Low-energy investigation of $^{24}Mg(p,\gamma)^{25}Al$ reaction at LUNA

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On the behalf of the **LUNA Collaboration**

XII NPA, 7-11 September 2026 – Cluj Napoca

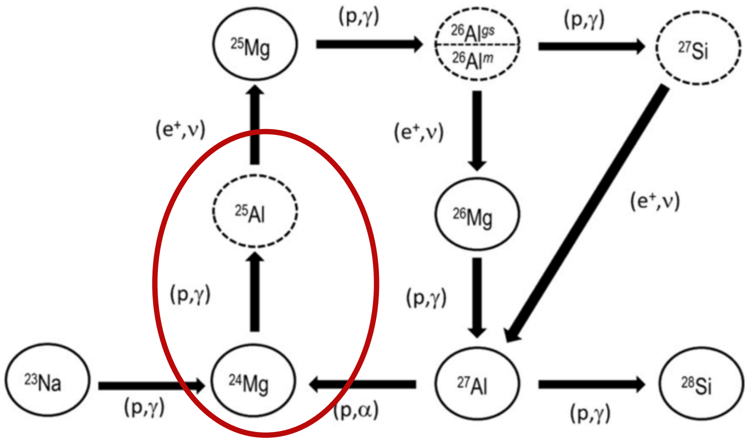
LUNA
Laboratory for Underground Nuclear Astrophysics

INFN

GSSI
GRAN SASSO SCIENCE INSTITUTE

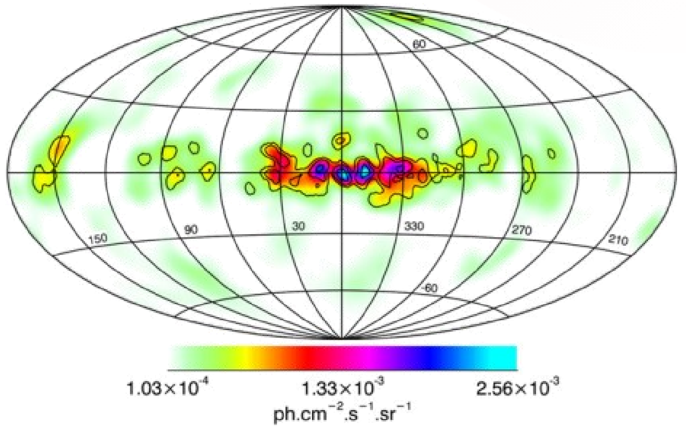
Astrophysical Motivation

$^{24}Mg(p,\gamma)^{25}Al$ is part of the MgAl cycle, activated during H burning for temperatures 30 MK < T < 60 MK



Signature:

^{26}Al presence in various astronomical environments is key evidence for active stellar nucleosynthesis



^{26}Al as deconvolved by INTEGRAL

Astrophysical Motivation

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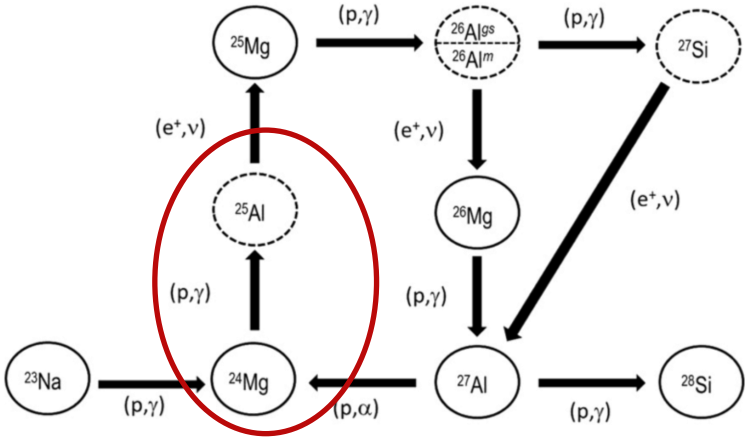
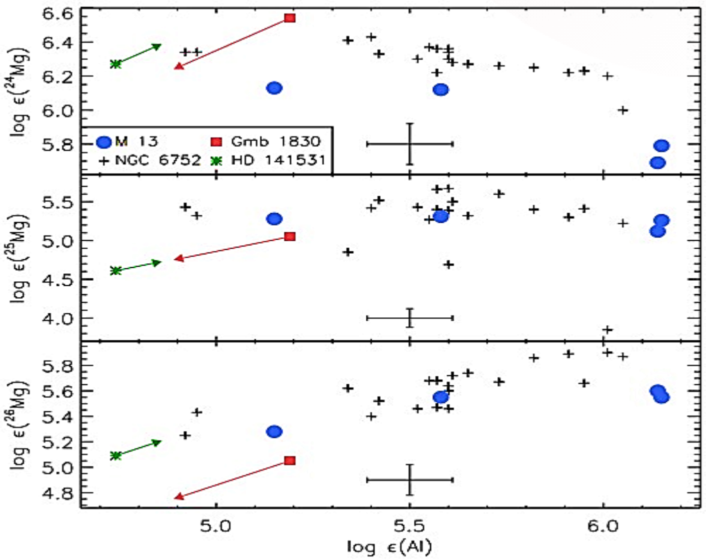


Signature:

Mg–Al anticorrelation in Globular Cluster, that may indicate an early ISM pollution (~13 Gyr ago) by massive AGB or super-AGB stars



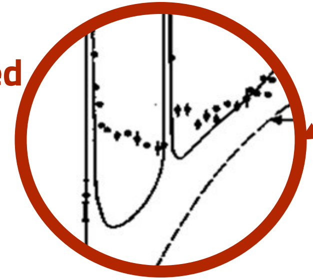
$^{24}Mg(p,\gamma)^{25}Al$ reaction study

