The Challenging First Direct Measurement of the 65 keV Resonance Strength in $^{17}O(p,\gamma)^{18}F$ at LUNA

Denise Piatti

University and INFN of Padua, via Marzolo 8 35136 Italy

email: denise.piatti@pd.infn.it

UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia Galileo Galilei

INFN PADOVA

LUNA

The Challenging First Direct Measurement of the 65 keV Resonance Strength in $^{17}O(p,\gamma)^{18}F$ at LUNA*

SPOILER ALERT!

* Do not miss the plenary talk on LUNA by A. Best tomorrow at 11:30, Rainbow Theatre

Denise Piatti

University and INFN of Padua, via Marzolo 8 35136 Italy

email: denise.piatti@pd.infn.it

Università degli Studi di Padova

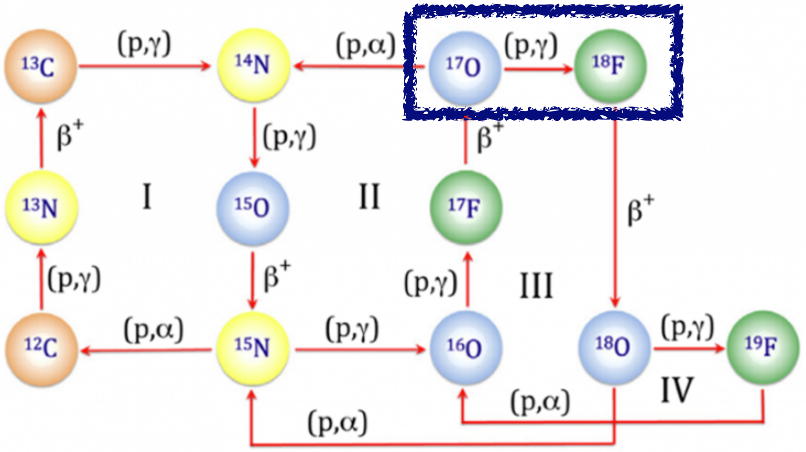
Dipartimento di Fisica e Astronomia Galileo Galilei

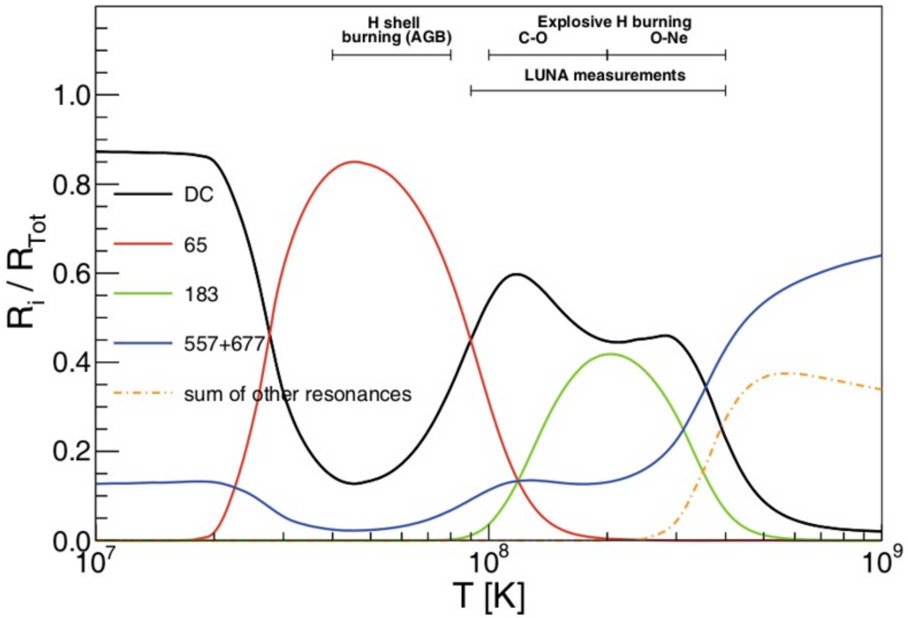
INFN Padova

LUNA

Astrophysical Motivation

- The $^{17}O(p,\gamma)^{18}F$ reaction (Q = 5607 keV) kicks off the CNOIII cycle.
- It contributes to determine the oxygen isotopic ratio, observed in giant stars and in stardust grains
- The observed oxygen isotopic ratio is a useful tool to understand the interplay between nuclear burning and mixing processes in giant stars, as well as the origin of stardust grains
- For 30 < T < 100 MK (35 < E_G < 140 keV) the resonance E_{cm}=65 keV (E_x = 5672 keV) dominates the reaction rate





Fractional contributions to the reaction rate of the $^{17}O(p,\gamma)^{18}F$ as a function of the temperature.

State of the Art

- Only indirect measurement reported in literature [via THM, $^{14}N+\alpha$ channels, $^{17}O(p,\alpha)^{14}N$ and $^{17}O(^{3}He,p\gamma)^{18}F$]

Reference	J^{π}	E_x [keV]	Γ_α [eV]	Γ_γ [eV]	Γ_p [neV]	$\omega\gamma$* [peV]
I. Berka et al. (1977)	1^-		200(60)	0.46(6)		
H.B. Mak et al. (1980)			130(5)			
H.W. Becker et al. (1982)				0.45(2)		
A. Chafa et al. (2005)		5671.6(2)				
M.Q. Buckner et al. (2015)					19(3)	16(3)
M.L. Sergi et al. (2015)					14(2)	11.8(21)
C.G. Bruno et al. (2016)					36(6)	

$$* \ \omega\gamma_{(p,\gamma)} = \frac{(2J_x+1)}{(2J_p+1)(2J_{^{17}O}+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_\alpha}$$

LUNA

State of the Art

- Only indirect measurement reported in literature [via THM, ^{14}N+α channels, ^{17}O(p,α)^{14}N and ^{17}O(^{3}He,pγ)^{18}F]

Reference	J^{+}	Ex [keV]	Γ_α [eV]	Γ_γ [eV]	Γ_p [neV]	$\omega\gamma$* [peV]
I. Berka et al. (1977)	1^{-}		200(60)	0.46(6)		
H.B. Mak et al. (1980)			130(5)			
H.W. Becker et al. (1982)				0.45(2)		
A. Chafa et al. (2005)		5671.6(2)				
M.Q. Buckner et al. (2015)					19(3)	16(3)
M.L. Sergi et al. (2015)					14(2)	11.8(21)
C.G. Bruno et al. (2016)					36(6)	

$$* \ \omega\gamma_{(p,\gamma)} = \frac{(2J_x + 1)}{(2J_p + 1)(2J_{^{17}O} + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_\alpha}$$

Values disagree by a factor ~2-2.5

State of the Art

- Only indirect measurement reported in literature [via THM, ^{14}N+α channels, ^{17}O(p,α)^{14}N and ^{17}O(^{3}He,pγ)^{18}F]

Reference	J^{π}	Ex [keV]	Γ_α [eV]	Γ_γ [eV]	Γ_p [neV]	$\omega\gamma$* [peV]
I. Berka et al. (1977)	1^-		200(60)	0.46(6)		
H.B. Mak et al. (1980)			130(5)			
H.W. Becker et al. (1982)				0.45(2)		
A. Chafa et al. (2005)		5671.6(2)				
M.Q. Buckner et al. (2015)					19(3)	16(3)
M.L. Sergi et al. (2015)					14(2)	11.8(21)
C.G. Bruno et al. (2016)					36(6)	

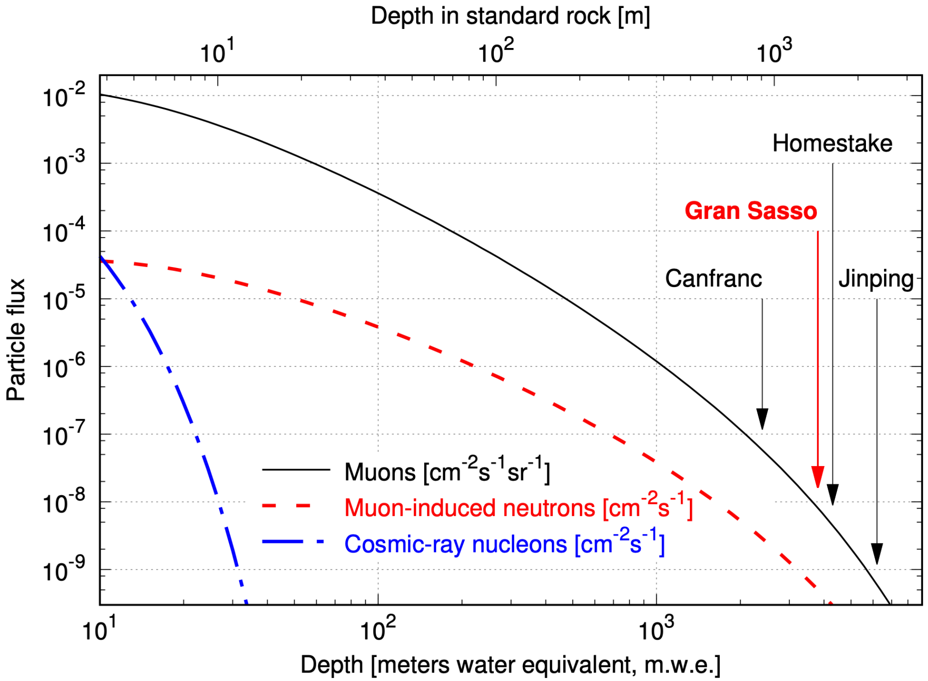
These correspond to cr < 0.08 reactions/h

$$* \ \omega\gamma_{(p,\gamma)} = \frac{(2J_x+1)}{(2J_p+1)(2J_{^{17}O}+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_\alpha}$$

