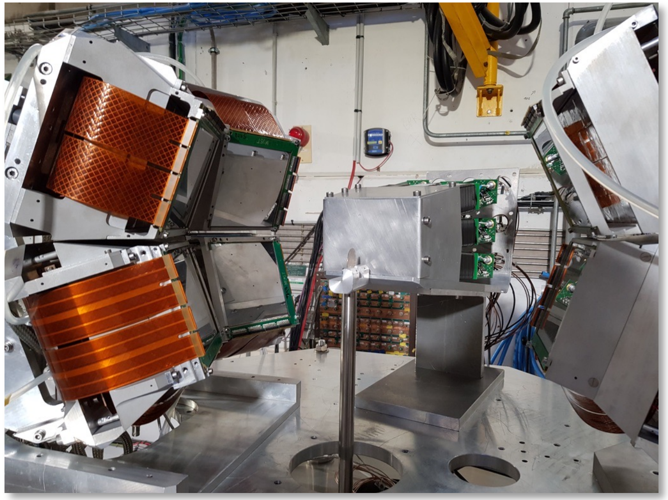
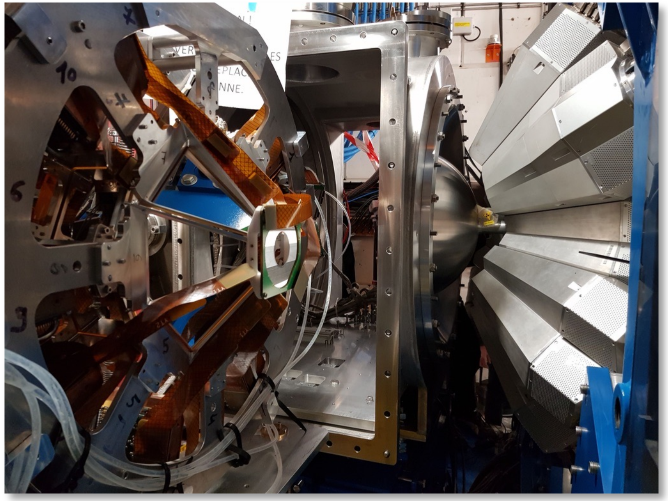
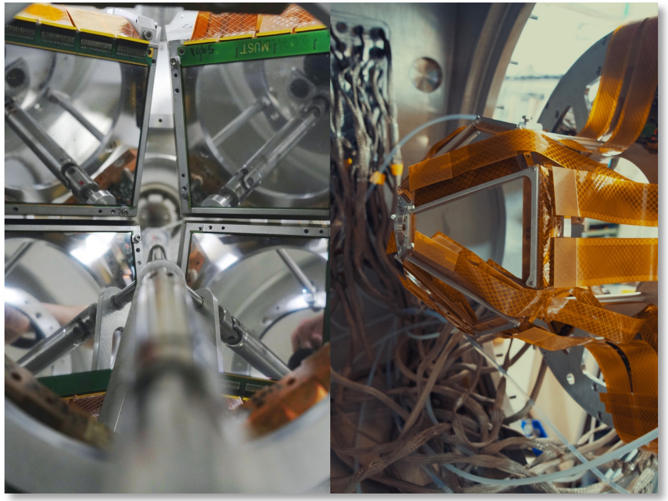
# Overview of MUST2/MUGAST silicon array at GANIL

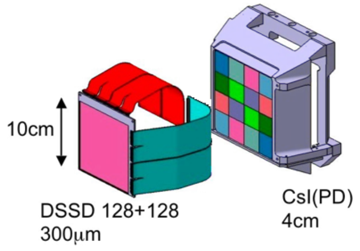




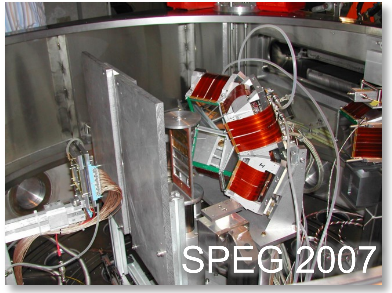


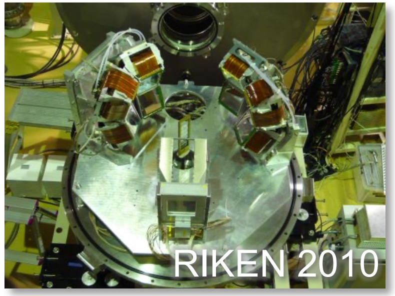
Colloque GANIL 2023
Girard-Alcindor Valérian - IJCLab

# Presentation of MUST2/MUGAST

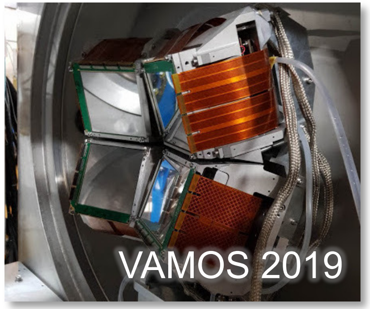


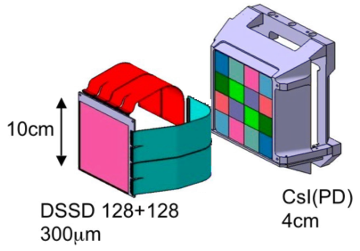

MUST2:
- 300 μm Si detector
- 4x4 CsI crystals
- Up to 8 telescopes
- In use since: 2007







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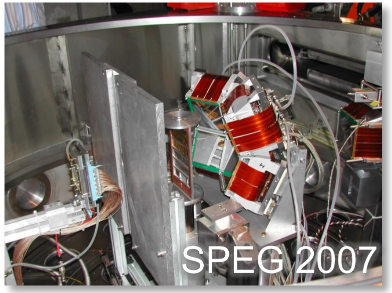
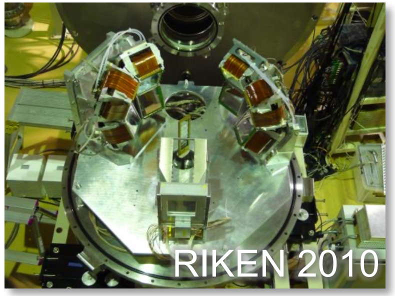
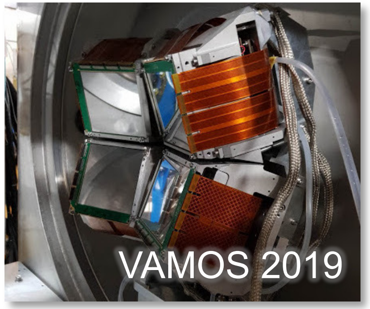
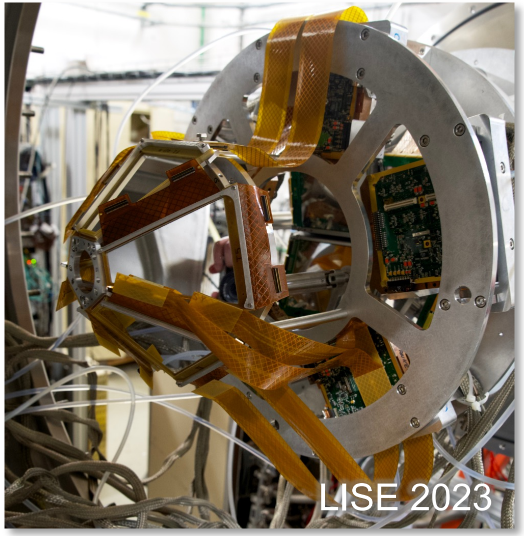

SPEG 2007


RIKEN 2010


LISE 2017


VAMOS 2019


VAMOS 2019


LISE 2023

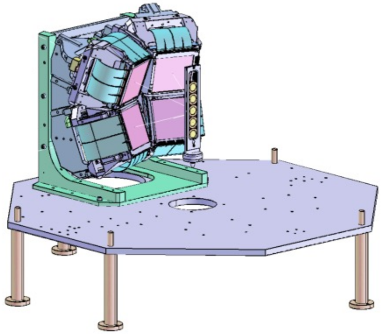
MUGAST:
- 4 MUST2 telescopes (forward)
- 5 - 7 trapezoid-shape 500 µm DSSD (backward)
- 1 annular DSSSD (backward)
- 2 square shape 500 µm DSSD + a 1.5 mm DSSD or 1 MUST2 (90°)
- First step toward the next generation Si detector: GRIT
- In use at GANIL since: 2019 ISOL + Fragmentation beam

# Brief (recent) history of MUGAST at GANIL



Last LISE (fragmentation) campaign:

- MUST2@LISE:
  - MUST2 + ZDD
  - 4 experiments (2017-2018)
  - 5 publications



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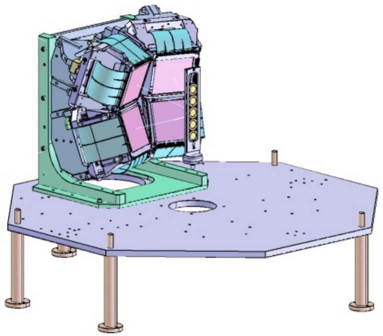
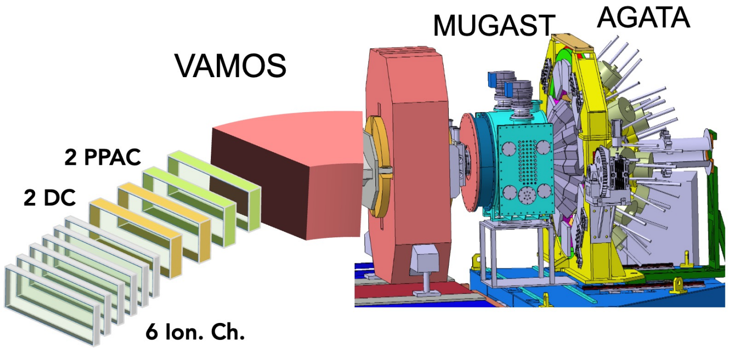


ISOL campaign:

- MUGAST/VAMOS/AGATA:
    - 5 experiments (2019-2021)
    - 3 Publications
    - More to come!
    - See talk of:
        - Irene Zanon
        - Charlie Paxman



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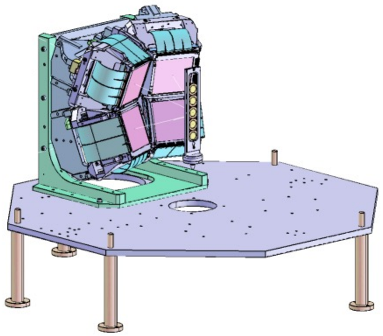
Last LISE (fragmentation) campaign:
- MUST2@LISE:
  - MUST2 + ZDD
  - 4 experiments (2017-2018)
  - 5 publications



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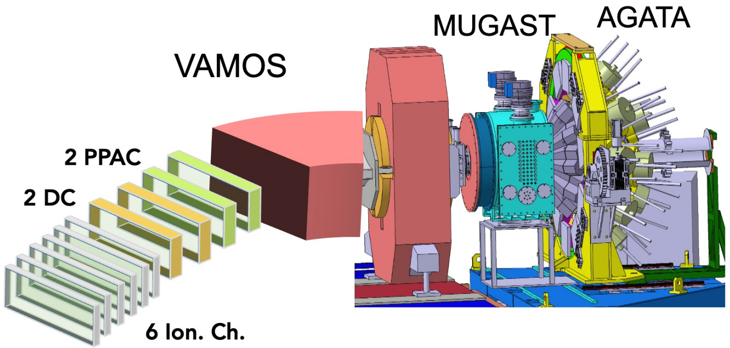
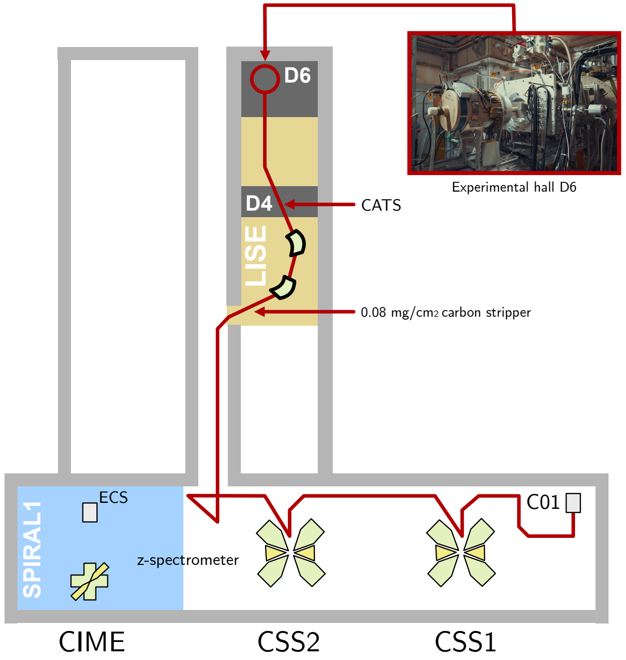


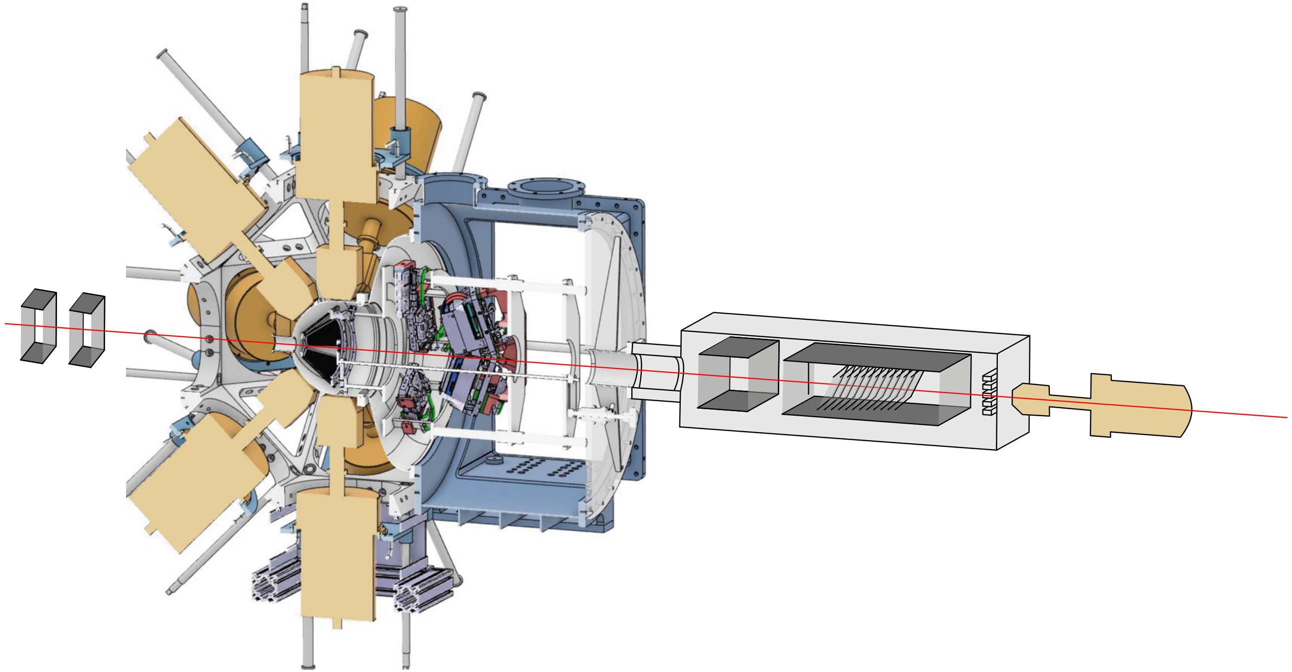

New LISE campaign:
- MUGAST + ZDD + Exogam
- 6+ experiments:
  - 2 performed (2023)
  - 4 scheduled (2024-2025)
  - Currently open to GANIL PAC!

