

Cross Section Measurements for the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ Reaction at LUNA

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Abstract. LUNA, the Laboratory for Underground Nuclear Astrophysics, is an accelerator facility for measurements of nuclear cross sections of astrophysical interest. The greatly reduced cosmic ray background at LUNA's underground location in the Gran Sasso National Laboratory (LNGS) allows direct measurements of weak reactions at low energies.

One of the reactions currently under study at LUNA is $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$, which links the NeNa and MgAl cycles in stellar burning. The LUNA facility is presented, with a focus on the current experimental efforts to study the reaction $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$.

1. Cross Sections in Nuclear Astrophysics

Precise cross section data are vital for many considerations in nuclear astrophysics, e. g. in nuclear reaction networks for stellar evolution or nucleosynthesis. Introductions to nuclear astrophysics can be found in [1] and [2].

At astrophysical energies, i. e. energies well below the Coulomb barrier between interacting nuclei, reaction cross sections drop exponentially and become increasingly difficult to measure at lower energies. The combination of the cross section and the energy distribution of the reaction partners (determined by the temperature of the astrophysical scenario) yields the Gamow peak, i. e. the energy region defining the most significant contribution to the reaction rate. Direct measurements in or close to this region are desirable, but often challenging due to the small cross sections involved. The extrapolation of cross section data from higher energies towards the energy region of interest can introduce uncertainties, hence experimental efforts aim at measurements in or close to this region of interest.

In addition to the direct capture cross section described above, the energy dependence of the cross section can be influenced by resonances. Their contribution to the reaction rate depends again on the energy distribution of the particles according to the temperature.

2. Direct Cross Section Measurements at LUNA

The Laboratory for Underground Nuclear Astrophysics (LUNA) is a facility at the Gran Sasso National Laboratory (LNGS), dedicated to direct cross section measurements at low energies. Thanks to its location underground, LUNA benefits from an effective shielding against cosmic rays, which reduces the cosmic ray background from muons by about six orders of magnitude. Muon induced backgrounds (e. g. high-energy gamma rays) are reduced accordingly, which also allows to employ more massive shielding setups against environmental radiation before reaching the limit due to background induced by cosmic rays in the shielding material.



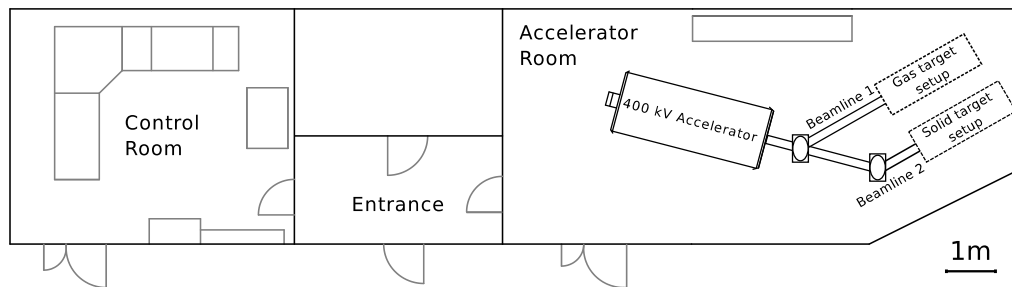


Figure 1. Schematic overview of the LUNA facility underground at LNGS.

The current stage of LUNA employs a 400 kV electrostatic accelerator that can provide beams of protons or ^4He with currents of the order of $100\ \mu\text{A}$. The beam can be directed to either one of the two beamlines located at LUNA, so that two experimental setups can be installed concurrently. Currently, different reactions are under study using a windowless gas target on one beamline and a solid target setup on the other one.

3. The Reaction $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$

The $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction ($Q \approx 11.7\ \text{MeV}^1$) provides a link between the NeNa and MgAl cycles in stellar burning, for example in asymptotic giant branch (AGB) stars. For temperatures up to about $10^9\ \text{K}$ the rate of this reaction is determined mostly by the direct capture component and three resonances at proton energies of 138 keV, 240 keV and 296 keV respectively (see [3] and references therein).

Whilst the resonance strength is known with relative uncertainties of 18% and 33% for the 240 keV and 296 keV resonance respectively [4], the value of the resonance strength for the 138 keV resonance is largely unknown. The most recent upper limit is given by [5], where the authors also report indications of a signal at 90% confidence level ($2.15 \pm 1.29\ \text{neV}$). Assuming the resonance strength implied by this indication, the 138 keV resonance would yield the dominant contribution to the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction rate at temperatures around $8 \cdot 10^7\ \text{K}$. Given the potential role of this resonance in this temperature range, a more precise determination of its strength is sought after, in order to achieve a more accurate determination of the reaction rate.

