2024 DESIR WORKSHOP

Total Absorption γ-ray Spectroscopy (TAGS) measurements

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)

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

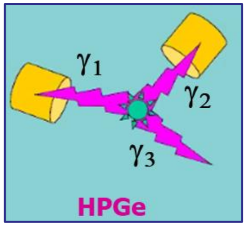
- **The (NA)^{2}STARS project**
  - STARS: 1st device in the World combining spectroscopy and calorimetry
  - 1st experiment with STARS: E891_23 @ GANIL
  - Future experiments @ DESIR

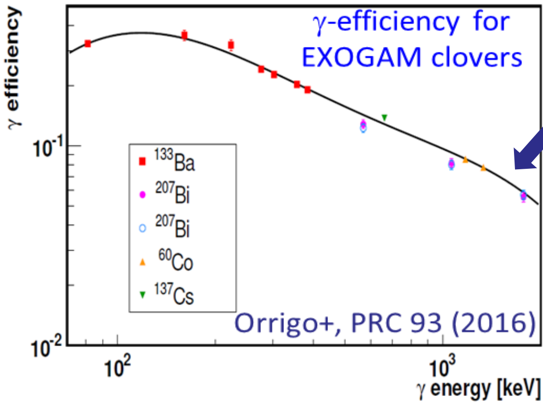
TAGS: to address the Pandemonium effect

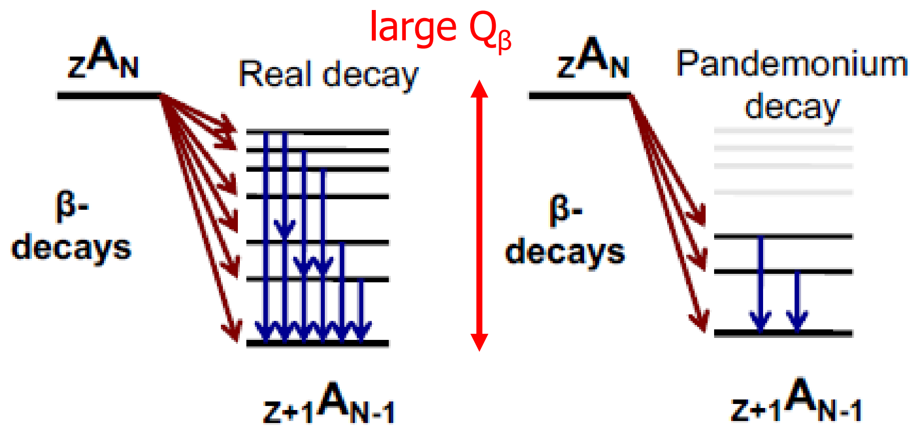
- Conventional β-decay spectroscopy with high-purity Ge detectors (HPGe) is affected by the **Pandemonium** systematic error
  - High-energy γ rays can remain undetected ⇨ missing and wrongly-assigned I_β

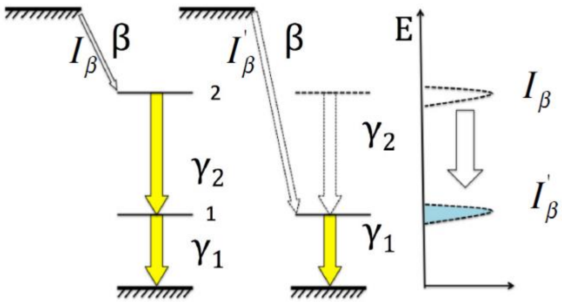
J.C. Hardy+, Phys. Lett. B 71, 307 (1977)

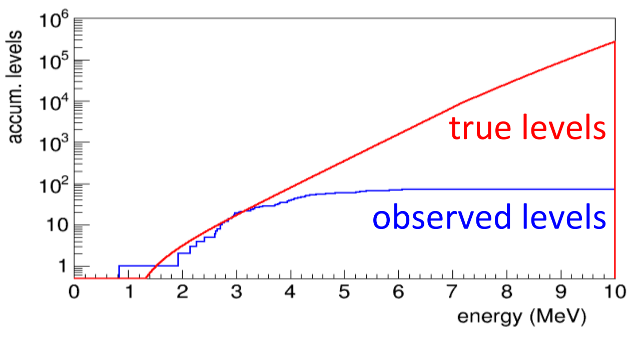
- Exotic nuclei: large Q_β

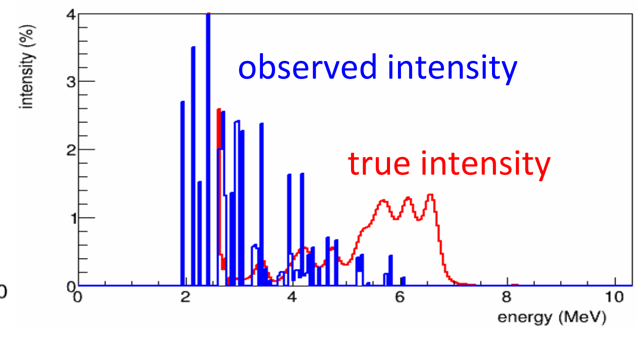








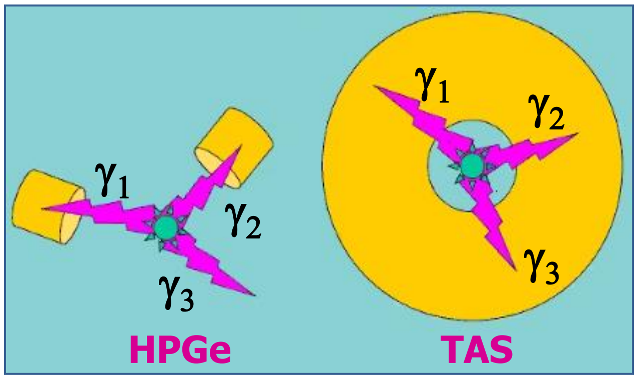


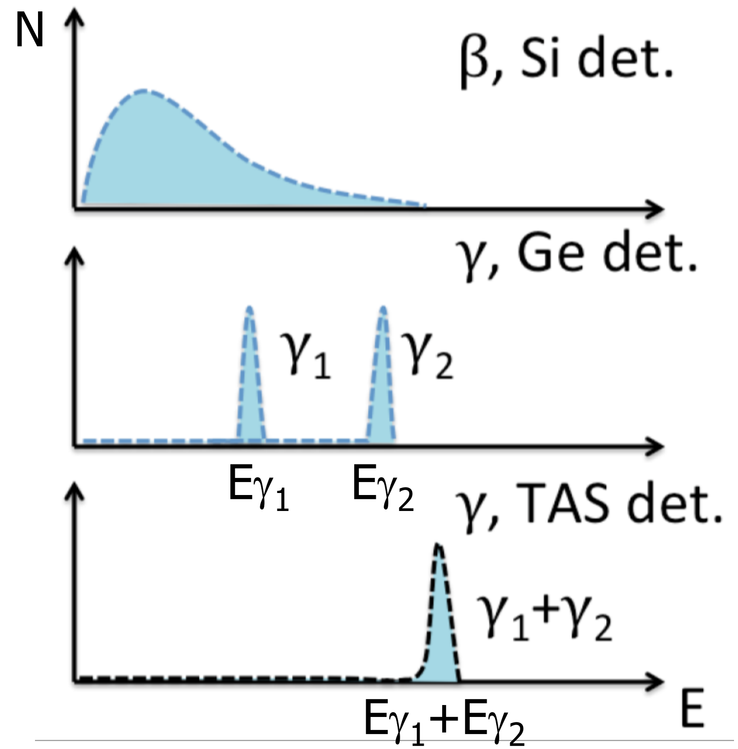


Masking real feeding to low-lying states

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
- 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

