Capturing Cosmic History in a Femtosecond: ^{15}O Excited State Lifetime with AGATA

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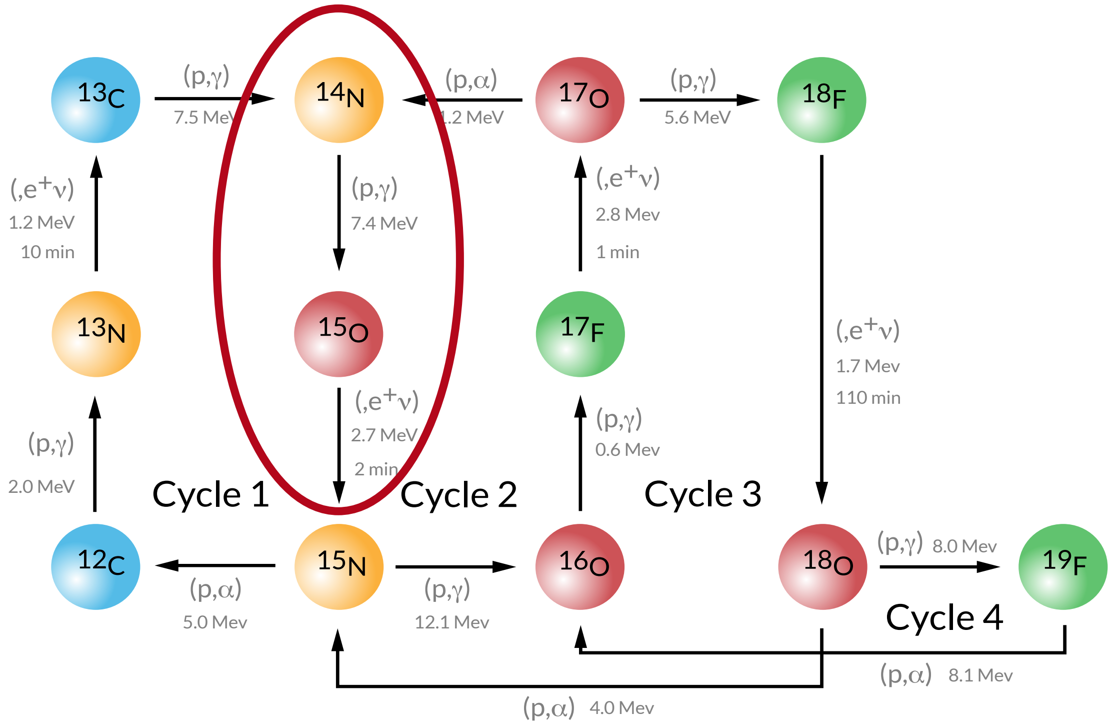
Astrophysical Motivation: $^{14}N(p,\gamma)^{15}O$ Reaction

CNO Cycle

$^{14}N(p,\gamma)^{15}O$ is the **slowest reaction** in the cycle



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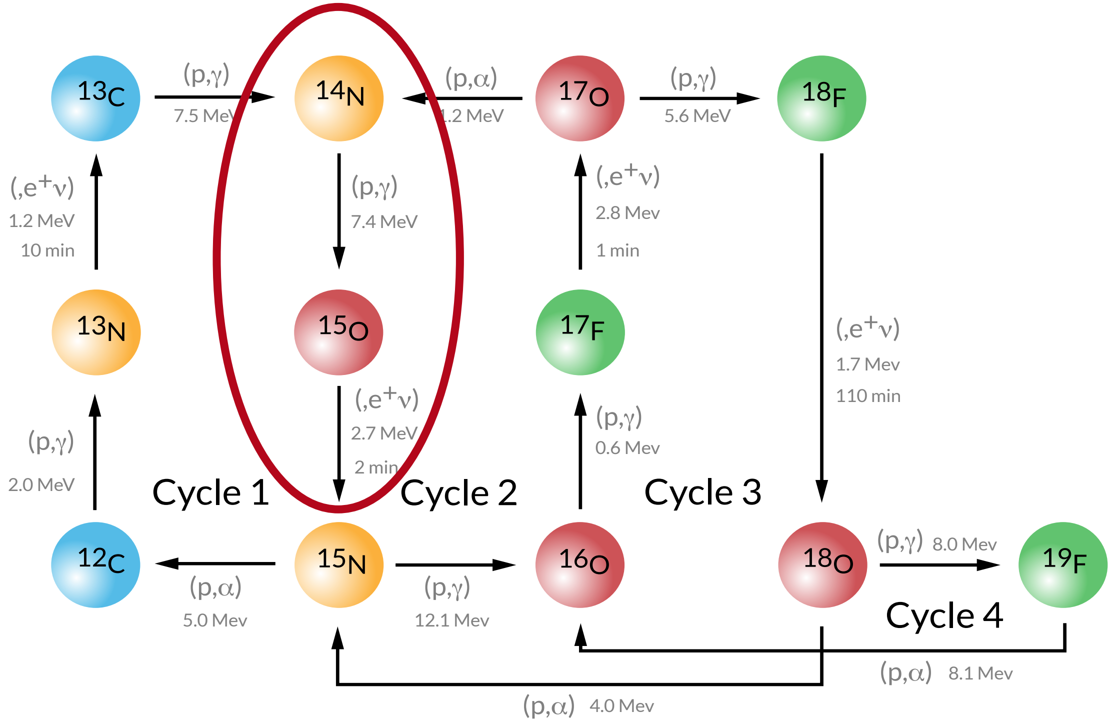

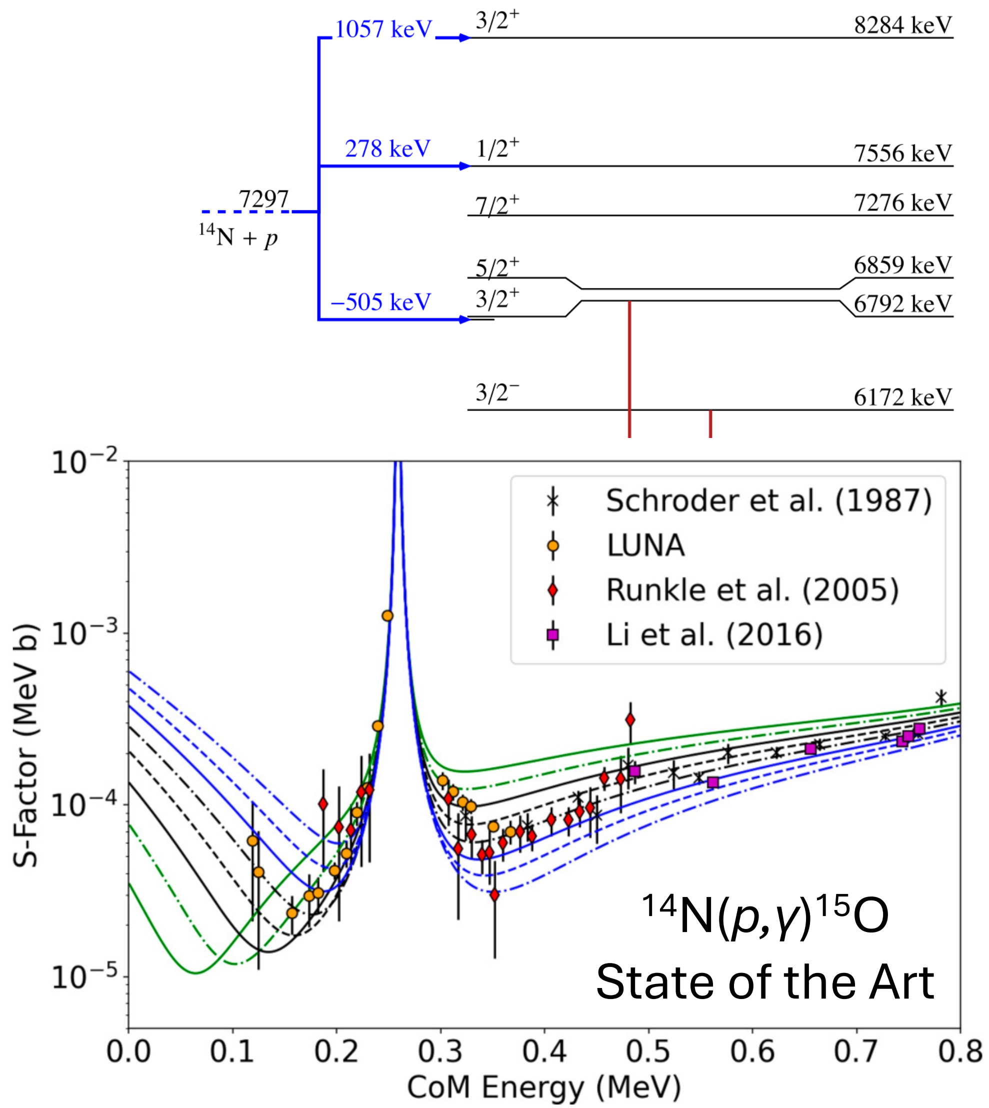

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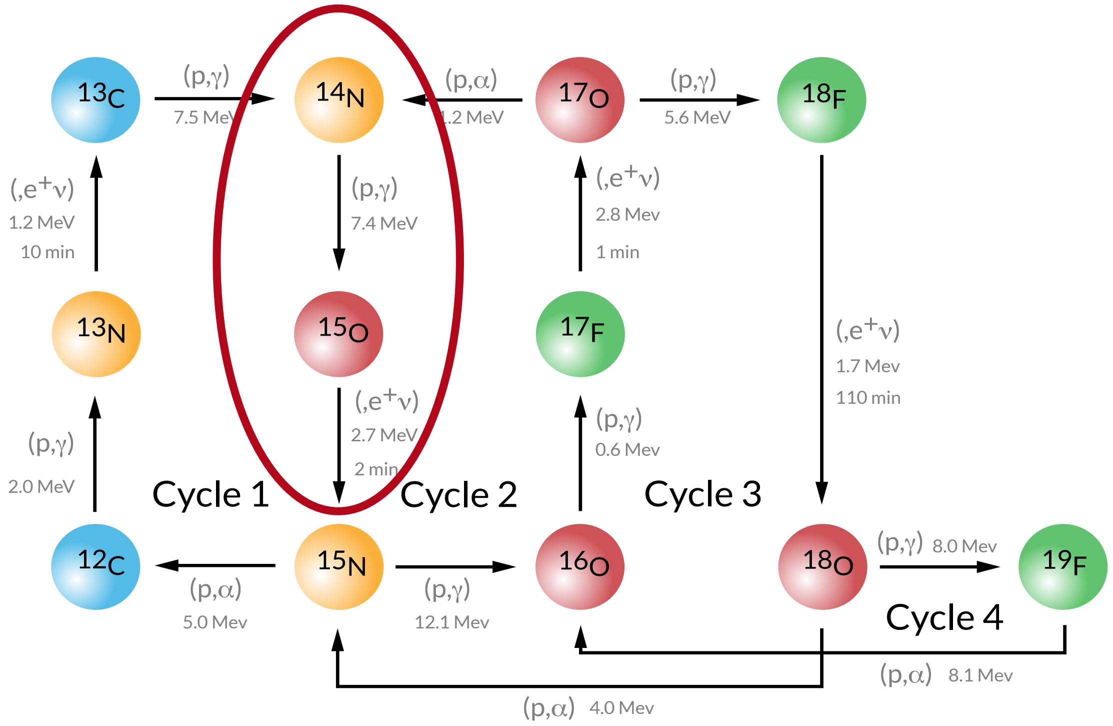

