Towards a $^{14}N(p,\gamma)^{15}O$ reaction measurement in the framework of the LUNA-MV project

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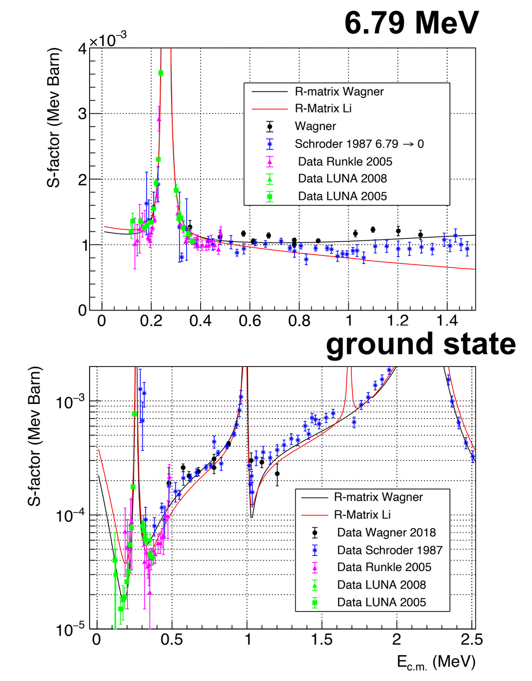
The $^{14}N(p,\gamma)^{15}O$ reaction: State of the art

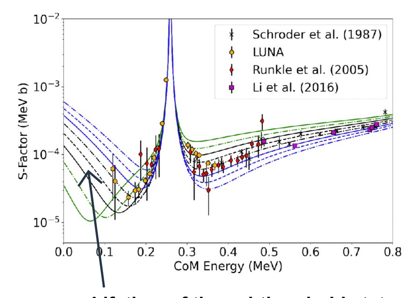
- The $^{14}N(p,\gamma)^{15}O$ reaction is **part of the CNO cycle** for hydrogen burning in stars, is the **slowest reaction** of the cycle and control its speed and the rate of energy generation of the process.
- Determines the **lifetime of massive stars** and the turning point for lower mass main-sequence stars. In the Sun ~1% of energy is produced through CNO, contributing also to **CNO solar neutrino flux**. → First detection made by BOREXINO [8].
- The uncertainty in the energy extrapolation of the S-factor of $^{14}N(p,\gamma)^{15}O$ dominates also the uncertainties in predicted CNO neutrino rates [1].
- This reaction has been extensively studied by the LUNA collaboration and other groups **down to 70 keV**, still far from the solar Gamow window at E_p=27 keV. Low energy reaction rate data relies on **extrapolations done with R-matrix analysis**. It was argued that **including higher-energy data in the fit** can lead to substantial difference in the results [6].
- **Main transitions** contributing to the total S-factor at low energies are the one to the **ground state**, that plays an important role because of a subthreshold resonance at E_R = -0.505 MeV, and the corresponding transition to **E_x = 6.79 MeV** of ^{15}O.

S-factor for the capture to the ground state and 6.79 MeV excited states of ^{15}O

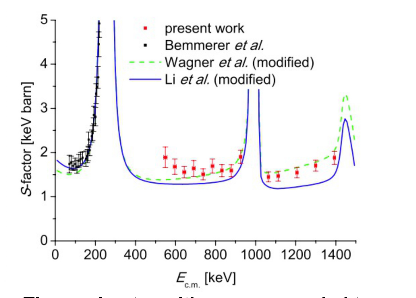


Recent results:

- Notre Dame, Li *et al.* (2016): **E_p = 0.7-3.6 MeV**, g.s and 6.79 Mev transitions, **angular distribution**, TiN and implanted targets, R-matrix fit.
- Dresden, Wagner *et al.* (2018): **E_p = 0.4-1.3 MeV**, g.s and 6.79 Mev transitions, TiN targets.
- Notre Dame, Frentz *et al.* (2021): **Lifetime** measurement of the 6.79 MeV excited state of ^{15}O with DSAM
- ATOMKI, Gyurky *et al.* (2022): Total cross section with **activation**, **E_p = 0.5-1.4 MeV**



Lifetime of the subthreshold state known still with high uncertainty



The weaker transitions were needed to high energy total cross section data

Goals of a new measurement at LUNA-MV

- **Differential cross-section measurement**, this is found by [6] to be critical in order to fit the higher energy data.
- Provide high-quality data over a **extensive energy range,** including for **weaker transitions**, in order to bridge the gap between low energy data and higher energy extrapolations.
- Verify the **performance of LUNA-MV** accelerator and characterization of the solid target beam line.