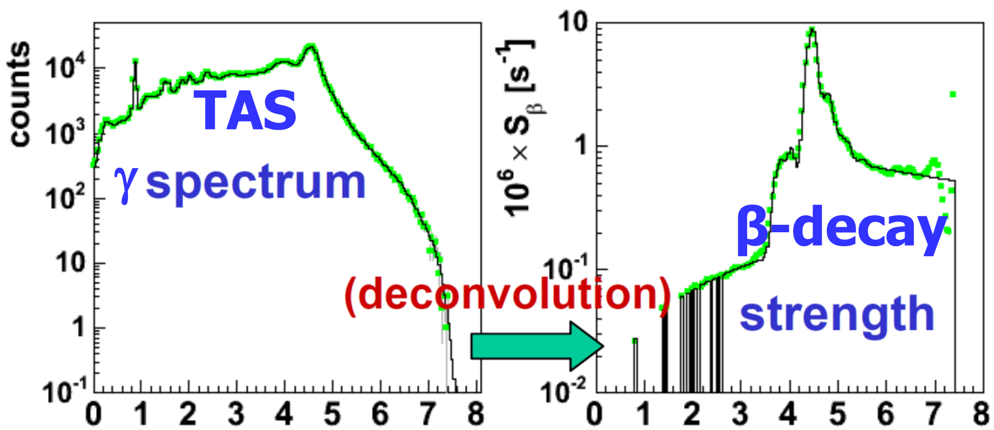
$$S_b^{th}(E_x) = \frac{1}{D}\frac{g_A^2}{g_V^2}\frac{1}{2J_i+1}\left|\langle f \| M_{/p}^b \| i \rangle\right|^2$$

The TAGS technique

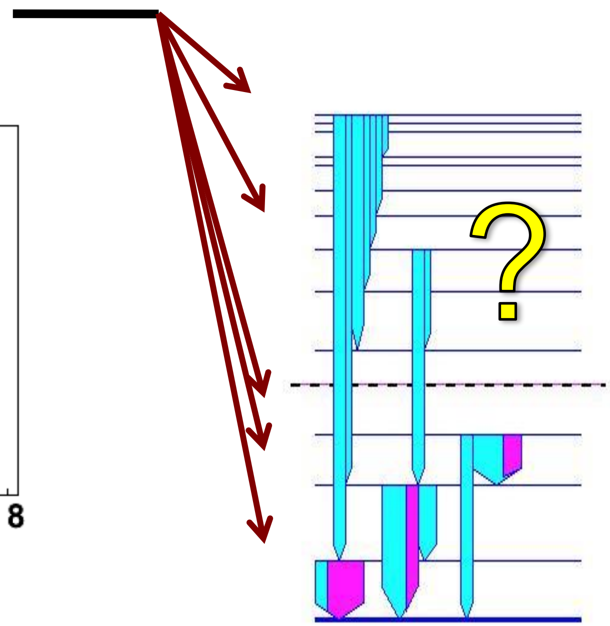
- A **TAGS deconvolution algorithm** is used to solve the linear inverse problem to extract the feeding intensities $I_\beta(E_x)$
  (d_i = measured data, R_{ij} = matrix detector response, f_j = level feeding I_β)

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

- 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 $I_\beta(E_x)$
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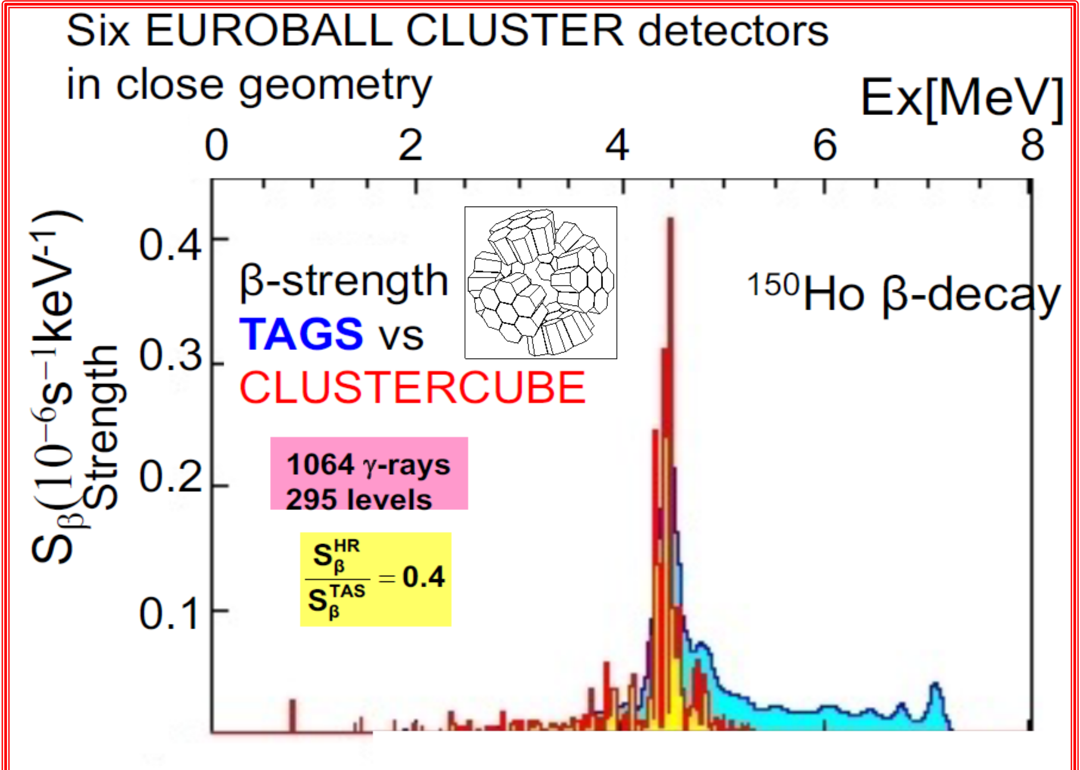
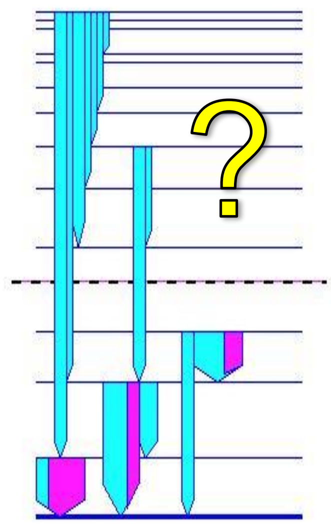
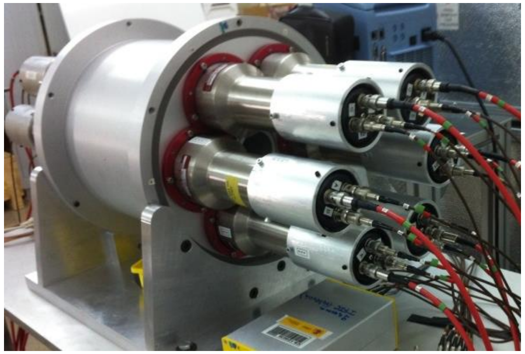


A. Algora, B. Rubio et al PRC 50 (2002)



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

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

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

B. Rubio+, JPG NPP 44 (2017)

E. Valencia+, PRC 95 (2017)

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

Many experiments performed at international facilities

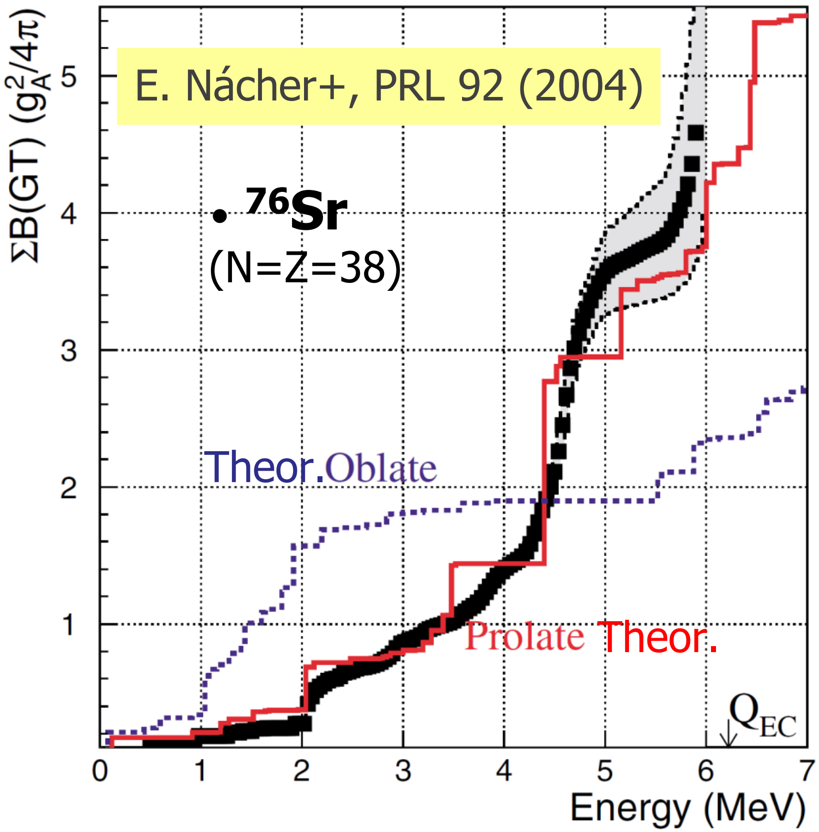
Nuclear shape from β-strength distribution

