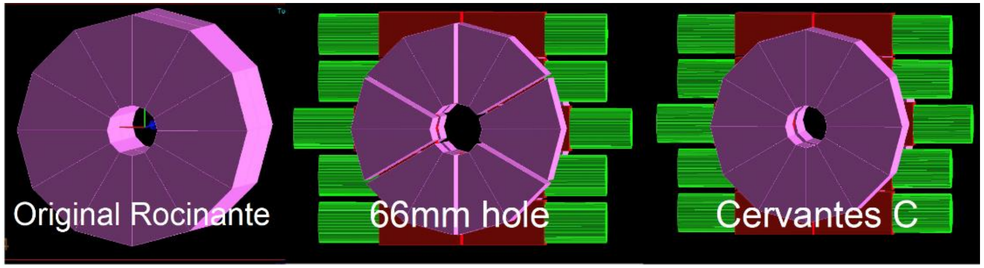
Subatech (M. Fallot), IFIC Valencia, IP2I Lyon, GANIL, Nucl. Phys. Inst. of the Czech Academy of Sciences (NPI CAS), CIEMAT Madrid, Univ. of Surrey (UK), IEM CSIC Madrid

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

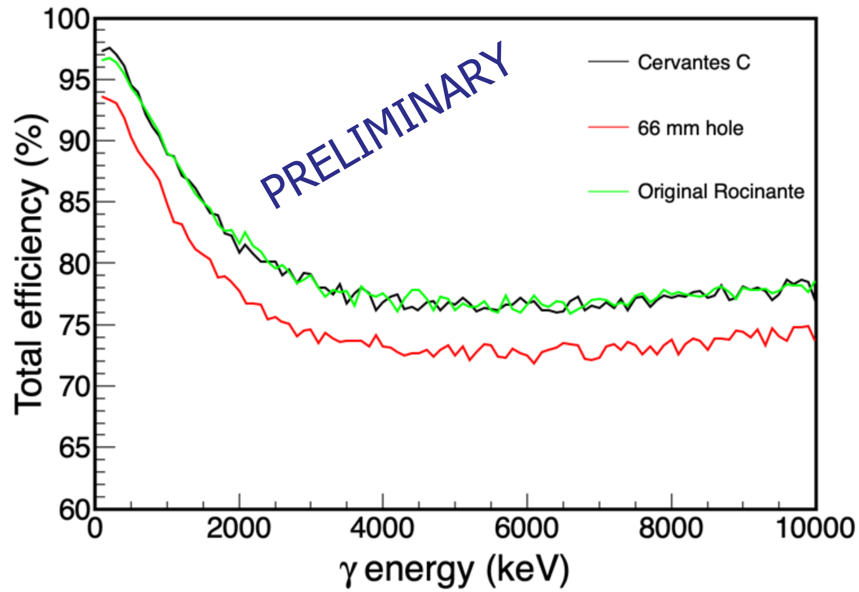
STARS

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

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

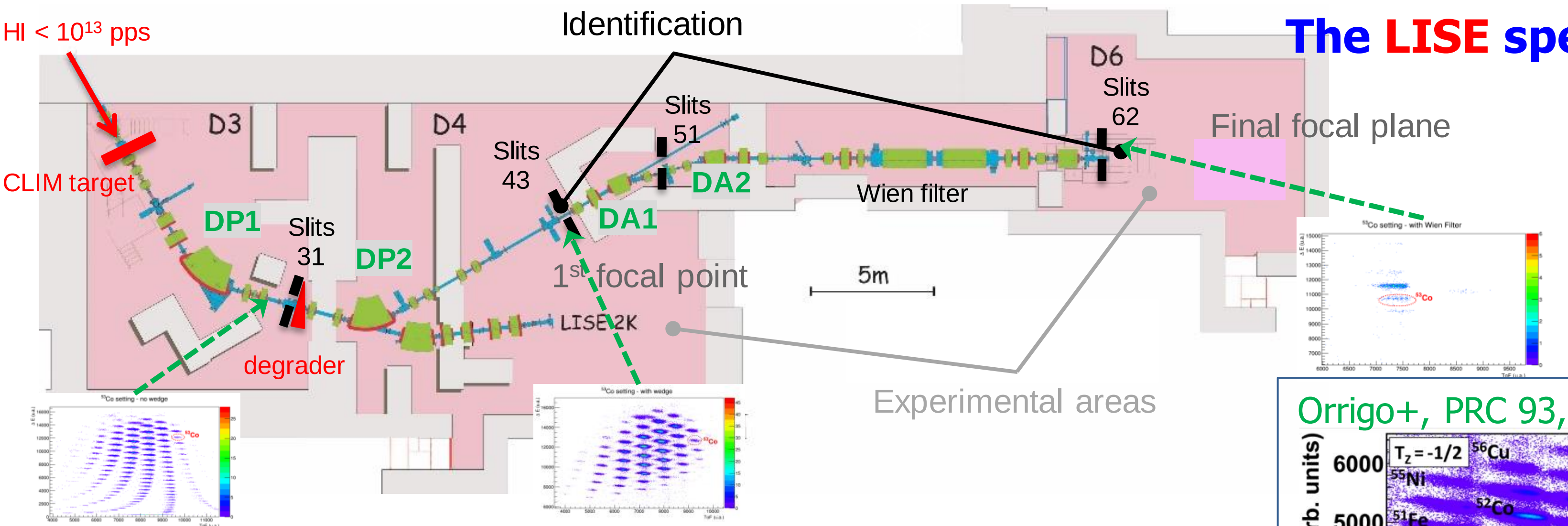