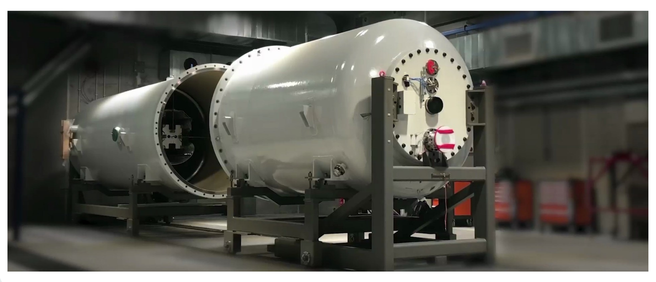
The accelerator system for the LUNA-MV project

- **High current, light ion 3.5 MV accelerator system** developed by High Voltage Engineering to meet the requirements of the LUNA-MV project.
- Ensures **stability below 10^{-5}**, terminal voltage ripple of 1.5×10^{-5} and uninterrupt operation time greater than 24 hours

Ion specie	Beam Intensity (eμA) TV range 0.3 MV–0.5 MV	TV range 0.5–3.5MV
$^{1}H^{+}$	500	1000
$^{4}He^{+}$	300	500
$^{12}C^{+}$	100	150
$^{12}C^{+2}$	60	100

Table 1: Beam intensity on target at different terminal voltage.

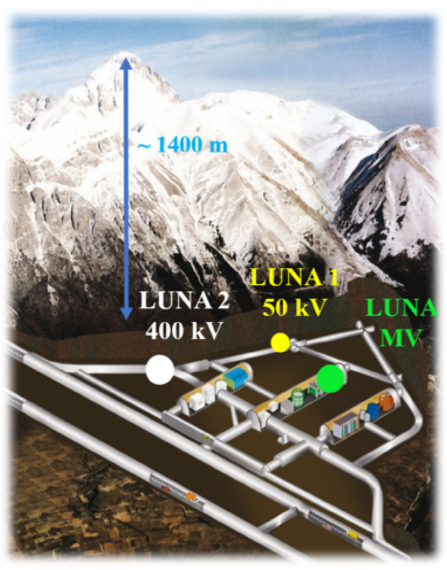
(See A. Sen et al. 2019)

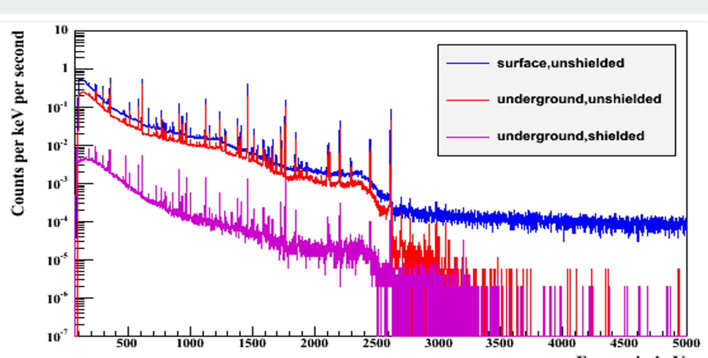


Status of the LUNA-MV facility @ hall B of LNGS

Detectors and environment

- **High-purity germanium detectors** with nominal relative efficiency of 120%.
- **Suppression of the cosmic ray background** by about six orders of magnitude given the experiment location, deep underground, at **Gran Sasso National Laboratories** is crucial, since the reaction has a fairly high Q-value (Q=7.29 MeV) and the transition to the g.s. of ^{15}O is one of the most important.





