The Study of the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg Reaction at LUNA

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Abstract. The $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg reaction is the competitor of the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction, an effective neutron source for element synthesis through s-process in massive and AGB stars. Currently the ratio between the rates of these two reactions is poorly constrained because of the high uncertainty affecting the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg reaction rate. Indeed a wide range of values for the 395 keV resonance strength ($10^{-15}$ - $10^{-9}$ eV) is reported in literature, all of them from indirect measurements. The present study represents the first direct measurement which was performed at the ultra-low background LUNA laboratory. An high efficiency detector was installed at the gas target beamline of LUNA 400kV accelerator and the 99% enriched in $^{22}$Ne neon gas was irradiated with a 399.9 keV $\alpha$-beam. No significant signal was detected in the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg region of interest, thus an upper limit for the 395 keV resonance strength was estimated. A new campaign was completed in August 2019 with an improved setup and some details are reported here.

1. Astrophysical Motivation

The $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg reaction is mainly involved in two stellar scenarios. First it was recently found that the uncertainty of the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg reaction rate affects the nucleosynthesis of isotopes between $^{26}$Mg and $^{31}$P in intermediate-mass AGB stars [1]. Then it competes with the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction which is an efficient source of neutrons for s-process in low-mass asymptotic giant branch (AGB) stars [2], and in massive stars (initial mass $M_{\odot}$ > 8 $M_{\odot}$) [3].

A key input to model the nucleosynthesis through s-process is the ratio between the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg and the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction rates. Currently this ratio is poorly constrained, see fig. 1, because of the high uncertainty affecting the $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg reaction rate. The main source is the wide range of values proposed for the $E_{\alpha}$ = 395 keV resonance strength, see tab. 1. All the values reported in literature were derived from indirect measurements [4–9]. It is evident that a direct measurement would greatly clarify the role of this resonance.

2. Experimental Setup

The $^{22}$Ne($\alpha$,\,$\gamma$)$^{26}$Mg 395 keV resonance was investigated at Laboratory for Underground Nuclear Astrophysics (LUNA) [10], located under 1400 m of Gran Sasso rock (Italy), which guarantee an unprecedented reduction of the cosmic rays background [11,12].

The current measurement was performed exploiting the gas target beamline combined with an high efficiency detection system [13,14], the same employed for the second campaign on $^{22}$Ne(p,\,$\gamma$)$^{23}$Na reaction [15]. The high intensity He$^+$ beam was delivered through three differential pumping stages to a
Figure 1. The ratio between the $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction rate and the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction rate assuming different reported values for the 395 keV resonance strength, solid lines, with reported uncertainty, dashed lines. The corresponding cross-over temperatures are reported.

Table 1. Values for the strength of $E_{\alpha} = 395$ keV resonance reported in literature.

| Reference                  | Lower Limit [eV] | Recommended $\omega\gamma$ [eV] | Upper Limit [eV] |
|----------------------------|------------------|---------------------------------|------------------|
| Giesen et al. 1993 [4]     | $1.4 \cdot 10^{-14}$ | $1.7 \cdot 10^{-13}$            | $1.6 \cdot 10^{-12}$ |
| Giesen et al. corrected     | -                | $4.7 \cdot 10^{-13}$            | -                |
| NACRE 1999 [5]             | -                | $1.4 \cdot 10^{-13}$            | $1.3 \cdot 10^{-12}$ |
| Iliadis et al. 2010 [6]    | -                | -                               | $3.6 \cdot 10^{-9}$ |
| Longland et al. 2012 [7]   | -                | -                               | $8.7 \cdot 10^{-15}$ |
| STARLIB 2013 [8]           | -                | -                               | $3.6 \cdot 10^{-9}$ |
| Lotay et al. 2019 [9]      | -                | $8.69 \cdot 10^{-14}$           | -                |

Figure 2. BGO detector with target chamber

devoted windowless scattering chamber, see fig. 2. The neon gas used for the measurement was 99.99% pure and 99.9% enriched in $^{22}\text{Ne}$. The gas target pumping system worked in recirculation mode [13, 14].