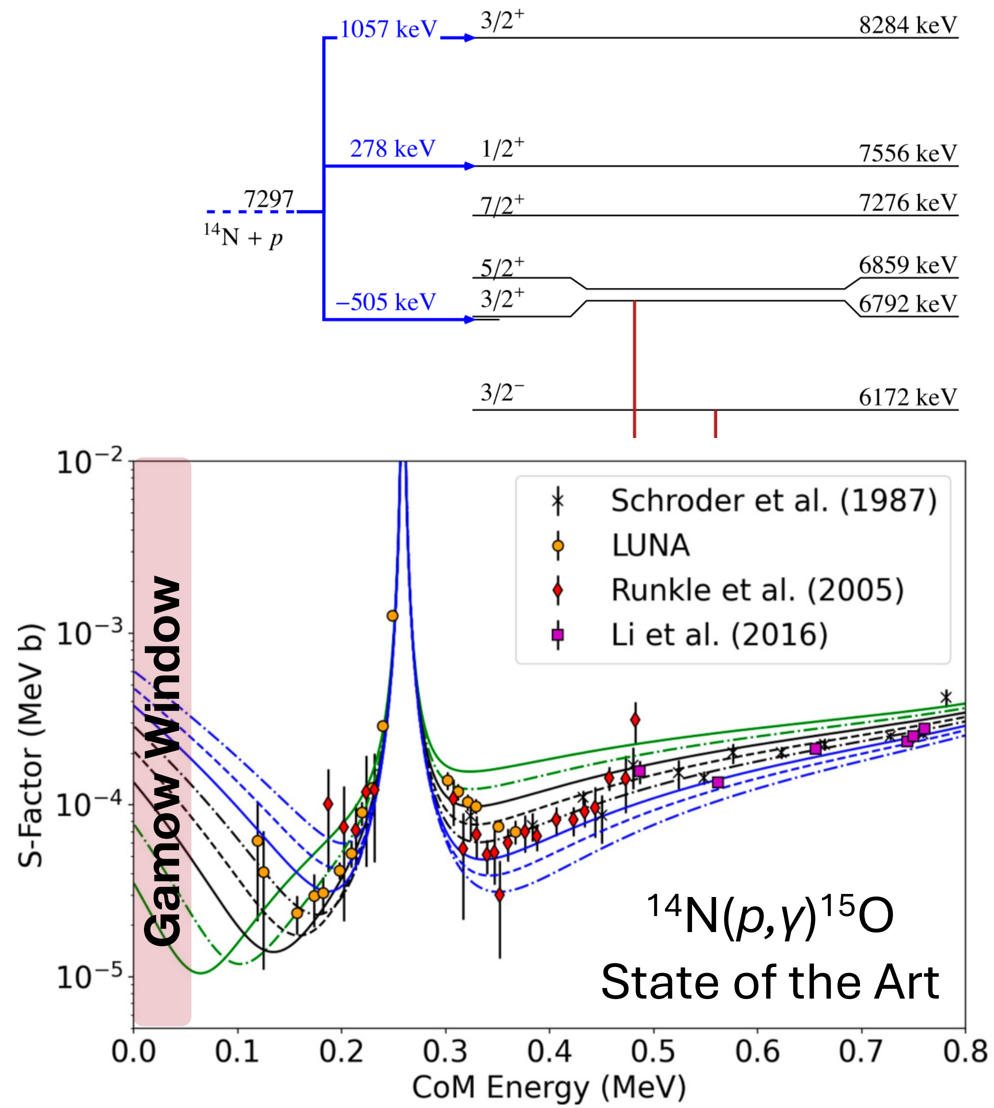

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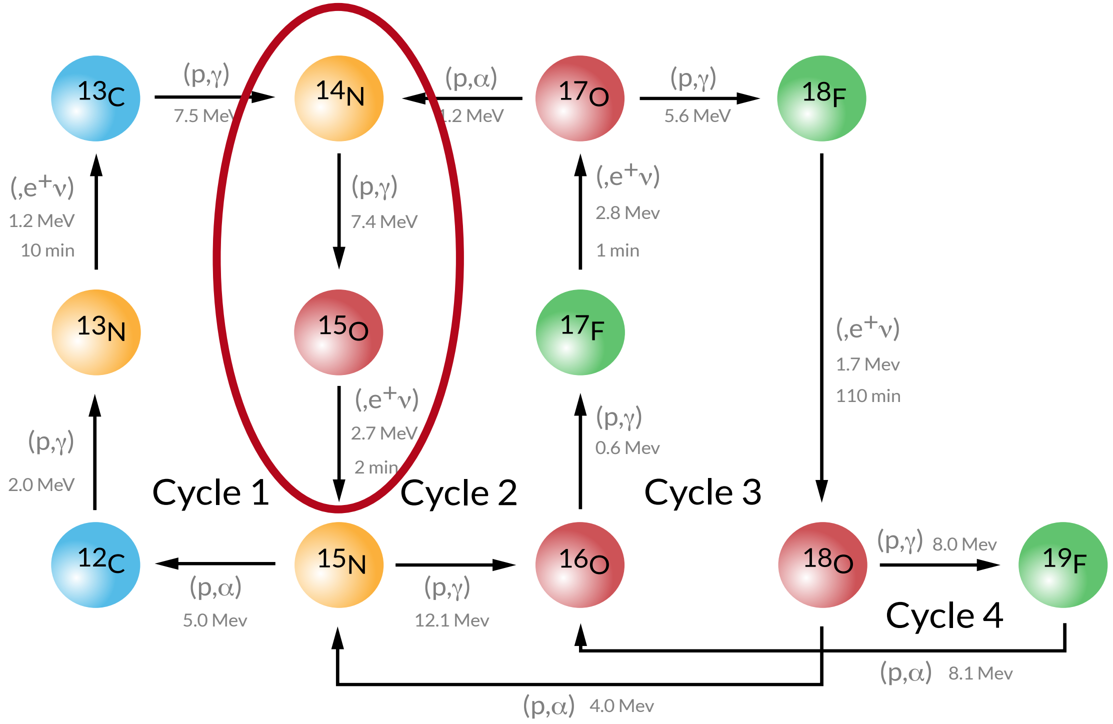
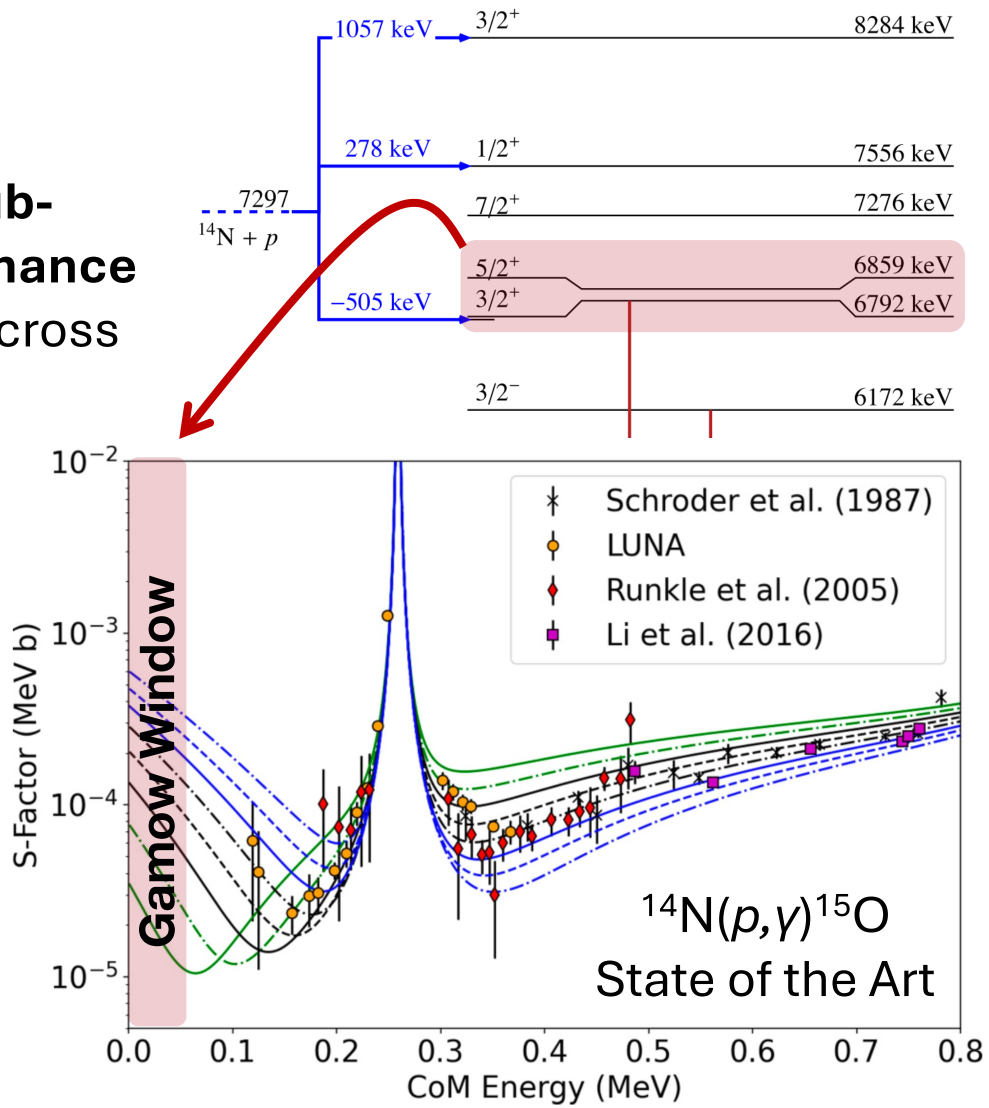


6.79 MeV sub-threshold resonance dominates the cross section



Astrophysical Motivation: Impact

Evolution of Massive Stars

Being the bottleneck, the $^{14}N(p,\gamma)^{15}O$ controls the **life** and **nucleosynthesis** in massive (> 1.5 M_{sun}) stars

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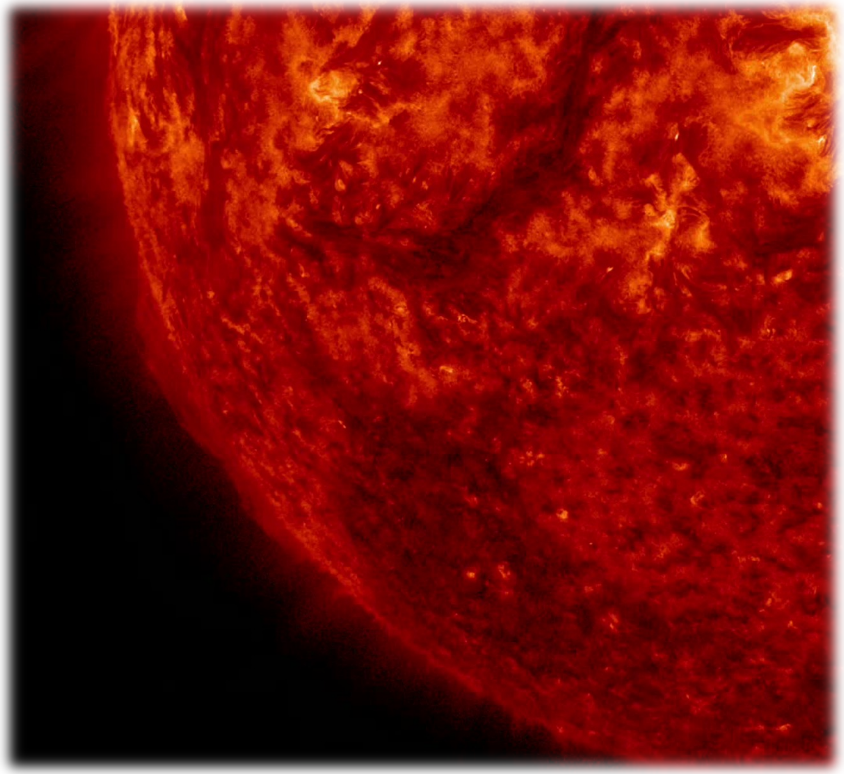

Solar Metallicity Problem

Two estimates of solar metallicity **disagree**, but from the recently measured CNO **ν-flux** an **independent estimate** can be obtained

^{15}O Lifetime: State of the Art

Year	Facility	τ (fs)	Author and Reference
2001	TUNL	$1.60^{+0.75}_{-0.72}$	Bertone *et al.* [30]
2004	RIKEN	$> 0.42^{\dagger}$	Yamada *et al.* [31]
2008	Ruhr-Universität Bochum	< 0.77	Schürmann *et al.* [32]
2012	INFN - LNL	< 1.0	Michelagnoli [33]
2014	TRIUMF	< 1.8	Galinski *et al.* [34]
2021	University of Notre Dame	0.6 ± 0.4	Frentz *et al.* [16]

Table 1.1: Measured lifetimes of the $3/2^+$ sub-threshold state in ^{15}O at 6.79 MeV, as determined by various experimental techniques over the past two and a half decades. Where applicable, upper or lower limits are shown.

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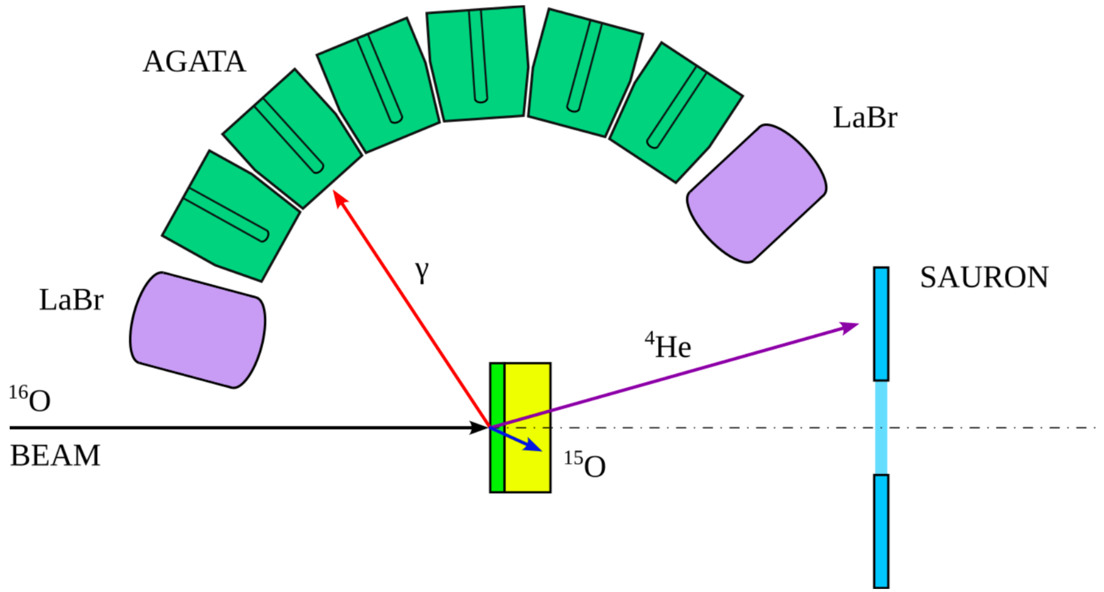
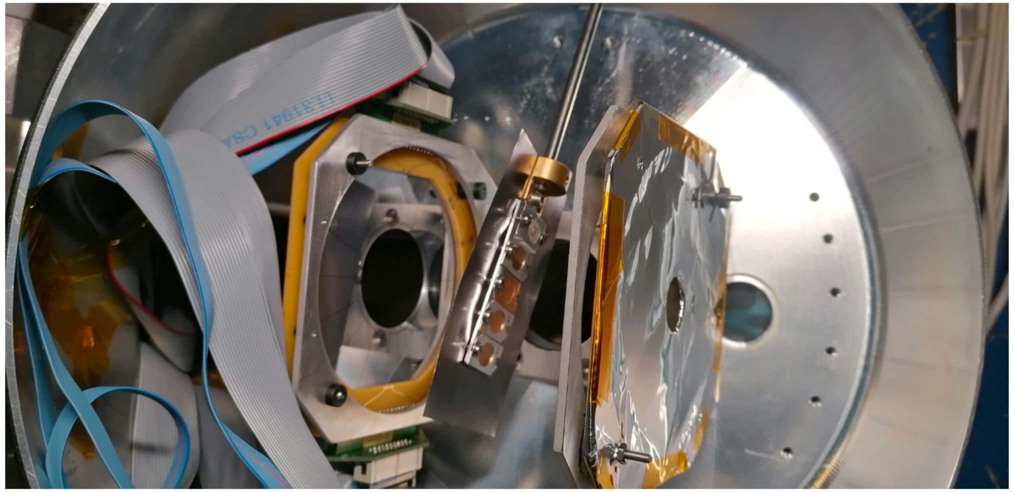
Already performed with **AGATA demonstrator**, but not published: problem due to the **^{14}N(*d*,*n*)^{15}O** reaction channel (in inverse kinematics) which did not allow a precise **kinematic reconstruction**

