Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Nuclear Physics in Astrophysics XI

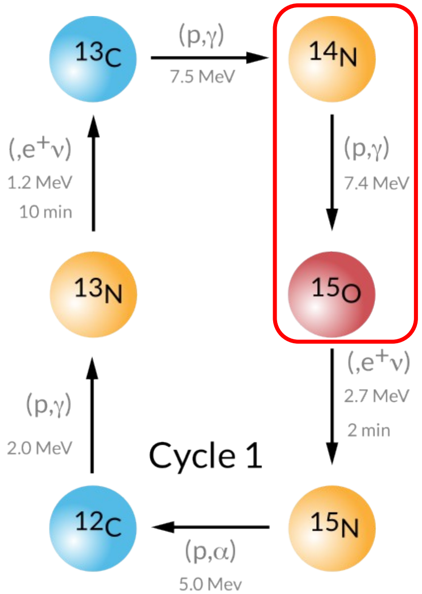
Lifetime measurement of 6.79 MeV state in ^{15}O for nuclear astrophysics

Speaker: Elia Pilotto

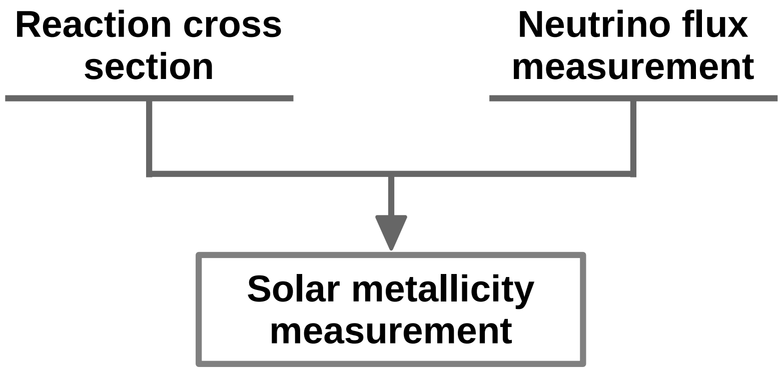
September 2024

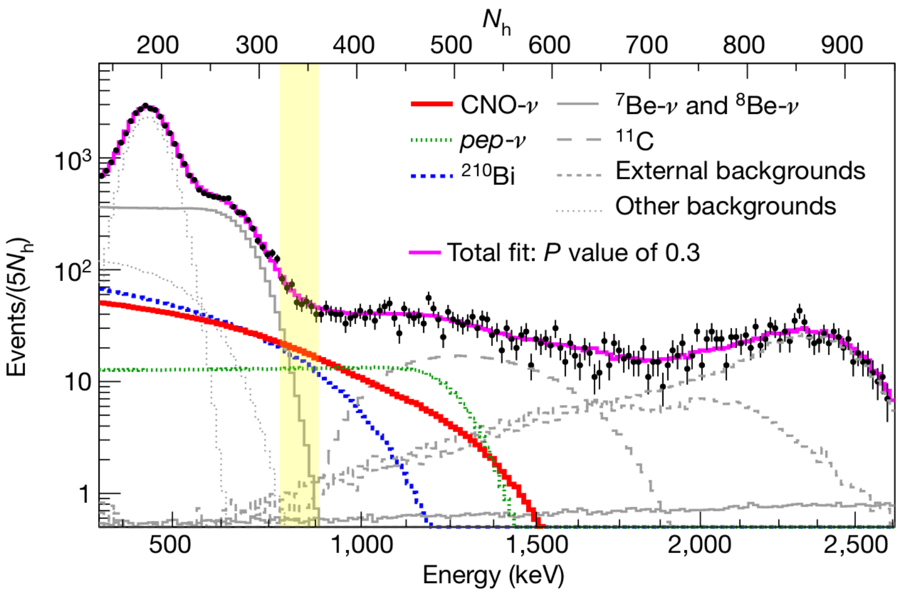
Introduction

CNO-cycle I



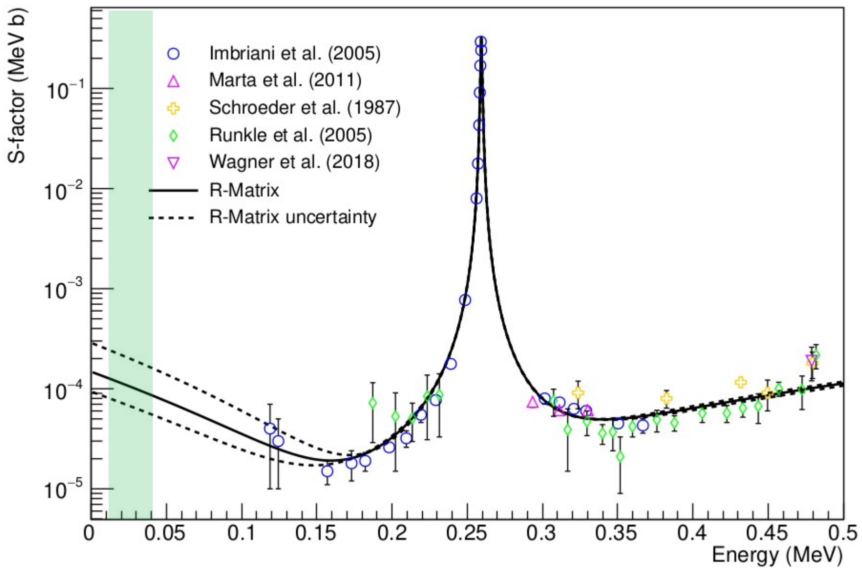
- Main energy production mechanism in stars larger than our Sun
- Equilibrium governed by the **$^{14}N(p,\gamma)^{15}O$** reaction, the slowest of the cycle
- Gamow peak is at 10 – 30 keV, direct measurement stop at 90 keV
- **Sub-threshold resonance** dominates at astrophysically relevant energies and heavily impacts extrapolation
- **Resonance width** is directly correlated to **lifetime** of the state



