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The Ongoing Deep Underground Measurement of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ at the Ion Beam Facility of the INFN-LNGS

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Abstract: The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is of major importance in nuclear astrophysics. It is the main neutron source for the weak s-process and as such is responsible for the nucleosynthesis of $60 < A < 90$ elements. In addition, it provides a strong neutron burst during the later, hottest phases of the main s-process, which modifies the final nucleosynthesis products, especially at so-called branch points, which can be used to provide insight into the stellar interior at that time. The reaction rate needs to be known below ca. 900 keV, and due to the low cross-section at these energies, a direct measurement has so far proven to be severely hampered by external neutron background at the surface of the Earth. To solve this problem, a measurement campaign (the ERC-funded SHADES project) was recently started at the deep underground Gran Sasso National Laboratory (LNGS) in Italy. We provide an overview of the experiment status and an outlook into the near future.

Keywords: nuclear astrophysics; deep underground laboratories; s-process; neutron detection



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1. Introduction

$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ is of crucial importance in various astrophysical nucleosynthesis scenarios: as the main neutron source of the weak s-process in massive stars, as a provider of a burst of neutrons in the late stages of the main s-process, and during the production of magnesium isotopes (see [1] and references therein).

The reaction has a negative Q value of -478.3 keV [2], and its cross-section needs to be known as far down in energy as possible to provide the required input for astrophysical calculations. The expected cross-section is in the picobarn range and below, thus proving extremely challenging to measure in the laboratory. Direct attempts basically stopped over twenty years ago, after a measurement that through enormous effort was able to push down the extrinsic background level to about 100 cts/h, but was still unable to measure resonances in the crucial region below a strong resonance at $E_{\alpha} = 832$ keV [3].

Instead, efforts have been focused on indirect measurements of resonance energies, spin-parities, and partial widths in order to calculate the contribution of low-energy states to the cross section. Significant improvements have been made, but many of the results are inconclusive or even contradictory, leading to large uncertainties in the astrophysical reaction rates [4–9].

To approach the problem through a direct measurement, the ERC-funded project “SHADES”¹ constructed a novel neutron detection array consisting of EJ-309 scintillators and ^3He counters, a recirculating gas target and, most importantly, is locating the measurement in the deep-underground Gran Sasso National Laboratories, using the newly commissioned accelerator of the INFN Bellotti Ion Beam Facility (IBF) [10,11]. $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ is also part of the Laboratory for Underground Nuclear Astrophysics (LUNA) [12,13] collaboration scientific program, which plans to conclude the cross-section measurement by 2025. Together with ASFIN [14,15], n-TOF [16,17], ERNA [18–21], and PANDORA [22], LUNA is one of the main contributors to nuclear astrophysics research in Italy.

2.2. Detector Array

As stated above, the detector is a hybrid array consisting of 18 ^3He counters with a steel body and low intrinsic activity [25], and 12 EJ-309 organic scintillators (12×12 cm). They are connected to CAEN V1725 250 Msamples/s 14 bit digitisers and read out in synchronised clock mode in order to allow for coincidences between events. The scintillator has the advantage of a high flashpoint, thus allowing its safe introduction into the sensitive underground environment of the LNGS, while maintaining characteristics close to standard materials like NE213. Its intrinsic background has been characterised as part of the SHADES campaign and consists of the common contaminants in the aluminium body and radon emanation in the scintillator liquid [26]. The full setup is surrounded by a 2-inch-thick 5% borated polyethylene shielding that also acts as support structure for the detectors (for a view of the assembly see Figure 2).

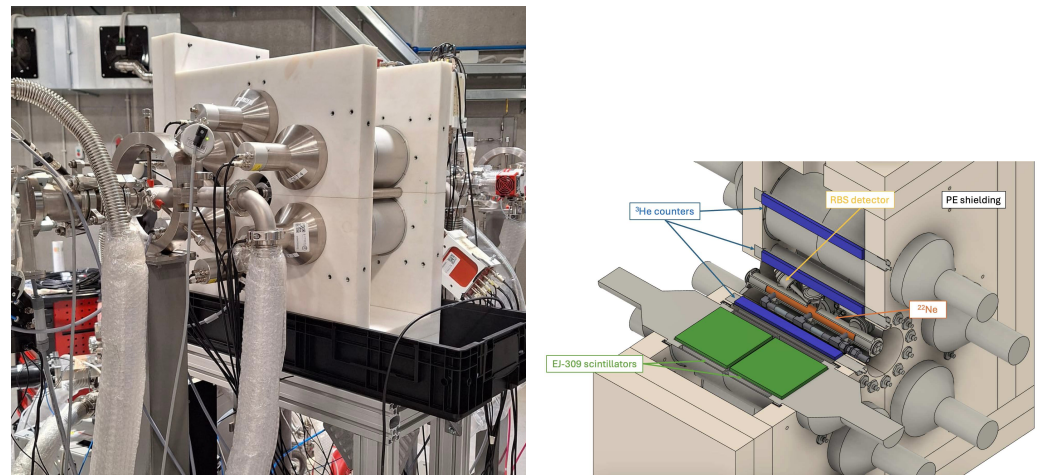


Figure 2. (Left) Partial SHADES detector array mounted around the recirculating gas target in the Bellotti IBF experimental hall. (Right) Schematic drawing of the detector array.