# The new LISE campaign: 2023-2026?

# MUGAST@LISE campaign 2023-2026?

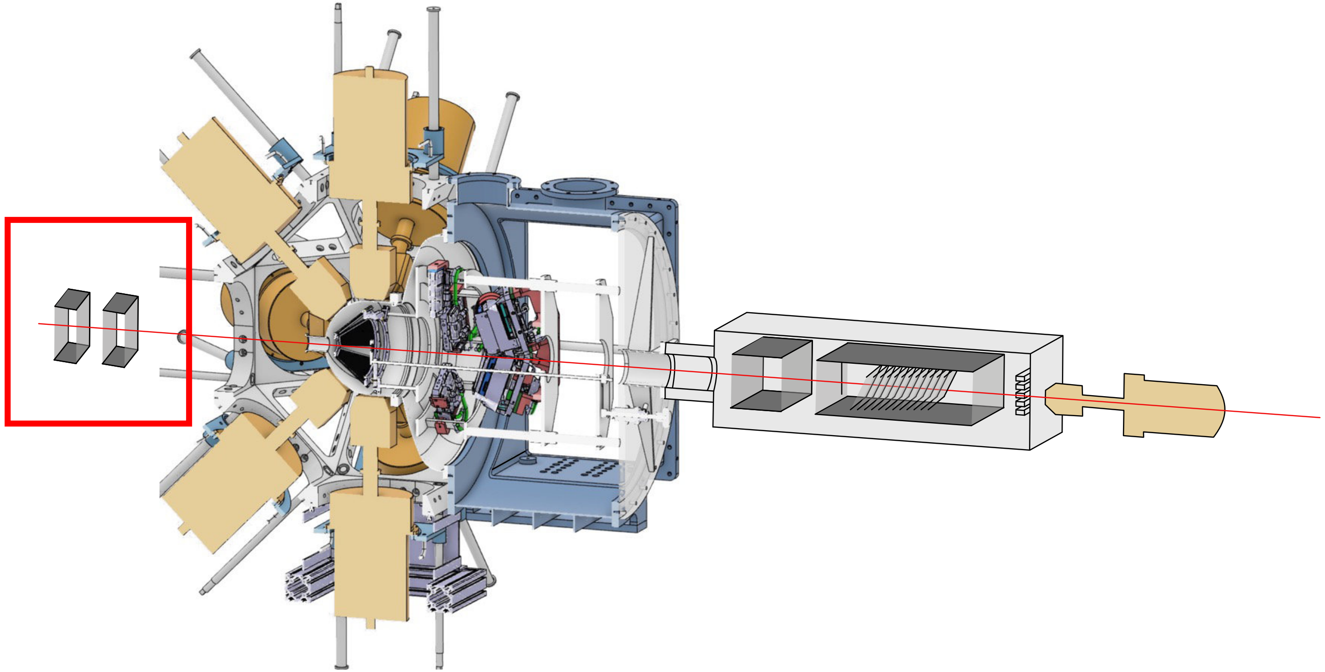


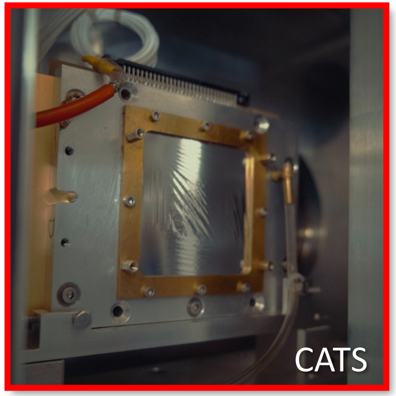
**Setup:**



**Setup:**

- CATS beam tracker



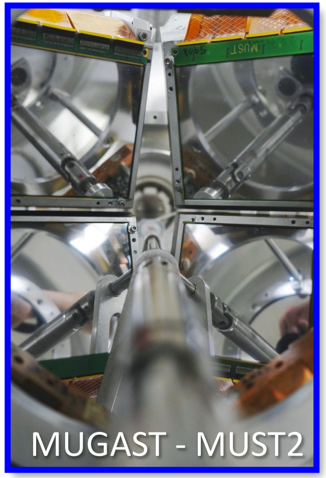


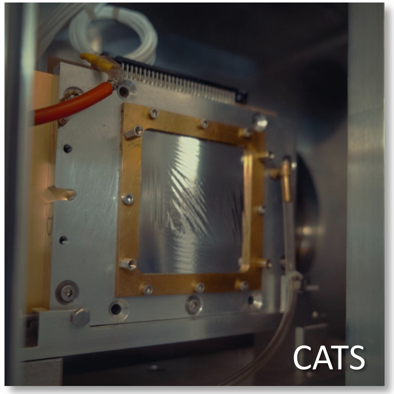
# MUGAST@LISE campaign 2023-2026?

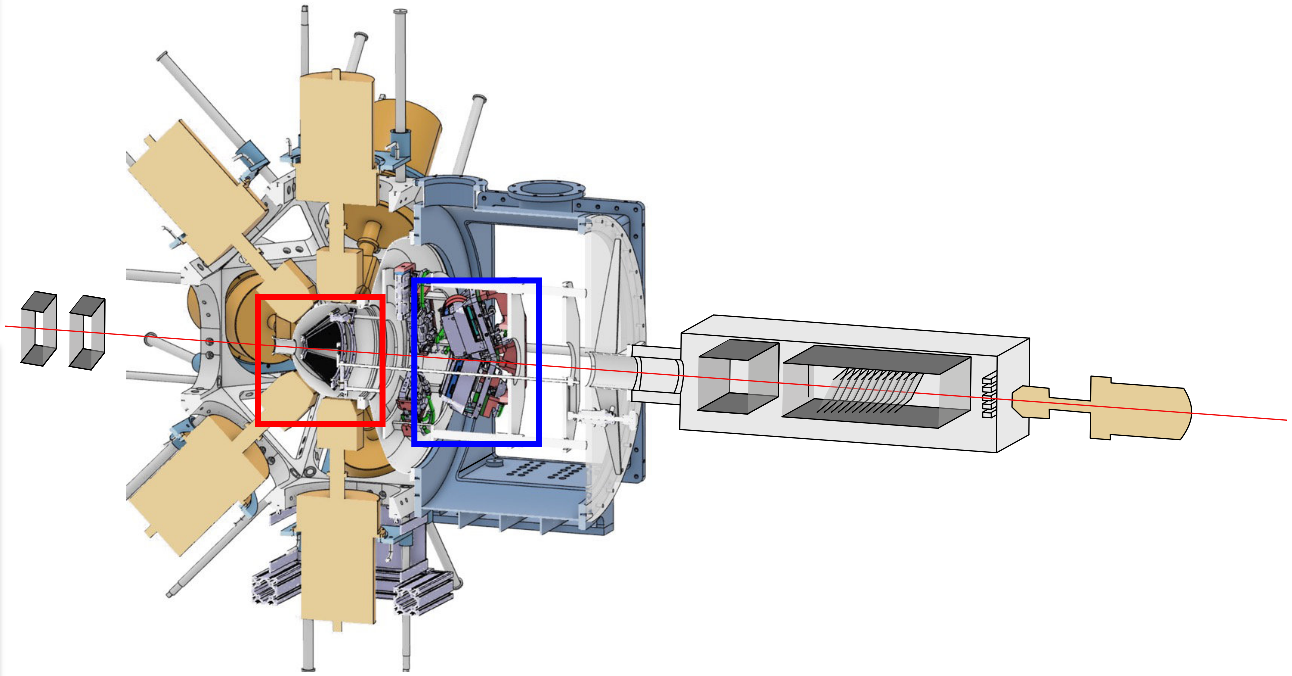


**Setup:**

- CATS beam tracker
- 5 trapezoidal DSSD (backward)
- 4 MUST2 telescopes (forward)
    - 300 um DSSSD
    - CsI crystals

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**Setup:**

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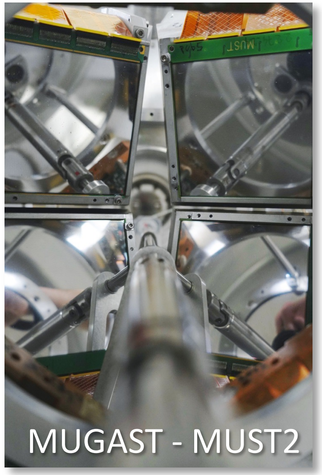
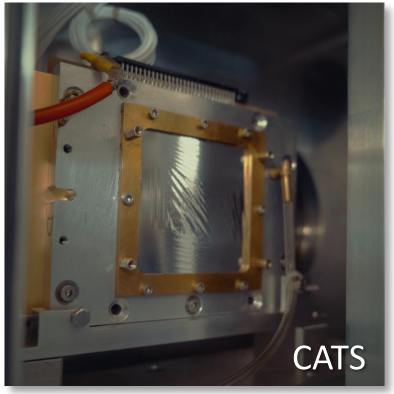
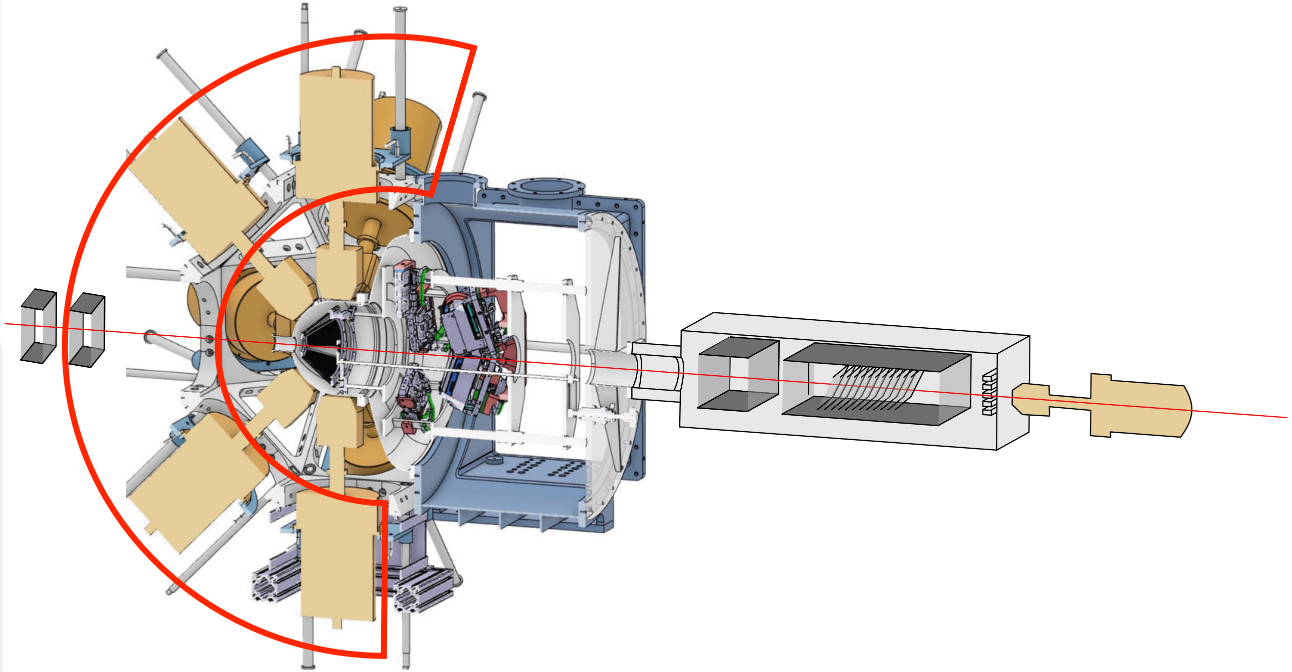
  - 300 um DSSSD
  - CsI crystals
- Exogam Ge y-ray spectrometer

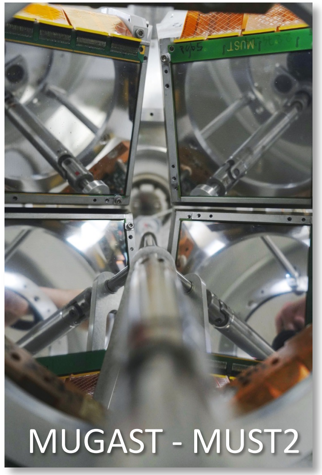



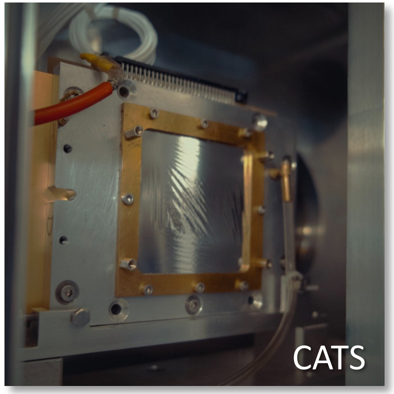



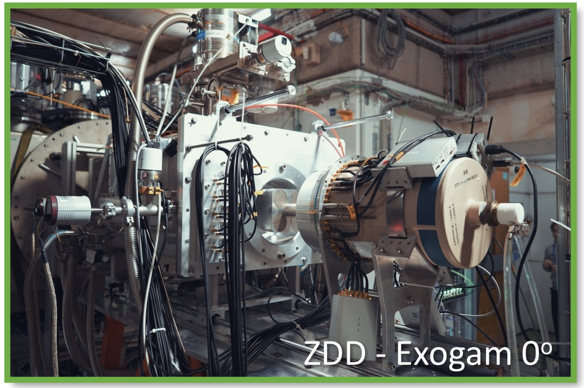
# MUGAST@LISE campaign 2023-2026?

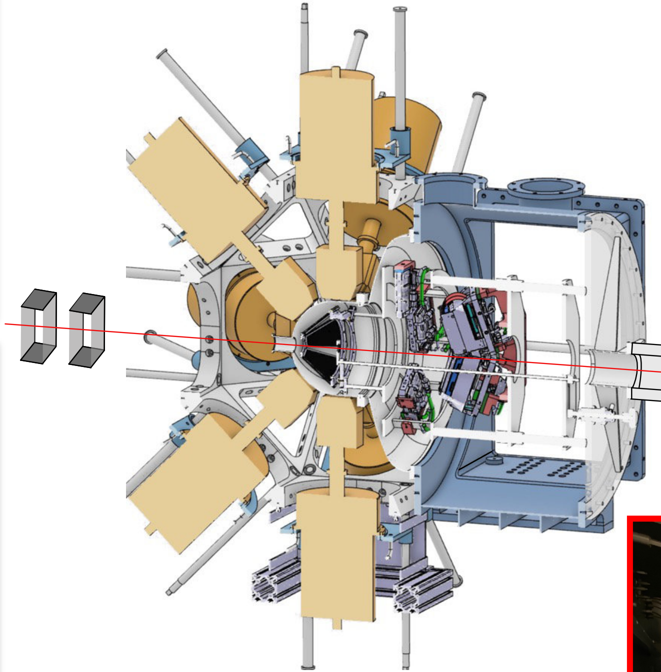
**Setup:**

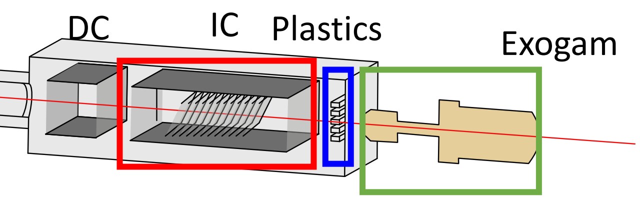
- CATS beam tracker
- 5 trapezoidal DSSD (backward)
- 4 MUST2 telescopes (forward)
    - 300 um DSSSD
    - CsI crystals
- Exogam Ge y-ray spectrometer
- 0º Detection: ZDD from LISE
    - Drift chamber (DC)
    - Ionization chamber (IC)
    - Plastic detector
    - Exogam

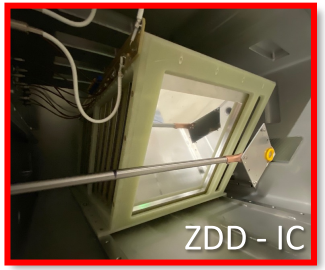






# Preliminary results of the first two experiments

# Two-nucleon transfer: $^{48}Cr(p,^{3}He)^{46}V$



**<u>M. Assié (IJCLab) PhD: Hugo Jacob (IJCLab)</u>**

- Beam : $^{48}Cr$ at 30 MeV/u, $3\times10^{5}$ pps, 90% purity
- Target : $CH_2$ 5 $mg/cm^2$
- Reaction studied : $^{48}Cr(p,^{3}He)^{46}V$
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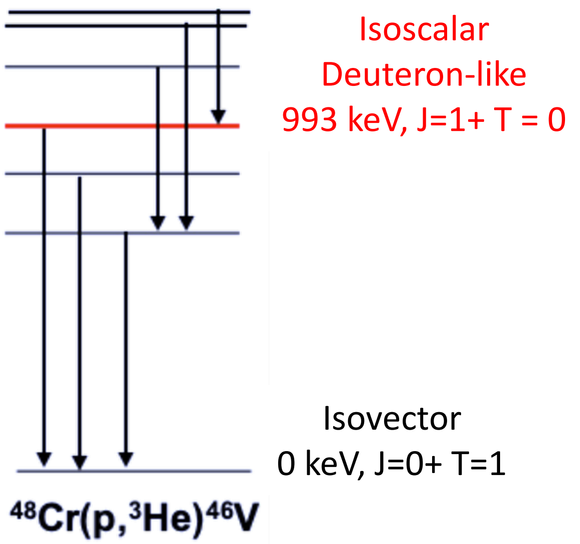


