Neutrinos, Applications and Nuclear Structure and Astrophysics with Total Absorption G-ray Spectroscopy and the $(NA)^2$STARS Project

GANIL Scientific Council

Collaboration
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Surrey: W. Gelletly

Outline

- **Intro: What is/Why the TAGS technique ?**
- **TAS Spectrometers**
- **Physics Cases & Current limitations of the existing TAS**
- **(NA)²STARS**
- **Experiments@GANIL**
- **Project Details**

Context

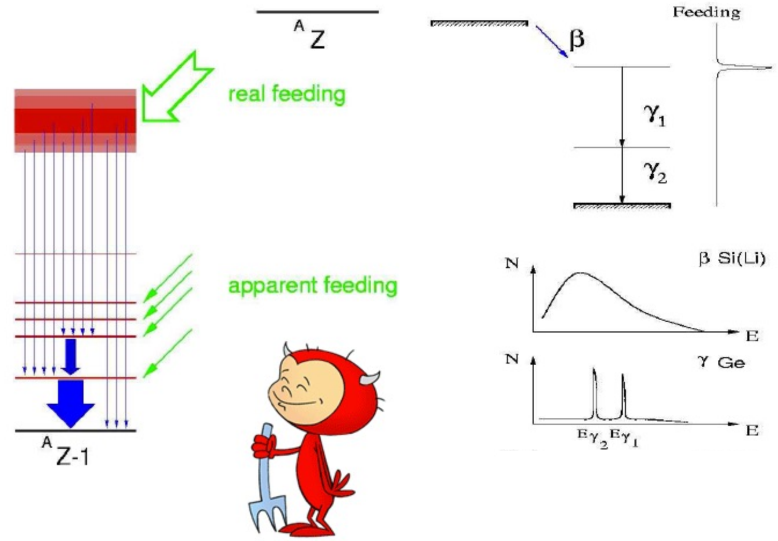
γ Measurement Caveat

- 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



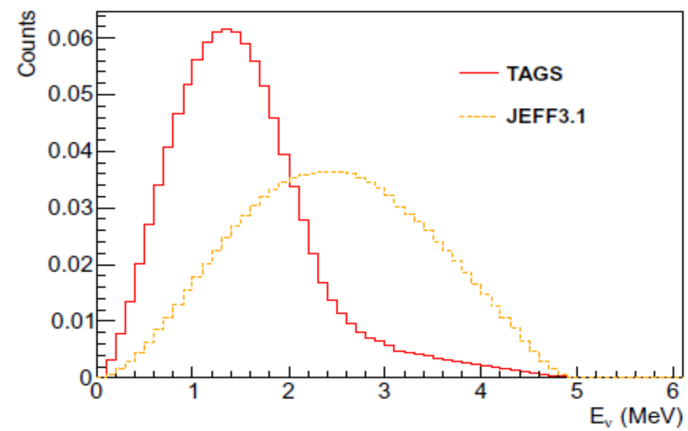
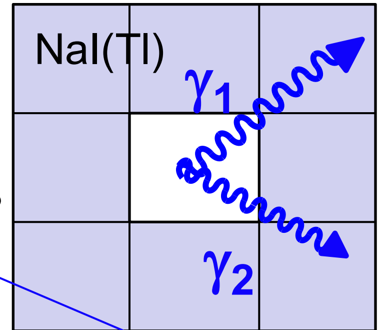
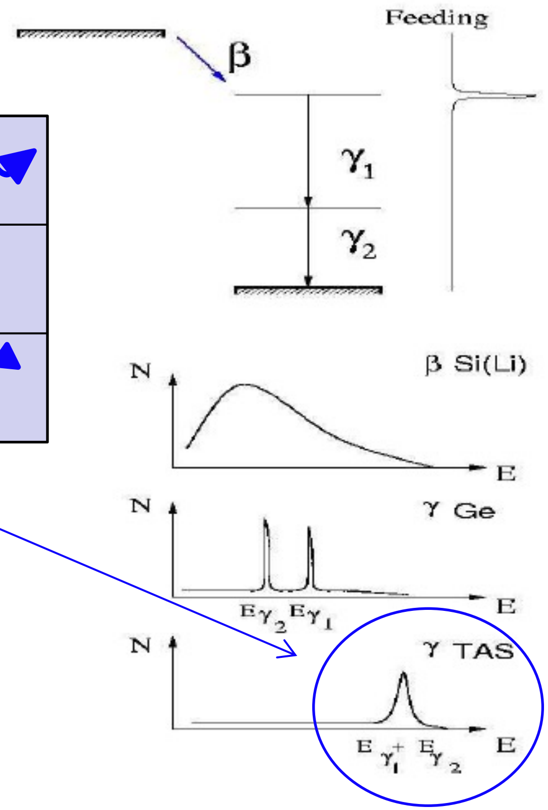


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

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.)

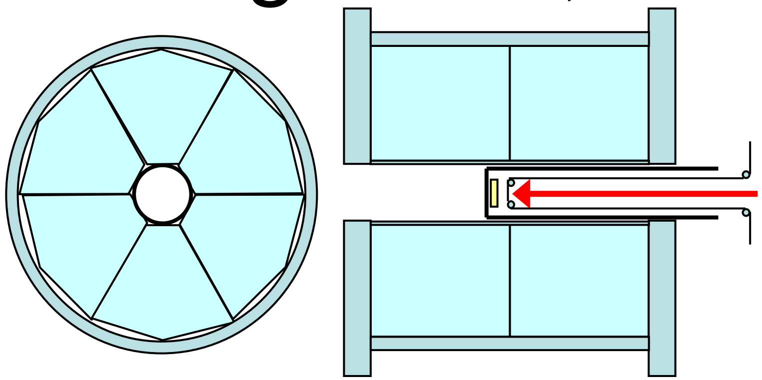
- Calculation of level energy feeding through the resolution of the inverse problem by deconvolution
  - R_{ij} = matrix detector response
  - d_i = measured data
  - Extract f_j the level feeding by deconvolution

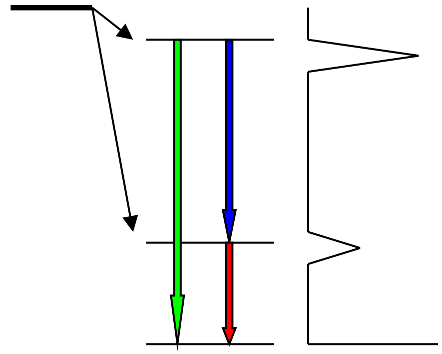
$$d_i = \sum_{j=1}^{m} R_{ij} \, . \, f_j \Rightarrow I_i = \frac{f_i}{\sum_k f_k}$$

J. L. Tain & D. Cano-Ott, NIMA 571 (2007) 728

Total Absorption γ-ray Spectroscopy (TAGS)

Big cristal, 4π => A TAS is a calorimeter !





Observable:

β-intensity => β-strength:
An ideal TAS would give directly the β-intensity I_β which is linked with the β-strength S_β:

$$S_i = \frac{I_i}{f(Q_\beta - E_i)T_{1/2}} \quad [s^{-1}]$$

$$I_i = \frac{f_i}{\sum_k f_k}$$

Statement of the problem:

Relation between TAS data and the β-intensity distribution:

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

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

Deconvolution (Inverse problem) algorithms

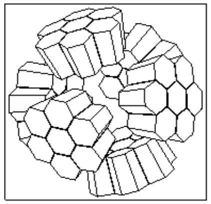
Monte Carlo simulations
+
Nuclear statistical model

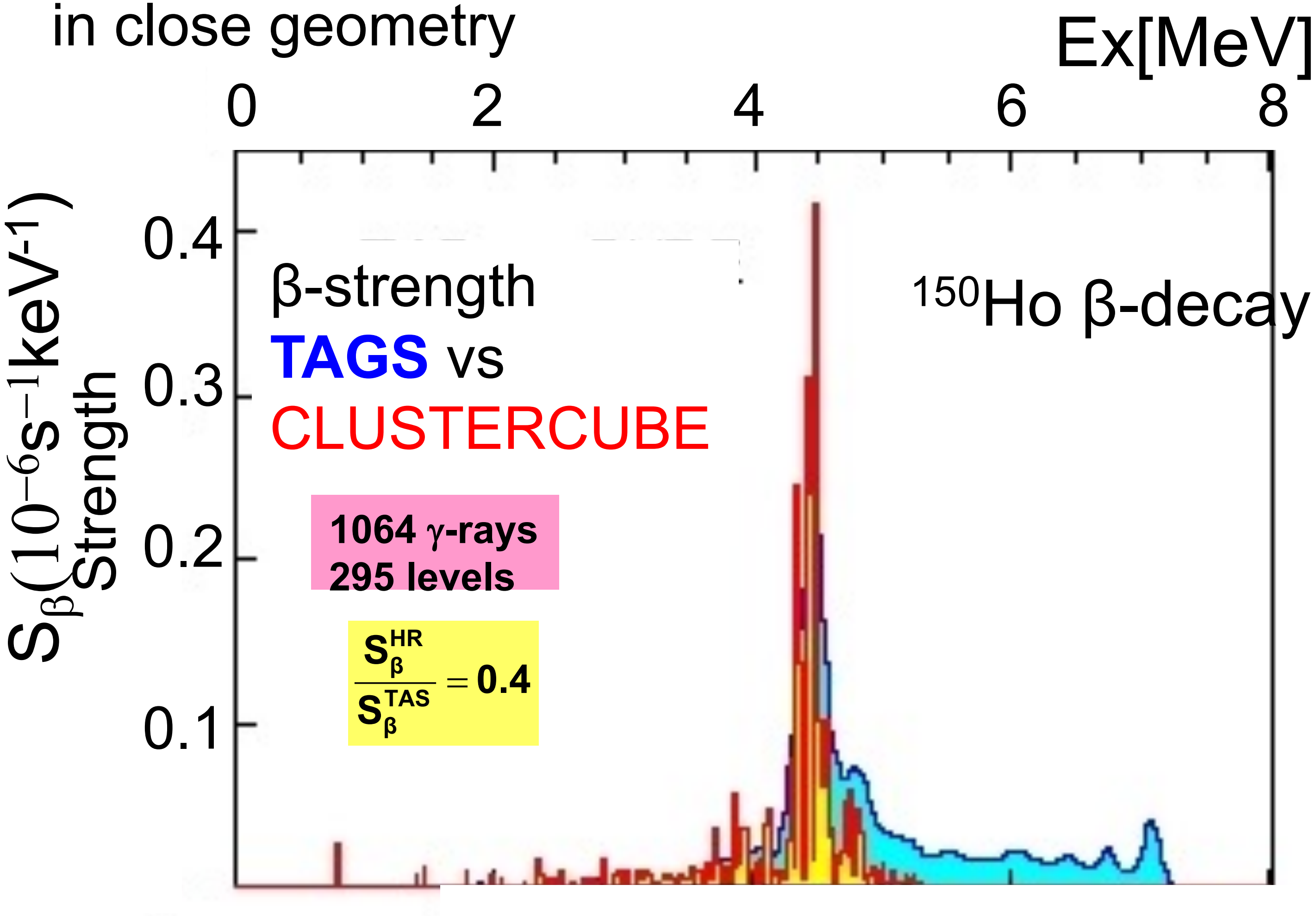
- Spectrum must be clean
- Response must be accurately known
- Solution of inverse problem must be stable (requires calorimetry)

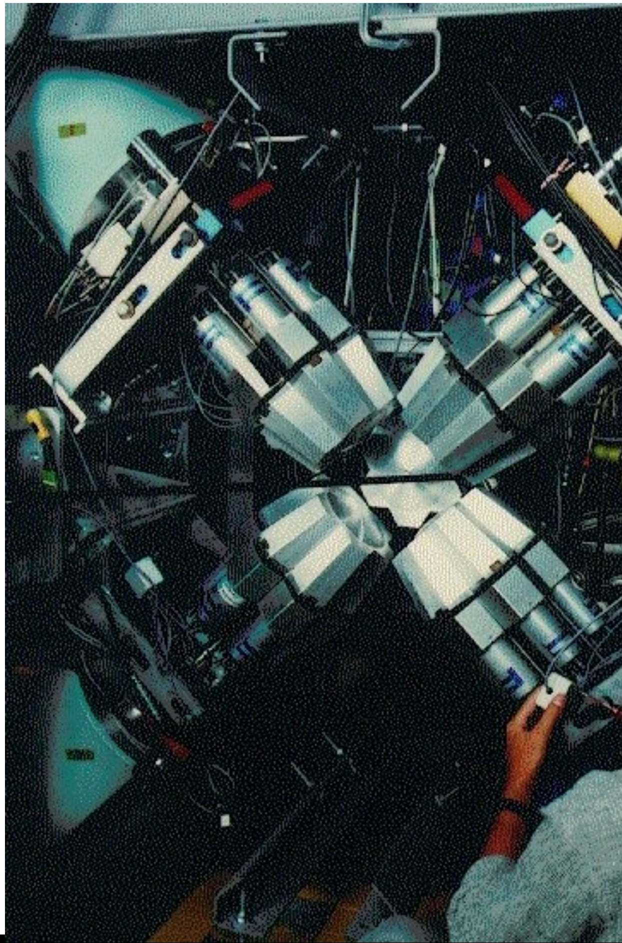
NIM A430 (1999) 333 NIM A571 (2007) 719
NIM A430 (1999) 488 NIM A571 (2007) 728

High Resolution & TAGS Complementarity

Six EUROBALL CLUSTER detectors
in close geometry



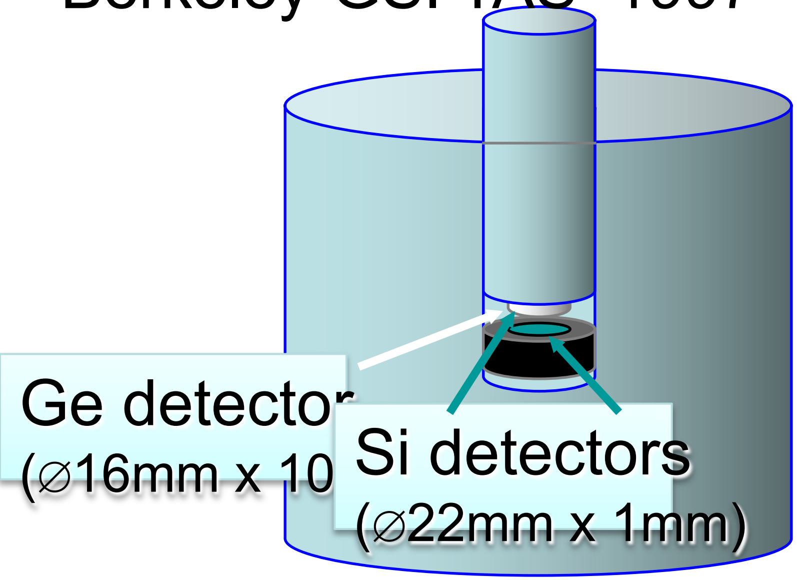




A. Algora, B. Rubio et al PRC 50 (2002)

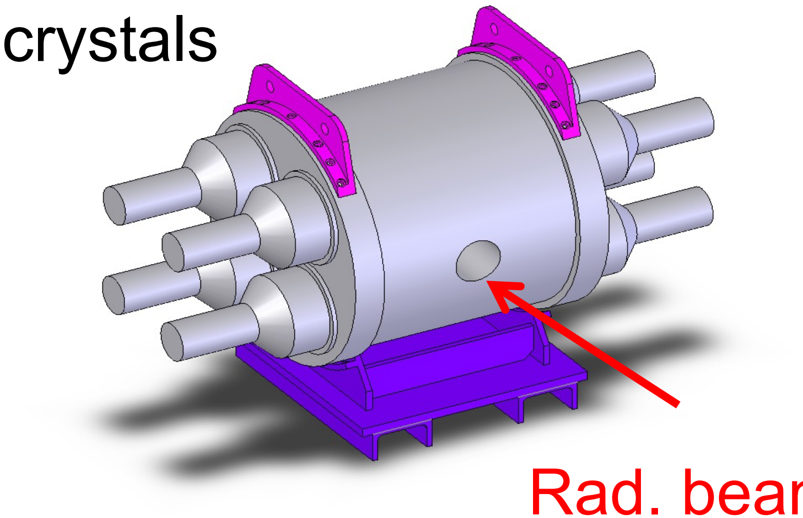
Past and Presently used TAS

Berkeley-GSI TAS 1997

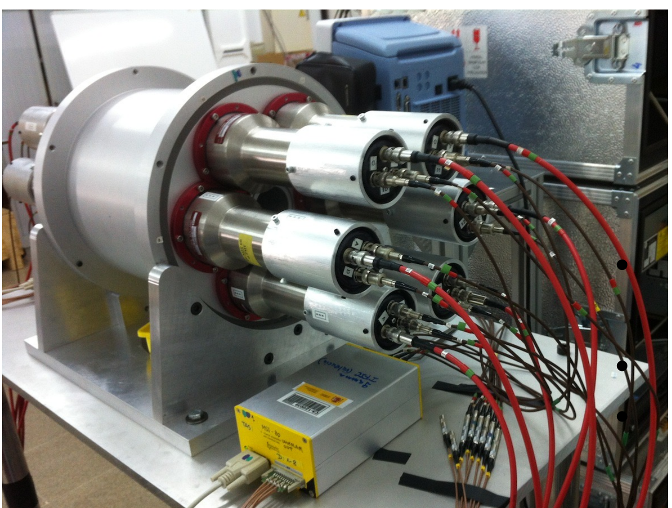


TAS "Lucrecia" @ ISOLDE, CERN

NaI large monocrystals

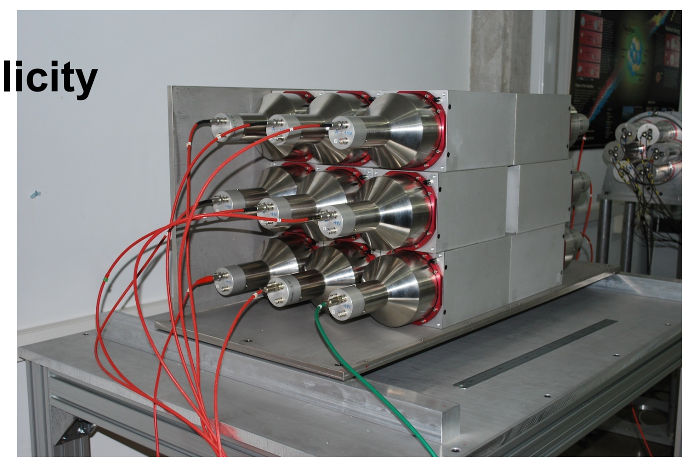


- **Large 18-fold segmented NaI spectrometer**
- **Cascade multiplicity information**



