^{23}Na(p,γ)^{24}Mg Cross Section Measurements

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Abstract. As a link between the NeNa and MgAl cycles in stellar burning, the reaction ^{23}Na(p,γ)^{24}Mg is of interest for various astrophysical scenarios, such as AGB stars. A combined effort at the Laboratory for Underground Nuclear Astrophysics (LUNA) and the Nuclear Science Laboratory (NSL) at the University of Notre Dame aims at a cross section determination for the this reaction, to constrain the astrophysical reaction rate by improving the knowledge of the resonance strengths and the non-resonant component. Experiments at LUNA benefit from the underground location at the Gran Sasso National Laboratory which allows for the measurement of resonances at low energies with high sensitivity in a low background environment. Measurements at the University of Notre Dame pursue a determination of the non-resonant cross section at higher energies. We present the two experiments and the status of the data analysis.

1 Introduction

The reaction ^{23}Na(p,γ)^{24}Mg links the NeNa and MgAl cycles in stellar hydrogen burning. For temperatures up to approximately 100 MK, typical for Red Giant Branch (RGB) and low and intermediate mass Asymptotic Giant Branch (AGB) stars, the rate of this reaction is predominantly determined by the non-resonant component of the cross section and possibly by a narrow resonance at $E_{\mathrm{c.m.}} = 138$ keV [1]. At slightly higher temperatures a narrow resonance at $E_{\mathrm{c.m.}} = 240$ keV starts to become more influential. An upper limit for the strength of the 138 keV resonance has been established in [2]. The non-resonant cross section of ^{23}Na(p,γ)^{24}Mg has not been observed in a direct experiment yet (cf. [3]). The uncertainty of these two contributions to the cross section yields large uncertainties in the astrophysical reaction rate in the temperature range given above.

2 Measurements Underground at LUNA

We used two complementary detector setups to study the ^{23}Na(p,γ)^{24}Mg reaction underground at LUNA: one setup employed a segmented BGO summing-detector [4] with high efficiency but modest energy resolution (e. g. about 4-5% energy resolution and 60% full energy detection efficiency for

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a single 12 MeV gamma ray), the other setup used a HPGe detector (ORTEC GEM120225-P-ST, located at 55° relative to the beam) that offered much better energy resolution but lower efficiency and angular coverage than the first setup (efficiency and solid angle depending on precise location of the detector relative to the target, but typically about two orders of magnitude lower compared to the BGO setup). The two setups are shown in the contribution of Pantaleo et al. in this issue.

Thin solid targets (e. g. with an energy loss of in the main target layer on the order of 10 keV for a a 300 keV proton beam) were produced by evaporating sodium compounds on 0.4 mm thick tantalum backings. Most of the measurements used targets that were produced with sodium tungstate (Na_2WO_4); other materials that were tested included Na_2SiO_3 and NaCl, but sodium tungstate appeared to provide the best compromise of uniformity and reproducibility of the production and target stability during the irradiation. We scanned the narrow $E_{\mathrm{lab}} = 309$ keV resonance in regular intervals to monitor the target degradation during bombardment. Targets were exchanged when degradation appeared to become significant (e. g. the thickness of the active target layer was significantly reduced). Ex-situ elastic recoil-detection analyses (ERDA) were performed on selected targets to obtain depth profiles of the chemical composition on various spots on the target surface.

The main purpose of the BGO detector setup was the search for the weak resonance at 138 keV. The HPGe detector was employed to study the properties of narrow resonances at higher energies, and to search for a signal from non-resonant capture or the tail of broader resonances at higher energies.

The primary signature of ^{23}Na$(p,\gamma)^{24}$Mg in the BGO summing detector is a signal at $E_{\mathrm{c.m.}} + Q$ in the spectrum of the total energy deposition (i. e. in all six detector segments combined). As the environmental backgrounds in this energy region ($Q = 11.693$ MeV for ^{23}Na$(p,\gamma)^{24}$Mg [5]) are very small, due to the underground location, the limiting factor for the sensitivity to this signature was beam-induced background. The reactions ^{11}B(p,γ) and ^{7}Li(p,γ) can both contribute to background in the ^{23}Na region of interest, as their Q-values are higher than the studied reaction on ^{23}Na. After tests with raw materials from various suppliers the level of beam-induced background could be reduced substantially (in particular the lithium contamination) by careful selection of the raw materials. Nonetheless, beam-induced backgrounds were still non-negligible at these beam energies.

For the measurement of an off-resonance cross section, the presence of weaker narrow resonances between the 309 keV resonance and the 400 keV proton energy limit at LUNA (as well as the comparatively strong 309 keV resonance itself, $\omega\gamma = (105 \pm 19)$ meV [6]) posed a problem. Resonant reactions occurring at depths beyond the main deposited layer of target material in the target (i. e. at lower proton energies) act as a background for the capture to excited states in ^{24}Mg that occurs at higher proton energies in the main layer of the target material. The observation of sodium in deeper layers of the target, caused either by diffusion or by a pre-existing contamination of sodium in the backing material, therefore limited the sensitivity to the signal of non-resonant capture to excited states.

Preliminary results from the measurements at LUNA show promise in achieving a better sensitivity for the search of the 138 keV resonance, as well as a reduced uncertainty of the strength of a narrow resonance at 240 keV and a first observation of the non-resonant capture to the ground state of ^{24}Mg.

3 Measurements at the University of Notre Dame

Whilst gamma rays from off-resonance reactions have been observed at the highest proton energies that are available at LUNA, additional information is required to constrain the direct-capture component of the cross section. This information includes the capture to excited states in ^{24}Mg, and the proper accounting for the tails of non-narrow resonances at higher energies.

To obtain this information, an experiment was conducted at the Nuclear Science Laboratory at the University of Notre Dame. A proton beam, provided by the 5U accelerator, was used to bombard a solid sodium tungstate target of the same type as previously described for the experiment at LUNA. Typical beam currents were on the order of $10\,\mu$A. We used an HPGe detector at an angle of 55° to acquire gamma ray energy spectra.

The studied range of beam energies includes resonances at $E_{\text{lab}} = 309\,\text{keV}$ and $512\,\text{keV}$, both with known resonance strengths [6], and extends up to proton energies slightly above 1 MeV. The measured range thus covers several resonances in $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ [6, 7], and data was acquired on these resonance as well as at proton energies in between them.

The analysis of this measurement is ongoing. Area and shape of the observed primary gamma lines are analyzed to obtain information on the reaction cross section and disentangle the direct capture and resonant contributions.

4 Summary

The cross section of $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ has been measured in the astrophysical energy region of interest underground at LUNA, and these measurements are expected to yield more precise information on the narrow resonances affecting the reaction rate for stellar temperatures below 100 MK. With hints of the non-resonant cross sections observed at LUNA, additional measurements were performed at the University of Notre Dame, with the aim to obtain better constraints on the non-resonant contribution to the cross section.

The analysis of both experiments is underway, and a combination of the results of both measurements is expected to reduce the uncertainty of reaction rate calculations for temperatures below 100 MK.

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