Lee J. et al. Ayyad Y. Phys. Rev. C, 2017.
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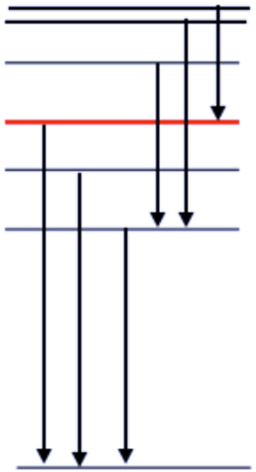
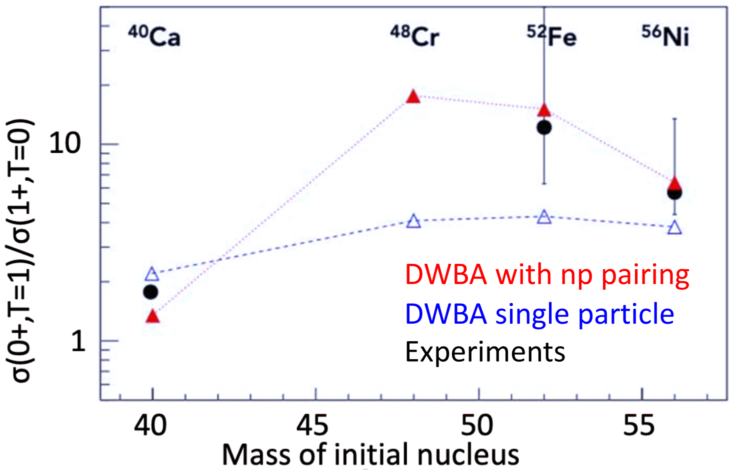



$^{48}Cr(p,^{3}He)^{46}V$

Ratio of cross-section

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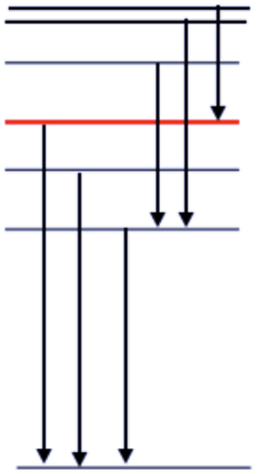
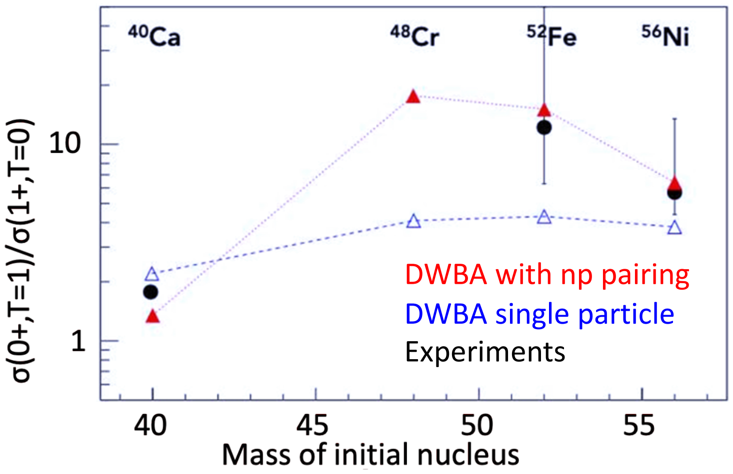


$^{48}Cr(p,^{3}He)^{46}V$

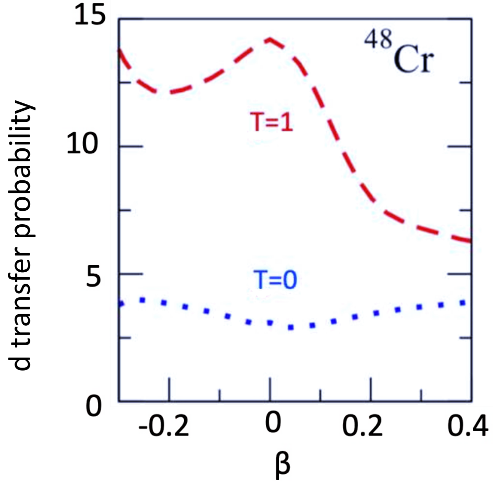
Isoscalar
Deuteron-like
993 keV, J=1+ T = 0

Isovector
0 keV, J=0+ T=1

**Ratio of cross-section**




**Effect of deformation on each pairing channel**

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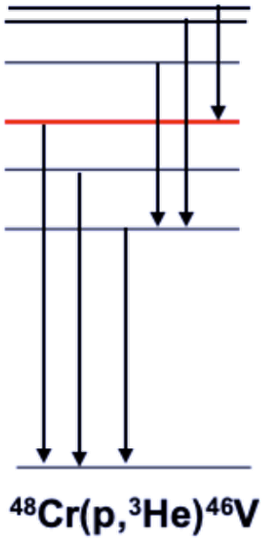


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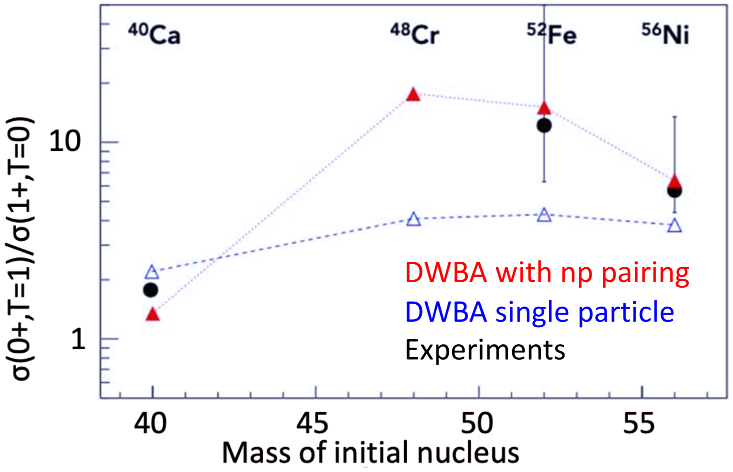


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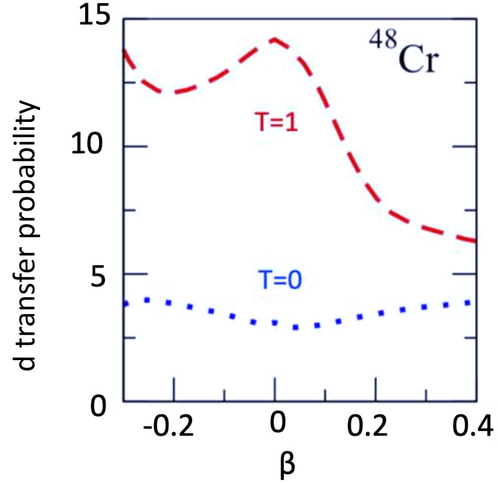


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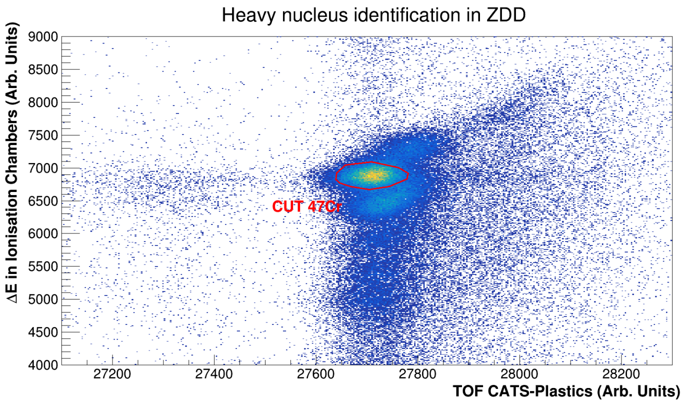
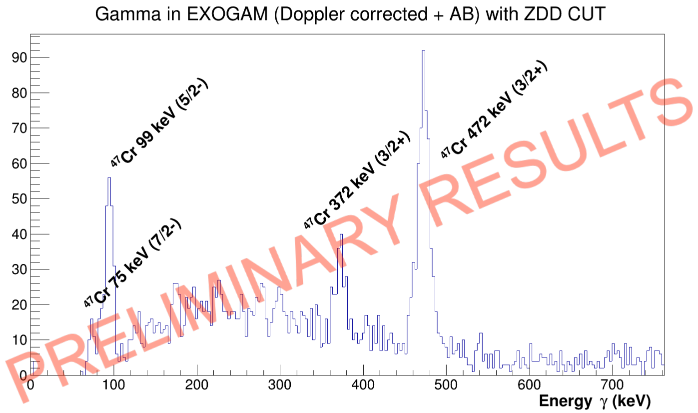
Chong Qi and Ramon Wyss, Physica Scripta, 2015.

- $^{48}Cr(p,^{3}He)^{46}V$ channel currently under analysis by Hugo… More to come soon!

## $^{48}Cr(p,d)^{47}Cr$ online analysis:




Courtesy of H. Jacob

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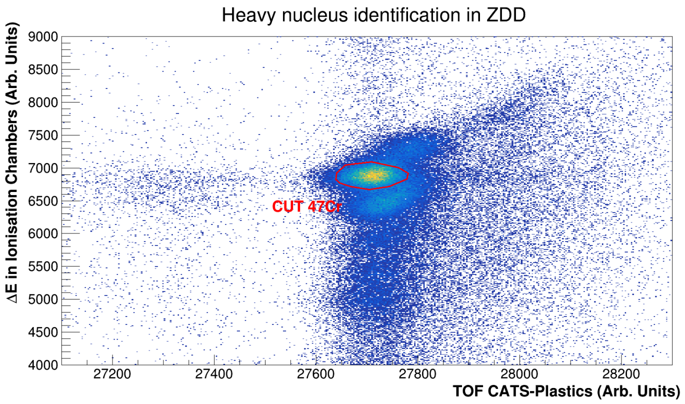
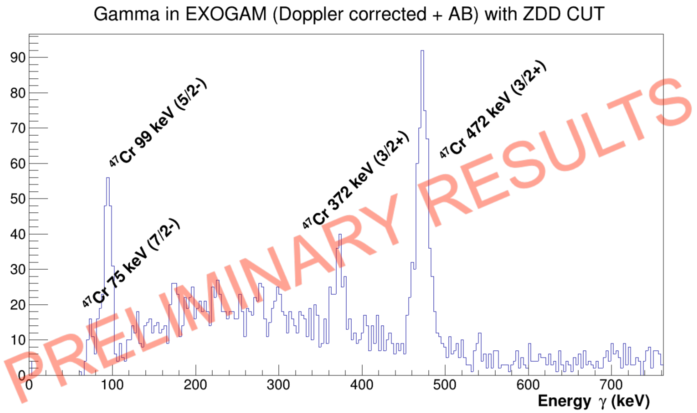
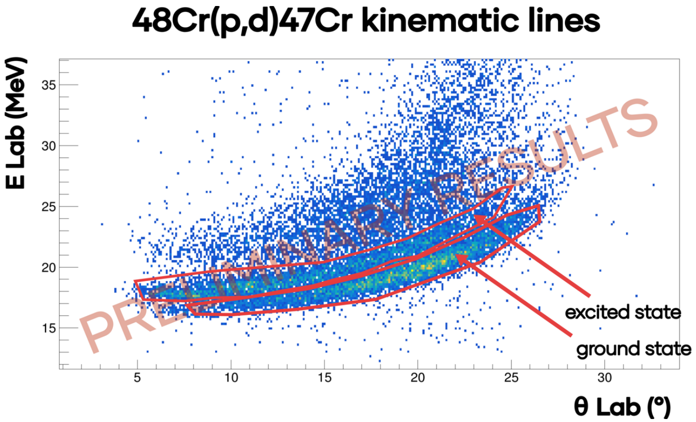
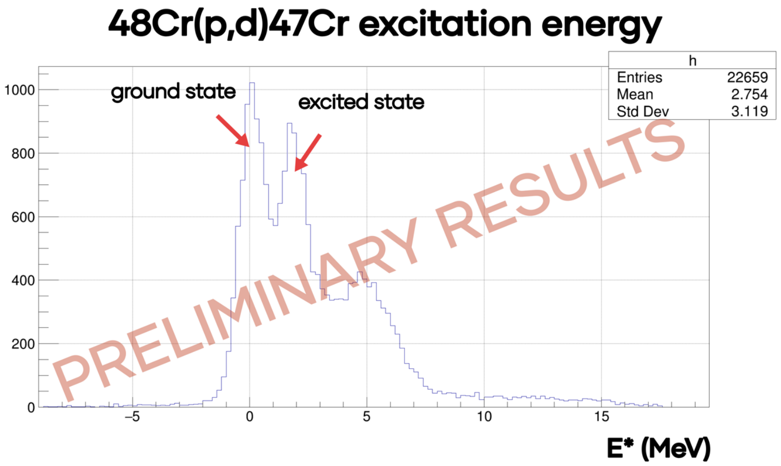


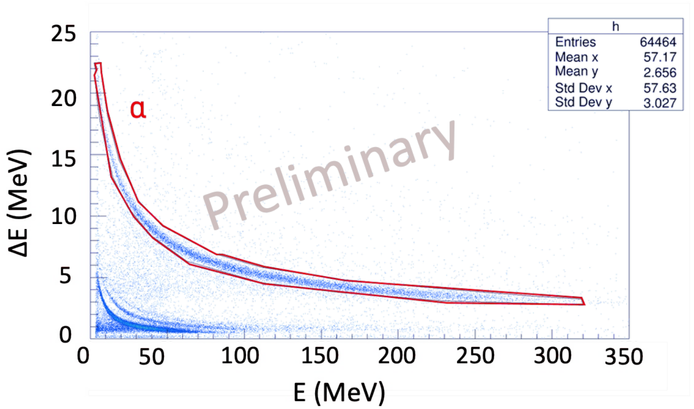



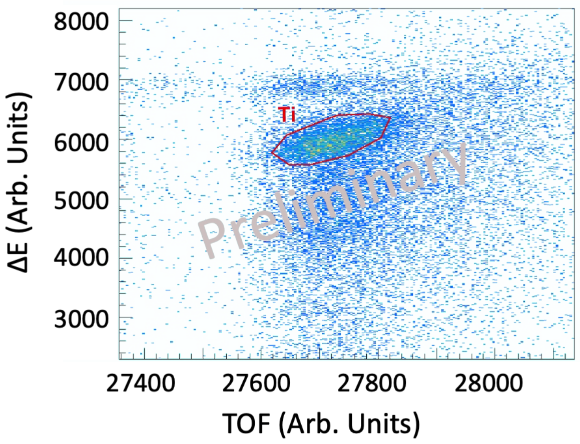




Courtesy of H. Jacob

**$^{48}Cr(p,^{4}He)^{44}Ti$ online analysis:**




Courtesy of L. Dienis

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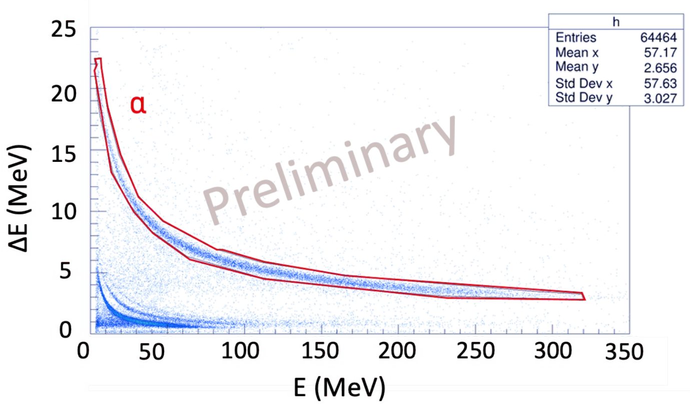


