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First direct measurement of 395 keV resonance of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction at LUNA

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Summary. — The ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction is the main competitor of the ^{22}Ne$(\alpha,n)^{25}$Mg reaction which is the main source of neutrons for the s-process in low-mass asymptotic giant branch (AGB) and massive stars. The ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate uncertainty is mainly due to the 395 keV resonance which has been studied only indirectly leading to a wide range of possible values for its resonance strength (10^{-14}–10^{-9} eV). In this paper I will describe the direct measurement of the 395 keV resonance of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction at the LUNA facility (Laboratory for Underground Nuclear Astrophysics), located at Gran Sasso National Laboratory. A description of the setup, measurement strategy, and some very preliminary results are presented.

1. – Astrophysical motivation and state of the art

The ^{22}Ne$(\alpha,\gamma)^{26}$Mg and ^{22}Ne$(\alpha,n)^{25}$Mg reactions play an important role in astrophysics due to their significant influence on the neutron flux during the s-process. In particular the ^{22}Ne$(\alpha,n)^{25}$Mg ($Q_{\text{value}} = -478$ keV) reaction is one of the two main neutron sources for the s-process in low-mass asymptotic giant branch (AGB) stars [1] and in massive stars [2]. The role of the ^{22}Ne$(\alpha,n)^{25}$Mg reaction as a neutron source is affected by the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction ($Q_{\text{value}} = 10.6$ MeV). Such reaction can be active during the entire He-burning phase, reducing the amount of the ^{22}Ne before the ^{22}Ne$(\alpha,n)^{25}$Mg reaction is activated. Therefore, to constrain the role of the ^{22}Ne$(\alpha,n)^{25}$Mg reaction in the s-process, the rate for both reactions is required. Moreover, in some recent studies, it has been found that the uncertainties of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate affects also the nucleosynthesis of isotopes between ^{26}Mg and ^{31}P in intermediate-mass AGB stars [3].

The uncertainty for the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate at astrophysical temperatures of interest (0.1 GK $\leq T \leq$ 0.4 GK) is dominated by the 395 keV (corresponding to

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TABLE I. – *Summary of the literature on the* $E_\alpha = 395$ keV *resonance strength.*

Lower limit [eV]	Adopted $\omega\gamma$ [eV]	Upper limit [eV]	Reference
$1.4\ 10^{-14}$	$1.7\ 10^{-13}$	$1.6\ 10^{-12}$	Giesen *et al.* 1993 [4]
–	$4.7\ 10^{-13}$	–	Giesen *et al.* corrected
–	$1.4\ 10^{-13}$	$1.3\ 10^{-12}$	NACRE 1999 [5]
–	–	$3.6\ 10^{-9}$	Iliadis *et al.* 2010 [6]
–	–	$8.7\ 10^{-15}$	Longland *et al.* 2012 [7]
–	–	$3.6\ 10^{-9}$	STARLIB 2013 [8]
–	–	$8.7\ 10^{-14}$	Lotay *et al.* 2019 [9]
–	–	$9.0\ 10^{-14}$	Jayatissa *et al.* 2020 [10]
–	–	$9.0\ 10^{-14}$	Ota *et al.* 2020 [11]
–	–	$8.7\ 10^{-14}$	Adsley *et al.* 2021 [12]

the $E_X = 10949$ keV excited level on the ^{26}Mg) resonance which has been studied only indirectly. All these studies lead to a wide range of reported values for its resonance strength (10^{-14}–10^{-9} eV). To reduce this wide range on the resonance strength and to constrain its role in the $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ reaction rate we have afforded the first direct study of the 395 keV resonance. Table I summarizes the state of the art for the 395 keV resonance and different adopted values for some recent evaluations of the $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ reaction rate.

2. – Experimental setup and data taking

The first direct measurement of 395 keV resonance for the $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ reaction was performed at the LUNA facility (Laboratory for Underground Nuclear Astrophysics), located at Gran Sasso underground laboratories (LNGS). The Gran Sasso rock overburden of about 1400 m (3800 meters of water equivalent) allows the attenuation of the cosmic-ray muon flux by a factor of 10^6 and the neutron component by a factor of 10^3 compared with the surface (of on-Earth) laboratories [13-15]. In the region of interest for the $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ reaction ($E_\gamma = 9998$–11286 keV) the muon flux is negligible and the main component of the background is due to neutrons.