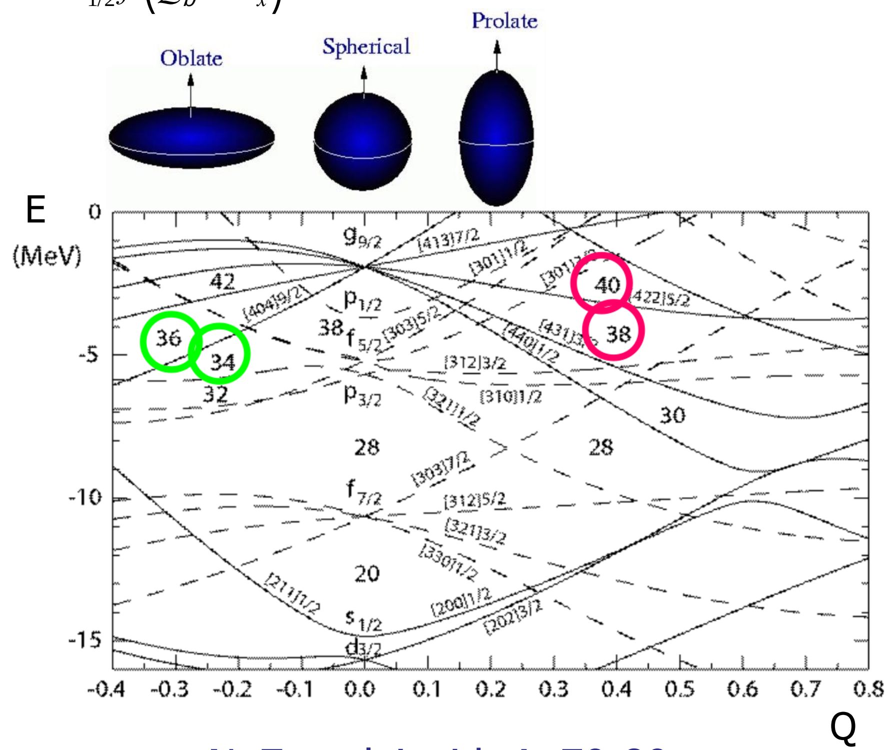
- Fundamental quantity depending on the underlying nuclear structure
- Useful probe to investigate the **shape of the progenitor state**
- Comparison to theor. **QRPA calculations** with different deformations
  - The pattern depends on the shape of the parent nucleus

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

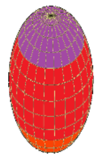
Nuclear shape from β-strength distribution

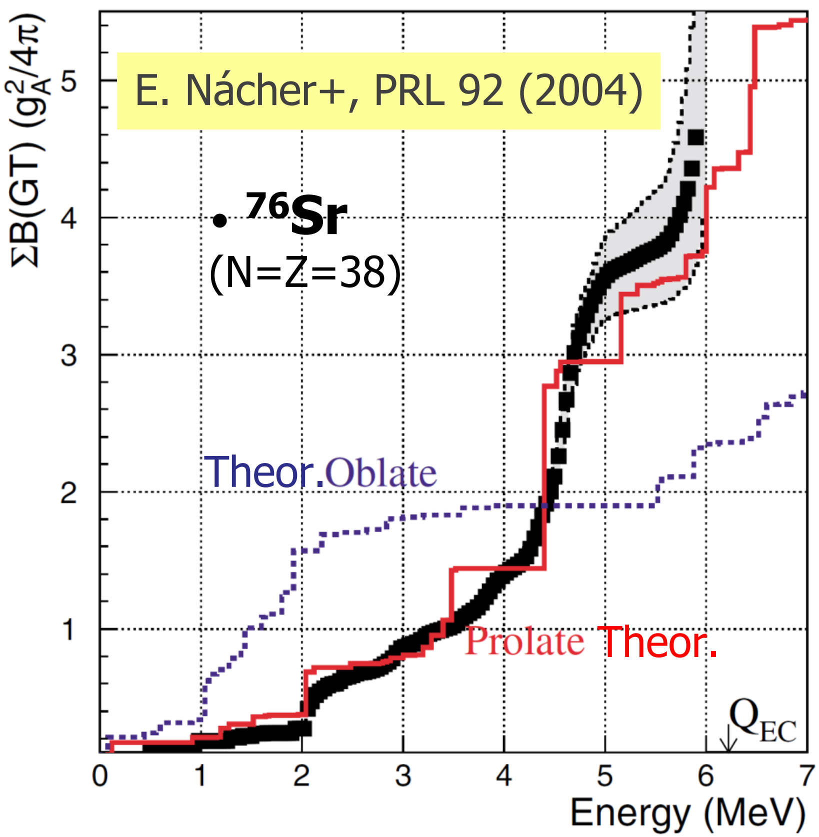
- Useful probe to investigate the **shape of the progenitor state**
- Comparison to theor. **QRPA calculations** with different deformations

I. Hamamoto ZPA 353 (1995)

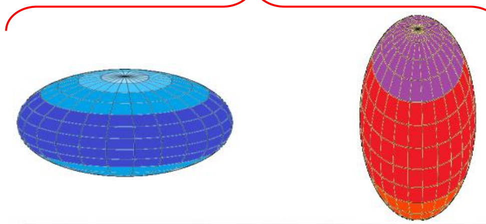
P. Sarriguren+, NPA 658 (1999)

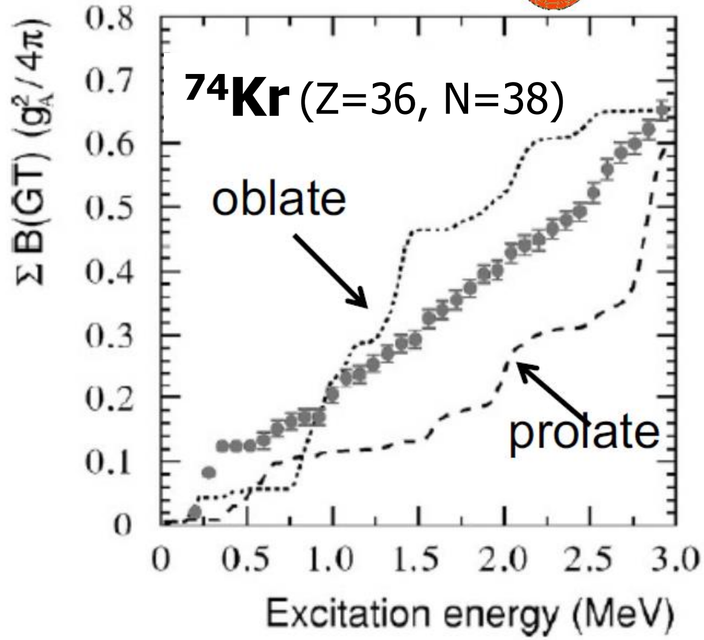
^{76}Sr clearly prolate





^{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

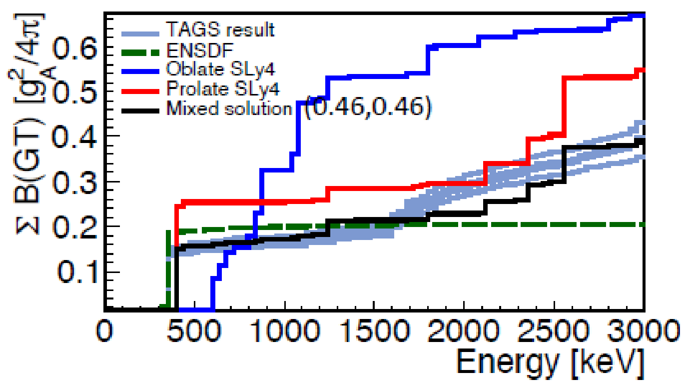
$$\varphi_{parent} = \lambda|oblate\rangle + \sqrt{1-\lambda^2}\,|prolate\rangle$$