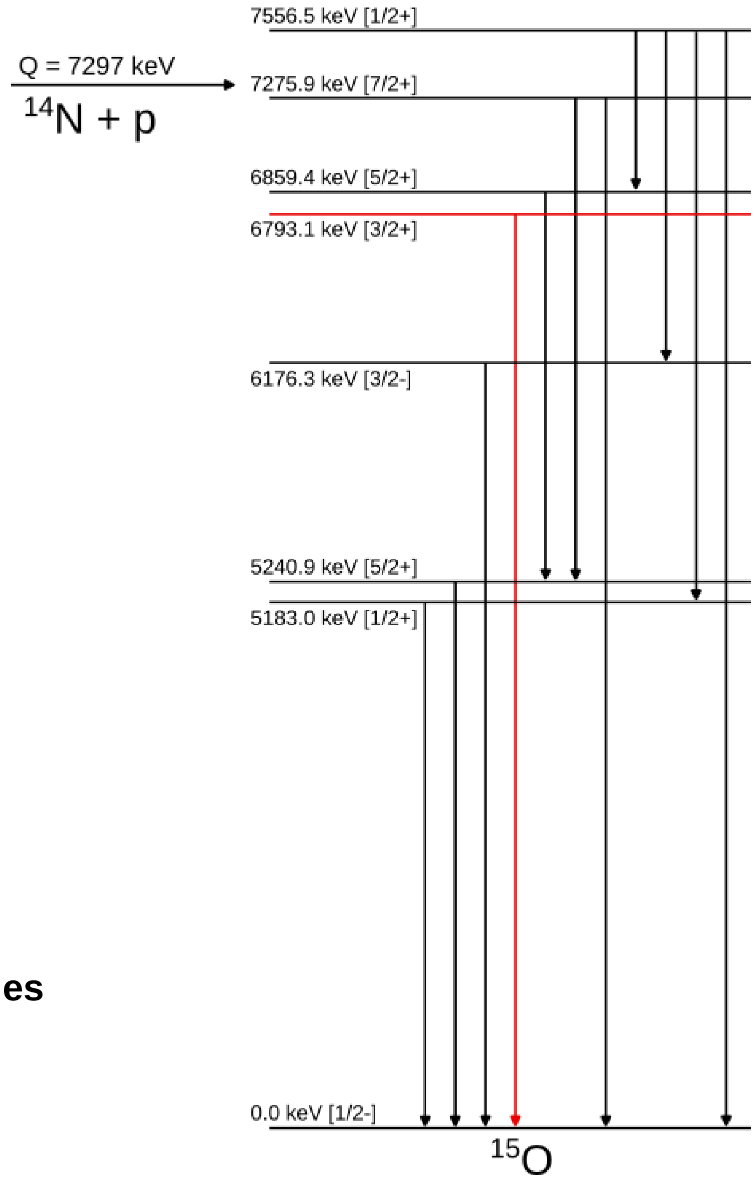


Borexino collaboration, Nature 587 (2020)

State of the art of the reaction



R-Matrix fit parameters according to Frentz et al, PRC (2021)



6.79 MeV state lifetime estimates

Dataset	τ_{obs} (fs)
Frentz et al. (2021)	0.6 ± 0.4
Bertone et al. (2001)	1.6 ± 0.75
Schurmann et al. (2008)	< 0.77
Galinski et al. (2014)	< 1.8
Sharma et al. (2020)	< 1.18