The study of the 395 keV resonance was completed in two different campaigns (summer 2016 and summer 2019). In both campaigns, the high intensity and stable alpha beam (accelerated up to 399.9 keV) coming from the LUNA 400 kV accelerator [16] were delivered to a differentially pumped windowless gas target [17] filled with 1 mbar enriched neon gas (^{22}Ne isotope at 99.99%). The energy of the beam and the pressure of the neon gas were chosen to populate the resonance at the position of the maximum detection efficiency. On the opposite side with respect to the beam direction, the inner part of the target chamber was occupied by the calorimeter which continuously measured the beam intensity. The target chamber together with the calorimeter were designed to be located inside the borehole of a high-efficiency BGO detector, optically divided into six BGO crystals, each covering an angle of 60 degrees, allowing a 4π configuration geometry. All six detector crystals were optically isolated and read out by independent

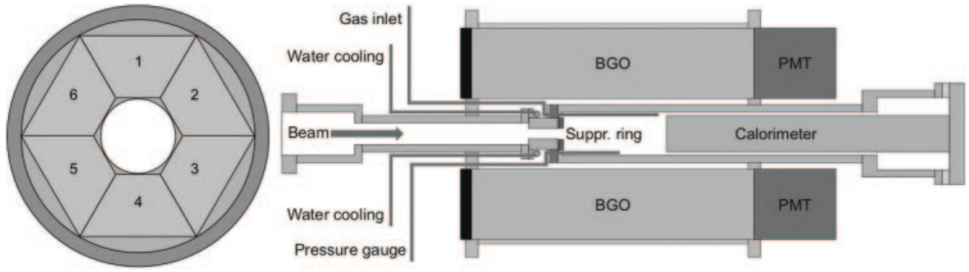

Fig. 1. – Sketch of the experimental setup used at LUNA for the study of the 395 keV resonance with the BGO detector. The main components are labeled. The beam comes from the left, where the target chamber flange is connected to the first pumping stage of the gas target.

acquisition chains. A simple sketch of the experimental setup is given in fig. 1 and a detailed description can be found in [18]. The acquisition of the list mode data was done using the MC^2 Analyzer software by CAEN which allows to acquire and save information event by event. The offline analysis was performed using a software program that was able to process the data after the acquisition and generate two types of spectra: the singles sum spectrum obtained by simply summing the individual histograms by each crystal and the add-back spectrum that sums the energies of all crystals.

The BGO detection efficiency was studied using both Geant3 and Geant4 Monte Carlo simulations combined and validated with experimental efficiency measurements. The low-energy efficiency was studied with several pointlike radioactive sources (^{137}Cs, ^{60}Co and ^{88}Y) placed in different positions along the beam axis inside the target chamber. The efficiency information at higher energies was obtained using the well-known resonance at $E_p = 278$ keV proton energy in the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction. Once validated the Monte Carlo code, a simulation of the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction assuming the branching ratios reported in [7] was performed. The above study determined a $(40 \pm 4)\%$ detection efficiency in the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ region of interest for the addback mode [18, 19].

In general the direct measurement of cross-sections of astrophysical interest at low energies and in particular the direct measurement of the 395 keV requires very low background. Both natural and beam-induced background should be considered. Thanks to the LUNA location, in the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ region of interest, the natural background is completely suppressed. Therefore, particular attention was devoted to the beam-induced background generated when the beam reaches particular contaminants in different parts of the setup. To reduce the amount of contaminants, several cleaning procedures for problematic parts of the setup have been used. Moreover, the beam-induced background was continuously monitored using α beam on inert Ar gas at 0.468 mbar. Such pressure was selected to assure the same energy loss as that of Ne gas at 1 mbar.

3. – Preliminary results

A detailed analysis of the first campaign showed that the net count in the region of interest for the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ reaction was lower than the critical limits which takes into account the statistical uncertainty of the background. Even if no significant signal was detected in the region of interest a preliminary upper limit for the 395 keV resonance strength of $\omega\gamma_{ul} = 1 \cdot 10^{-10}$ eV was estimated [19]. In the second campaign, an additional shielding made of 10 cm borated polyethylene was mounted around the BGO detector to reduce the neutron-induced background by a factor $\sim$4 with respect to the first campaign. Moreover, the accumulated charge in neon and argon was increased. This latter one was enough to determine the absence of beam-induced background in the region of interest. A detailed analysis of the second campaign is ongoing and the preliminary results show sensitivity on the 395 keV resonance strength of one order of magnitude lower with respect to the first campaign.

4. – Conclusions

The ^{22}Ne$(\alpha,n)^{25}$Mg and its competitor ^{22}Ne$(\alpha,\gamma)^{26}$Mg are key reactions for the (weak) s-process in different astrophysical scenarios. To fully understand their role in the observed s-isotopes abundances, a precise knowledge of both reaction rates is needed. At the state of the art, the uncertainty of the ^{22}Ne$(\alpha,\gamma)^{26}$Mg reaction rate is mainly influenced by the 395 keV resonance. To fix its contribution to the total reaction rate, the first direct measurement was performed deep underground at LUNA in two different campaigns using a high-efficiency detection system. The first campaign reached a sensitivity of 10^{-10} eV on the resonance strength [19] which excludes one of the previous upper limits in the literature [6]. This result would be reduced by an order of magnitude with the improvements in the experimental setup. The final results and their astrophysical impact accomplished in the second campaign will soon be published.

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