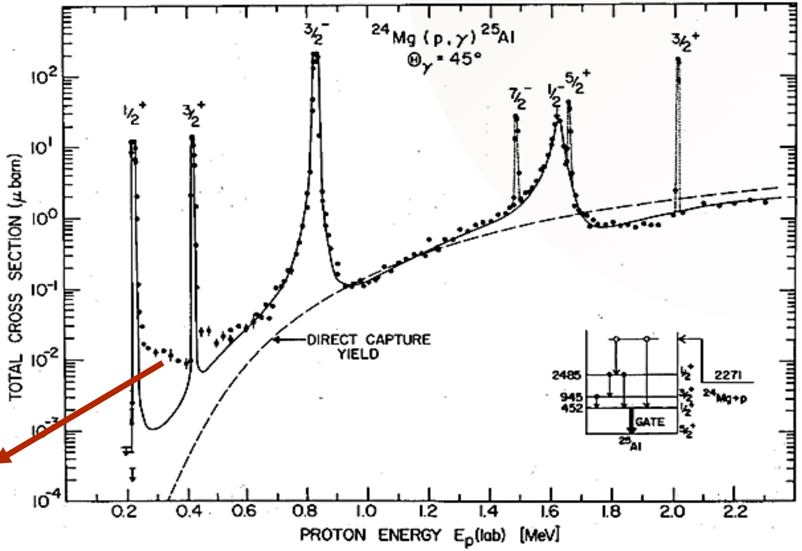
Reference work in literature by Trautvetter and Rolfs in 1975.

- **Resonant captures quite well understood** and reproduced by models

Powell et al. 2000 $E_R = (223 \pm 1)\ keV$

- **DC mechanism not well reproduced** by models at the lower energies -> possible **experimental misinterpretations**





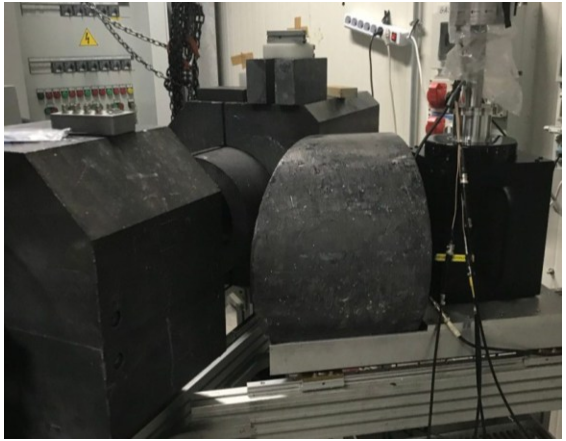
Need for **direct measurements at low energies**, but cross section is extremally low!

Going **UNDRERGROUND is not enough:** an appropriate analysis technique has to be developed

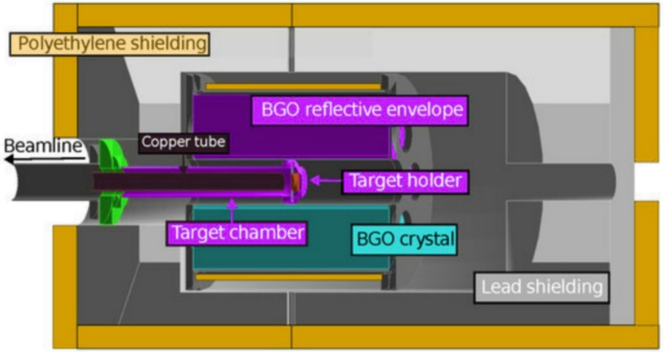
$^{24}Mg(p,\gamma)^{25}Al$ reaction study @ LUNA

Two different **EXPERIMENTAL SETUP at LUNA-400** accelerator

- **HPGe detector**
  - GeBochum Detector at 55° from beam axis
  - Detector–target distance: 0.7 cm
  - Very good **energy resolution**



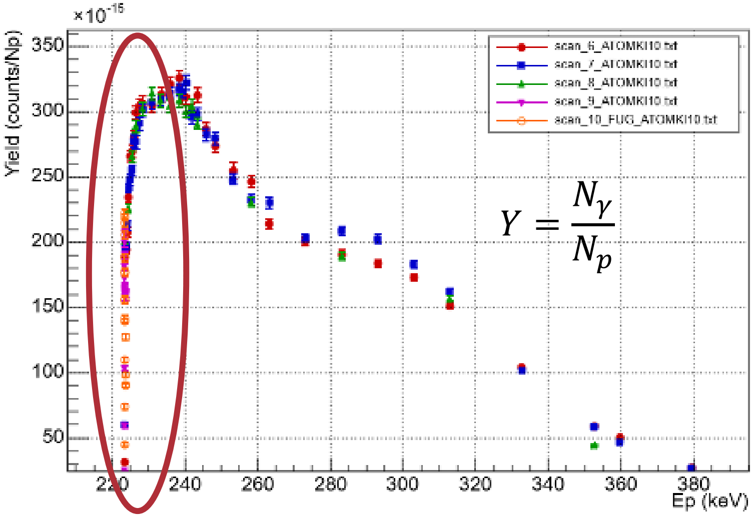
- **BGO array**
  - 6 prismatic $Bi_4Ge_3O_{12}$ crystals
  - Nearly 4π geometry around the target
  - High efficiency for **summing**