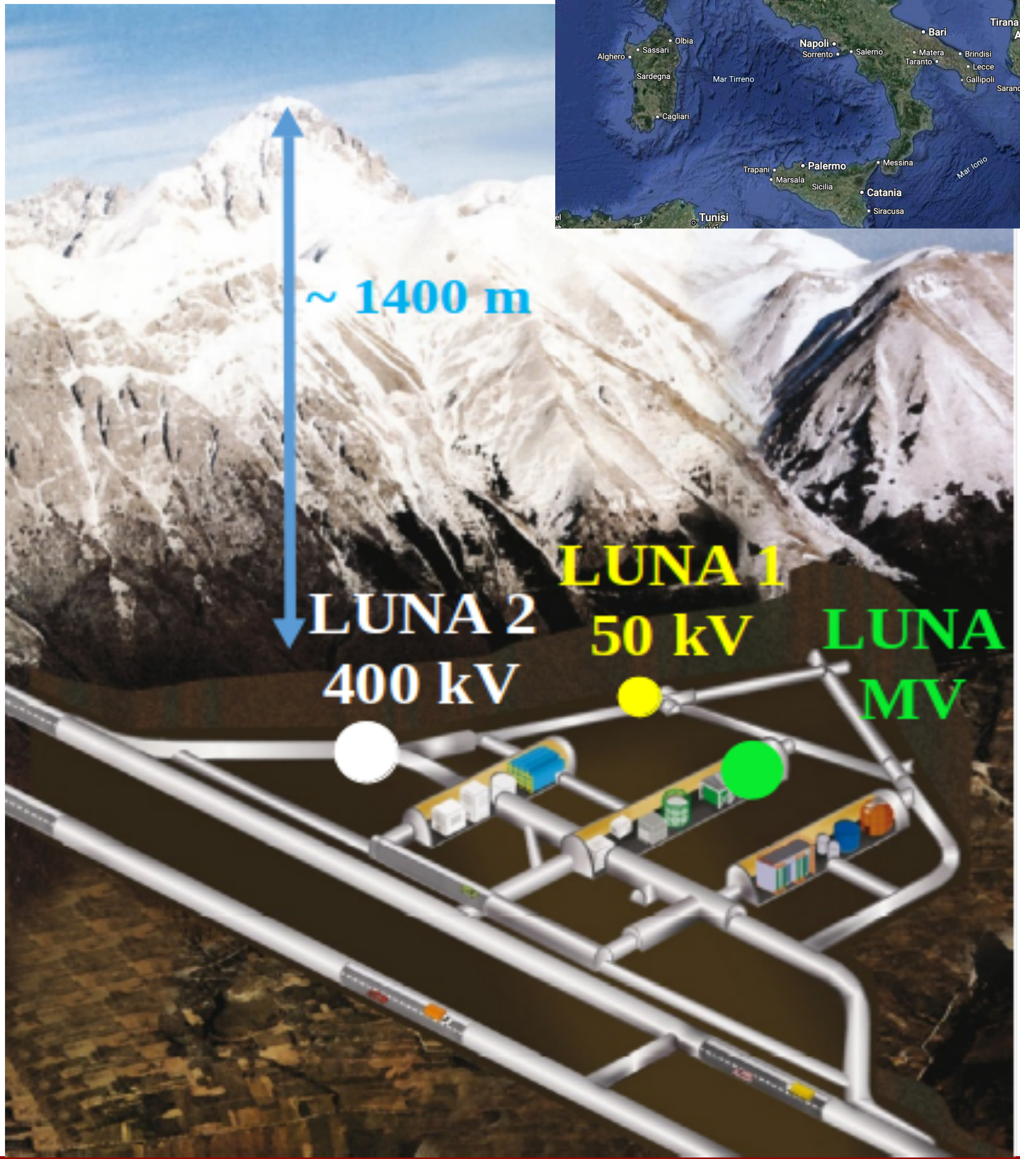
LUNA

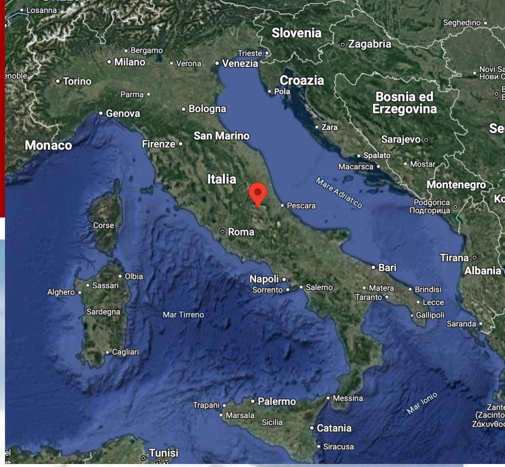
To the limit

- LUNA is located at Laboratori Nazionali del Gran Sasso, Italy
- Shielded by 1400 m of rock (4000 m w.e.)
- Cosmic-ray flux is significantly suppressed



Broggini C., Prog. Part. Nucl. Phys. 98, 55-84 (2018)