^{15}O Lifetime: Experimental Setup @ LNL

$^{16}O(^{3}He,^{4}He)^{15}O$ @ 50 MeV

- ^{16}O beam impinged on two types of **^{3}He targets**
- ^{4}He recoils detected with the **SAURON** (DSSD) array
- AGATA at **40 – 160 deg** for the γ-rays
- **AmBe** source with **Fe** for constant energy calibration





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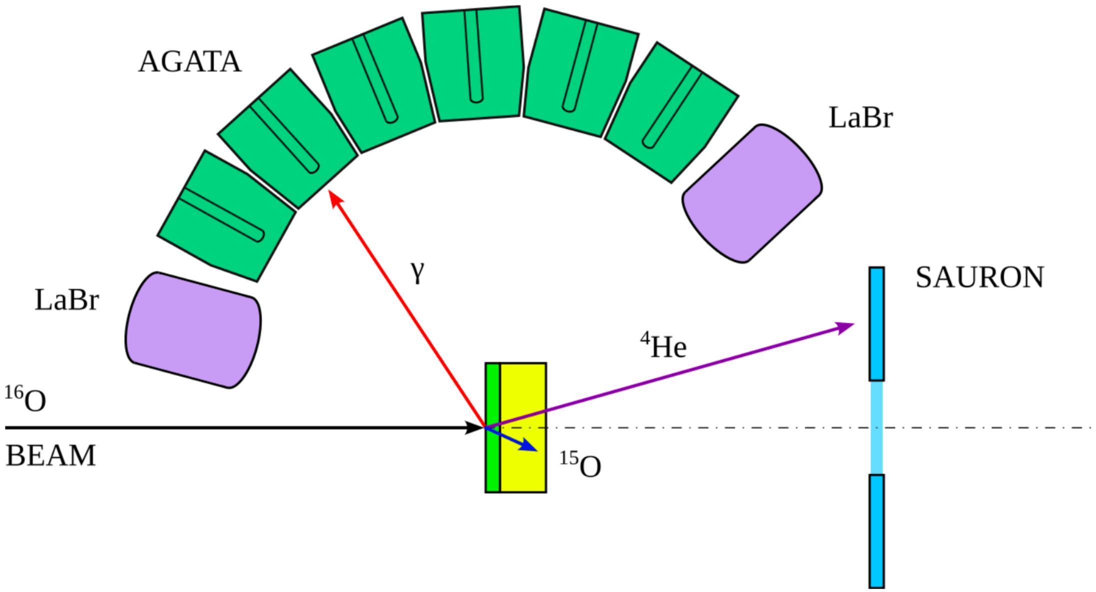
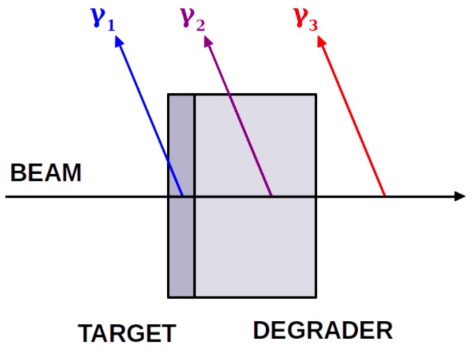
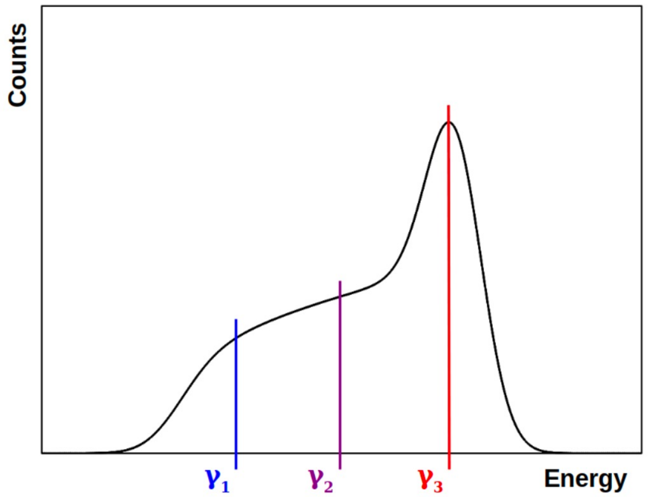
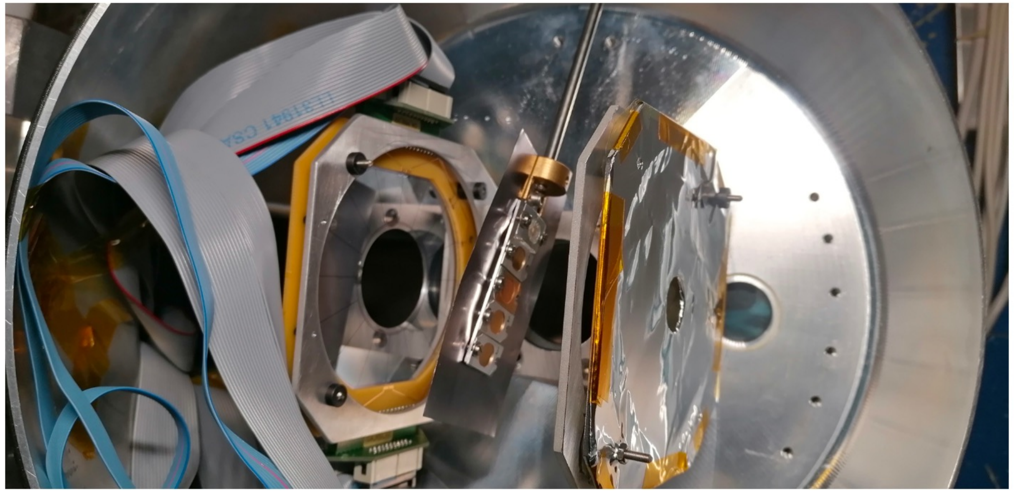


Doppler Shift Attenuation Method



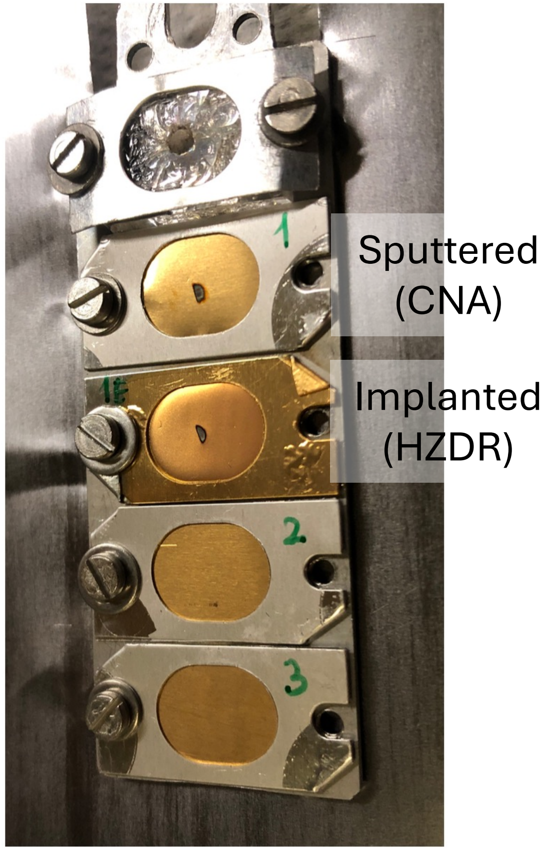




^{15}O Lifetime: Targets

Two different types of ^{3}**He targets** in **Au** backing were used:

- Sputtered ones produced at CNA (Seville) ~ **2.2 × 10^{18} at/cm^{2}**
- Implanted ones produced at HZDR (Dresden) ~ 4.7 × 10^{17} at/cm^{2}



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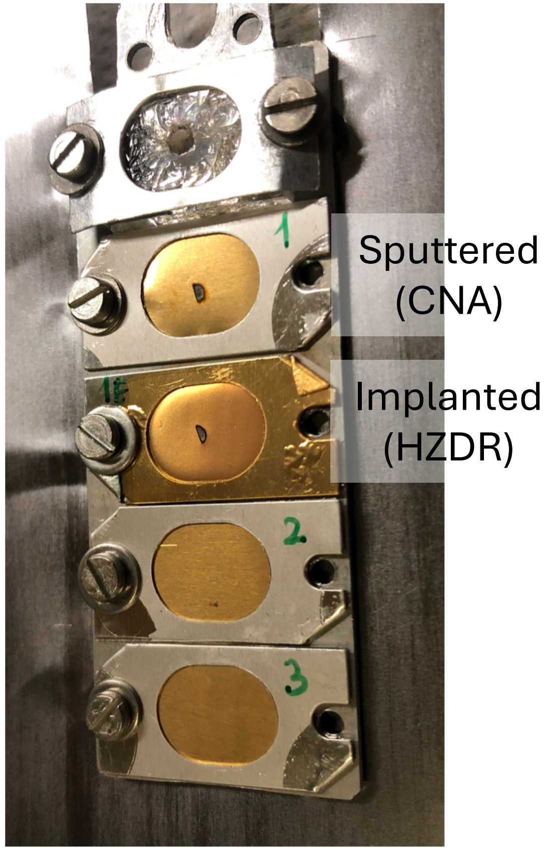

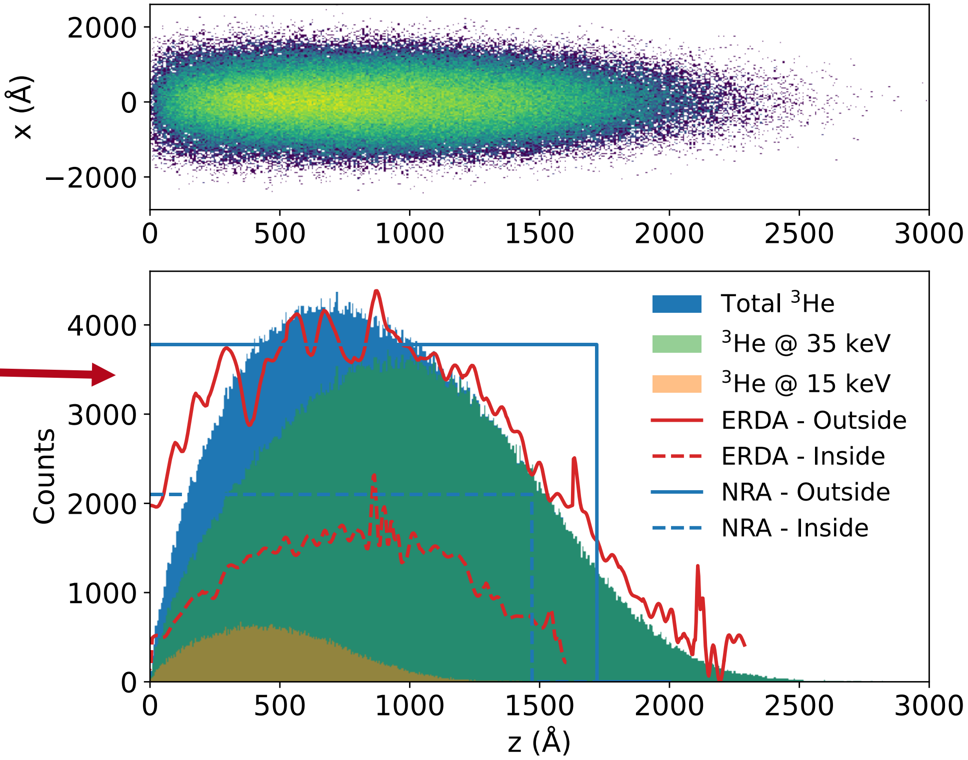

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Regular Article - Experimental Physics

Comparing ^{3}He content in magnetron sputtered and implanted targets for nuclear studies

E. Pilotto[1,2], F. J. Ferrer[3,4], S. Akhmadaliev[5], A. Fernández[6], A. Gadea[7], J. Gómez Camacho[3,4], D. Hufschmidt[6], M. C. Jiménez de Haro[6], E. Masha[5], F. Munnik[5], M. Osswald[8], D. Piatti[1,2], J. Skowronski[1,2,a], S. Turkat[1,2], J. J. Valiente-Dobón[7,9]

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[5] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany
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[8] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany
[9] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

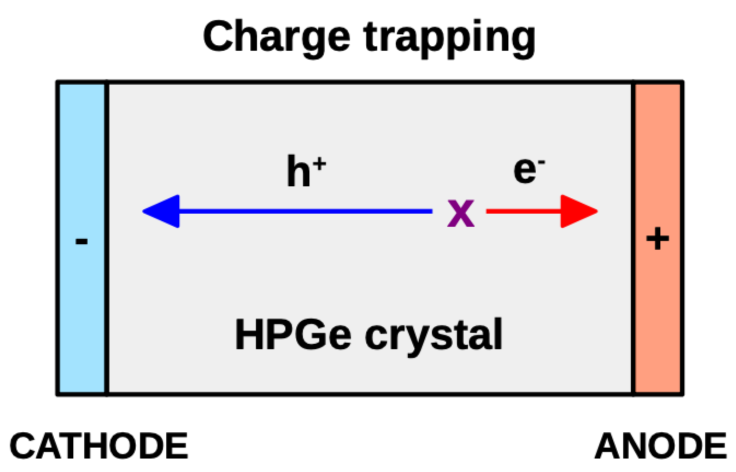
Pilotto et al. (2025) Eur. Phys. J. A 61:117

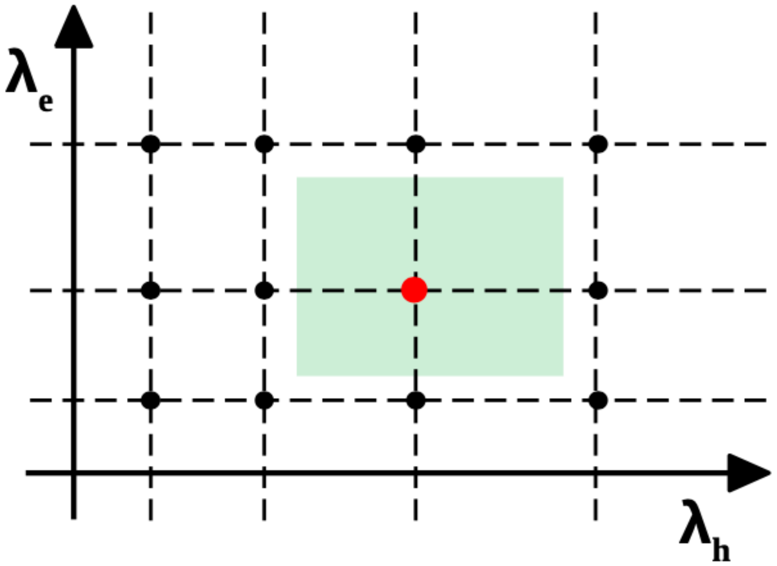
Table 1 ^{3}He areal density calculated by NRA and ERDA