The scattering chamber was partially occupied by the calorimeter, see fig. 2, which was used to measure the beam intensity run by run. It consists mainly of two parts: the cold side, kept at $T = (7 \pm 0.1) \degree \text{C}$ by a chiller providing the circulation of a refrigerating liquid, and the hot side kept at the constant temperature of $(70 \pm 0.2)\degree \text{C}$ by eight heating resistors. The beam deposited its energy on the calorimeter and from the difference in the resistors power supply required to
keep the hot side at a constant temperature without, \( W_0 \), and with the beam, \( W_{\text{run}} \), it was possible to evaluate the beam intensity:

\[
I = \frac{W_0 - W_{\text{run}}}{E_\alpha - \Delta E} q, \tag{1}
\]

where \((W_0 - W_{\text{run}})\) is the power provided by the beam, \( W_{\text{beam}} \). \( E_\alpha \) is the energy of the beam entering the scattering chamber. \( \Delta E \) is the beam energy loss inside the target along the path to the calorimeter.

The calibration of the calorimeter was performed comparing the current measured by the calorimeter with the one measured by the scattering chamber and the calorimeter, which works as a Faraday Cup in vacuum. The calibration function was found to be [13,14]:

\[
W_{\text{elec}} = (0.936 \pm 0.002) \cdot W_{\text{calo}} + (-0.67 \pm 0.13) [W]. \tag{2}
\]

The energy loss is a fundamental quantity in beam intensity calculation, see eq. (1), thus a precise knowledge of the gas density along the beam path is required. According to the ideal gas law, the density can be derived directly from the pressure and temperature profiles which were measured with a new scattering chamber, called flute, identical to the one used during the experiment, except for seven additional KF25 flanges welded on its side (in fig. 3 right: positions A-D along the chamber, K1-K3 on the collimator and E-G on the tube before the chamber), which allowed to put in place the baratrons and the Pt 100 for the pressure and temperature measurement, see fig. 3 left, further details are reported in [13,14]. Combining the pressure and the temperature profiles the target density profile was obtained, red points in fig. 3 right. The density profile must be corrected for the beam heating effect, which was derived from previous experimental campaigns at LUNA, see blue points in fig. 3 right. The estimated uncertainty on the density profile is 1.3% [13].

The scattering chamber and the calorimeter were located inside the borehole of the detector, see fig. 2 which consists of six optically independent BGO crystals, 28 cm long and 7 cm thick. The addback spectrum, which contains the sum of the coincident signals in two or more crystals, could be obtained offline. The BGO efficiency was studied during the second campaign of the \(^{22}\text{Ne}(p,\gamma)^{23}\text{Na}\) reaction study combining two methods [14]: an experimental approach and Monte Carlo simulations. Geant3 and Geant4 codes were used to simulate the setup design and to derive the detection efficiency. The codes were tested and validated on a wide range of energies (from 0.5 MeV up to 7.6 MeV) using the efficiency measurements performed with
four pointlike sources (\(^7\)Be, \(^{60}\)Co, \(^{88}\)Y and \(^{137}\)Cs) and exploiting the well known resonance at \(E_p = 278\) keV in the \(^{14}\)N\((p,\gamma)\)\(^{15}\)O reaction [16], see fig.4. Once the codes were validated, the simulation of the \(^{22}\)Ne\((\alpha,\gamma)\)\(^{26}\)Mg was performed assuming the cascade and the branching ratios reported in [17]. The efficiency was found to be \(\sim 40\%\) in the \(^{22}\)Ne\((\alpha,\gamma)\)\(^{26}\)Mg region of interest for the addback mode. The uncertainty to the validation of the simulations has been assumed to be 4\%.

![Figure 4](image_url)

**Figure 4.** Comparison between experimental spectrum, black line, obtained on 278 keV resonance in the \(^{14}\)N\((p,\gamma)\)\(^{15}\)O reaction and simulation, red line.