Spokespersons: M. Fallot[1], S. E. A. Orrigo[2], A. M. Sánchez Benítez[3],

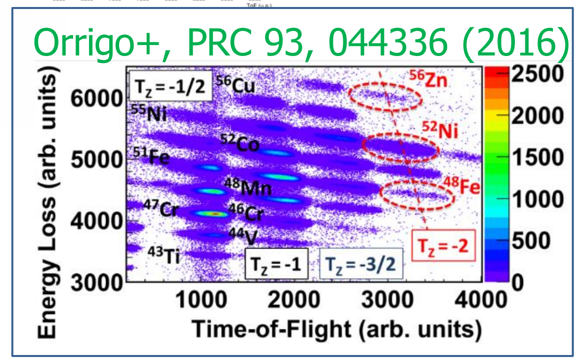
B. Rubio[2], A. Algora[2,4], J.-C. Thomas[5], W. Gelletly[6], B. Blank[7], L. Acosta[8], J. Agramunt[2], P. Aguilera[9], O. Aktas[5], G. Alcala[2], P. Ascher[7], D. Atanasov[7], B. Bastin[5], A. Beloeuvre[1], E. Bonnet[1], S. Bouvier[1], M. J. G. Borge[10], J. A. Briz[11], A. Cadiou[1], D. Cano Ott[12], 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]