Target	^{3}He areal density NRA [10^{15} at/cm^{2}]	ERDA [10^{15} at/cm^{2}]
HZDR-2 (Fresh)	478 ± 35	
HZDR-1 - Outside	470 ± 34	445 ±45
HZDR-1 - Inside	224 ± 17	143 ±14
ICMS-2 (Fresh)	2221 ± 153	
ICMS-1 - Outside	2206 ± 152	
ICMS-1 - Inside	1732 ± 120	

^{15}O Lifetime: Neutron 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



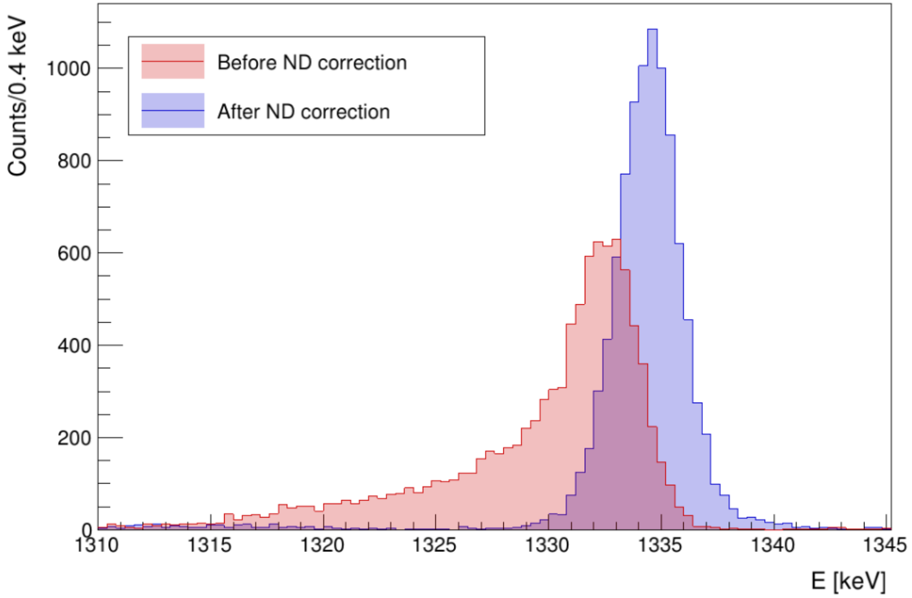


Adaptive Grid-Search Algorithm

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

$\lambda_{e/h}$: inverse e/h trap density

$t_{e/h}$: sensitivity to e/h trapping

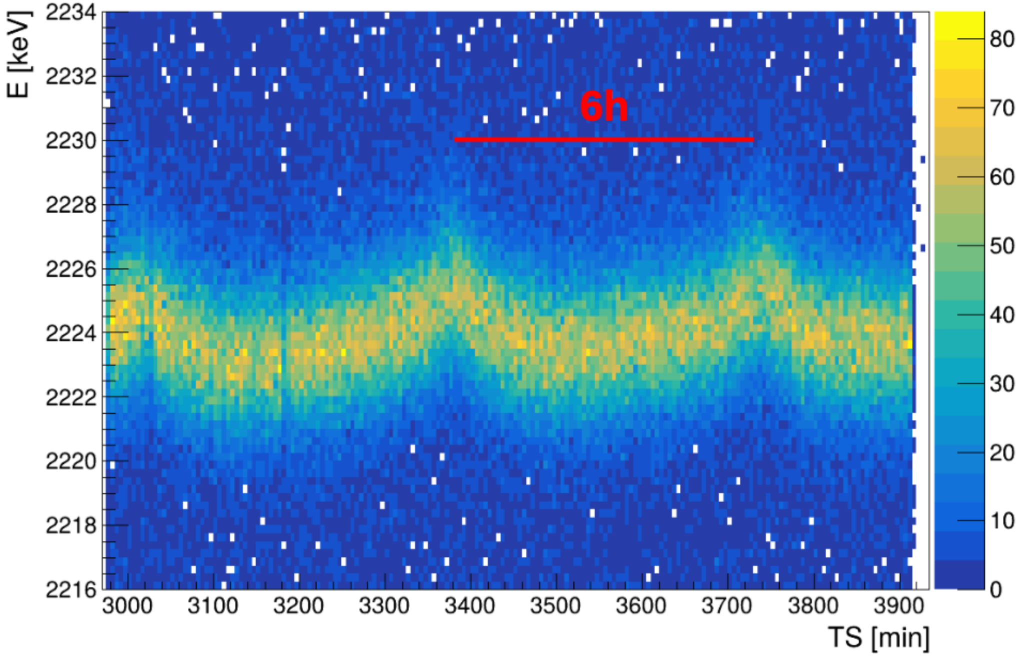


^{15}O Lifetime: Energy Calibration

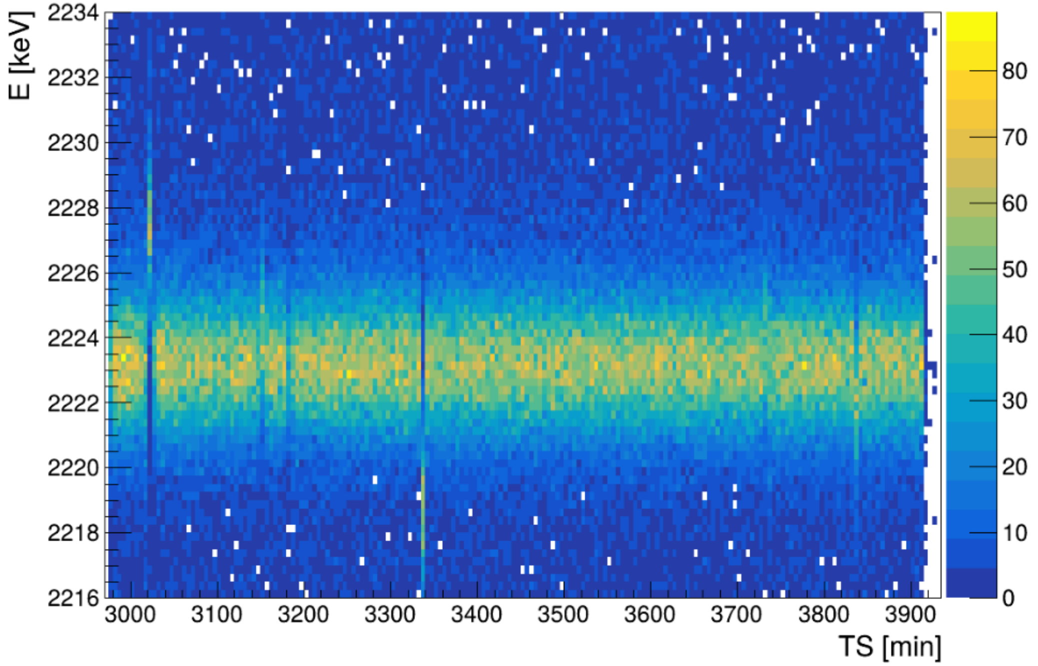
- **Energy gain oscillations** were observed, attributed to temperature effects
- Implementation of a **time dependent gain correction**
- Correction parameters were estimated using **Cross Correlation Method*** (CCM)

* Balogh et al. (2021) NIM 1004 165368

Before



After

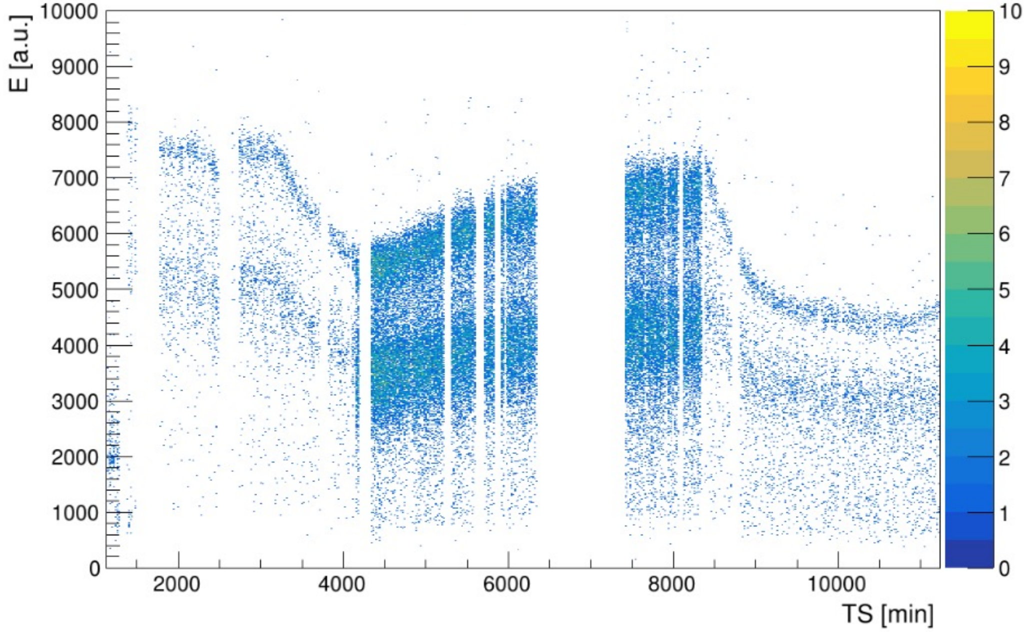


FWHM = 3.81 (2) keV @ 2.2 MeV → FWHM = 3.53 (2) keV @ 2.2 MeV

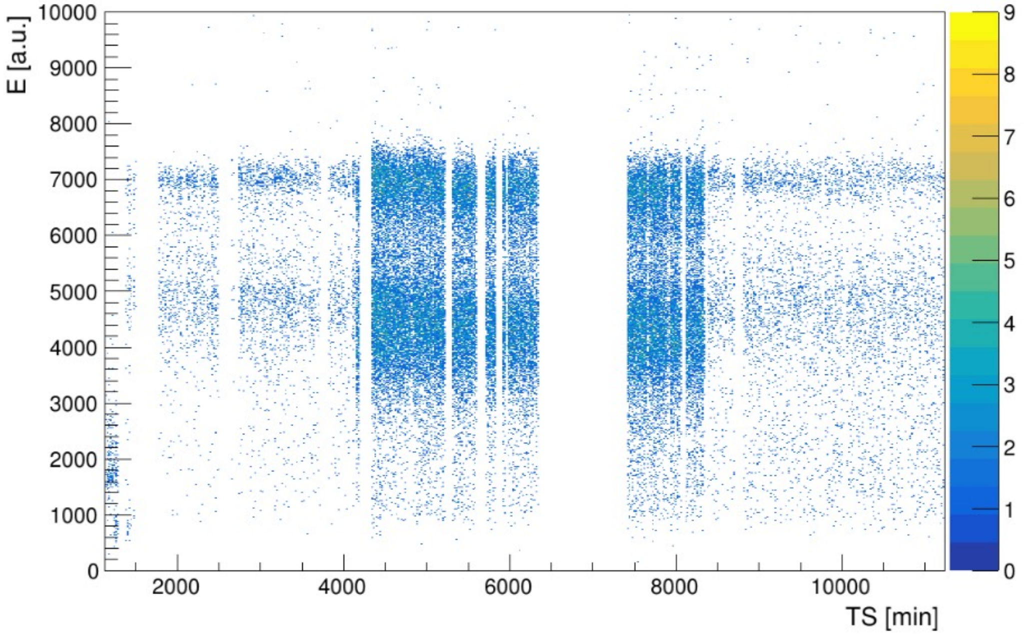
^{15}O Lifetime: Energy Calibration (2)

Similar issue was found for the **DSSD detector** and was adjusted using the same method...

