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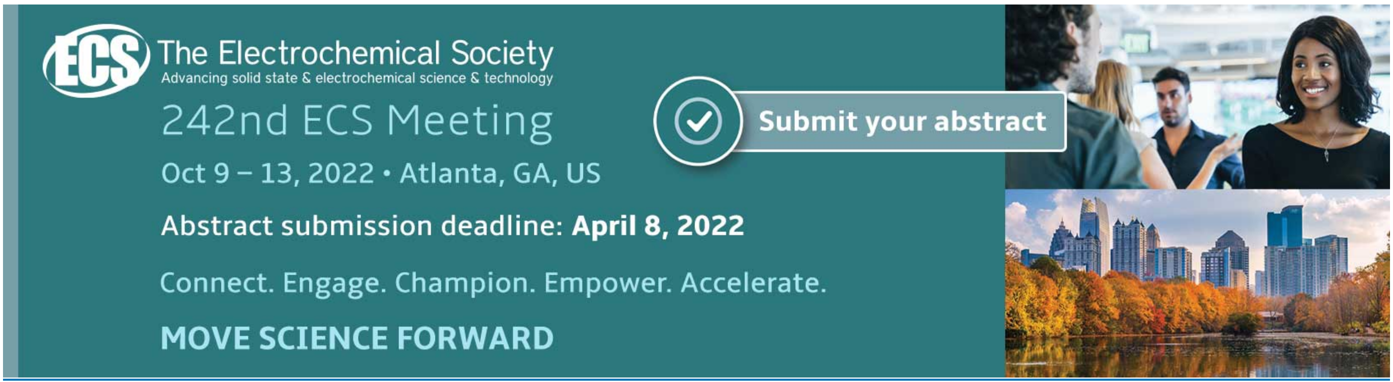

Direct measurement of the ^{22}Ne$(p,\gamma)^{23}$Na reaction cross section at LUNA

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Abstract. The ^{22}Ne$(p,\gamma)^{23}$Na reaction takes part in the NeNa cycle of hydrogen burning, influencing the production of the elements between ^{20}Ne and ^{27}Al in red giant stars, asymptotic giant stars and classical novae. The ^{22}Ne$(p,\gamma)^{23}$Na reaction rate is very uncertain because of a large number of tentative resonances in the Gamow window, where only upper limits were quoted in literature. A direct measurement of the ^{22}Ne$(p,\gamma)^{23}$Na reaction cross section has been carried out at LUNA using a windowless differential-pumping gas target with two high-purity germanium (HPGe) detectors. A new measurement with a 4π bismuth germanate (BGO) summing detector is ongoing. During the HPGe phase of the experiment the strengths of the resonances at 156.2 keV, 189.5 keV and 259.7 keV have been directly measured for the first time and their contribution to the reaction rate has been calculated. The decay scheme of the newly discovered resonances has been established as well and some improved upper limits on the unobserved resonances have been put. The BGO detector with its 70% γ-detection efficiency allows to measure the cross section at lower energy. In order to further investigate the resonances at 71 keV and 105 keV and the direct-capture component, the data taking is ongoing.

1. Introduction

The oxygen-sodium anticorrelation in globular clusters [1] requires, in order to be understood, a precise knowledge of the sodium production and destruction rates. One common explanation is that the stars showing this anticorrelation were formed in an environment that was polluted by previous generation AGB stars. Indeed the AGB stars may reach, at the base of their convective H-rich envelope, temperatures high enough to let the Hot Bottom Burning occur and change the surface abundances thanks to convection. It has been found, for metal-poor and very metal-poor AGB stars, that models would better match the observations if ^{22}Ne$(p,\gamma)^{23}$Na reaction rate was higher than the literature one [2]. Another possible explanation has been proposed in [3], suggesting a core hydrogen burning and rotation-driven winds.

In both cases ^{23}Na is produced via the ^{22}Ne$(p,\gamma)^{23}$Na reaction, which is part of the neon-sodium cycle of hydrogen burning. The ^{22}Ne$(p,\gamma)^{23}$Na reaction cross section is required in order to calculate the reaction rate. A new experimental effort was asked [4] in order to reduce the uncertainties on the cross section, thus reducing the uncertainty on the reaction rate and the predicted ^{23}Na abundance.

Many resonances contribute to the ^{22}Ne$(p,\gamma)^{23}$Na cross section. The resonances above 400 keV, which affect the thermonuclear reaction rate for temperatures $T > 0.5$ GK, have already been studied [5, 6, 7, 8]. Below 400 keV only a few resonance strengths have been directly measured

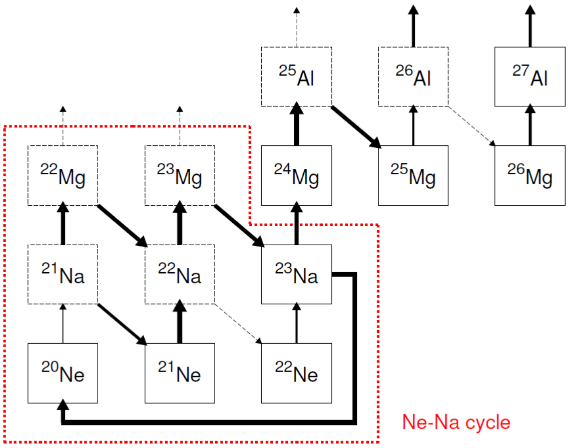

Figure 1. The NeNa cycle and its link to the MgAl cycle.