"Rocinante" TAS

- **Compact 12-fold segmented BaF_2 spectrometer**
- **Low neutron sensitivity**
- **Cascade multiplicity information**
- **Good timing**
- **Resolution 10%@1.33MeV**

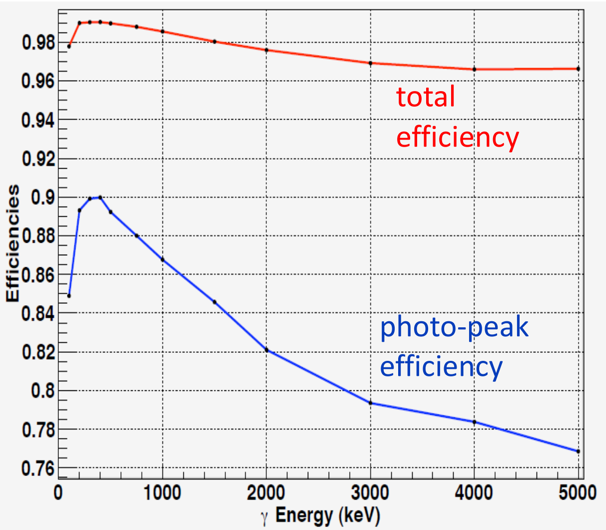


DTAS (NUSTAR) + AIDA DSSSD

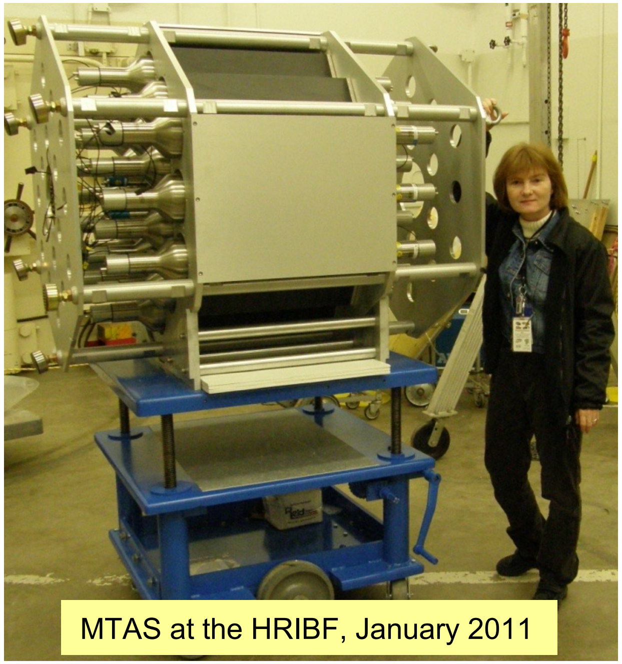
Decay Studies of Fission Products w/ a new Modular Total Absorption Spectrometer (MTAS)

PI's : K. P. Rykaczewski (ORNL) and R.K. Grzywacz (UTK/ORNL)

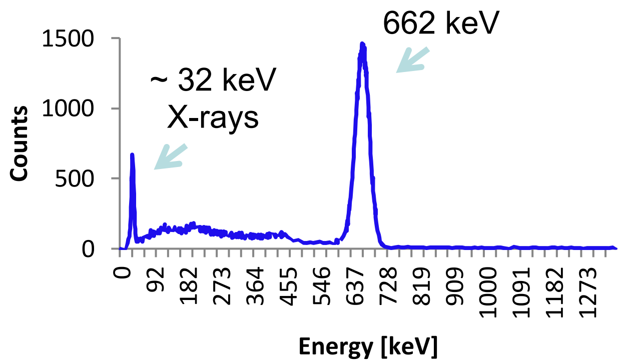
A **Modular Total Absorption Spectrometer (MTAS**) has been constructed from 19 NaI(Tl) scintillator segments. MTAS is designed to perform decay studies with pure beams of neutron-rich nuclei produced in the ^{238}U fission at HRIBF. The total absorption gamma spectra measured with MTAS will be used to derive a true beta-feeding pattern and resulting beta strength function. The studies are important for the verification and development of **the microscopic description of neutron-rich matter** will be performed as well **as applied studies of decay heat released by radioactive nuclei produced in nuclear fuels at power reactors.**



MTAS has superior g-efficiency according to GEANT4 simulations performed by B. C. Rasco (LSU)



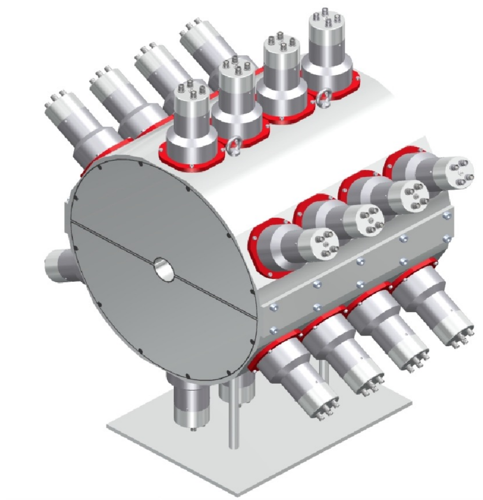
MTAS at the HRIBF, January 2011

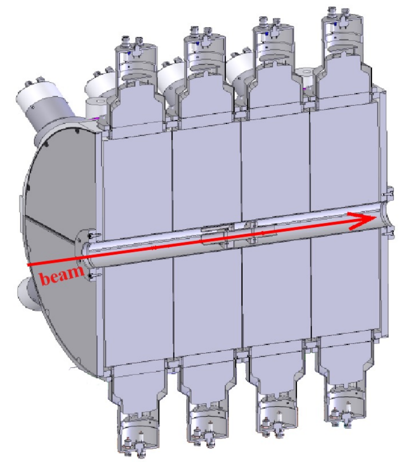


g-energy spectrum of ^{137}Cs activity measured with a single MTAS module.
The energy resolution, fwhm(662 keV) ~ 7%, was found to be better than 8% requested in the detector specifications.

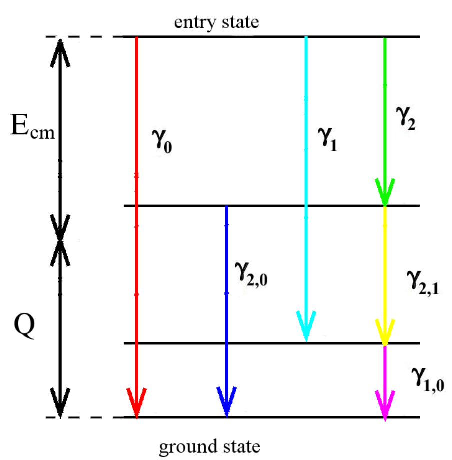
Status: the MTAS has been manufactured at the SGC (Hiram, OH) and delivered to the HRIBF. The tests done using digital electronics show the energy resolution superior to requested specs. Two PhDs were hired full time, one PhD part time.
Funding: $ 698 K capital + $ 882 K operations (includes $ 815 K salaries) = $ 1580 K
Funds committed/spent : $ 658 K capital and $ 512 K operations = $ 1270 K

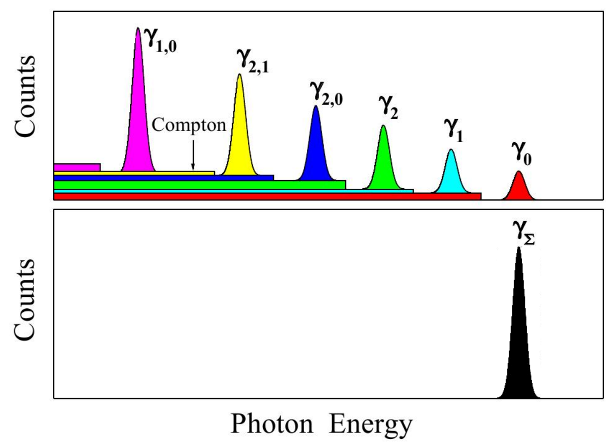
SuN (Summing NaI(Tl))





Since 2011, SuN: barrel shaped scintillator detector, divided into eight optically isolated segments. Each of the segments is read by three photomultiplier tubes,. The diameter and length of the detector are both 16 inches. The diameter of the beam line bore hole along the detector axis is 45 mm.





γ-summing technique similar to TAGS

Used for capture reactions as well as β-decay studies

For Nuclear Astrophysics

A. Simon et al. Nuclear Instruments and Methods in Physics Research A 703 (2013)16.

$(NA)^2$STARS Project

- **Addition of 16 2” x 2” x 4” $LaBr_3$:Ce modules between the two halves of the DTAS**

⇒ **large efficiency combined with the very good energy resolution and timing** of the $LaBr_3$: solution to the study of more exotic nuclei with the TAGS technique, n/γ discrimination with TOF

⇒ higher segmentation: **γ-γ coincidences and angular correlations of specific γ-ray cascades: study of more exotic nuclei or cross-section measurements**.

⇒ **knowledge of γ-cascade multiplicity = good control of the uncertainty on the sum peak efficiency**

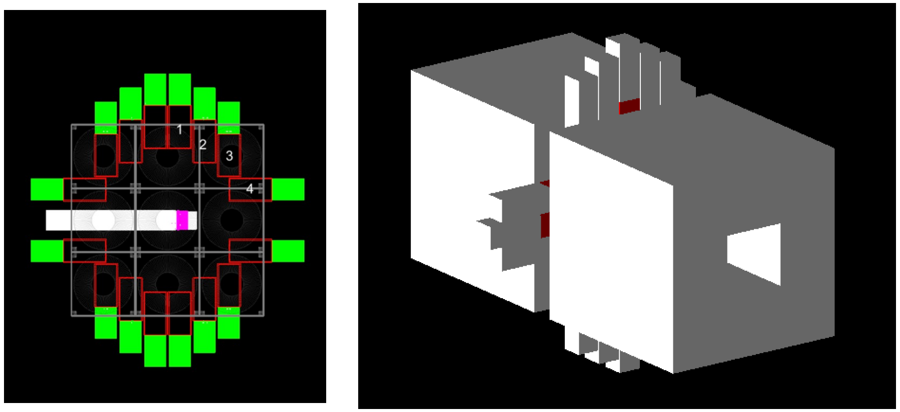


Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

⇒ 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

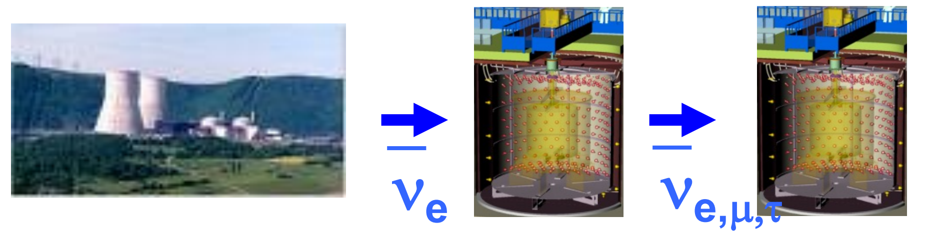
Collaboration: Subatech – IP2I - IFIC Valencia – CIEMAT Madrid - Surrey

Scientific Case

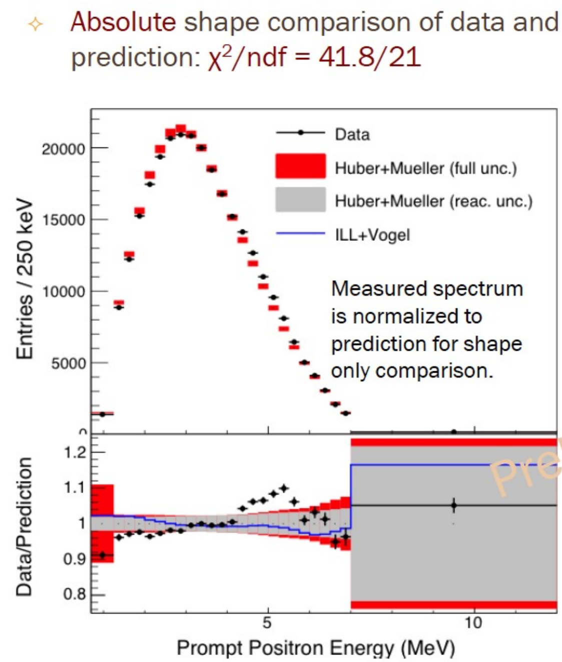
- **Applications: Reactor Physics, Neutrino Physics**
- **Nuclear Astrophysics (& Structure)**
- **Nuclear Structure**

Reactor Antineutrinos & Fundamental Physics

- Measurement of the θ_{13} **oscillation param by Double Chooz, Daya Bay, Reno**
  - Independent computation of the anti-ν spectra using nuclear DB: conversion method



- Sterile neutrino measurement to explain the **"reactor anomaly"**
  - 6% deficit of the absolute value of the measured flux compared to the best prediction ILL data
  - **Shape anomaly** (spectral distorsion) in the full spectrum (btw 4.8-7.3 MeV)
  - Daya Bay PRL points-out a **pb in the converted antineutrino spectra from ^{235}U** measured beta spectrum @ILL



- **Next generation reactor neutrino experiments** like JUNO or background for other multipurpose experiment

- **Reactor Monitoring:** prediction of antineutrino emission of future reactor designs rely on nuclear data

➡ Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and sterile neutrinos into question.

➡ Growing interest in Summation Method (SM) to calculate anti-ν spectra, but new measurements needed due to Pandemonium problem

Reactor Decay Heat (DH)

- **Definition:** following the shut-down of the chain reaction in a reactor, **the nuclear fuel continues to release energy called decay heat.**
- Evaluation of the **reactor safety** as well as **various economic aspects** of nuclear power
- **Emitters: essentially made up of FP and actinides**
  - ❑ DH: residual power of **6-12% of the nominal power** of the reactor just after its shut-down

- Estimate through **the only predictive method** for future reactors: **the « summation method »**

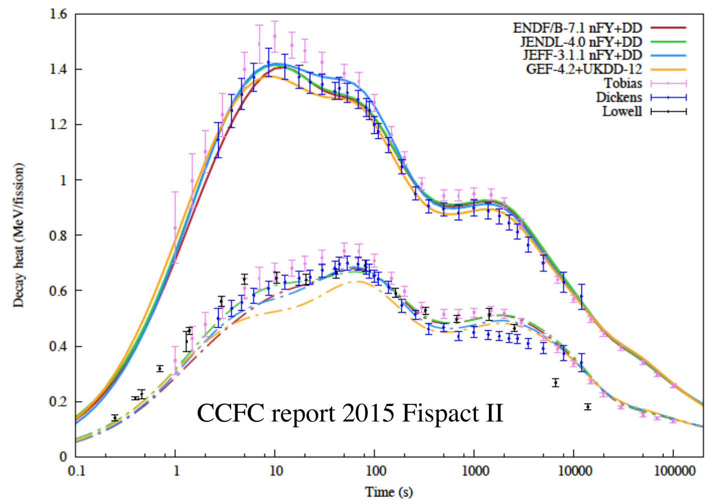
⇒ Summation of all the fission product and actinide contributions:

$$\mathbf{f}(t) = \sum_i \underbrace{(\bar{E}_{\beta,i} + \bar{E}_{\gamma,i})}_{\beta,\gamma \text{ decay}} \underbrace{\boldsymbol{\lambda}_i \mathbf{N}_i(t)}_{\text{Total decay constant (half-life) and Fission Yield}}$$

β,γ decay — Total decay constant (half-life) and Fission Yield

⇒ **Comparisons btw nuclear data & integral measurements show that there remains important discrepancies between data and simulations using different DataBases**

⇒ **Pandemonium effect + unknown decay schemes**



Figur **Total (solid) and gamma (dashed) decay heat from thermal pulse on ^{235}U**

Nuclear Science NEA/WPEC-25 (2007), Report INDC(NDS)-0577 (2009), Report INDC(NDS-0551, Report INDC(NDS)-0676 (2016)

3 TAGS Campains at IGISOL Jyväskylä in 2009, 2014 and 2022

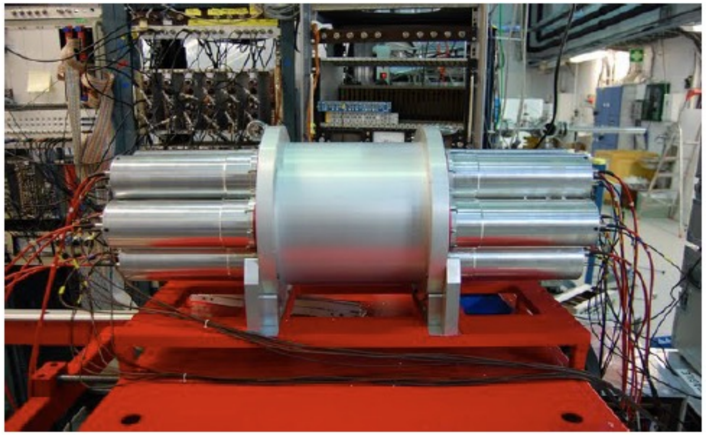
- IGISOL@Jyväskylä:
  - ❑ Proton induced fission ion-guide source
  - ❑ Mass separator magnet
  - ❑ Double Penning trap system to clean the beams

B. Rubio, J. L. Tain, A. Algora et al., Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013)

- 2 (segmented) TAS campains :

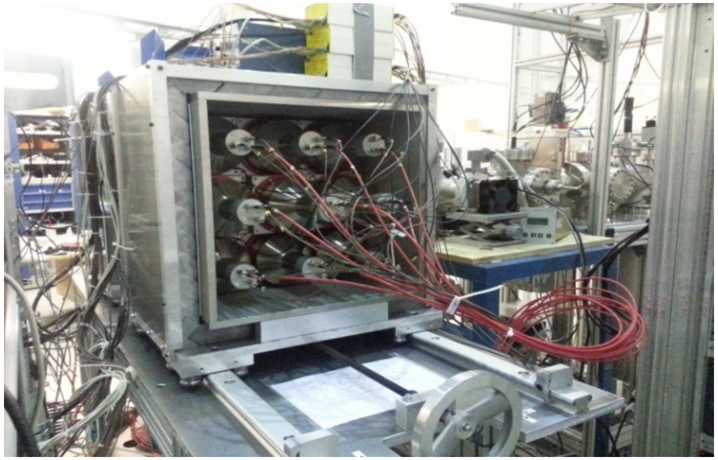
J.L. Tain et al., NIMA 803 (2015) 36
V. Guadilla et al., submitted to NIMA (2018)

❑ ROCINANTE (IFIC Valencia/Surrey):