→

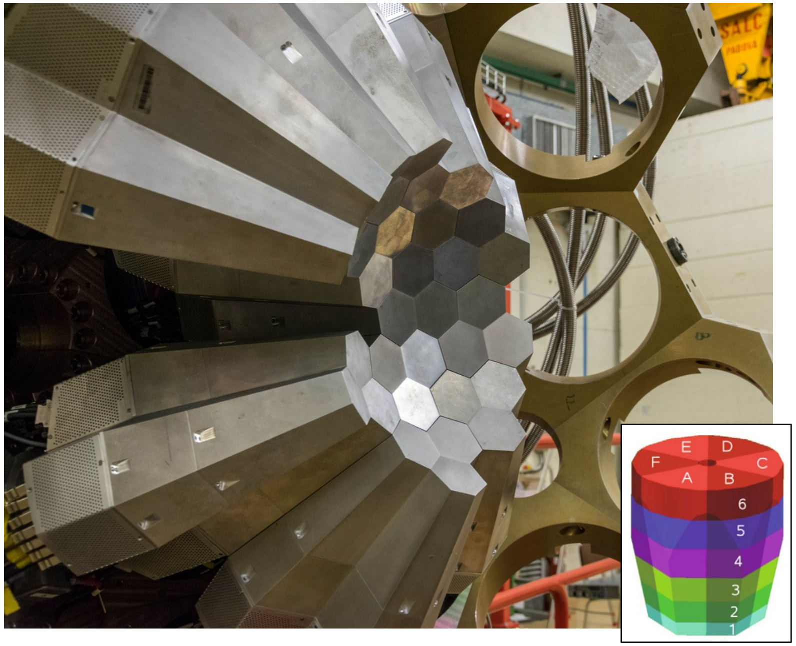
- **Sub-fs lifetime**
- **Large uncertainties**

+ recent direct measurements at LUNA 400 and Bellotti facility

Technique and Setup

- Reaction: **^{3}He(^{16}O,^{15}O)^{4}He @ 50 MeV**
- **A**dvanced **GA**mma **T**racking **A**rray (**AGATA**)
- Annular **DSSSD** Si detector

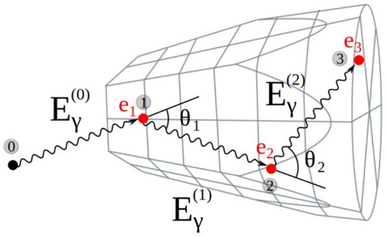
The AGATA array

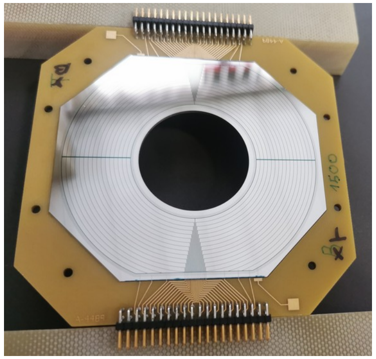


State of the art in γ – ray spectroscopy array of highly **segmented** coaxial **HPGe** detectors

<u>AGATA main features</u>

- **P**ulse **S**hape **A**nalysis (**PSA**)
  - γ – interaction position reconstruction (3 – 5 mm resolution)
  - excellent **angular resolution** of 1 deg
- γ – ray tracking





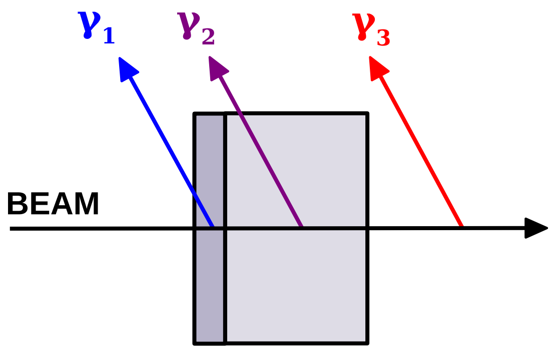
<u>Annular DSSSD Si detector</u>

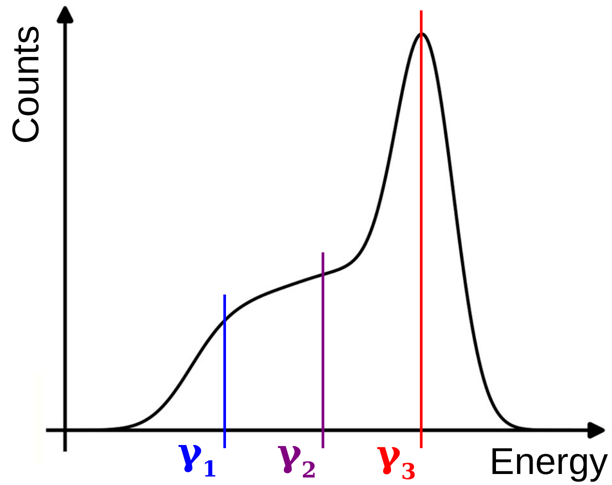
- Good granularity and angular resolution
- **P**ulse **S**hape **D**iscrimination (**PSD**) for **particle identification**

Technique and Setup

Doppler Shift Attenuation Method (DSAM)