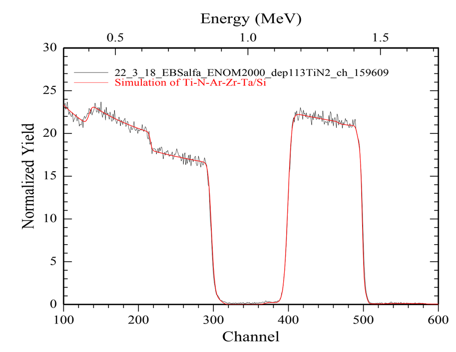
Background suppression:

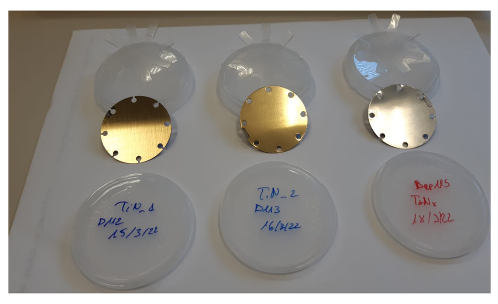
- Muon: 10^{-6}
- Neutrons: 10^{-3}

Solid Targets

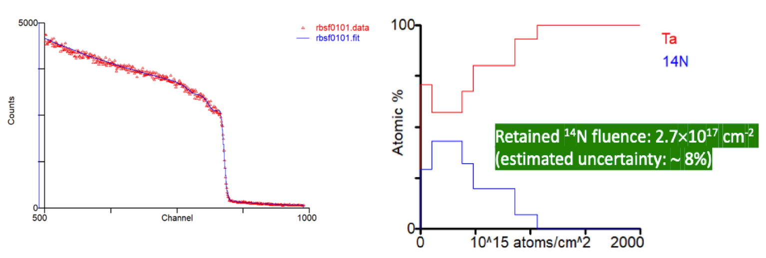
- **Sputtered targets** (**Matteo Campostrini, Valentino Rigato** @ LNL, Italy)
  - Thin films of Ta backings produced using **Reactive Magnetron Sputtering**
  - TiN, already proved to be very stable under beam, or TaN_x → **Higher Z metal** necessary to reduce beam-induced background at higher energies
- **Implanted targets** (**João Cruz** @ IST, Lisbon)
  - Isotopically pure ^{14}N on Tantalum
  - Higher beam energy reachable ($^{15}N(p,\alpha\gamma)$ an issue at higher energies)

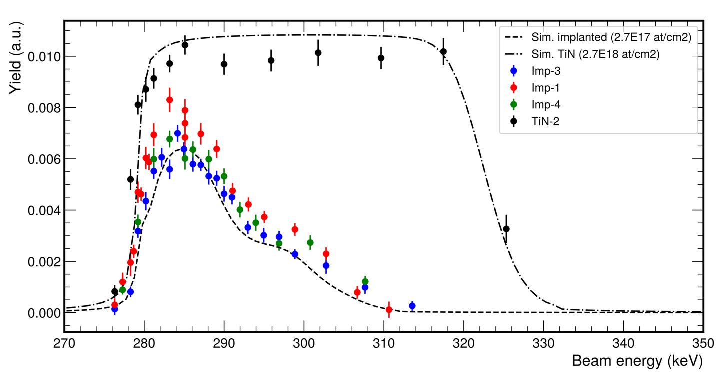
RBS analysis of a TiN film deposited on Si (E=2.0MeV, LNL-AN2000 accelerator)