- ✓ 12 BaF_2 covering 4π
- ✓ Detection efficiency of a single g ray >80% (up to 10 MeV)
- ✓ Coupled with a Si detector for β
- ✓ 7 nuclei (4 delayed neutron emitters) measured (6 for DH and 2 for anti-ν)

❑ DTAS (IFIC Valencia):



- ✓ 18 NaI(Tl) crystals of 15cm × 15cm × 25 cm
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- ✓ Coupled with plastic scintillator for β
- ✓ 12 nuclei for anti-ν measured & 11 for DH

30 Measured Nuclei

- 2014 campain (23 nuclei): Table from IAEA Report INDC(NDS) 0676 (2015)

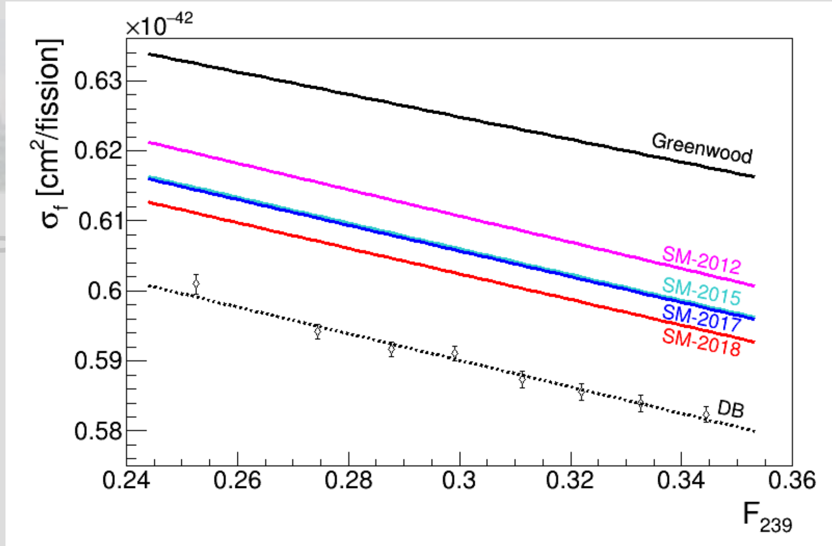
Nuclide	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$	Nuclide	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$
^{95}Rb	1	2		^{102m}Nb	-	1	-
^{95}Sr	-	-	1	^{103}Tc	1	2	-
^{95}Y	-	-	1	^{103}Mo	1	2	-
^{96gs}Y	2	2	1	^{108}Tc	-	-	-
^{96m}Y	-	1	-	^{108}Mo	-	-	-
^{99}Y	-	-	1	^{137}Xe	1	3	-
^{99}Zr	2	1	-	^{138}Xe	-	1	-
^{98gs}Nb	1	1	1	^{137}I	1	2	1
^{98m}Nb	-	-	-	^{138}I	-	-	2
^{100gs}Nb	1	1	1	^{140}Cs	-	-	1
^{100m}Nb	-	1	-	^{142}Cs	3	-	1
^{102gs}Nb	2	2	1				

V. Guadilla's PhD thesis (9 nuclei Valencia)
L. Le Meur's PhD thesis and J. – A. Briz-Monago's Postdoc (3 nuclei Subatech)
V. Guadilla's Postdoc (5 nuclei Subatech)
A.Beloeuvre's PhD (1 nucleus Subatech, waiting for planned TAGS experiment@Jyväskylä)

Reactor Antineutrinos & Fundamental Physics

- **TAGS results from the last decade have improved the quality of the predictions for reactor antineutrinos reaching the best agreement with the Daya Bay** ones obtained so far with a model, leaving little room for the RAA, **provided that the correction of more Pandemonium data should reduce this discrepancy**

- **Shape anomaly unexplained**



M. Estienne et al. PRL 123, (2019) 022502.
Algora et al., *Eur. Phys. J. A* 57, 85 (2021).

⇒ **Several Focusses for Future:**

⇒ above 4.5 MeV « shape anomaly », shorter-lived nuclei ($T_{1/2}$ from hours-minutes to a few tens of ms), mostly in the light fission products, a few in the heavy ones

⇒ Isomer decays play a major role in the high energy part of the spectrum

⇒ Need for more precise predictions for short times after fission: shorter-lived nuclei (CNNS experiments)

⇒ Better understanding of the antineutrino spectra for the future neutrino exp. (ex. JUNO-TAO)

Reactor Decay Heat (DH)

- TAGS results from the last decade have improved the quality of the predictions for reactor decay heat
- Still some Pandemonium candidates in the priority lists
- Still unexplained discrepancies especially for ^{235}U thermal fission pulse
- Still need improved predictions for future reactor designs & fuels
- Need to better control uncertainties on decay heat at short times

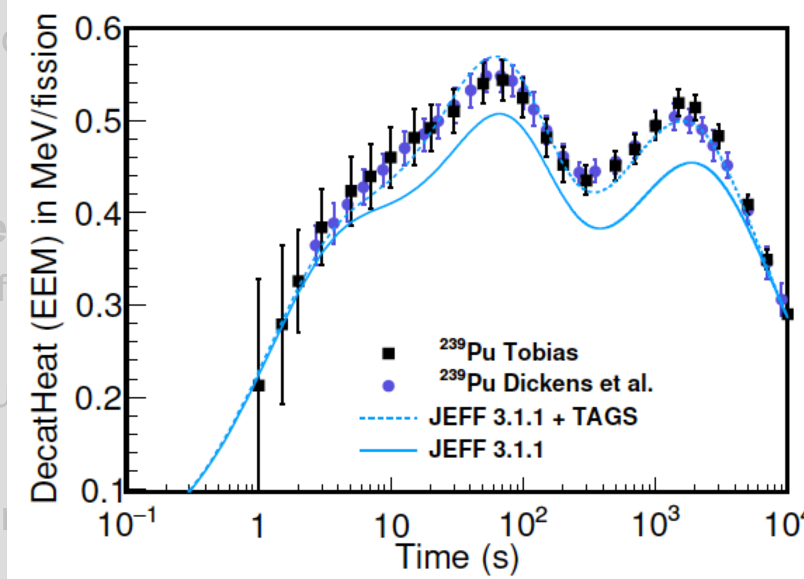


Fig. 13. Impact of the inclusion of the total absorption measurements performed for 13 decays (^{86,87,88}Br, ^{91,91,94}Rb, ^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc) published in Refs. [7,8,24, 62,67] in the gamma component of the decay heat calculations for ^{239}Pu.

Algora et al., *Eur. Phys. J. A* 57, 85 (2021). Calc. By L. Giot (Subatech)

⇒ **Several Focusses for Future:**

⇒ Focus on shorter-lived contributors: already existing lists (IAEA reports)

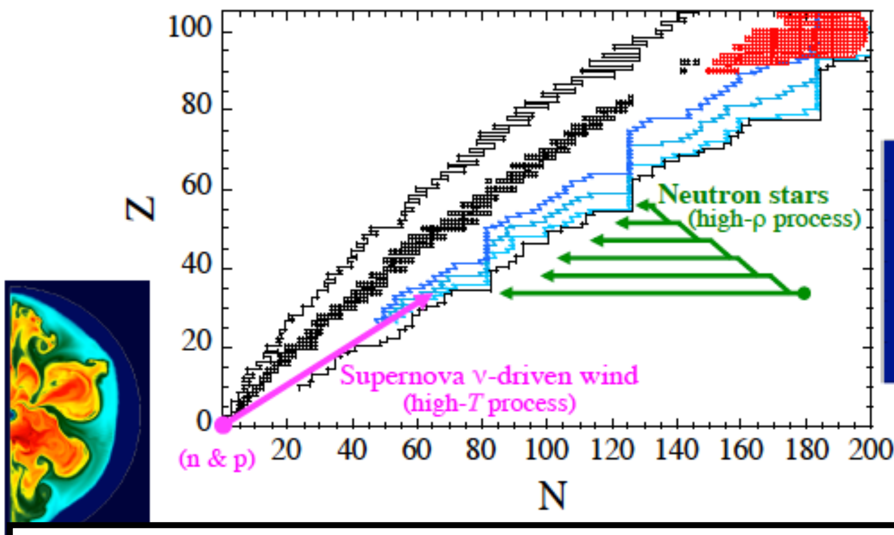
⇒ new lists to be established for innovative reactor designs (on-going)

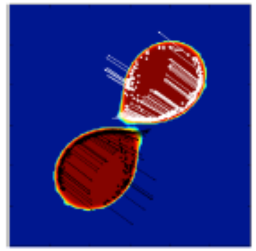
Scientific Case

- Applications: Reactor Physics, Neutrino Physics
- **Nuclear Astrophysics (& Structure)**
- Nuclear Structure

R-Process

one of the still unsolved puzzles in nuclear astrophysics
… the r-process site remains unknown …





Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as one of the top 11 questions in Physics and Astronomy
("Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century": 2003, National research council of the national academies, USA)

The Astrophysical Journal Letters, 848:L16 (7pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa9059

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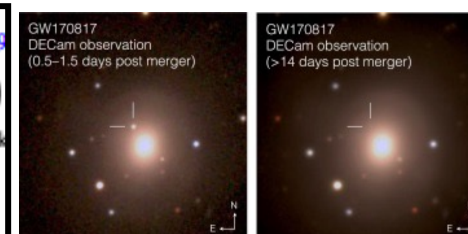
CrossMark

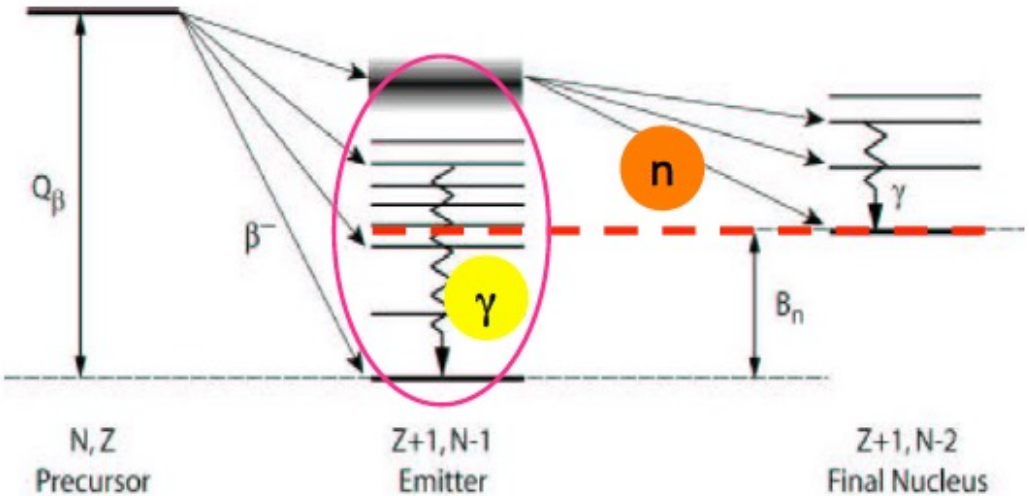
The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera

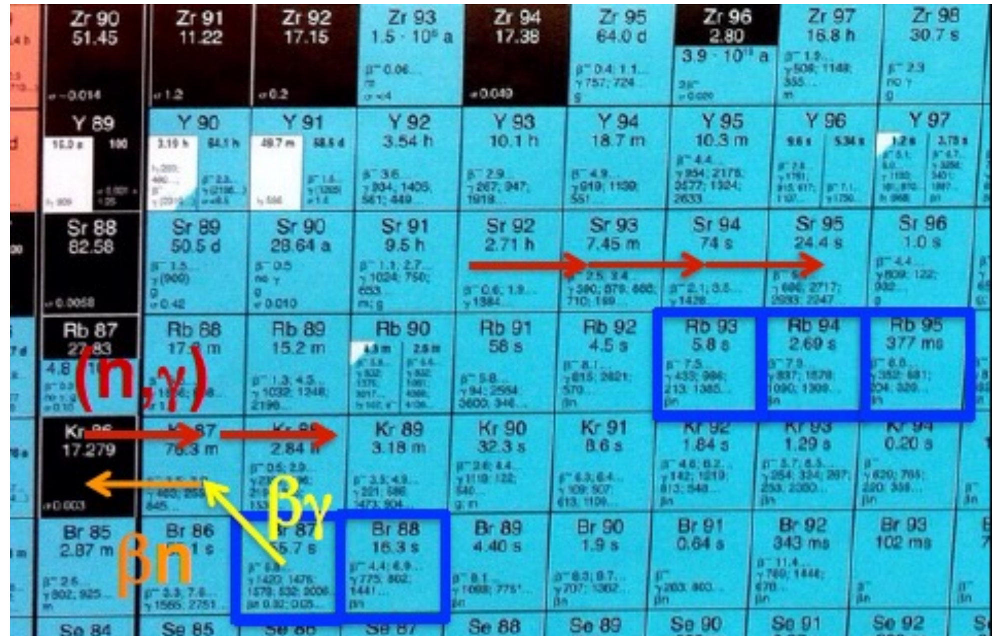


Kilonova predicted by astronuclear physicists Metzger et al. in 2010 !!!

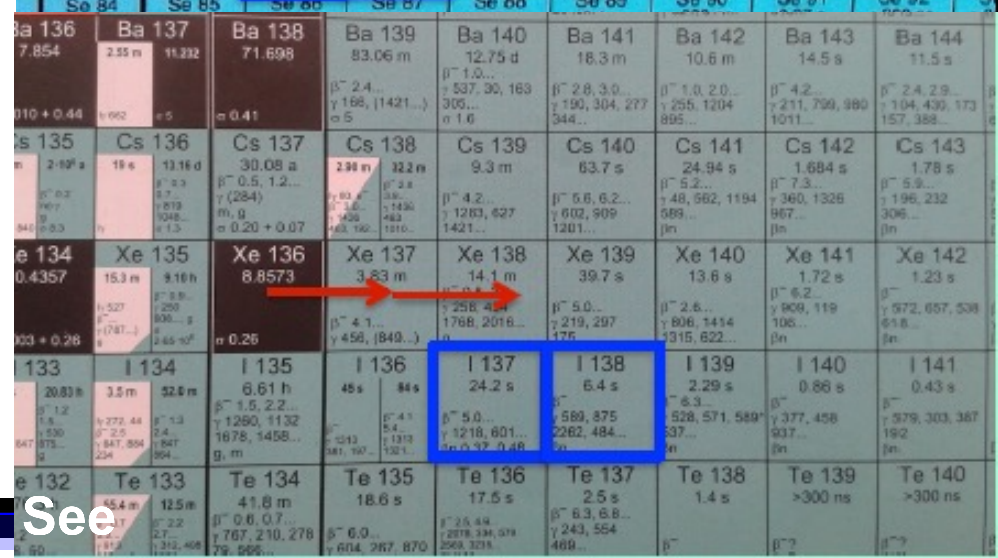
« Both the light curves and spectra closely **resemble predictions for a 'kilonova' a transient powered by radioactive decay of heavy nuclei and isotopes synthesized through the r-process in the merger ejecta**. This is the **first clear demonstration that r-process nucleosynthesis occurs in neutron star binary mergers,** and although this is a single event, the inferred ejecta mass and event rate suggest that such mergers could be the dominant r-process site. »

Total Absorption Spectroscopy of β-delayed neutron emitters





Isotope	P_n (%)	S_n (MeV)	Q_β (MeV)
^{87}Br	2.60(4)	5.5152(3)	6.818(3)
^{88}Br	6.58(18)	7.054(3)	8.975(4)
^{93}Rb	1.39(7)	5.290(9)	7.466(9)
^{94}Rb	10.18(24)	6.828(10)	10.281(8)
^{95}Rb	8.7(3)	4.348(7)	9.228(21)
^{137}I	7.14(23)	4.0256(1)	6.027(9)
^{138}I	5.56(22)	5.660(3)	7.992(7)



β-decay of delayed neutron emitters as a "surrogate" of the (n,γ) reaction

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)

Table 7. P_γ obtained from our measurements [24, 25] in comparison with the Pn values of the decays. P_γ is defined as the gamma emission probability above the S_n value (in analogy to P_n). The values are given in % (see the text for more details).

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)

^{94}Rb: γ-ray branching one order of magnitude higher than H-F calculation with standard parameters.