[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

PROPOSAL E891_23

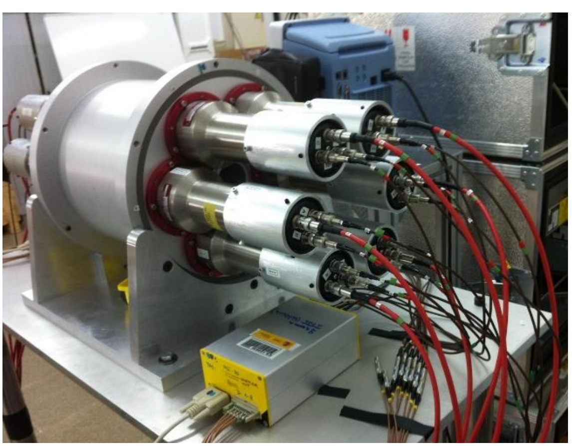
The LISE spectrometer



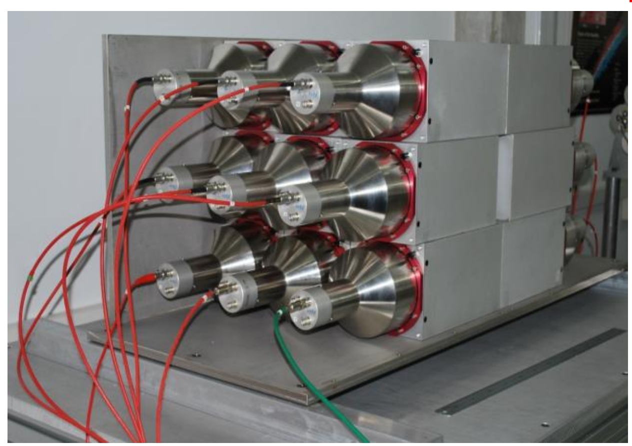


- New DSSSD (GANIL) 1 mm-thick, 40x40 mm^2
- 13 $LaBr_3$ crystals expected (already 8)

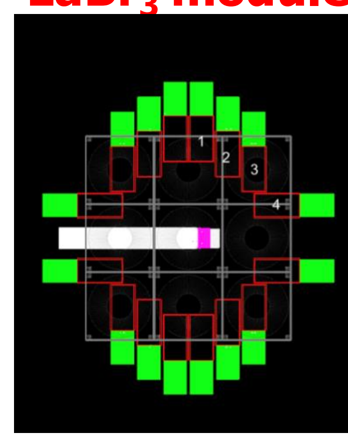
Rocinante



DTAS



+ $LaBr_3$ modules



STARS

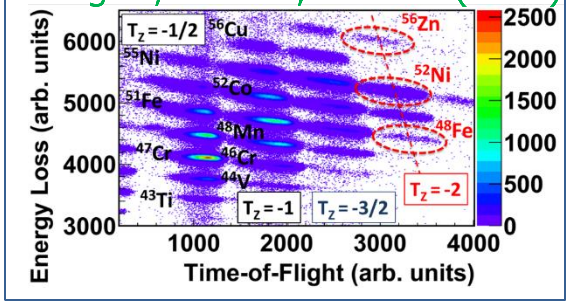
PROPOSAL E891_23

Approved by GANIL PAC (11/2023)

Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

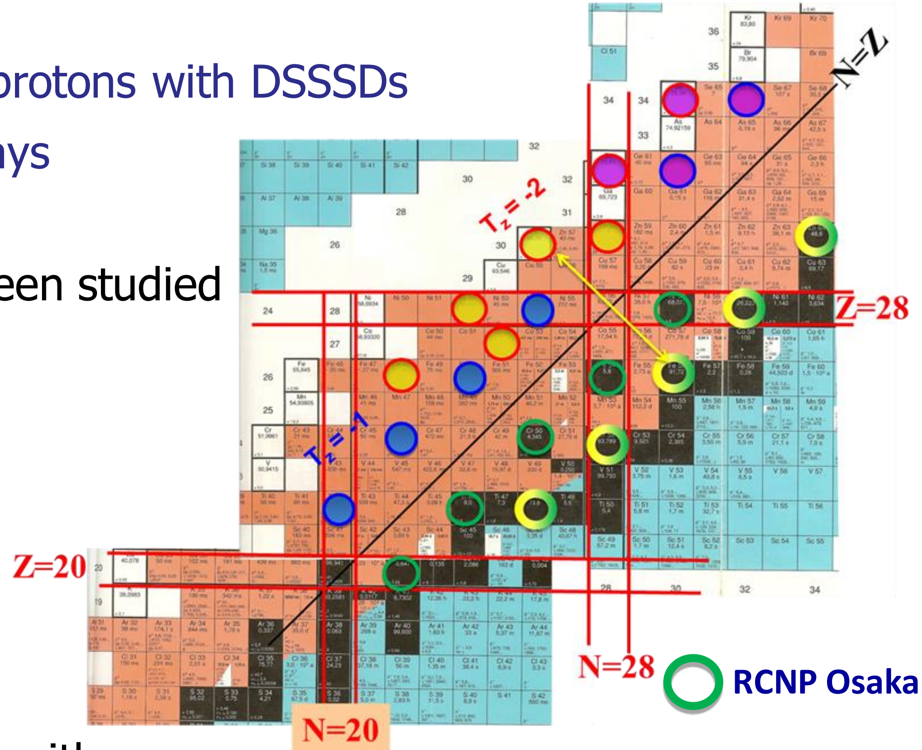
- 1st experiment with **STARS**
- Measure the β-decay properties of several p-rich nuclei in the Cr-Zn region of great interest for:

