GRAN SASSO SCIENCE INSTITUTE

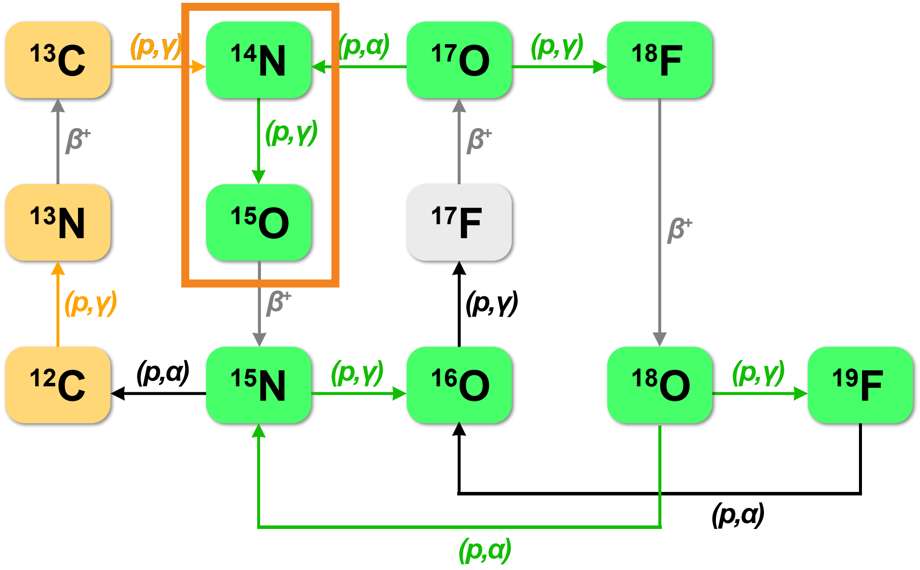
$^{14}N(p,\gamma)^{15}O$ reaction measurement at the LNGS Bellotti Ion Beam Facility

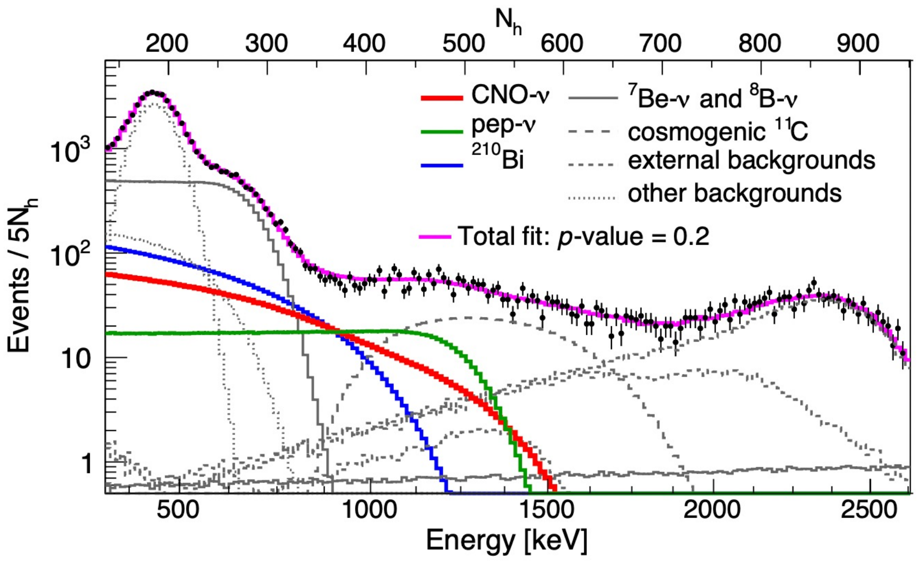
PhD project status report

Alessandro Compagnucci

Astrophysical motivation

- The Borexino collaboration has recently succeded in measuring the **solar CNO neutrino flux** from the β-decay of ^{15}O, providing first direct probe of the solar chemical composition
- The **$^{14}N(p,\gamma)^{15}O$** has been the subject of renewed interest → better extrapolation of its cross section at Solar energies is needed.
- It still remains after the CNO flux itself, the biggest contribution to the uncertainty budget in determining the Solar metallicity