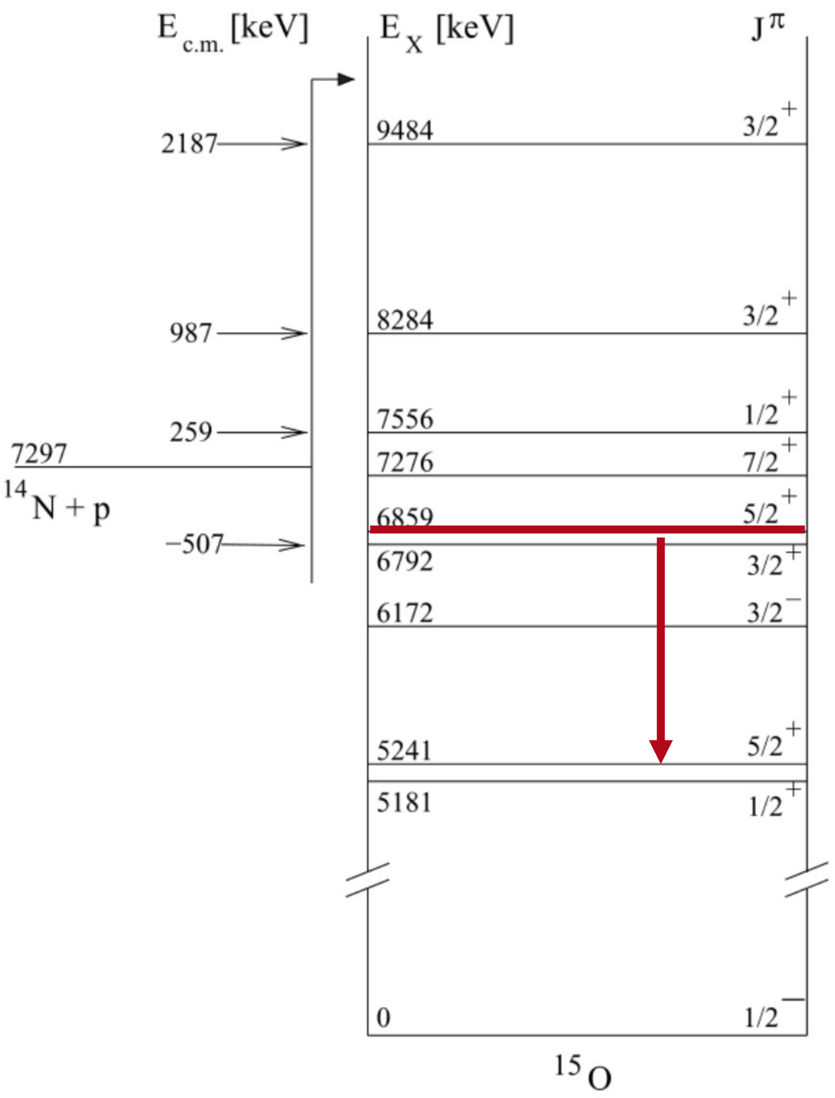
Before

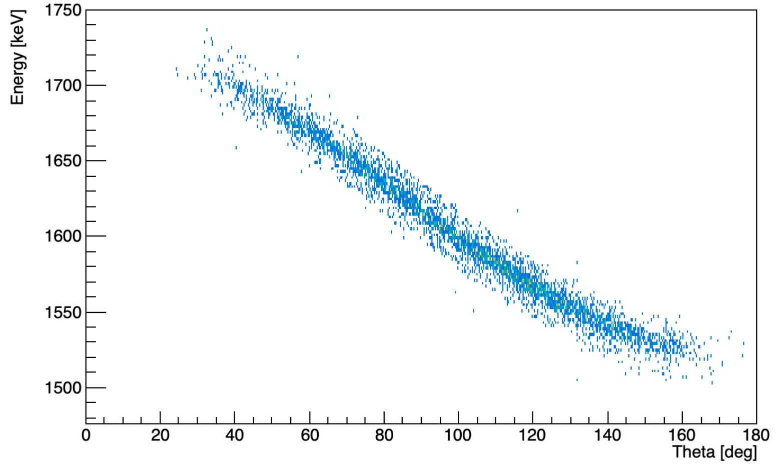


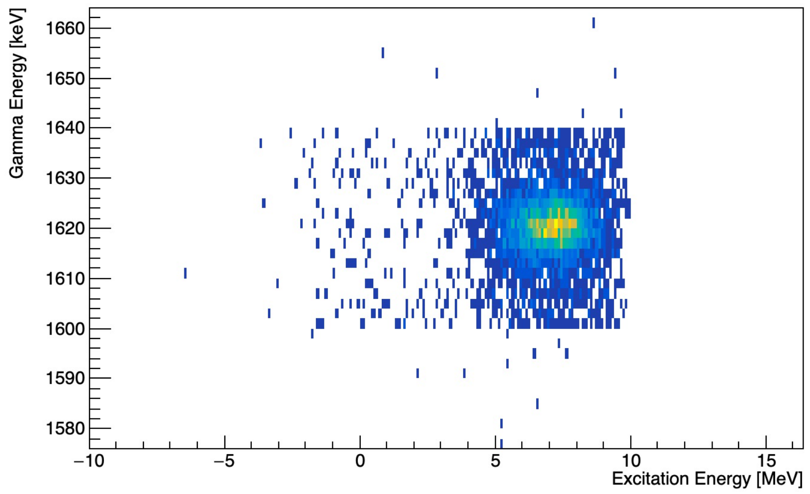
After

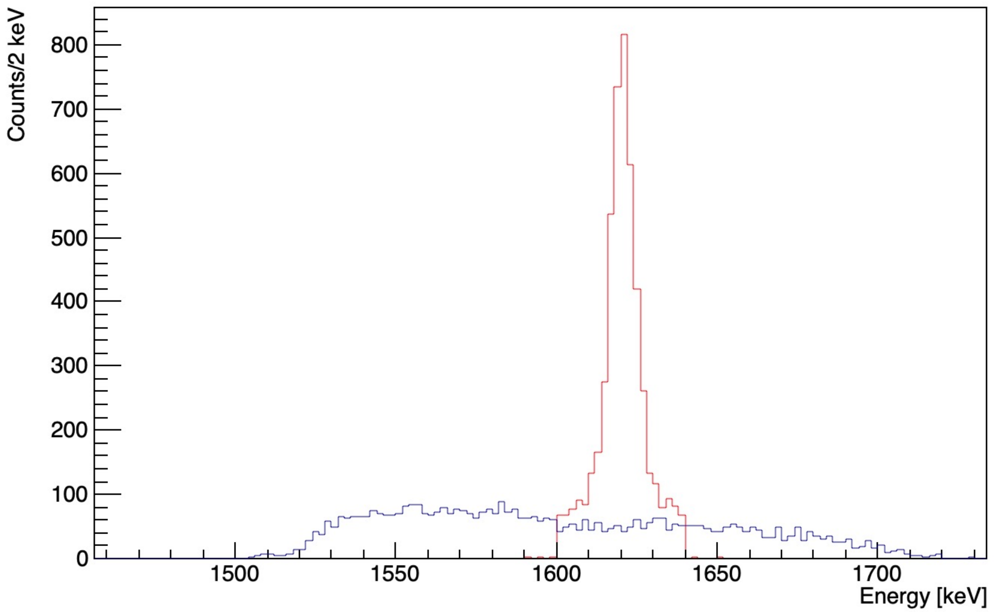


^{15}O Lifetime: 6859 keV State



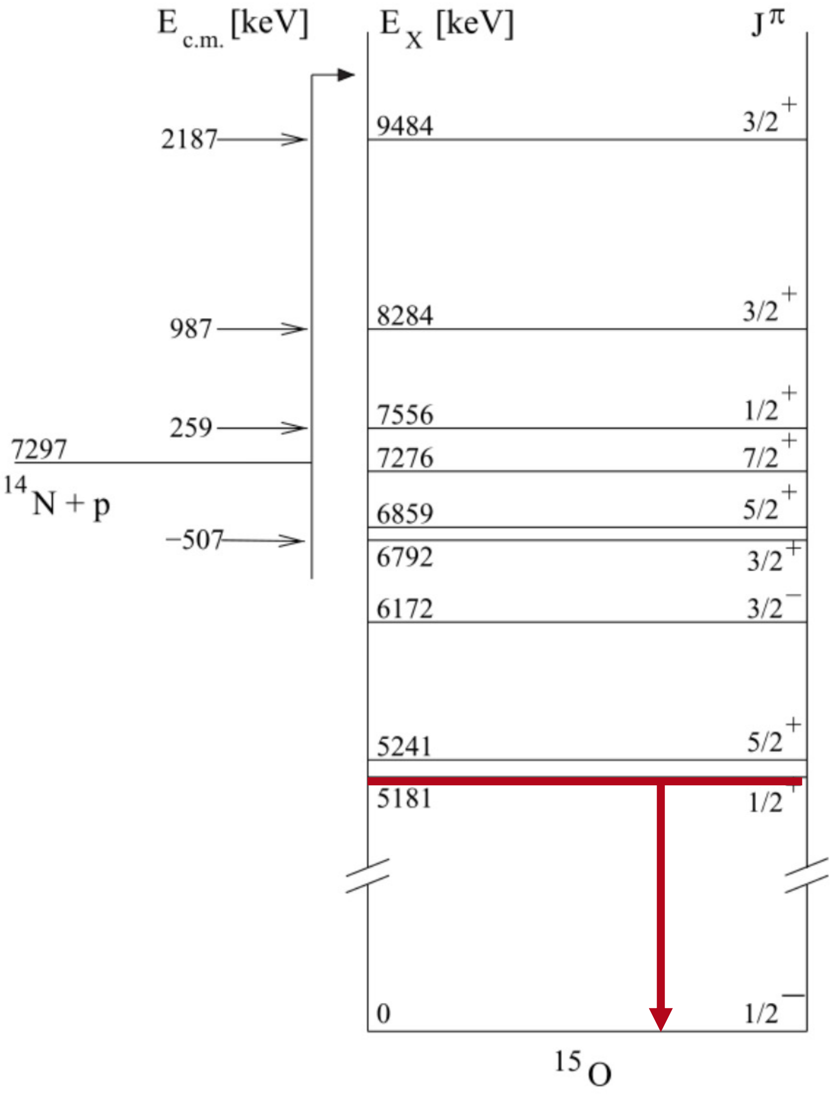


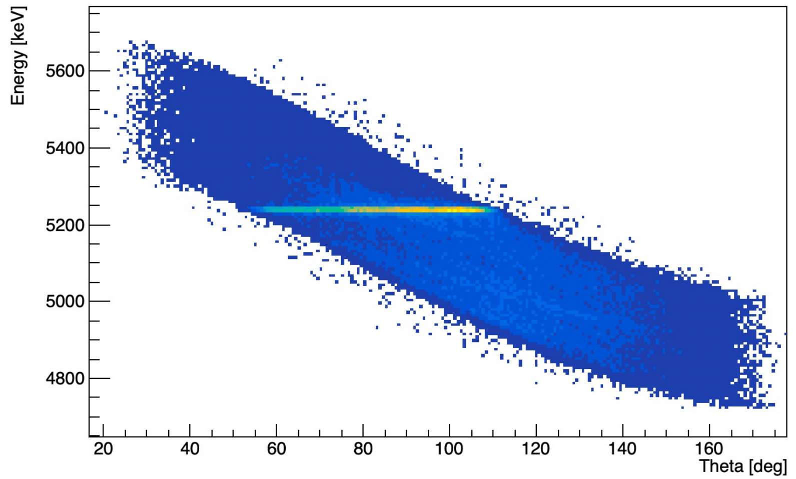


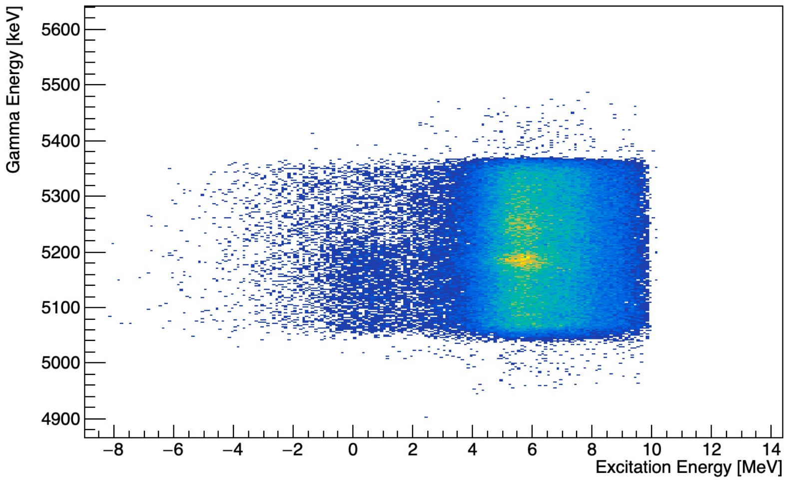


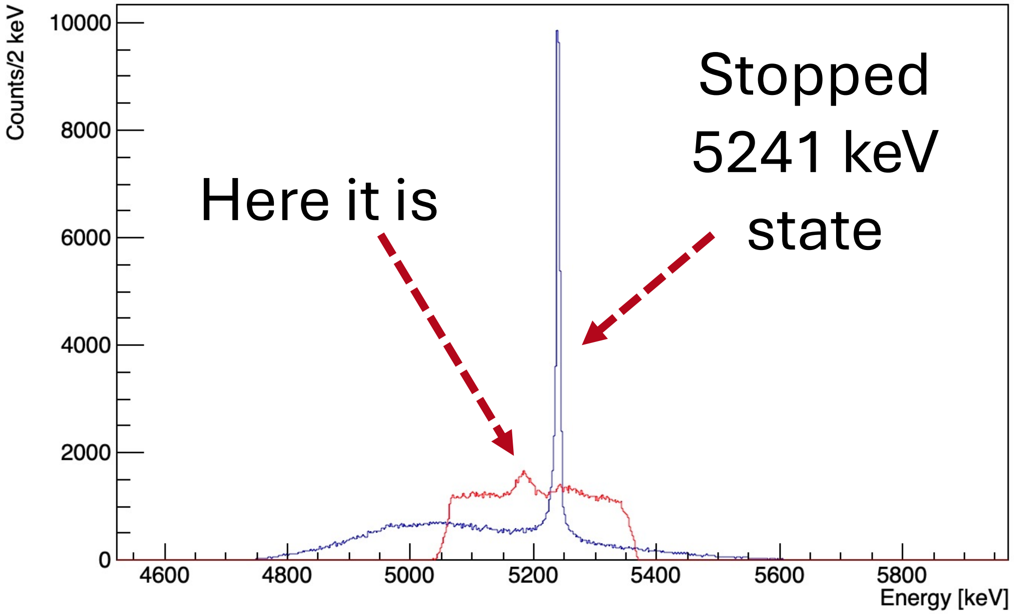
- Decays with **1618 keV** γ-ray
- Known lifetime of **13.3 (9) fs**