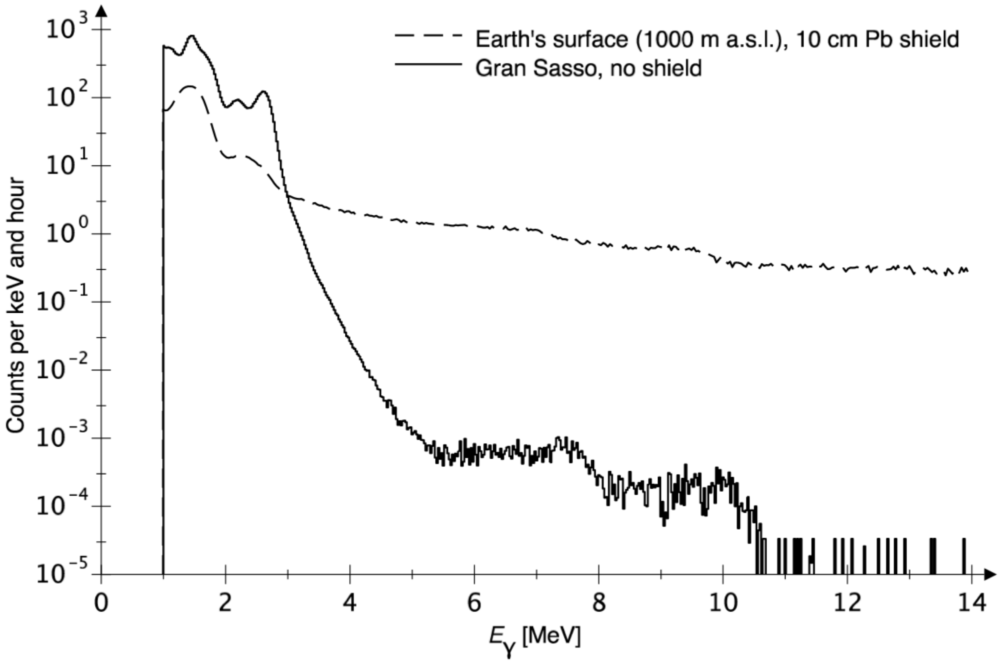




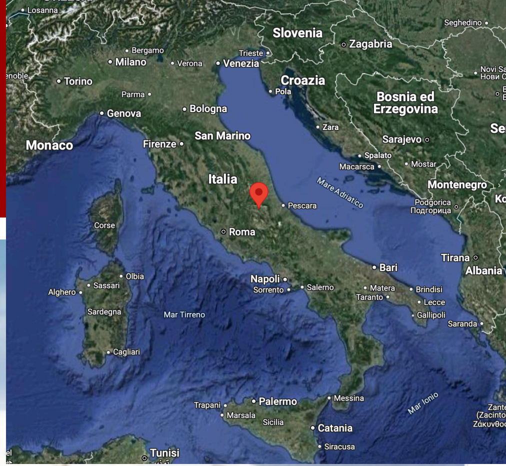
LUNA

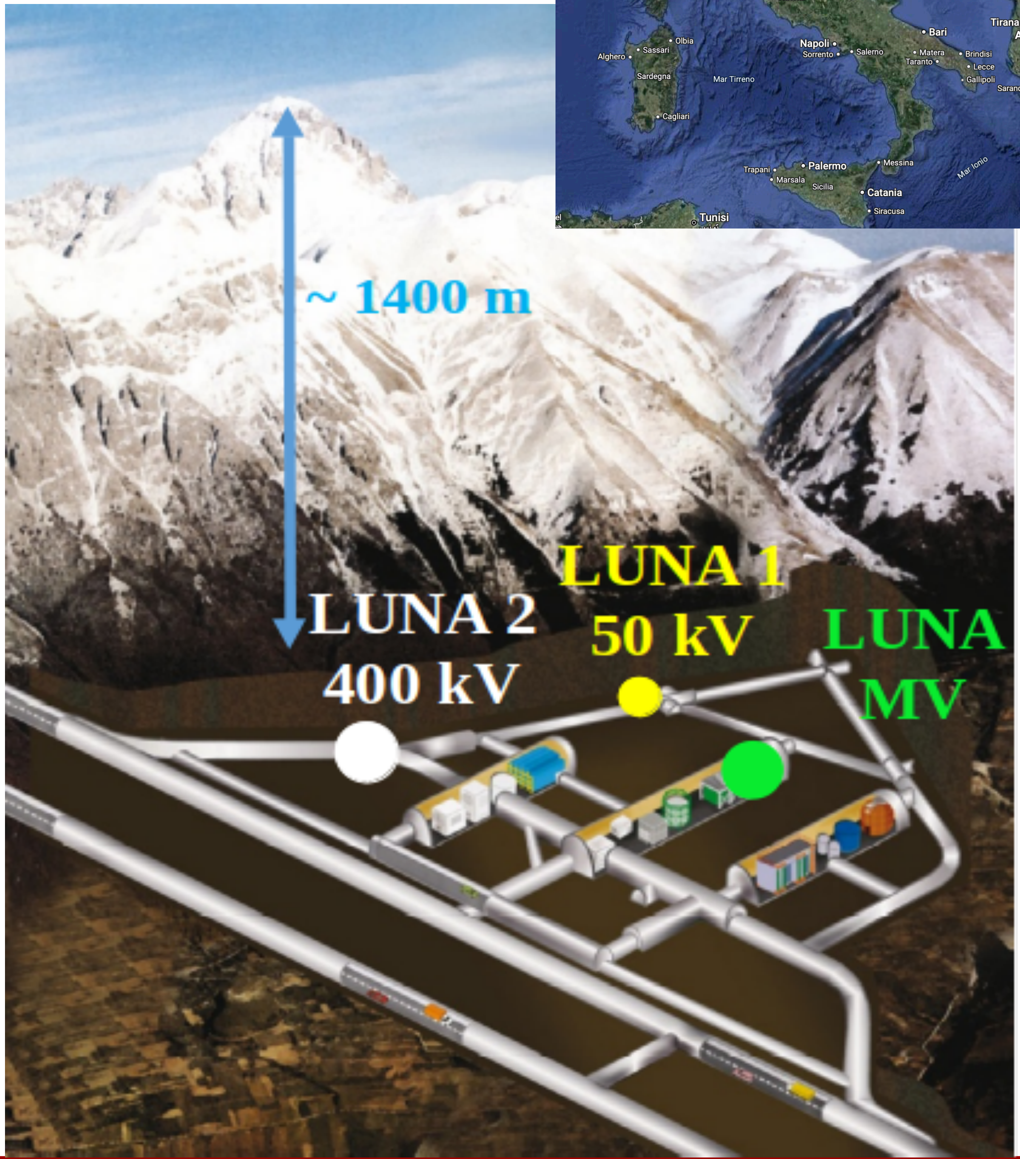
To the limit

- LUNA is located at Laboratori Nazionali del Gran Sasso, Italy
- Shielded by 1400 m of rock (4000 m w.e.)
- Cosmic-ray flux is significantly suppressed → Cosmic-ray induced background is significantly reduced



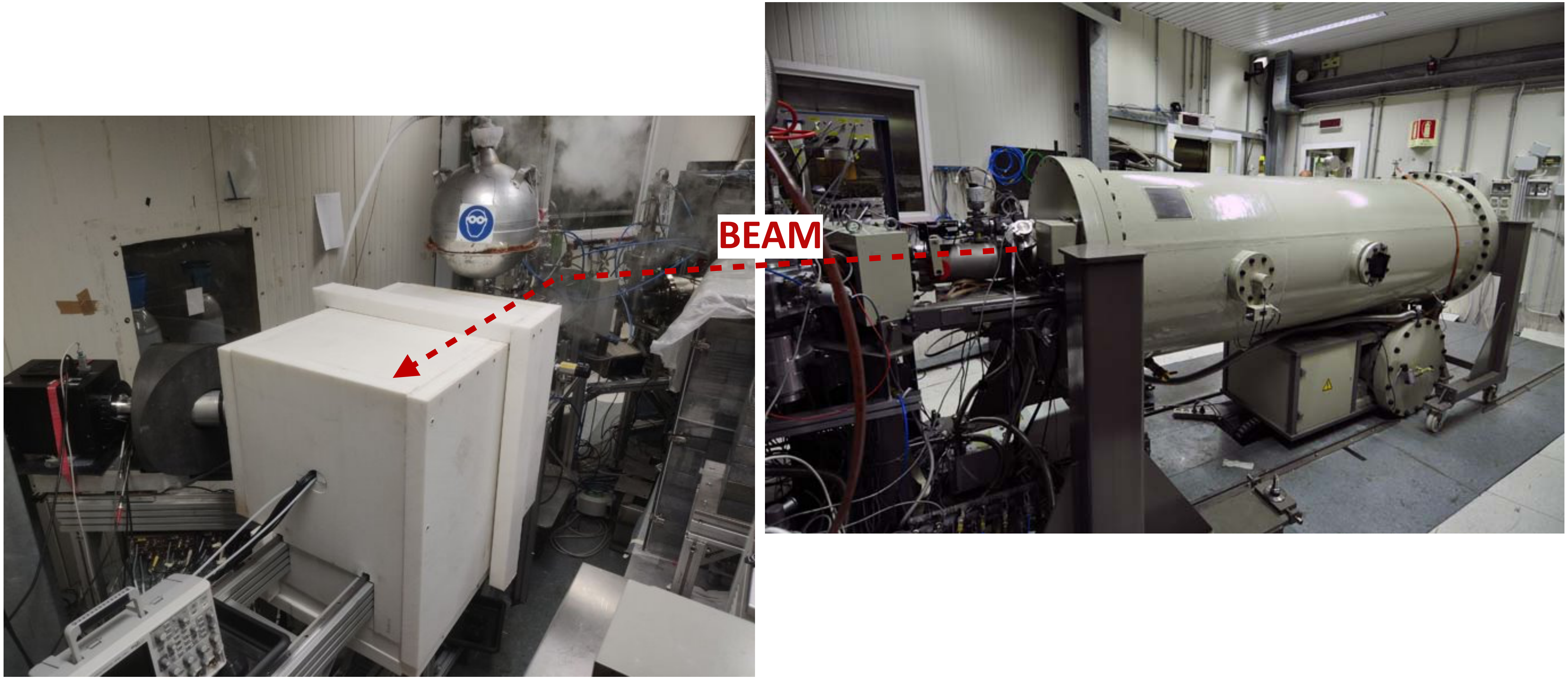
Bemmerer D., EPJ A 24, 313-319 (2005)