$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1+\beta\cos\theta}$$





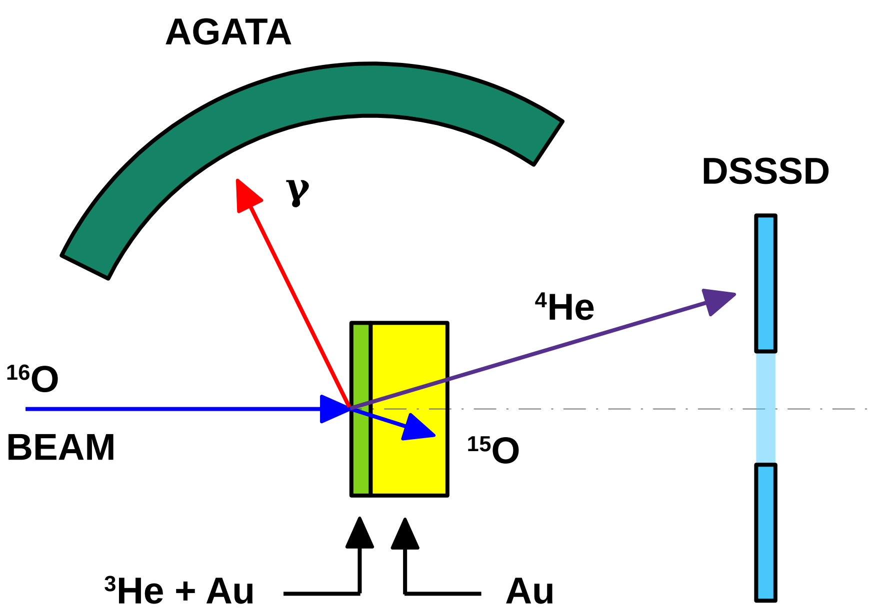
Targets used

1st set of targets

- Produced at HZDR (Dresden) by ^{3}He **implantation**
- 13 um Au substrate
- 0.1 um ^{3}He + Au implantation layer

2nd set of targets

- Produced at ICMS (Seville) by **magnetron sputtering***
- 13.6 um Au substrate
- 0.4 um ^{3}He + Au growth layer



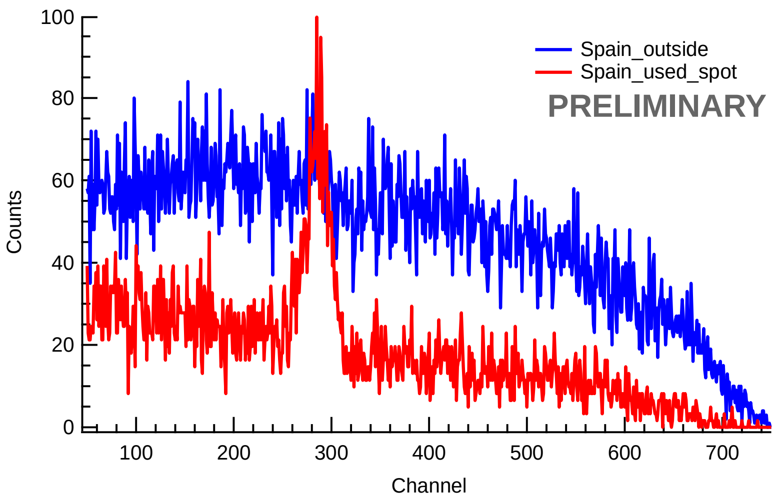
**A. Fernandez et al, Materials and Design 186 (2020)*

Target characterization

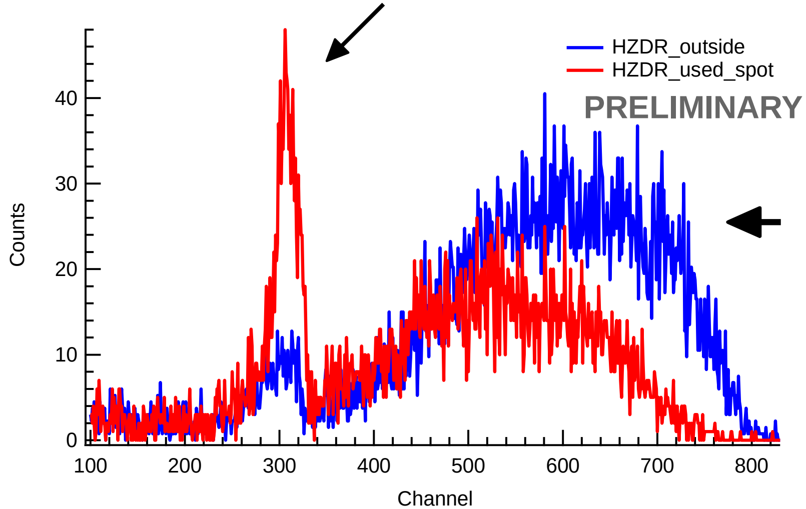
Objectives
- Contaminants
- ^{3}He depth profile

In Beam Analysis (IBA)
- **N**uclear **R**eaction **A**nalysis (**NRA**) performed at CNA in Seville
- **E**lastic **R**ecoil **D**etection **A**nalysis (**ERDA**) performed at HZDR in Dresden

