IL NUOVO CIMENTO **42 C** (2019) 118
DOI 10.1393/ncc/i2019-19118-6

Colloquia: EuNPC 2018

Low-energy cross section measurements of the ^{22}Ne(p, γ)^{23}Na reaction

F. Ferraro(*) on behalf of the LUNA Collaboration(**)

INFN, Sezione di Genova and Dipartimento di Fisica, Università degli Studi di Genova
Via Dodecaneso 33, 16146 Genova, Italy

received 5 February 2019

Summary. — Because of a large number of uncertain resonances in the Gamow window, the ^{22}Ne(p, γ)^{23}Na reaction rate was the most uncertain in the NeNa cycle. Recently, a new direct study of the ^{22}Ne(p, γ)^{23}Na reaction has been performed at the Laboratory for Underground Nuclear Astrophysics (LUNA). A windowless gas target and two complementary setups have been used, to obtain both high resolution and high efficiency measurements. The new resonances at 156.2, 189.5 and 259.7 keV have been discovered and their decay scheme has been determined. The tentative resonances at 71 and 105 keV have not been observed and improved upper limits have been put on their strength. Moreover, the high-efficiency setup allowed the measurement of the non-resonant cross section at unprecedentedly low energies. The thermonuclear reaction rate based on the new measurements has been evaluated.

1. – Introduction

During the Hot Bottom Burning (HBB) process, which takes place in the innermost region of the convective envelope of asymptotic giant branch (AGB) stars, the temperature can be as high as 0.1 GK. In massive stars, advanced hydrogen burning cycles such as the neon-sodium (NeNa) and magnesium-aluminum (MgAl) cycles can significantly contribute to nucleosynthesis [1, 2]. Within the NeNa cycle, the ^{22}Ne(p, γ)^{23}Na reaction links ^{22}Ne to ^{23}Na, the only stable isotope of sodium.

A neon-sodium anti-correlation was observed in galactic globular clusters in stars on the red giant branch, where the ^{22}Ne(p, γ)^{23}Na is crucial for the synthesis of sodium [3,4]. The ^{22}Ne(p, γ)^{23}Na reaction rate affects the outcome of models which try reproduce such anticorrelation [1, 5]. This rate was very uncertain, showing differences up to three orders of magnitude between the rates from the NACRE [6] compilation, and following evaluations by Hale et al. [7], Iliadis et al. [8], and STARLIB [9].

(*) E-mail: `federico.ferraro@ge.infn.it`
(**) `luna.lngs.infn.it`

The Laboratory for Underground Nuclear Astrophysics (LUNA) [10] recently studied this reaction, observing three new low-energy resonances with two high-purity germanium (HPGe) detectors [11-14]. The existence of the two lowest out of the three new resonances at $E_p = 156.2$, 189.5, and 259.7 keV (E_p is the proton energy in the laboratory system) was recently confirmed in a surface-based experiment at the Triangle Universities Nuclear Laboratory (TUNL) [15].

In order to measure the low-energy cross section, new measurements have been performed at LUNA using a high-efficiency setup including a Bismuth Germanate (BGO) detector. The resonances at $E_p = 156.2$, 189.5, and 259.7 keV have been studied, determining their strength and branching ratios. Two resonances at $E_p = 71$ and 105 keV, reported as tentative in an previous indirect experiments [16] and not confirmed later [7,17] have been investigated with high sensitivity. The direct capture contribution, as well as the contribution from a broad sub-threshold resonance have been measured.

2. – Experiment

2˙1. *Setup*. – A differential-pumping, extended gas target was used in combination with a segmented BGO detector with $\sim 4\pi$ solid angle coverage [18]. Isotopically enriched ^{22}Ne ($\geq 99.9\%$) was recycled and purified by a chemical getter in order to remove hydrocarbons, oxygen and nitrogen. The density profile was determined by means of pressure and temperature measurements in several position inside the target chamber.

A power compensation calorimeter with constant temperature gradient measured the beam current. Each segment of the six-fold BGO detector was optically insulated, coupled to a PMT and independently digitized. Recorded events were time-stamped to allow offline coincidence analysis.

2˙2. *Measurements*. – For each of the three previously observed resonances [11-14] a yield curve was measured varying the beam energy in steps of 1-3 keV. For each resonance, long runs were performed at a beam energy corresponding to maximum yield. Long runs with argon inside the target chamber were performed to properly subtract the beam-induced background. The spectrum with the argon target was fundamental to subtract the beam-induced background due to the ^{11}B(p, γ)^{12}C reaction and its Compton continuum [18]. This spectrum was scaled for equal counting rate in the 10-19MeV region, where the contribution of the ^{11}B(p, γ)^{12}C is dominant. Singles spectra, gated on add-back events in the region of interest were compared with GEANT4 [19] and GEANT3 [20] Monte Carlo simulations using previously measured branching ratios [13, 18], showing good agreement.