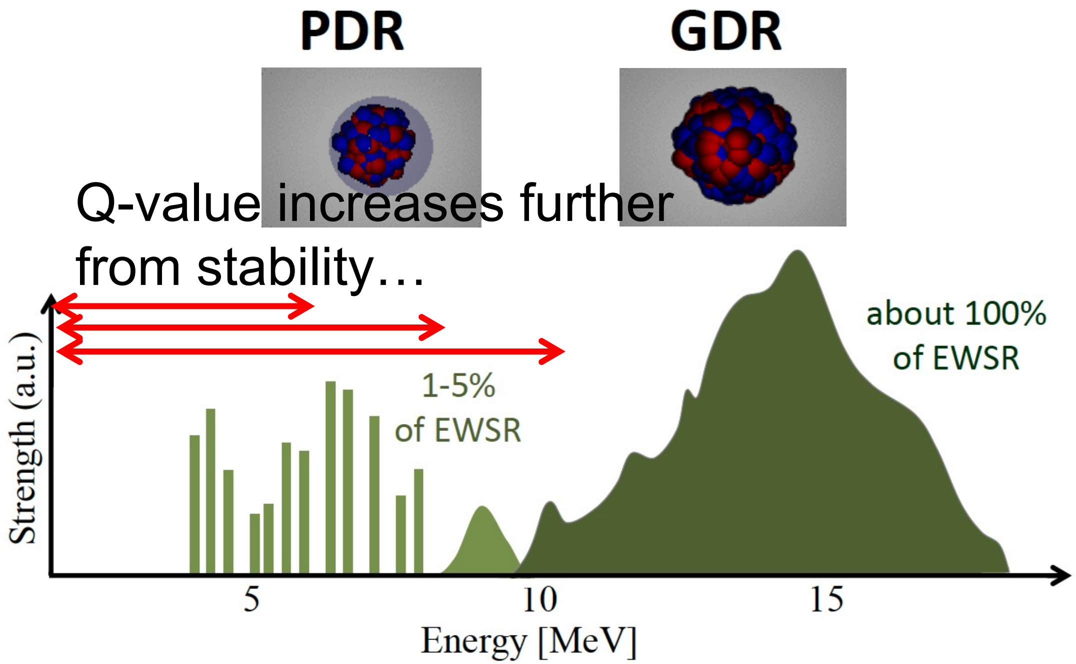
⇒**Such an enhancement of Γγ will have a similar effect on the (n,γ) cross section: impact on r-process abundance**

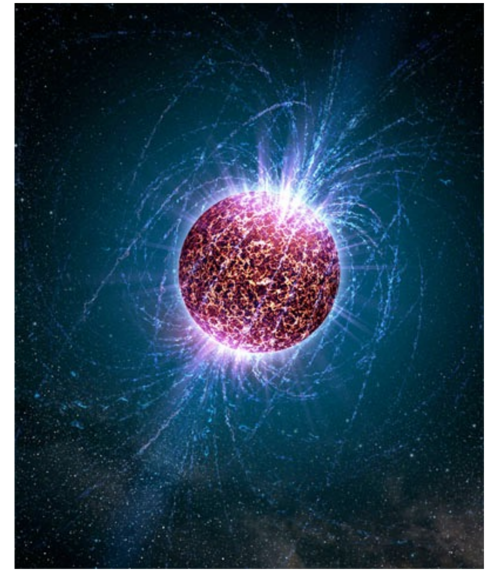
⇒ Experiment done using the Total Absorption γ-ray Spectroscopy (TAGS) technique (calorimetry), the most suited for detection of high energy gamma rays

⇒ **Very interesting as (n,γ) reaction rates are very hard to measure on such exotic nuclei**

Low-lying Collective Modes

Q-value increases further from stability…

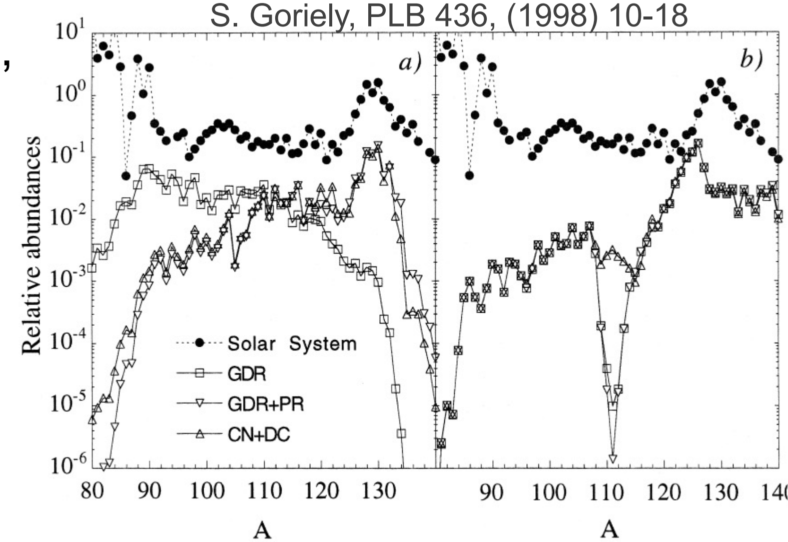




Credit: Casey Reed, Penn State Uni.

- Studying collective modes in exotic nuclei is a challenge, use the β-decay as a probe for low-lying collective modes in the daughter nucleus would allow to:
  - ❑ Go further from the stability than using reactions
    - ➢ a real opportunity to study their presence systematically when spins/parities are favorable
  - ❑ Complement other techniques such as (g,g'), (a,a'), etc…
  - ❑ Get almost background free data

S. Goriely, PLB 436, (1998) 10-18



Beta Decay and the N = 82 Waiting Point nuclei

B. Rubio, J. Agramunt, A. Algora, C. Domingo, S. Origo, J.L. Taín

IFIC-CSIC Valencia, Spain

B. Gomez-Hornillos, F. Calviño, G. Cortes

SEN-UPC Barcelona, Spain

D. Cano-Ott, T. Martinez

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W. Gelletly, Z. Podolyak, P. H. Regan

Univ. if Surrey, Guilford, UK

A. Jungclaus

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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

distribution shows peaks near A= 80, 130 and 195 corresponding to progenitors

LoI, day-one-experiments Jan 2011

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

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B. Gomez-Hornillos, F. Calviño, G. Cortes
SEN-UPC Barcelona, Spain

D. Cano-Ott, T. Martinez
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W. Gelletly, Z. Podolyak, P. H. Regan
Univ. if Surrey, Guilford, UK

M. Fallot, A. Porta
Subatech, CNRS/IN2P3, U. of Nantes, France

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.

Cross section measurements for p-process nucleosynthesis

Scientific motivation

p-nuclei = rare, stable proton-rich isotopes
~ 35 nuclei from 74Se to 196Hg

Produced in **explosive nucleosynthesis** (supernovae)

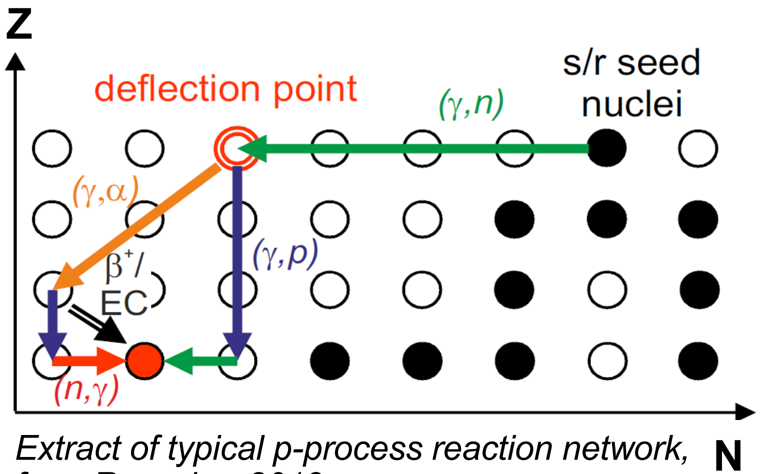
Reaction network :
~ 2000 nuclei (mostly exotic), 20 000 reactions
Reaction cross sections from **statistical model**

Experimental data needed
to constrain the **statistical parameters**
(optical potentials, level densities, gamma strength)

Photo-disintegrations (γ,n), (γ,p), (γ,α)
Radiative captures (p,γ), (α,γ)

Astrophysical energy range :
deep below Coulomb barrier
challenge of very low cross sections (below 1 μb)

Crab nebula (SN remnant)



Extract of typical p-process reaction network, from Rauscher 2013

Cross section measurements for p-process nucleosynthesis

Experimental project for gamma-summing at NFS

p-process collaboration *in France : IP2I-Lyon, GANIL, LPC-Caen, IJCLab, Subatech, IPHC,*
in Europe : Demokritos, Universities of Bruxelles (ULB), Jyväskylä, Huelva, Surrey, Lisbon, and beyond : iThemba

Objective : use **high-intensity beams to access low cross sections** for radiative captures (p,γ), (α,γ) at astrophysical energy

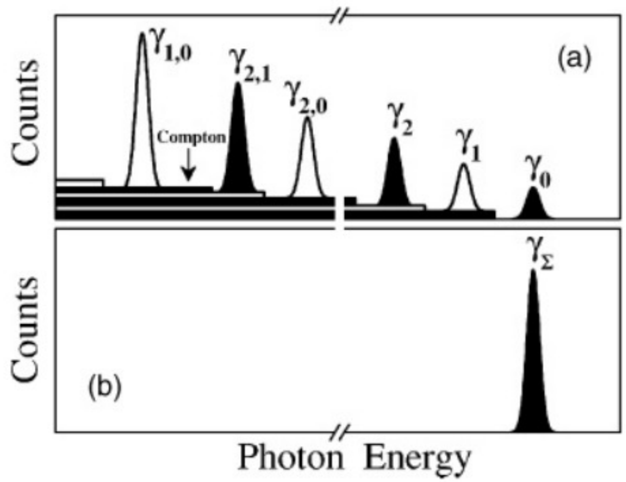
Required beams : **protons** 1-3 MeV, **alphas** 8-12 MeV

Measurement techniques :
- **activation** when allowed by lifetime of reaction product
- in many cases, **in-beam** measurements are needed :
gamma angular distribution (spectrometers)
or **gamma summing** (calorimeter)

New approach for in-beam measurements :
Gamma summing with **segmented calorimeter**
=> information on gamma cascade **multiplicity**
=> better knowledge of **sum peak efficiency**

Needs concerning **targets :**
- **manufacturing of thin targets of enriched isotopes in mass range A ~ 100-200**
- solutions for **sustaining high intensity beams**

γ-summing, from Spyrou+ 2007



LoI @ SPIRAL2 NFS

Letter of Intent for SPIRAL2

Measurement of (p,γ), (p,n) and (α,γ) cross sections at energies relevant for the *p*-process at the SPIRAL2 facility

Spokesperson: G. Randisi and I. Companis
Co-spokespersons: B. Bastin*, C. Ducoin and O. Stezowski
(*contact person: B. Bastin)

B. Bastin,[1] A.M. Blebea-Apostu,[2] C. Borcea,[2] F. Boulay,[3] I. Companis,[4] F. de Oliveira Santos,[1] C. Ducoin,[4] J. Dudouet,[4] D. Etasse,[5] D.G. Ghita,[2] C.M. Gomoiu,[2] J. Grinyer,[1] D. Guinet,[4] O. Kamalou,[1] C. Mancuso,[4] G. Maquart,[4] R. Margineanu,[2] J. Mrazek,[6] A. Negret,[2] G. Randisi,[1] N. Redon,[4] I. Stefan,[7] O. Stezowski,[4] J.C. Thomas,[1] and L. Trache[2]

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[6] Euratom/IPP.CR Fusion Association, Nuclear Physics Institute, 25068 Rez, Czech Republic
[7] Institut de Physique Nucléaire, Université Paris-Sud-11-CNRS/IN2P3, 91406 Orsay, France

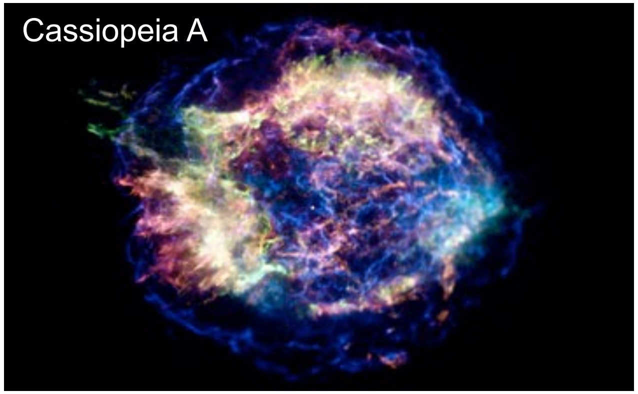
We propose an experimental program to measure key (p,γ), (p,n) and (α,γ) reaction cross sections with high impact on models describing the abundances of the so-called *p*-nuclei. Information on most specific cross sections is missing in the relevant energy region and the reaction rates used to determine the *p*-process abundances rely on statistical model (Hauser-Feshbach) calculations. The unprecedented intensity of the low-energy p and α beams foreseen at the SPIRAL2 LINAC constitutes a unique possibility to perform accurate measurements in the relevant energy range and significantly improve the understanding of *p*-nuclei abundances. Three experimental campaings are envisaged : one using the activation method and two using in-beam techniques. While the activation technique is indicated to study the reactions leading to a short-lived nucleus, several reactions of interest lead to a stable nucleus and the measurement of their cross sections require in-beam γ spectroscopy, using either angular distribution or gamma-summing technique. Details concerning the experimental program is provided in this Letter of Intent.

1. Motivation: understanding the observed abundances of p-nuclei

Most of the observed heavy nuclei ($Z \geqslant 26$) have been produced in neutron-induced nucleosynthesis processes, like the slow neutron capture (s-process) and rapid neutron capture (r-process) [1–4]. Nevertheless, about 35 nuclei are observed in nature on the neutron-deficient side of the valley of stability, from ^{74}Se to ^{196}Hg, which are shielded from production by n-capture processes. The nucleosynthesis process corresponding to the production of the so-called *p*-nuclei in stars is referred to as *p*-process and its nature is still under debate.

Study of core-collapse supernovae

masses around ^{78}Ni (JYFL)



Credit: NASA

Core-Collapse Supernovae simulation : One of the BIG astro challenges

Present best 3D hydro simulations do not yet produce satisfactory CCSN explosion **=> Microphysics is essential !**

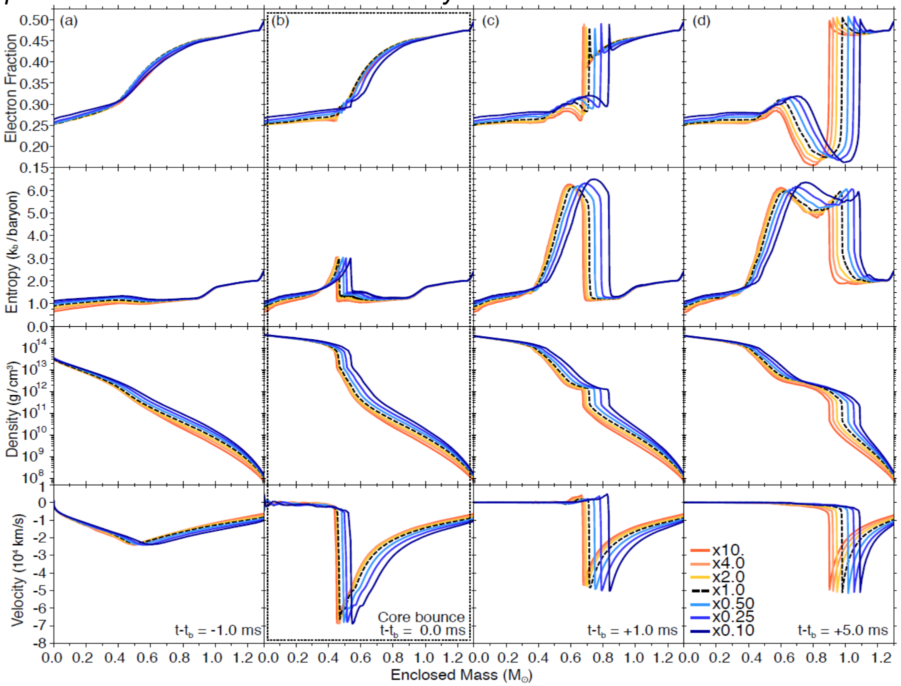
Key observables

- **EC rates : GT response** (β-decay, charge exchange)
- **Nuclear mass**
- **EoS**

Key regions of the nuclear chart

- **Around ^{78}Ni (N=50)**
- **Around ^{128}Pd (N=82)**

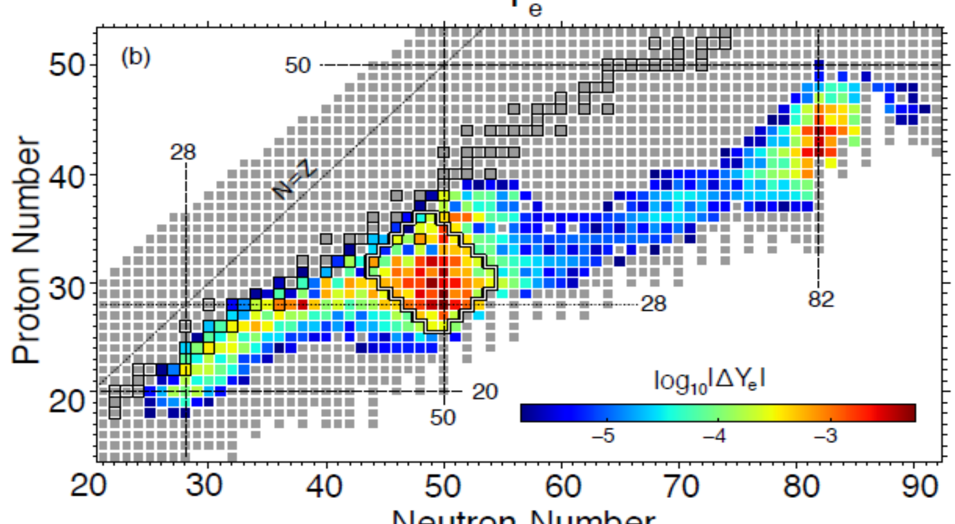
position of the shock front is extremely sensitive to the nuclei EC rates



Sullivan *et al.* ArXiV:1508.0734

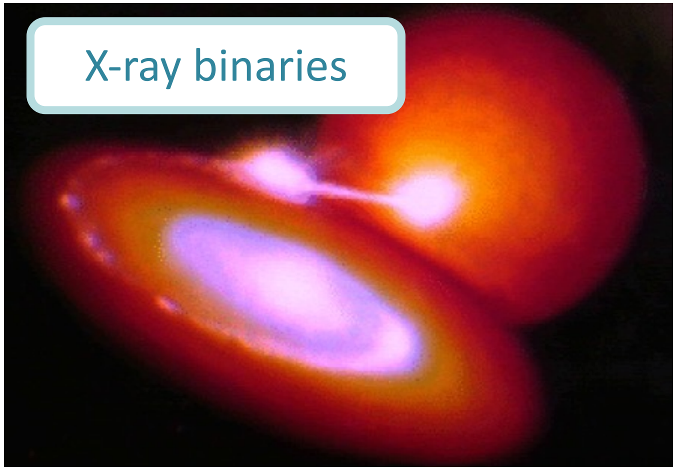
Electron-capture rates

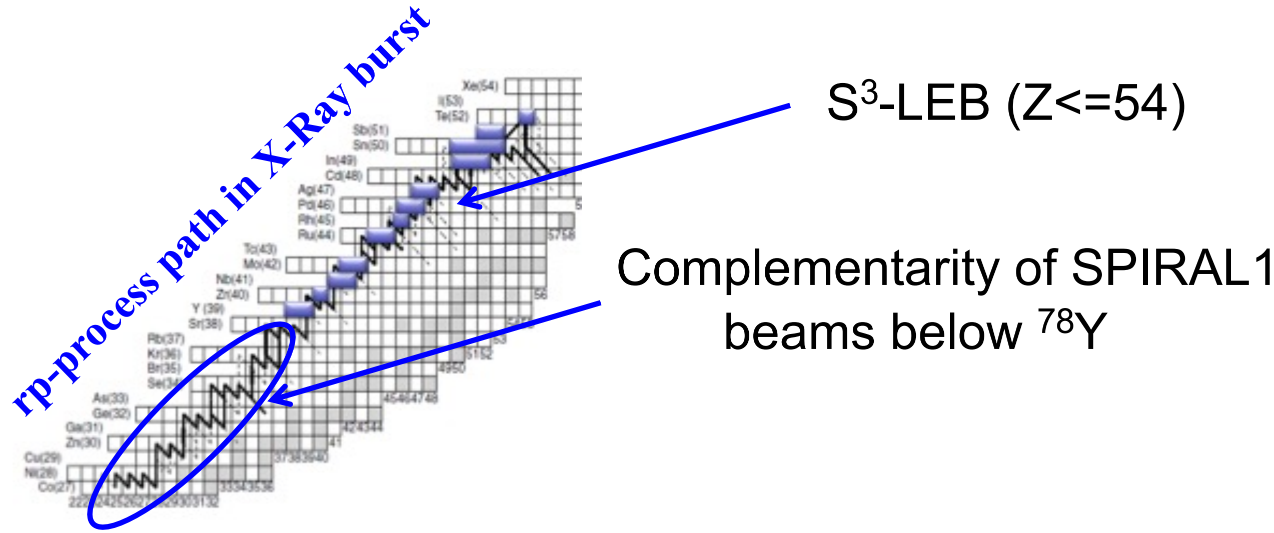
- EC : crucial all along the life of a star *(particularly in massive stars → CCSN!)*
- but: model uncertainties (especially in **n-rich nuclei**!)