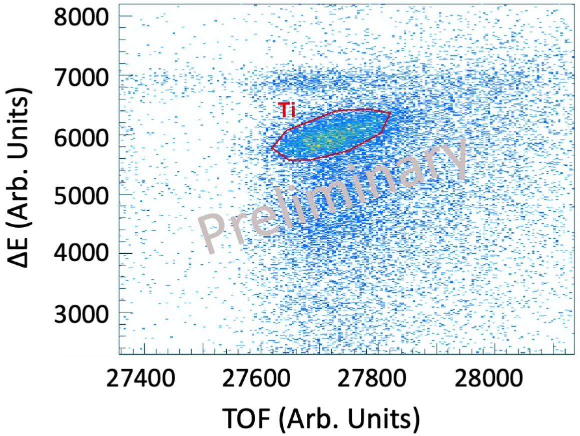


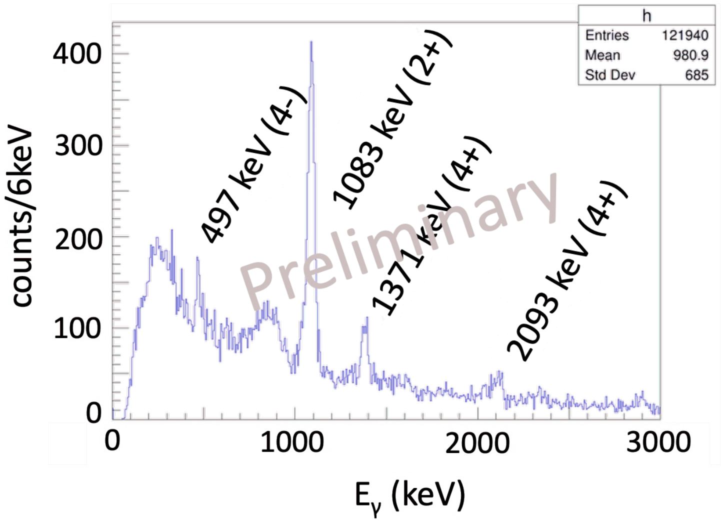


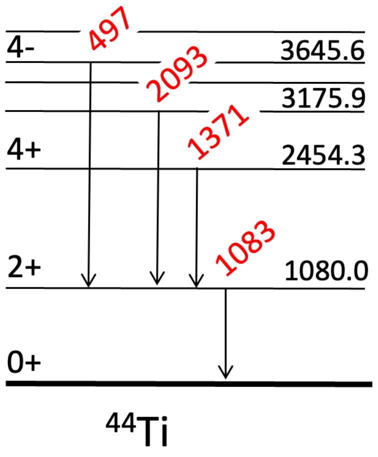


Courtesy of L. Dienis

# MUGAST@LISE: Online performances



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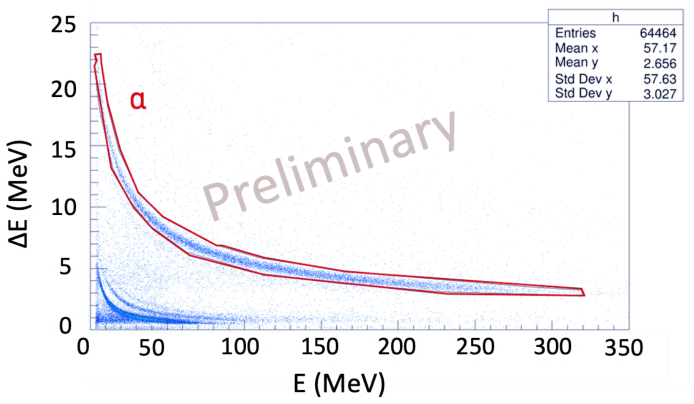


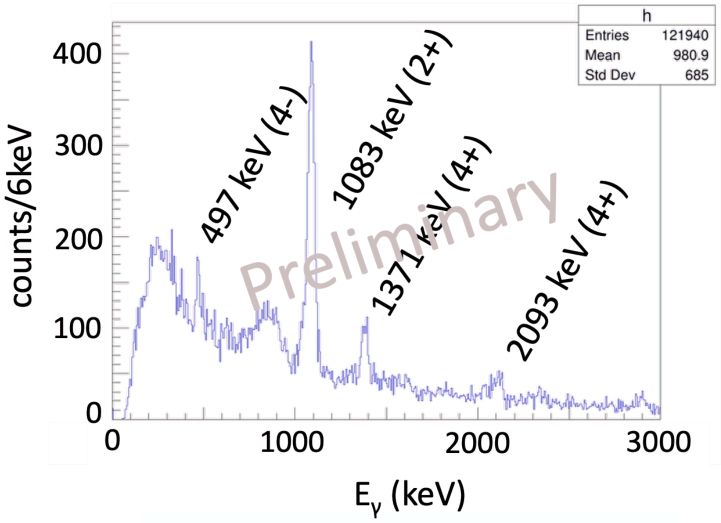


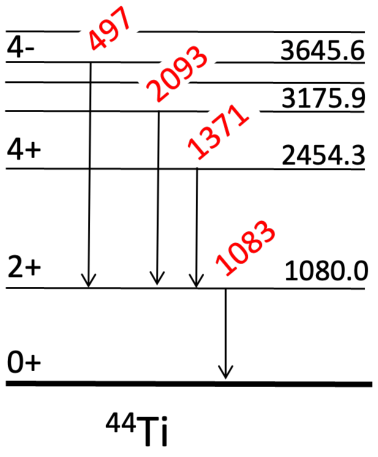


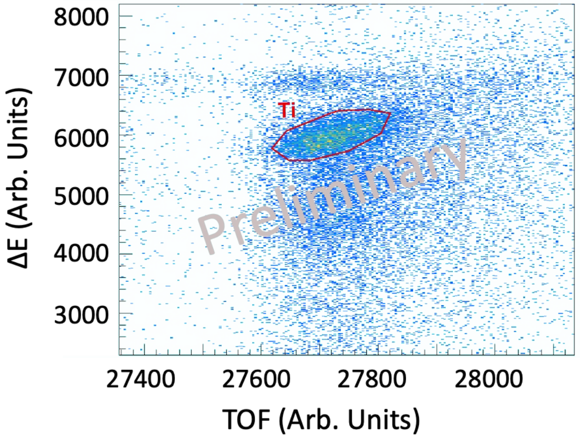


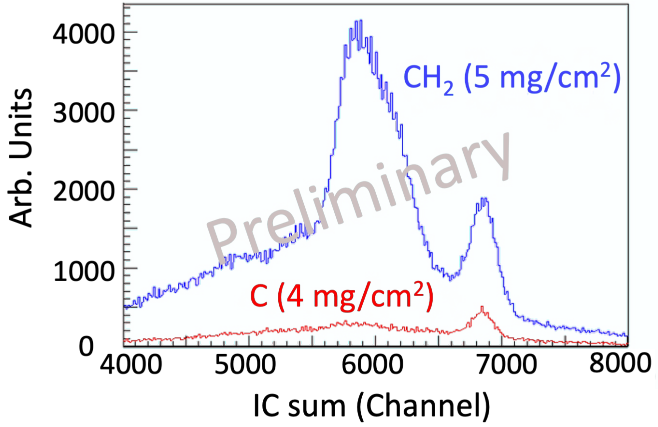


Seemingly large $^{48}Cr(p,^{4}He)^{44}Ti$ cross-section
Not visible in the Carbon background!
**To be investigated…**

Courtesy of L. Dienis

# Study of $^{68}$Ni by +1n and -1n transfer

**<u>S. Koyama (GANIL), O. Sorlin (GANIL):</u>**

- Beam : $^{68}$Ni at 18 MeV/u and 40 MeV/u, $10^5$ pps, 80% purity
- Target : $CH_2$ 5 mg/cm$^2$ and $CD_2$ 0.5 mg/cm$^2$
- Reaction studied : $^{68}$Ni(p, d)$^{67}$Ni, $^{68}$Ni(d, p)$^{69}$Ni
- Phenomenon studied : SO splitting and N=40/50 shell gap

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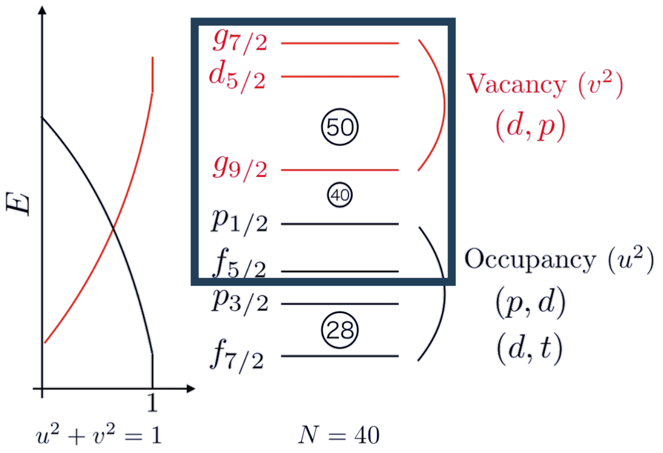
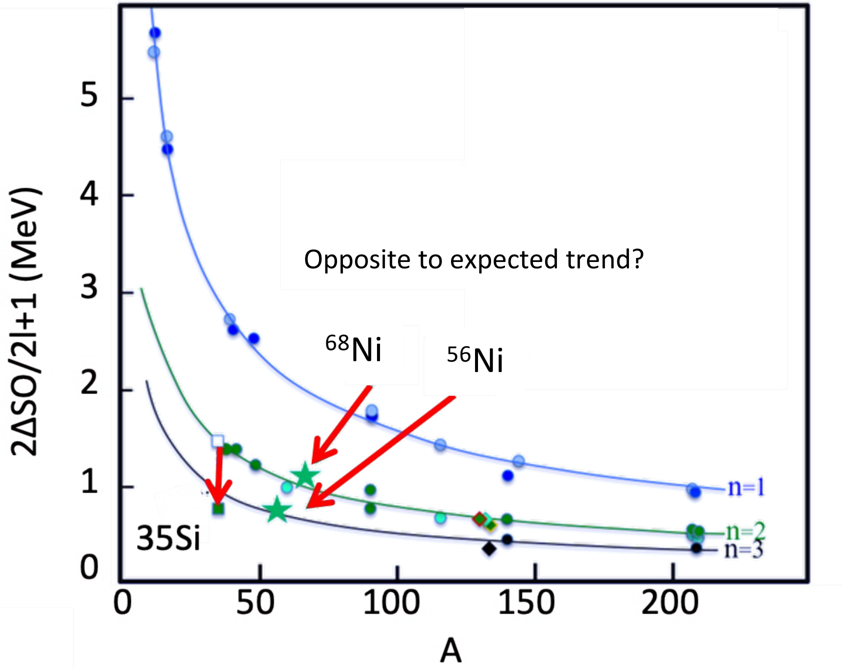
**Neutron Fermi surface at N=40**




$^{68}$Ni: 40ν + 28π

**2p, 1f and 1g SO splitting**




O. Sorlin, F. de Oliveira Santos, and J.P. Ebran. 2020
O Sorlin and M-G Porquet. Physica Scripta, 2013

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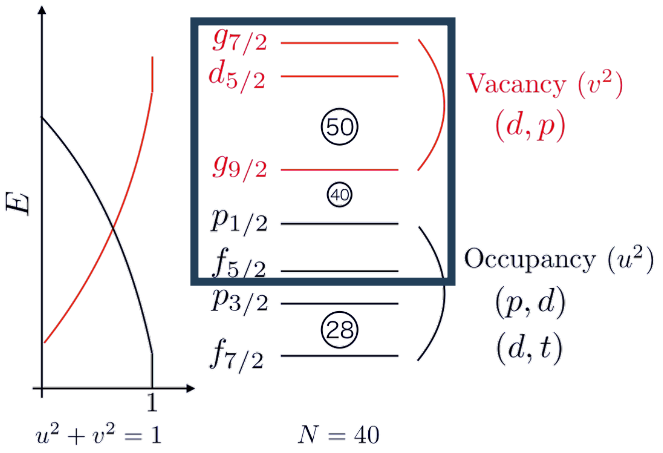


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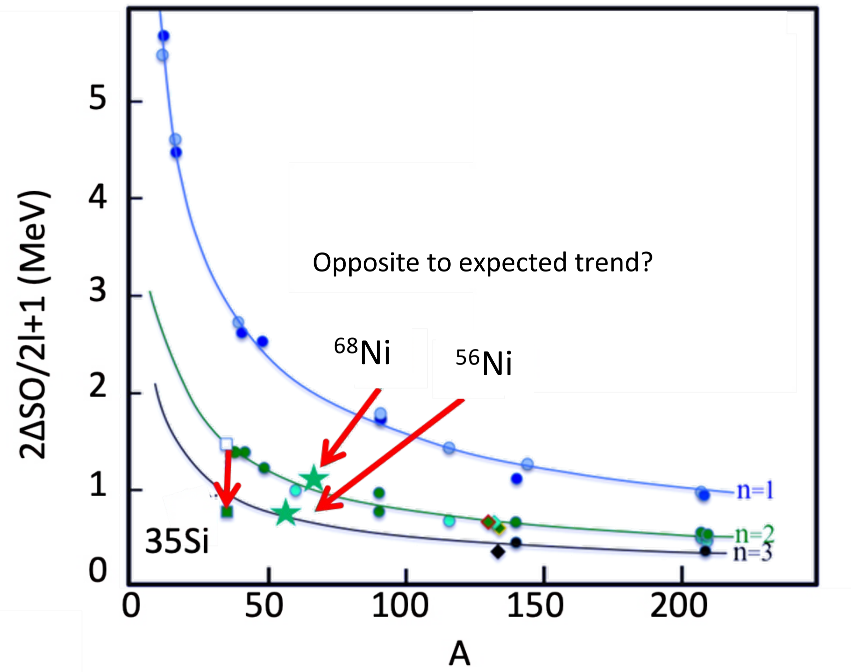
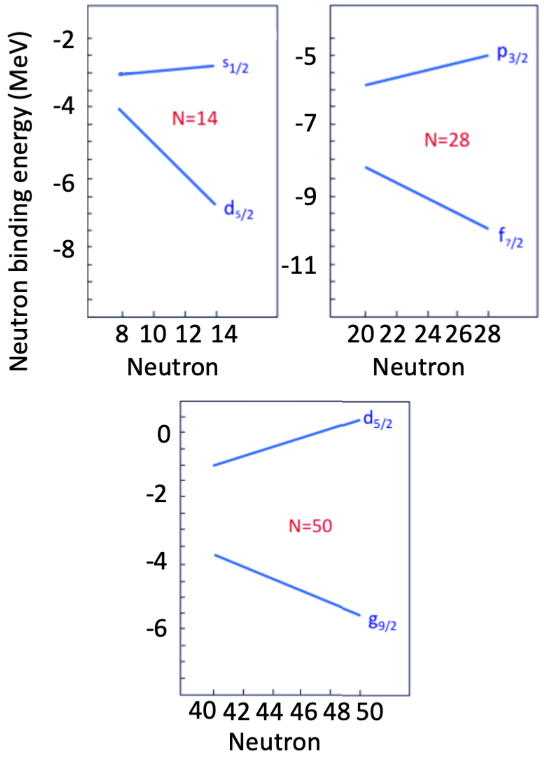



**$g_{9/2}$-$d_{5/2}$ spacing at N=40**





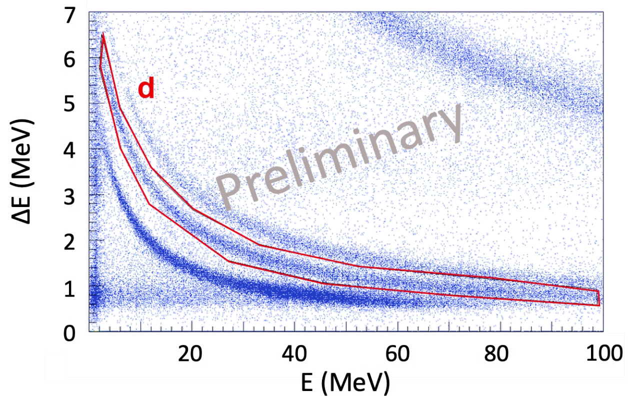
O. Sorlin, F. de Oliveira Santos, and J.P. Ebran. 2020

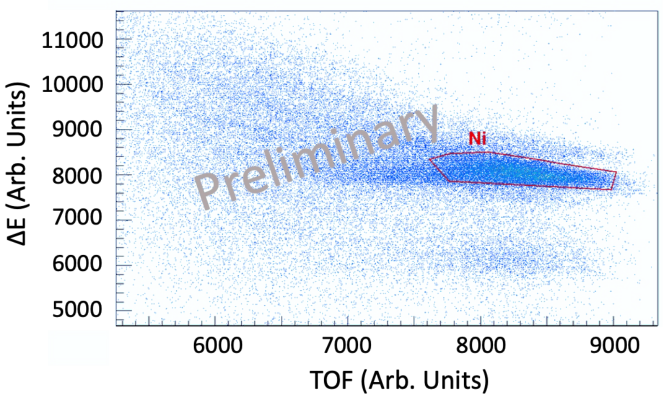
O Sorlin and M-G Porquet. Physica Scripta, 2013

