The study of the $^{20}Ne(p,\gamma)^{21}Na$ reaction at LUNA

Sandra Zavatarelli[1]*and *Eliana* Masha[2] on behalf of the LUNA Collaboration

[1]INFN Sezione di Genova, 16146 Via Dodecaneso 33, Genoa, Italy
[2]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Bautzner Landstraße 400, Dresden Germany

Abstract. The NeNa and MgAl cycles have been the subject of much experimental activity during the last decade because of their relevance to the synthesis of Ne, Na, and Mg isotopes during the H burning in several astrophysical scenarios. Key reactions in these cycles are also believed to be the main agents of the observed anti-correlations in O-Na and Al-Mg abundances exhibited by the stars of Galactic globular clusters. The $^{20}Ne(p,\gamma)^{21}Na$ is the first reaction and the bottleneck of the NeNa cycle: having the slowest reaction rate, it controls the speed of the entire cycle. In order to better constrain the overall astrophysical reaction rate of this important reaction, the LUNA collaboration has started a new experimental effort to study the 366 keV resonance and to improve the knowledge of the cross section at proton energies below 400 keV. This contribution describes the experimental setup and preliminary results.

1 Introduction

Proton captures on ^{20}Ne nuclei could proceed effectively if the temperature reaches T = 0.05 GK [1] (Table 1). They may occur in different stellar scenarios such as red giant stars, asymptotic giant branch stars, novae, and massive stars.

The LUNA collaboration has recently measured the strength and properties of low energies states populated by the $^{22}Ne(p,\gamma)^{23}Na$ and $^{23}Na(p,\gamma)^{24}Mg$ reactions [2-6]. As results of these improved studies, existing uncertainties on the $^{20}Ne(p,\gamma)^{21}Na$ are now the ones that affect the estimated elements production in the NeNa cycle [7, 8] such as ^{22}Na, a stellar γ-ray signature.

In the temperature range between T = 0.1 − 1.0 GK (Fig.1) the rate of the $^{20}Ne(p,\gamma)^{21}Na$ reaction (Q-value = 2431.68 keV) is dominated by the narrow resonance at E_R = 366 keV, corresponding to an excited level at Ex = 2797.5 keV in ^{21}Na and by the direct capture component with contributions from different cascade branching [9]. At lower temperatures the high energy tail of a sub-threshold state at E_R = −6.7 keV, corresponding to the E_x = 2424.9 keV excited level in ^{21}Na, contributes significantly.

The strength of the resonance at 366 keV was measured with a 20% uncertainty by Rolfs and co-workers in 1975 at the California State University Van der Graaf facility [10]: the quoted value is ωγ=0.11±0.02 meV. A second and more recent study (2019) at the Triangle University Laboratory for Nuclear Astrophysics, is reported but still unpublished, in

* Corresponding author: zavatare@ge.infn.it

Cooper's PhD Thesis [11]: the deduced weighted average for the resonance strength, $\omega\gamma$ = (0.0722 ± 0.0068) meV, is 35% lower than the Rolfs *et al* value.
The direct capture process was measured by Rolfs *et al* and by Lyons *et al* (Notre Dame University, 2018) [9] in the energy range between 0.4 and 2 MeV: Fig. 2 summarises the results available in literature for strongest transition, the DC→ 2425 keV.
In general, only poorly precision data exists at $E_{c.m.}$ < 400 keV, making relevant further experimental investigations.

Table 1. Energy and temperature ranges for the $^{20}Ne(p,\gamma)^{21}Ne$ reaction in the relevant astrophysical sites.

