IL NUOVO CIMENTO **40 C** (2017) 59
DOI 10.1393/ncc/i2017-17059-8

Colloquia: IFAE 2016

Direct measurement of nuclear cross sections of astrophysical relevance at LUNA: The ^{22}Ne(p, γ)^{23}Na reaction

F. Ferraro on behalf of the LUNA Collaboration
Università degli Studi di Genova and INFN, Sezione di Genova - Genova, Italy

received 17 October 2016

Summary. — Most of the elements constituting the universe were produced in stars through a series of nuclear reactions. LUNA performs direct measurements of nuclear cross sections relevant to astrophysics, taking advantage of the low background at LNGS. The ^{22}Ne$(p,\gamma)^{23}$Na reaction rate, which belongs to the NeNa cycle of hydrogen burning, has been recently studied. Its rate is still very uncertain because of a lot of resonances lying inside the Gamow window. LUNA discovered three new resonances using two high-purity germanium detectors and considerably improved the existing upper limits on the lower energy resonances using a high-efficiency optically-segmented BGO crystal.

1. – Introduction

Understanding the production of different isotopes in stars requires the knowledge of the cross section of the several reactions involved in the nuclear reactions network. These cross sections depend on the interacting nuclei and their relative kinetic energy. As widely explained in [1], the cross section can be written as

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E), \tag{1}$$

where η is the Sommerfeld parameter. The dependence on kinetic energy and electric charge is factorized and separated from the nuclear effects, which are represented by the astrophysical factor $S(E)$. While the cross section decreases very quickly with energy, the astrophysical factor changes much more gently, allowing therefore for a more reliable extrapolation down to the low-energy region. The typical stellar energy ranges from hundreds of keV down to few keV, and the cross section may be as small as few pb.

The ^{22}Ne(p, γ)^{23}Na reaction belongs to the NeNa cycle of hydrogen burning (see fig. 1) and it is relevant to red giant branch (RGB) stars, asymptotic giant branch (AGB) stars, classical novae (CN) and supernovae Ia (SN Ia) explosions [2, 3]. This cycle greatly

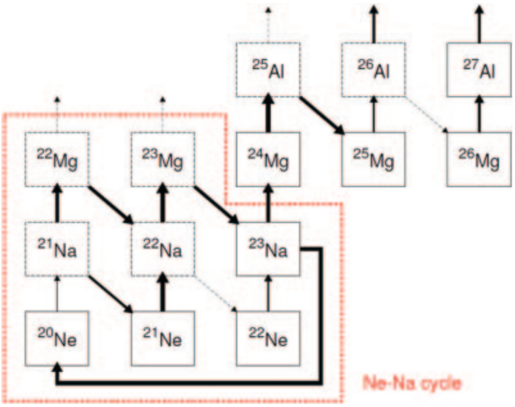

Fig. 1. – The NeNa cycle and its link to the MgAl cycle.

influences the nucleosynthesis of the elements between ^{20}Ne and ^{27}Al since it is linked to the MgAl cycle. According to the literature, several low-energy resonances give a relevant contribution to the reaction rate, but some of them have never been directly observed. Below 400 keV only a few resonance strengths have been directly measured so far, yet many upper limits have been settled [4-7]. Indirect measurements rely on spin-parity assignments or spectroscopic factor normalizations which may be uncertain [8-10] and the very existence of the resonances at $E_p^{res} = 71$, 105 and 215 keV is not sure. Depending on the method adopted to consider existing upper limits and indirect data, different reaction rates have been predicted [11-14]: NACRE [11] and STARLIB [14] compilations differ up to a factor of 1000 at temperatures of about 0.1 GK.

2. – LUNA

The LUNA (Laboratory for Underground Nuclear Astrophysics) experiment is located in the Gran Sasso National Laboratory (LNGS), Italy. It consists in the world's only deep underground accelerator facility in running conditions, operating a 400 kV high-current electrostatic accelerator already used to study many reactions of astrophysical relevance.

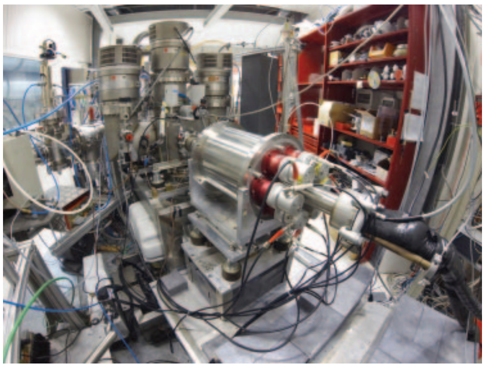

Fig. 2. – The BGO detector (in the center) surrounds the interaction chamber.