# Study of $^{68}$Ni by +1n and -1n transfer



## $^{68}Ni(p,d)^{67}Ni$ online analysis:

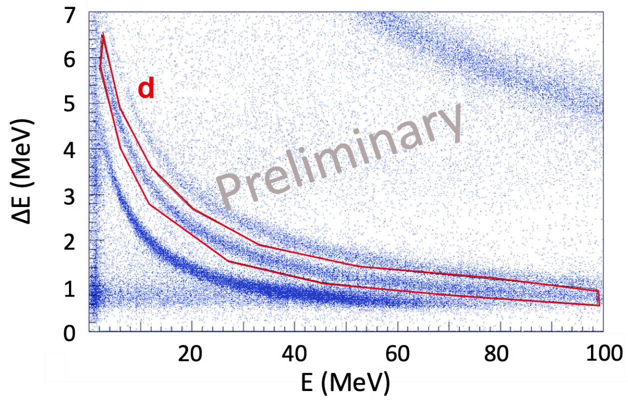


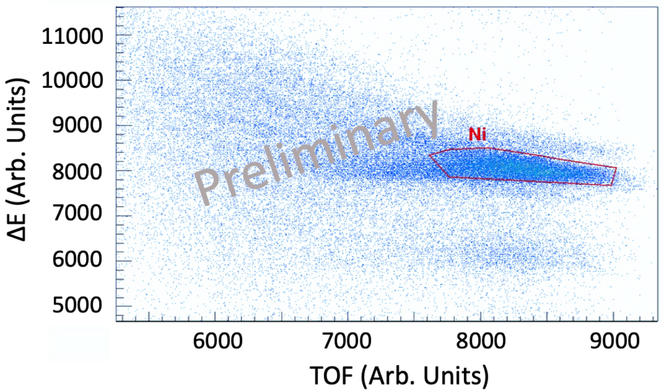



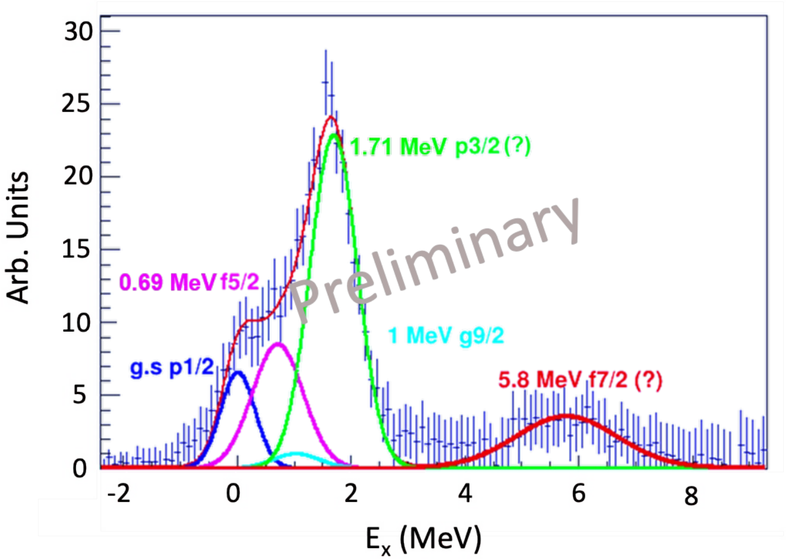
# Study of $^{68}$Ni by +1n and -1n transfer

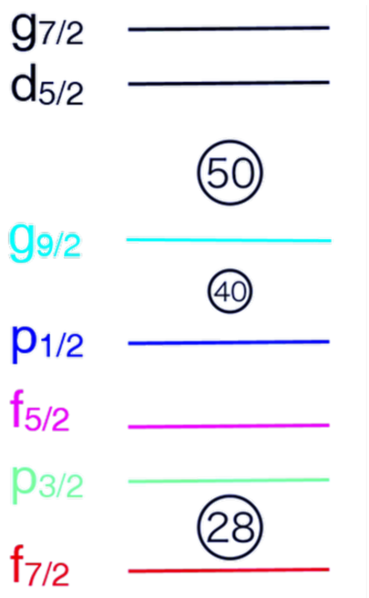


**$^{68}$Ni(p,d)$^{67}$Ni online analysis:**



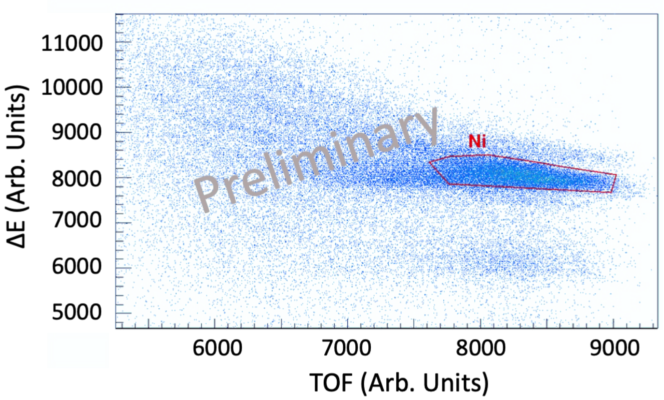

- $f_{5/2} - f_{7/2}$ SO splitting
- $p_{1/2} - p_{3/2}$ SO splitting
- Partial filling of the $g_{9/2}$ orbital

See Ozgë Aktas poster's

# Study of $^{68}$Ni by +1n and -1n transfer



**$^{68}$Ni(d,p)$^{69}$Ni online analysis:**




- No selection in MUGAST yet
- Selection of Ni isotopes in ZDD

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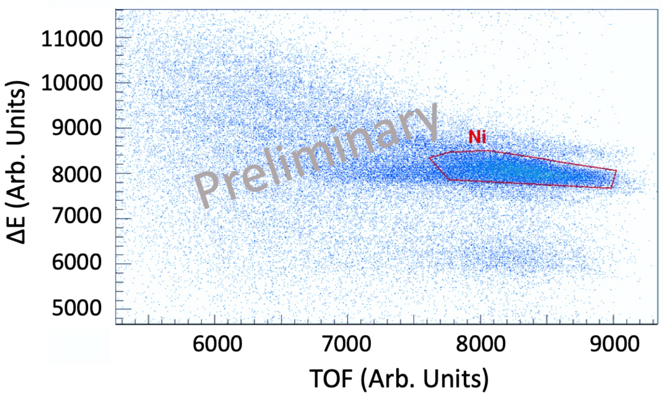


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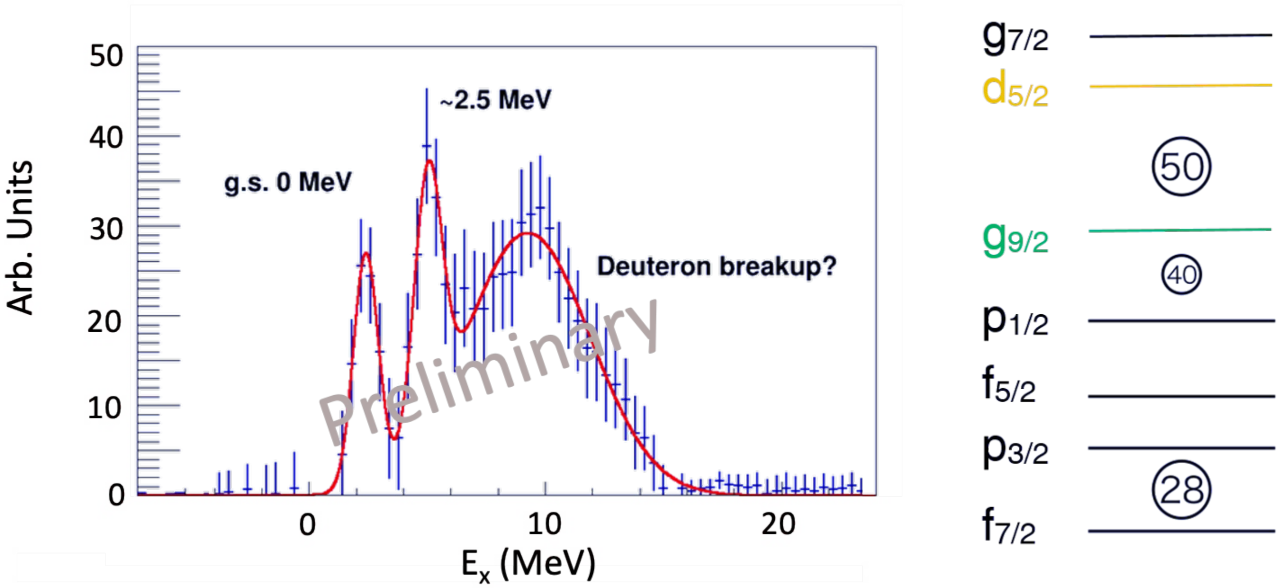



- $g_{9/2} - d_{5/2}$ spacing
- $g_{9/2} - g_{7/2}$ SO splitting ?
- Only two visible states? Similar to previous experiments…

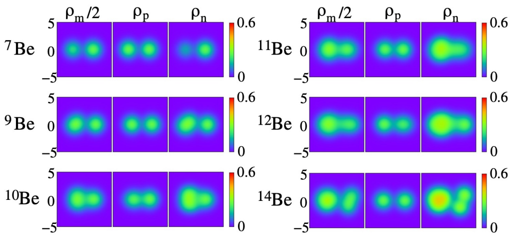
# What’s next?

# MUGAST@LISE: Upcoming experiments

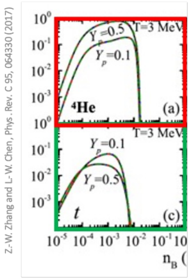


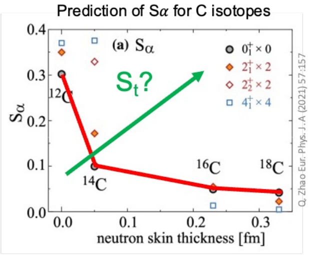
**<u>V. Girard-Alcindor, D. Beaumel</u>**: (To be scheduled in 2024)

Cluster structure of the ground state of light exotic nuclei beyond alpha-clustering




Clustering in Be isotopes




Expected triton clustering in neutron rich isotopes

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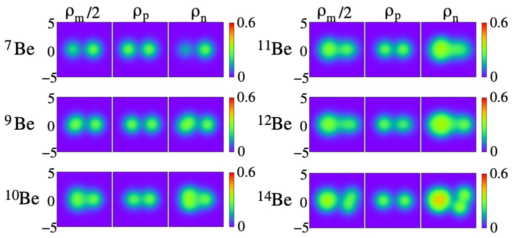


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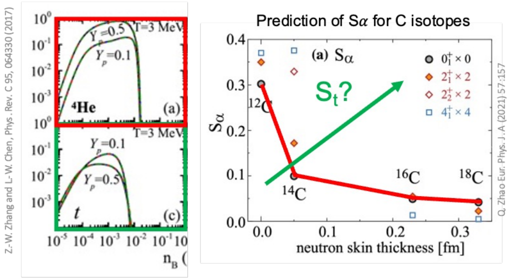


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**F. Galtarossa**: (To be scheduled in 2024)

Evolution of the neutron $1d_{3/2}$-$1d_{5/2}$ spin-orbit splitting in N = 19 isotones and Fermi surface in $^{34}$Si

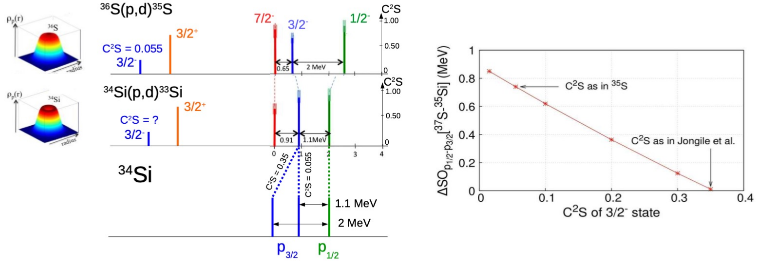


FIG. 3: Pictorial representation (left) and graphic (right) of the predicted variation of the difference between the $\nu p_{1/2}$-$\nu p_{3/2}$ SO splitting in $^{37}$S and in $^{35}$Si as a function of the C$^2$S of the $3/2^-$ state at 1.981 MeV in $^{33}$Si.

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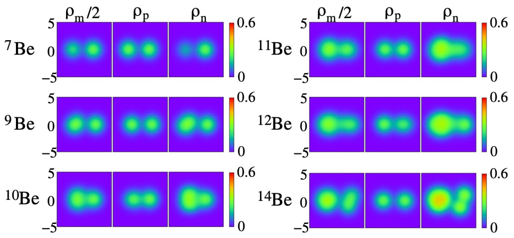


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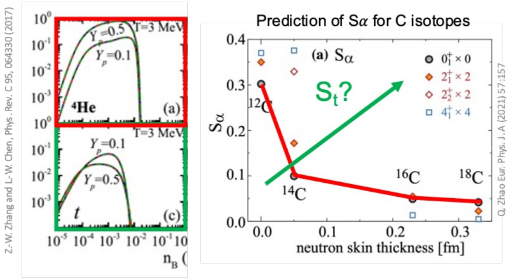


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Determining the thermonuclear $^{18}Ne(\alpha,p)^{21}Na$ reaction rate by measurement of the $^{7}Li(^{18}Ne,t)^{22}Mg(p)^{21}Na$ reaction

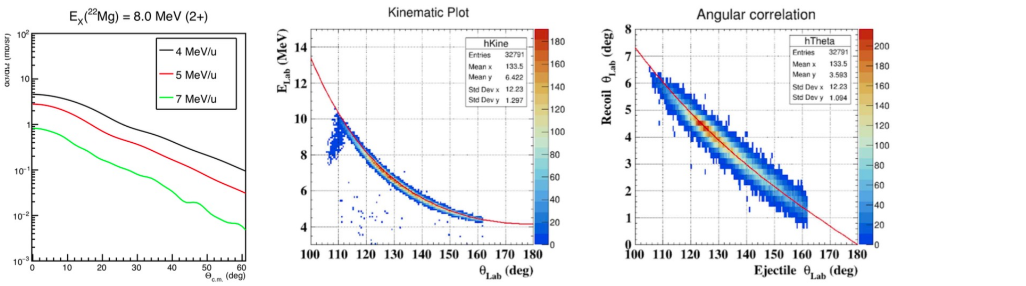


Figure 1: Differential cross section for 2+ state with $C^2S = 1$ (left); triton kinematics for $^{22}$Mg resonance (middle); and heavy-ion ($^{22}$Mg) angle against triton angle (right).