Astrophysical site	Initial mass ($M_\odot$)	T [MK]	E_G (keV)
RGB, Low mass AGB	1 - 3	20 - 60	40-85
Interm. and massive AGB	3 - 8	20 - 120	40-135
Novae		200 - 500	190-350

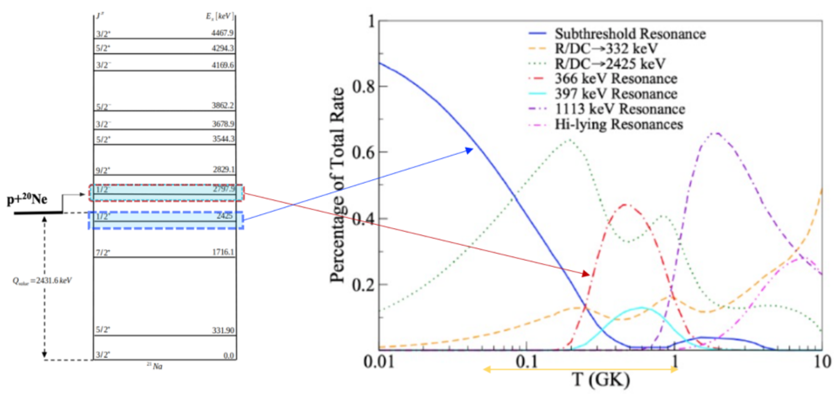

Fig. 1. Dominant contribution to the stellar rates as a function of the temperature [9].

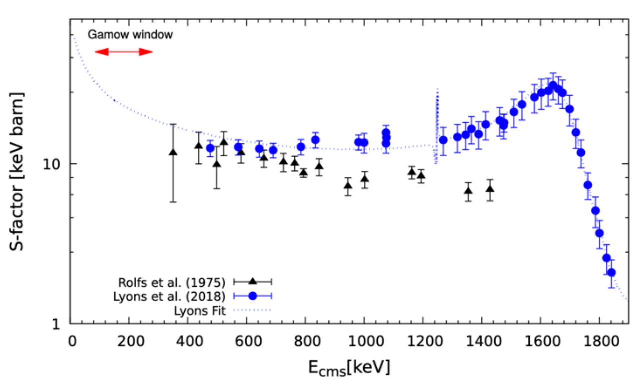

Fig. 2. Literature data for the astrophysical factor of the DC→2425 keV transition [10-11].

2 Experimental setup

The low background environment of the Gran Sasso National Laboratory, about one million times lower than that on Earth's surface, together with the high intensity beams of protons and alpha particles of the LUNA-400 accelerator, guarantees enhanced sensitivity to the cross section studies of stellar fusion processes. Details about the LUNA-400kV accelerator facility can be found in [12].
In the case of the reaction under study, because of the relatively low Q-value (2431.68 keV), most of the expected gamma-ray lines are below 3 MeV, i.e. in a region of the spectrum dominated by ambient radioactivity [13, 14]. At the beam energies achievable at LUNA-400 (E_p = 50 – 400 keV) we expect to observe mainly the transitions to the 2424.9 keV and the 331.9 keV excited states in ^{21}Na, while transitions to the ground state should be much weaker. In order to better reject environmental background, HPGe detectors are the best solution thanks to their very good resolution. In any case, a fully shielded setup should be used to reduce the ambient background. Thus, the same setup already used to successfully study the ^{22}Ne(p,γ)^{23}Na reaction has been adopted (Fig.3) [15, 16]. It consists of two HPGe: an Ortec low background detector with 90% relative efficiency (named GeDD) and a Canberra low background detector with 130% relative efficiency (named GePD).
Both detectors are shielded by a few centimetres of high-conductivity oxygen-free copper and by about 25 cm of low radioactivity lead. An anti-radon box, made of Plexiglas and flooded with nitrogen gas, was added to remove any residual radon contamination. Thanks to the overall shielding, the environmental background is reduced by about three orders of magnitude [16, 17].

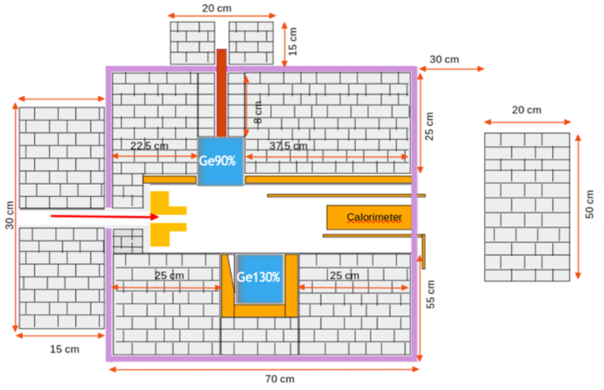

Fig. 3. Experimental setup adopted for the ^{20}Ne(p,γ)^{21}Na study at LUNA.