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,γ)^{46}Cr and ^{47}V(p,γ)^{48}Cr

- 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

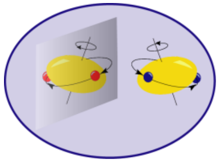
GSI
^{58}Ni @680 AMeV

RIKEN
^{78}Kr @345 AMeV

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

Isospin symmetry in mirror nuclei

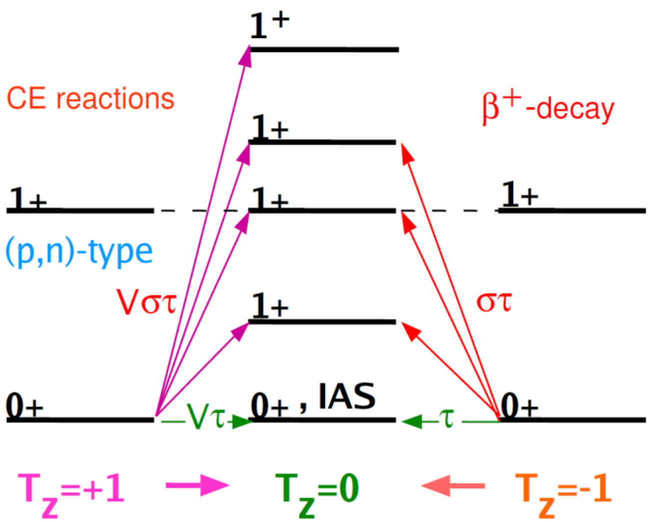
- Mirror **Fermi** and **Gamow Teller** transitions are expected to have the same strength
- What can we learn from the comparison?
  - Investigate **isospin symmetry** in mirror nuclei
  - Improve our knowledge of **GT transitions** close to the proton drip-line and along the **rp-process pathway**