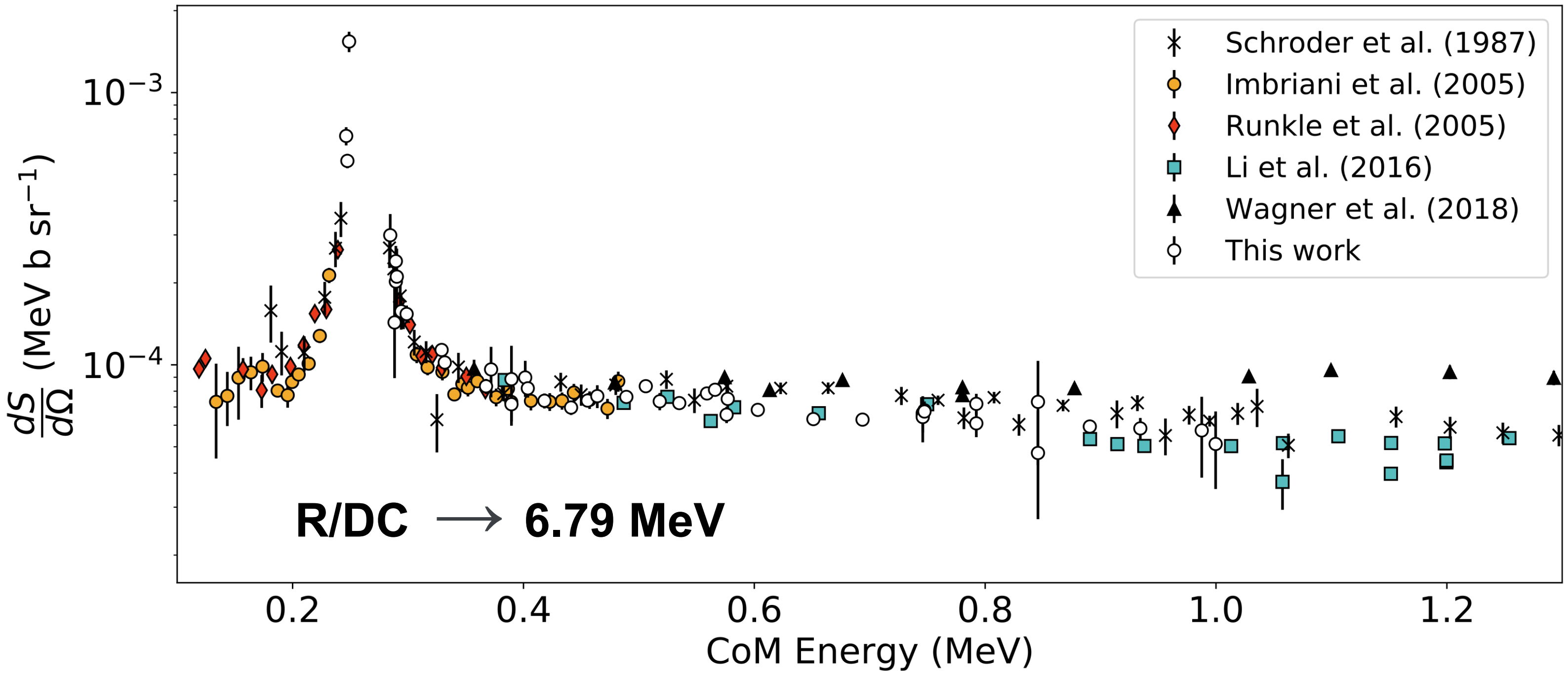




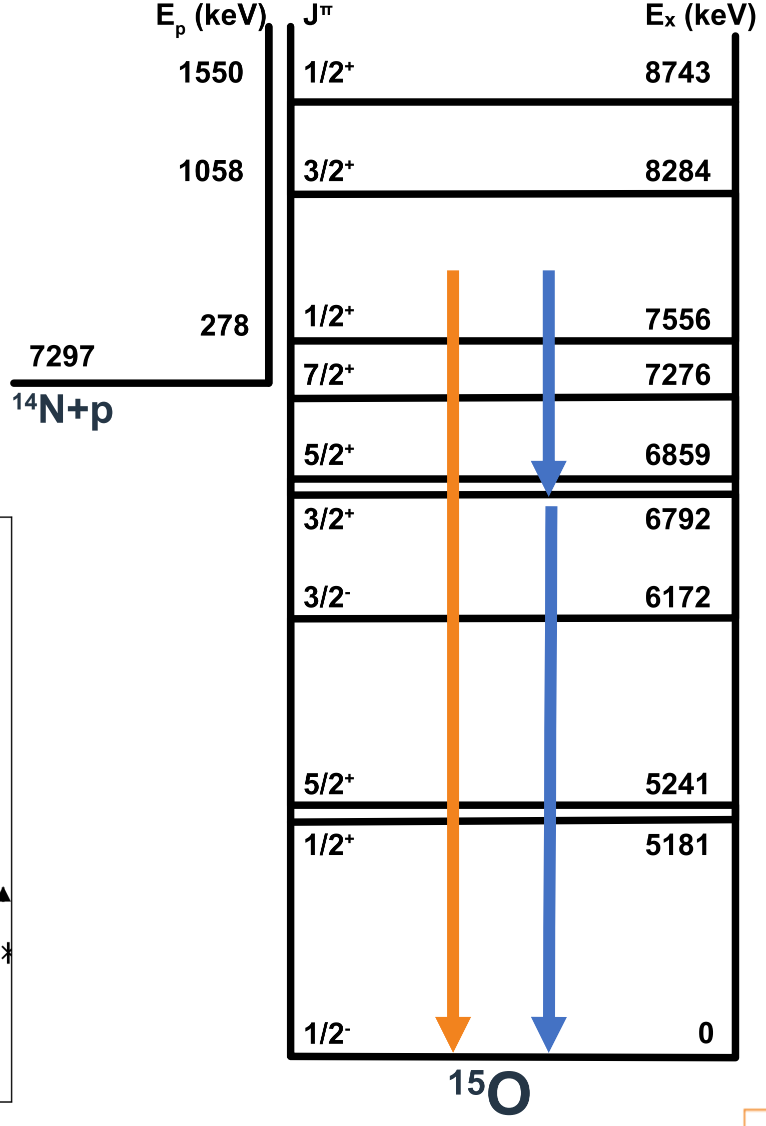
Appel, S. et al. (2022) PRL

Open issues with $^{14}N(p,\gamma)^{15}O$

- The transition to the **6.79 MeV** excited state of ^{15}O and to the **ground state** are fairly well know but effected to problems with their extrapolations at low energies



Frentz et al. (2022)



Level scheme for ^{15}O

GSSI

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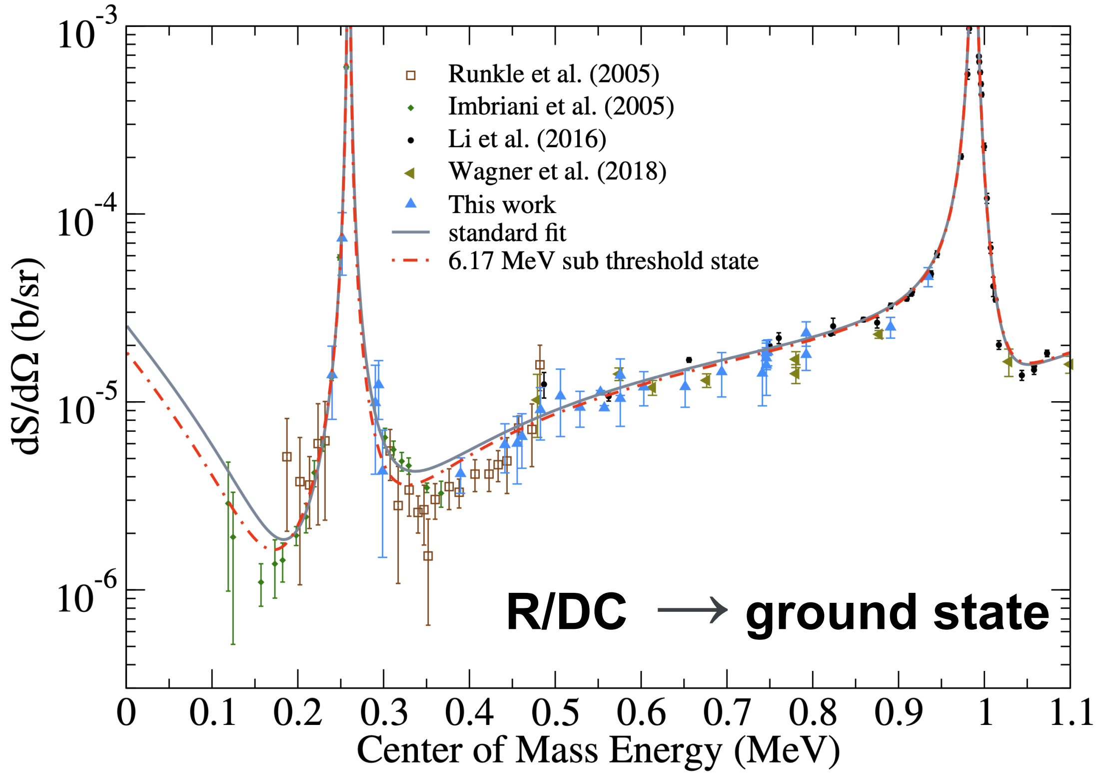