HPGe: probing the E_R=223keV resonance

Energy determination

By varying the beam energy and evaluating the yield, one obtains a **resonance scan**:



$$Y = \frac{N_\gamma}{N_p}$$

HPGe: probing the E_R=223keV resonance

Energy determination

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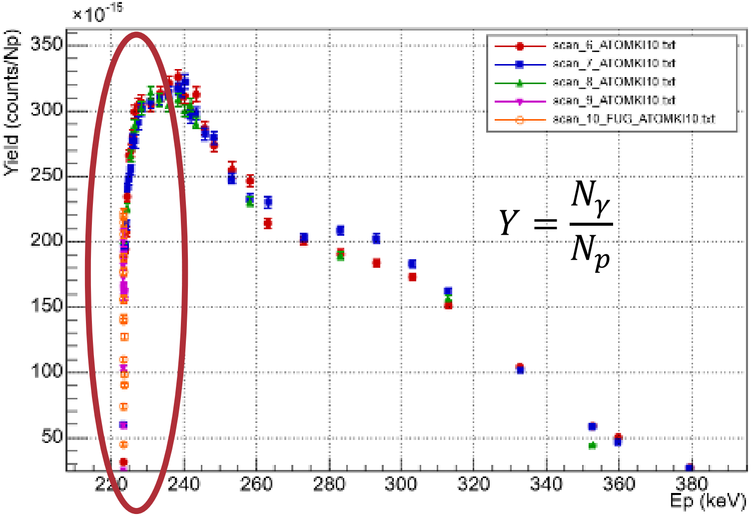
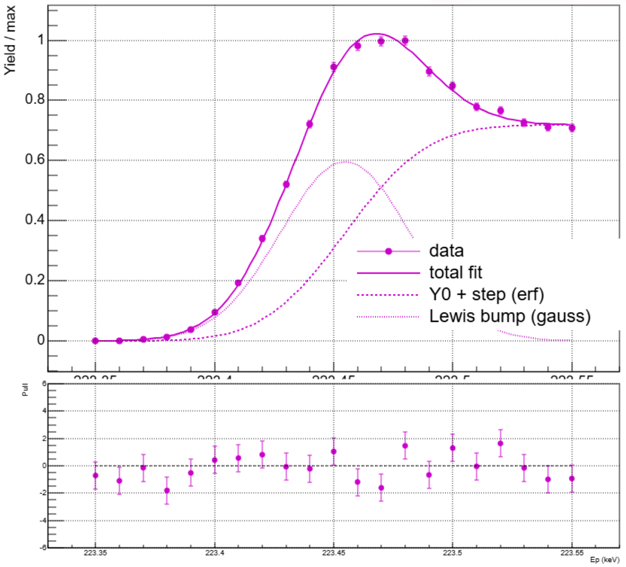


$$Y = \frac{N_\gamma}{N_p}$$

focusing on the **rising edge**:

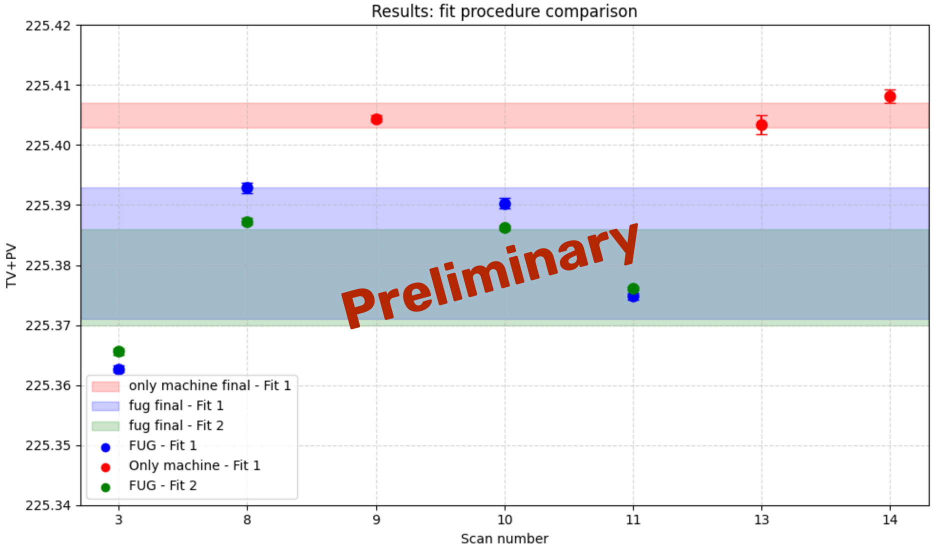
$$F(E) = Y_0 + Y_1\left[\mathrm{erf}\left(\frac{E-E_R}{\sqrt{2}\sigma}\right)+1\right] + Y_2\, G(E; E_R, \sigma)$$

Formicola et al. / Nuclear Instruments and Methods in Physics Research A 507 (2003) 609–616

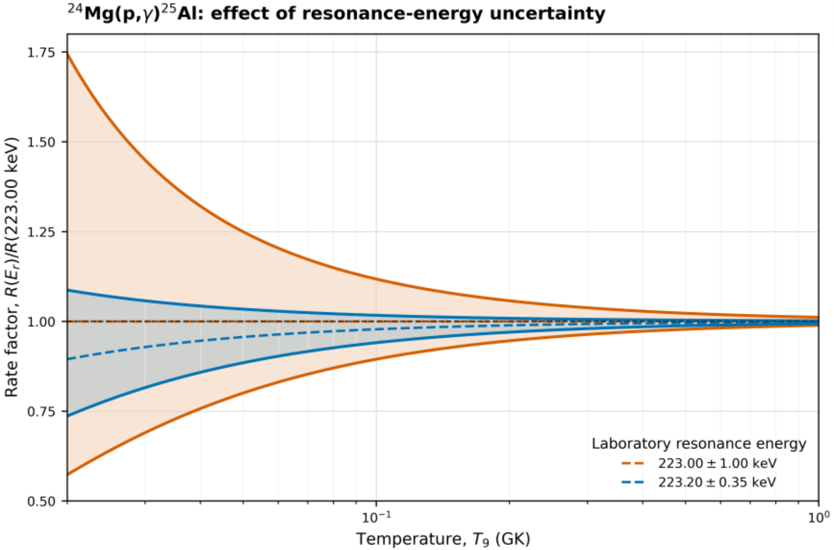


200 eV

Resonance energy determination



Reducing the uncertainty has an impact on the evaluation of the **reaction rate** (in fig. narrow resonance approximation):



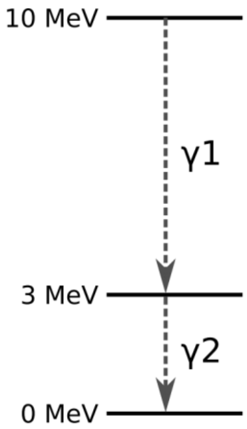
Using LUNA400 calibration:

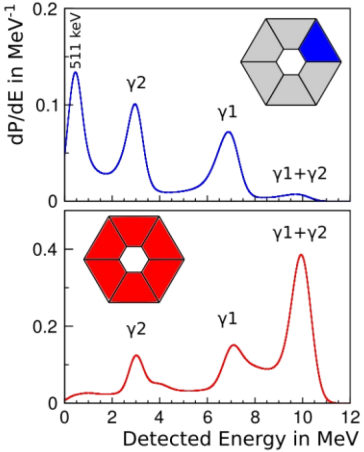
$$E_R = (223{,}18 \pm 0{,}07_{stat} \pm 0{,}35_{syst})\ \mathrm{keV}$$

Preliminary

BGO setup: what can we do?