Mirror symmetry

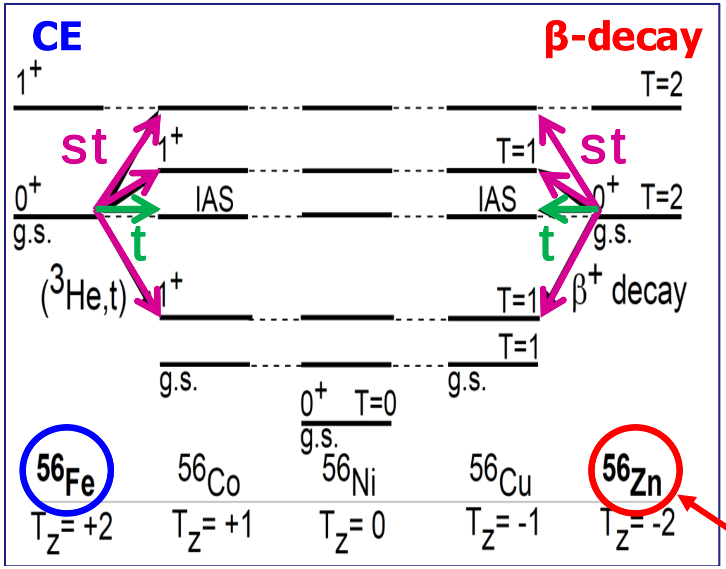
$$^{A}_{Z}X_{N} \qquad ^{A}_{N}Y_{Z}$$

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



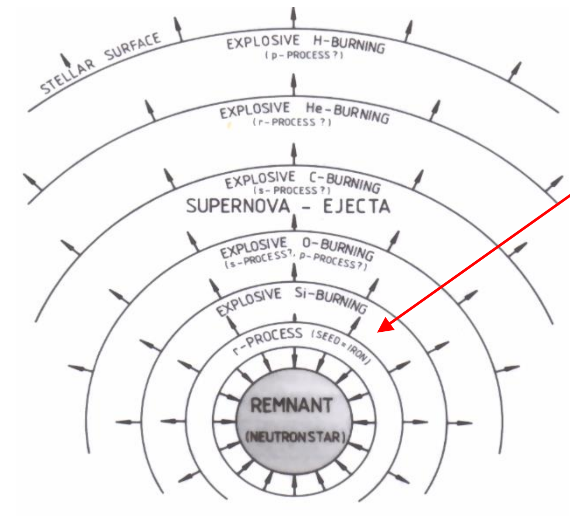
Y. Fujita, B. Rubio, W. Gelletly, PPNP 66, 549 (2011)

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



Orrigo+, PRL 112, 222501 (2014)

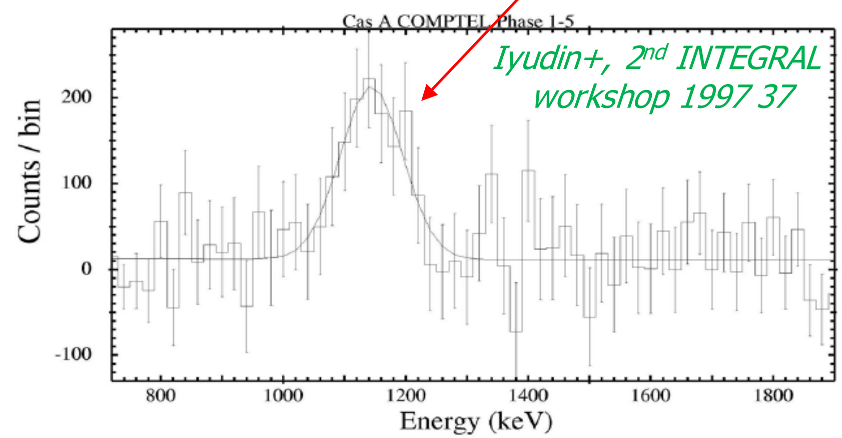
Nuclear astrophysics: ^{44}Ti nucleosynthesis



- ^{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

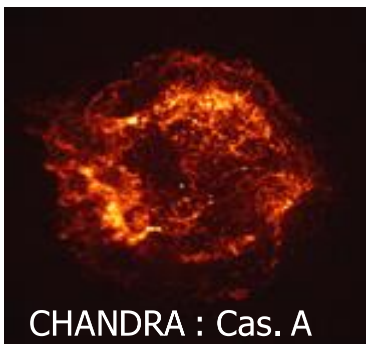
  ^{44}Ti → ^{44}Sc → ^{44}Ca

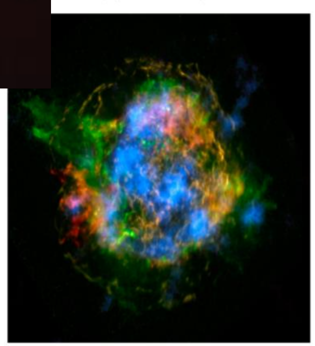
- ^{44}Ti production rate is a sensitive probe for core-collapse models



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

Outlook

- **The TAGS technique**
  - Perfect tool to measure high-energy γ-rays and β-strength without Pandemonium
    - Complementary to high-resolution γ-ray spectroscopy
- **The TAGS Collaboration** (IFIC, Subatech, Surrey, Jyvaskyla, …)
  - Large physics program spanning both n/p-rich nuclei, performed at many international facilities (GANIL, RIKEN, GSI, ISOLDE, IGISOL)
- **$(NA)^2$STARS project:** the new **STARS** spectrometer
  - 1^{st} TAS worldwide combining high efficiency with high resolution and timing as well as increased segmentation
    - 1^{st} experiment already approved @ GANIL

Thank you
for your attention!