To investigate the possible resonances at $E_p = 71$ and 105 keV, several long runs were performed around their nominal energy, in the energy range between 63-78 and 95-113 keV respectively. These resonances were not observed and new upper limits were put on their strength. The non-resonant yield was measured at $E_p = 188.0$, 205.2, 250.0, and 310.0 keV to study the contribution by broad resonances and direct capture.

3. – Conclusion

The new strengths of the resonances at $E_p = 156.2$, 189.5, and 259.7 keV are slightly higher than previous values obtained at LUNA [11-14] but consistent within 2 σ. Because of the particular setup used in the LUNA-HPGe experiment, the observed difference may

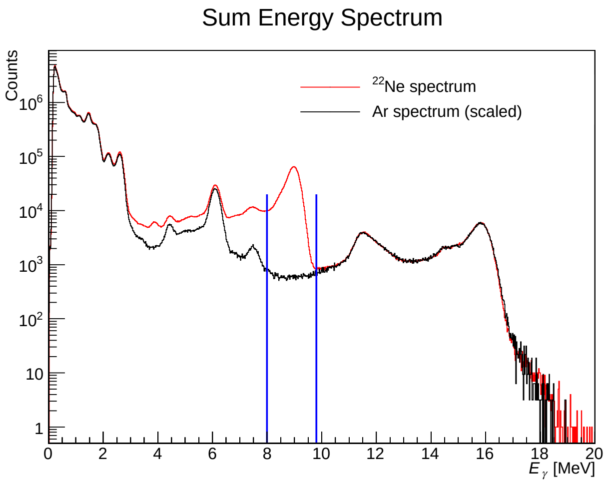

Fig. 1. – 259.7 keV resonance. Spectra obtained with ^{22}Ne (red) and Ar (black) targets.

be due to angular distribution effects. These effects can only play a minor role in the present LUNA-BGO experiment, thanks to the $\sim 4\pi$ solid angle coverage of the detector.

The existing uncertainty on the measured resonance strengths and the off-resonance measurements at 250.0 and 310.0 keV is mainly due to the detection efficiency (5% systematic uncertainty). On the lowest-energy off-resonance measurements, instead, the uncertainty is mainly due to statistics and is as high as 9%.

From now on, the thermonuclear reaction rate will be based on direct measurements of the relevant low-energy resonances. Detailed results are about to be published [21].

REFERENCES

[1] Slemer A. *et al.*, *Monthly Notices of the Royal Astronomical Society*, **465** (2017) 4817.
[2] Denissenkov P. A. *et al.*, *Monthly Notices of the Royal Astronomical Society*, **448** (2015) 3314.
[3] Carretta E. *et al.*, *Astron. Astrophys.*, **505** (2009) 117.
[4] Gratton R. G. *et al.*, *Astron. Astrophys. Revs.*, **20** (2012) 50.
[5] Ventura P. *et al.*, *Monthly Notices of the Royal Astronomical Society*, **475** (2018) 2282.
[6] Angulo C. *et al.*, *Nuclear Physics A*, **656** (1999) 3.
[7] Hale S. E. *et al.*, *Phys. Rev. C*, **65** (2001) 015801.
[8] Iliadis C. *et al.*, *Nucl. Phys. A*, **841** (2010) 31.
[9] Sallaska A. L. *et al.*, *Astrophys. J. Suppl. Ser.*, **207** (2013) 18.
[10] Broggini C. *et al.*, *Progress in Particle and Nuclear Physics*, **98** (2018) 55 .
[11] Cavanna F. *et al.*, *The European Physical Journal A*, **50** (2014) 179.
[12] Cavanna F. *et al.*, *Phys. Rev. Lett.*, **115** (2015) 252501.
[13] Depalo R. *et al.*, *Phys. Rev. C*, **94** (2016) 055804.
[14] Bemmerer D. *et al.*, *EPL (Europhysics Letters)*, **122** (2018) 52001.
[15] Kelly K. J. *et al.*, *Phys. Rev. C*, **95** (2017) 015806.
[16] Powers J. R. *et al.*, *Phys. Rev. C*, **4** (1971) 2030.
[17] Jenkins D. *et al.*, *Phys.Rev. C*, **87** (2013) 064301.
[18] Ferraro F. *et al.*, *Eur. Phys. J. A*, **54** (2018) 44.
[19] Agostinelli S. *et al.*, *Nucl. Inst. Meth. A*, **506** (2003) 250.
[20] Arpesella C. *et al.*, *Nucl. Inst. Meth. A*, **360** (1995) 607.
[21] Ferraro F. *et al.*, *Phys. Rev. Lett.*, **121** (2018) 172701.