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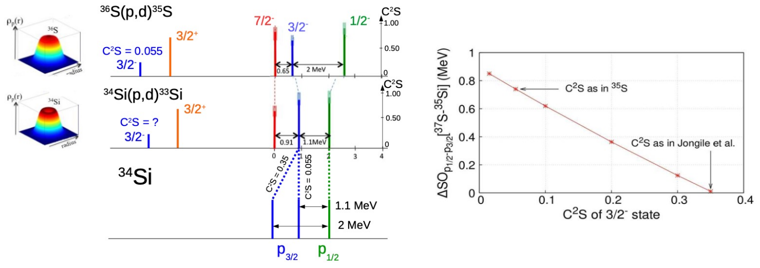


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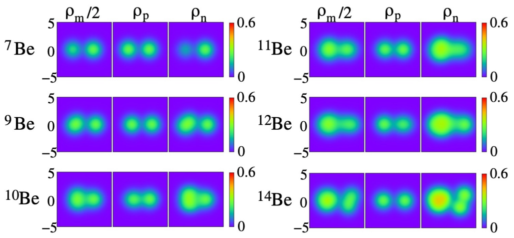


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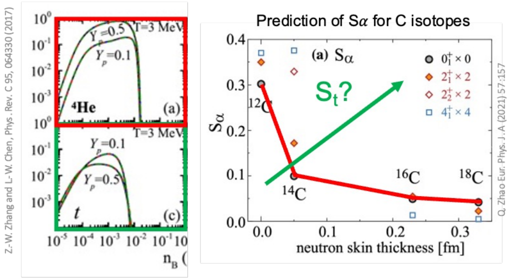


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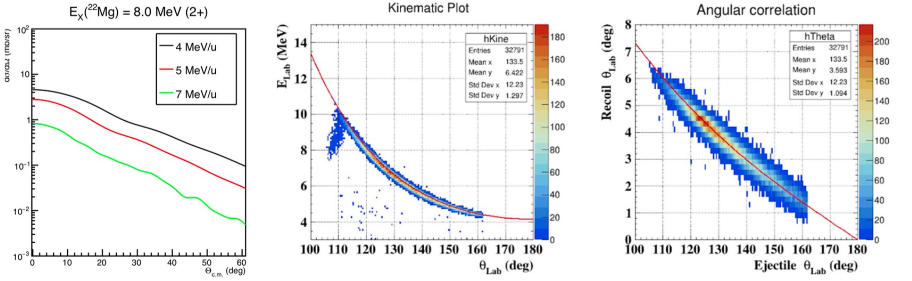


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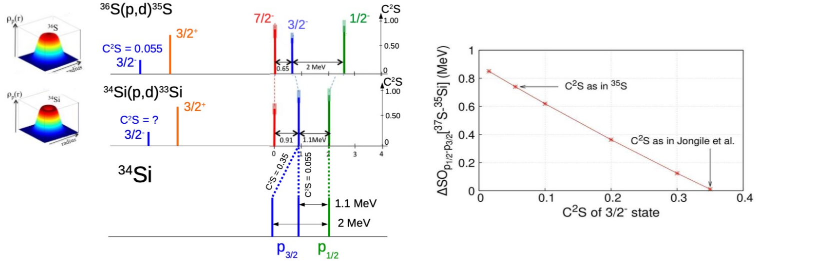


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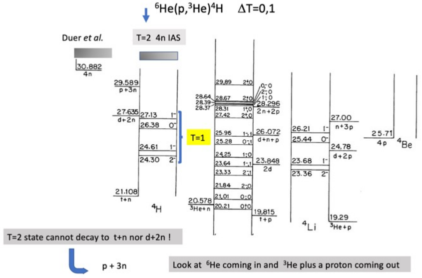
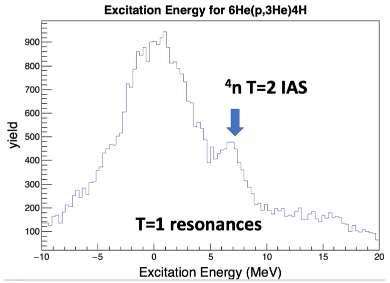
**A. Machiavelli, M. Assié**: (To be scheduled in 2025)

The tetra-neutron Isobaric Analog State in $^4$H : The case for the $^6$He(p,$^3$He) reaction



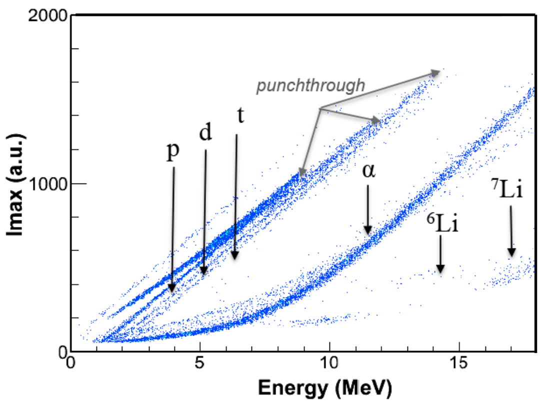



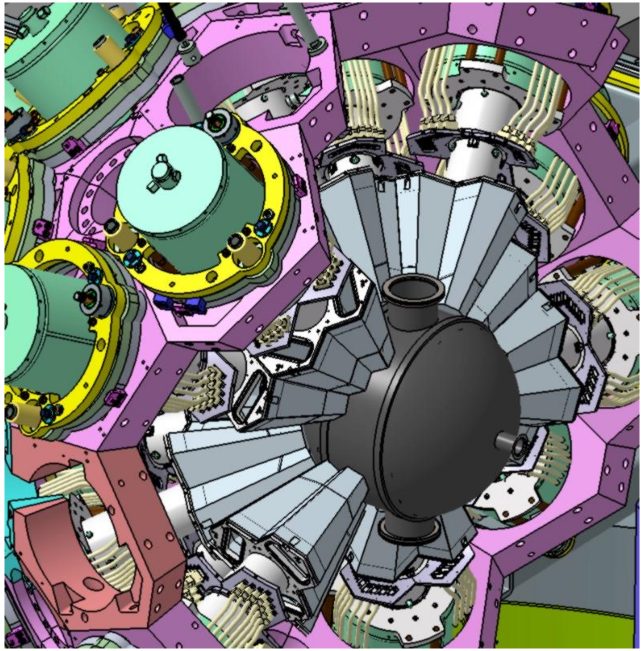
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

# GRIT
# 2026/27-?

GRIT: **G**ranularity, **R**esolution, **I**dentification and **T**ransparency

- ~4$\pi$ silicon detector
- Coupled to AGATA
- Missing mass
- With PSA identification



# GRIT - AGATA@SPES: 2026 - ?



<u>GRIT: **Gr**anularity, **R**esolution, **I**dentification and **T**ransparency</u>

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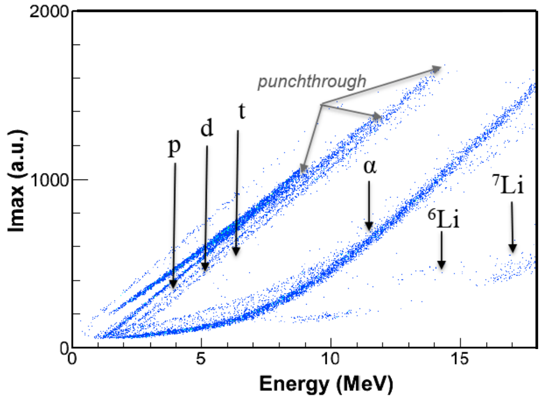
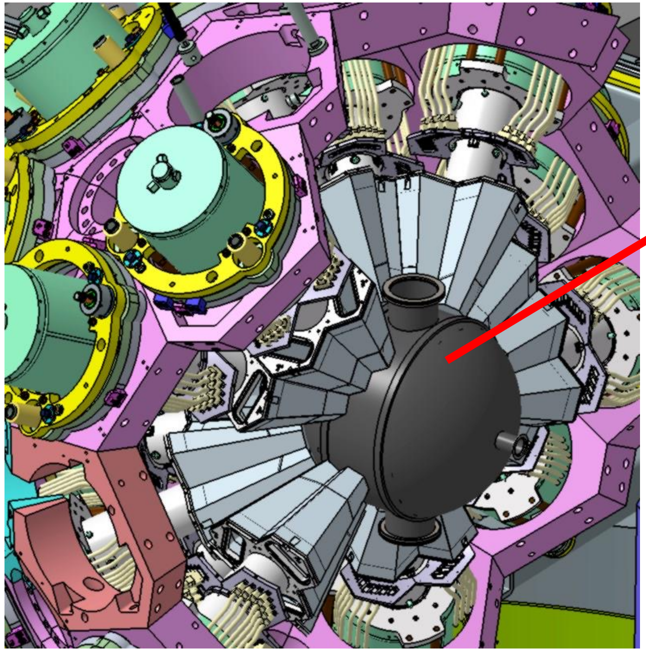
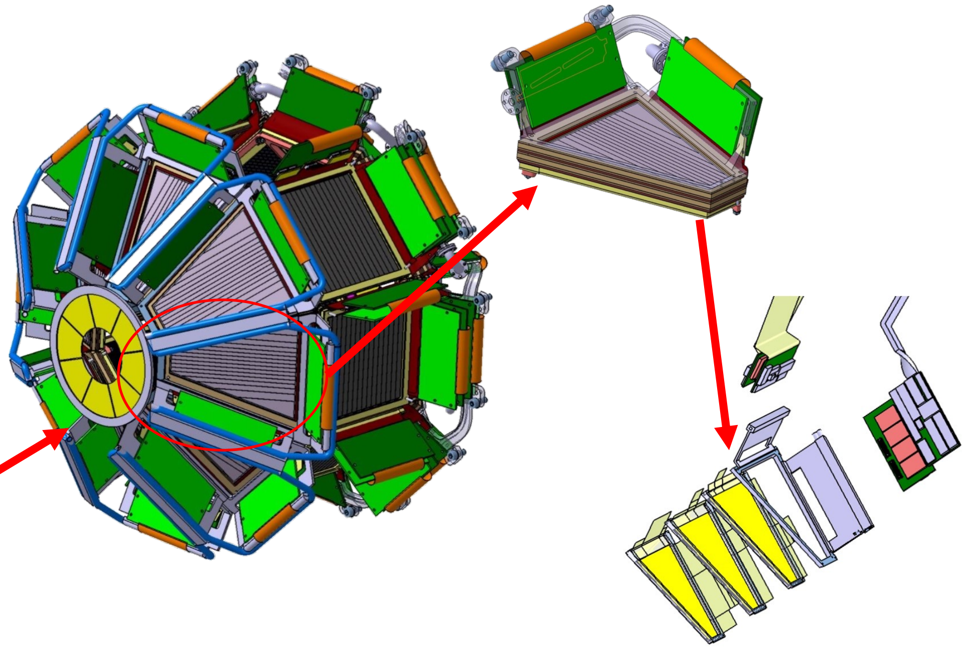
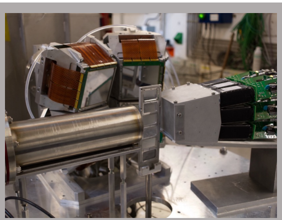


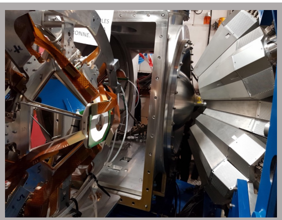


**<u>Integration challenge:</u>**
- GRIT is inside the 450 mm sphere of AGATA
  - 90 electronics card
  - 24 silicon detectors
- To be ready in 2026/27

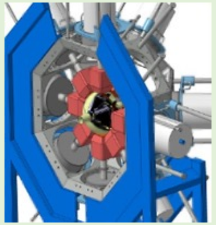
# Summary and next steps



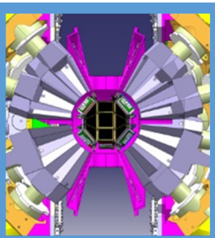
MUST2
@LISE



MUGAST
VAMOS
AGATA



MUGAST
EXOGAM
LISE
@GANIL



GRIT
AGATA
@SPES?
@GANIL?

GRIT AGATA?
GRIT EXOGAM?
@GANIL ?

2017-2021 → 2023-2026? → 2027?-2030? → after 2030?

**What has been done:**

- 11 Experiments
- 7 published articles (2 submitted)
- Broad range of topics (shell-model, astrophysics, drip-line…)
- Combination of Light-particle + gamma-ray + Residue detection
- Coverage of forward + backward angles

**What is coming:**

- 4+ experiments with MUGAST@LISE
- GRIT@SPES with AGATA
- GRIT-AGATA@GANIL?
- GRIT-EXOGAM? GRIT-EXOGAM-PARIS?

# Thank you for your attention!

**Collaboration:**

**IJCLab Orsay**: M. Assié, D. Beaumel, Y. Blumenfeld, N. De Séréville, V.Girard-Alcindor, J. Guillot, F. Hammache, H. Jacob, A.Korichi, L. Lalanne, I. Stefan

**INFN-Padova, LNL**: D. Brugnara, J.Casal, F. Galtarossa, A Goasduff, A. Gottardo, D. Mengoni, D. Testov

**INFN-Legnaro**: A. Raggio, A. Montanera Piza, I. Zanon

**INFN-Milano**: S.Leoni, B.Million

**GANIL:** E. Clément, A. Lemasson, D. Ramos, M. Rejmund, O. Sorlin, F. de Oliveira, C.Fougères, G. De France, B. Bastin, S. Leblond

**LPC Caen:** F. Delaunay, J.Dudouet, F. Flavigny, C.Lenain, A.Matta, F.Noury, N.Orr

**IRFU-CEA-Saclay**: M.Siciliano

**IPHC Strabourg**: K. Rezynkina, G. Duchêne, F. Didierjean

**University of York**: C. Diget, A. Laird, J.S. Rojo

**University of Surrey**: W. Catford, G. Lotay, C. Paxman

**HHNIPNE Magurele**: R.Borcea, F. Rotaru, M.Stanoiu

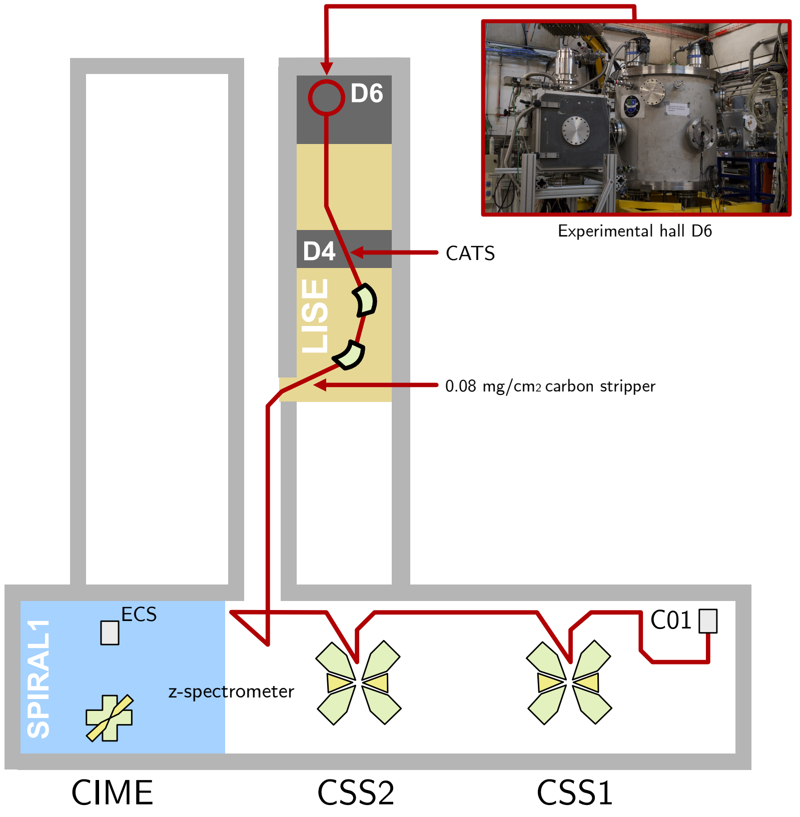
**University of Santiago**: B. Fernandez-Dominguez

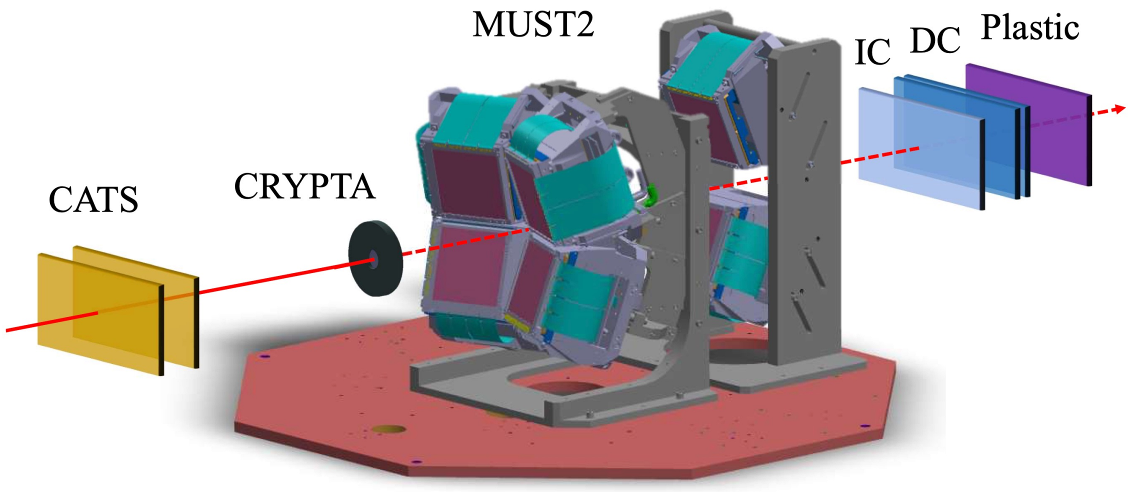
**University of Valencia**: A. Gadea

# BACKUP SLIDES

# MUST2@LISE: 2017 - 2018






- 4 - 8 MUST2 telescopes
- CspI + LaBr3 γ-ray detectors
- 0° Detection (MUST2 or ZDD)
- Cryogenic target compatible