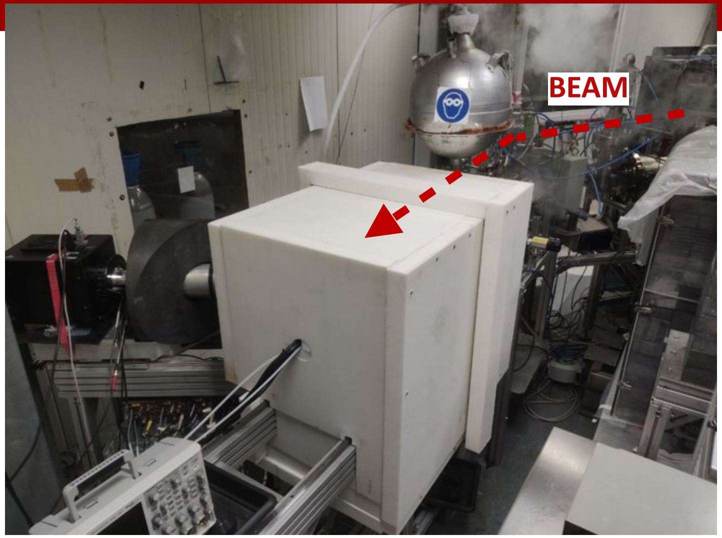


To the limit

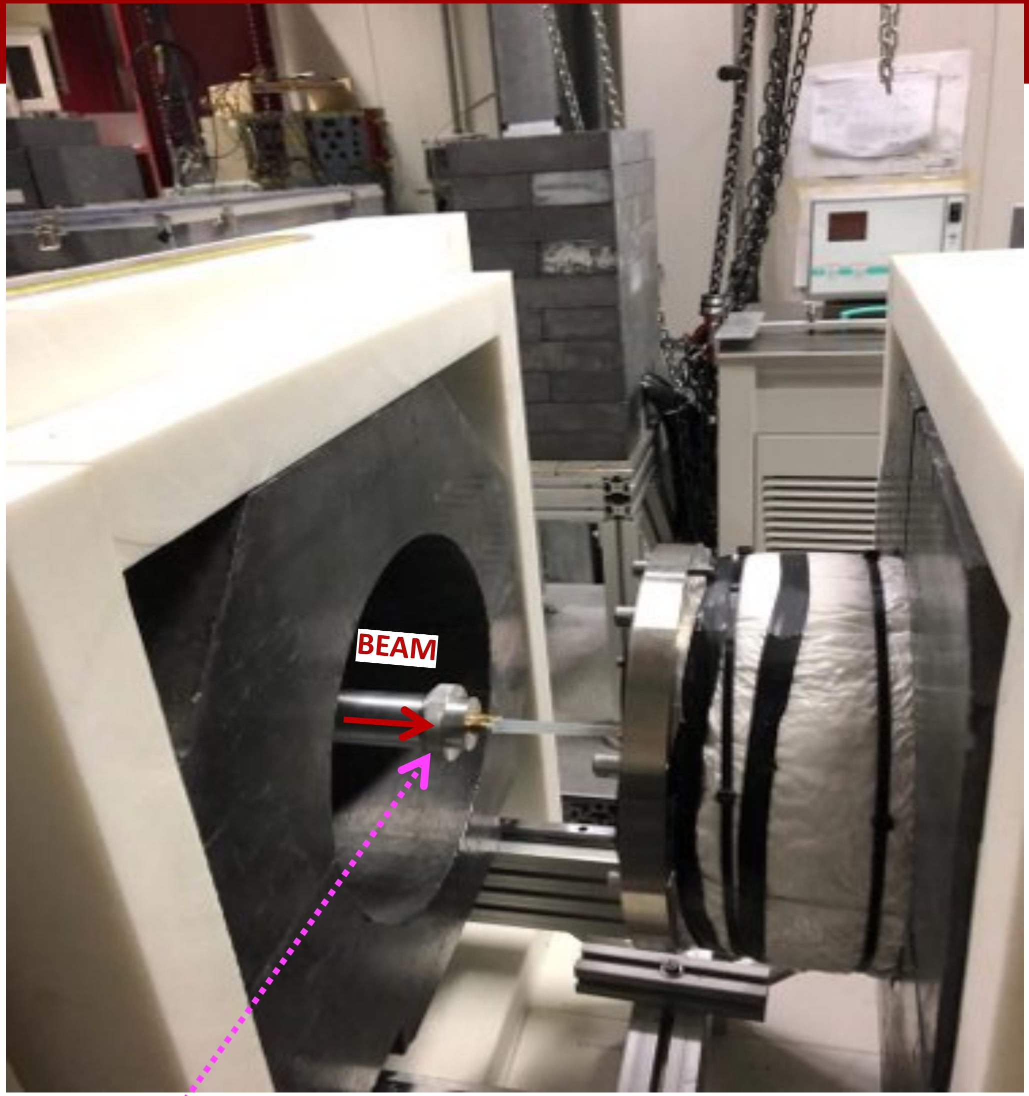
LUNA400kV high intensity (up to 500 μA on target) and stability proton beam (5eV/h)



To the limit



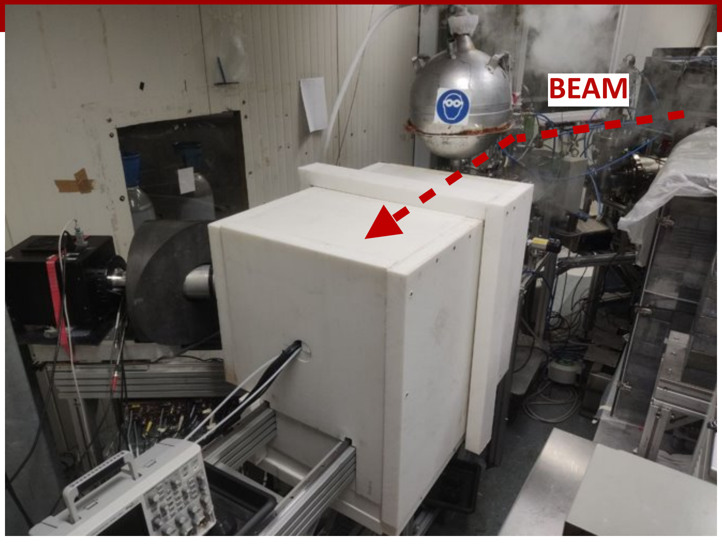
Ta_2O_5 target made by anodic oxidation with ^{17}O (90%) enriched water



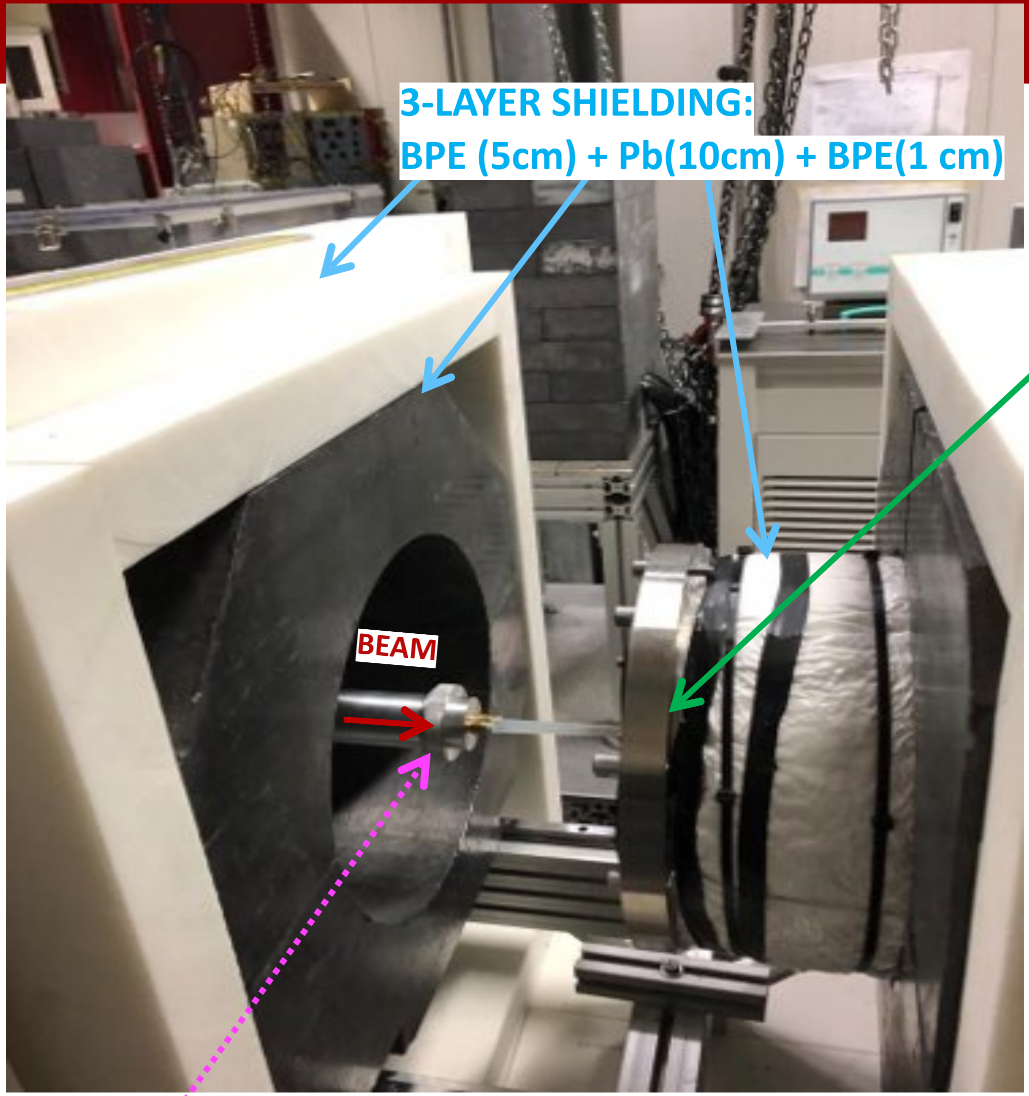
Aluminum CHAMBER AND TARGET HOLDER

LUNA

To the limit



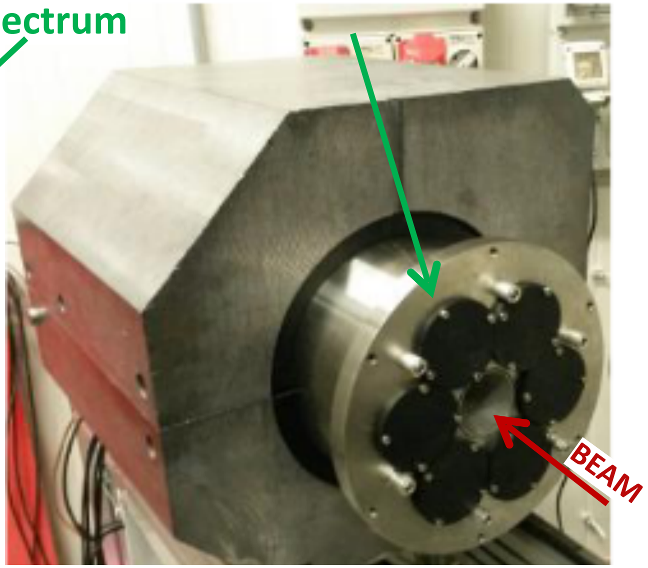
Ta_2O_5 target made by anodic oxidation with ^{17}O (90%) enriched water