1. Add back-spectrum



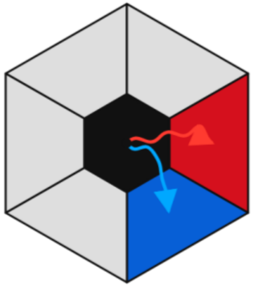


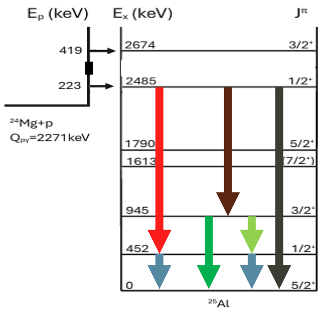
When a reaction occurs, a cascade is produced whose gammas are **temporally correlated** and can be detected by different crystals within a **coincidence window**.

2. Coincidence analysis

Select only events with these requirements:

1. **Total detected energy** falls within a **window centered at Q +** E_{cm}
2. **One of the crystals** has detected a **gamma ray at a characteristic energy (e.g. the secondary gamma ray)**
3. Only a **specific number of crystals with a detected signal**

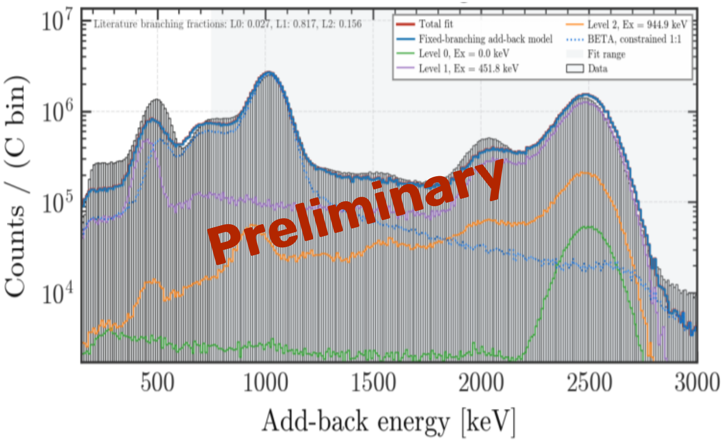




BGO: resonance strenght determination

1. Add back-spectrum

Fit **Add-back Spectrum**

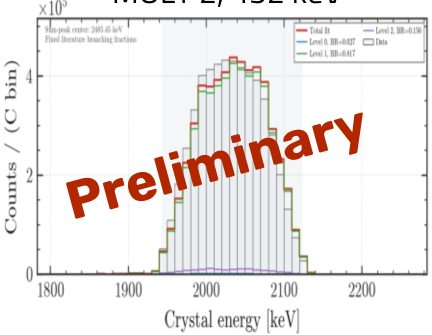


Simulation has to take in to account the **beta decay** of 25Al

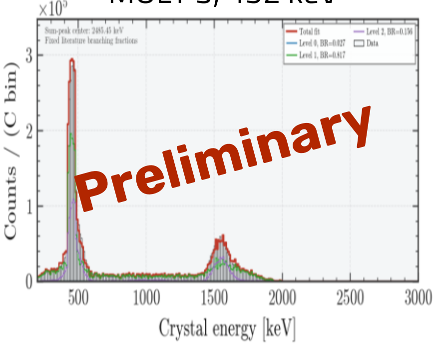
2. Coincidence analysis

Gating procedure applied to emphasize the transition with the highest probability:

MOLT 2, 452 keV



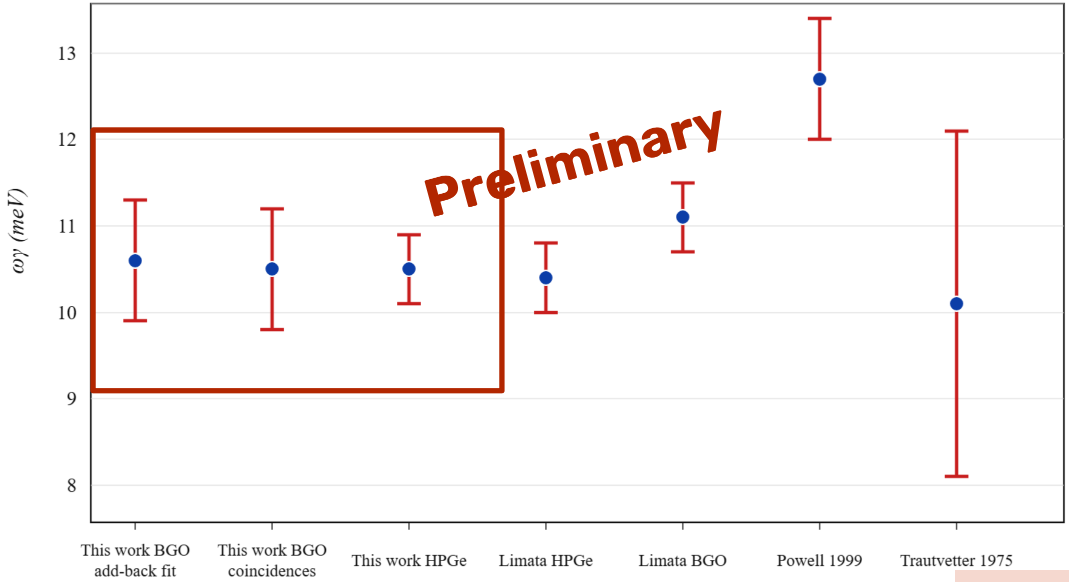
MOLT 3, 452 keV



Resonance strength in agreement between the two methods.