- 4 experiments (2017-2018)
  - Shell model
  - Drip-line
  - Clustering

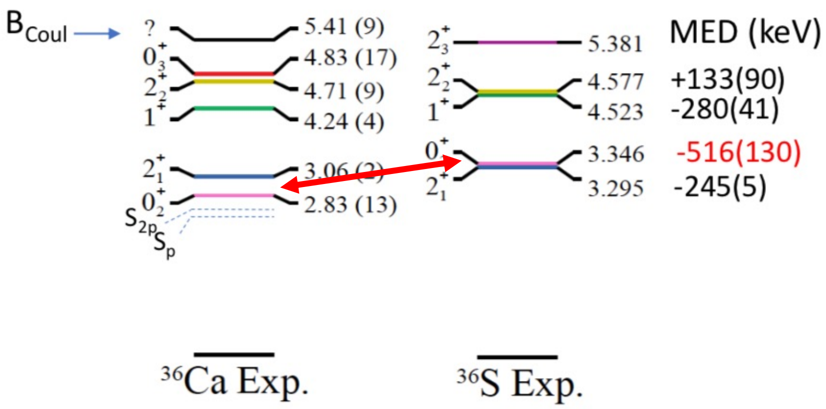
# MUST2@LISE: 2017 - 2018

O. Sorlin, D. Suzuki, M. Assié: Colossal mirror energy difference between $^{36}$Ca and $^{36}$S evidenced through transfer reactions

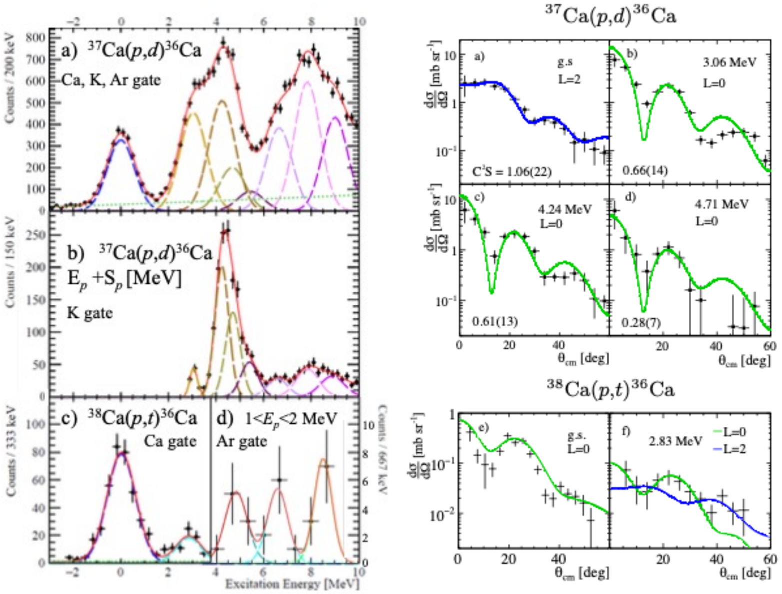
Topic: Shell model
Reaction: $^{37}$Ca(p,d)$^{36}$Ca and $^{38}$Ca(p,t)$^{36}$Ca
Goal: Study of MED between $^{36}$Ca and $^{36}$S
Specificities: Use of LH2 target (*S. Koyama et al., NIM A 1010,165477 (2021)*)

Motivations:

- Colossal MED (-700 keV) predicted between $0^+_1$ and $0^+_2$ states in $^{36}$S - $^{36}$Ca
- Explained by the very different configuration between the spherical ground state and the intruder $0^+_2$ state - *Valiente-Dobon et al., PRC 98 (2018)*



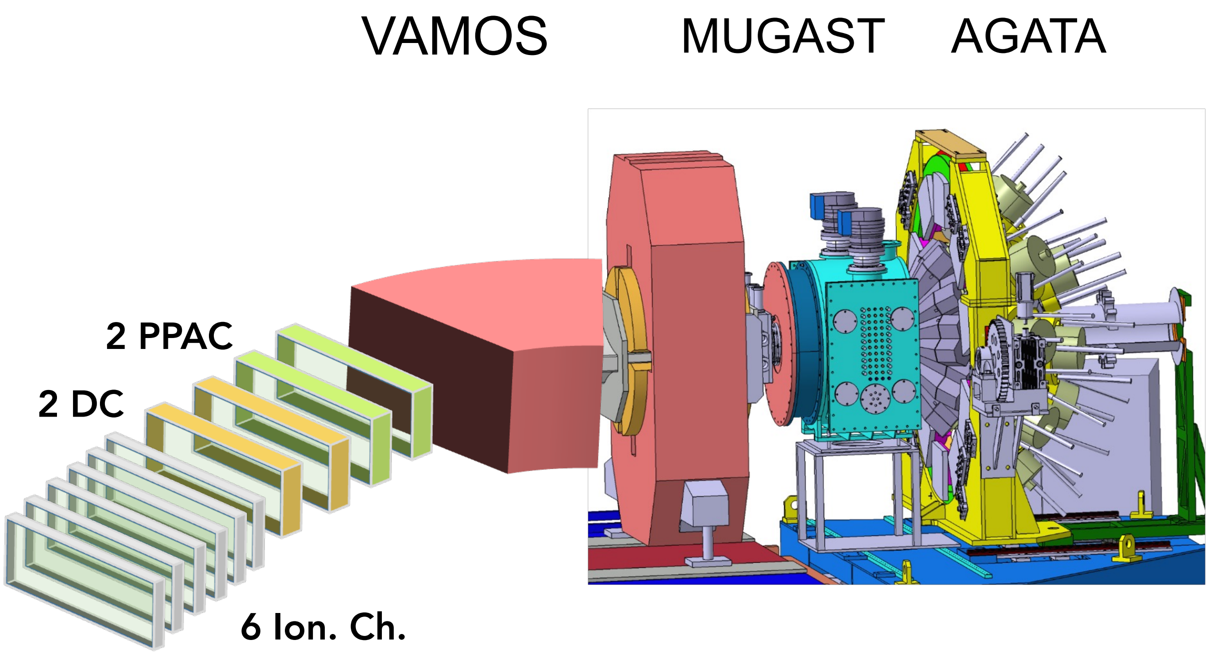

*PhD : L. Lalanne*

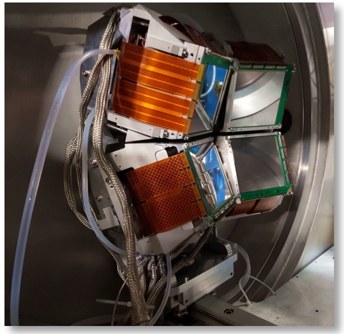


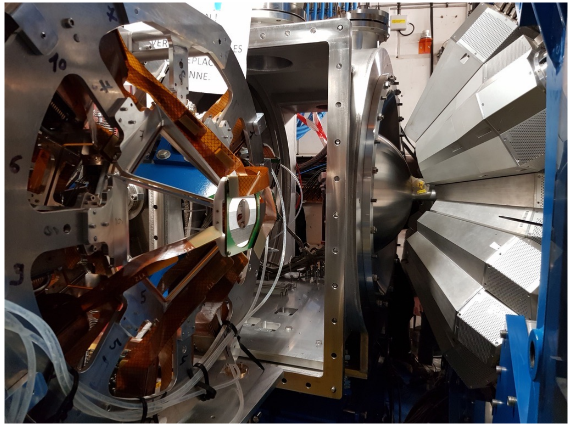

- -500 keV MED for the $0^+_2$ the **largest** one ever observed
- -250 keV MED for the 2+ and 1+ states.
- 1st time evidence of MED breaking in shape coexistence

*L. Lalanne et al., PRL 129 122501 (2022)*

# MUGAST-VAMOS-AGATA: 2019 - 2021



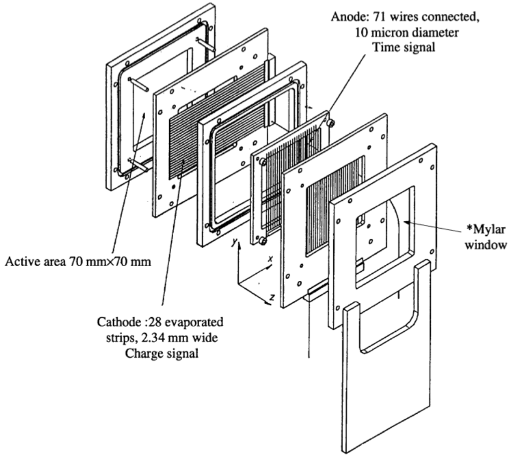


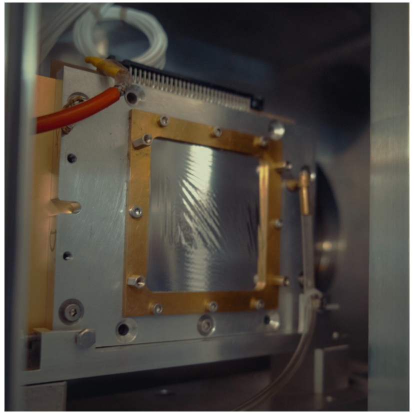
- $0^{o}$ Detection: VAMOS
- AGATA Ge γ-ray spectrometer
- 4 MUST2 telescopes (forward)
- 5-7 trapezoidal DSSD + 1 Annular DSSD (backward)
- 2 Square DSSD or 1 MUST2 at $90^{o}$
- Cryogenic-target compatible

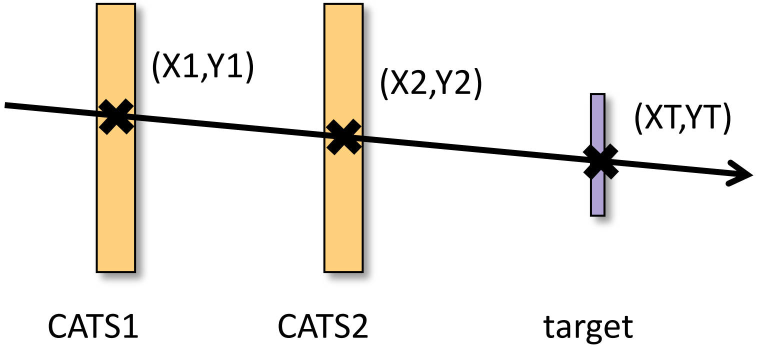
- 5 experiments (2019-2021)
  - Shell-model
  - Drip-line
  - Nuclear astrophysics