^{15}O Lifetime: 5181 keV State



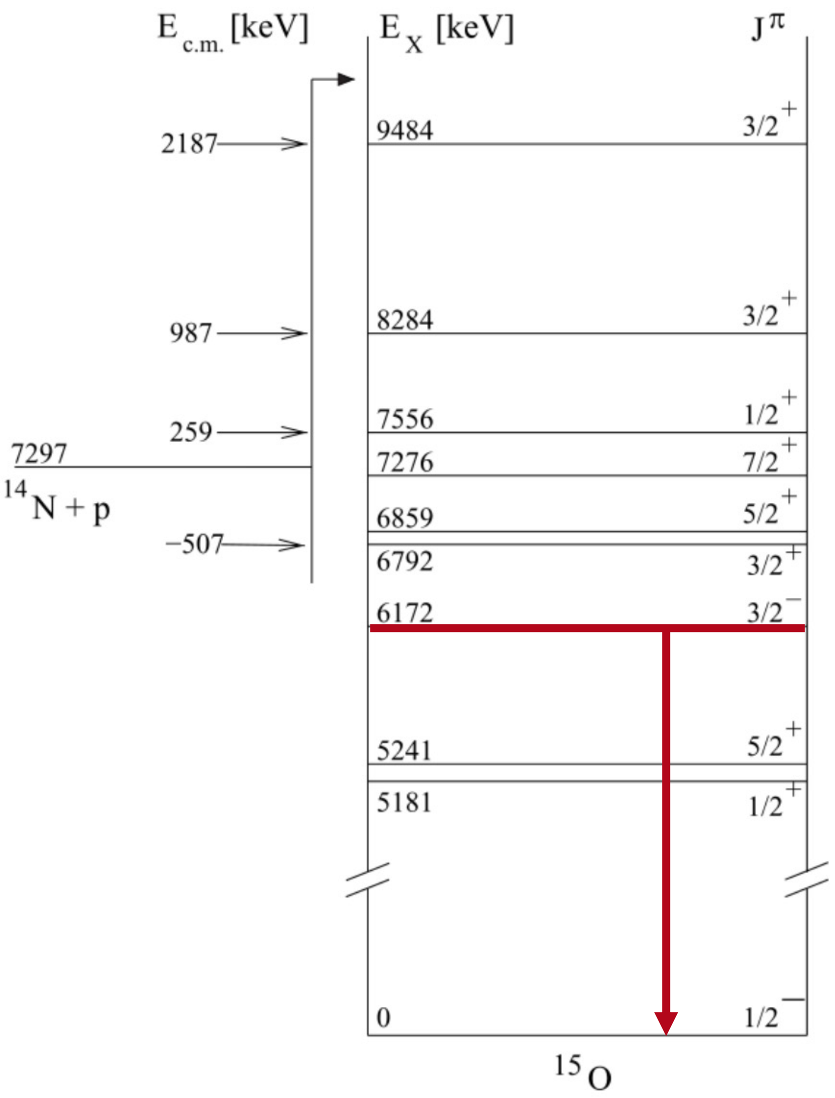


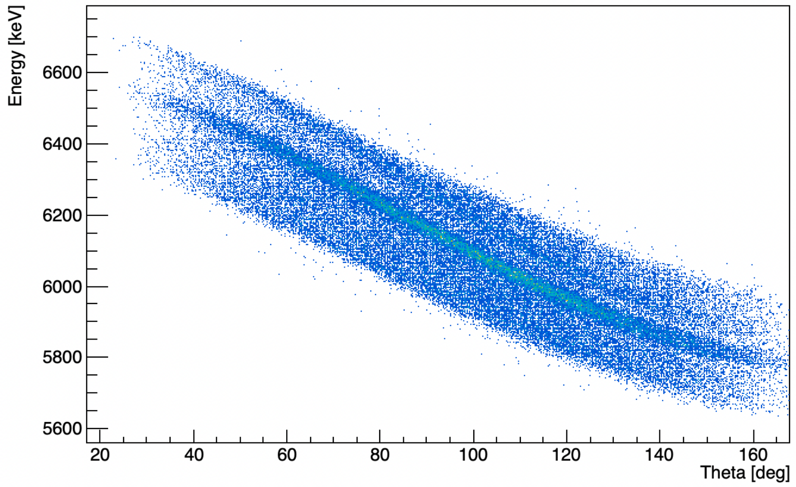


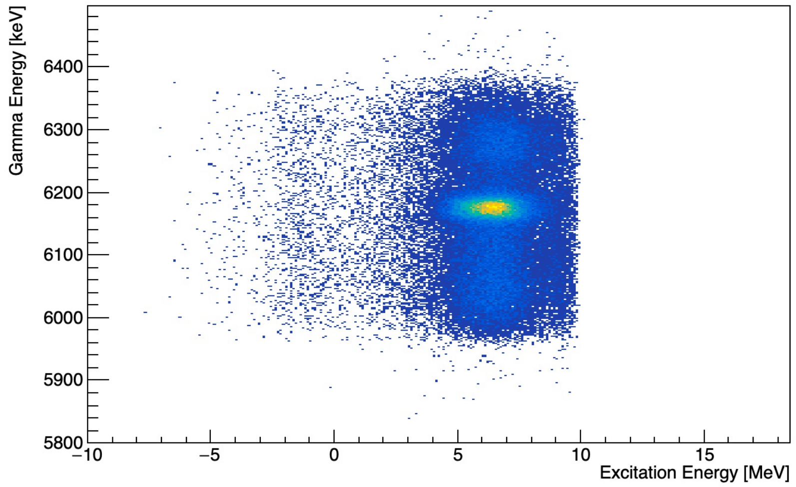


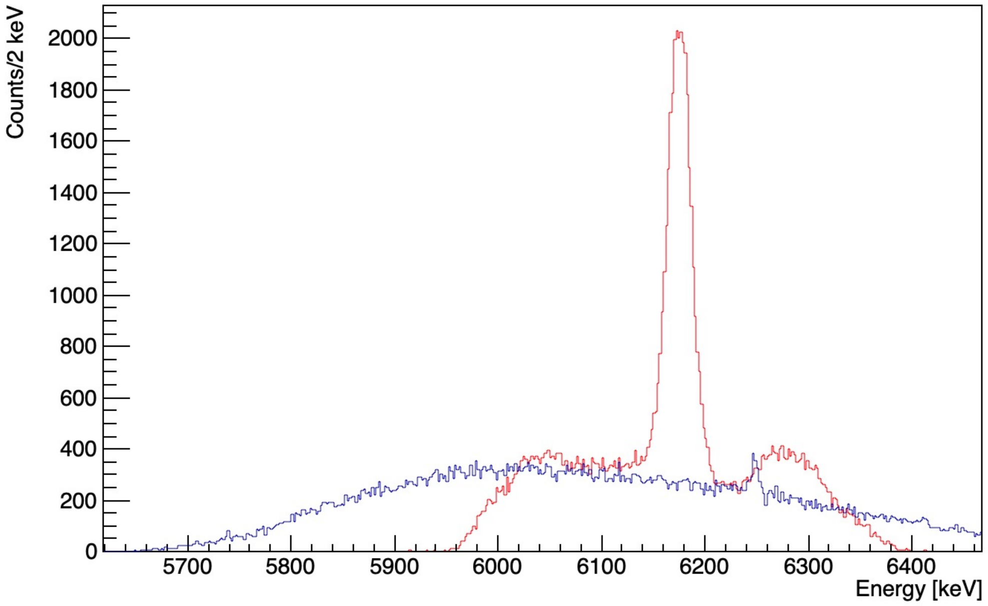
- Decays with **5181 keV** *γ*-ray
- Known lifetime of **9.7 (13) fs**
- A lot of background

^{15}O Lifetime: 6172 keV State



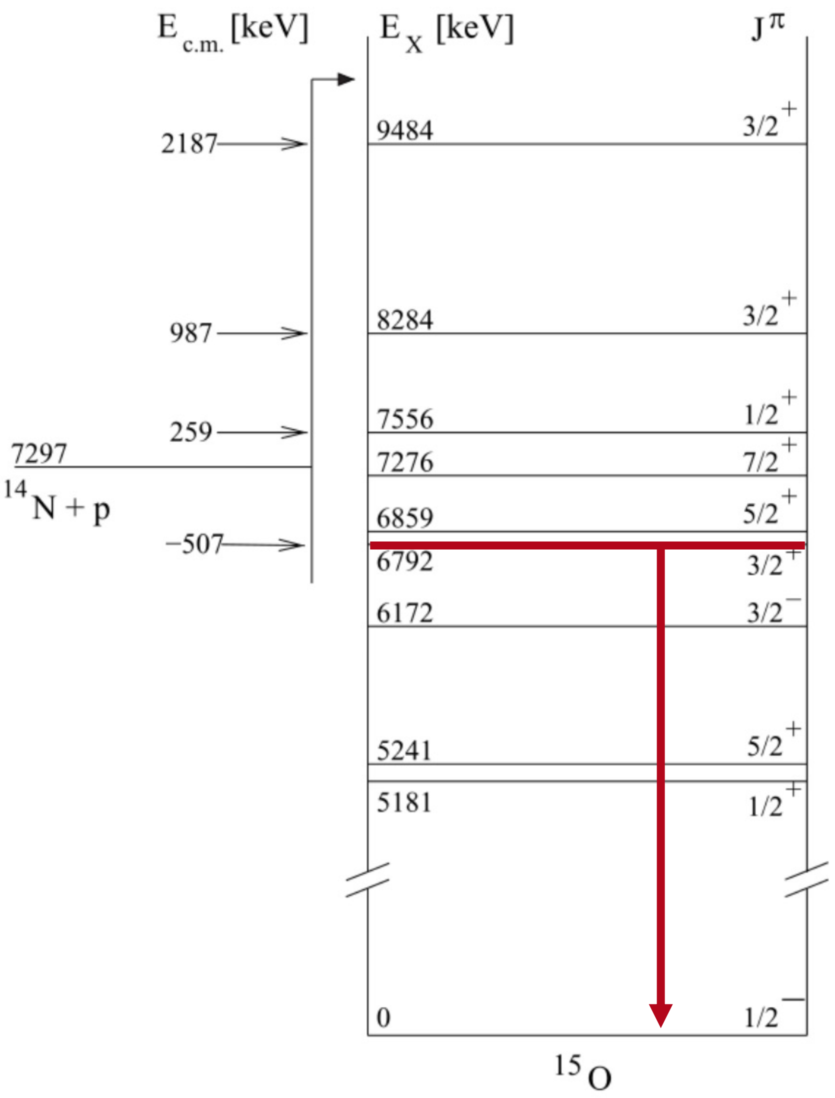


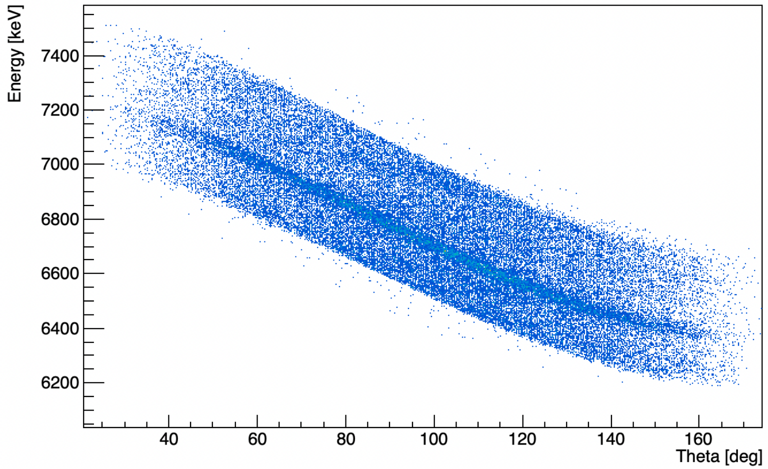


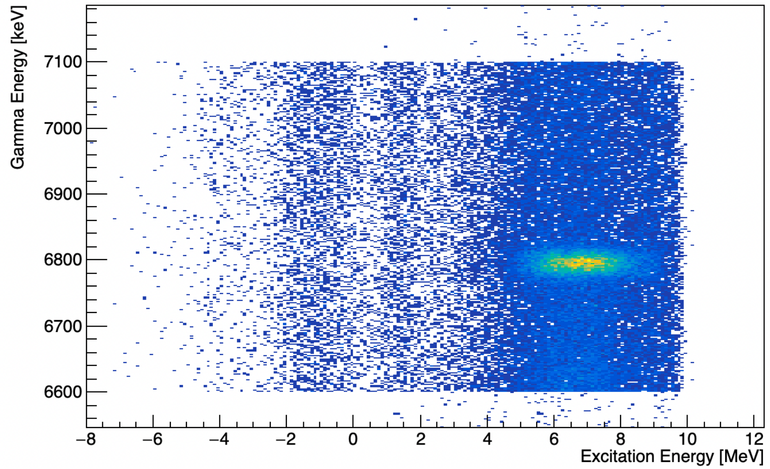


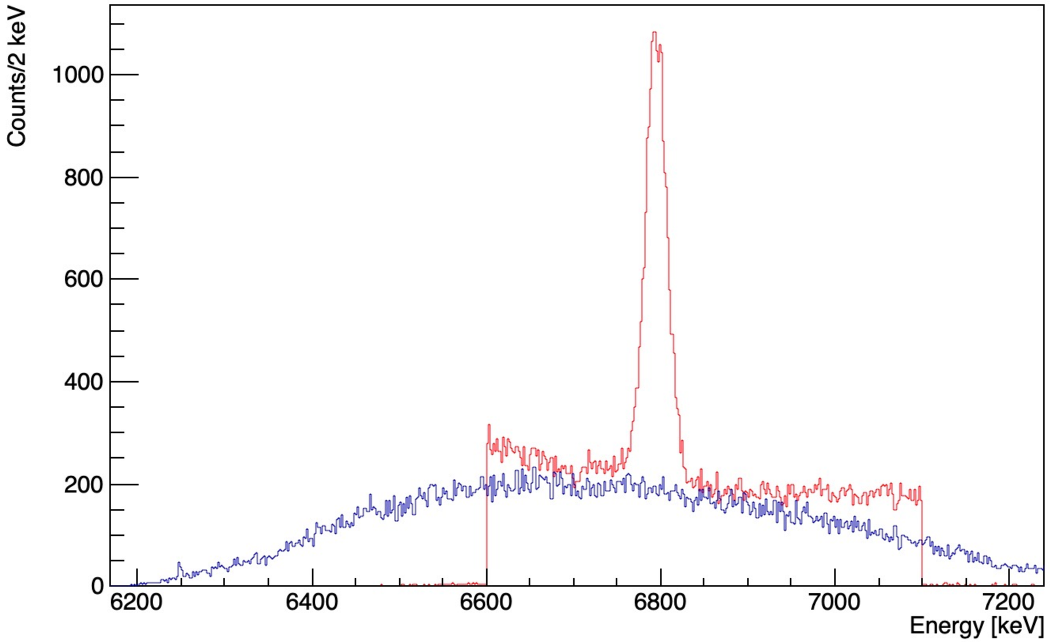
- Decays with **6172 keV** *γ*-ray
- Lifetime either **2.1 (17) fs** or **0.7 (5) fs**

^{15}O Lifetime: 6792 keV State









- **Our state**
- Decays with **6792 keV** γ-ray
- Lifetime either **1.6 (8) fs** or **0.6 (4) fs**

^{15}O Lifetime: DSAM Analysis (1)

To retrieve the lifetime, we pursued the approach of Fougeres et al. (2023)

- First, we define the $\boldsymbol{\beta_{ems}}$ at emission time

$$R := \frac{E_\gamma}{E_0} = \frac{\sqrt{1-\beta_{ems}^2}}{1-\beta_{ems}\cos\theta} \qquad \beta_{ems} = \frac{R^2\cos\theta \pm \sqrt{1+R^2\cos^2\theta - R^2}}{1+R^2\cos^2\theta}$$