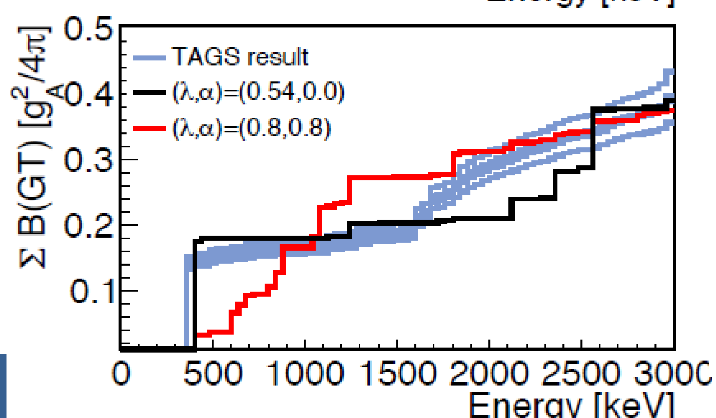
$$\phi_{daugther} = \alpha|oblate\rangle + \sqrt{1-\alpha^2}\,|prolate\rangle$$

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

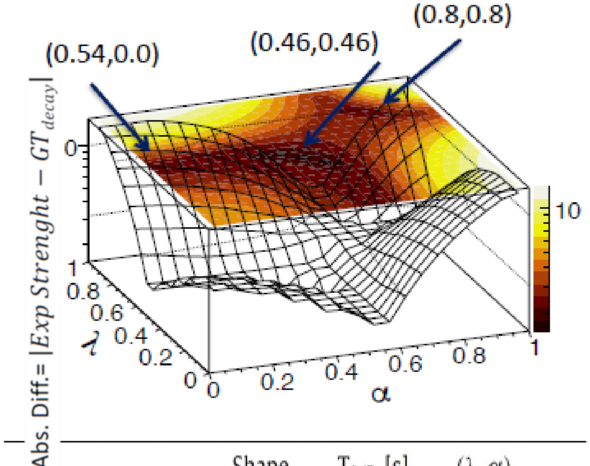
A. Algora+, PLB 819 (2021)

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)	

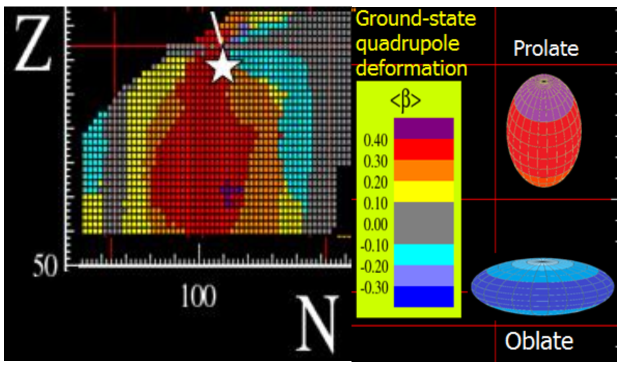
Algora et al. , PLB **819**, 136438 (2021)

Nuclear shape from β-strength distribution

IS707 @ ISOLDE-CERN

β-strength of ^{183,185,187}Hg

- Beamtime @ ISOLDE
  26-31 May 2023
- Shape transitional region around A~186:
  oblate / prolate competition



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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

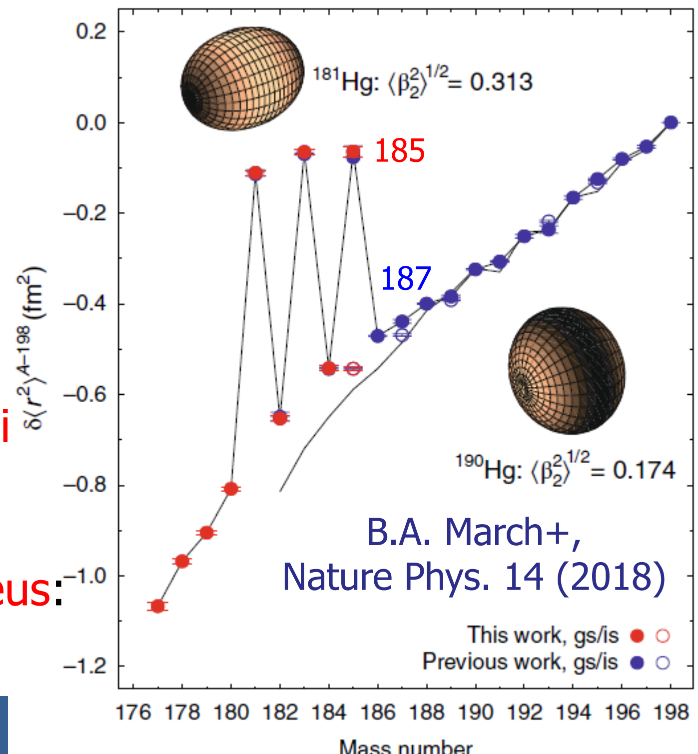
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

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)