Sullivan *et al.* ArXiV:1508.0734

Rp-process





Sequence of rapid proton captures and β+ decays near the proton dripline

Existing proposals and LoI @ ISOLDE and Riken

Some complementary measurements could be proposed for the rp-process

@SPIRAL1 + S^3-LEB(DESIR): S^3 will provide access to the most exotic nuclei + refractory elements

^{44}Ti Nucleosynthesis

Quest for resonances in the reaction $^{45}V(p,\gamma)^{46}Cr$

Proposal resonant elastic scattering 2007 : F. De Oliveira, M. Fallot et al. Proposal E773 : Á. M. Sánchez Benítez, J.-C. Thomas et al.

TABLE 5

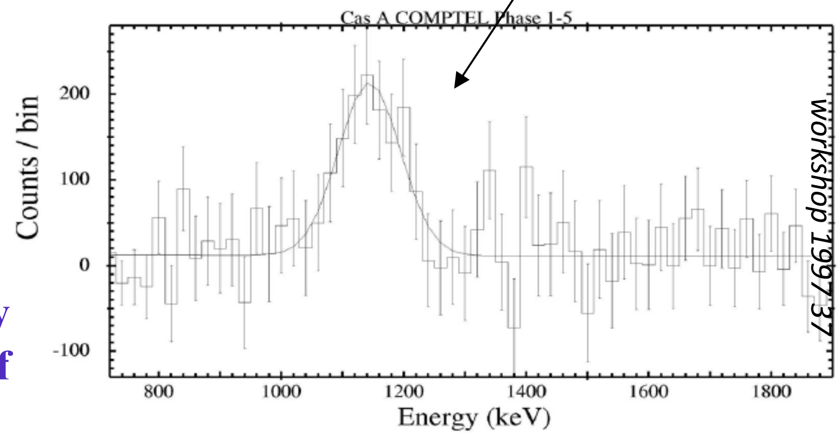
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
$^{44}Ti(\alpha, p)^{47}V$	−0.394
$\alpha(2\alpha, \gamma)^{12}C$	+0.386
$^{45}V(p, \gamma)^{46}Cr$	−0.361
$^{40}Ca(\alpha, \gamma)^{44}Ti$	+0.137
$^{57}Co(p, n)^{57}Ni$	+0.102
$^{36}Ar(\alpha, p)^{39}K$	+0.037
$^{44}Ti(\alpha, \gamma)^{48}Cr$	−0.024
$^{12}C(\alpha, \gamma)^{16}O$	−0.017
$^{57}Ni(p, \gamma)^{58}Cu$	+0.013
$^{58}Cu(p, \gamma)^{59}Zn$	+0.011
$^{36}Ar(\alpha, \gamma)^{40}Ca$	+0.008
$^{44}Ti(p, \gamma)^{45}V$	−0.005
$^{57}Co(p, \gamma)^{58}Ni$	+0.002
$^{57}Ni(n, \gamma)^{58}Cu$	+0.002
$^{54}Fe(\alpha, n)^{57}Ni$	+0.002
$^{40}Ca(\alpha, p)^{43}Sc$	−0.002

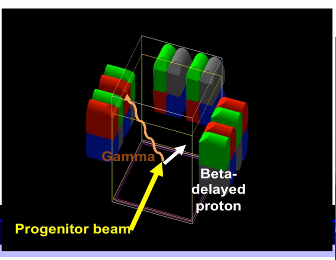
[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}Ti)$ near the standard reaction rates.

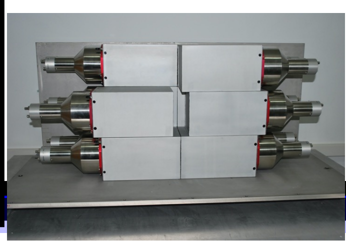
- ^{44}Ti is produced in type II supernovae (SN II) mechanism: α-rich freeze-out. Shock-wave after core-collapse reaches the α-rich region in the cooling phase, $1 < T_9 < 5$
- ^{44}Ti ($T_{1/2}$= 59 y) is a cosmic gamma ray emitter (67.9, 78.4, 1157 keV). Observed by COMPTEL and INTEGRAL satellites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

Abundance of produced ^{44}Ti is **very sensitive to the reaction rate of ^{45}V(p,γ) (not known exp.)**



Iyudin et al. 2nd INTEGRAL workshop 1997 37





Spectroscopy of key nuclei in astrophysics:

Experimental approaches: TAGS technique to measure the γ-rays emitted above the p emission threshold, constraining then the (p, γ) cross-section @ LISE/GANIL, and then with Spiral1/S^3

Beta-delayed proton emission studied with ACTAR TPC & EXOGAM

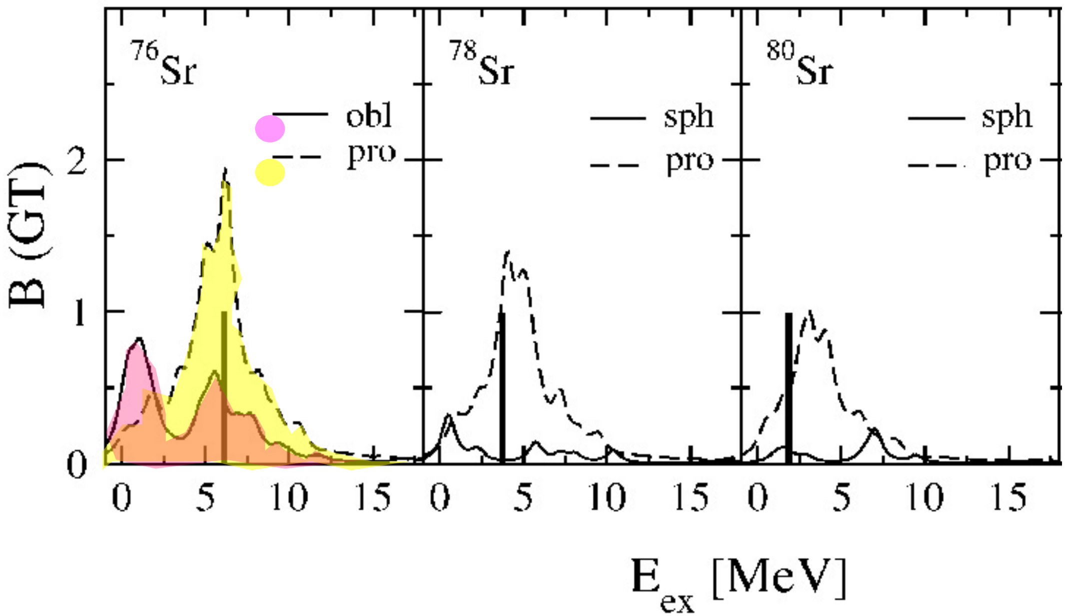
Scientific Case

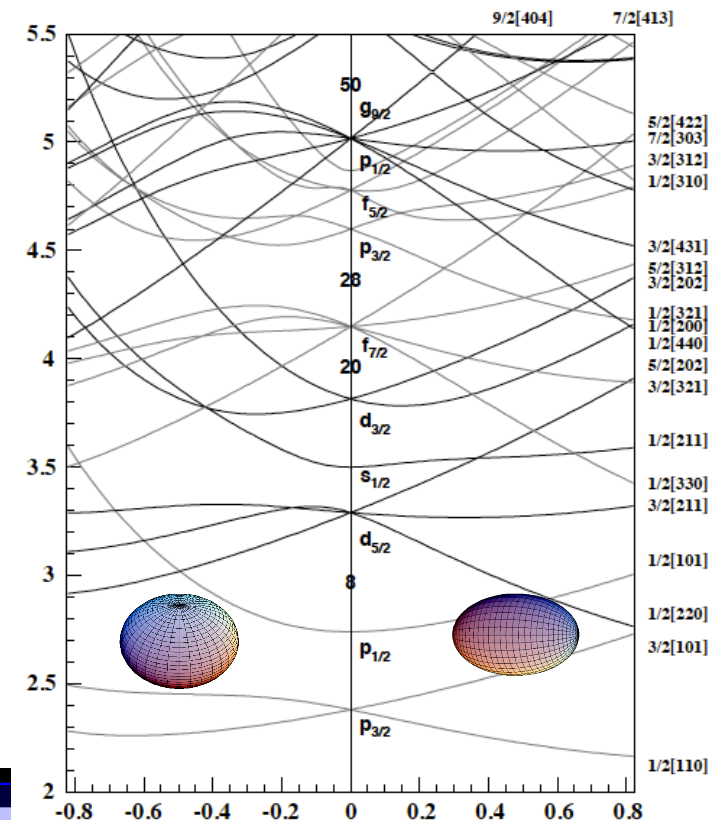
- **Applications: Reactor Physics, Neutrino Physics**
- **Nuclear Astrophysics (& Structure)**
- **Nuclear Structure**

What can beta decay offer apart from spectroscopy?

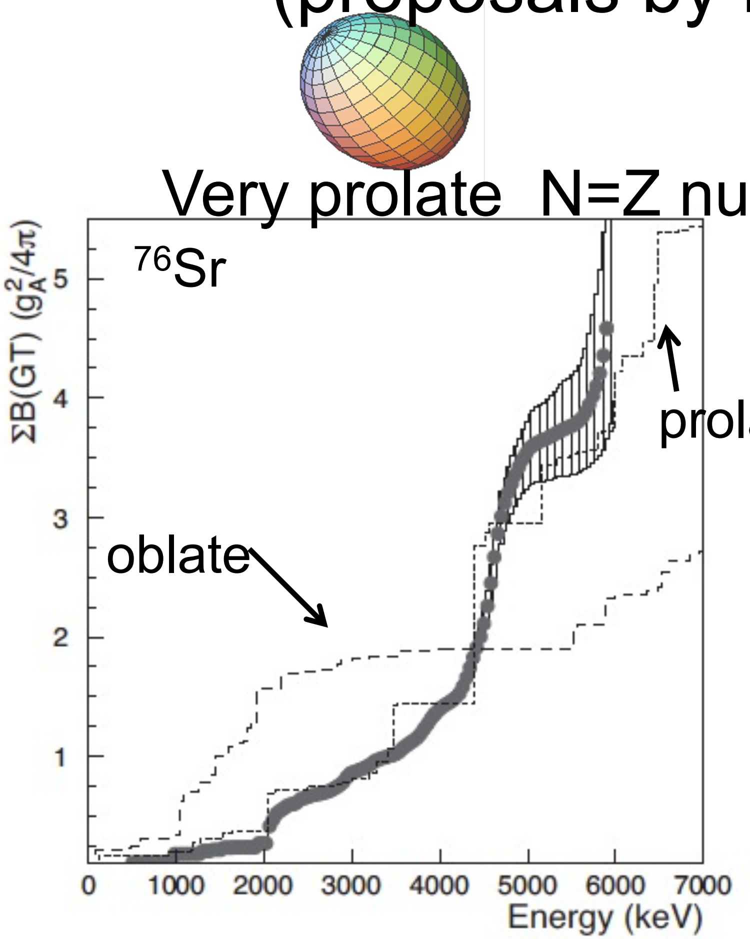
There is an alternative, based on the pioneering work of I. Hamamoto, (Z. Phys. A353 (1995) 145) later followed by studies of P. Sarriguren *et al*., Petrovici *et al*. related to the dependency of the strength distribution in the daugther nucleus depending on the shape of the parent. It can be used when theoretical calculations predict different B(GT) (strength) distributions for the possible shapes of the ground state (prolate, spherical, oblate).

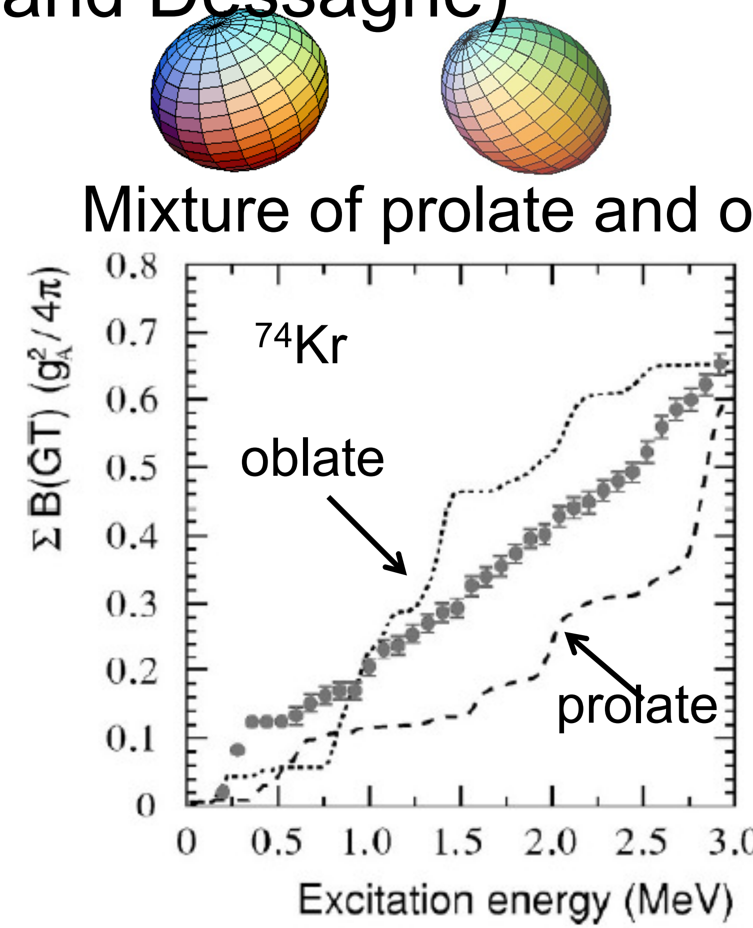
P. Sarriguren *et al*., Nuc. Phys. A635 (1999) 13





Some earlier examples of shape studies (proposals by Rubio and Dessagne)

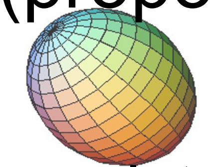




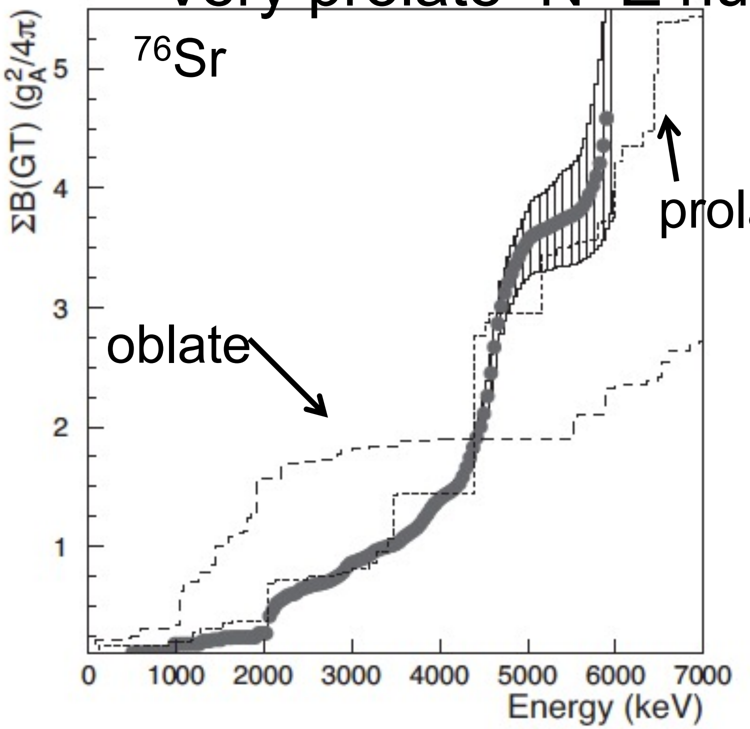
E. Nácher *et al. PRL 92 (2004) 232501 and PhD thesis Valencia*
Ground state of ^{76}Sr prolate (β_2 ~0.4) as indicated in Lister et al., PRC 42 (1990) R1191

E. Poirier *et al., Phys. Rev. C 69, 034307 (2004) and PhD thesis Strasbourg*
Ground state of ^{74}Kr:(60±8)% oblate, in agreement with other exp results and with theoretical calculations (A. Petrovici et al.)