ERDA measurement at HZDR – Dresden



Spurious H peak



^{3}He loss concentrated in the surface

ERDA performed by F. Munnik (HZDR)

Target characterization

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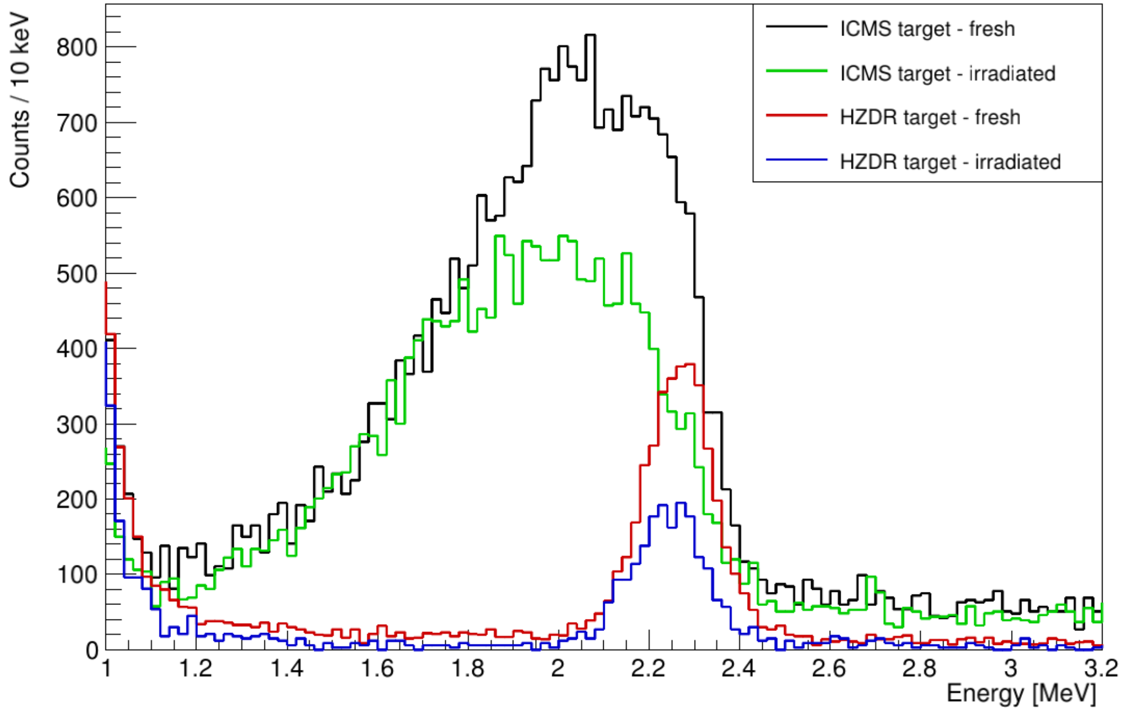
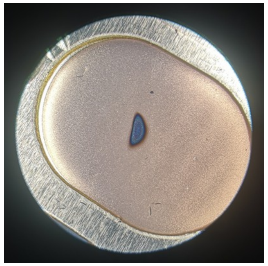
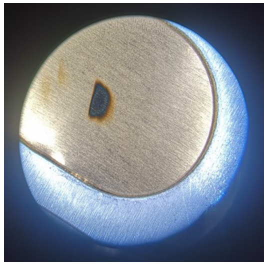
NRA measurement at CNA – Seville







- C, O contaminants only in the beam spot
- Sputtering targets have a thicker ^{3}He layer → factor 4
- Sputtering targets show higher initial ^{3}He content → factor 7
- Sputtering targets retain ^{3}He content better → factor 14

NRA performed by J. Ferrer (CNA)

AGATA presorting

INFN LNL
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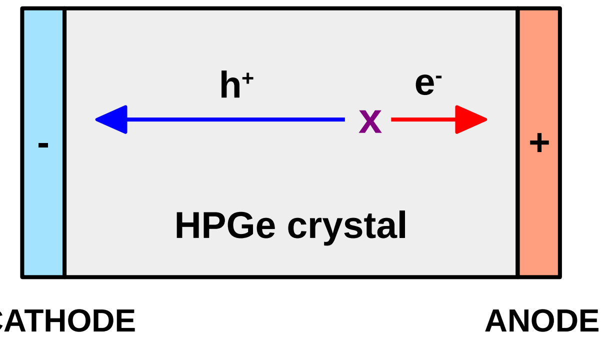
Neutron damage correction

- In HPGe detectors fast neutrons damage the crystal lattice, causing **charge trapping** and **energy resolution degradation**
- The loss in signal amplitude is dependent on the **path length**, the **electric field** and the **trap density**
- In segmented HPGe detectors, **PSA** can be used to determine the **position of interaction** of the γ – rays inside the crystal