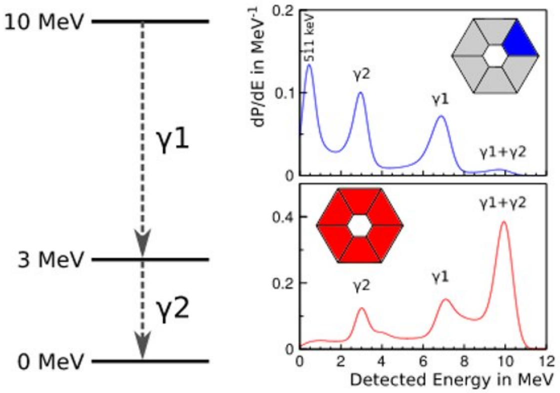


Aluminum CHAMBER AND TARGET HOLDER

This part moves back and forth

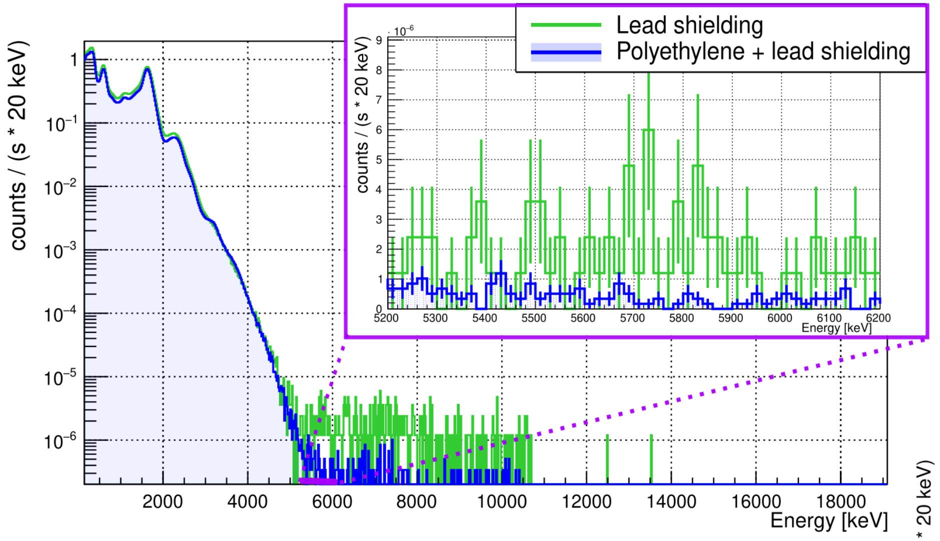
4Π BGO DETECTOR
6 independent crystals
TAS mode possible: coincident events in different channels are summed up OFFLINE to produce the addback spectrum

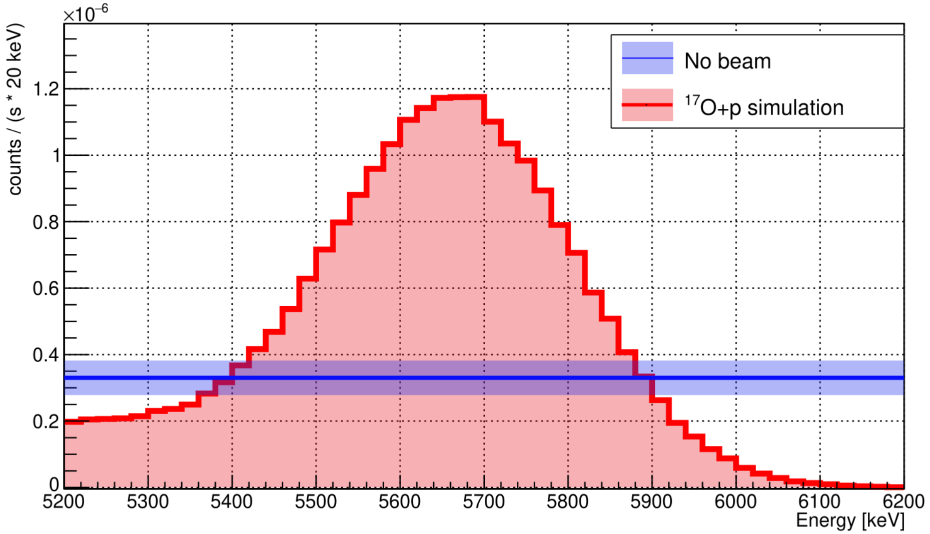


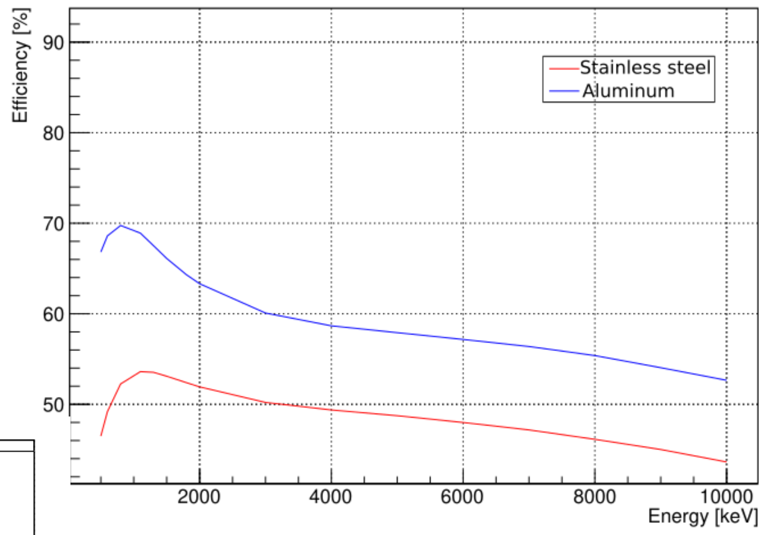


We made it!

- 3 layer shielding: BPE + Pb + BPE -> reduction of the background by a factor ~5
- Al chamber and target holder -> ~20% increase in efficiency w.r.t. previous brass and stainless steel setup



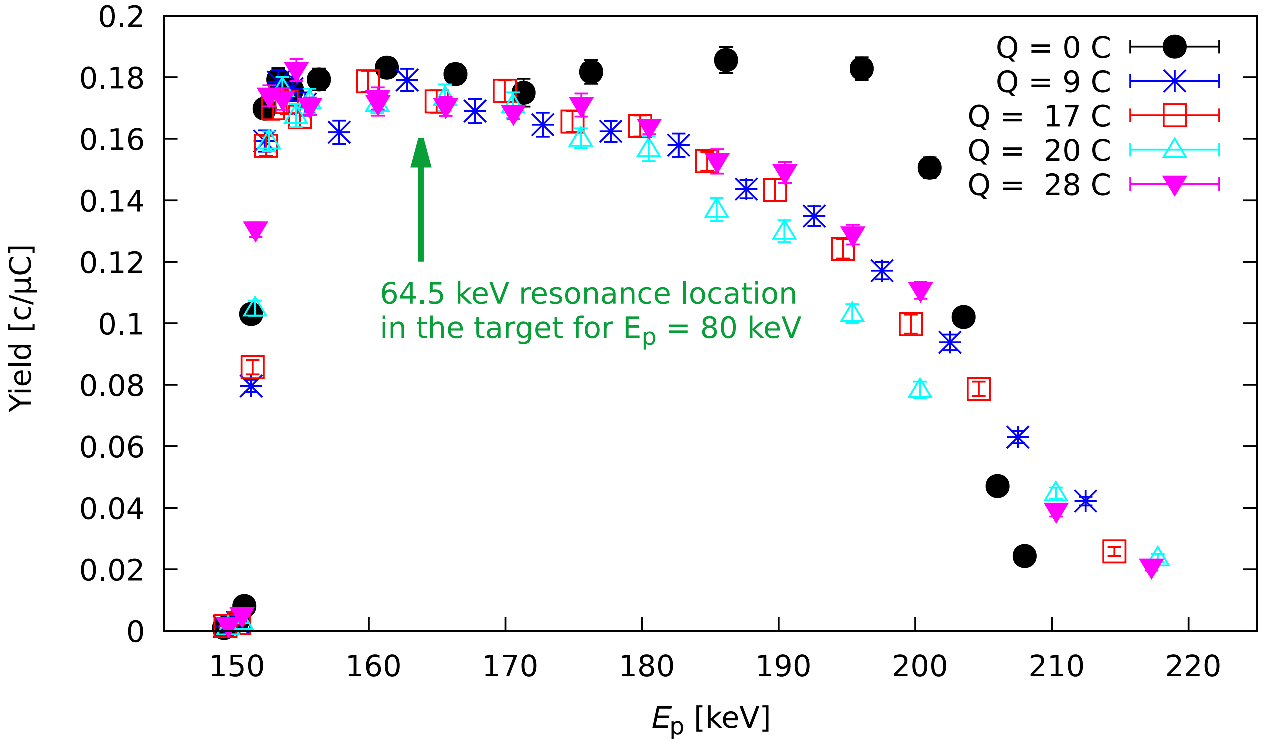




[Skowronski J., J Phys. G 50, 045201 (2023)]

Let's measure it!