Resonance strenght determination

Comparing our results with literature:



$$Y_\infty = \frac{N_\gamma}{N_p \varepsilon_{\mathrm{FE}} B C_{\mathrm{sum}}} \qquad Y_\infty = \frac{\lambda_R^2}{2}\frac{m_t + m_p}{m_t}\frac{\omega\gamma}{\varepsilon_{\mathrm{eff}}}$$

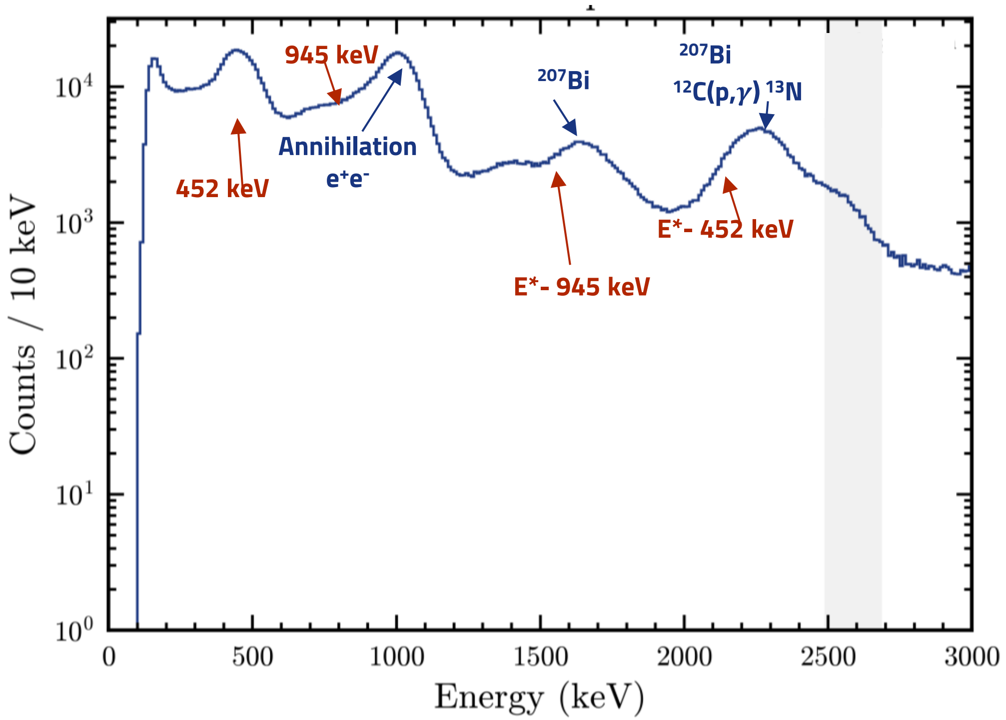
$$\varepsilon_{\mathrm{eff}} = \varepsilon_a + \sum_i \frac{N_i}{N_a}\varepsilon_i(E)$$

From **RBS** measurement

Note the agreement between the two different detectors.

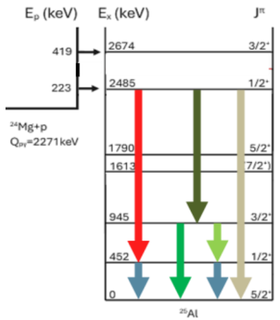
BGO off resonance analysis

Ep = 330 keV



Signal invisible in the total spectrum

- **Blu:** add-back spectrum → no reaction peak visible



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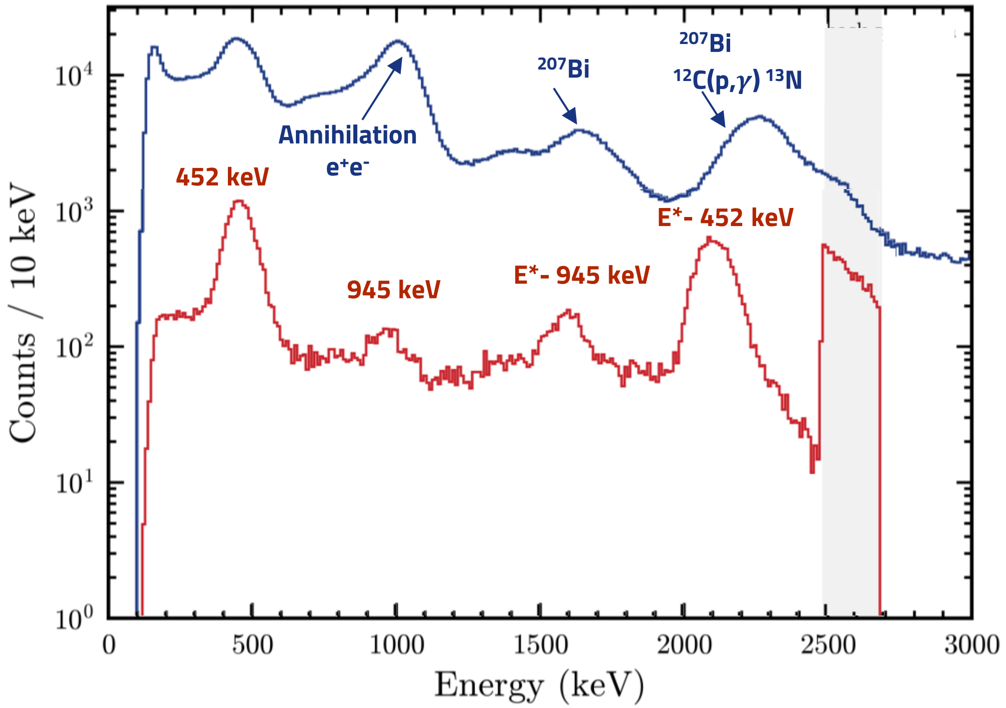
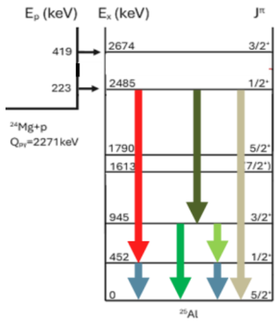