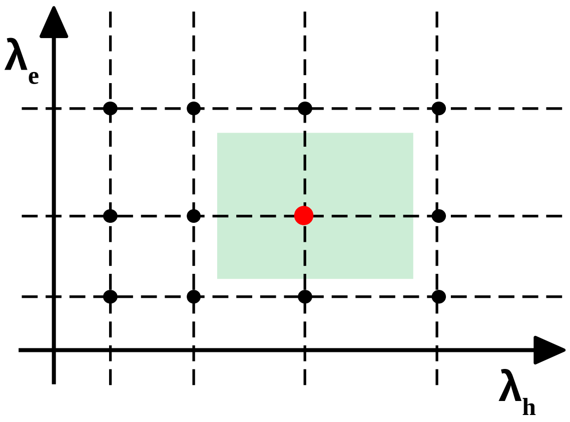
Charge trapping



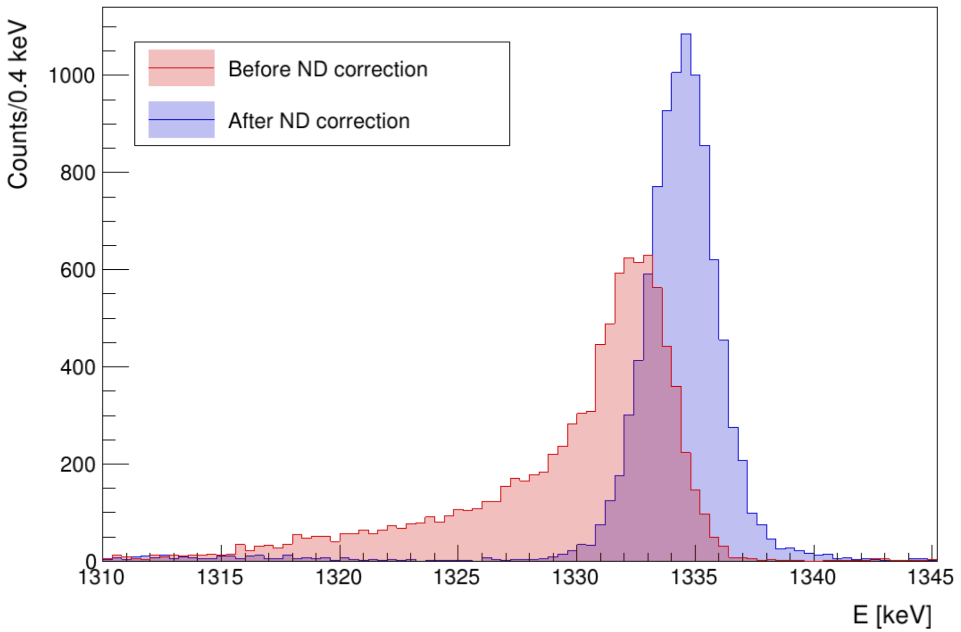
$$\frac{E_{meas}(x)}{E_{corr}(x)} = 1 + \frac{t_e(x)}{\lambda_e} + \frac{t_h(x)}{\lambda_h}$$