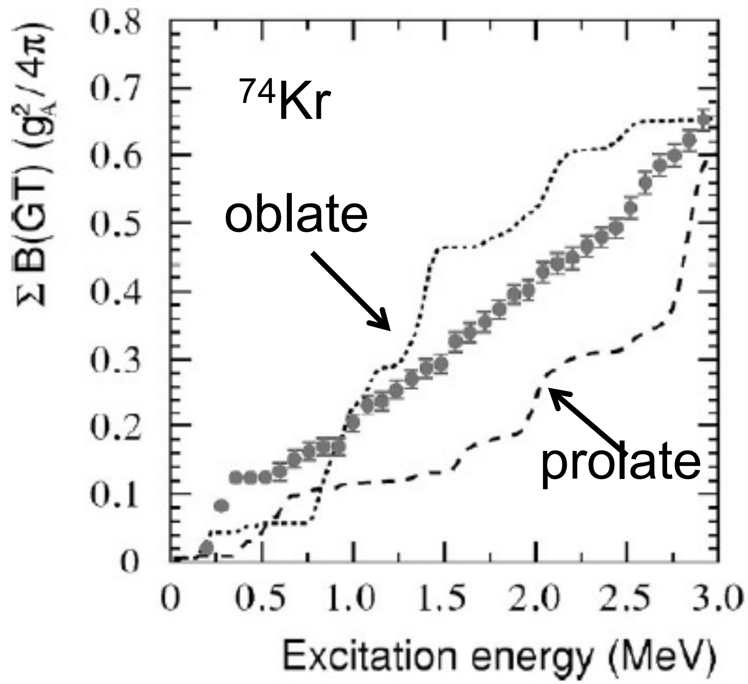
Some earlier examples of shape studies (proposals by Rubio and Dessagne)



Very prolate N=Z nucleus



Mixture of prolate and oblate



E. Nácher e…

PhD thesis …

Ground stat…

Lister et al., …

… *(2004)*

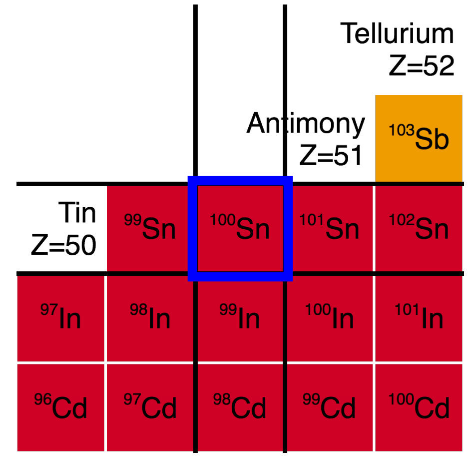
… *agreement with other exp results and with theoretical calculations (A. Petrovici et al.)*

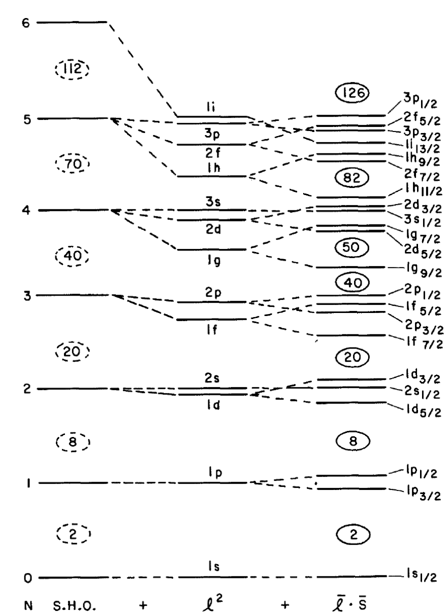
○Recent summary of results from the last decade(s):

Algora et al., *Eur. Phys. J. A* **57**, 85 (2021).

^{100}Sn region

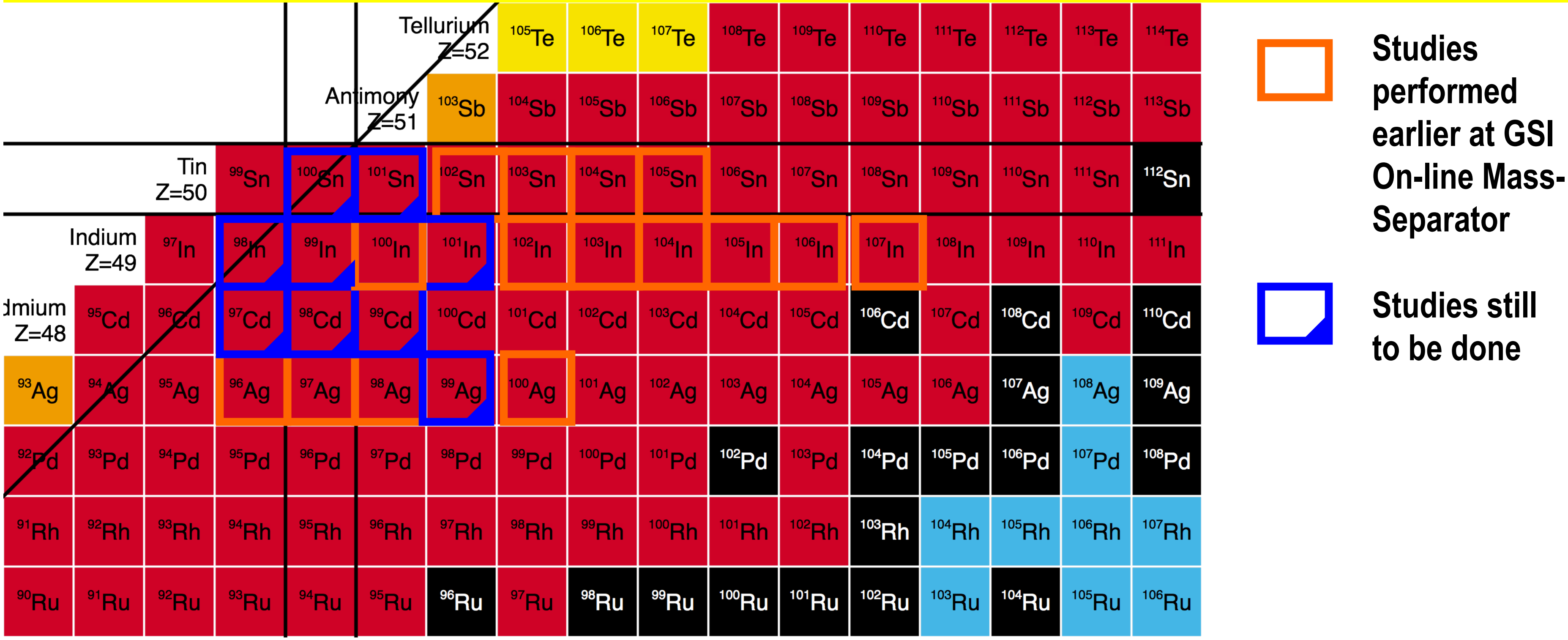
- ^{100}Sn is the last accessible N~Z nucleus
- Double magic nucleus (N=Z=50), its structure is determined by the very well defined shell gap between the $g_{9/2}$, $g_{7/2}$ orbitals
- Its beta decay is of particular interest, because the BGT should be concentrated in only a few levels and accessible within the Q_{EC} value of the decay, which allows for the possibility of studying the quenching of the GT strength in beta decay.
- The fragmentation of the strength is expected to be small (and possibly detectable with proper detectors)
- Shell model calculations are possible and available





Courtesy A. Algora

TAGS studies in the ^{100}Sn region



- Study the GT resonance in a region where it can be accessible within the Q_{EC} window (πg9/2 -> νg7/2)
- Study the quenching of the GT strength. The measurement of the strenght distribution and its comparison with theory provides an stringent test of theory
- Study of the shell structure of nuclei in the vicinity of N=Z=50
- Study of the πg9/2 -> νg9/2 and πg9/2 -> νg7/2 transitions and their competition (south-west of 100Sn)

LoI, day-one-experiments Jan 2011

Beta strength measurements in the ^{100}Sn region

A. Algora, B. Rubio, J.L. Tain, J. Agramunt, C. Domingo, E. Valencia, E. Estevez
IFIC (CSIC-Univ. Valencia), Valencia, Spain

D. Cano-Ott, T. Martinez
CIEMAT Madrid, Spain

W. Gelletly, Z. Podolyak, P. H. Regan, S.Rice
Univ. if Surrey, Guilford, UK

Zs. Dombrádi, D. Sohler, J. Timár,
MTA ATOMKI, Debrecen, Hungary

L. Caceres,
GANIL,CEA/DSM-CNRS,IN2P3, Caen, France

L. Batist,
PNPI-Gatchina, Russia

A. Jungclaus
IEM, Madrid Spain

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.

TAGS Experimental Challenges

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).

⇒ Natural improvement of the existing TAS: combine efficiency, energy resolution, segmentation and timing !

- Physics cases:

⇒ **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

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

⇒ **P-process**: TAGS = γ-summing technique, actual limitations come from the **uncertainty on the sum peak**

TAGS Experimental Challenges

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- Physics cases:

⇒ **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 **efficiency, n/γ separation through timing, better energy resolution, potential angular correlations**

⇒ **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**

⇒ **P-process**: TAGS = γ-summing technique, actual limitations come from the **uncertainty on the sum peak** **combine calorimetry & spectroscopy**

$(NA)^2$STARS Project

(NA)^{2}STARS Project

- **Upgrade of the DTAS detector with 16 $LaBr_3$**
- Already **7** crystals among partners
- **Large impact**: **GANIL, DESIR,** RIKEN, Jyväskylä, ISOLDE, FAIR, …
- **Broad Physics Case**: n-rich and n-deficient nuclei, further away from stability
- **Improved energy resolution of $LaBr_3$**
- **n/γ discrimination with TOF**
- **Higher segmentation: possible γ,γ correlation studies**
- Complement other setups

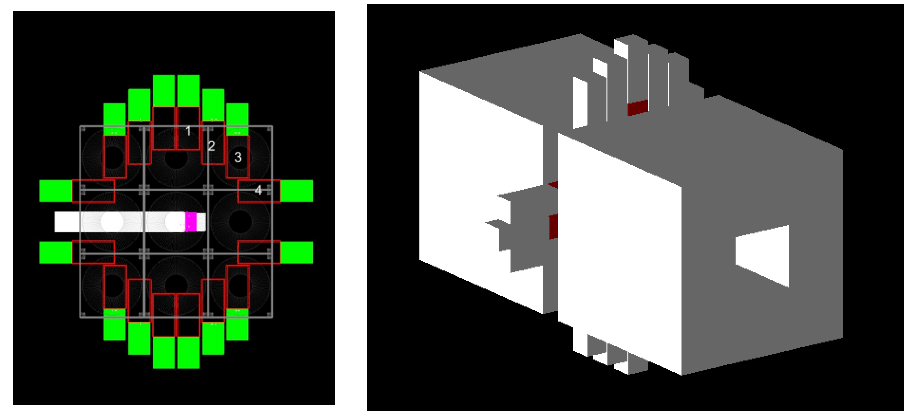


Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

⇒ Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer: Combination of calorimetric and spectroscopic tools for beta decay and in-beam measurements

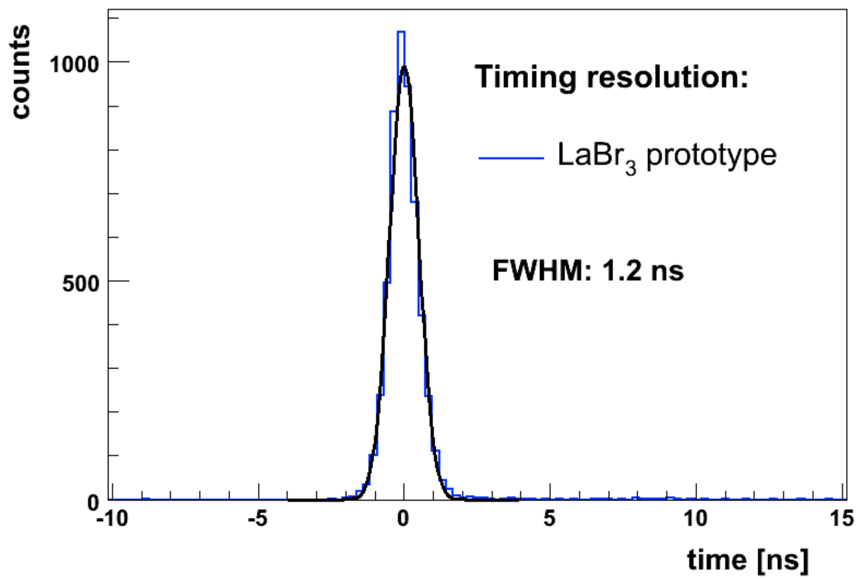
Technical Report for the Design, Construction and Commissioning of the DESPEC Beta Decay Total Absorption Gamma-Ray Spectrometer (DTAS)
presented by the DTAS collaboration

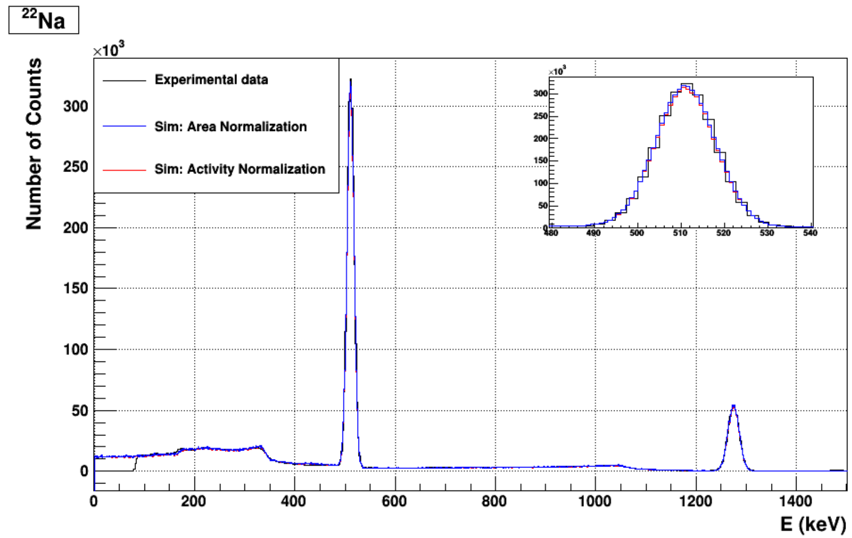
The high-resolution capabilities of the $LaBr_3$ detectors and their superior timing characteristics are indeed worth considering and we endorse the authors' proposal to include, if financially feasible, a ring of $LaBr_3$ detector modules into the final TAS instrument. It is precisely the combination of the high-resolution discrete spectroscopy with the calorimetric TAS that would lead to better understanding of the Sβ fine structure for neutron-rich nuclei.

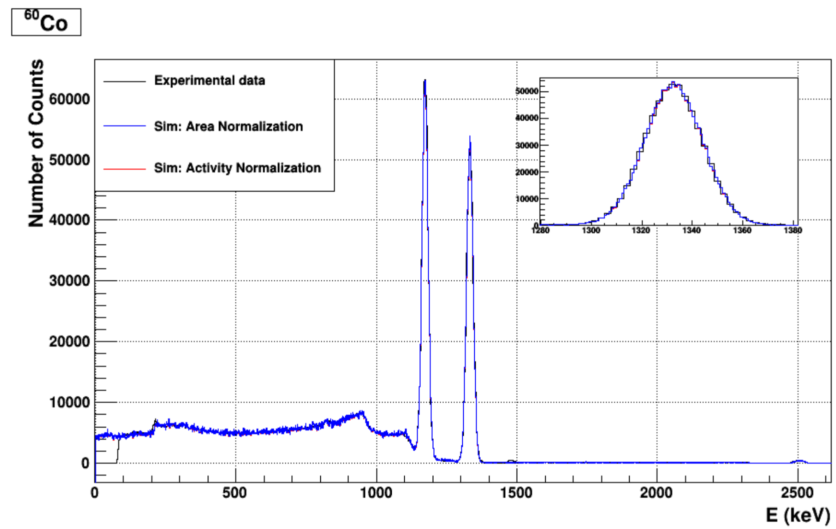
Individual Module Characterization

Energy Resolution: ~3% @ 1.33 MeV

Time Resolution:

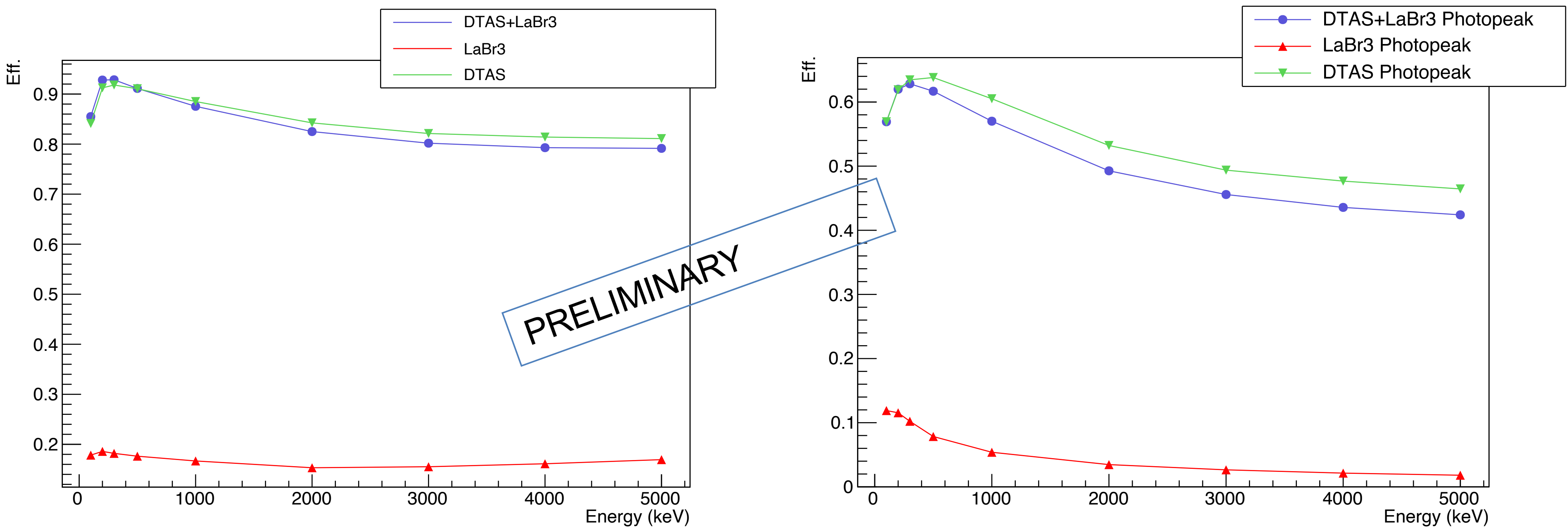






Gamma Efficiency

Geometry : Compromise between the TOF and efficiency



Gamma efficiency and photopeak for the geometry used

Also simulated: neutron efficiency, possible spectroscopic information in favorable cases