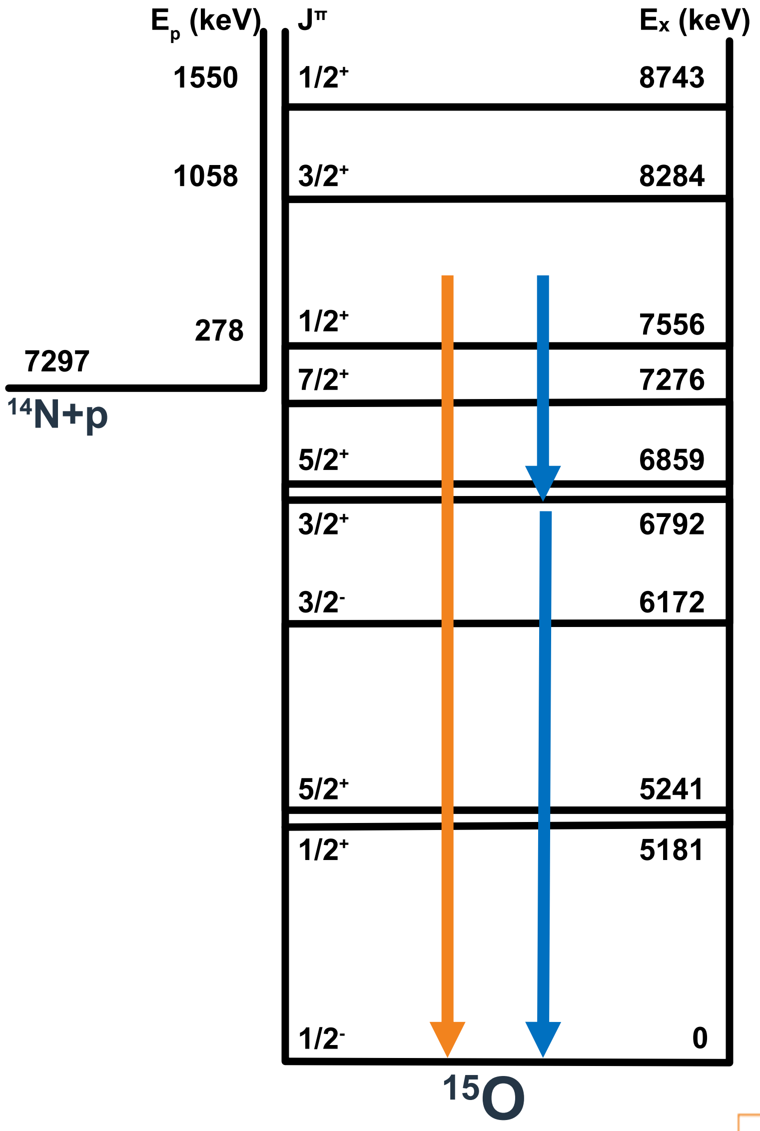

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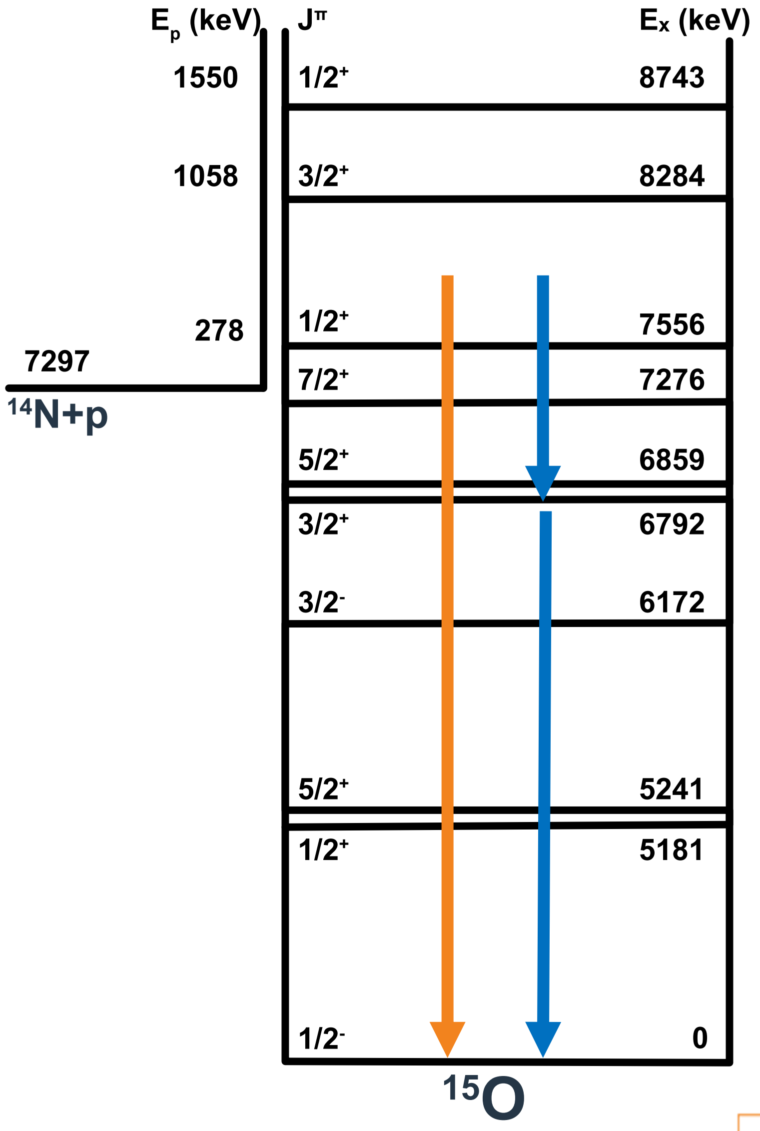
TABLE I. A summary of zero energy S factors for the $^{14}N(p,\gamma)^{15}O$ reaction.

Year	Reference	Astrophysical S factor $S(0)$ (keV b)				
		R/DC → 0.00	R/DC → 6.792	R/DC → 6.172	Others[d]	Total
1987	Schröder *et al.* [9]	1.55 ± 0.34	1.41 ± 0.02	0.14 ± 0.05	0.1	3.20 ± 0.54
2001	Angulo *et al.*[a] [10]	$0.08^{+0.13}_{-0.06}$	1.63 ± 0.17	$0.06^{+0.01}_{-0.02}$	––	1.77 ± 0.20
2003	Mukhamedzhanov *et al.* [16]	0.15 ± 0.07	1.40 ± 0.20	0.133 ± 0.02	0.02	1.70 ± 0.22
2004	Formicola *et al.* [17]	0.25 ± 0.06	1.35 ± 0.05 (stat) ± 0.08 (sys)	$0.06^{+0.01}_{-0.02}$[b]	0.04	1.7 ± 0.1 (stat) ± 0.02 (sys)
2005	Imbriani *et al.* [11]	0.25 ± 0.06	1.21 ± 0.05	0.08 ± 0.03	0.07	1.61 ± 0.08
2005	Runkle *et al.* [15]	0.49 ± 0.08	1.15 ± 0.05	0.04 ± 0.01	––	1.68 ± 0.09
2005	Angulo *et al.* [18]	0.25 ± 0.08	1.35 ± 0.04	0.06 ± 0.02	0.04	1.70 ± 0.07 (stat) ± 0.10 (sys)
2006	Bemmerer *et al.* [13]	––	––	––	––	1.74 ± 0.14 (stat) ± 0.14 (sys)[c]
2008	Marta *et al.* [14]	0.20 ± 0.05	––	0.09 ± 0.07	––	1.57 ± 0.13
2010	Azuma *et al.* [19]	0.28	1.3	0.12	0.11	1.81
2011	Adelberger *et al.* [3]	0.27 ± 0.05	1.18 ± 0.05	0.13 ± 0.06	0.08	1.66 ± 0.08
2016	Li *et al.* [20]	0.42 ± 0.04 (stat) $^{+0.09}_{-0.19}$(sys)	1.29 ± 0.06 (stat) ± 0.06 (sys)	––	––	––
2018	Wagner *et al.* [21]	0.19 ± 0.01 (stat) ± 0.05 (sys)	1.24 ± 0.02 (stat) ± 0.11 (sys)	––	––	––
2022	This work	$0.33^{+0.16}_{-0.08}$	1.24 ± 0.09	0.12 ± 0.04	––	1.69 ± 0.13

[a] R-matrix analysis on available data, not a measurement.
[b] Adopted from Angulo and Descouvement [10].
[c] Measured S factor at 70 keV.

Frentz et al (2022)



Level scheme for ^{15}O

Open issues with $^{14}N(p,\gamma)^{15}O$

- Lack of recent data for the other transitions
  R/DC → 6.17, 5.24, 5.18 …

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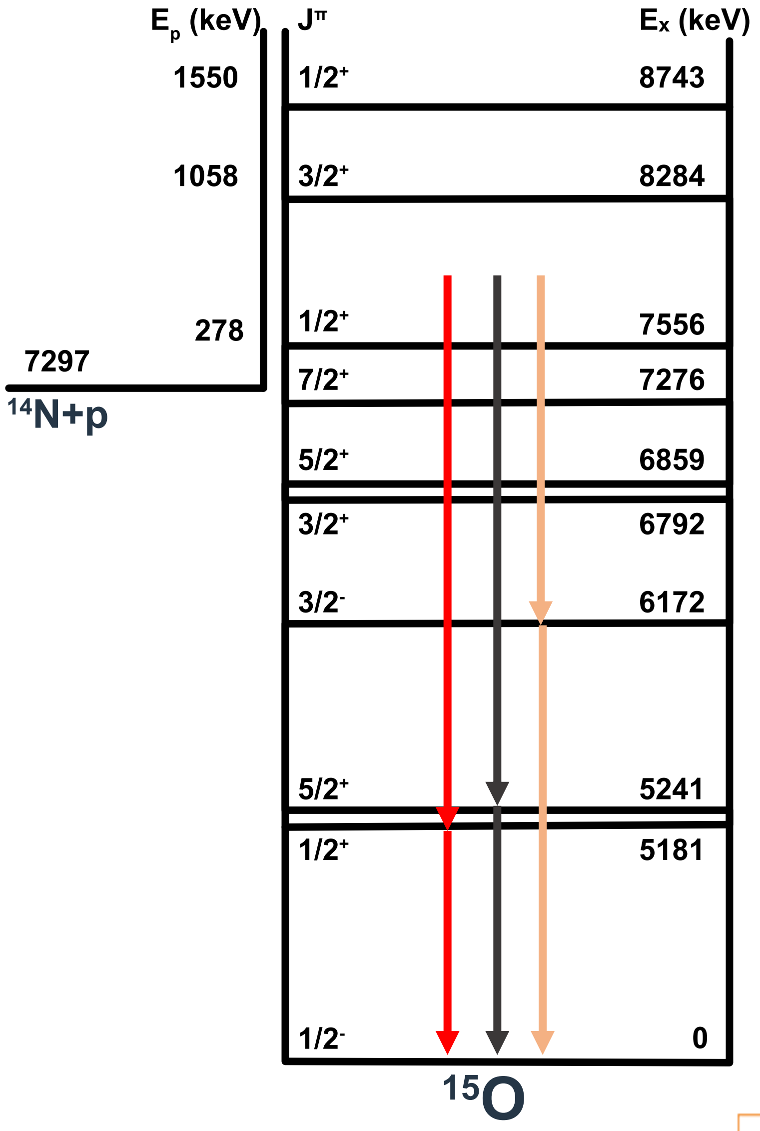
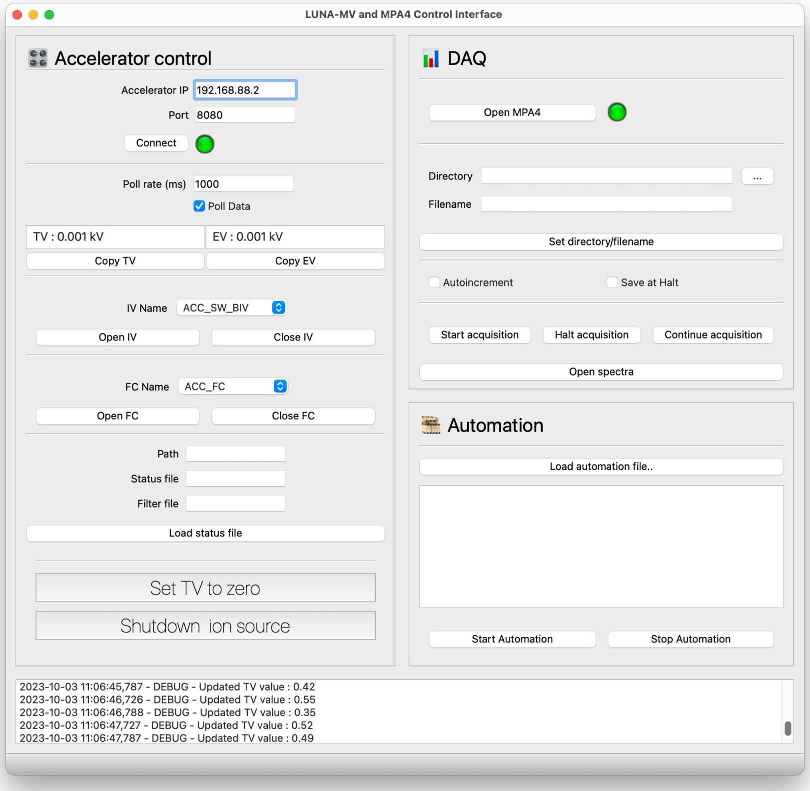