$\lambda_{e,h}$ = inverse electron / hole trap density

$t_{e,h}(x)$ = sensitivity to electron / hole trapping



Adaptive Grid-Search Algorithm

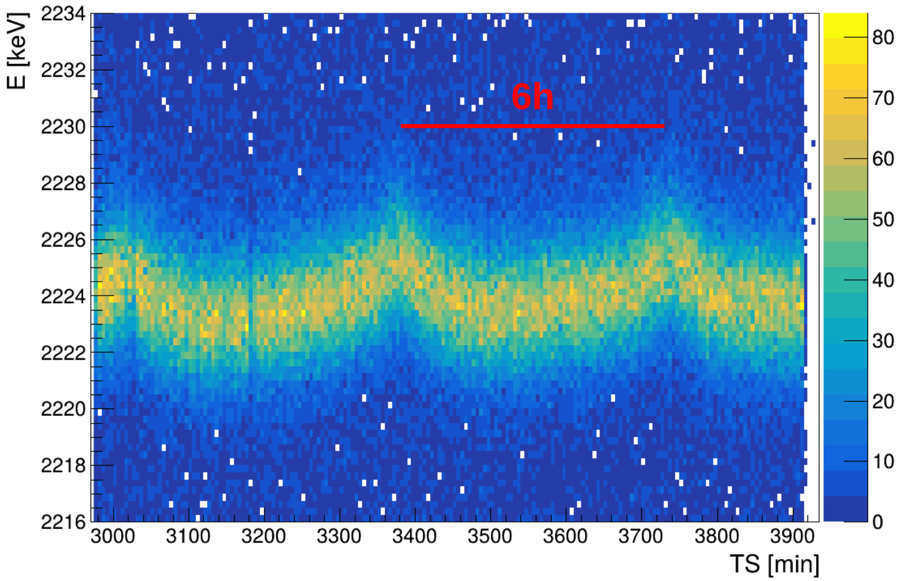


AGATA presorting

Time dependent calibration

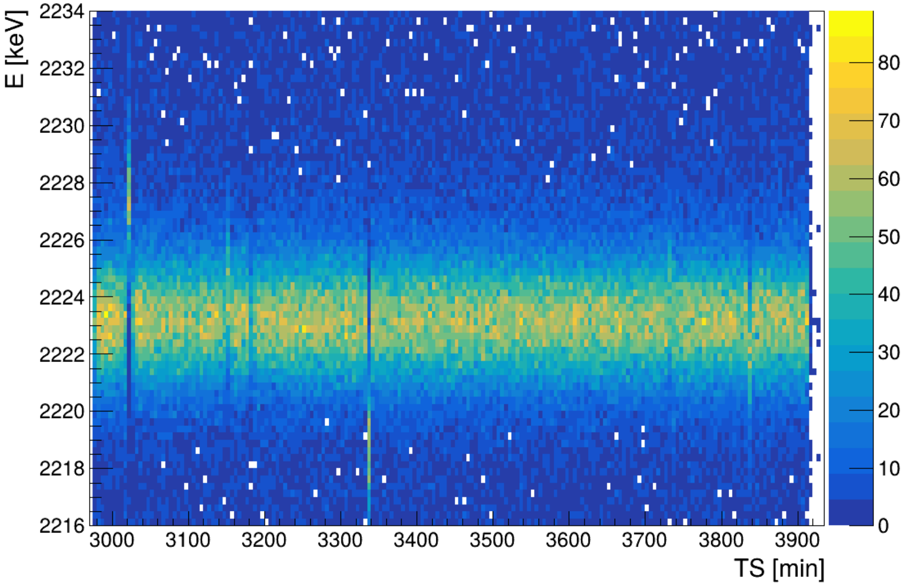
- Energy **gain oscillations** were observed, attributed to temperature effects
- Implementation of a **time dependent gain correction**
- Correction parameters were estimated using **Cross Correlation Method* (CCM)**