- The data taking covered 4 months
- 420 C accumulated on O-17 targets, 50 and 20 keV thick
- Long runs performed at E_p = 80 keV
- Targets monitored with periodic scan of the 151 keV resonance and run on top of the 193 keV resonance
- 300 C accumulated on Ultra Pure Water targets, same thickness but negligible O-17 content

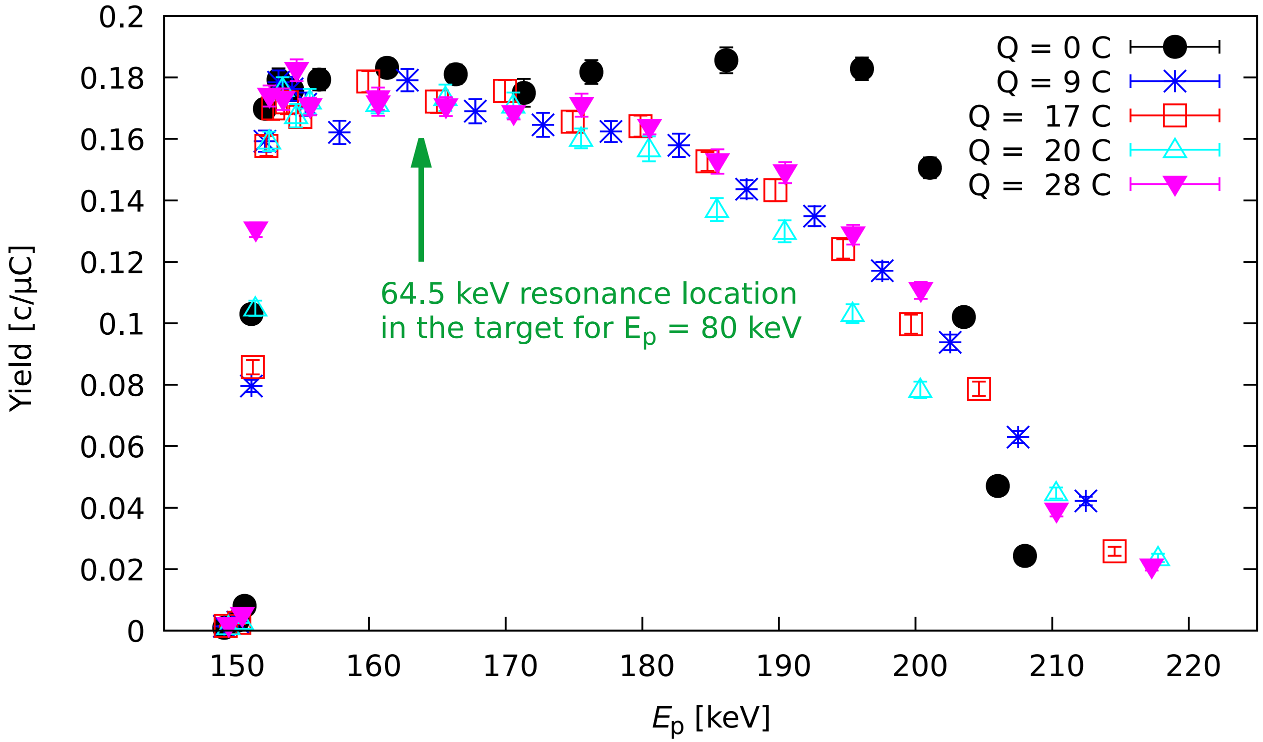


[Gesué R.M., PRL 133, 052701 (2024)]

Let’s measure it!

- The data taking covered 4 months
- 420 C accumulated on O-17 targets, 50 and 20 keV thick
- Long runs performed at E_p = 80 keV
- Targets monitored with periodic scan of the 151 keV resonance and run on top of the 193 keV resonance
- 300 C accumulated on Ultra Pure Water targets, same thickness but negligible O-17 content

→ ?

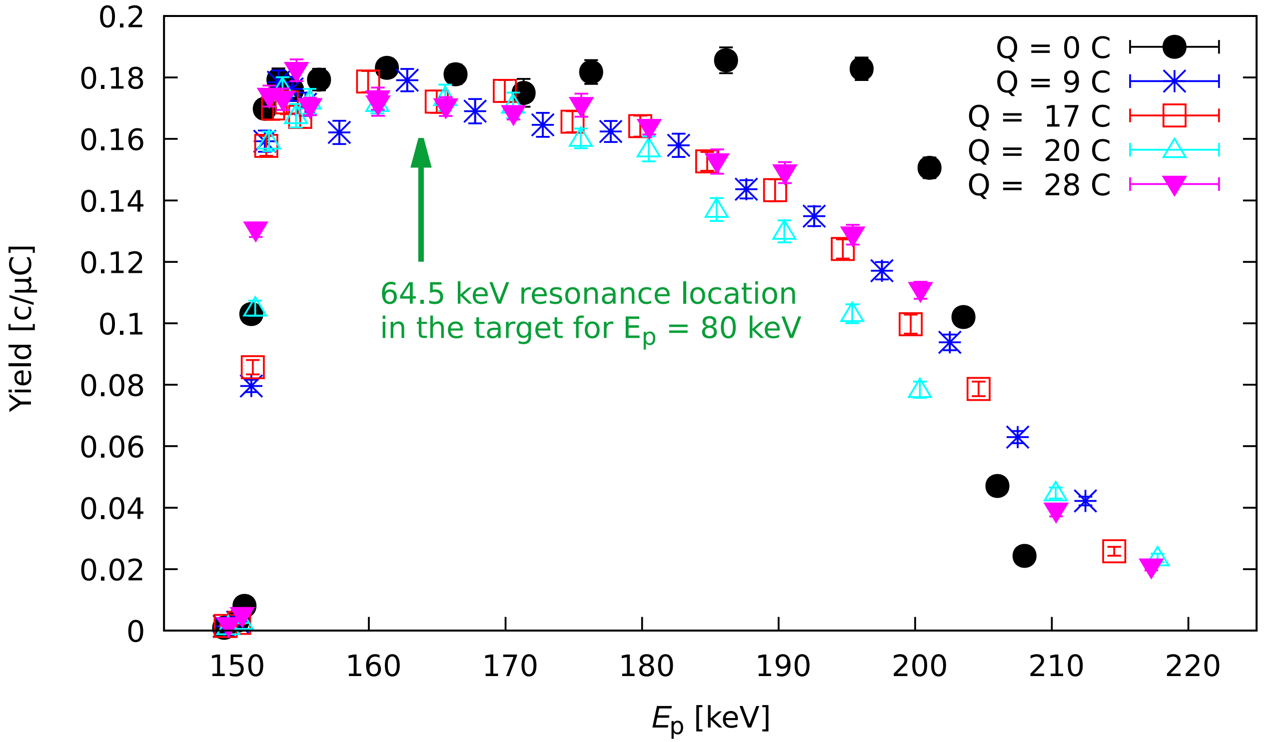


[Gesué R.M., PRL 133, 052701 (2024)]

LUNA

Let's measure it!

- The data taking covered 4 months
- 420 C accumulated on O-17 targets, 50 and 20 keV thick
- Long runs performed at E_p = 80 keV
- Targets monitored with periodic scan of the 151 keV resonance and run on top of the 193 keV resonance
- 300 C accumulated on Ultra Pure Water targets, same thickness but negligible O-17 content



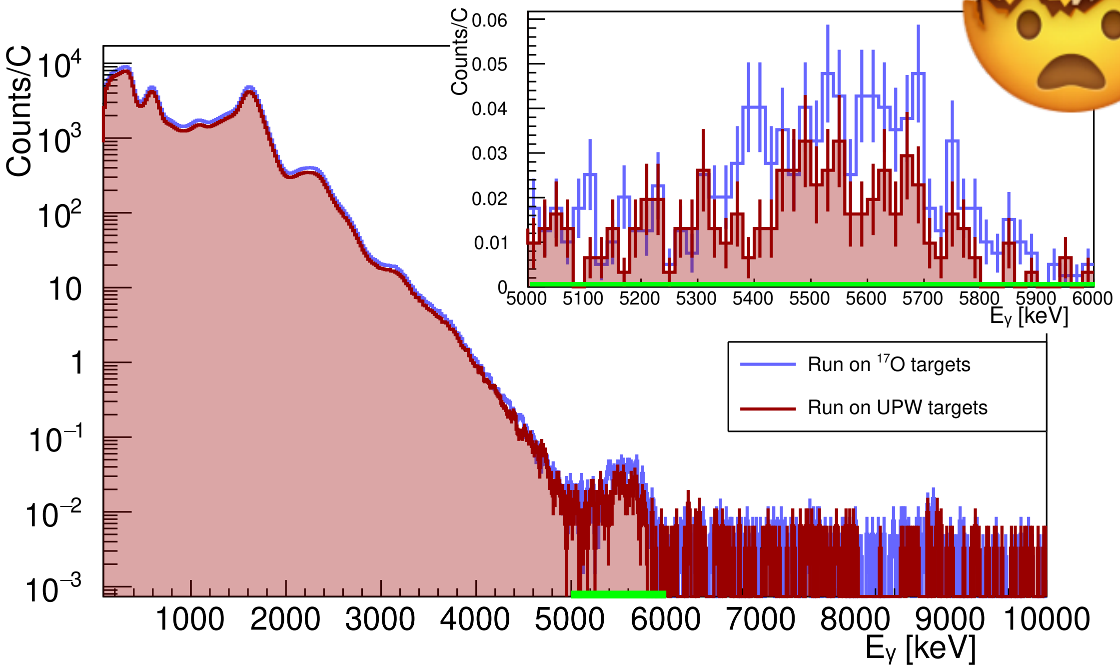
[Gesué R.M., PRL 133, 052701 (2024)]

→ To monitor the Beam Induced Background

LUNA

The Beam Induced Background Nightmare

- BIB is due to contaminants in the oxide layer or in the backing that react with the beam
- The scariest contaminants are those that populates the ROI, mimicking the signal of interest, and have much higher cross section than the reaction of interest
- Ta is known for its H and D storage properties
- p+D reaction has a Q = 5493.5 keV (only ~ 100 keV lower than the $^{17}O(p,\gamma)^{18}F$ reaction) and a cross section higher by many orders of magnitudes
- With BGO poor resolution the ROI for $^{17}O(p,\gamma)^{18}F$ reaction is 5200-6200 keV



[Gesué R.M., PRL 133, 052701 (2024)]

No way to distinguish/resolve the p+D and the $^{17}O(p,\gamma)^{18}F$ *sum* peak

LUNA

Never give up and be smart!