Level scheme for ^{15}O

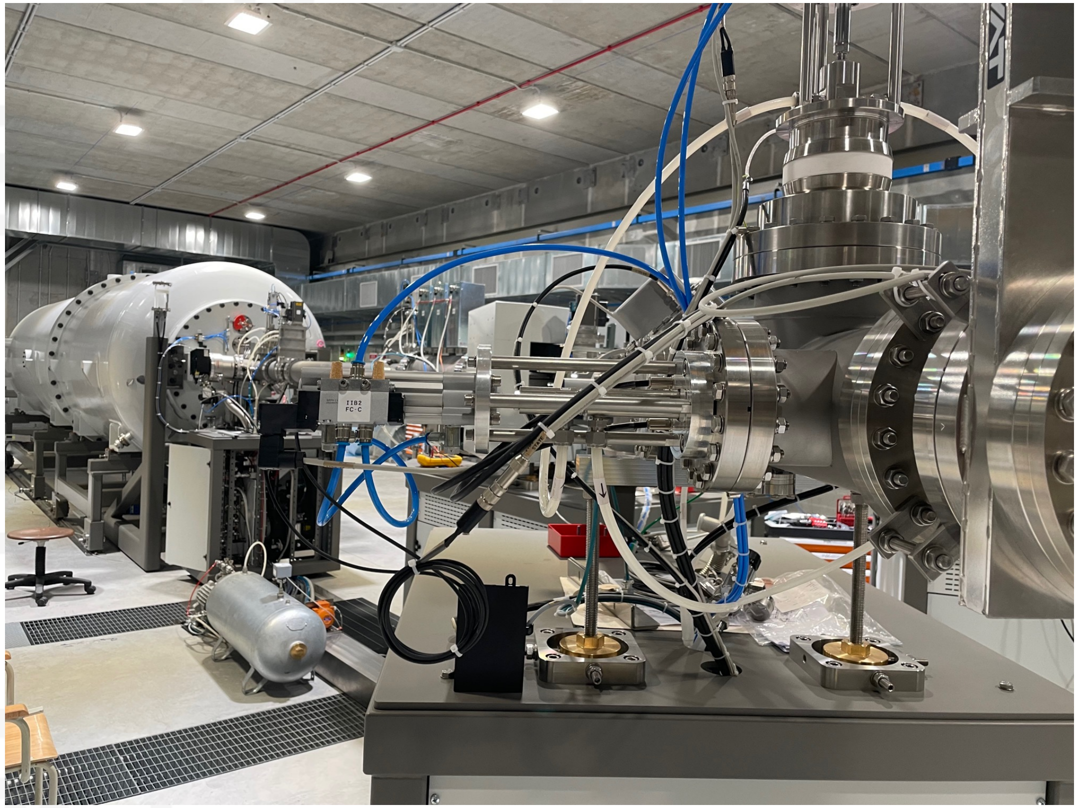
The LNGS Bellotti Ion Beam Facility

- Installation and acceptance of the high current, light ion new 3.5 MV accelerator was completed in **February 2022**



- **My work**: Development of a software interface for communication with the accelerator (Restful API, PyQT)

Goals of my PhD project



- **Differential cross-section measurement** and angular distributions, critical in order to fit the higher energy data.
- Provide high-quality data over a **extensive energy range**, including the often neglected **weaker transitions**, with the aim to bridge the gap between low energy data and the extrapolations for higher energy measurements.
- Assess the performance of 3.5 MV accelerator installed at the new LNGS facility.

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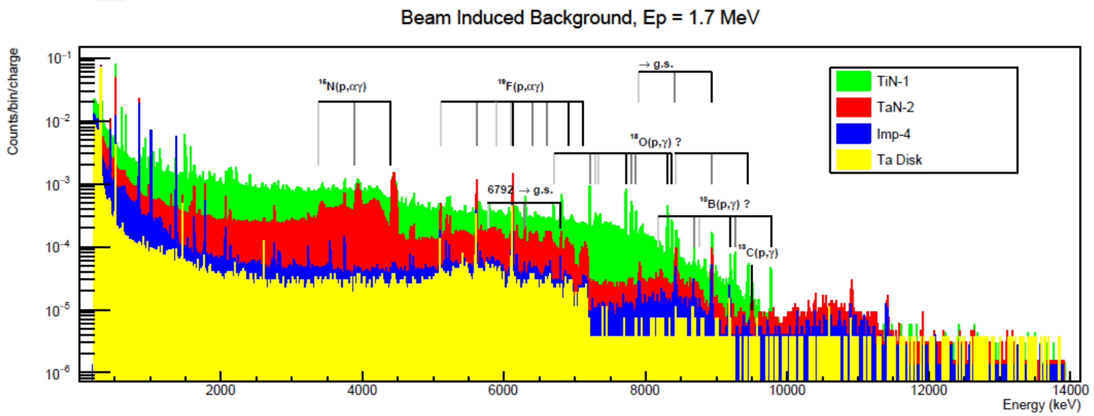
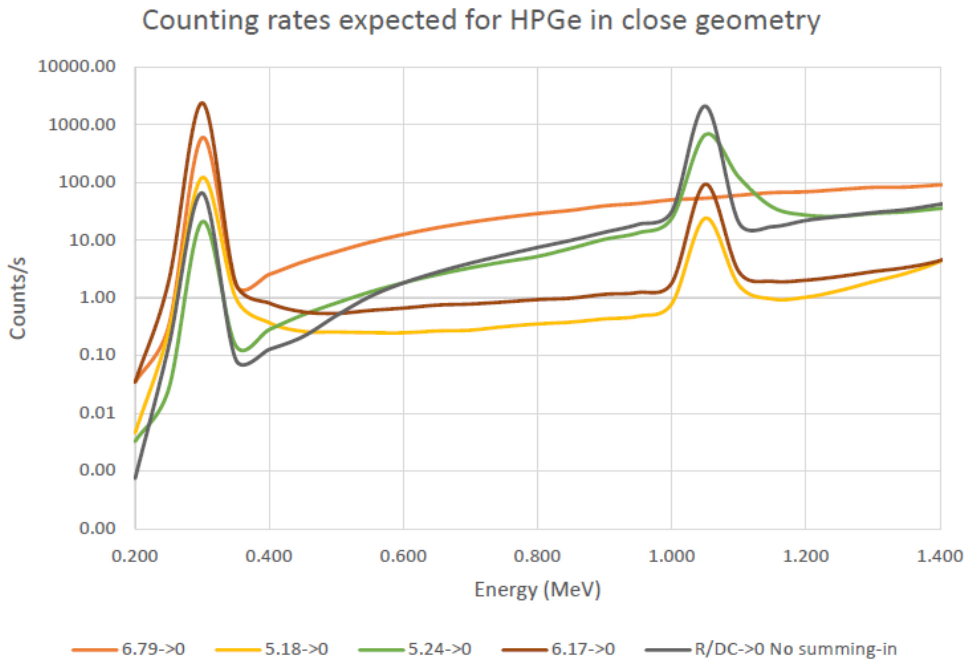
Proposal to the PAC of the Bellotti IBF