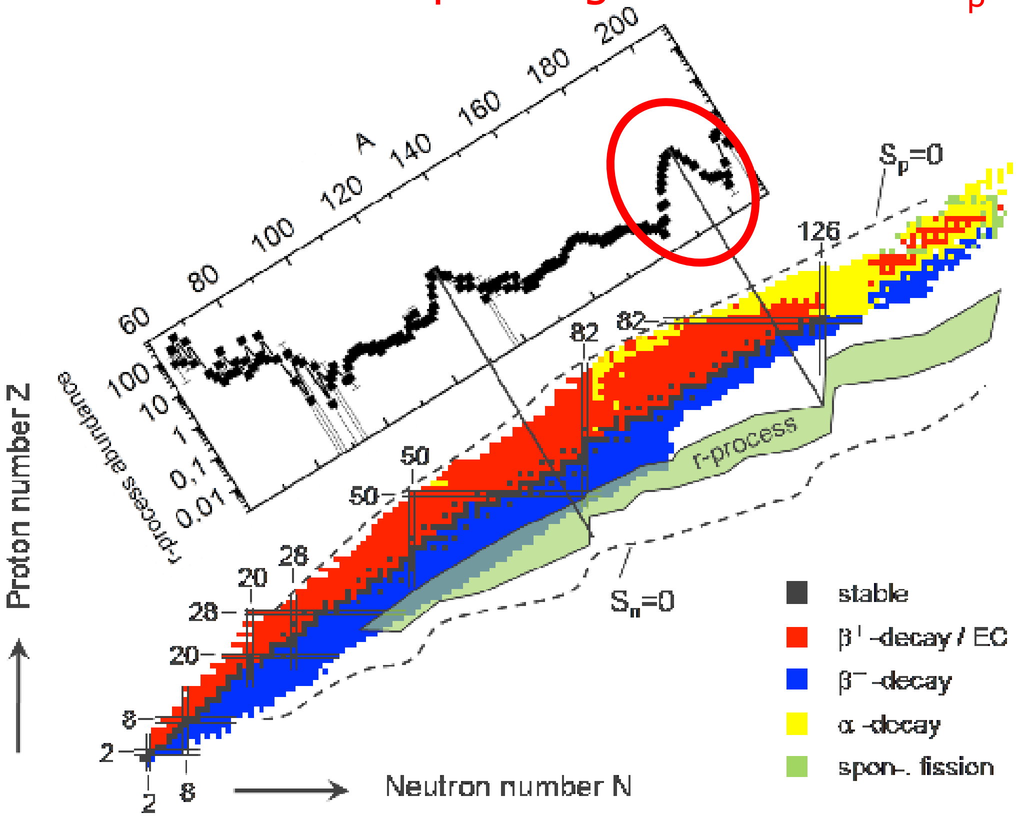
Hg isotopes

- 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



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

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

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

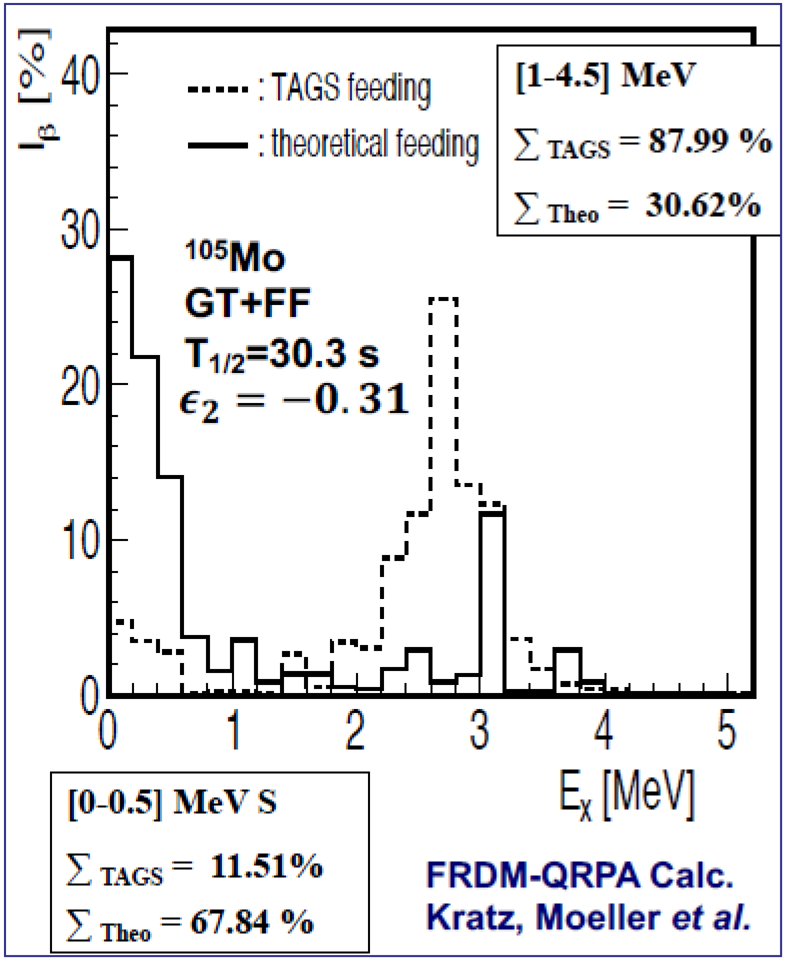
$$S_b^{exp}(E_x) = \frac{I_b(E_x)}{T_{1/2} f(Q_b - E_x)}$$

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



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

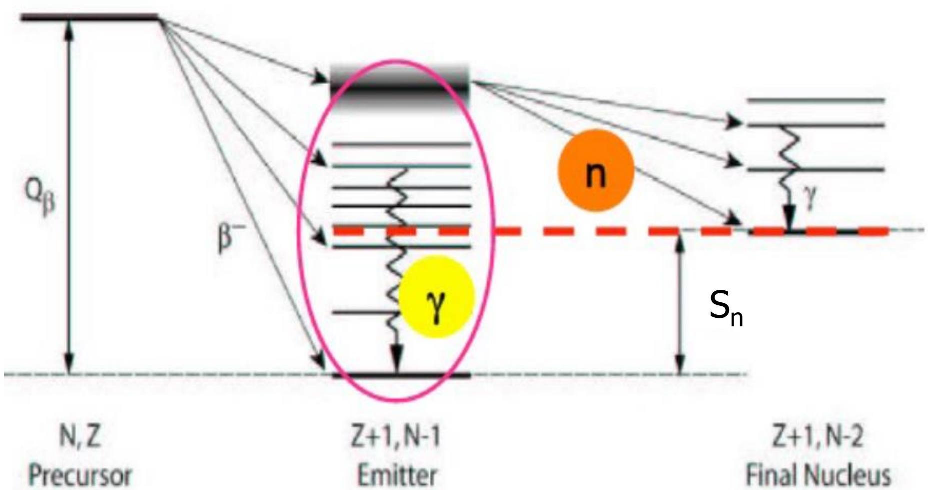
Decay of ^{105}Mo

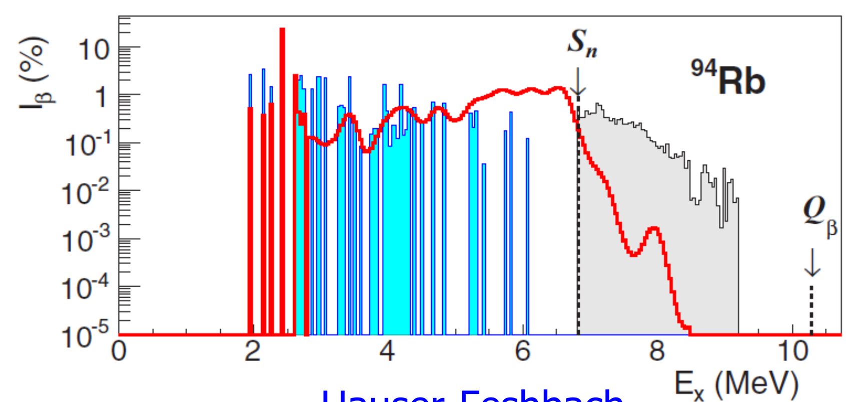
- Experiment: $T_{1/2}$ = 35.6(16) s
  A. Algora+, PRL 105 (2010)

- 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)

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

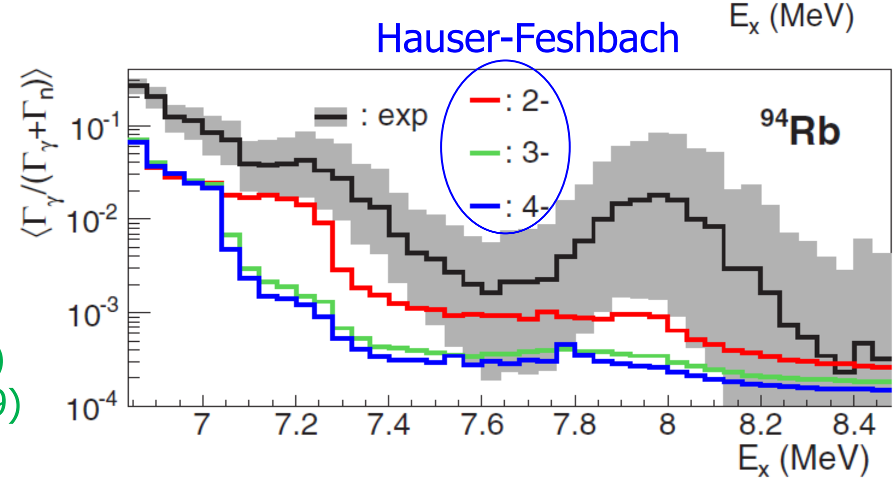


FIG. 12. Average γ to total width from experiment (black line) and calculated for the three spin-parity groups populated in allowed decay (red, green, blue). The gray-shaded area around the experiment indicates the sensitivity to systematic effects. See text for details.