### 3. Results and Discussion

The measurement time was allocated, following some experimental issues encountered during the measurement, as described in table 2.

The beam induced background was studied delivering the 399.9 keV \(\alpha\)-beam to 0.468 mbar of Ar gas in the target chamber. The pressure was calculated in order to match the same energy loss as in 1 mbar of \(^{22}\)Ne. The argon gas is expected to be not reactive to the ion beam at this energy. This feature allows to identify contaminants in the target chamber which can be source of background for the experiment. Because of some experimental issues and delays the data acquired were insufficient for the purpose, see table 2.

The study of the 395 keV resonance was performed impinging an high intensity \(\alpha\)-beam (\(I > 200\) \(\mu\)A), accelerated up to 399.9 keV, on 1 mbar of enriched \(^{22}\)Ne target gas. The energy of the beam and the pressure of the target gas were chosen in order to have the beam at the resonance energy exactly at the location of the maximum detection efficiency, the middle of the chamber. Because there were no evident peaks in the expected region of interest, see fig. 5, the analysis had to proceed through a precise comparison with the laboratory background in order to understand the origin of the counts in the region of interest.

49 day of background were acquired with the same setup in the same geometry with the beam off. In the current case it was found that the net count in the region of interest was lower than the critical limit which takes into account the statistical uncertainty of the background. Thus no significant signal was detected and a preliminary upper limit for the 395 keV resonance strength was estimated: \(\omega_{\gamma_{ul}} = 1\cdot10^{-10}\) eV [13]. The new value seems to rule out the result reported in [6]. The astrophysical impact of LUNA result is under evaluation.
| $t_m$ | Charge | Target Gas | Target Pressure | $E_\alpha$ | Aim                     |
|-------|--------|------------|-----------------|-----------|-------------------------|
| days  | [C]    | [mbar]     | [keV]           |           |                         |
| 49    | -      | -          | -               | -         | Laboratory background   |
| 0.5   | 13.5   | Ar         | 0.468           | 399.9     | Beam induced background |
| 21.2  | 430    | $^{22}$Ne  | 1               | 399.9     | 395 keV resonance       |

Table 2. Time of measurement ($t_m$) and collected charge for each experiment task.

Figure 5. In red the sum of all the addback spectra acquired to investigate the laboratory background. In blue the same for the study of $^{22}$Ne($\alpha$, $\gamma$)$^{26}$Mg reaction. A zoom of the region of interest (R.O.I) for the 395 keV resonance is also reported.

4. Future Outlooks

Some problems were encountered and identified during the present study data acquisition and analysis. A new campaign of the $^{22}$Ne($\alpha$, $\gamma$)$^{26}$Mg reaction was completed at LUNA in August 2019, for which some solution were designed in order to avoid the problems encountered during the previous experiment. First a 10 cm polyethylene borated shielding was mounted around the BGO detector, see fig. 6 in order to reduce the neutrons induced background at the left side of the region of interest for the $^{22}$Ne($\alpha$, $\gamma$)$^{26}$Mg reaction, see fig. 5. The statistics acquired for the beam induced background investigation was increased in order to be significant. In particular the beam time was allocated as following: $\sim$ 120 C accumulated with Ar and $\sim$ 430 C with $^{22}$Ne, while $\sim$ 40 days were devoted to laboratory background investigation. In addition the beamline was improved with detailed maintenance.

The analysis is ongoing and the expected impact of the new campaign on the previous results is either to measure the resonance or to reduce the upper limit found in the current study by one order of magnitude. This would definitely make the contribution of the 395 keV resonance to the $^{22}$Ne($\alpha$, $\gamma$)$^{26}$Mg reaction rate negligible and it would fix the role of the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction as neutron source for the s-process. In addition, it would better constrain both the AGB star and massive star model parameters and their impact on the chemical evolution of galaxies.

Acknowledgements

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Figure 6. Neutrons shielding around the BGO used in the new campaign on the $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$ reaction

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