Natural composition neon gas (90.48% ^{20}Ne) is used inside a windowless gas target system [18], with a typical working pressure of 2 mbar. The beam intensity (I_{beam} ~ 300μA) is measured following a calorimetric approach in order to avoid possible uncertainties due to charge state fluctuations when the beam crosses the gas target [18, 19].
The adopted setup has allowed not only to study the 366 keV resonance but also to cover the proton energy range down to 250 keV, where the contribution due to the DC process and sub-threshold resonance become relevant.

3 First results

For the study of the 366 keV resonance a complete scan has been performed by changing the beam energy and therefore populating the resonance in different positions along the target [17]. The yield measured by the two detectors is shown in Fig. 4. The resonance energy and the branching ratios for the transitions to the 2424.9 keV and the 331.9 keV excited states in ^{21}Na, as well to the ground state have been determined. Once corrected for the detection efficiency, each position of the resonance scan returns a very well consistent value for the strength for both detectors (Fig. 5). The average value confirms the result obtained by Rolfs and co-workers: after a final refinement of the analysis, a 5% precision will be achieved.

In March 2022 we have started a first campaign to measure the direct capture process for energies E_p = 260 - 380 keV taking long runs at p = 2 mbar. At E_p = 400 keV the pressure was decreased to 0.5 mbar in order to not excite the 366 keV resonance. We observed both the primary and secondary gamma line for the strongest transition, the DC→ 2425 keV, getting consistent result for the astrophysical factor. In July 2022 we concluded the measurements by increasing the statistics at two energies (E_p = 260 and 310 keV) where the peaks from weaker transition were visible, with the aim to derive the branching ratios for all the direct capture components and find the total S-factor. New results will come soon.

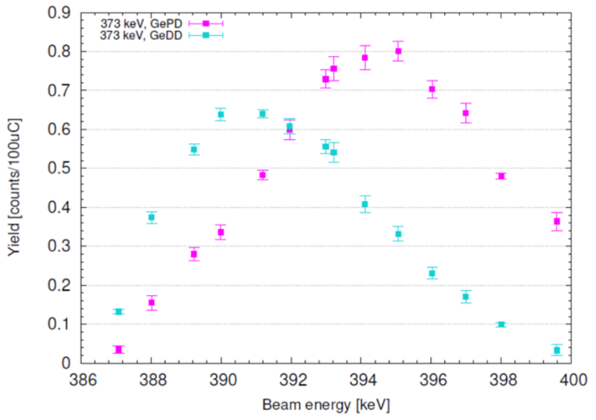

Fig. 4 Gamma yield measured by the two detectors for the DC-> 2425 keV transition (E_γ=373 keV).

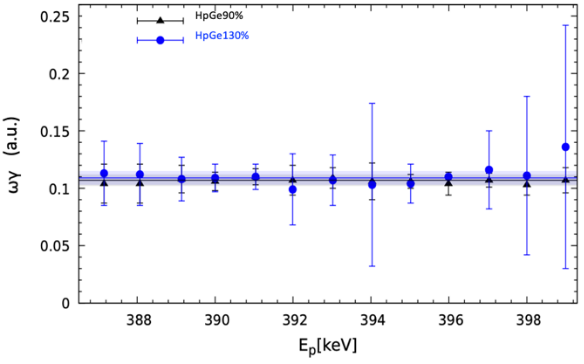

Fig. 5. The 366 keV resonance strength evaluate for each position of the scan and for the two detectors.