4. $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ Efforts at LUNA

LUNA aims for a measurement of the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction with a solid target setup, in which sodium samples are bombarded by a proton beam. The targets are prepared by evaporation of sodium salts (such as Na_2WO_4) onto a tantalum backing. The area density of the evaporated layer determines the energy loss of the impinging protons in the sodium target layer, defining the "thickness" of the target. Thickness and stoichiometry of the target need to be well known for the analysis of the measured reaction yields. Different techniques are used to study the target composition, in situ (with the target mounted in the setup for bombardment at LUNA) and ex situ (before or after irradiation). Ex situ, Rutherford Backscattering (RBS) and Elastic Recoil Detection Analysis (ERDA) have been used to study the composition of several targets. The main technique used in situ is Nuclear Resonance Reaction Analysis (NRRA): the stronger resonances in $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ at 240 keV and 296 keV center of mass energy and a resonance

¹ given by the mass difference of the reaction partners and products: $Q = (m(^{23}\text{Na}) + m(p) - m(^{24}\text{Mg})) \cdot c^2$

in $^{18}\text{O}(\text{p},\gamma)^{19}\text{F}$ at 151 keV proton energy yield information on the concentration of the two elements in the target. The obtained yields can for example be compared with the expectation from the stoichiometry of Na_2WO_4 . The results can also be used to monitor changes in the target composition due to the irradiation.

The challenge for a direct search of the resonance at 138 keV is the detection of event rates that are expected to be as low as a few events per Coulomb of charge accumulated on target. To detect these events with statistical significance, the experimental setup has to provide a large detection efficiency and a low background level in the signal region of interest. To achieve this, the first stage of the experiment employs a segmented Bismuth Germanium Oxide (BGO) detector [6]. The detector provides a coverage close to 4π solid angle around the target and a large gamma ray detection efficiency, due to the properties of BGO, at a moderate energy resolution (4-5% FWHM at 12 MeV). The six identical segments of the detector are read out individually, generating list mode data with time-stamped events. By adding the energy deposition of coincident events, a spectrum resembling that of one large detector can be obtained offline, optimizing the detection efficiency of a signal at the total gamma ray energy released in the reaction. The individual spectra, on the other hand, hold more information on individual gamma rays in the cascades. The full energy peak detection efficiency for a single 12 MeV gamma ray with this detector is about 60%. The efficiency can be lower for a cascade of gamma rays which is often the case for the deexcitation of a level populated in a resonance.

In a second stage, a high purity germanium (HPGe) detector will be used to study the cross section at the high end of the LUNA energy range. A HPGe detector provides a greatly improved energy resolution compared to the BGO detector, at the prize of a lower detection efficiency. Together with its lower solid angle coverage, this detector setup is suited to resolve individual gamma ray energies and determine their branching ratios. Thus the HPGe phase provides complementary information to the measurements with the BGO detector.

The same customized lead shielding is used for both detector setups, providing 10 cm (BGO) or 15 cm (HPGe) of lead around the detector as a shield against environmental gamma rays, whilst allowing fast and easy access to the target chamber at the center of the shield.

Besides environmental backgrounds, beam-induced backgrounds from reactions on nuclides other than the target nuclide are an important issue for the background budget of these direct cross section measurements. If the energy released as gamma rays following a reaction (corresponding to the Q value of this reaction) is larger than in the case of $^{23}\text{Na}(\text{p},\gamma)^{24}\text{Mg}$, this reaction can directly contribute to the $^{23}\text{Na}(\text{p},\gamma)^{24}\text{Mg}$ region of interest in the BGO detector phase. Reactions with lower Q values can contribute via pile-up. Owing to their large cross sections or strong resonances, certain reactions are particularly critical, e.g. $^{11}\text{B}(\text{p},\gamma)^{12}\text{C}$ ($Q \approx 16.0$ MeV) or $^7\text{Li}(\text{p},\gamma)^8\text{Be}$ ($Q \approx 17.3$ MeV). Careful selection of materials in the setup is required to minimize contaminations from these elements. With the gamma ray branching information of the involved reactions, the energy deposition patterns in the crystal segments can also be used to discriminate background events.

5. Status and Outlook

Measurements of the $^{23}\text{Na}(\text{p},\gamma)^{24}\text{Mg}$ reaction at LUNA with the BGO detector are ongoing, with a focus on the search for the 138 keV resonance. In addition, measurements of the direct capture component are performed in the accessible energy range. The current limiting factor for the sensitivity of the resonance search are beam induced backgrounds. Several ways to further reduce these backgrounds are under investigation. The HPGe phase will start in early 2016.

A precise model of the background contributions has to be included in the data analysis to extract the $^{23}\text{Na}(\text{p},\gamma)^{24}\text{Mg}$ signal. The analysis of BGO and HPGe data will yield cross sections and, where possible, gamma ray branching ratios. In the overlapping energy region a combined analysis is foreseen to benefit from the advantages of both techniques. Measurements at energies

above those at LUNA are planned in cooperation with the Institute for Structure and Nuclear Physics at the University of Notre Dame. A combined analysis of the low- and high-energy data, for example in the framework of R-matrix theory [7], can help to better constrain extrapolations of the cross section data.

References

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