Signal invisible in the total spectrum

- **Blu:** add-back spectrum → no reaction peak visible
- **Red:** after total-energy gate → weak structures emerge



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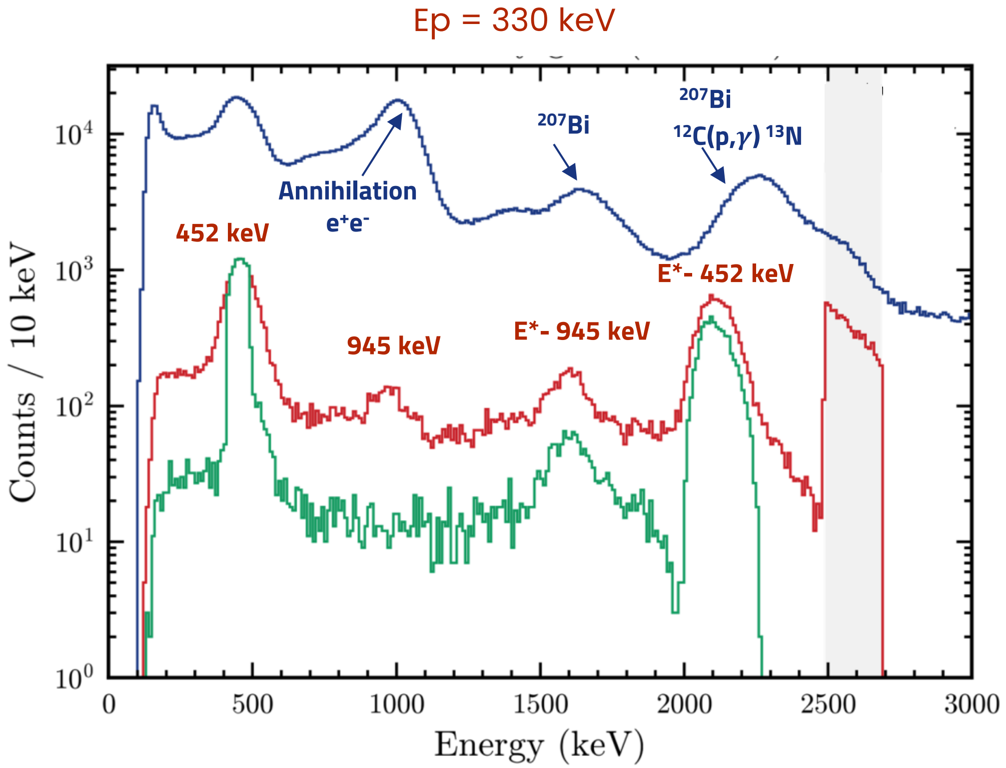
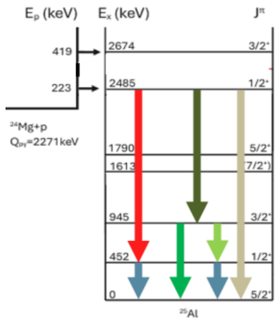


Signal invisible in the total spectrum

- **Blu:** add-back spectrum → no reaction peak visible
- **Red:** after total-energy gate → weak structures emerge
- **Green:** after secondary gate → only events with a 452 keV γ-ray



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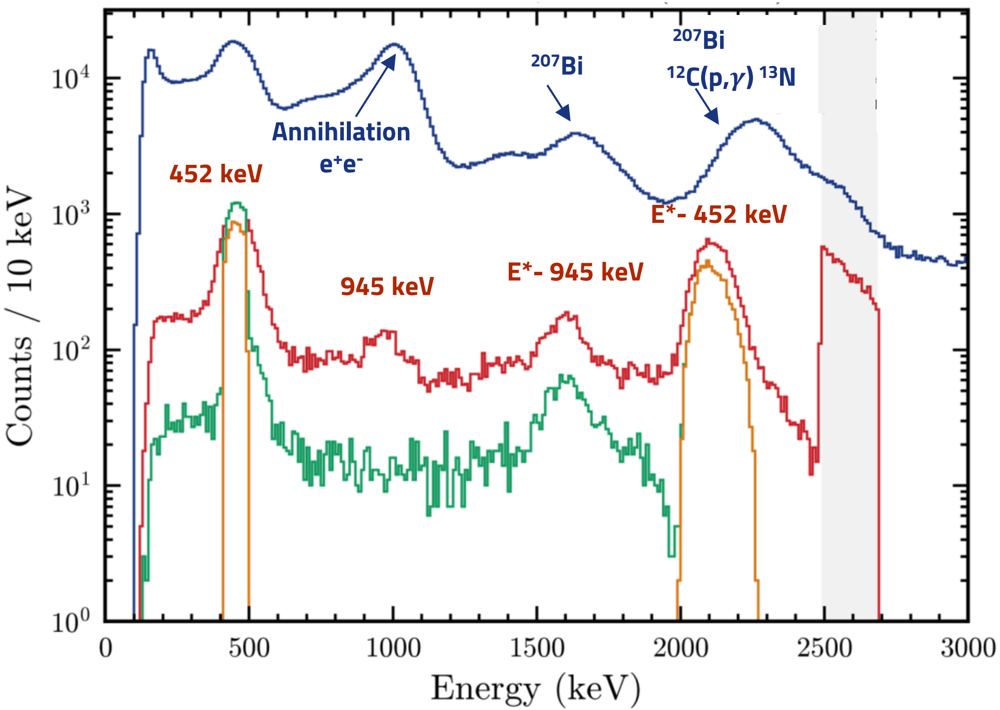
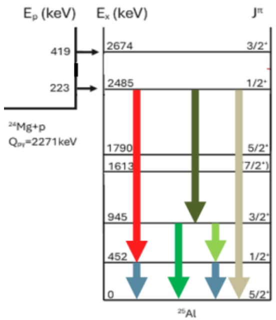
Ep = 330 keV