- Requested for 7 weeks of beam time was issued to the PAC of the facility
- Assigned with **high priority** for the first available slot given the readiness demonstrated

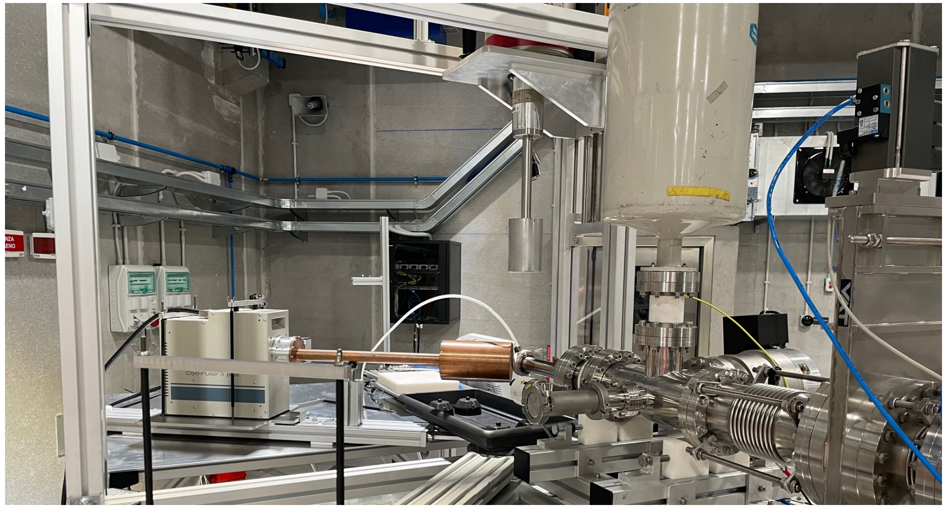


Target characterization performed at Atomki Tandetron in 2022



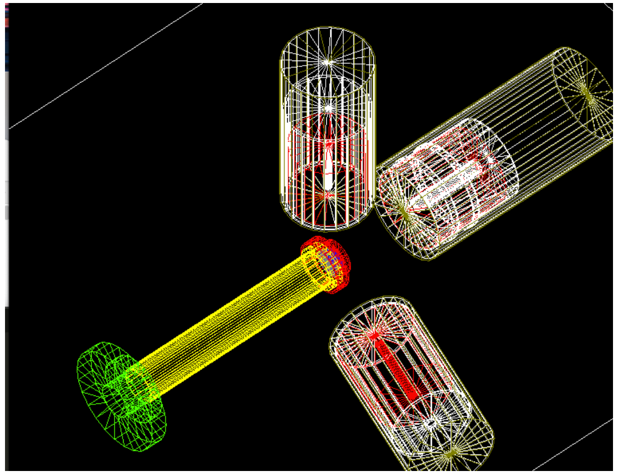
The $^{14}N(p,\gamma)^{15}O$ measurement at the Bellotti IBF

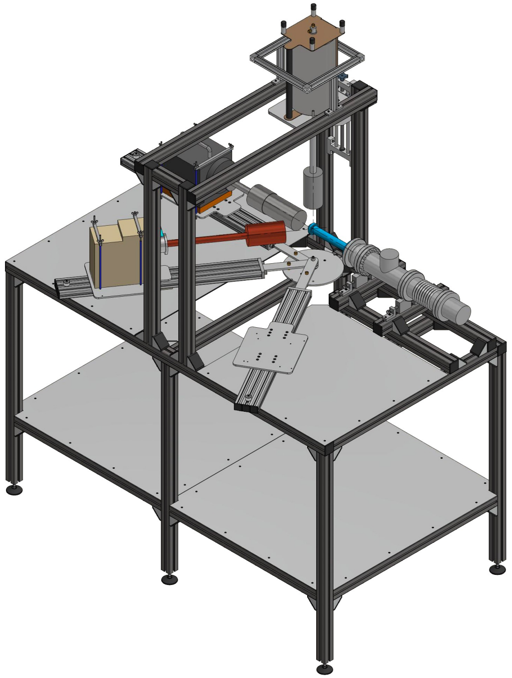
- Two phases:
  - Single HPGe detector in close geometry. Excitation function. (**completed, June-July 2023**)
  - Three HPGe detectors, angular distribution measurement. (**Started in October 2023**).



Setup

- The **support structure** for the beamline and the detectors has been designed and constructed in collaboration with Bari INFN Mechanical Workshop
- Moved to LNGS and installed on the beam line in March 2023.





Setup

LN2 for cold finger

Gate Valve

HPGe detectors

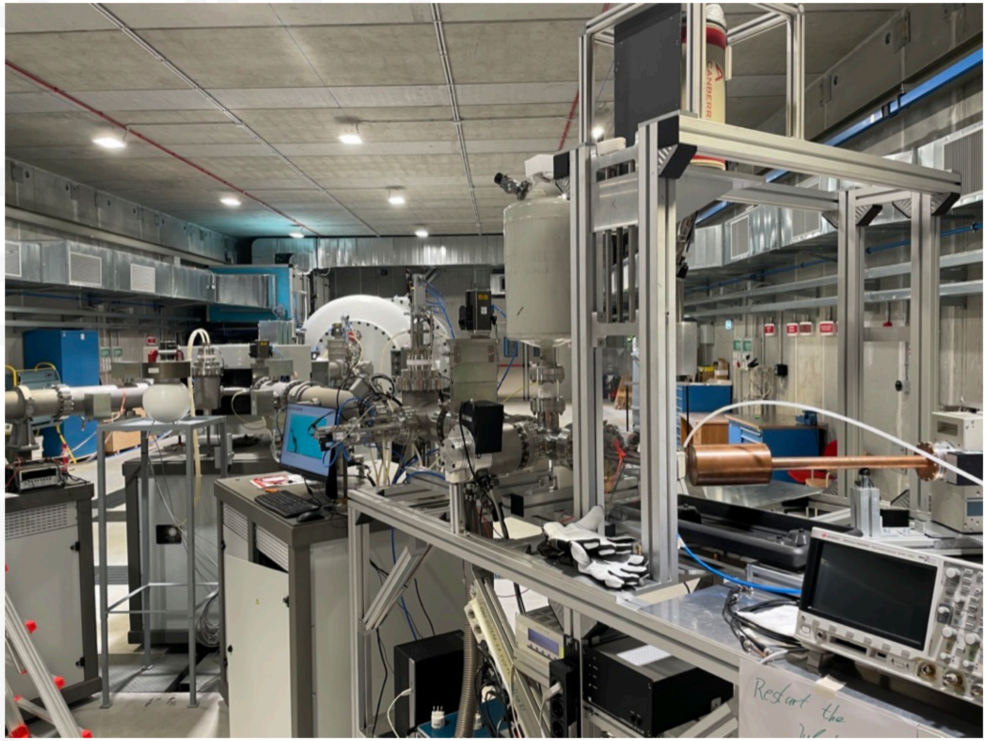
Target chamber

Upstream:

- Faraday cup
- BPM
- Steerer/Wobbler
- Switching Magnet
- …

Start of data taking

- Data taking started on **June 19.**
- **First beam ever** delivered to users of the Bellotti Ion Beam Facility.