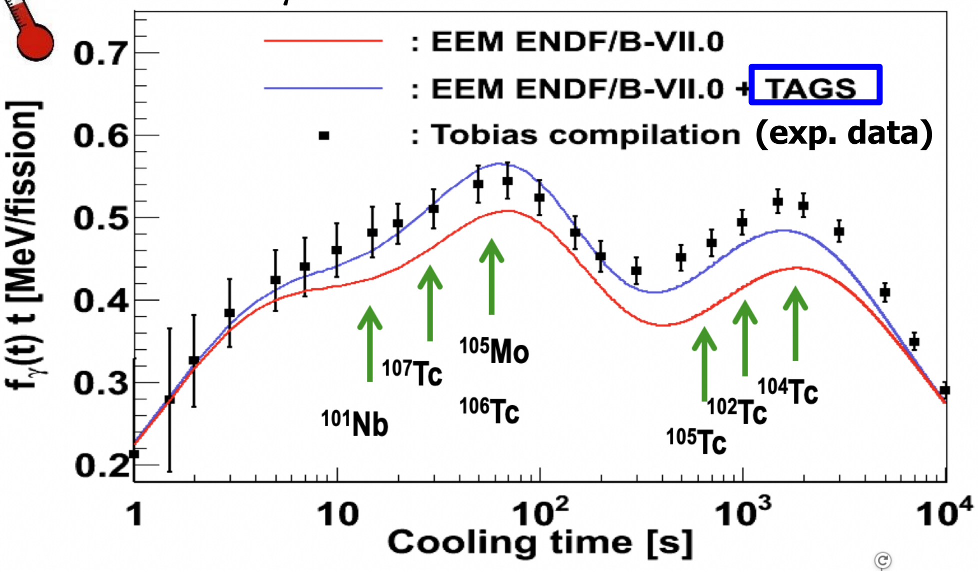
Reactor Decay Heat (DH)

- **Decay Heat**: energy released from the decay of the fission products (without ν)
  - DH continues to be generated after the reactor has been shut down
  - Main contributor: β decay
- DH power function *f(t)*: determined by the summation method
  - Very good knowledge of the levels and feedings is needed ⇨ address Pandemonium

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i = decay energy of nucleus i (γ and/or β)

EEM: $E\gamma$ for ^{239}Pu



A. Algora+, PRL 105 (2010)
D. Jordan, PhD thesis (2010)
D. Jordan+, PRC 87 (2013)

EEM: γ component of ^{239}Pu DH

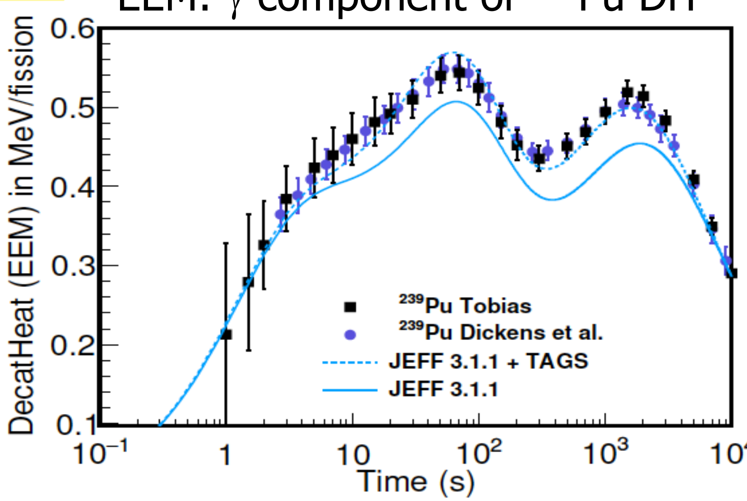


Fig. 13. Impact of the inclusion of the total absorption measurements performed for 13 decays (^{86,87,88}Br, ^{91,91,94}Rb, ^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc) published in Refs. [7,8,24, 62,67] in the gamma component of the decay heat calculations for ^{239}Pu.

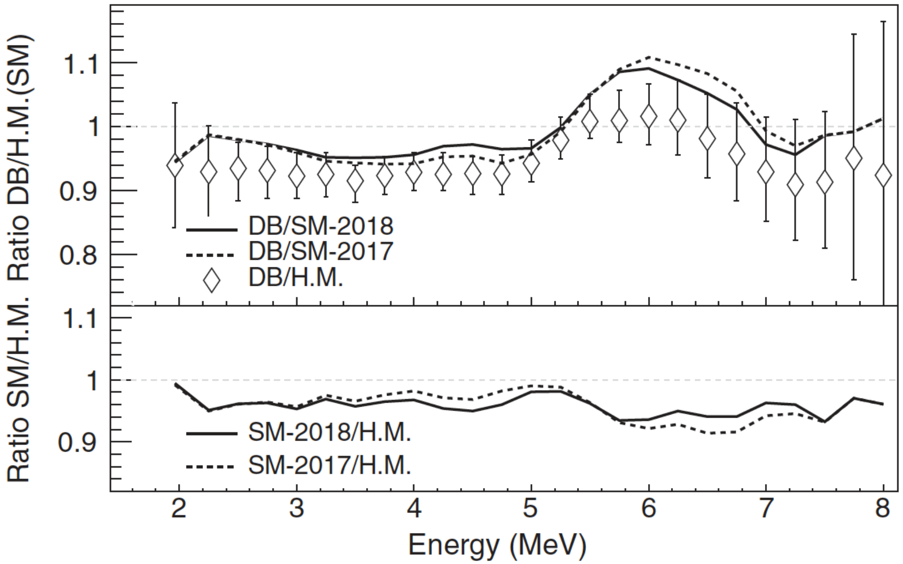
A. Algora+, EPJA 57 (2021)
Calc. by L. Giot (Subatech)

TAGS measurement from the last decade (>20 nuclei) have improved the quality of DH predictions. Still many cases for the future

Reactor antineutrino spectrum

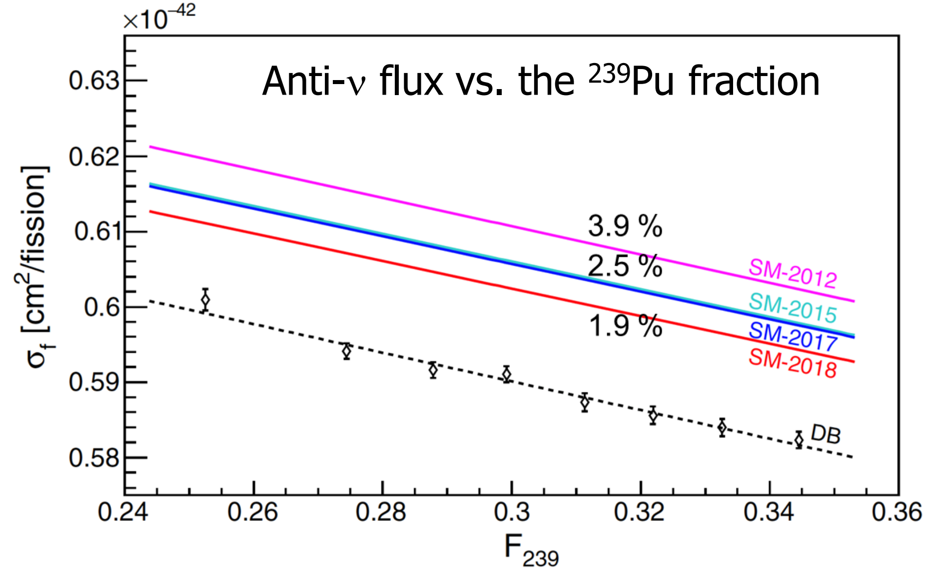
- **Reactor neutrino anomaly**: 6% discrepancy & shape anomaly observed between:
  (1) the reactor antineutrino spectrum measured in Double Choz, Daya Bay, Reno
  (2) the independent computation with the conversion method (Huber-Mueller) from available nuclear data measured at ILL
- Alternative method: (3) summation method (similar to DH) to calculate anti-ν spectra using TAGS data to address Pandemonium

M. Estienne, M. Fallot, A. Algora+, PRL 123 (2019)



Ratio between two anti-ν spectra:
DB = measured by Daya Bay
H.M. = Huber-Mueller conversion method
SM-2017 and SM-2018: summation calculations including TAGS data

TAGS measurement from the last decade
SM-2018: anomaly decreased at 2%



- Is the reactor anomaly dead?
- Shape anomaly still unexplained
- Future: short-lived nuclei, role of isomers…

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

- 1st 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

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 Jan. 2023
- $LaBr_3$ co-funded by GANIL
- 2 TAS ⇨ Large impact: measurements in different facilities