# Beam tracking

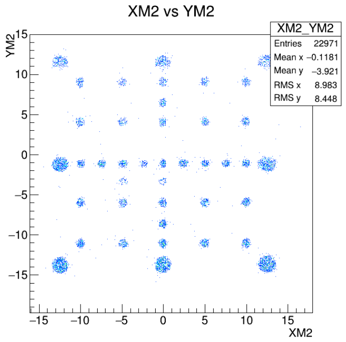
## Beam tracking: CATS

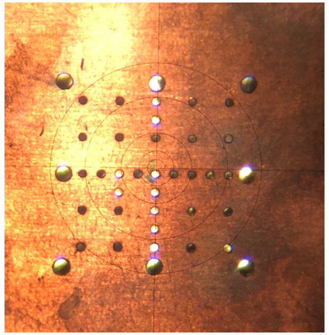


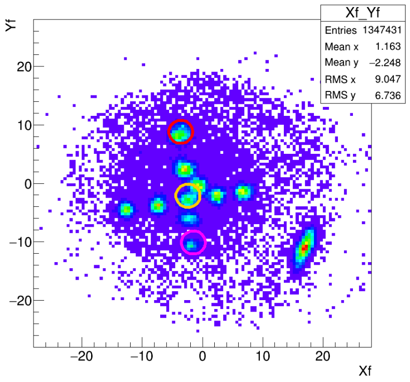



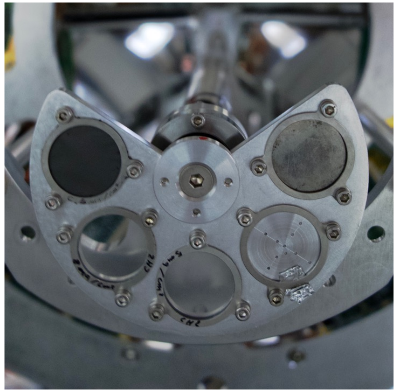



## Mask on CATS:



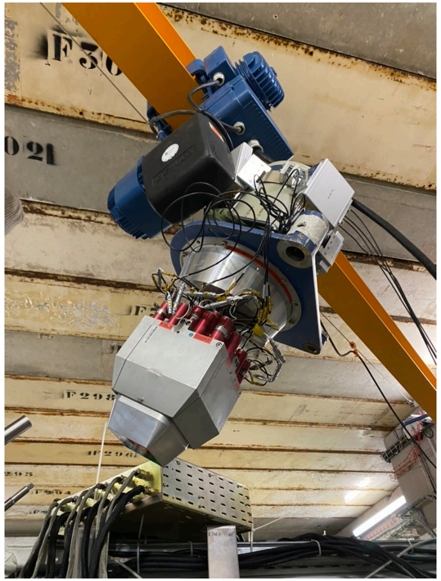





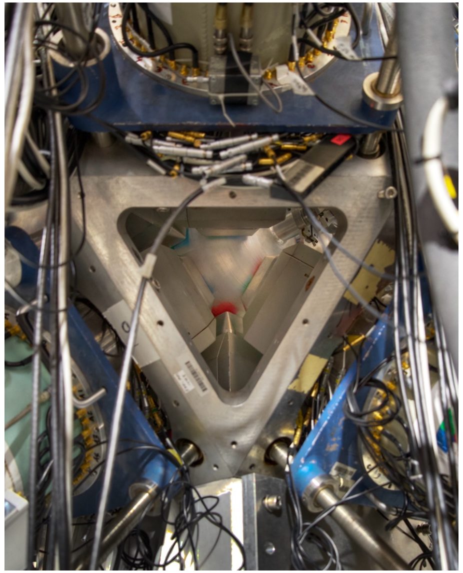



# Gamma spectroscopy

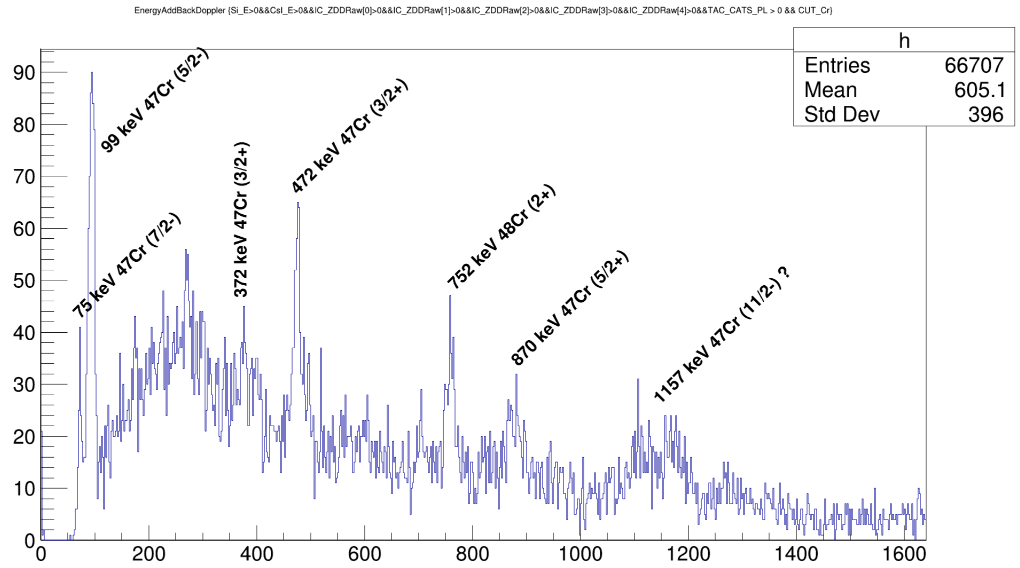
**Exogam:**



Exogam cluster before mounting



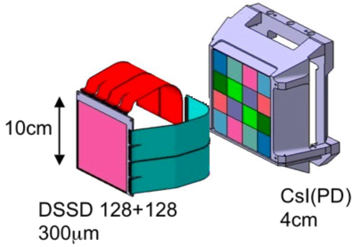
Exogam clusters around the trapezoids

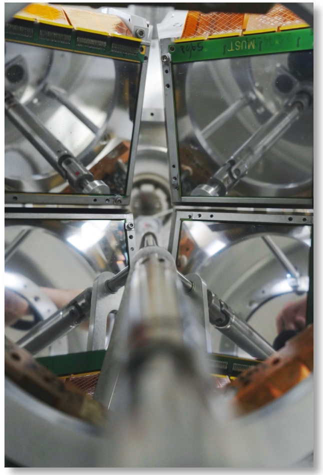


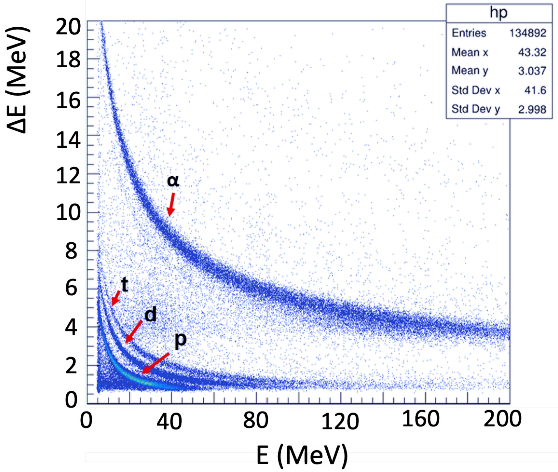

Example of online add-back doppler corrected spectra

# Particle identification

## ΔE-E identification in MUGAST:

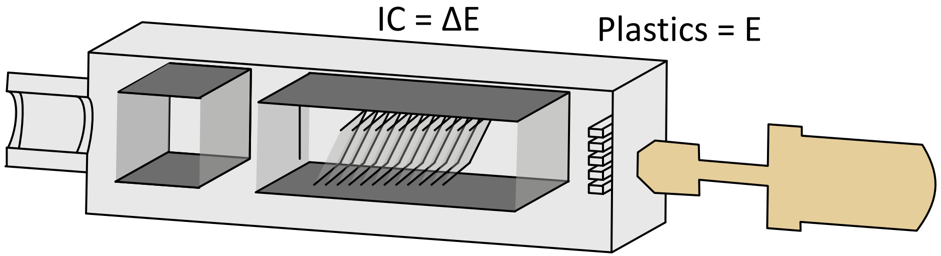


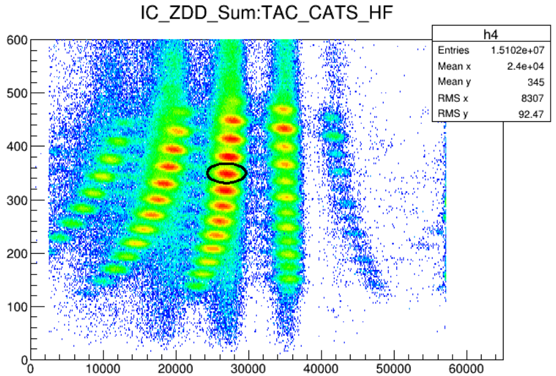



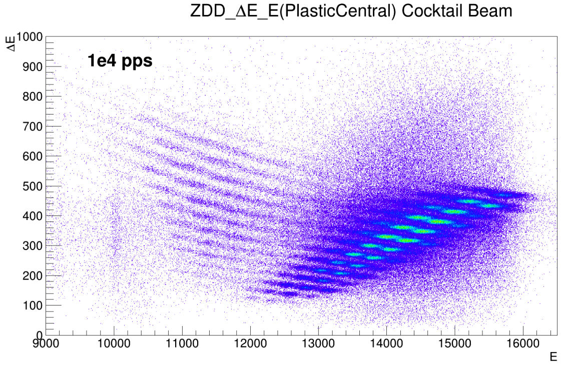



ToF identification also possible with MUST2/MUGAST but not used online

## ΔE-E + ToF identification in the ZDD:



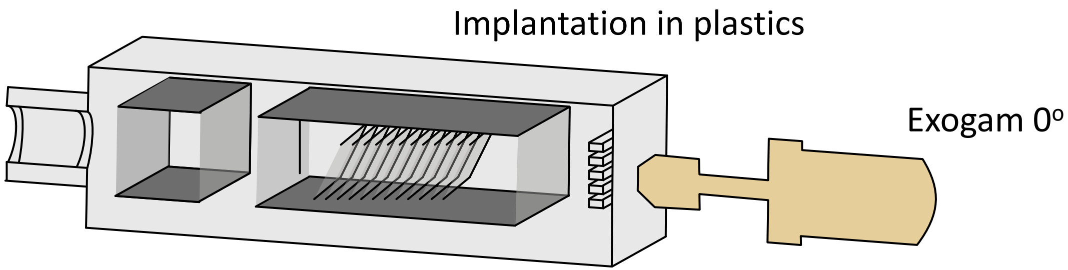



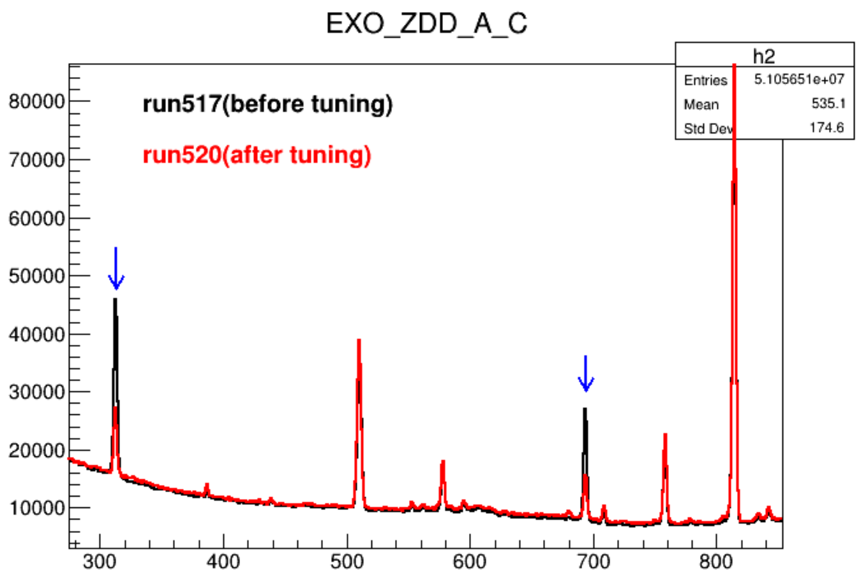

Damage to the central plastic due to direct beam -> bad ΔE-E:
-> identification ΔE - ToF CATS_HF (or CATS-Plastic)

# Decay station



**Isomer identification: ZDD Exogam**




- Beginning of beam time, large contamination from 67Ni isomer
- Contamination estimated thanks to the decay station
- Help diagnose and reduce the contamination !
- The decay station is  also of interest for reaction induces by isomers
  - To estimate their production
  - To subtract the “isomer-induced” background

# Highlights MUGAST/VAMOS/AGATA Campaign

# MUGAST-VAMOS-AGATA

<u>C. Diget, N. De Séréville: Determining the α+$^{15}$O radiative capture rate</u>

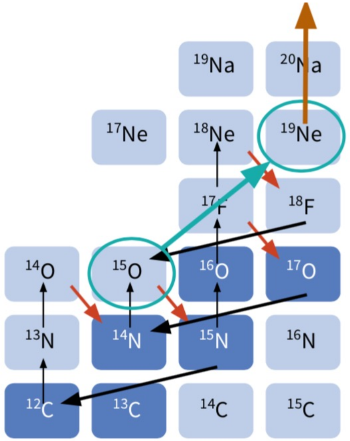
Topic: Nuclear astrophysics
Reaction: $^{15}$O($^{7}$Li,tγ)$^{19}$Ne indirect measurement
Goal: Important reaction for breakout from Hot-CNO cycle to rp-process in Type I X-ray bursts
Specificities:

- High intensity beam : up to $10^8$ pps
- High energy gammas (~4 MeV)
- Triple coincidences: background free !

Motivations:

- Breakout to rp-process $^{15}$O(α,γ)$^{19}$Ne and $^{18}$Ne(α,p)$^{21}$Na
- Key beak-up route from the Hot-CNO
- Start-up of Type I X-ray burst depends upon this reaction rate
- Resonant reaction rate $^{15}$O(α,γ)$^{19}$Ne expected to dominate through 4033 keV resonance *(to be measured in AGATA)*

*PhD : J. Sanchez Rojo*



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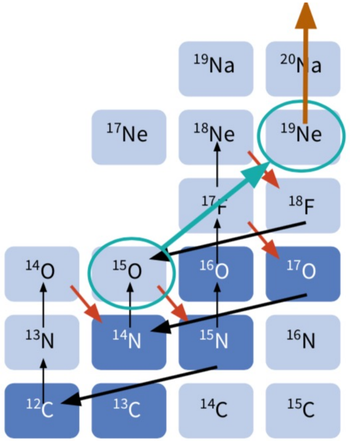
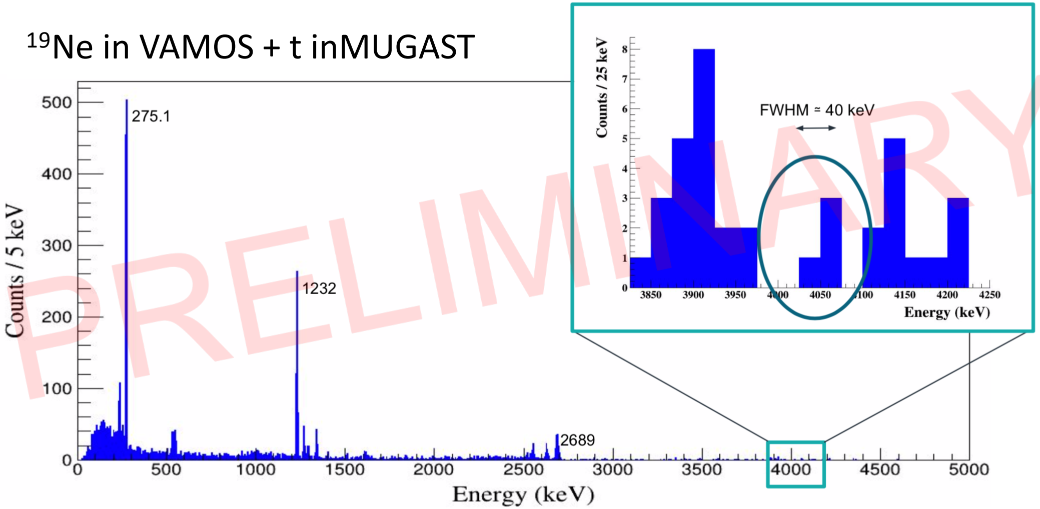



$^{19}$Ne in VAMOS + t inMUGAST



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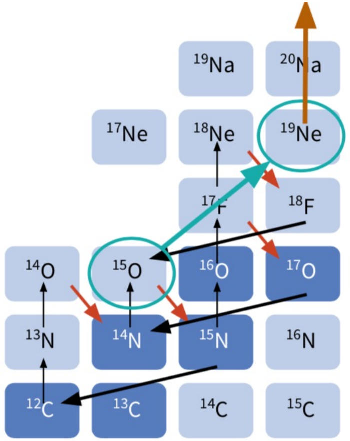


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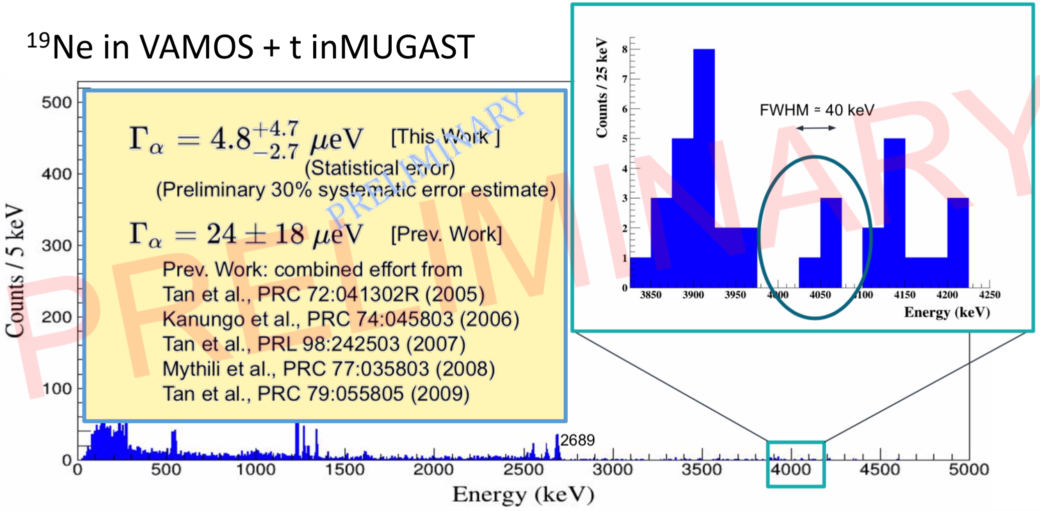


# MUGAST-VAMOS-AGATA

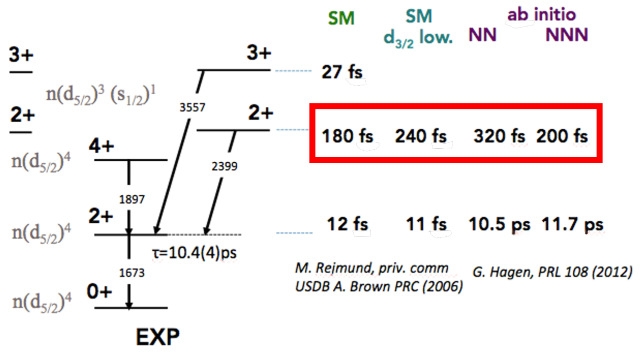


E. Clément, A. Goasduf: Lifetime measurements of the $2^+_2$ and $3^+_1$ states in $^{20}O$ populated by direct nucleon transfer

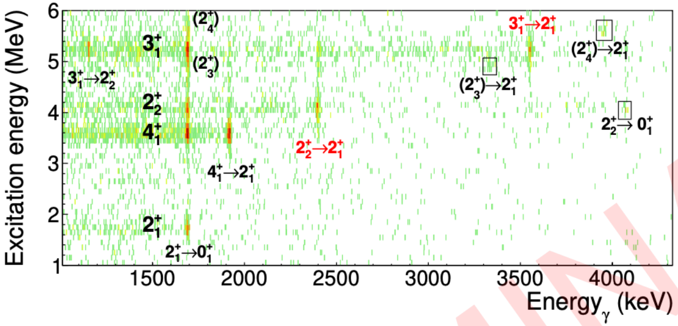
Topic: Shell model
Reaction: $^{19}O(d,p\gamma)$ + DSAM
Goal:

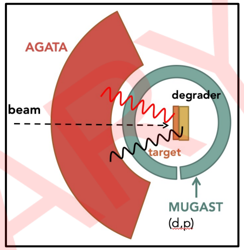
- Constrain relative position of $s_{1/2}$ and $d_{3/2}$ in n-rich oxygen
- Probe the 3-body interaction
- Combination of DSAM + transfer to identify the entrance channel

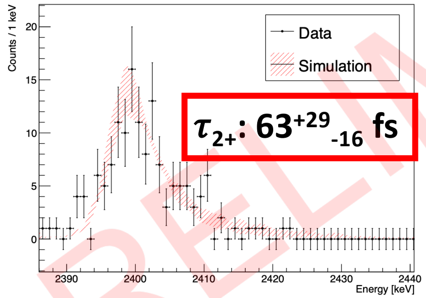
**Motivation** : Oxygen drip-line anomaly explained microscopically by including three-nucleon force contribution in the nuclear interaction.
**Predictions** : from Shell model and ab-initio (2N and 3N forces):

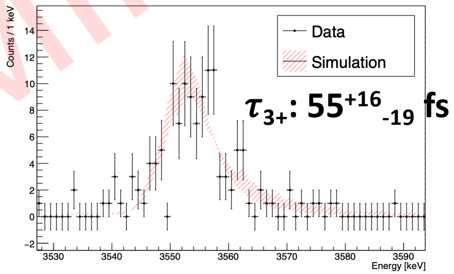



*PhD : I. Zanon*




PRELIMINARY

- $2^+$ $t_{1/2}$ < predictions and previous measurements
- 3+ $t_{1/2}$ measured for the first time
- Strong constraints on the theoretical models
- Paves the way for similar measurements