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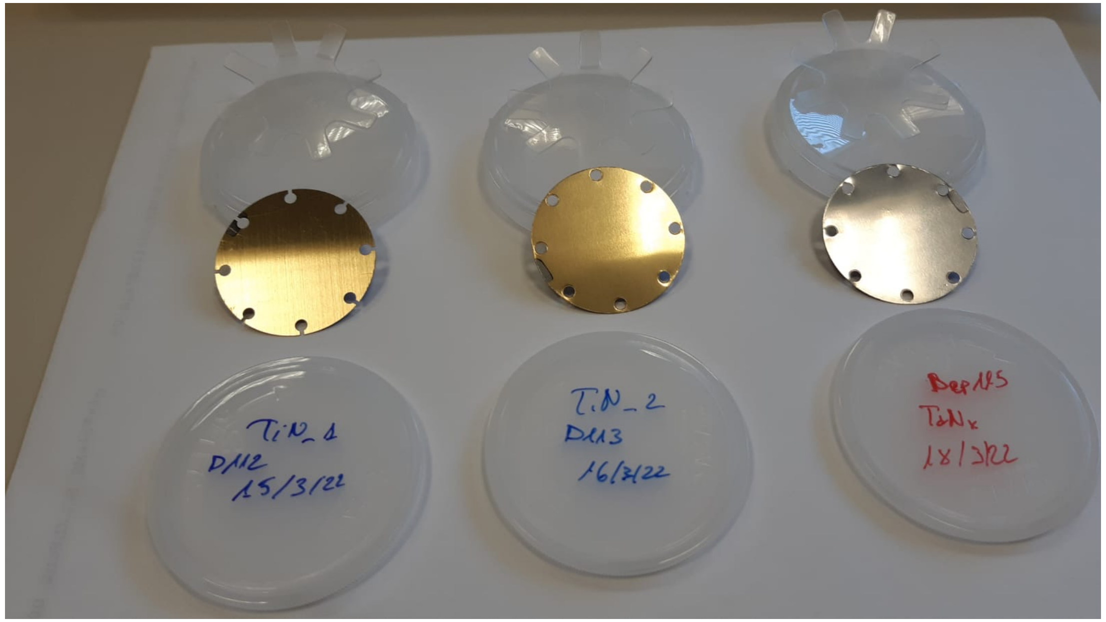
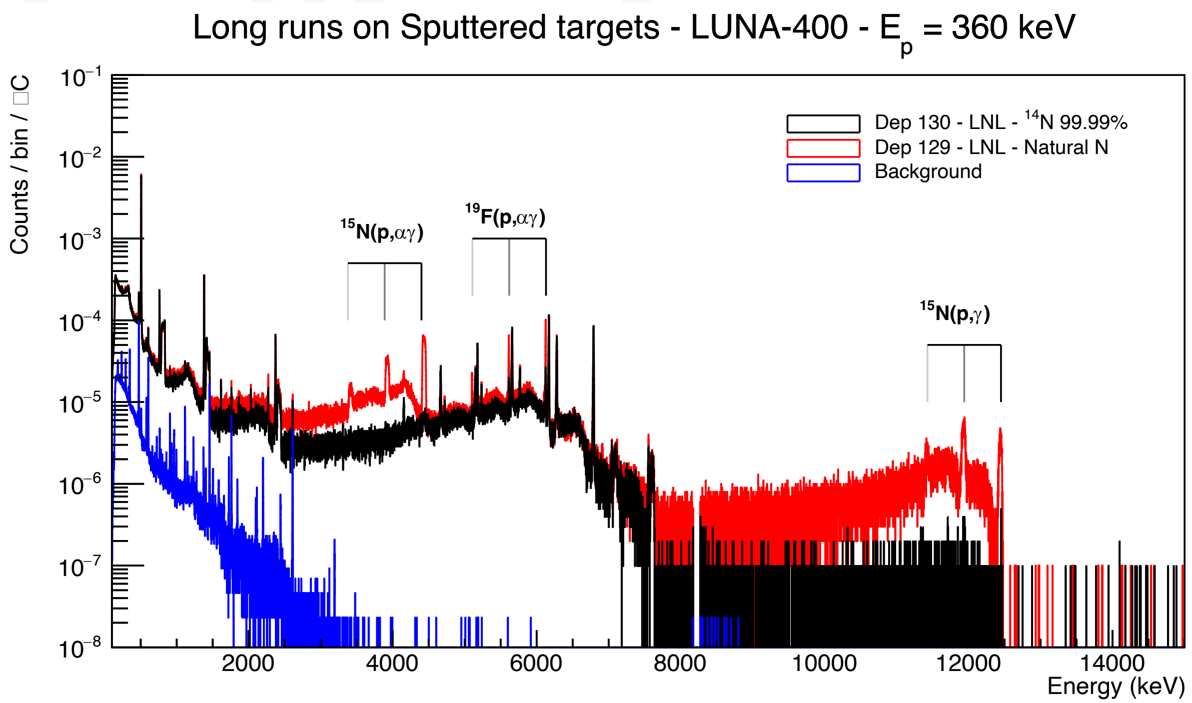
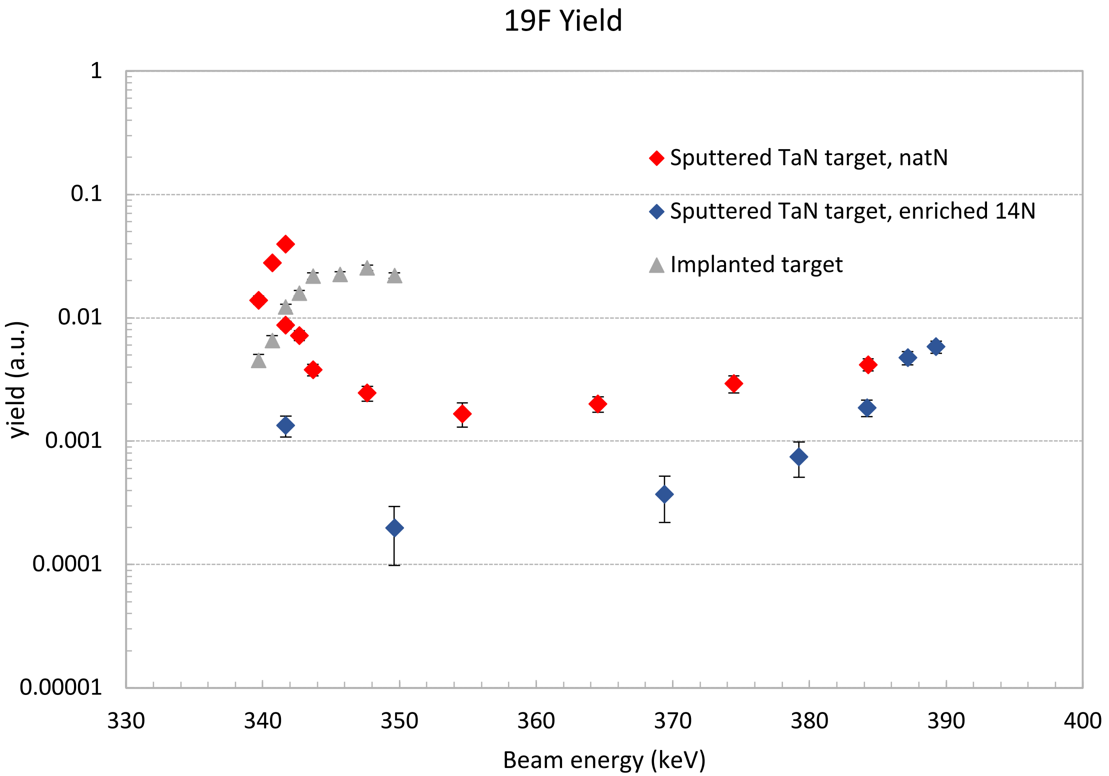
Solid Targets

- **Sputtered TaN targets**: Produced at LNL, Italy by M. Campostrini and V. Rigato. Enriched (99.95%) nitrogen gas. Tested for stability up to 15 C. Characterization via RBS and on-site using 278 keV 14N+p resonance scans.
- **Implanted targets**: Produced at IST, Lisbon by J.Cruz. Tested for stability up to 15 C.



