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Low-Energy resonances in the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction directly observed at LUNA

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Abstract. The neon-sodium cycle of hydrogen burning influences the synthesis of the elements between ^{20}Ne and ^{27}Al in AGB stars and classical novae explosions.

The $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction rate is very uncertain because of a large number of unobserved resonances lying in the Gamow window.

A new direct study of the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction has been performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) using a windowless gas target and two HPGe detectors. Several resonances have been observed for the first time in a direct experiment.

1. Introduction

The neon-sodium cycle of hydrogen burning contributes to the synthesis of the isotopes between ^{20}Ne and ^{23}Na in Red Giant Branch (RGB) stars, Asymptotic Giant Branch (AGB) stars and classical novae explosions.

The synthesis of sodium in RGB stars is still puzzling. Observations of galactic globular clusters show that the surface abundance of sodium in RGB stars anticorrelates with the oxygen abundance [1]. A possible explanation for this anticorrelation involves the pollution of the interstellar medium with material processed through hydrogen burning reactions at high temperatures in AGB stars. In the hydrogen burning shell of AGB stars, oxygen is efficiently destroyed by the CNO cycle and sodium is mainly produced by the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction of the NeNa cycle [2].

Another scenario where the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction is active are classical novae explosions. A sensitivity study showed that the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction rate uncertainty strongly affects the final abundances of neon, sodium and magnesium isotopes, calling for new experimental efforts on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ cross section [3].

The $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ Gamow window for AGB stars and classical novae extends from 50 to 600 keV. In this energy range, the proton capture on ^{22}Ne is dominated by a large number of resonances. None of the resonances below 436 keV has ever been observed in either direct or indirect experiments (tab. 1). Moreover, the mere existence of the three resonances at 71, 105 and 215 keV is still debated since it has been tentatively reported in [4] but has not been observed in subsequent experiments [5, 6].

As a consequence, the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction rates reported in the widely adopted compilations by NACRE [7] and C. Iliadis et al. [8] are up to three orders of magnitude discrepant in the energy range of interest for hydrogen burning in AGB stars and novae.



Table 1. Summary of literature resonance strengths for $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ resonances below 400 keV proton energy.

$E_{res,LAB}$ [keV]	$\omega\gamma$ [eV]		
	J. Görres (direct) [9]	NACRE [7]	Iliadis et al. [8]
29	-	-	$\leq 2.6 \cdot 10^{-25}$
37	-	$(6.8 \pm 1.0) \cdot 10^{-15}$	$(3.1 \pm 1.2) \cdot 10^{-15}$
71	$\leq 3.2 \cdot 10^{-6}$	$\leq 4.2 \cdot 10^{-9}$	-
105	$\leq 6.0 \cdot 10^{-7}$	$\leq 6.0 \cdot 10^{-7}$	-
158	$\leq 1.0 \cdot 10^{-6}$	$(6.5 \pm 1.9) \cdot 10^{-7}$	$(9.2 \pm 3.7) \cdot 10^{-9}$
186	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$
215	$\leq 1.4 \cdot 10^{-6}$	$\leq 1.4 \cdot 10^{-6}$	-
259	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$	$\leq 1.3 \cdot 10^{-7}$
291	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$
323	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$	$\leq 2.2 \cdot 10^{-6}$
334	$\leq 3.0 \cdot 10^{-6}$	$\leq 3.0 \cdot 10^{-6}$	$\leq 3.0 \cdot 10^{-6}$
369	-	-	$\leq 6.0 \cdot 10^{-4}$
394	-	-	$\leq 6.0 \cdot 10^{-4}$

2. Experimental setup

The Laboratory for Underground Nuclear Astrophysics (LUNA) is located at Gran Sasso National Laboratories, Italy, where the 1400 meters of rocks dominating the laboratory guarantee a reduction of six orders of magnitude in the cosmic muon flux and a reduction of three orders of magnitude in the neutron flux.

The 400 kV electrostatic accelerator provides high intensity ($\sim 200 \mu\text{A}$) proton or alpha beam. The beam can be delivered either to a solid or to a gas target. Different gamma-ray or particle detectors can be used, depending on the nuclear reaction to be studied [10].

