Status of the direct measurements of ^{18}O(p,γ)^{19}F and ^{23}Na(p,γ)^{24}Mg cross sections at astrophysical energies at LUNA

A Boeltzig[1], F R Pantaleo[2,3], A Best[4], G Imbriani[5,6] and M Junker[1,4]

[1] Gran Sasso Science Institute, L'Aquila, Italy
[2] Università degli Studi di Bari Aldo Moro, Bari, Italy
[3] INFN Sezione di Bari, Bari, Italy
[4] Laboratori Nazionali del Gran Sasso, Assergi, Italy
[5] Università degli Studi di Napoli Federico II, Napoli, Italy
[6] INFN Sezione di Napoli, Napoli, Italy

E-mail: axel.boeltzig@gssi.infn.it

Abstract. $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ and $^{23}\mathrm{Na}(\mathrm{p},\gamma)^{24}\mathrm{Mg}$ are reactions of astrophysical interest for example in AGB star scenarios. The rates of both reactions are potentially influenced by low-energy resonances for whose strengths either exist only values with large uncertainties, upper limits or even contradictory claims. Measurements at the Laboratory for Underground Nuclear Astrophysics (LUNA) aim at a direct observation of these low-energy resonances, and additional cross section measurements to aid a more precise determination of the reaction rates in astrophysical scenarios. We report the experimental setup and the status of the ongoing measurements of the two reactions at LUNA.

1. Motivation and Objectives

The $^{18}\mathrm{O}(\mathrm{p},\gamma)^{19}\mathrm{F}$ reaction ($Q \approx 7.99\,\mathrm{MeV}$) competes with $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$ in AGB star nucleosynthesis and may provide an explanation for an observed ^{18}O depletion in presolar grains. In the temperature range up to 10^8 K, the rate of this reaction is determined by direct capture and up to three resonances at center of mass energies of 19 keV, 90 keV and 144 keV. So far, only the 144 keV resonance has been observed in direct measurements. A recent experiment resulted in an upper limit for the resonance strength of $\omega\gamma < 7.8\,\mathrm{neV}$ (90% CL) [1]. Using data obtained from $^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}$ and $^{18}\mathrm{O}(^{3}\mathrm{He},\mathrm{d})^{19}\mathrm{F}$, a value for $\omega\gamma$ that is 90(36) times larger than this limit was derived in [2]. This resonance strength would enhance the reaction rate significantly for temperatures around 50 MK. To resolve this discrepancy, a closer study of this resonance in a direct measurement is thus desirable. Additionally, measurements of the non-resonant cross section below the 144 keV resonance with a low-background setup would complete available data from earlier measurements [3].

The reaction $^{23}\mathrm{Na}(\mathrm{p},\gamma)^{24}\mathrm{Mg}$ ($Q \approx 11.69\,\mathrm{MeV}$) links the NeNa and MgAl cycles, competing with $^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$. The reaction rates up to temperatures of 10^9 K are determined by the direct capture component and three narrow resonances at 138 keV, 241 keV and 296 keV center of mass energy. A direct measurement of the strength of the 138 keV resonance [4] resulted in an upper limit of $\omega\gamma < 5.17\,\mathrm{neV}$ (95% CL) and an indication of a signal at $\omega\gamma = 2.15(129)\,\mathrm{neV}$

Journal of Physics: Conference Series **703** (2016) 012014 doi:10.1088/1742-6596/703/1/012014

(68% CI). For the latter value, the 138 keV resonance would be the dominant contribution to the reaction rate for temperatures around 80 MK. A confirmation and more precise determination of the resonance strength would reduce the reaction rate uncertainty in this temperature range. Additionally the non-resonant cross section for this reaction is of interest.

The Laboratory for Underground Nuclear Astrophysics (LUNA) is dedicated to the direct measurement of cross sections at low energies. Thanks to its underground location at the Gran Sasso National Laboratory (LNGS) it benefits greatly from a reduced cosmic-ray background, which also allows the construction of massive shielding setups against environmental radioactivity. The low background levels that are achieved this way allow for the measurement of reactions with small cross sections. The efforts to study ^{18}O(p, γ)^{19}F and ^{23}Na(p, γ)^{24}Mg at LUNA use the same setup. They aim at the study of the resonances at 90 keV in ^{18}O(p, γ)^{19}F and 138 keV in ^{23}Na(p, γ)^{24}Mg. Measurements on the 241 keV resonance in ^{23}Na(p, γ)^{24}Mg and the non-resonant contribution for both reactions are further objectives.

2. Setup

The LUNA accelerator provides a beam of protons with energies up to 400 keV. Beam currents of 100-200 μA on target are achieved. A solid target setup, installed on one of the two beamlines present at LUNA, is used for studies of the two reactions. Solid target setups have been used in previous measurements at LUNA, the setup has been refurbished and extended for the current measurements.

Tantalum sheets are used as backings for both target types. Oxygen targets are produced by anodization, a well-established technique already used at LUNA [5]. Sodium targets are obtained by evaporation of sodium salts on the backing material. Required properties for these targets are a regular and well-defined target density profile, stability of the target composition under proton bombardment and high-purity from contaminants to avoid beam-induced backgrounds. To achieve these properties, different salts are under study, including Na_2WO_4 that has been used in earlier studies such as [4]. The target density profiles are studied and monitored in situ using narrow resonances of well-known strength in ^{18}O(p, γ)^{19}F and ^{23}Na(p, γ)^{24}Mg. Further analyses ex situ are employed in the development of Na targets.