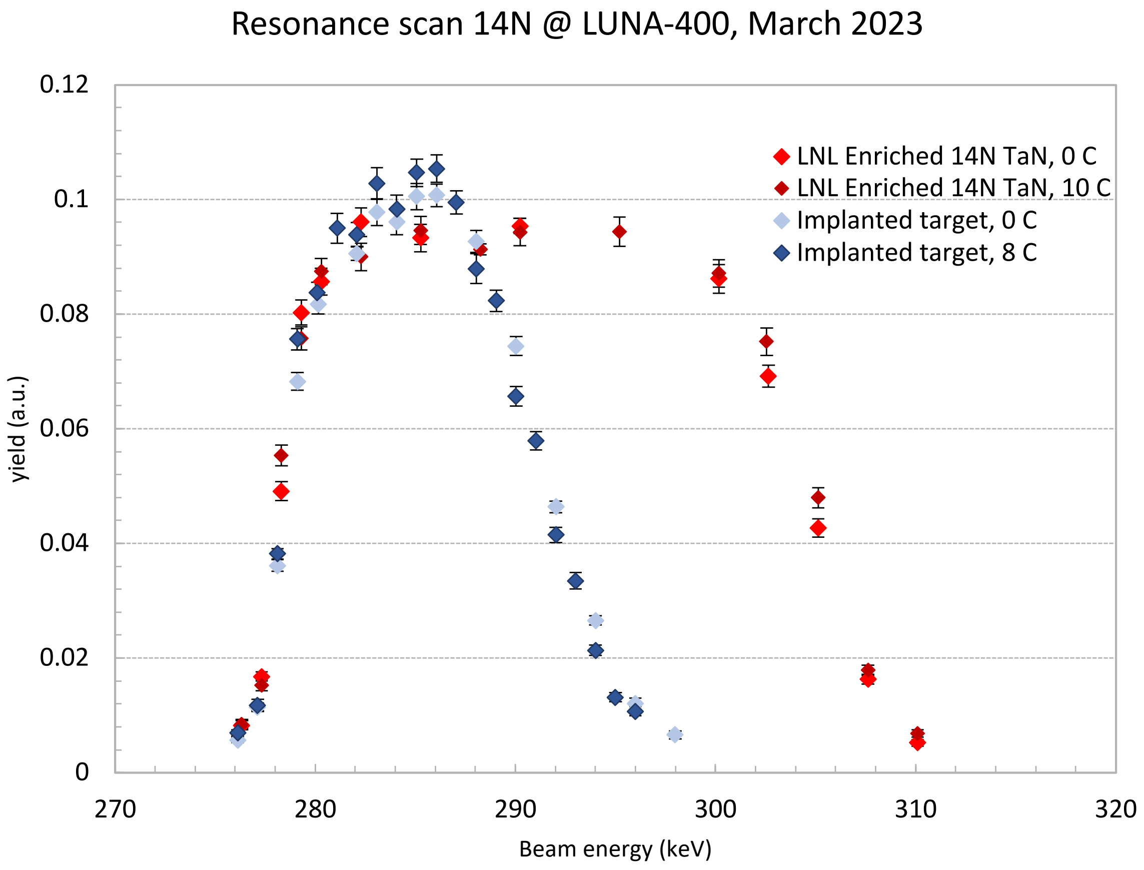
Solid Targets: Characterization of the contaminants



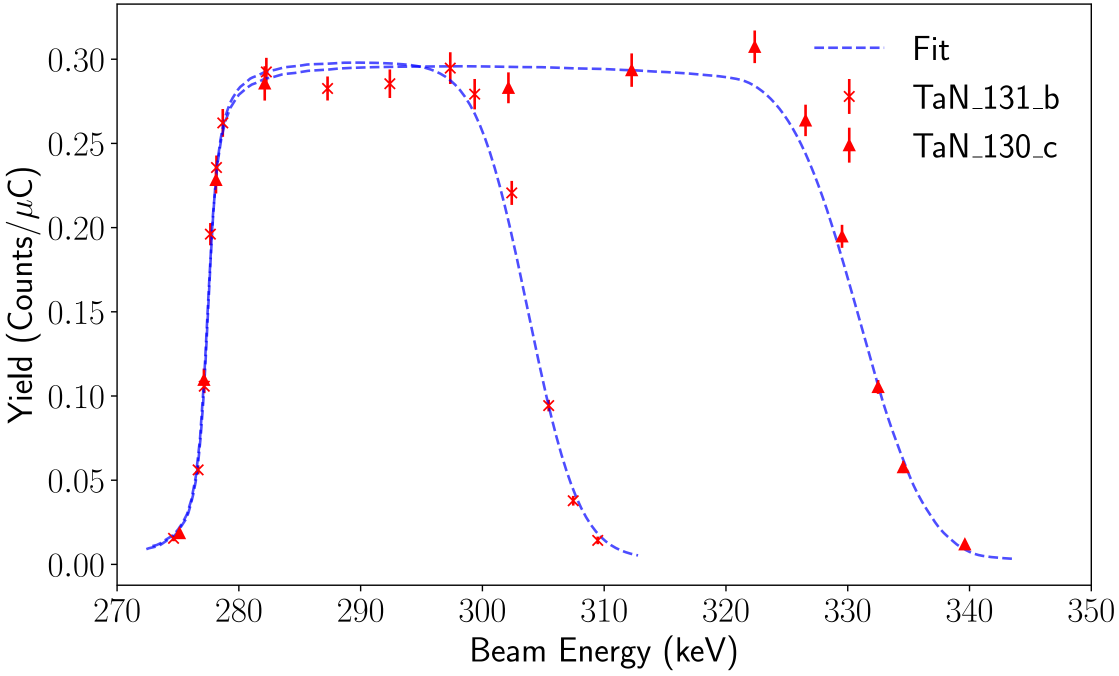


Significantly improved solid targets in terms of ^{15}N and ^{19}F contaminations!

Solid Targets: Stability monitoring



Resonance scan of 278 keV resonance for two TaN sputtered target with different thicknesses @ Bellotti IBF 3.5 MV accelerator



On site during the measurement

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Efficiency characterization for the HPGe detector

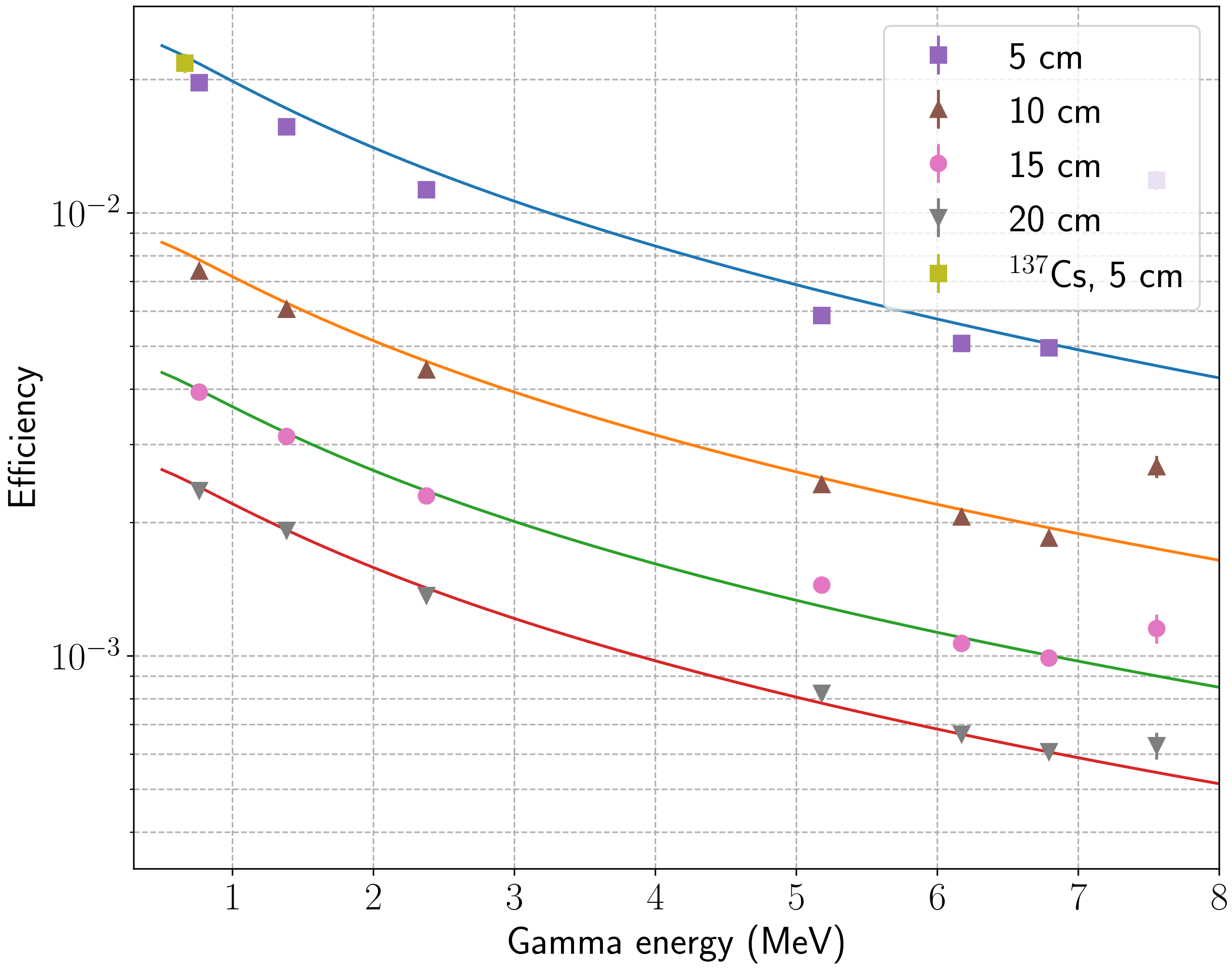
- **Efficiency calibration** using ^{137}Cs, ^{60}Co and ^{14}N+p reaction
- Reaction data have been corrected for summing effects