RBS analysis of ^{14}N implanted target sample →

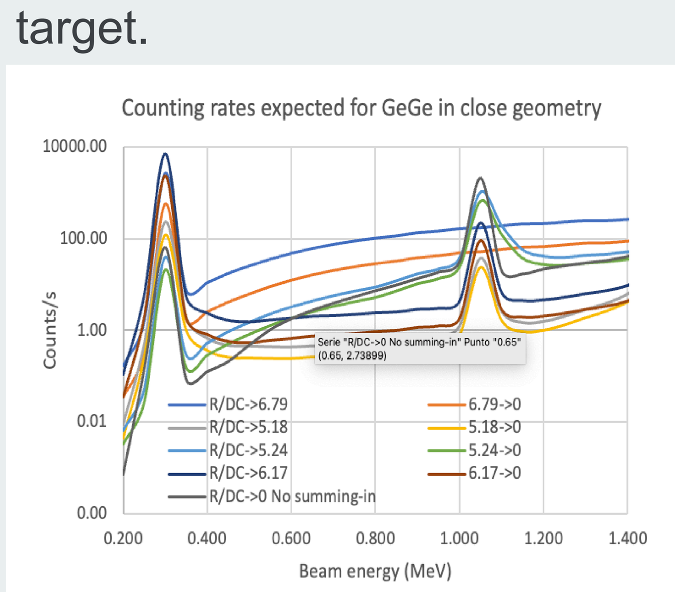


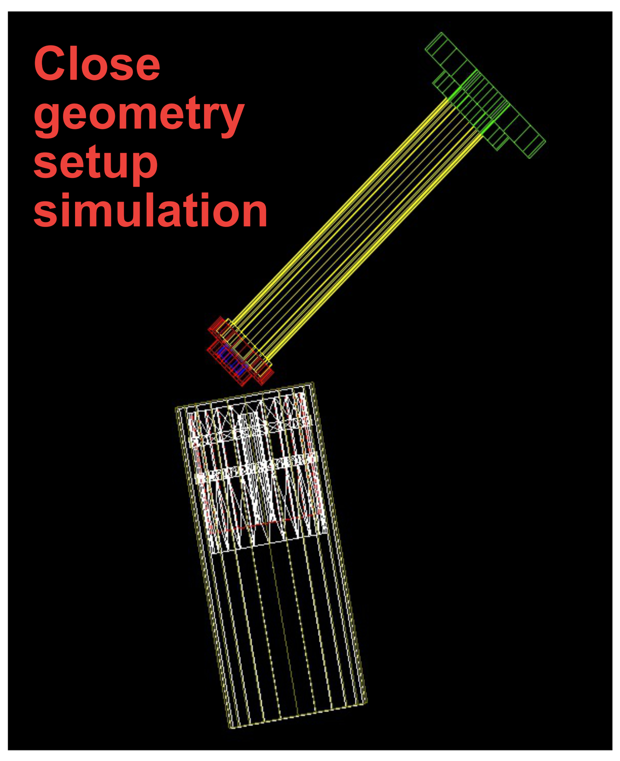


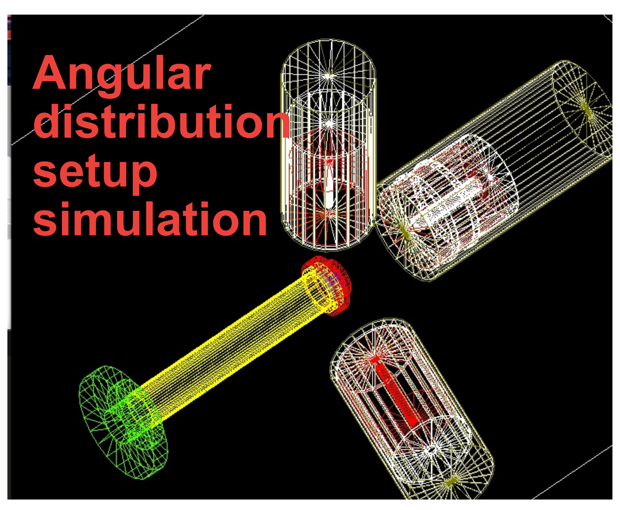
278 keV $^{14}N(p,\gamma)$ resonance scan for 3 implanted targets and the TiN sputtered target performed @ ATOMKI, Tandetron

Setup and preliminary studies

- Excitation function with one HPGe detector in **close geometry** @ 55°
- **Angular distribution** setup: 3 HPGe detectors at 10 cm from the target @ 0°,90°,135°.
- Higher energy reachable with TiN targets: ~1.5 MeV.
- Expected counting rates calculated using typical assumptions of 100 μA beam current and 200 nm thick TiN target.







References

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