Possible Timeline for Experiments@ GANIL

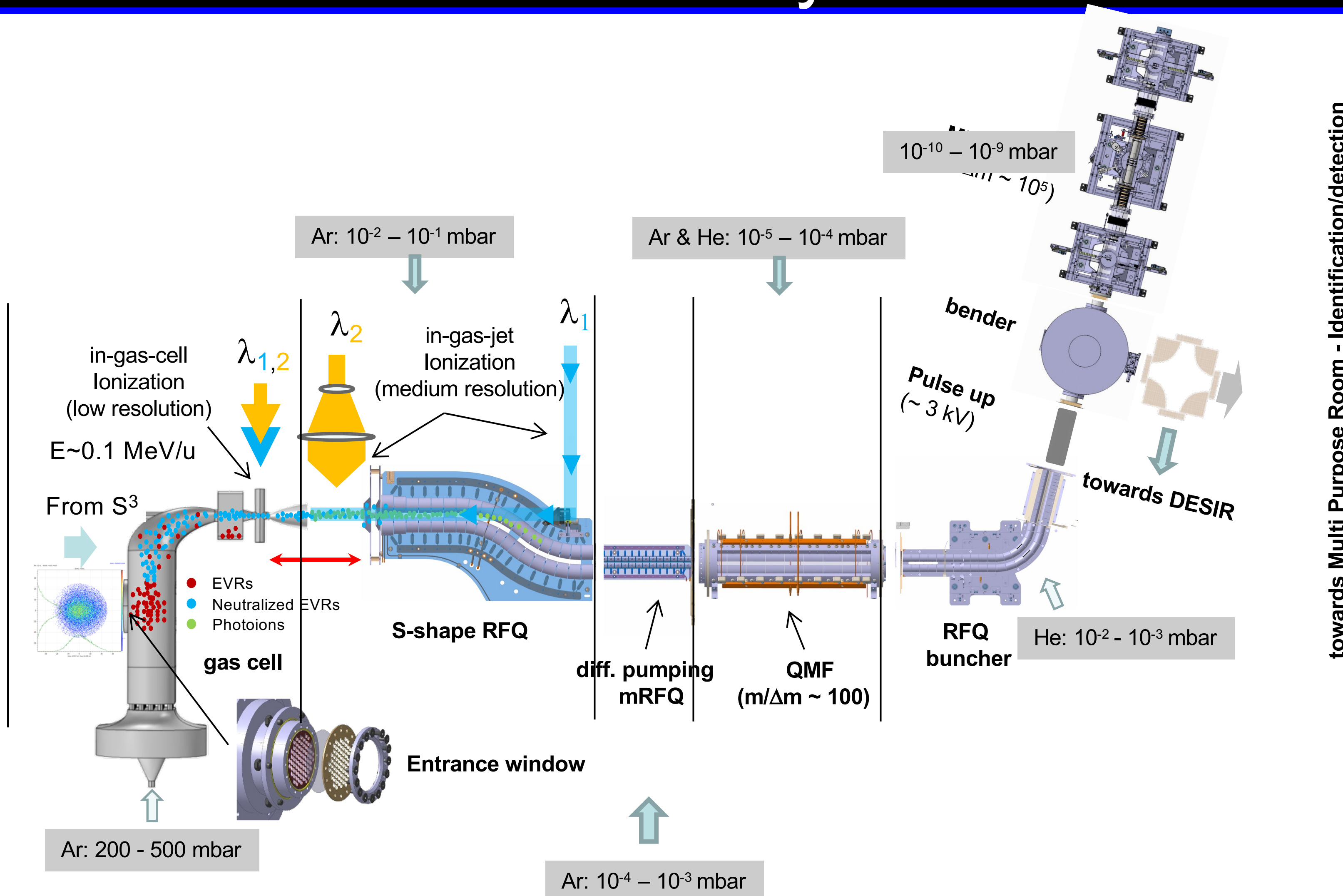
-

DESIR, NFS

- TAGS@DESIR: as contemplated more than a decade ago: the « easiest » for TAGS experiments: pure beams after the PIPERADE Penning trap. Horizon 2027-2028, neutron-deficient physics goals ;
- TAGS@NFS: cross-section measurements for p-process. Horizon 2027-2028 ;

DESIR Layout: Courtesy J. –C. Thomas

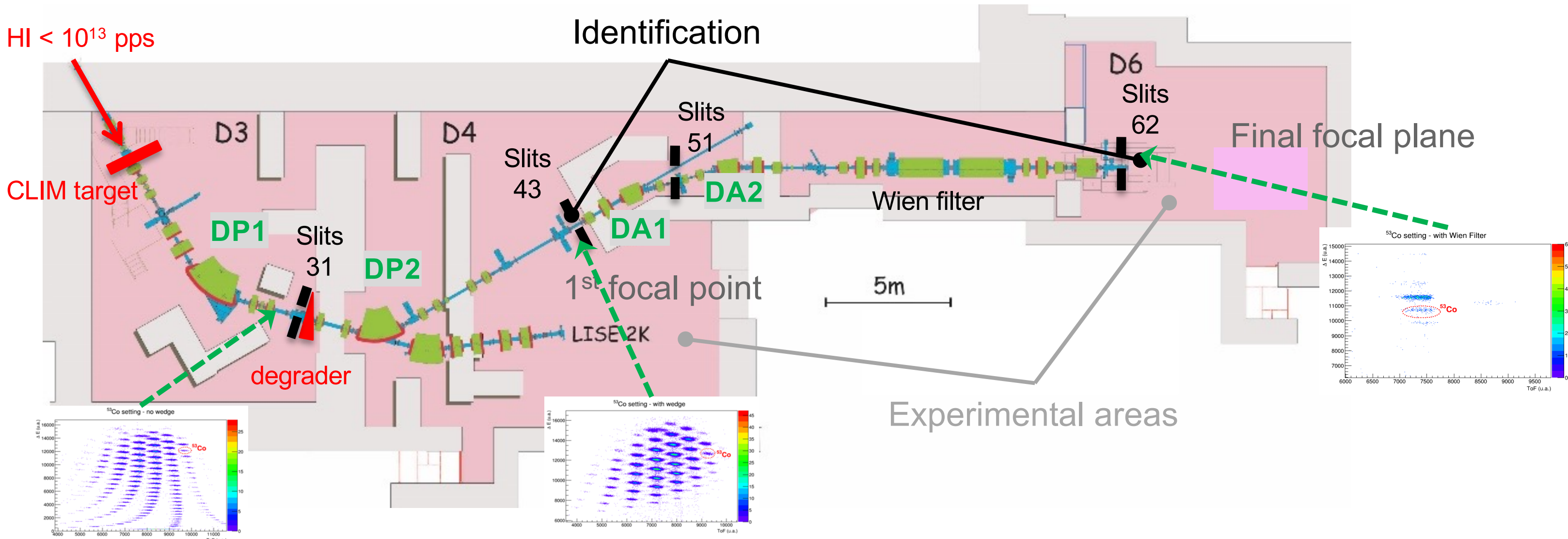
S3-LEB Layout



- TAGS@S3-LEB: would allow to tackle physics cases like the region around 100Sn (TAGS LoI in 2011) before. Day-1 experiments@S3-LEB: investigate technical possibility to install the STARS after the MR-TOF-MS, horizon 2025-2026 ;

LISE

The LISE spectrometer (44 m)



- TAGS@LISE3: **discussions on-going.** First proposal with the STARS could be in 2024, depending on the funding timeline. Take advantage of the $LaBr_3$ better energy resolution for the study of very short-lived nuclei:
  - ❑ N-rich cases @ LISE not possible (NB: some cases may be possible SP1 beam @ LIRAT)
  - ❑ N-deficient cases:
    - ➢ i.e. for ^{44}Ti nucleosynthesis: measurement of g-rays above the p emission threshold ;
    - ➢ or nuclear structure cases already investigated @LISE3 by IFIC-Valencia with high-resolution spectroscopy: ^{48}Fe, ^{52}Ni, ^{56}Zn. Goals: Missing b-strength, g-rays above p-emission threshold. **Set-up and beam conditions currently under investigation**.

LISE Layout: Courtesy J. –C. Thomas

^{44}Ti Nucleosynthesis: surrogate method

in beta-delayed proton emitters

Proposal resonant elastic scattering 2007 : F. De Oliveira, M. Fallot et al. Proposal E773 : Á. M. Sánchez Benítez, J.-C. Thomas et al.

TABLE 5

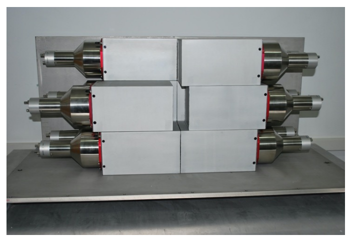
ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0^a$

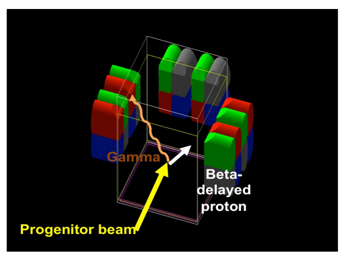
Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

Spectroscopy of key nuclei in astrophysics on n-deficient nuclei: several posible cases, example of ^{45}V(p,γ)^{46}Cr :

Experimental approaches: TAGS technique to measure the γ-rays emitted above the p emission threshold, constraining then the (p, γ) cross-section
@ LISE/GANIL (and then with Spiral1/S^3)
Beta-delayed proton emission studied with ACTAR TPC ?





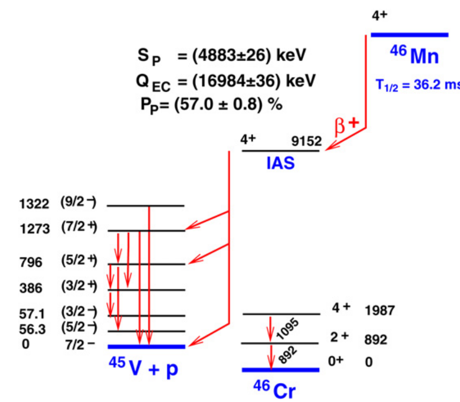


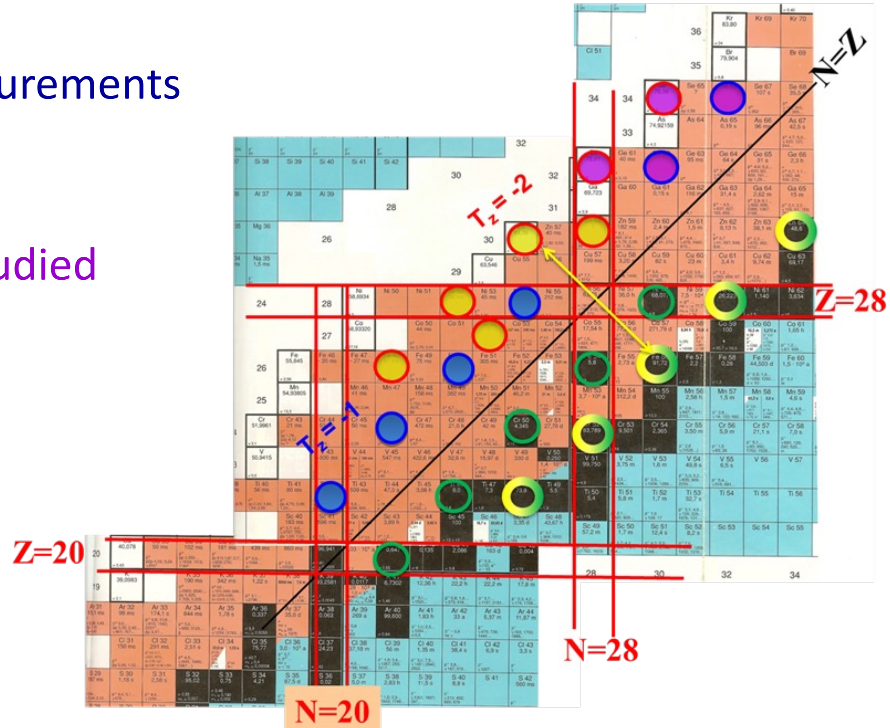
Fig. 24. Partial decay scheme for the β decay of ^{46}Mn. The decay scheme summarises the experimental results obtained in the present campaign.

From C. Dossat et al. / Nuclear Physics A 792 (2007) 18–86

Preliminary calculations of production rates and beam purity performed by J.-C. Thomas
Important constraint on beam purity for TAGS experiments

β decay of neutron-deficient nuclei

- During last decade the IFIC-Valencia group has performed a systematic study of the **β decay of n-deficient nuclei**
  - High-resolution γ-spectroscopy measurements
  - Detection of β-delayed protons

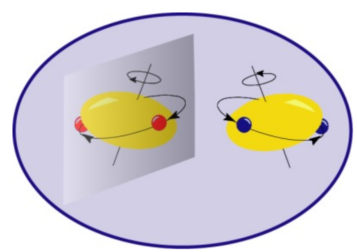


- Many cases with T_z=-1 and -2 have been studied

  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)

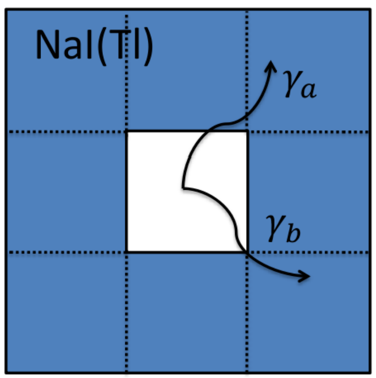
- β-decay data is enriched by the comparison with **complementary Charge Exchange (CE) reactions** on the stable mirror target

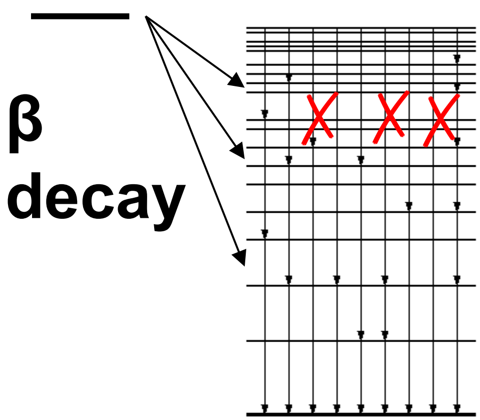
  Y. Fujita, B. Rubio, W. Gelletly, PPNP 66, 549 (2011)
  H. Fujita+, PRC 88, 054329 (2013)
  E. Ganioglu+, PRC 93, 064326 (2016)

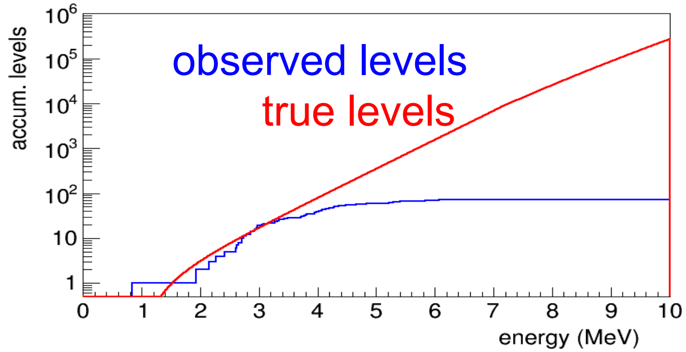


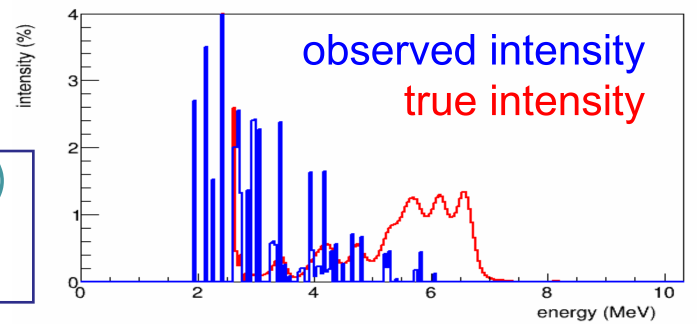
TAS measurements of n-deficient nuclei

- We propose to measure these decays with the **Total Absorption Spectroscopy technique**
  - Improve the knowledge on the decay schemes (**Pandemonium**)
    - In some case: missing B(F) → missing γ-rays from populated levels?
    - From CE data: missing B(GT) strength at high energy
  - Validate the TAS technique with well-known cases for the 1st time
    - TAS experiments done mostly at ISOL facilities







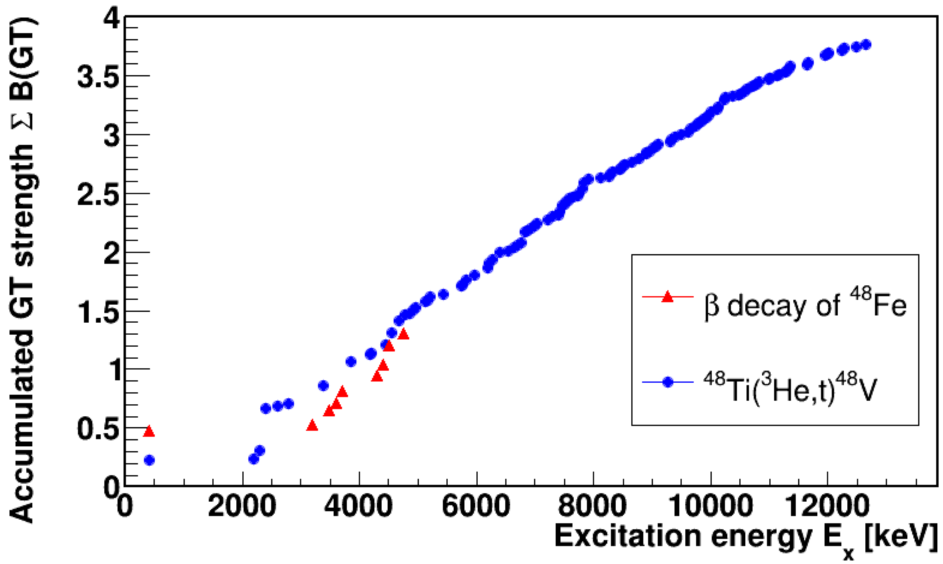


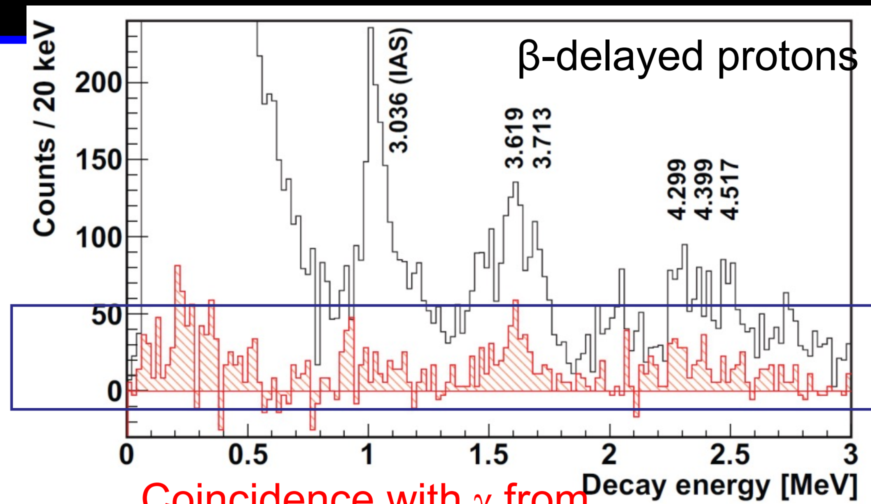
- T_z=-1 cases: ^{54}Ni, ^{50}Fe, ^{46}Cr, ^{42}Ti — Molina+, PRC 91, 014301 (2015)
- T_z=-2 cases: ^{48}Fe, ^{52}Ni, ^{56}Zn — Orrigo+, PRC 93, 044336 (2016)