The (NA)^{2}STARS project

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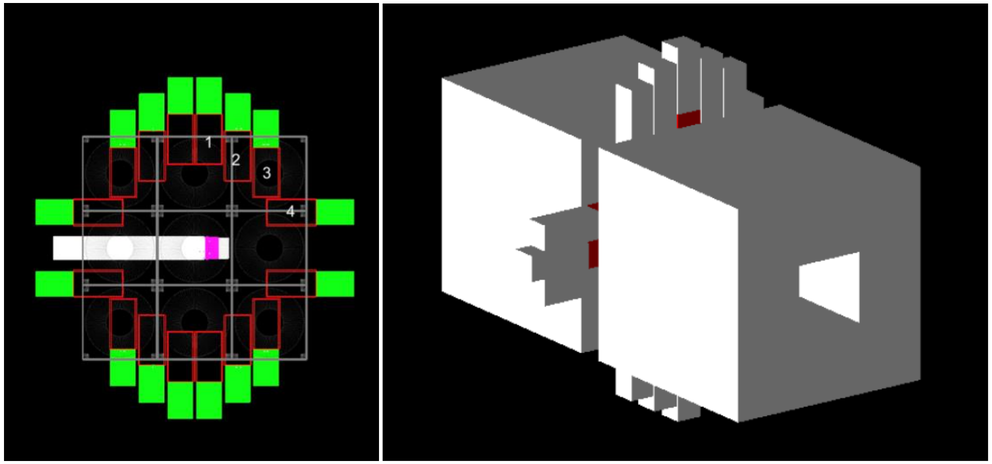
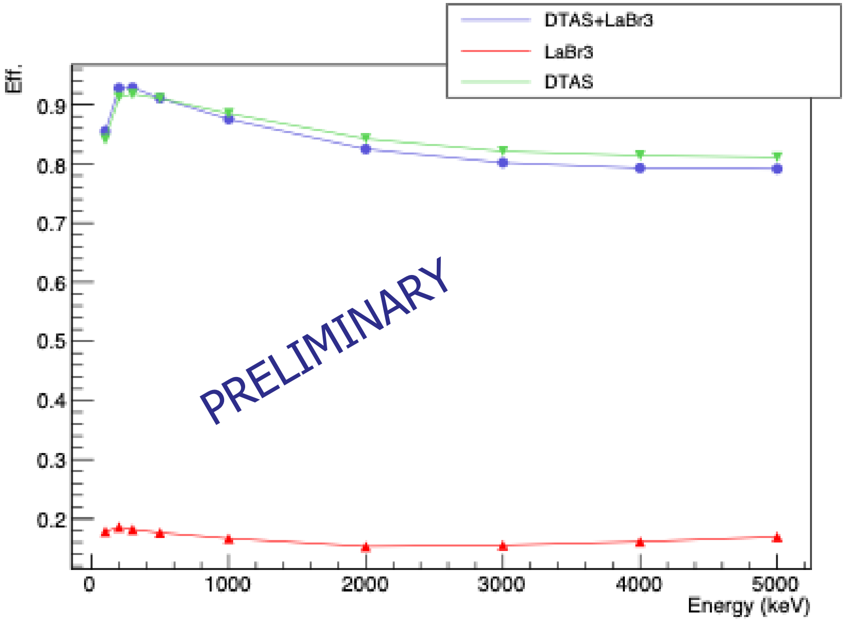
STARS



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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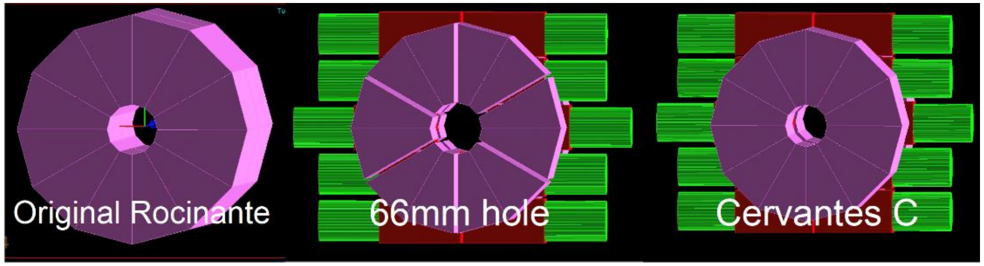
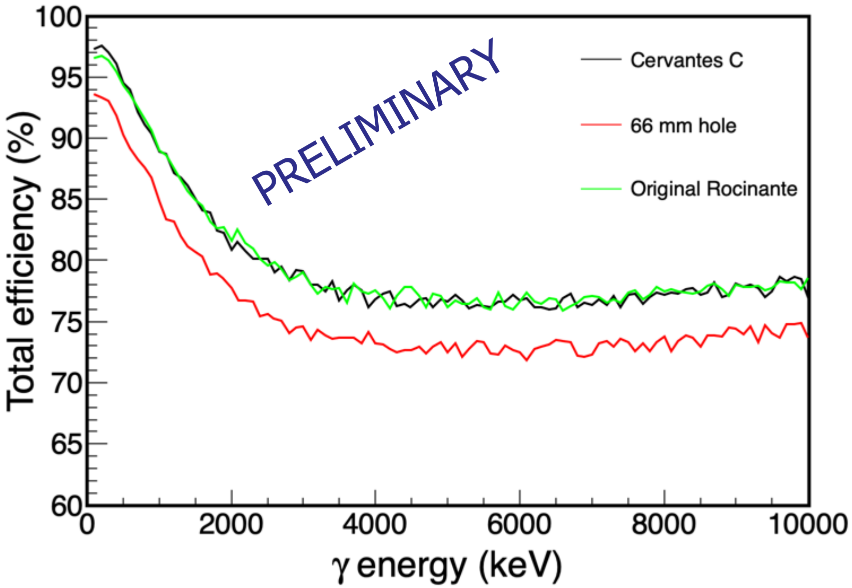
STARS

Rocinante: to be refurbished



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



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

- Rocinante refurbishment in 2024
- Already 8 $LaBr_3$ crystals among partners, performances tests ongoing

- E891_23: first proposal already approved by GANIL PAC (11/2023)
  - Experiment @ LISE in 2025-2026
  - A minimum of 9 crystals for the 1st exp. (most pessimistic case)
  - FASTER electronics: ready for electronics tests in GANIL from 2nd half of 2024

- Ready for DESIR by ~2027

PROPOSAL E891_23

GANIL PAC 14/11/2023

Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

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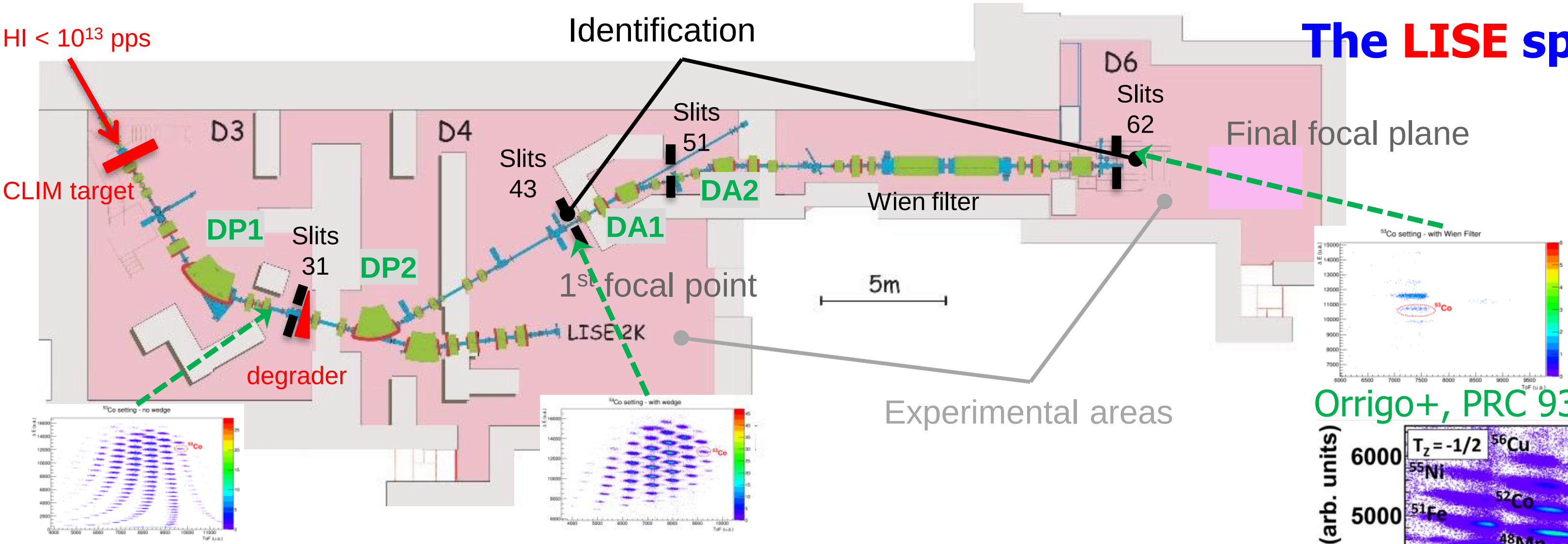
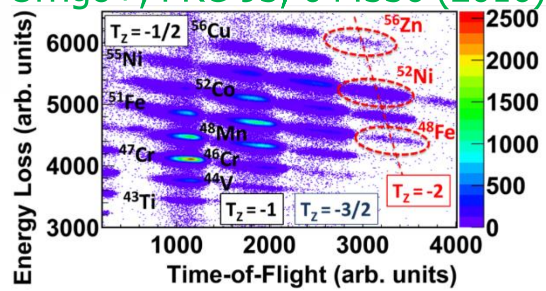
Total Absorption Spectroscopy for Nuclear Structure and Nuclear Astrophysics