3. Preliminary Results and Status

Preliminary gas target tests show that a good vacuum level can be achieved, as shown from Table 1. At the first pumping stage, which acts as the interface with the beam line, a pressure as low as 10^{-8} mbar can be achieved, which meets the requirements of the Bellotti IBF. An increase of one order of magnitude at each stage is measured, whereas a vacuum better than 10^{-4} mbar is achieved in the reaction chamber, which is at the low end of the measurement range of the employed sensors. This estimate is sufficient, as the ^{22}Ne injection pressure inside the reaction chamber is in the mbar range. Downstream of the gas target, from a lower pressure of about 10^{-6} mbar a value of about 10^{-7} mbar is reached at the latest pumping stage. When the ^{22}Ne gas is injected at the estimated work pressure, i.e., up to 4 mbar, the vacuum level rise remains inside the IBF requirement.

Table 1. Best vacuum and pressure levels of SHADES gas target. The pressure inside the chamber (p_{ch}), in the stages next to it (p_{UP1} and p_{DW1}), in the turbo-molecular stages closer the reaction chamber (p_{UP2} and p_{DW2} , TP2 and TP3 in Figure 1), and in the first pumping stage (p_{UP1} , TP3) are reported.

p_{ch}	p_{UP1}	p_{DW1}	p_{UP2}	p_{DW2}	p_{UP3}	
$<1.0 \times 10^{-4}$	5.8×10^{-6}	6.5×10^{-6}	1.1×10^{-6}	8.5×10^{-7}	8.6×10^{-8}	mbar
1.0	6.8×10^{-2}	6.8×10^{-2}	5.7×10^{-4}	4.8×10^{-4}	7.3×10^{-6}	
2.1	1.3×10^{-1}	1.3×10^{-1}	1.8×10^{-3}	1.9×10^{-3}	1.8×10^{-5}	
3.1	1.6×10^{-1}	1.6×10^{-1}	3.5×10^{-3}	2.7×10^{-3}	2.7×10^{-5}	

The array has been taken into operation underground, and measurements with a neutron source and first alpha beam tests on natural neon were performed, whose data are under analysis. An example 2D Energy vs PSD histogram and coincidence timing between ^3He counter and scintillator signals are shown in Figure 3. In this case, the discrimination parameter is based on the long-vs-short method $\text{PSD} = \frac{I_L - I_S}{I_L}$, where I_L is the integral over the entire pulse and proportional to the energy, and I_S is the integral over the rising part. The coincidence characteristics are currently under investigation.

Some beam-induced background was seen and located to the source from one of the gas target collimators, most likely caused by a straggled beam hitting a contaminated surface. The collimator was replaced and exposed surfaces were coated with gold.

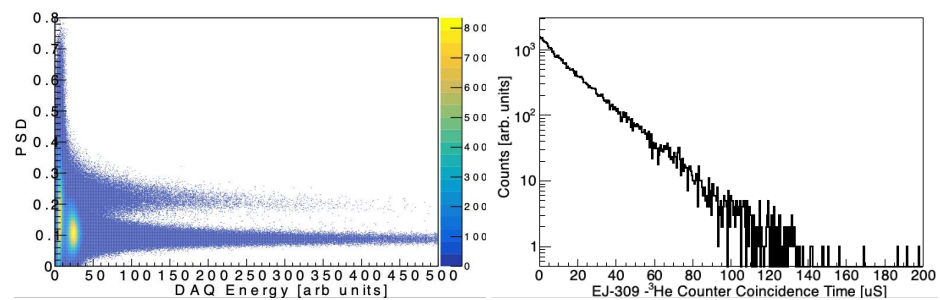


Figure 3. (Left) Example Energy vs. PSD histogram of the EJ-309 scintillators. Neutron signals fall in the PSD region above ca. 1.5, whereas photons lie in the band blue centred around $\text{PSD} = 0.1$. (Right) Coincidence time between neutron events gated on ^3He counter signals.

4. Outlook

After a maintenance shutdown of the MV accelerator, tests for beam-induced background were performed in late summer 2024, with promising preliminary results and a reduction in the background levels below those of Jaeger et al. A first long beam time for low-energy neutron measurements was foreseen for winter/spring 2024/2025. The 832 keV resonance will be repeatedly measured, to extract resonance energy, strength and possibly its width as well as reproducibility standard during the long low energy runs. Promising candidate states in the compound nucleus that have been identified in the indirect measurement campaigns will be focused on in order to improve the upper limits or, for the first time, measure their resonance strength. The underground campaign will conclude with efficiency measurements and a final characterisation of beam-heating effects and a gas target density profile. More efficiency measurements with reactions that are not possible underground are foreseen to take place in 2025, most likely at the ATOMKI laboratory in Debrecen, Hungary.

In conclusion, after more than 20 years, a new direct measurement campaign for the astrophysically important reaction $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ has entered its production phase in the Bellotti IBF at the INFN-LNGS. Over the following year, it is expected that the experiment will drastically improve upper limits or measure low-energy resonance strengths that are crucial for astrophysical calculations in a variety of scenarios.

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Conflicts of Interest: The authors declare no conflicts of interest.

Notes

- ¹ ERC-StG 2019 #852016, “Scintillator-³He Array for Deep-underground Experiments on the S-process”.
- ² The three turbo-molecular pumps employed are Pfeiffer Vacuum HiPace 60.
- ³ The two scroll pumps employed are Pfeiffer Vacuum HiScroll 12.

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