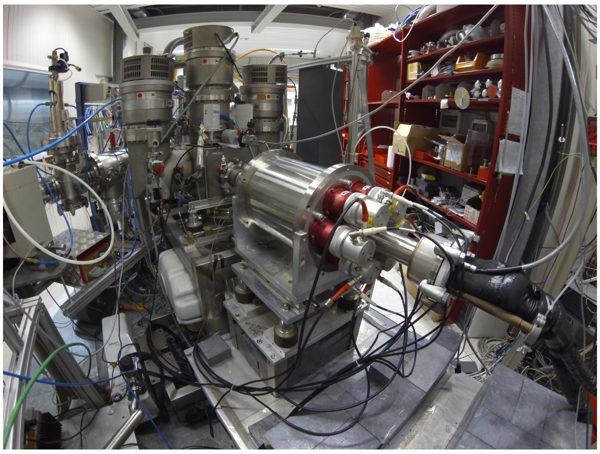

Figure 2. The BGO detector (in the center) surrounds the interaction chamber.

so far, yet many upper limits have been put [9, 10, 6]. Some indirect measurements have been carried out [11, 12, 13], but they rely on spin-parity assignments or spectroscopic factor normalizations which may be uncertain. Consequently, the very existence of the resonances at $E_p^{res} = 71$, 105 and 215 keV is not certain [11, 12, 10]. The way the experimental upper limits and indirect data have been considered in the literature led to different reaction rate evaluations. The reaction rate has been calculated in 1999 by the NACRE collaboration [14] from the resonance measurements [6, 15] and the direct capture component [15]. Later on, a similar evaluation has been performed in 2001 [12], updated in 2010 [16, 7] and again in 2013 [17] by the STARLIB group, completely disregarding the uncertain resonances. As a result, the NACRE and the STARLIB compilations differ up to a factor of 1000.
Our goal is to solve this ambiguous situation with a direct measurement at low energy.

2. The direct measurement at LUNA

LUNA (Laboratory for Underground Nuclear Astrophysics) is located in the Gran Sasso National Laboratory, Italy. It consists in the world's only underground accelerator facility, operating a 400 kV high-current electrostatic accelerator already used to study many reactions of astrophysical relevance. LUNA benefits from the 1400 m thick rock overburden which shield the Gran Sasso National Laboratory from cosmic muons suppressing their flux by six orders of magnitude [18] and leading to a very low γ-ray background.
In a first phase a feasibility study has been carried out [9] 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 the first direct observation of three new low-energy resonances [10, 19] and the significant reduction of the upper limits for other three uncertain resonances.

2.1. The BGO campaign

In order to better study the low-energy resonances at $E_p^{res} = 71$ and 105 keV and the direct capture component, a dedicated high-efficiency setup with a segmented BGO detector surrounding the target chamber has been developed. A new cylindrical interaction chamber has been designed, provided with a water-cooled, electrically-insulated collimator. A copper calorimeter with 200 W operating power was developed, including the NI CompactRIO control system and its LabVIEW software, so that the beam current is sampled every second and integrated over the duration of the run. A copy of the interaction chamber was made, provided

with tubes and flanges. Thanks to this test chamber we measured the gas pressure and temperature along the beam direction in different positions (inside the chamber, the collimator and the connecting pipe) so that the density profile without the beam can be obtained. The effect of the beam on the Ne gas target has been already studied in [9] and the beam-heating correction has to be applied in order to obtain the density profile with the proton beam impinging on the gas target. Once the target characterization was completed, the final interaction chamber was mounted in its position, passing through the BGO detector. The BGO detector 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 DAQ is based on the CAEN V1724 digitizer (8 Channel, 14 bit, 100 MS/s) and it is performed in list mode, so that offline coincidence analysis is possible. The efficiency have been measured by means of four radioactive sources (^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y) and the well known ^{14}N$(p,\gamma)^{15}$O reaction in different positions inside the interaction chamber. The same sources were used also for the energy calibration, together with the peaks originating from the ^{15}O excited states decay, that were also used to verify the calibration from time to time. In a first time, in order to have a link with the HPGe measurements, we measured the strength of the $E_p^{res} = 189.5$ KeV resonance and the result is consistent with [10].
Some data on the direct capture were already taken, and the ^{22}Ne peak clearly emerge from the background. The data taking is now focused on the low-energy resonances and further interesting details will be published soon.

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