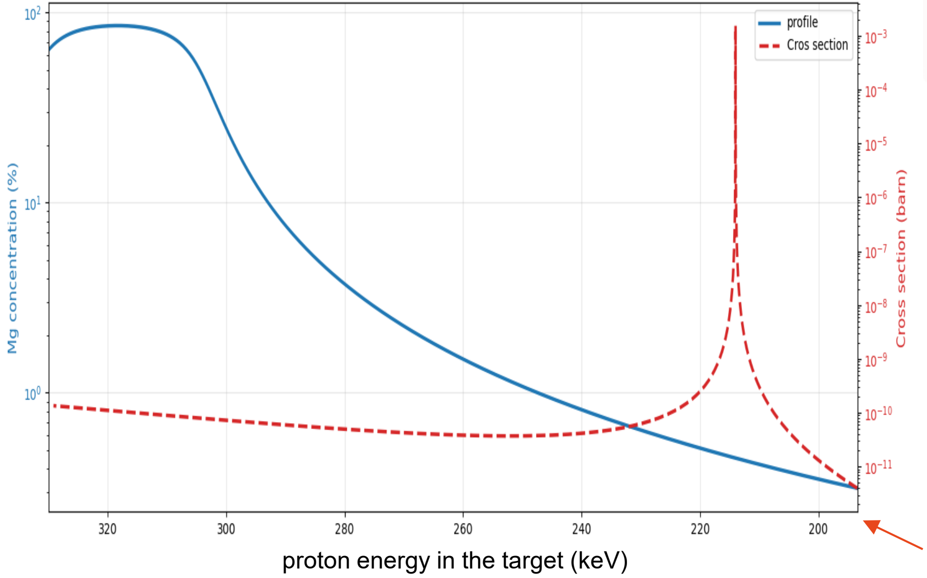
Signal invisible in the total spectrum

- **Blu:** add-back spectrum → no reaction peak visible
- **Red:** after total-energy gate → weak structures emerge
- **Green:** after secondary gate → only events with a 452 keV γ-ray
- **Orange:** after multiplicity gate → isolated transition $E^* \rightarrow 452\ keV \rightarrow 0$



BGO off resonance analysis

Separate simulations for each possible cascade, including the **contribution of the resonance** that can be populated in the deeper layers of the target.



beam

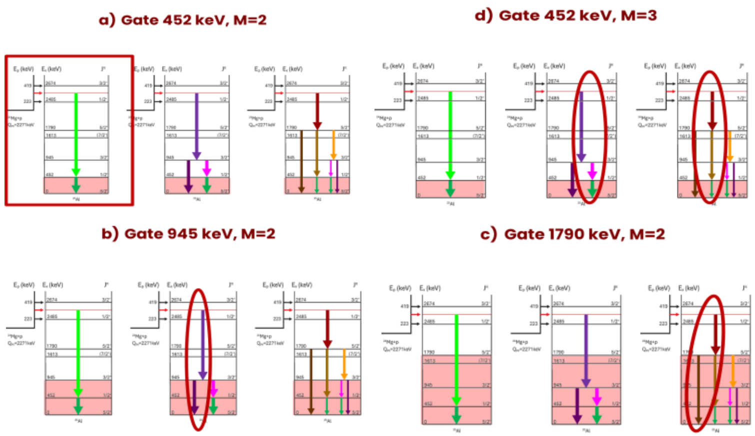
@ 330 keV

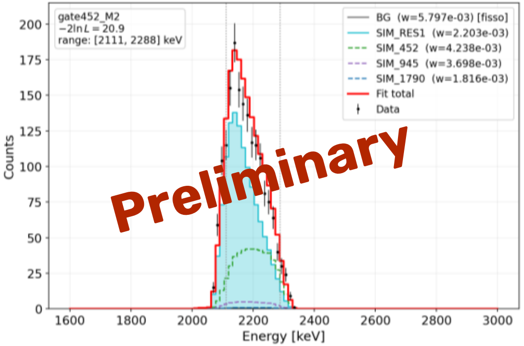
TARGET

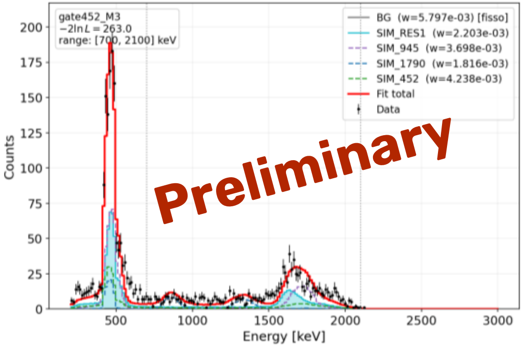
NOTE: proton energy decreases going to the right

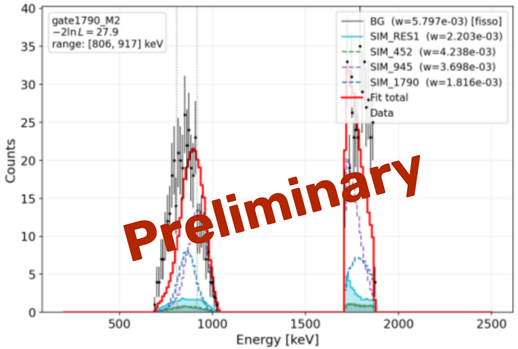
Example: Run @ 396 keV

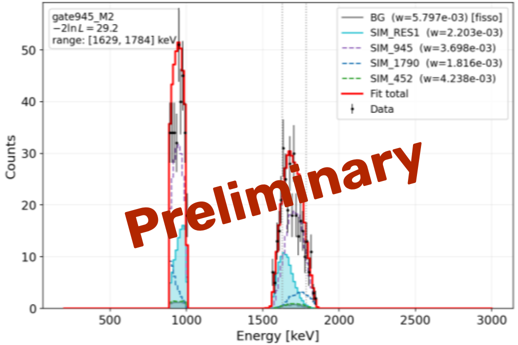
Separate simulations for each possible cascade, including the **contribution of the resonance** that can be populated in the deeper layers of the target.