Ok looking at the sum peak we cannot tell a difference between our signal and BIB signal but is there any difference?

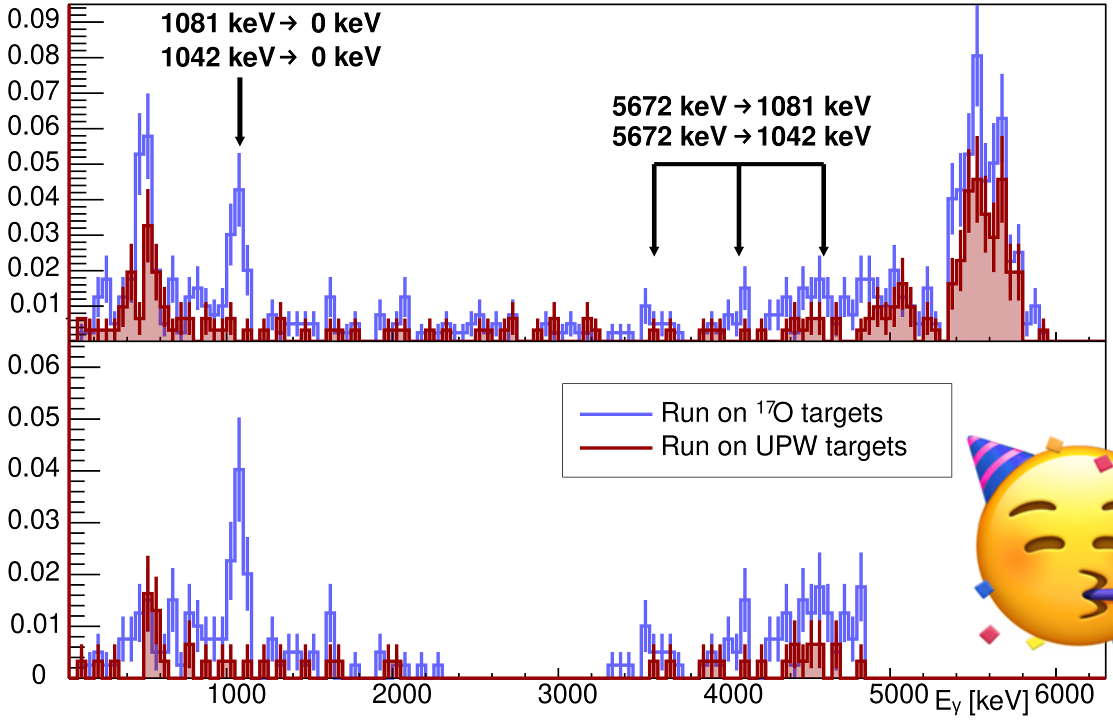
Sure, check NNDC (https://www.nndc.bnl.gov/):

E(level) (keV)	E(γ) (keV)	I(γ)	Final Levels	
5672.57 *32*	2539	28.5 *20*	3133.87	1-
	2611	4.0 *4*	3061.84	2+
	3572	0.4 *2*	2100.61	2-
	3972	0.8 *3*	1700.81	1+
	4592	52 *3*	1080.54	0-
	4631	8.1 *7*	1041.55	0+
	5673	6.2 *4*	0.0	1+

...while the p+D give rise to single γ-rays of Eγ ~ 5560 keV

This is a not trivial difference

- As well as you can construct the sum peak you can also de-construct it
- Gating in the ROI and looking at which γ-rays contributed to the sum peak
- You consider only coincident γ-rays corresponding to the $^{17}O(p,\gamma)^{18}F$ cascade



[Gesué R.M., PRL 133, 052701 (2024)]

LUNA

Results, Conclusions and Outlooks

$$Y_{\text{exp}} = \frac{N_\gamma}{Q} = \frac{\lambda^2}{2e\epsilon_{\text{eff}}}\omega\gamma_{(p,\gamma)}\eta W,$$

N_γ is the net count taking into account random coincidence and direct capture contribution

Q is the charge

ϵ_{eff} is the effective stopping power

η is the detection-gate efficiency

W is the angular distribution

$\lambda^2/2$ is the De Broglie factor

and correcting for the screening

LUNA

Results, Conclusions and Outlooks

Reference	J^{π}	Ex [keV]	Γ_{α} [eV]	Γ_{γ} [eV]	Γ_{p} [neV]	$\omega\gamma$ [peV]
I. Berka et al. (1977)	1^{-}		200(60)	0.46(6)		
H.B. Mak et al. (1980)			130(5)			
H.W. Becker et al. (1982)				0.45(2)		
A. Chafa et al. (2005)		5671.6(2)				
M.Q. Buckner et al. (2015)					19(3)	16(3)
M.L. Sergi et al. (2015)					14(2)	11.8(21)
C.G. Bruno et al. (2016)					36(6)	
R.M. Gesué et al. (2024)					34(8)	30(6)

[Gesué R.M., PRL 133, 052701 (2024)]

SPOILER ALERT! A paper on astrophysical impact has been submitted! Stay focused!

LUNA

LUNA Collaboration

A. Compagnucci*, R. Gesue'*, M. Junker, F. Ferraro | INFN LNGS *and GSSI, Italy

C. Broggini, A. Caciolli, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski, S.Turkat | Università di Padova and INFN Padova, Italy

A. Formicola, C. Gustavino | INFN Roma 1, Italy

D. Bemmerer, A. Boeltzig, E. Masha | HZDR Dresden, Germany

L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs | MTA-ATOMKI Debrecen, Hungary

M. Lugaro | Konkoly Observatory and ELTE University Budapest, Hungary

O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy

P. Corvisiero, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy

R. Depalo, G. Gosta, A. Guglielmetti | Università di Milano and INFN Milano, Italy

C. Ananna, A. Best, D. Dell'Aquila, A. Di Leva, D. Mercogliano, G. Imbriani, D. Rapagnani | Università di Napoli and INFN Napoli, Italy

F. Cavanna, P. Colombetti, G. Gervino | Università di Torino and INFN Torino, Italy

M. Aliotta, L. Barbieri, C. Bruno, T. Davinson, J. Marsh, D. Robb, R. Sidhu, | University of Edinburgh, United Kingdom

F. Barile, G. Ciani, V. Paticchio, L. Schiavulli | Università di Bari and INFN Bari, Italy

R. Perrino | INFN Lecce, Italy

"The amazing thing is that every atom in your body came from a star that exploded. And, the atoms in your left hand probably came from a different star than your right hand. It really is the most poetic thing I know about physics: You are all stardust."

L.M.Krauss

Thank you for your attention

Backup

M.Q. Buckner et al. 2015

In the paper the data available are collected and the $\omega\gamma$ is calculated using:

the individual partial widths, we find values of $\Gamma_p = (19.0 \pm 3.2) \times 10^{-9}$ eV, $\Gamma_\alpha = 130 \pm 5$ eV, and $\Gamma_\gamma = 0.44 \pm 0.02$ eV.

with Γ_p from Blackmon et al. (1995)

M.L. Sergi et al. 2010 and 2015

The (p,α) channel was measured via the $^2H(^{17}O,\alpha^{14}N)n$ reaction at LNS and at Notre Dame University.

Then they used the following:

$$(\omega\gamma)^{THM}_{p\gamma} = (\omega\gamma)^{THM}_{p\alpha}\frac{\Gamma_\gamma}{\Gamma_\alpha},$$

C.G. Bruno et al. 2016

The resonance $\omega\gamma_{(p,\alpha)}$ was obtained for the first time via a direct measurement at LUNA.