- 1st experiment with **STARS**
- Measure the β-decay properties of several p-rich nuclei in the Cr-Zn region of great interest for:
  - 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 $^{47}V(p,\gamma)^{48}Cr$

Experimental setup @ GANIL

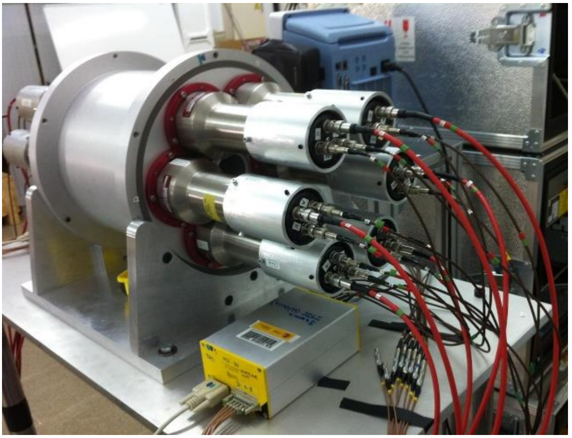


Orrigo+, PRC 93, 044336 (2016)



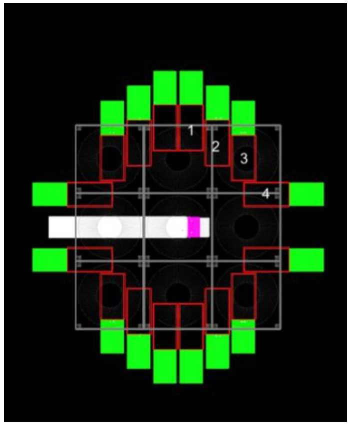
- New DSSSD (GANIL) 1 mm-thick, 40x40 mm^2
- Already 8 $LaBr_3$ crystals

Rocinante



DTAS

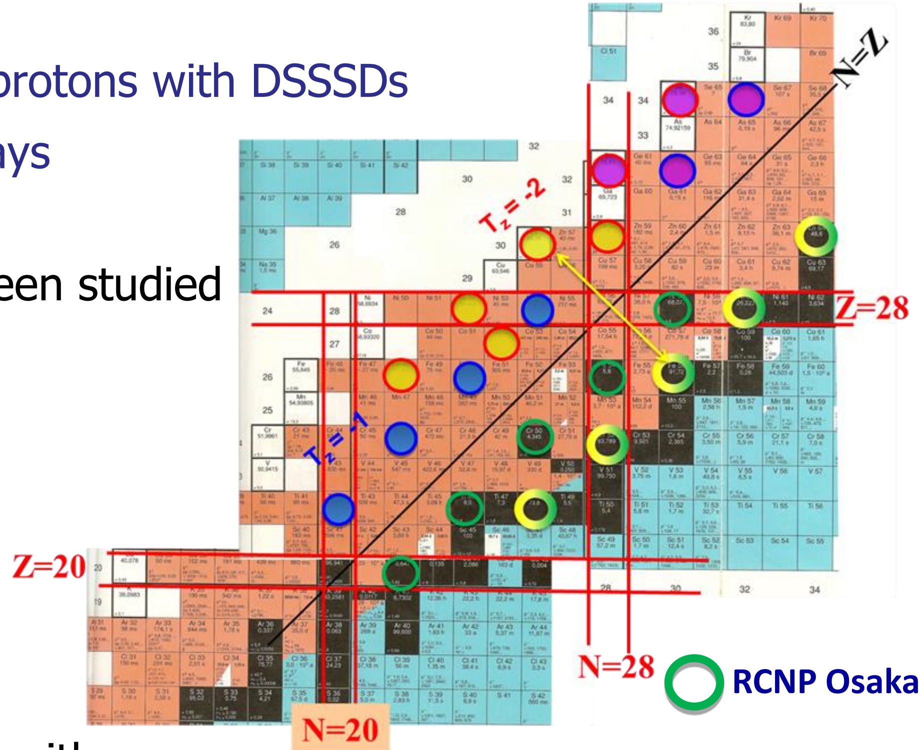
+ $LaBr_3$ modules



STARS

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 RIB production:

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

GSI
^{58}Ni @680 AMeV

RIKEN
^{78}Kr @345 AMeV

TAGS LoIs, day-one-experiments @ DESIR – Jan 2011

Beta strength measurements around the doubly-magic neutron-rich ^{78}Ni

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^{78}Ni region

For nuclear structure and astrophysics

Motivation

There are least two reasons to study the beta decay properties of nuclei in the vicinity of the doubly magic nucleus ^{78}Ni: 1) the beta decay is rather sensitive to the nuclear wave functions of the parent and daughter nuclei what makes it a useful tool for investigation of the nuclear structure in this region, 2) these nuclei are on or very close to the path of the astrophysical r-process in which the beta decay plays a significant role in determining abundances in the synthesis of elements and the speed of the process.

Beta Decay and the N = 82 Waiting Point nuclei

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N=82 waiting point nuclei

For nuclear structure and astrophysics

The astrophysical r-process creates about half of the nuclei with mass above 70. It proceeds through very neutron-rich and unstable isotopes produced in stellar explosions or other violent events. Beta decay is one of the important processes that contribute to the r-process abundances (neutron capture, photodisintegration, temperature and densities are also important ingredients). In particular the beta decay half-lives of the progenitors of stable nuclei help to define the abundances of stable nuclei and are thus important ingredients in r-process network calculations

TAGS LoIs, day-one-experiments @ DESIR – Jan 2011

- ^{100}Sn is the last accessible N~Z nucleus
- Double-magic nucleus (N=Z=50)
- B(GT) should be concentrated in a few levels and accessible within Q_{EC}
  ⇨ possibility of studying the B(GT) quenching in β decay

^{100}Sn region

Beta strength measurements in the ^{100}Sn region

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Zs. Dombrádi, D. Sohler, J. Timár,
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GANIL,CEA/DSM-CNRS,IN2P3, Caen, France

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Much effort has been devoted in recent years to identifying and studying nuclei in the region of ^{100}Sn. There are several reasons for this: the shell structure of nuclei in the vicinity of Z=N=50 closed shells, the possibility of studying the heaviest accessible N=Z nucleus ^{100}Sn and the study of the quenching of the Gamow-Teller resonance, which is available within the Q_β window.

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:** will allow studying more exotic nuclei with TAGS technique
- STARS: the 1st TAS worldwide combining high efficiency with high resolution and timing as well as increased segmentation
- The TAGS collaboration in Europe has a large physics program spanning both n-rich and n-deficient nuclei, performed presently @ IGISOL, ISOLDE, GSI and RIKEN
- Strong interest in performing part of this program @ GANIL: E891_23; 3 existing LoIs @ DESIR + new experiments to be proposed in the future

Thank you
for your attention!