For the resonance searches a segmented BGO detector with a solid angle coverage close to 4π [6] is used, as it provides a large full energy detection efficiency (on the order of 50% for a single 10 MeV gamma ray) at a moderate energy resolution (17% FWHM at 662 keV from ^{137}Cs).

The experimental setup also allows to use a High Purity Germanium (HPGe) detector instead of the BGO, with relatively small changes in the setup. This detector provides a much lower detection efficiency compared to the BGO detector but a greatly improved energy resolution. It is therefore well-suited to measure individual gamma ray intensities and deduce branching ratios at proton energies where the reaction rate is sufficiently large for detection given the efficiency of the detector.

3. Backgrounds

The environmental backgrounds in the BGO detector, in particular the γ ray component, are reduced by a 10 cm lead shielding surrounding the detector. With this setup the dominant environmental background in the signal region of interest for ^{18}O(p, γ)^{19}F, i. e. around its Q value, is dominated by radiative capture of thermal neutrons in the detector materials, but only on the order of 10^{-4} counts per MeV per second. In the case of ^{23}Na(p, γ)^{24}Mg the Q value lies significantly above the largest Q value of radiative neutron capture, and hence the environmental background is even lower.

Beam-induced backgrounds from reactions on beamline elements or in the target can be problematic if the Q value or the cross section of these reactions is large. Examples for potentially critical background reactions from contaminants include ^{7}Li(p,γ)^{8}Be, ^{11}B(p,γ)^{12}C

Journal of Physics: Conference Series **703** (2016) 012014 doi:10.1088/1742-6596/703/1/012014

and ^{19}F(p,$\alpha\gamma$)^{16}O. A background due to the composition of the sodium tungstate targets is ^{18}O(p, γ)^{19}F, relevant in vicinity of the stronger resonances of this reaction.

The importance of these backgrounds depend on the proton energy and the reaction under study. The ^{11}B(p,γ)^{12}C resonance, for example, is rather critical for the 138 keV resonance search in ^{23}Na(p, γ)^{24}Mg, as it has a broad resonance at 161 keV proton energy and a peak in the detected total energy spectrum that is very close to the expected signal from the resonance in ^{23}Na(p, γ)^{24}Mg. The reduction of beam-induced background contributions by careful material selection, and the subtraction and discrimination of backgrounds during the analysis are important to achieve the necessary sensitivity for competitive measurements.

4. Measurements

Measurements for both reactions are ongoing with the BGO detector setup. The non-resonant component of ^{18}O(p, γ)^{19}F has been measured from slightly above the 90 keV resonance up to 400 keV, including measurements of the resonances in this energy range for the purpose of cross checks of the normalization. The focus of the current measurements is on the search for the 90 keV resonance, and possibly the measurement of the non-resonant cross section below this resonance.

The ^{23}Na(p, γ)^{24}Mg measurements started with a focus on the 138 keV resonance search, measuring the 296 keV resonance at regular intervals as a normalization. The uncertainty of the energy of the low energy resonance is 4.0 keV [7] or 1.5 keV [8], which requires a trade-off for the proton energy studied to be high enough to be above the resonance energy, but low enough to reduce backgrounds from the broad ^{11}B(p,γ)^{12}C resonance discussed above. As a compromise, a set of energies around the central value of the resonance energy was chosen for measurements. Additionally, the non-resonant cross section is being measured.

5. Conclusions and outlook

Measurements of the ^{18}O(p, γ)^{19}F and ^{23}Na(p, γ)^{24}Mg with a high-efficiency BGO detector are currently running at LUNA. For both reactions the current phase of measurements focuses on the search for known resonances at low energies and the measurement of non-resonant cross section contribution where possible.

After this phase, measurements of both reactions with a HPGe detector are foreseen. These measurements will focus on the determination of gamma ray branching ratios in the energy ranges where the reaction rate is sufficiently high for a measurement, given the lower efficiency of the HPGe compared to the BGO detector. In particular these measurements will concern the 241 keV resonance in ^{23}Na(p, γ)^{24}Mg and the non-resonant cross section in both reactions, where the energy ranges to be studied will be guided by the results obtained in the BGO detector phase.

References

[1] Buckner M Q *et al.* 2012 *Phys. Rev.* C **86** 065804
[2] Fortune H T 2013 *Phys. Rev.* C **88** 015801
[3] Wiescher M *et al.* 1980 *Nucl. Phys.* A **349** 165–216
[4] Cesaratto J M *et al.* 2013 *Phys. Rev.* C **88** 065806
[5] Caciolli A *et al.* 2012 *Eur. Phys. J.* A **48** 144
[6] Casella C *et al.* 2002 *Nucl. Instr. Meth. Phys. Res.* A **489** 160–169
[7] Firestone R B 2007 *Nucl. Data Sheets* **108** 2319–2392
[8] Hale S E *et al.* 2004 *Phys. Rev.* C **70** 045802