Courtesy S.E.A Orrigo, B. Rubio

T_z=-2 cases: ^{48}Fe

Orrigo+, PRC 93, 044336 (2016)

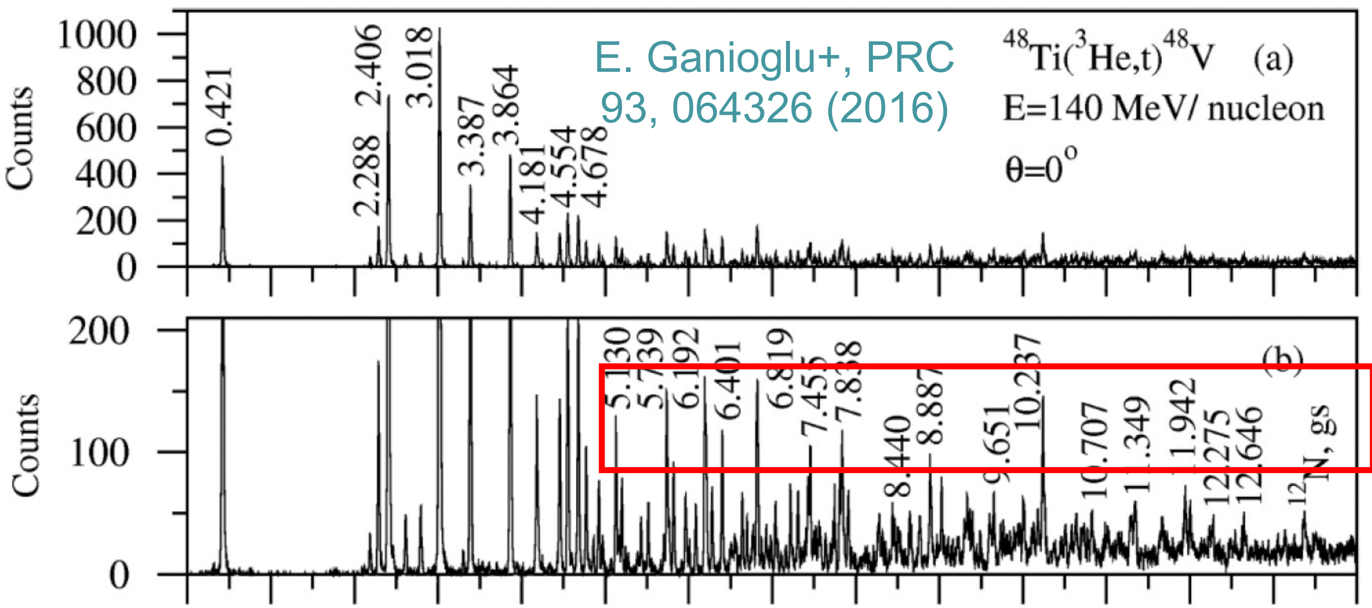




Coincidence with γ from p-daughter: **increases x3 in DTAS!**

- Missing B(F)
- Missing B(GT) at high E_x

E. Ganioglu+, PRC 93, 064326 (2016)



Not observed in β decay

Project Milestones

- Upgrade of the DTAS
  - Geant4 simulations already developed
  - Depending on the funding, possible intermediate step with 9 to 12 LaBr3 with minimal mechanical design
  - First proposal @ PAC of end 2023
  - Full ring in 2024 (16 modules) with mechanics
  - DTAS-STARS ready for experiment @ LISE by end 2024
  - Ready for DESIR by end 2027

- Upgrade of Rocinante
  - Geant4 simulations start in 2023 (internships) in parallel
  - Second Mechanical design in 2025
  - Rocinante-STARS Ready for experiments in Autumn 2026

- Experiment@ NFS
  - Geant4 simulations 2023-2025
  - Third mechanical design (?) in 2026
  - Ready for NFS in ~2027

Collaboration and Involvements

Collaboration and Involvements

- **Subatech:** technical coordination and interfaces (mechanics, FASTER electronics), analysis and GEANT4 developments
- **IFIC:** 1 LaBr3, DTAS + Rocinante, analysis methodology and TAGS expertise
- **IP2I Lyon**: γ-summing analysis development + GEANT4
- **CIEMAT**: 4 LaBr3, analysis + GEANT4 + neutron detection
- **Surrey**: Rocinante + expertise
- **GANIL**: technical reviews, interfaces
- **All:** physics program, proposals, management board…

(NA)2STAR Work Breakdown Structure

Last update: 16/11/2022 (S.Bouvier)

			Collaboration Institutes					
WBS Number	WBS Name	Responsible-Institute	Ciemat	IFIC	IP2I	Subatech	GANIL	Surrey
0	**(NA)2STAR Management**							
0.1	Physics program and institutional relations	management board	x	x	x	x		x
0.2	Technical coordination and interfaces	Subatech		x	x	x	x	x
0.3	Finances	Subatech	x	x	x	x		x
0.4	Planning and breakdown structure follow-up	Subatech				x		
0.5	Product assurance, Product Database, Documentation	Subatech				x		
1	Detector module							
1.1	NaI : control, upgrade and calibration	IFIC		x				
1.2	LaBr3 : purchase, control and calibration	Subatech	x	x		x		
1.3	BaF2 : control, upgrade and calibration	IFIC		x				
1.4	Implantation detector : design, purchase, assembly and test	Subatech - IFIC		x		x	x	
1.5	Documentation : storage of the detector modules status and calibration results	Subatech						
2	DTAS							
2.1	Geant4 simulation	Subatech for TAGS and IP2I for inbeam cross-section meas.	x	x	x	x		
2.2	Interface with Ganil	Subatech - IP2I			x	x	x	
2.3	Detection structure : design, fabrication	Subatech	x	x	x	x		
2.4	Shielding : design, fabrication	Subatech		x	x	x		
2.5	Beam tube : design, fabrication	Subatech		x	x	x	x	
2.6	Support table : design& fabrication	Subatech		x	x	x		
2.7	Documentation : storage of the design in the database	Subatech				x		
2.8	Assembly	Subatech		x		x		
2.9	Test with electonics and DAQ	Subatech		x		x		
2.10	Design reveiw	Ganil	x	x	x	x	x	x
3	Rocinante							
3.1	Geant4 simulation	IFIC	x	x	x	x		
3.2	Interface with Ganil	Subatech		x	x	x	x	x
3.3	Detection structure : design, fabrication	Subatech	x	x	x	x		
3.4	Shielding : design, fabrication	Subatech		x	x	x		
3.5	Beam tube : design, fabrication	Subatech		x	x	x	x	x
3.6	Support table : design& fabrication	Subatech		x	x	x		
3.7	Documentation : storage of the design in the database	Subatech				x		
3.8	Assembly	Subatech		x		x		
3.9	Test with electonics and DAQ	IFIC		x		x		
3.10	Design reveiw	Ganil	x	x	x	x	x	x
4	Detector Power Supply							
4.1	Low voltage power supply : design, configuration, control software	Subatech		x	x	x		
4.2	High voltage power supply: design, configuration, control software	Subatech		x	x	x		
5	Readout electronics and DAQ system							
5.1	Spectroscopy amplifier : configuration & purchase	IFIC		x		x		
5.2	Faster : hardware, software configuration & purchase	Subatech				x		
5.3	Gasifics : hardware and software configuration	IFIC		x				
5.4	DAQ for implantation detector: hardware and software design	IFIC or subatech depending on the detector		x		x		
5.5	Coupling system : design and realisation	Subatech		x		x		
5.6	Interface modules with Ganil beam system : design and realisation	Subatech		x	x	x		
5.7	Câbles and connectors : configuration & purchase	Subatech		x		x		
6	Vaccum equipment							
6.1	Primary and turbomolecular pump : purchase or borrowing	IFIC		x			x	x
7	Simulation and data reconstruction							
7.1	Geant4 DTAS_1 simulation	IFIC or Subatech	x	x		x		
7.2	Geant4 DTAS_2 simulation	Subatech	x	x	x	x		
7.3	Geant4 Rocinante simulation	IFIC						
7.4	Data analysis	Subatech or IFIC or IP2I depending on the experiment	x	x	x	x		x
7.5	software documentation and storage	Subatech				x		
8	Transportation							
8.1	Transport box for DTAS : design & purchase	Subatech				x		
8.2	Transport box forRocinante : design & purchase	IFIC		x				

Requested Resources

- 18 LaBr3 (16 + 2 spares) : 18 * 34000
- 40 channels CARAS (10 CARAS boards + 1 spare) : 11*4500
- 36 channels MOSAHR (5 MOSAHR boards) : 5*4500
- 1 FASTER crate 5000€
- HV Crate from CAEN + 3 HV boards 12 channels + 1 LV board 12 channels (20000€)
- Cables and connectors 2k€
- Mechanical supports : 120k€
- NIM modules: 1 * NIM/TTL/NIM converter 1200€, logic and analogic FIFOs : 4000€
- DAQ Computer 1800€
- Hard drives for experiments (2000€)
- Transportation and travels

Total Cost: 976.8k€ for 5 years, without manpower

262.8 k€ have been invested in the project by the partners

714k€ remain to be funded from 2023 to 2027 to reach the objectives

Budget and TDR…

	<=2020	2021	2022	2023	2024	2025	2026	2027	Total
Equipment	208	51,5	3,3	222,5	188,5	107	20	10	810,8
LaBr3 modules	180	31,5	0	170	136	68			585,5
Electronics	28	20	3,3	22,5	22,5	9			105,3
Mechanics				30	30	30	20	10	120
Other				8	8	20	20	20	76
material transportation				5	5	15	15	15	55
miscellanous				3	3	3	3	3	15
data storage						2	2	2	6
Travels for collaboration + experiments				6	6	26	26	26	90
meetings				6	6	6	6	6	30
experiments						20	20	20	60
Manpower (non permanent)									
Postdoc :1 for 5 yrs or 2 (3+2 yrs)				x	x	x	x	x	
PhD(s) (at least 1)					x	x	x	x	
Total (all sources without manpower)	208	51,5	3,3	236,5	202,5	153	66	56	976,8

Table 1: Total cost of the project and possible timeline of the funding of the project.

Example of funding timeline

- **2023:**
  - o 5 LaBr3 modules;
  - o 3 CARAS and 2 MOSAHR boards (FASTER);
  - o Start of the mechanical design for LISE or S3-LEB/DESIR facilities, some equipment should be purchased (see the PBS, beam tube, table, vacuum equipment...) ;
  - o Some travel expanses (meetings for the design of the STARS, for the preparation of the implantation in GANIL, etc.)
- **2024:**
  - o 4 LaBr3 modules ;
  - o 3 CARAS and 2 MOSAHR boards;
  - o The mechanical design for LISE or S3-LEB/DESIR (see the PBS) ;
  - o Some travel expanses for the collaboration
- **2025:**
  - o 2 LaBr3 modules ;
  - o 2 CARAS boards;
  - o The mechanical design associated to the support of the STARS (with Rocinante) and to the installation at GANIL on the LISE or S3-LEB/DESIR or NFS
- **2026**: some mechanical adaptation to the S3-LEB and / or DESIR facilities
- **2027:** some mechanical adaptation to the S3-LEB and / or DESIR facilities

Possible Funding Scheme

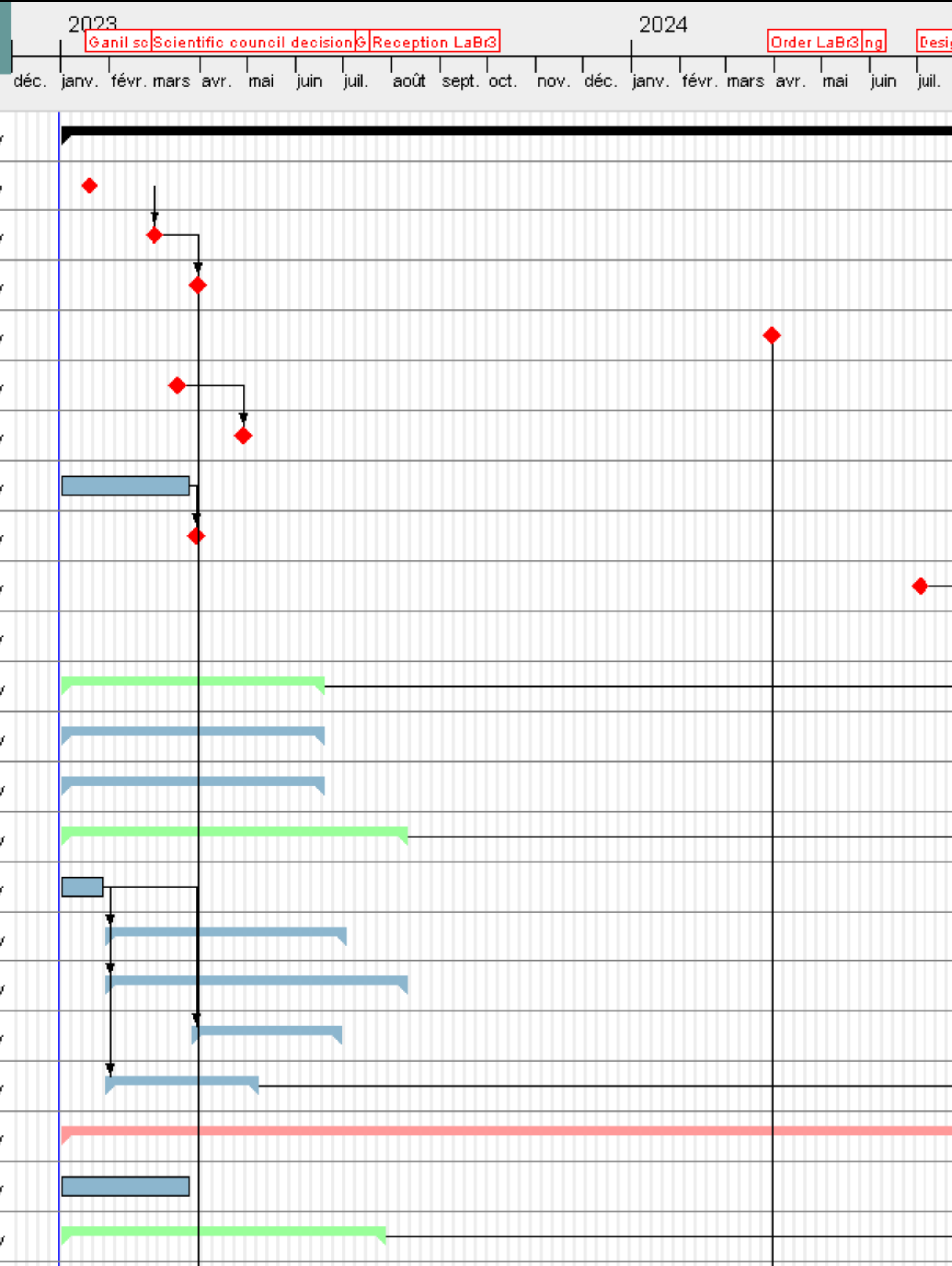
Possible funding partners of the project are: the GANIL facility, the CNRS/in2p3 and the Nantes University (with the NEXT project).
If supported by CNRS/in2p3 and GANIL, Nantes University could fund mainly manpower associated to the project, for instance a postdoc for 5 years and one or two PhD students with some environment.

The GANIL and CNRS/in2p3 would thus have to share the main cost of equipment, transportation of the equipment and travels.

The discussion with the Nantes University partner is conditioned by an agreement to fund partly the project by the GANIL and the CNRS/in2p3.

Note that a Memorandum of Understanding is in preparation by the partners of this project.

Nom	Date de début	Date de fin	Durée
(NA)2STARS	02/01/2023	17/07/2026	925.0 day
Ganil scientific council	17/01/2023	17/01/2023	0.0 day
Scientific council decision	28/02/2023	28/02/2023	0.0 day
2023 Founding	28/03/2023	28/03/2023	0.0 day
2024 Founding	28/03/2024	28/03/2024	0.0 day
PAC Ganil	15/03/2023	15/03/2023	0.0 day
PAC Decision	26/04/2023	26/04/2023	0.0 day
technical discussion with Ganil	02/01/2023	24/03/2023	60.0 day
technical agreement Ganil (NA)2STARS	27/03/2023	27/03/2023	0.0 day
Design review LISE in 2024	01/07/2024	01/07/2024	0.0 day
Design review DESIR in 2025	06/07/2026	06/07/2026	0.0 day
Detector Power Supply	02/01/2023	19/06/2023	121.0 day
Low Voltage Power Supply	02/01/2023	19/06/2023	121.0 day
High Voltage Power Supply	02/01/2023	19/06/2023	121.0 day
Readout electronics & DAQ	02/01/2023	11/08/2023	160.0 day
Global Design	02/01/2023	27/01/2023	20.0 day
Spectroscopy amplifier	30/01/2023	03/07/2023	111.0 day
DAQ system	30/01/2023	11/08/2023	140.0 day
Interface with beam system	27/03/2023	30/06/2023	70.0 day
Cables and connectors	30/01/2023	08/05/2023	71.0 day
DTAS for LISE	02/01/2023	04/12/2024	503.0 day
Simulation Geant4	02/01/2023	24/03/2023	60.0 day
Detection structure integration	02/01/2023	28/07/2023	150.0 day



Conclusion and Outlooks

- 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
- Part of this program could be performed at GANIL in the future: existing LoIs @ DESIR + new experiments that could be proposed in the near future
- The $(NA)^2$STARS project would allow studying more exotic nuclei with the TAGS technique and make in-beam measurements of key cross-sections for astrophysics with the γ-summing method
- The STARS would be the first TAS worldwide allying efficiency with improved energy resolution, timing, increased segmentation

TAGS COLLABORATION

IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, V. Guadilla, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt

SUBATECH Nantes: A. Beloeuvre, J.A. Briz, M. Fallot, V. Guadilla, A. Porta, A.-A. Zakari-Issoufou, M. Estienne,_T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyvaskyla: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber

CIEMAT Madrid: T. Martinez, L.M. Fraile, V. Vedia, E. Nacher

IPN Orsay: M. Lebois, J. Wilson

BNL New-York: A. Sonzogni

Istanbul Univ.: E. Ganioglu

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Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Orrigo, W. Gelletly, C. Ducoin, O. Stezowski, J.-C. Thomas, P. Chauveau, P. Delahaye, H. Savajol, F. de Oliveira, B. Blank, B. Bastin, A. Sanchez, E. Bonnet, M. Estienne, L. Giot, A. Porta, …are acknowledged

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