Can be calculated event by event using **AGATA energy**

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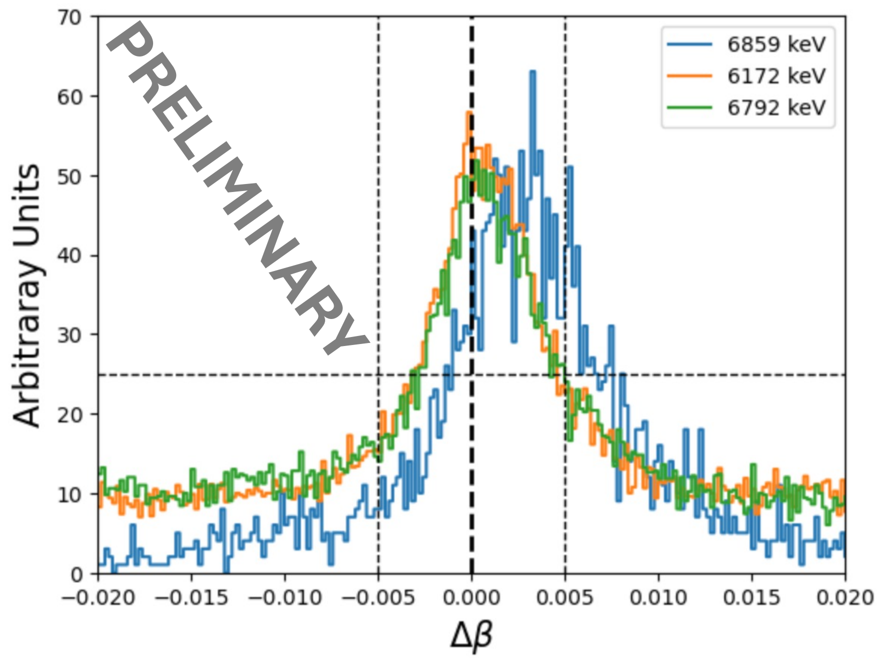
Can be calculated event by event using **AGATA energy**

- Then we calculate the β_{reac} at reaction time using **DSSD reconstruction**
- Finally, we calculate the **Δβ** of the two and **fit the centroid**



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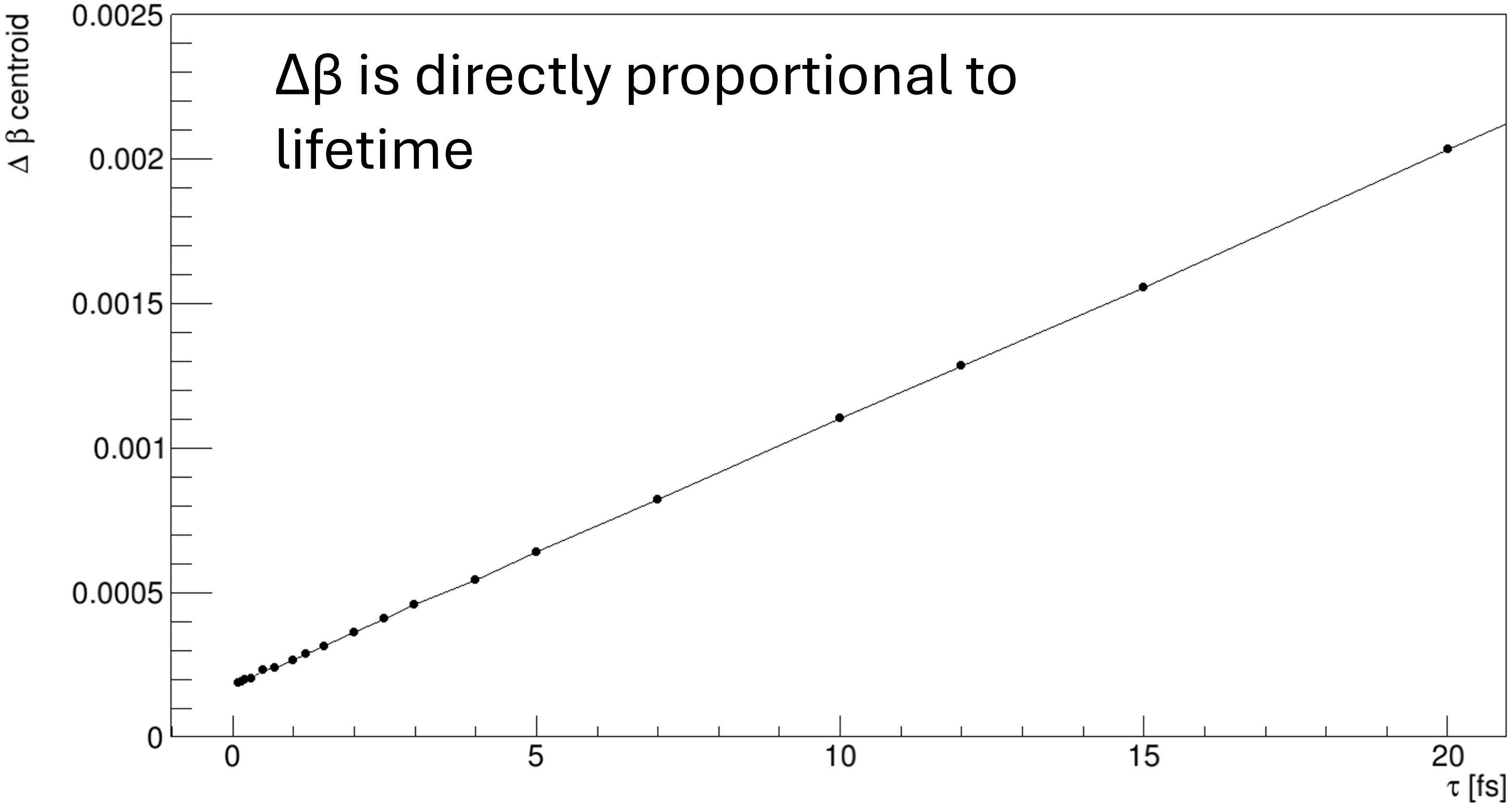
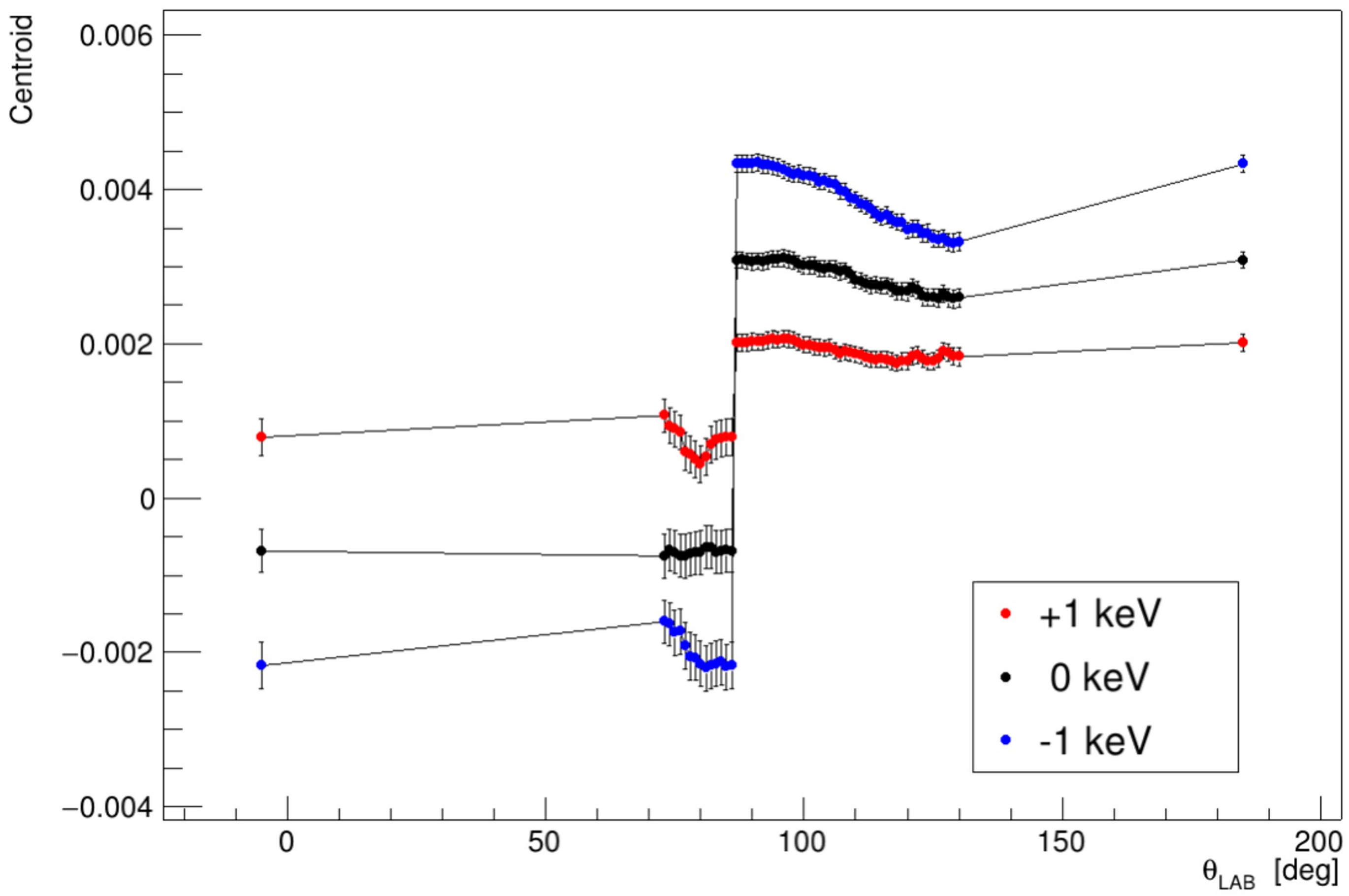
- Additionally, a simulation was developed to **validate the method**



^{15}O Lifetime: DSAM Analysis (2)



The discontinuity at 90 degrees seems to come from an **incorrect E_γ value**...

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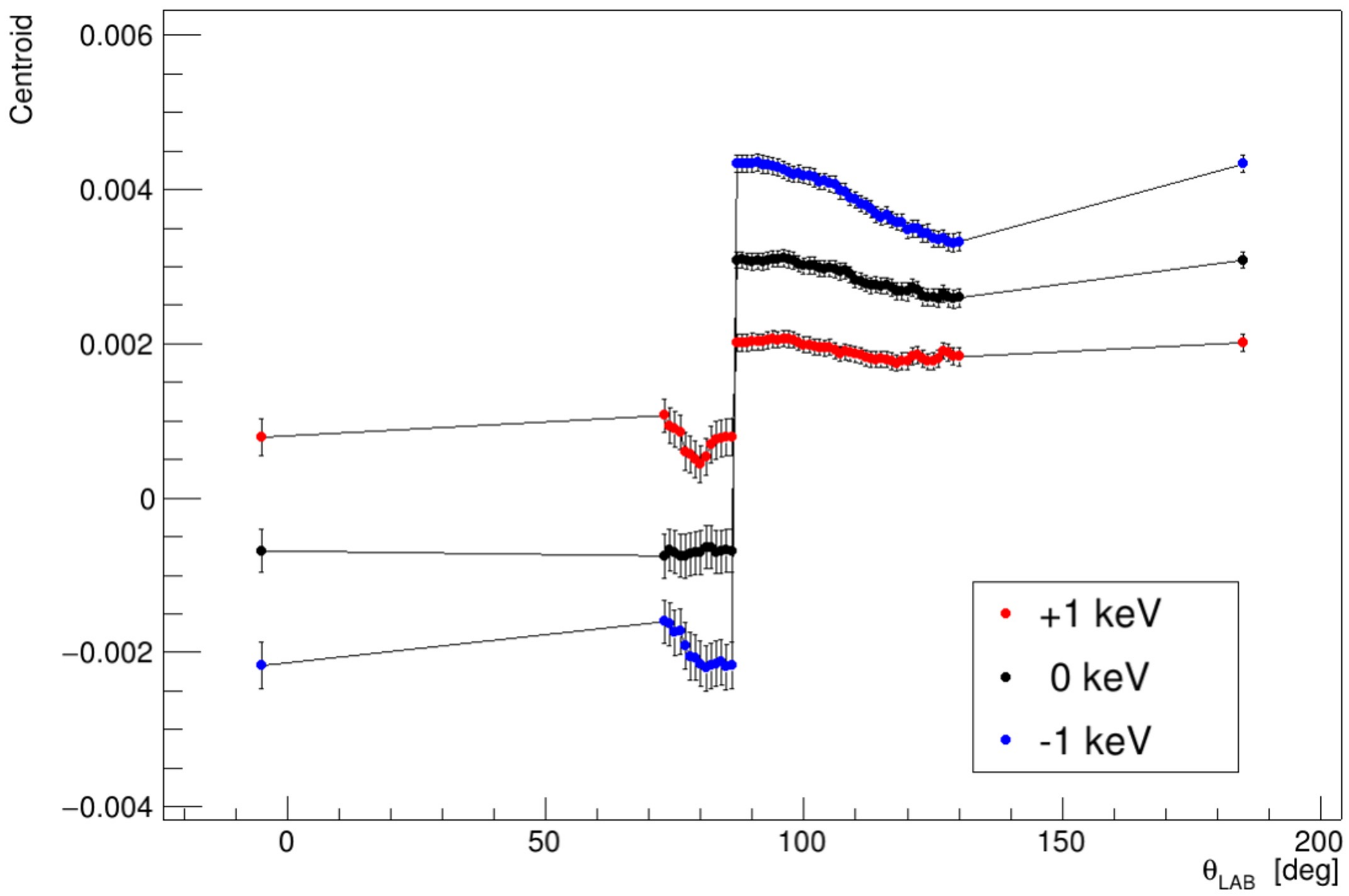