BEFORE



fwhm = 3.807(15) keV @ 2223 keV

AFTER



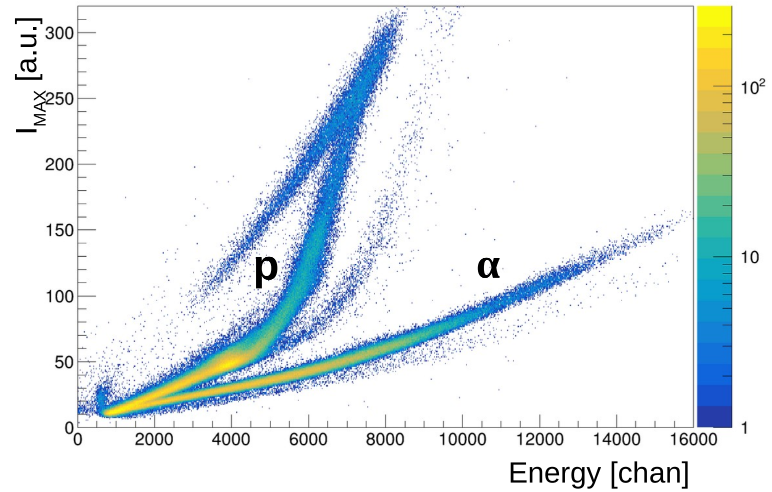
fwhm = 3.525(17) keV @ 2223 keV

**NIM paper: https://doi.org/10.1016/j.nima.2021.165368*

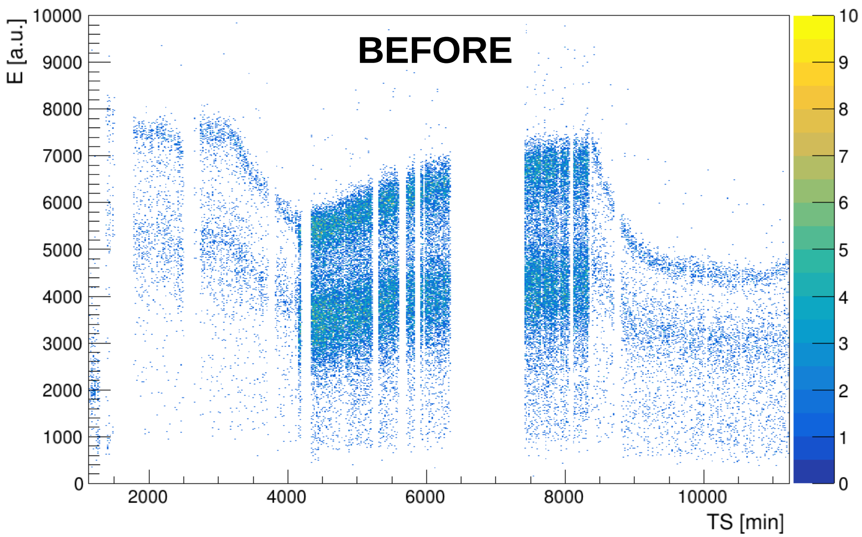
Annular DSSSD presorting

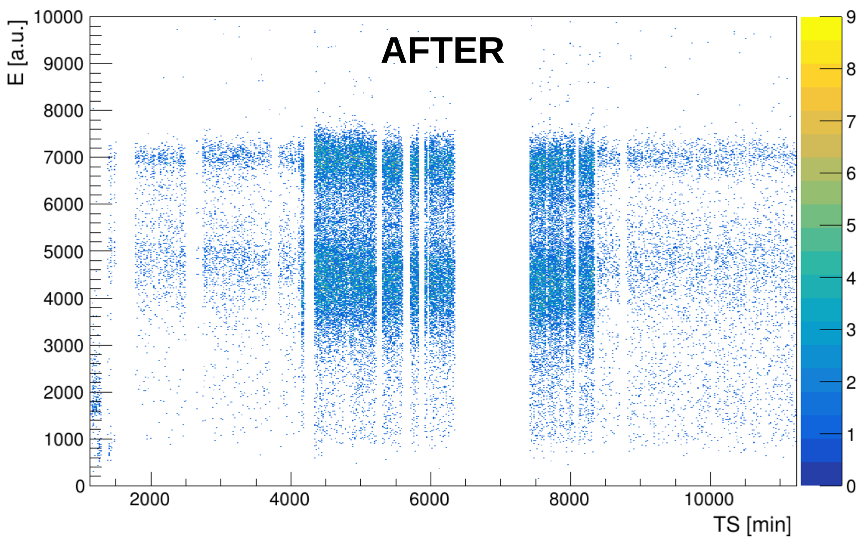
<u>Main features</u>

- **P**ulse **S**hape **D**iscrimination (**PSD**) used for **particle identification**
- Kinematic reconstruction to estimate excitation energy and binary partner kinematics
- Stability issues, highlighted with on γ – ray from $^{16}O(^{3}He,p)^{18}F$ reaction



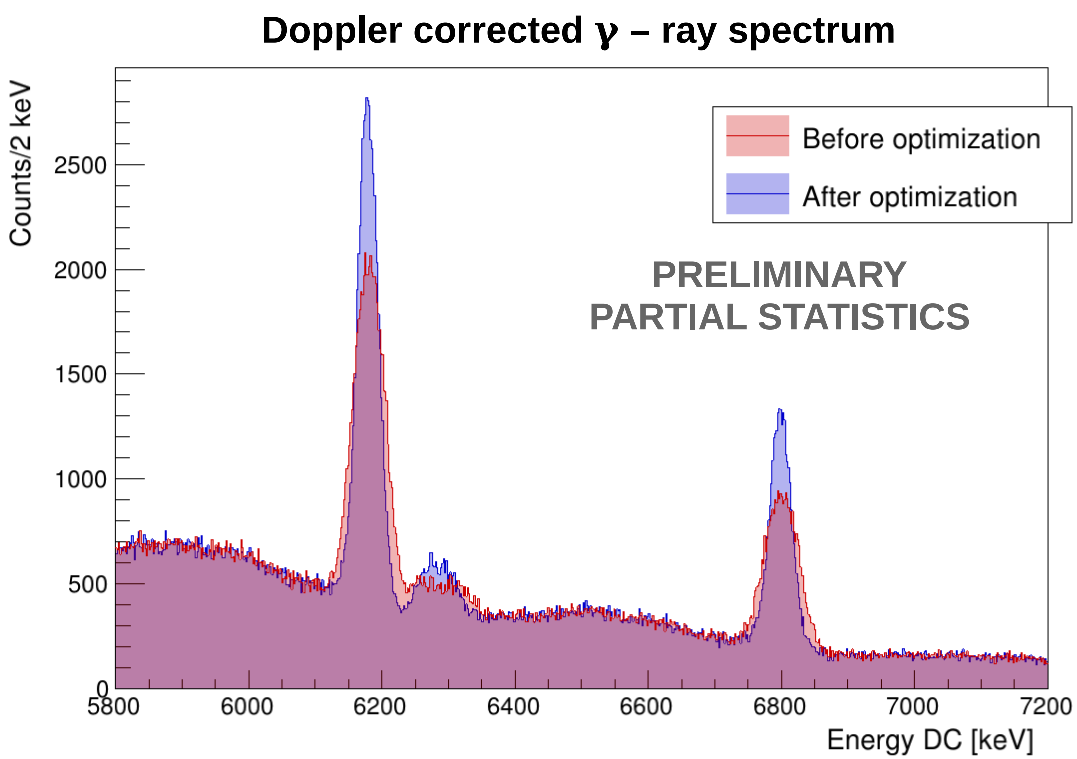
<u>Instability correction</u> [preliminary, yet to be included in the analysis]





Further analysis

Optimization of setup geometry



fwhm 55 → 33 keV [26 keV in simulations]

To do list

- Implementation of DSSSD instability correction
- Simulation fine tuning
- Lifetime analysis of 6.18 MeV state for validation of the method
- Lifetime analysis of 6.79 MeV state

Nuclear Physics in Astrophysics XI

Thank you for your attention

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