As a first step, a feasibility test was performed using the setup of the previous $^2\text{H}(\alpha,\gamma)^6\text{Li}$ experiment [11].

For this test, neon gas with natural isotopic composition was used (90.48% ^{20}Ne , 0.27% ^{21}Ne and 9.25% ^{22}Ne). The aim of the test was to study the possible sources of beam induced background, and to have some hints on the sensitivity to the $^{22}\text{Ne}+p$ resonant cross section.

During the test, runs on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ resonances at 105, 158, 186 and 259 keV have been performed. Despite the use of non enriched gas (only 9.25% ^{22}Ne) and a setup which was not optimized for this measurement, gamma-rays from the 186 keV resonance have been observed in a 12 hours run. This resonance was never observed in previous experiments, and the literature upper limit for the resonance strength is $\omega\gamma < 2.6 \cdot 10^{-6}$ eV. Thanks to the LUNA observation it was possible to provide a lower limit $\omega\gamma \geq 0.12 \cdot 10^{-6}$ eV for the 186 keV resonance strength and thus to improve the literature information on this resonance [12].

Following the feasibility test, the characterization of the setup for the first experimental campaign on the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ resonances was started. In this phase the gas density profile along the beam path was first measured without beam using natural neon gas and a dedicated target chamber. Then the beam heating effect in natural neon gas has been measured for the first time with the resonance scan technique, using the intense and well known $^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$ resonance at 271.6 keV beam energy [13] and a collimated NaI detector [12].

For the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ cross section measurement, a proton beam was delivered to the windowless gas target filled with 99.9% enriched ^{22}Ne .

The gamma-rays emitted in the de-excitation of ^{23}Na were detected by two HPGe detectors collimated at 55° and 90° with respect to the beam direction.

In order to reduce the environmental background at gamma ray energies below 3 MeV, the two detectors were surrounded by a 4 cm thick copper shielding and a 25 cm thick lead shielding.

3. Results

During about five months of data taking, all the resonances between 70 and 334 keV have been investigated. The resonances at 158, 186 and 259 keV have been observed for the first time in a direct experiment. For these resonances, the complete excitation function was measured and then a long run at the energy of maximum yield was performed. New gamma decay modes have also been observed for the three resonances detected.

For the non-detected resonances new upper limits have been measured. The new upper limits are two to three orders of magnitude lower than the previous direct measurement, proving the improvement in sensitivity that can be achieved in underground experiments.

Fig. 1 shows the updated reaction rate for the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction, calculated including the new LUNA results. Literature reaction rates adopted in references [7] and [8] are also shown for comparison.

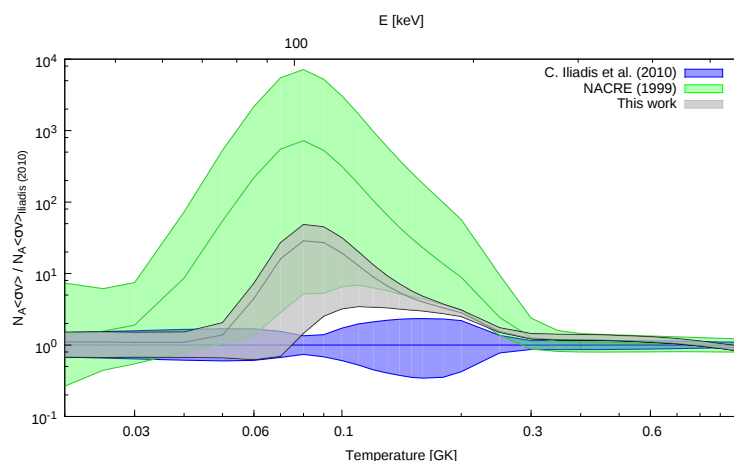


Figure 1. Thermonuclear reaction rate from LUNA, NACRE [7] and Iliadis et al. [8] normalized to [8]. Colored bands represent the reaction rate uncertainties.

The final results will be presented and discussed in detail in a forthcoming publication [15].

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