LUNA

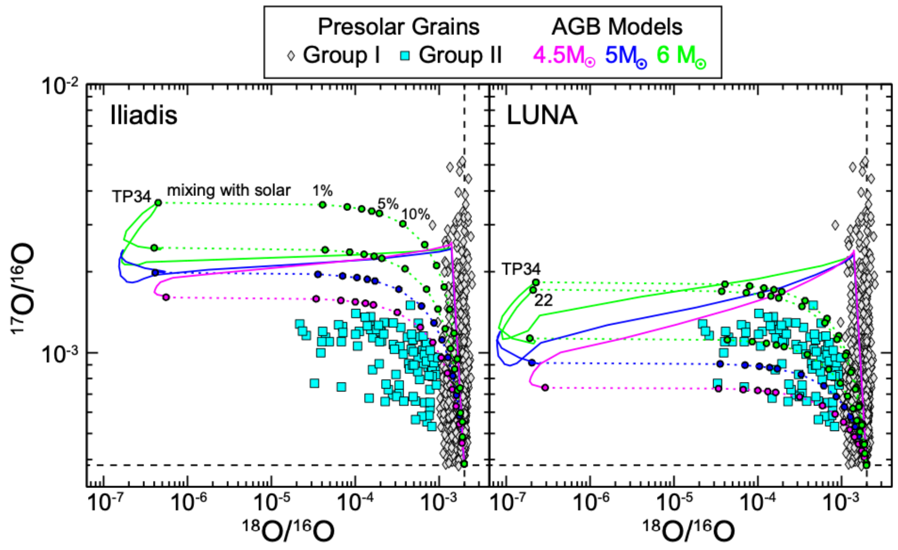
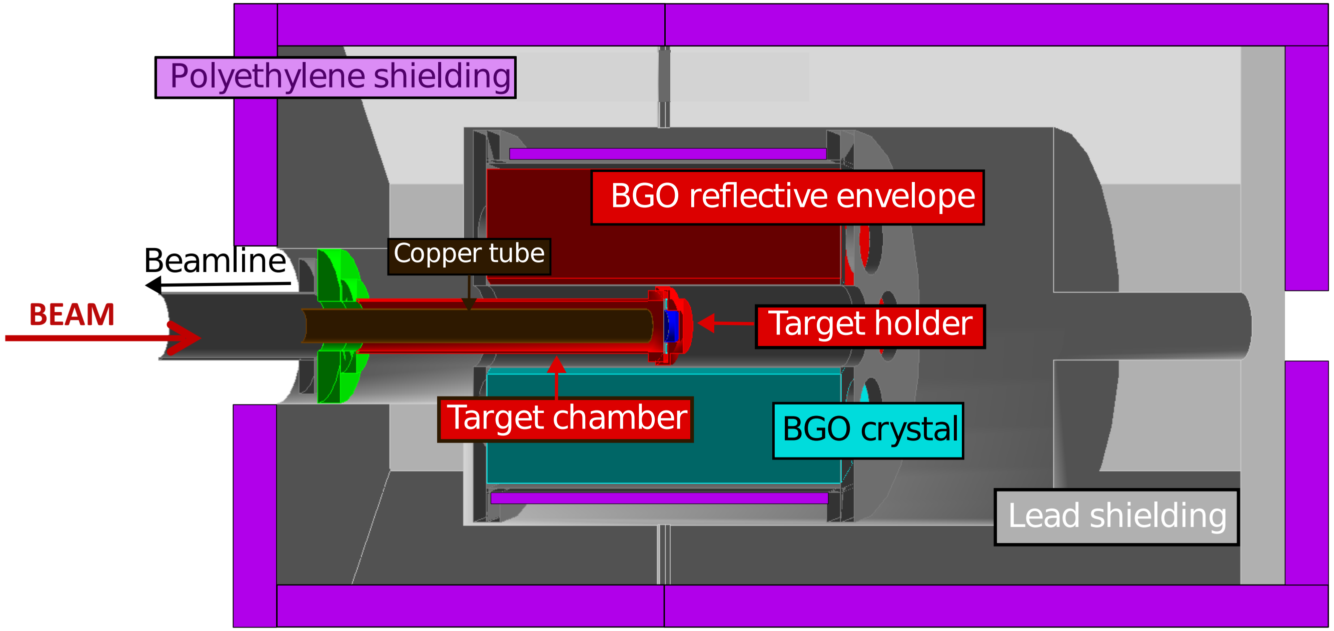


Figure 3: Evolution of the oxygen isotopic ratios at the surface of AGB models of different masses. The evolutionary (solid) lines in panel a were calculated using the old (Iliadis[12]) and in panel b using the new (LUNA[6]) $^{17}O(p,\alpha)^{14}N$ reaction rate. Uncertainties in either rate translate into changes in the $^{17}O/^{16}O$ ratio by at most 20%, i.e., within the differences between the different stellar models. Isotopic ratios observed in Group II grains (filled square symbols[21] with error bars typically within the size of the symbol) cannot be reproduced by the old rate, regardless of the amount of dilution of AGB material with solar material (dotted lines), but are well reproduced with the new rate. The dilution is applied to the AGB composition at the end of the evolution for the three masses and, as examples, also at one-half and one-third of the AGB lifetime for the 6 $M_\odot$ star (labels TP34 and 22 indicate that the star evolved, respectively, through 34 and 22 thermal instabilities of the He shell out of the 53 computed in the models). Dashed vertical and horizontal lines indicate solar ratios for reference.

M. Lugaro et al., Nat. As. 1, 0027 (2017)

Setup_2

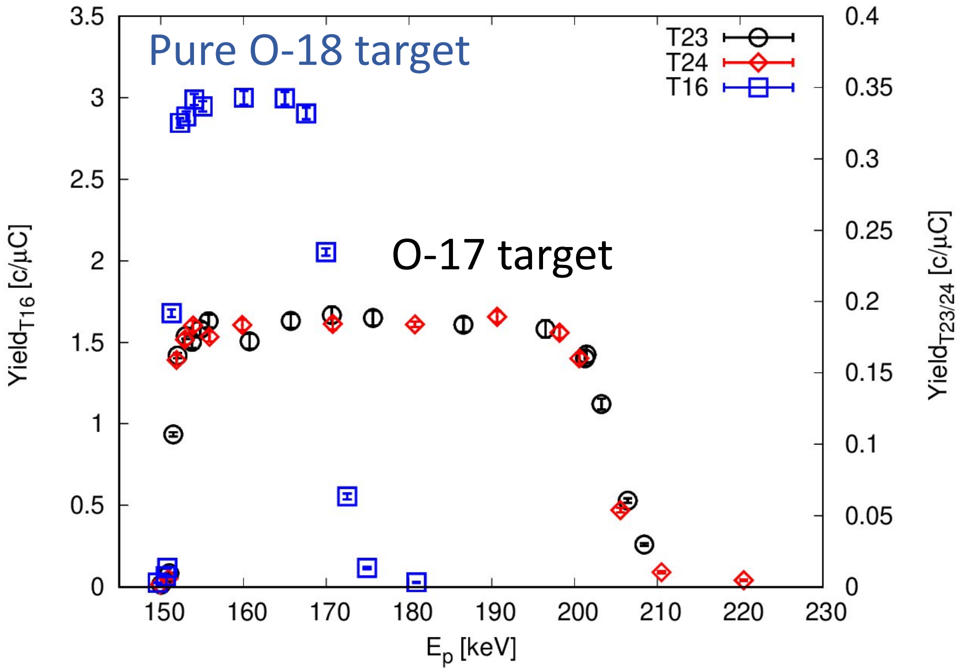
- LUNA400kV high intensity (up to 500 μA on target) and stability proton beam
- Al chamber and target holder to minimize the γ-ray absorption
- 90% O-17 enriched target
- High efficiency 4πBGO detector, made of 6 crystals to be used in TAS mode
- 3 layered shielding [from outer to inner layer):
  - 5 cm borated (5%) Polyethylene
  - 10 cm Pb
  - 1 cm bPe



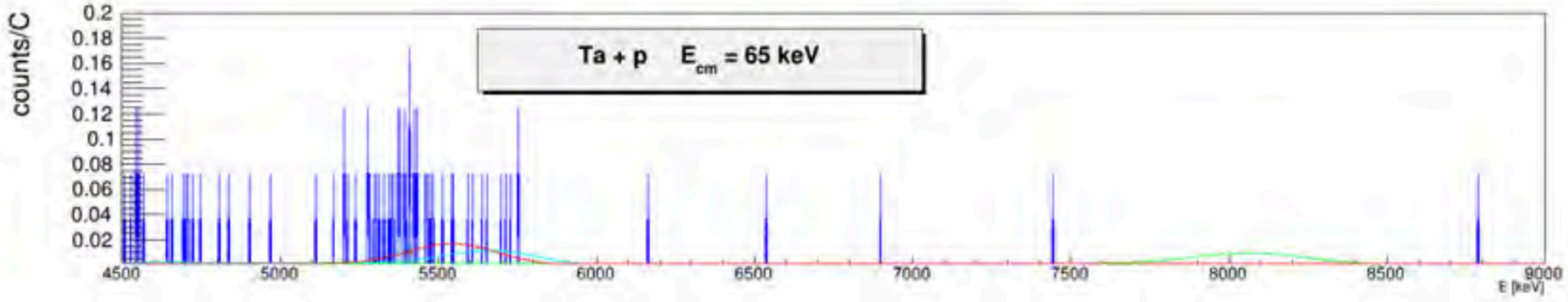
[Skowronski J., J Phys. G 50, 045201 (2023)]

Target characterization:

- Composition is Ta_2O_5 well known from previous studies and from the anodic oxydation technique (see A.Caciolli et al. 2012 and reference therein)
- Isotopic composition was determined from comparison of the plateau from a 99% O-18 targets and using the runs on top of the 193 keV resonance (known with a precision of 9% and 7% respectively)
- Target profile and degradation monitored via 151 keV resonance scan, resonance of the $^{18}O(p,\gamma)$ channel



- Deuterium in Ta is a well known “issue” see T. Asakawa et al., J. Vac. Sci. Technol. B 38, 034008 (2020)



Error budget:

- Stat : 20%
- Syst:
  - efficiency: 3%
  - br: 6%
  - sp: 4%
  - charge: 2%

Gate analysis steps:

- coincidence time window 3.5 μs
- ROI determination, via resolution study + simulation

- Selection of events contributing to the sum peak, corresponding to the cascade we were interested in
- p+D is gone but you can still have_
    - random coincidences, obtained applying the same gate on UPW target
    - DC contribution obtained analytically and by simulations