LUNA benefits from a 1400 m (3800 m.w.e.) thick rock overburden which shield the Gran Sasso National Laboratory from cosmic muons, suppressing their flux by six orders of magnitude [15].

LUNA is provided with two beam lines, respectively equipped with a solid target and a windowless extended gas target. The latter was recently used in the ^{22}Ne(p, γ)^{23}Na cross section measurement.

3. – ^{22}Ne(p, γ)^{23}Na cross section measurement

A feasibility study was carried out [6] in order to develop an optimized setup for the gas target and study the beam-induced background. A new setup with two HPGe detectors allowed for the first direct observation of three new low-energy resonances [7] and the sizable reduction of the upper limits for other three uncertain resonances.

To improve the knowledge of the low-energy resonances at $E_p^{res} = 71$ and 105 keV and of the direct capture component, a dedicated high-efficiency setup using a BGO detector surrounding the target chamber was developed (fig. 2). The beam current, measured by a calorimeter with 200 W operating power and a NI CompactRIO control system (programmed in LabVIEW), is sampled every second and integrated over the duration of the run. A devoted setup was used to measure the gas pressure and temperature along the beam direction in different positions and obtain the density profile without the beam. The effect of the beam on the Ne gas target was already studied in [6] and the beam-heating correction is applied. Once the target characterization was completed, the final interaction chamber was mounted in its position. The detection system consists of six BGO crystals arranged in a cylindrical configuration and coupled with a PMT on one side. The crystals are individually enclosed in a reflector film and placed together inside their casing. The signals of the different segments were independently acquired and offline coincidence analysis is possible. The efficiency was measured by means of radioactive sources (^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y) and the well-known ^{14}N$(p,\gamma)^{15}$O resonance at E_p^{res} = 278 keV, populated in different positions inside the chamber. The same sources were used for the energy calibration, together with the peaks originating from ^{15}O excited states decay. As crosscheck we measured the strength of the resonances at $E_p^{res} = 156.2$, 189.5 and 259.7 KeV and the results are consistent with the previous HPGe phase [7]. High statistics was collected around the tentative resonances at 71 keV and 105 keV. Data on direct capture were taken as well and the ^{22}Ne peak at $Q + E_{cm}$ clearly emerges from the background. The analysis is in progress and the results will be published soon.

REFERENCES

[1] Rolfs C. E. and Rodney W. S., *Cauldrons in the cosmos: Nuclear astrophysics*, (University of Chicago Press, Chicago) 1988.

[2] Marion J. and Fowler W., *Astrophys. J.*, **125** (1957) 221.

[3] Iliadis C., Champagne A., José J., Starrfield S. and Tupper P., *Astrophys. J. Suppl. Ser.*, **142** (2002) 105.

[4] Görres J. *et al.*, *Nucl. Phys. A*, **385** (1982) 57.

[5] Görres J. *et al.*, *Nucl. Phys. A*, **408** (1983) 372.

[6] Cavanna F. *et al.*, *Eur. Phys. J. A*, **50** (2014) 179.

[7] Cavanna F. *et al.*, *Phys. Rev. Lett.*, **115** (2015) 252501.

[8] Powers J. R. *et al.*, *Phys. Rev. C*, **4** (1971) 2030.

[9] Hale S. E. *et al.*, *Phys. Rev. C*, **65** (2001) 015801.

[10] Jenkins D. G. *et al.*, *Phys. Rev. C*, **87** (2013) 064301.
[11] Angulo C. *et al.*, *Nucl. Phys. A*, **656** (1999) 3.
[12] Iliadis C. *et al.*, *Nucl. Phys. A*, **841** (2010) 31.
[13] Iliadis C. *et al.*, *Nucl. Phys. A*, **841** (2010) 251.
[14] Sallaska A. L. *et al.*, *Astrophys. J. Suppl. Ser.*, **207** (2013) 18.
[15] Costantini H., Formicola A., Imbriani G., Junker M., Rolfs C. and Strieder F., *Rep. Prog. Phys.*, **72** (2009) 086301.