$$\ln(\varepsilon_{fe}) = a + b\ln(E_\gamma) + c[\ln(E_\gamma)]^2\,,$$

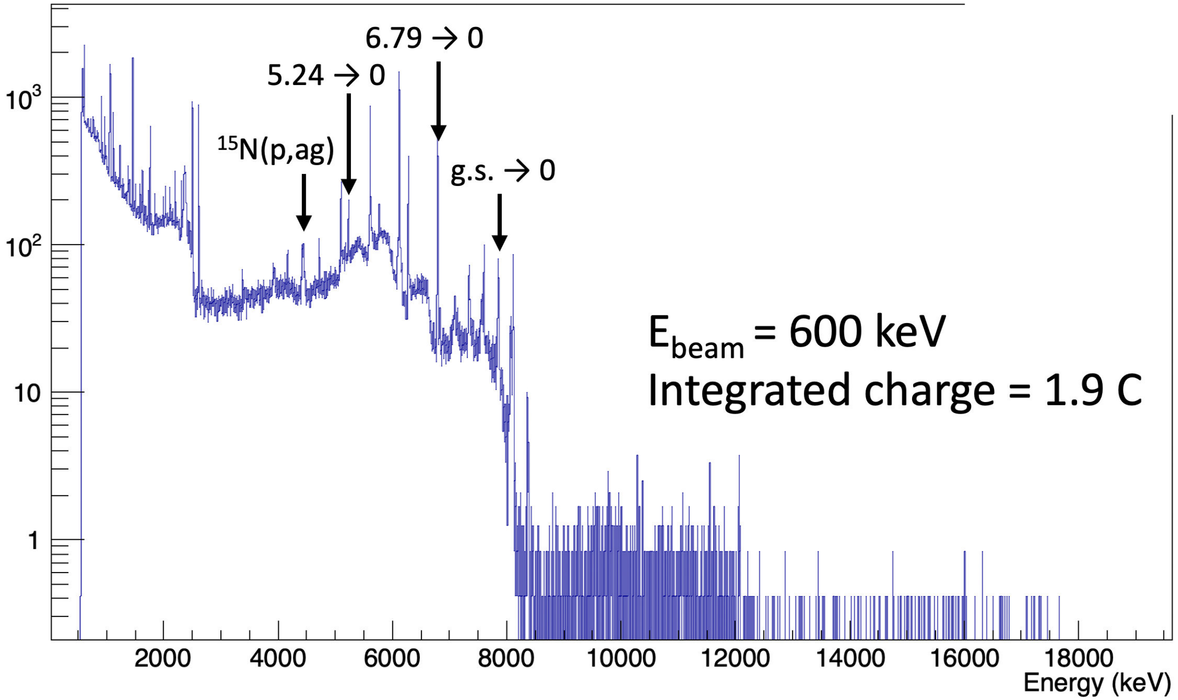
$$\varepsilon_{fe}(d) = \frac{1 - e^{\frac{d+d_0}{1+\beta\sqrt{E_\gamma}}}}{(d+d_0)^2}\,.$$

$$Y_{gs} = R\left(b_{gs}\varepsilon_{fe}(E_{gs}) + \sum_i b_i\varepsilon_{fe}(E_i^{sec})\varepsilon_{fe}(E_i^{pri})\right),$$

$$Y_{i_{pri}} = Rb_i\varepsilon_{fe}(E_{i_{pri}})(1 - \varepsilon_{tot}(E_{i_{sec}}))\,,$$
$$Y_{i_{sec}} = Rb_i\varepsilon_{fe}(E_{i_{sec}})(1 - \varepsilon_{tot}(E_{i_{pri}}))\,,$$



Preliminary results



A typical gamma-ray spectrum.

- Data collected during the first beam time in **June 2023**
- Energy range covered: **0.25 - 1.3 MeV** in 50 keV steps
- one HPGe detector at 55° and 5 cm from the target.
- Three sputtered target and one implanted target
- Total charge collected: 38 C (up to 300 uA of current on target)

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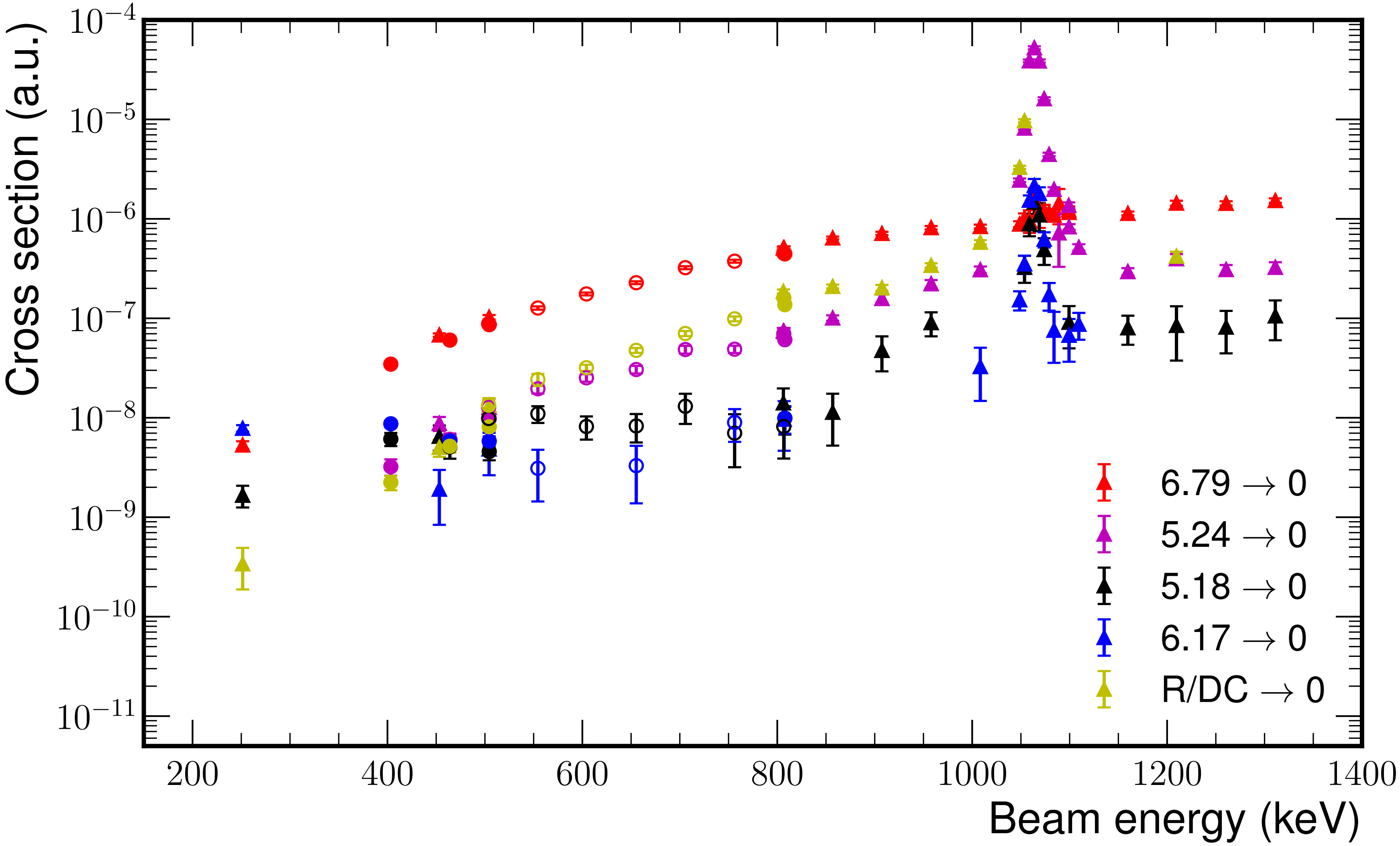
Preliminary results



First ever scientific results from the Bellotti IBF shown at NIC XVII in September 2023 (poster presentation)

Conclusion

- During my second year of activities I followed all the critical activities (e.g. characterization of solid target, setup design ...) that lead to the **first ever scientific measurement** at the new Bellotti IBF.
- A first campaign of measurements for the $^{14}N+p$ (excitation function) was completed in **July 2023.** Preliminary results shown at international conference (NIC XVII).
- I am collaborating with the accelerator service of LNGS for the energy calibration of the machine and its software interface with the users.
- Second beam time (angular distribution measurement) started on **October 9**, additional two weeks of beam time already assigned (early 2024).
- During the next year I expect to finalize the data taking and the analysis, providing an **R-matrix fit** (with international collaborators) and explore the **astrophysical impact** of the results.

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Thank you for your attention!