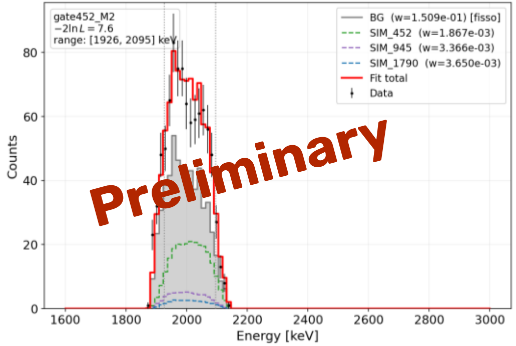


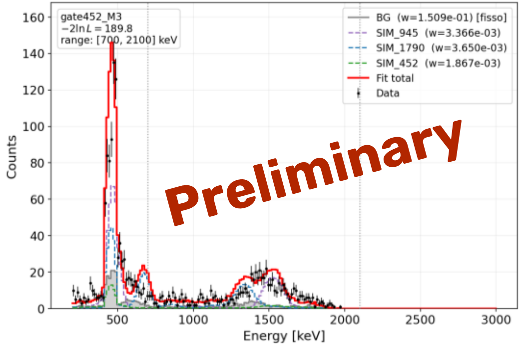




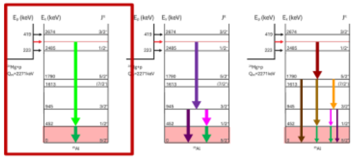
Example: Run @ 200 keV

Separate simulations for each possible cascade, including the **contribution of the resonance** that can be populated in the deeper layers of the target.

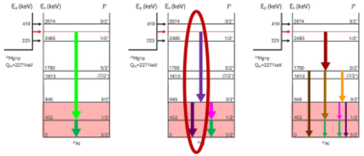




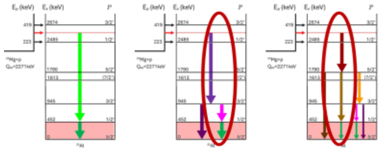
a) Gate 452 keV, M=2

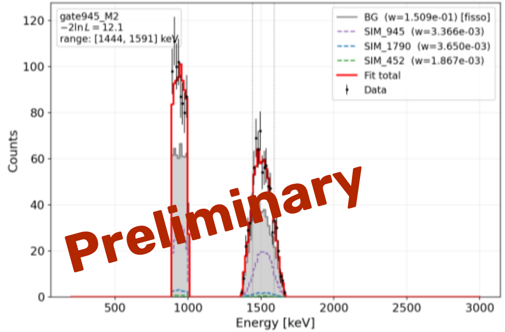


b) Gate 945 keV, M=2



d) Gate 452 keV, M=3

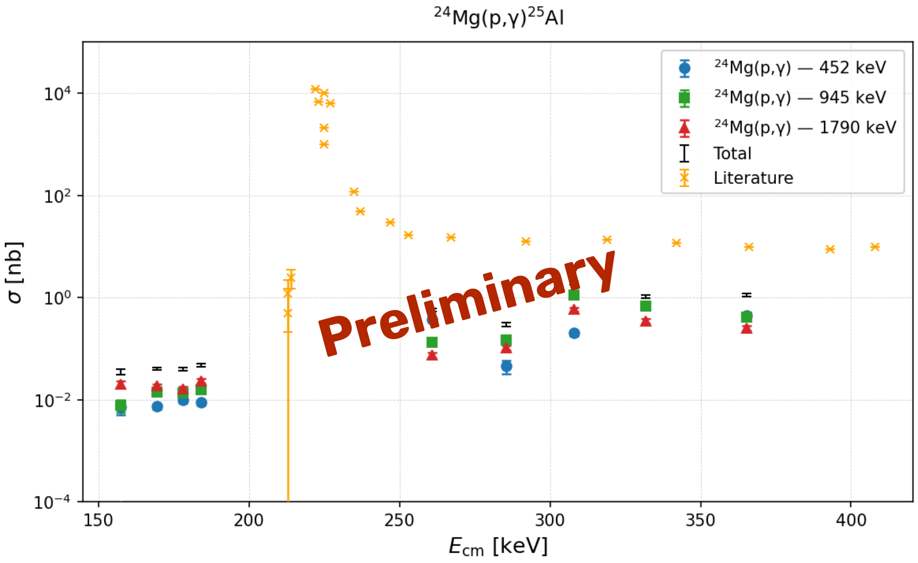




Cross section evaluation

The cross section σ(E) was obtained by inverting this integral relation, using the fit results and accounting for the beam energy loss and target thickness.

$$Y(E_{eff}) = \int_{E_p-\Delta E}^{E_p} \frac{\sigma(E)}{\varepsilon(E)}\, dE$$



Conclusion

This work represents a significant step forward in the experimental study of the $^{24}Mg(p,\gamma)^{25}Al$ reaction at astrophysical energies.
Thanks to the unique low–background environment of the underground ***LUNA facility*** *at Gran Sasso, and the high stability of the LUNA-400 accelerator, it is possible to have:*

-First-ever direct measurements below the resonance

-Better understanding of target effects above the resonance (276–396 keV)

-Lower uncertainty in the determination of the low-energy resonance

Outlooks:

-Global R-matrix analysis for a refined reaction rate

Thank you for your attention

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