References

1. J. B. Marion and W. A. Fowler, ApJ **125**, 221 (1957)
2. F. Ferraro, M. P. Takacs, D. Piatti, F. Cavanna, R. Depalo, M. Aliotta, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, et al. (LUNA Collaboration), Phys. Rev. Lett. **121**, 172701 (2018)
3. A. Boeltzig, C. G. Bruno, F. Cavanna, S. Cristallo, T. Davinson, R. Depalo, R. J. deBoer, A. Di Leva, F. Ferraro, G. Imbriani, et al., Eur. Phys. J. A **52** (2016), ISSN 1434-6001, 1434-601X
4. F. Cavanna, R. Depalo, M. Aliotta, M. Anders, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, et al., Phys. Rev. Lett. **115**, 252501 (2015), 1511.05329.
5. R. Depalo, F. Cavanna, M. Aliotta, M. Anders, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, et al. (LUNA Collaboration), Phys. Rev. C **94**, 055804 (2016).
6. F. Cavanna, R. Depalo, M. Aliotta, M. Anders, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, et al. (The LUNA Collaboration), Phys. Rev. Lett. **120**, 239901 (2018).
7. A. Slemer, P. Marigo, D. Piatti, M. Aliotta, D. Bemmerer, A. Best, A. Boeltzig, A. Bressan, C. Broggini, C. G. Bruno, et al., Monthly Notices of the Royal Astronomical Society **465**, 4817 (2017).
8. C. Iliadis, J. M. D'Auria, S. Starrfield, W. J. Thompson, and M. Wiescher, Astrophys. J. Suppl. Ser. **134**, 151 (2001).
9. S. Lyons, J. Görres, R. J. deBoer, E. Stech, Y. Chen, G. Gilardy, Q. Liu, A. M. Long, M. Moran, D. Robertson, et al., Phys. Rev. C **97**, 065802 (2018)
10. C. Rolfs, W. S. Rodney, M. H. Shapiro, and H. Winkler, Nucl. Phys. A 241, 460 (1975).
11. A. A. Cooper, A Low-Energy Study of the ^{20}Ne(p, γ)^{21}Na Reaction with High-Current Proton Beams at LENA, Ph.D. thesis, University of North Carolina, Chapel Hill, Department of Physics and Astronomy (2019).
12. A. Formicola, G. Imbriani, M. Junker, D. Bemmerer, R. Bonetti, C. Broggini, C. Casella, P. Corvisiero, H. Costantini, G. Gervino, C. Gustavino, A. Lemut, P. Prati, V. Roca, C. Rolfs, M. Romano, D. Schürmann, F. Strieder, F. Terrasi, H.P. Trautvetter and S. Zavatarelli, Nucl. Instr. Meth. Phys. Res. A **507**, 609–616 (2003)
13. Broggini C, Bemmerer D, Caciolli A and Trezzi D. Progress in Particle and Nuclear Physics **98**, 55-94 (2018)
14. F. Ferraro F, G. F. Ciani, A. Boeltzig, F. Cavanna and S. Zavatarelli, Frontiers in Astronomy and Space Sciences **7** (2021) ISSN 2296-987X
15. A. Caciolli, L. Agostino, D. Bemmerer, R. Bonetti, C. Broggini, F. Confortola, P. Corvisiero, H. Costantini, Z. Elekes, A. Formicola, et al., Eur. Phys. J. A **39**, 179 (2009)
16. F. Cavanna, R. Depalo, M.-L. Menzel, M. Aliotta, M. Anders, D. Bemmerer, C. Broggini, C. G. Bruno, A. Caciolli, P. Corvisiero, et al., Eur. Phys. J. A **50**, 179 (2014), 1411.2888.
17. E. Masha, Astrophysical nuclear reaction on Neon isotopes at LUNA, Ph.D. thesis, Università degli studi di Milano (2022)
18. F. Ferraro, M. P. Takacs, D. Piatti, V. Mossa, M. Aliotta, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, et al., The European Physical Journal A **54**, 44 (2018), ISSN 1434-601X.

19. V. Mossa et al, Eur. Phys. J. A **56**, 144 (2020)