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Low energy resonances in the ^{22}Ne(p,γ)^{23}Na reaction directly observed at LUNA

R. Depalo[*]
Università di Padova and INFN Padova, Padova, Italy
E-mail: `rdepalo@pd.infn.it`

F. Cavanna
Università degli Studi di Genova and INFN Genova, Genova, Italy E-mail:
`francesca.cavanna@ge.infn.it`

for the LUNA collaboration

The neon-sodium cycle of hydrogen burning influences the synthesis of the elements between ^{20}Ne and ^{27}Al in red giant stars and novae explosions.
In order to reproduce the observed elemental abundances, the cross sections of the reactions involved in the nucleosynthesis process should be accurately known. The ^{22}Ne(p,γ)^{23}Na reaction rate is very uncertain because of a large number of unobserved resonances lying in the Gamow window. For proton energies below 400 keV, in the literature there are only upper limits for the resonance strengths. A new direct study of the ^{22}Ne(p,γ)^{23}Na reaction has been performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) in Gran Sasso using a windowless gas target and two high-purity germanium detectors. Several resonances have been observed for the first time in a direct experiment.

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[*] Speaker.

1. Astrophysical motivation

The neon-sodium cycle of hydrogen burning (fig. 1) 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.

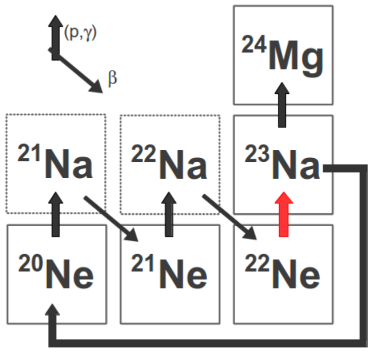

Figure 1: The neon - sodium cycle of hydrogen burning.

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}Ne(p,γ)^{23}Na reaction of the NeNa cycle [2].
Another scenario where the ^{22}Ne(p,γ)^{23}Na reaction is active are classical novae explosions. A sensitivity study showed that the ^{22}Ne(p,γ)^{23}Na reaction rate uncertainty strongly affects the final abundances of neon, sodium and magnesium isotopes, demonstrating the need for new experimental efforts on the ^{22}Ne(p,γ)^{23}Na cross section [3].
The ^{22}Ne(p,γ)^{23}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).

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 an high intensity ($\sim$200 μA) 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 characteristics of the nuclear reaction to be studied.
As a first step, a feasibility test was performed using the setup of the previous ^{2}H(α,γ)^{6}Li experiment [7].

$E_{res,LAB}$	$\omega\gamma$ [eV]		
[keV]	J. Görres (direct) [4]	NACRE [5]	Iliadis et al. [6]
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	$\leq 2.6 \cdot 10^{-6}$	$\leq 2.6 \cdot 10^{-6}$	$\leq 1.3 \cdot 10^{-6}$
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	-	-	$\leq 6.0 \cdot 10^{-4}$

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

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}Ne+p resonant cross section.

During the test, runs on the ^{22}Ne(p,γ)^{23}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 h 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.

Following the feasibility test, the characterization of the setup for the first experimental campaign on the ^{22}Ne(p,γ)^{23}Na resonances was started.

Using an extended gas target system requires to accurately know the gas density profile along the beam path. The gas density without beam was deduced from pressure and temperature values measured at different positions inside the target chamber. For this measurement, a dedicated setup was used with a target chamber of the same geometry as the one used for the measurement, but equipped with several flanges along the beam axis allowing to connect pressure or temperature gauges. 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}Ne(p,γ)^{22}Na resonance at 271.6 keV beam energy [8] and a collimated NaI detector.

For the ^{22}Ne(p,γ)^{23}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° (where the second order legendre polynomimal is zero and possible angular distribution effects are minimal) and 90° with respect to the beam direction (fig. 2). The use of two

detectors looking at different angles allows to estimate the effect of the gamma ray angular distribution on the resonance strength. The data from the two detectors will be analyzed independently to check if, for each resonance, the corresponding strengths from the two detectors are compatible within the error bars.
In order to reduce the environmental background, the two detectors were surrounded by a 4 cm thick copper shielding and a 25 cm thick lead shielding. GEANT 4 simulations of the setup indicate that this shielding will ensure about four orders of magnitude background reduction for γ ray energies below 3 MeV.

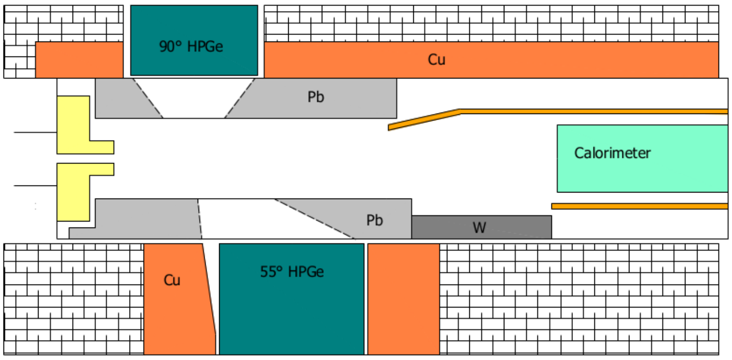

Figure 2: Sketch of the experimental setup used to study the ^{22}Ne(p,γ)^{23}Na resonances.

The gamma detection efficiency for the two detectors has been measured at several positions along the target chamber with ^{7}Be, ^{137}Cs, ^{60}Co and ^{88}Y point-like sources. The efficiency curve was then extended up to 6.79 MeV using the intense ^{14}N(p,γ)^{15}O resonance at 278 keV [9].

3. Results and Conclusions

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. For these resonances, a complete resonance scan was performed, together with a long run at the energy of maximum yield. The resonance decay modes are also observed, and in some cases the statistics is high enough to allow gamma-gamma coincidences. Fig. 3 shows the long run spectrum over the 186 keV resonance. The observed transitions are also indicated.
For the non-detected resonances new improved upper limits will be provided. The final data are still under analysis.

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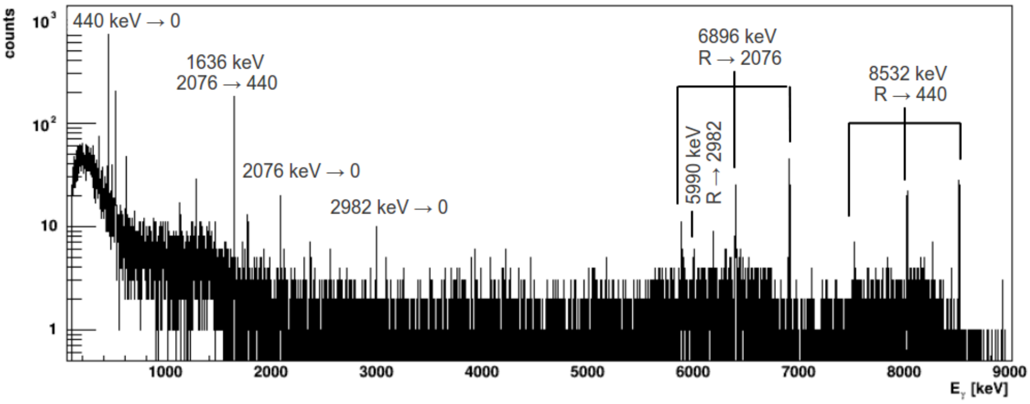

Figure 3: Long run spectrum taken with the 55° at 194 keV beam energy, over the 186 keV resonance.

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