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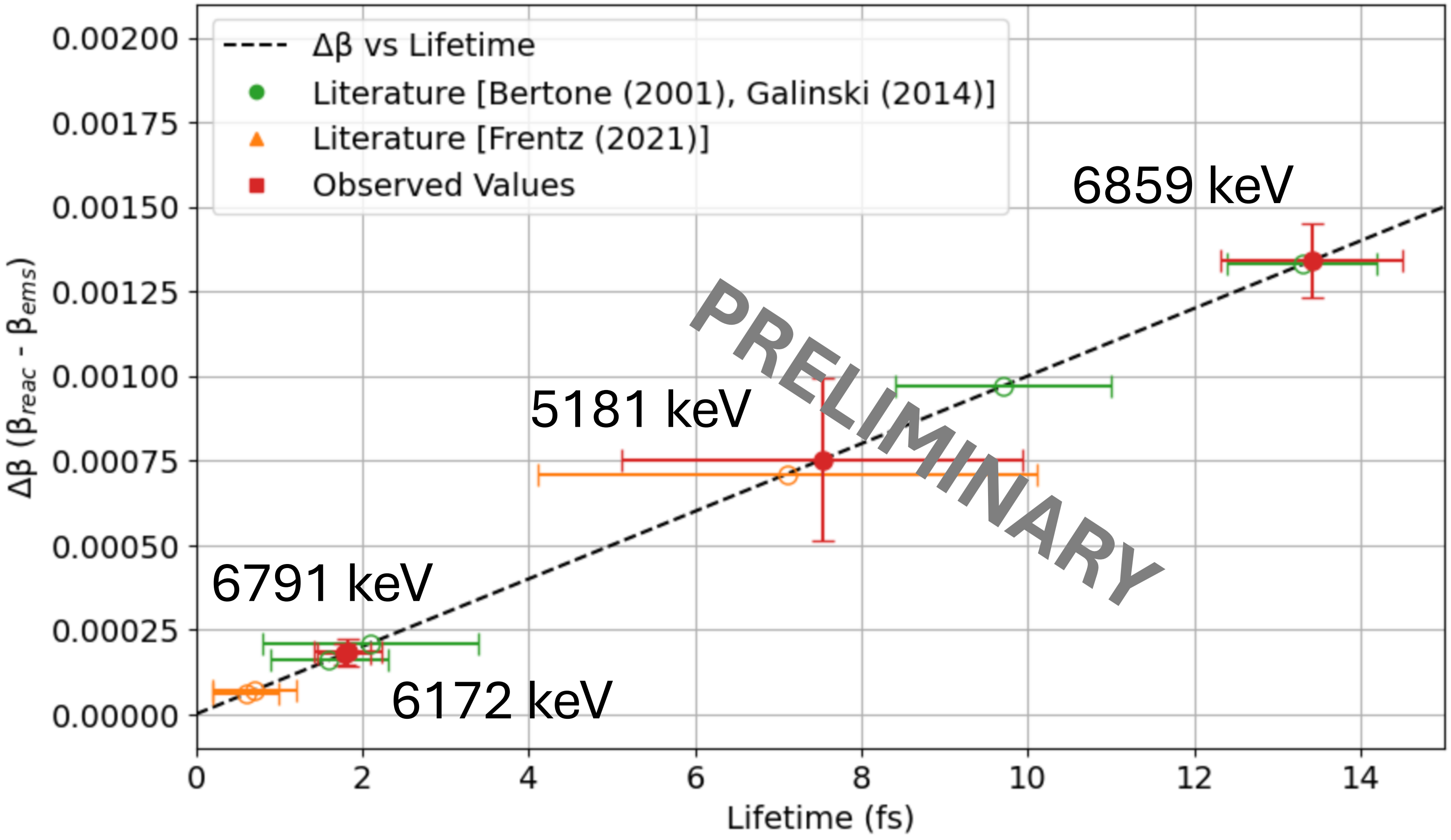
Preliminary Solution

Take the **weighted mean** of > 90 deg and < 90 deg regions

+

Calibrate the Δβ curve on the **known lifetimes**

^{15}O Lifetime: DSAM Analysis (2)



- Blue curve given by the simulation
- Observed Δβ scaled so the 6859 keV **match the known lifetime**
- **Proper uncertainty treatment still to be done**
- Seems to be close to **Bertone** and **Galinski**, far from **Frentz**

Conclusions

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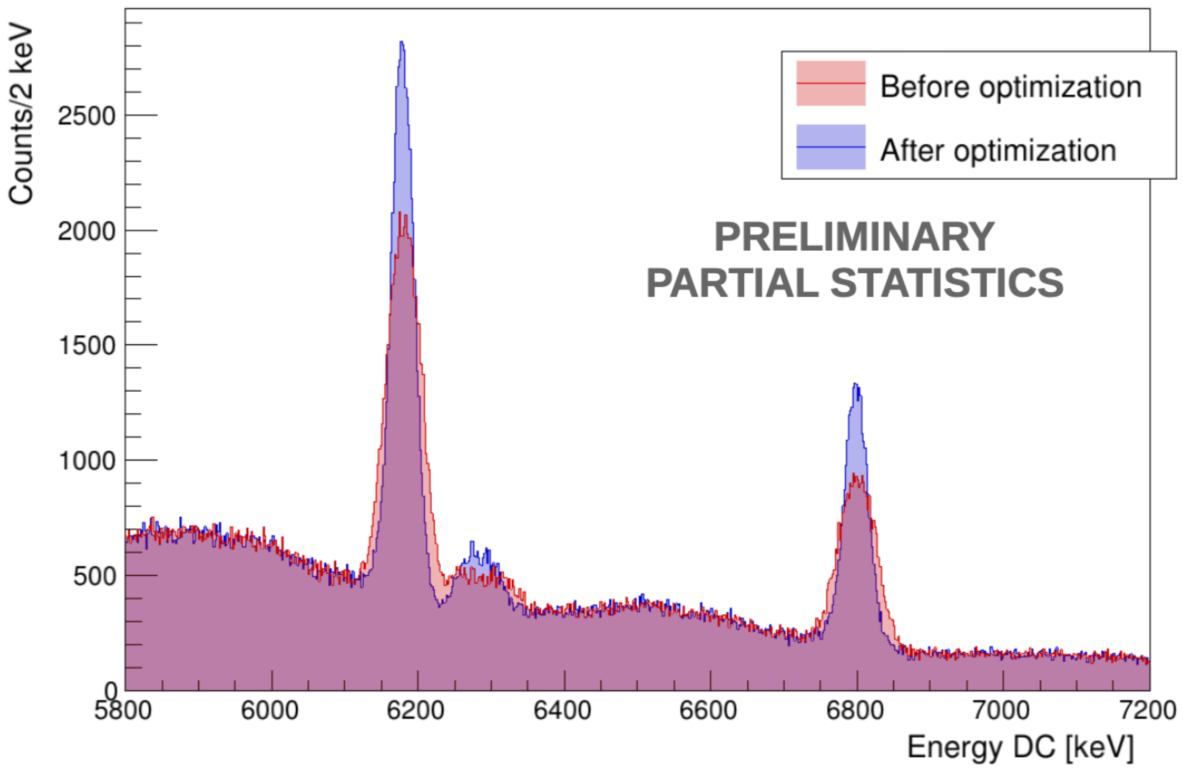
... and special thank you for Elia Pilotto who is currently writing his PhD thesis!

^{15}O Lifetime: Backup (1)

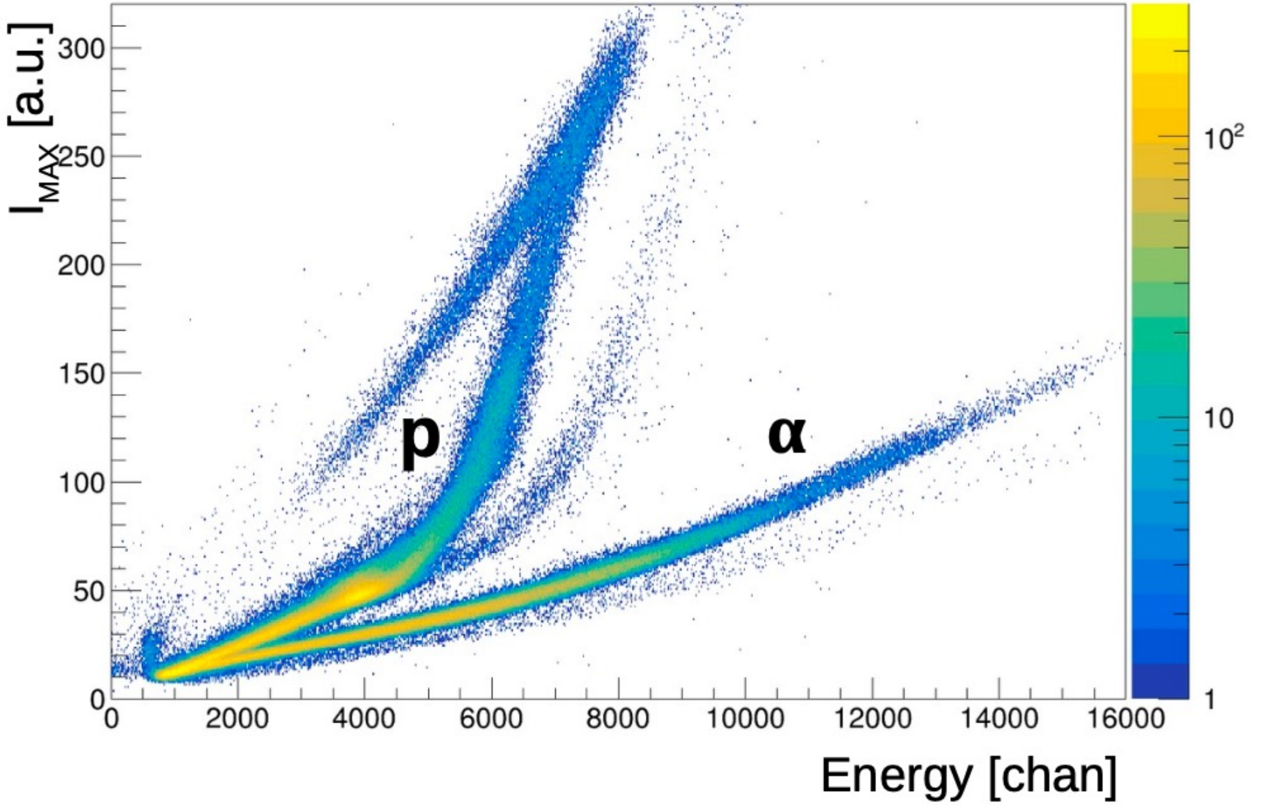
Replay Fine Tuning

Doppler corrected γ – ray spectrum



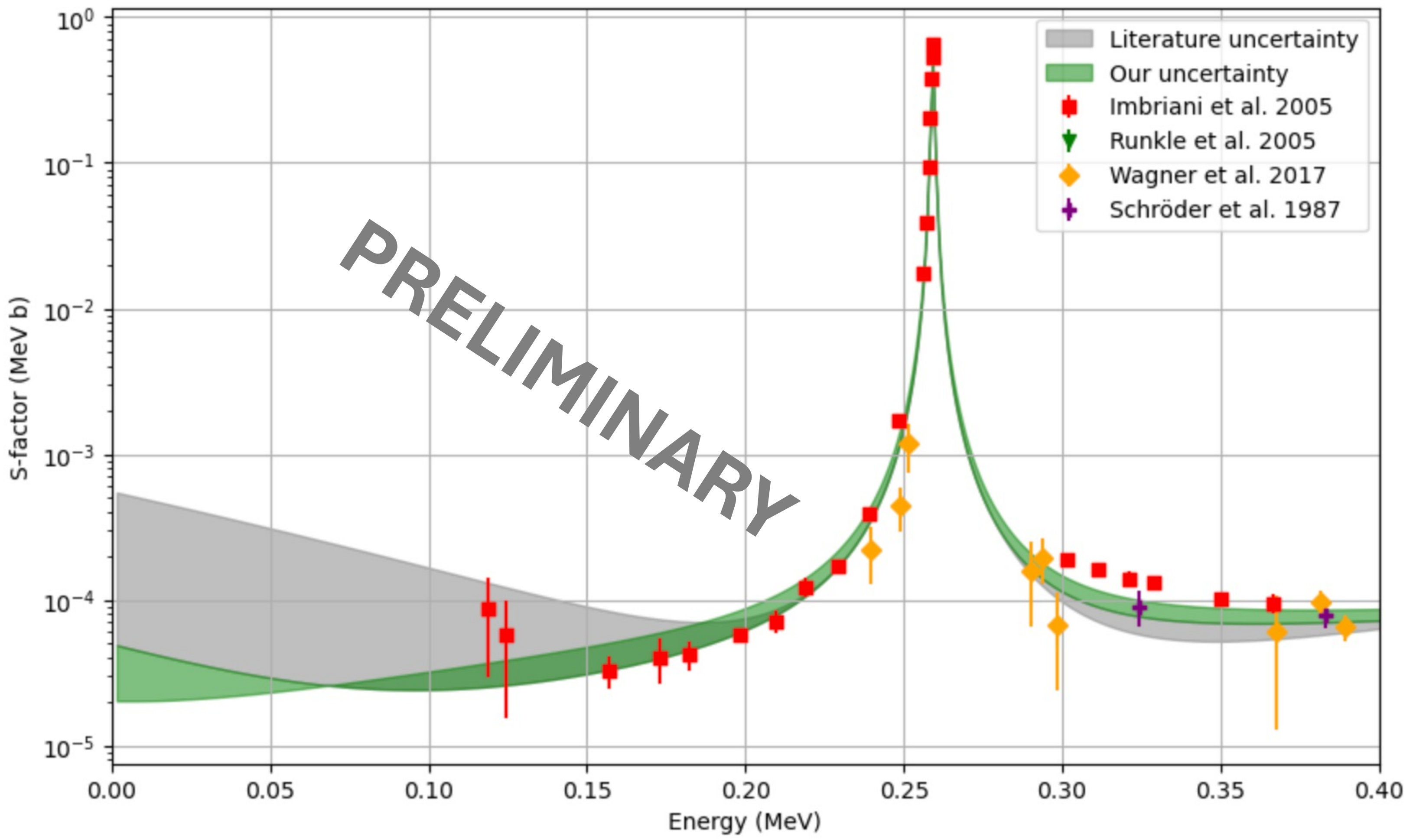
FWHM from **55 keV** to **33 keV**
[26 keV in simulations]

PSD



Thanks to SAURON PSD we can **gate on the α particles**

^{15}O Lifetime: Backup (2)



^{15}O Lifetime: Backup (3)