

Study of the $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$ reaction rate important for X-ray bursts nucleosynthesis

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X-ray bursts (XRBs) are thermonuclear flashes that occur in the envelope of a neutron star accreting mass from a companion star [1]. Type I X-ray bursts are the most frequent type of thermonuclear stellar explosions in the galaxy. The bursts are characterized by a sudden rise of the X-ray luminosity followed by an exponential decay, typically lasting from 10 seconds to several minutes with a recurrence time of hours to days. The abundance flow and nucleosynthesis of XRBs are related to the temperature and density conditions and the interplay of charged-particle reactions and β decays. The main thermonuclear runaway is driven by the rp-process and the α p-process, where proton- or α -particle induced reactions on stable and radioactive nuclei occur using H and He accreted onto the surface of the neutron star. A recent study of the nucleosynthesis and nuclear processes important for type I X-ray bursts was published in Ref. [1]. This study identified about 30 nuclear reactions as the main sources of uncertainty in XRB nucleosynthesis, particularly because for most of these reactions there is no experimental rate information available. Thus, measuring the key reactions outlined in Ref. [1] will help to constrain the predictions of nucleosynthesis and light curves in XRBs.

One of the critical reactions identified in Ref. [1] is the $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$ reaction. A variation in the rates of this α capture process was found to affect the final yields of at least three isotopes around $A\approx 30$. Little experimental information exists for the states near the α and proton thresholds in ^{36}Ar located at 6.64 MeV and 8.5 MeV, respectively. Several attempts have been made to measure these near-threshold states in ^{36}Ar [2,3]. A study by Ref. [2] was performed to investigate the influence of the SCl reaction cycle in explosive hydrogen burning that may occur in a variety of scenarios such as novae, type II supernovae, and X-ray bursts. In that work, states near the proton threshold in ^{36}Ar were studied using the $^{35}\text{Cl}({}^3\text{He},d)^{36}\text{Ar}$, $^{32}\text{S}({}^6\text{Li},d)^{36}\text{Ar}$, $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$, $^{35}\text{Cl}(p,\gamma)^{36}\text{Ar}$, and $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$ reactions. However, the measurement of the $^{32}\text{S}({}^6\text{Li},d)^{36}\text{Ar}$ reaction suffered from low statistics, preventing the authors from measuring deuteron angular distributions. Therefore, only proton partial widths were measured and no spectroscopic information for the α channel was obtained. Although they were able to determine rates for the $^{35}\text{Cl}(p,\gamma)^{36}\text{Ar}$ reaction, the authors of [2] concluded that additional experimental work is needed in order to determine the (p,α) rates. In Ref. [3], the $^{35}\text{Cl}({}^3\text{He},d)^{36}\text{Ar}$ reaction was used to study states near the proton threshold, but only upper limits for the relative α widths were obtained. It is clear that additional experimental information, especially about the α channel, is needed for the reaction rate calculations of the $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$ and the $^{32}\text{S}(\alpha,p)^{35}\text{Cl}$ reactions.

The Asymptotic Normalization Coefficient (ANC) technique has been shown to be successful for measuring α partial widths of sub-threshold states and near-threshold resonances using the α -transfer reaction $({}^6\text{Li},d)$ [4-7]. It can be used to extract α partial widths of excited states in order to study α -particle induced reactions. Moreover, using this approach at sub-Coulomb energies is a very powerful technique

for studies of astrophysically important reaction rates since the results are practically model independent. This technique was first suggested in Ref. [4] and was later verified in Ref. [5] using the reaction $^{16}\text{O}(^6\text{Li},\text{d})^{20}\text{Ne}$ as a benchmark. It has also been successfully applied to study the $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ and $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reactions [6,7].

We propose to measure the spins and ANCs of the near-threshold states in order to extract the α partial widths using the α -transfer reaction $^{32}\text{S}(^6\text{Li},\text{d})^{36}\text{Ar}$ in inverse kinematics. Only states of natural parity that are strongly populated in α -transfer reactions are important for the $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$ reaction. Assuming a temperature of 1 GK, the Gamow window for this reaction covers the energy range of 1.5-2.5 MeV above the α -threshold with a peak at about 2 MeV. This corresponds to an excitation energy range of 8.14-9.2 MeV. Based on the work carried out in [2], where the $^{32}\text{S}(^6\text{Li},\text{d})^{36}\text{Ar}$ reaction was studied, we expect to populate the states at 8.28, 8.5, 8.68, 8.91, 9.12 and 9.24 MeV. It is important to note that in the work of [2] measurements of states below 8.28 MeV were not possible due to ^{16}O contaminations in the sulfur target. Since we will use inverse kinematics, the problem with this contaminant will be avoided. The aim of our study is to measure the spins and ANCs of these near-threshold states in the energy range of 8-9.2 MeV and obtain the α partial widths, important for the $^{32}\text{S}(\alpha,\gamma)^{36}\text{Ar}$ and $^{32}\text{S}(\alpha,\text{p})^{35}\text{Cl}$ reaction rate calculations. This measurement will help to better constrain predictions of nucleosynthesis and light curves in XRBs.

I. EXPERIMENT

We choose to measure the $^{32}\text{S}(^6\text{Li},\text{d})^{36}\text{Ar}$ reaction in the MDM spectrometer, capitalizing on the excellent resolution that can be achieved. An important point of using inverse kinematics is that we will avoid the difficulties associated with the use of sulfur targets such as contaminants and target deterioration effects that complicate measurements in normal kinematics. This experiment would utilize the α -transfer reaction $^{32}\text{S}(^6\text{Li},\text{d})^{36}\text{Ar}$ at sub-Coulomb energies to study states in ^{36}Ar in the excitation energy range of 8-9.2 MeV. The states that we are interested in are separated by more than 120 keV, and are thus can be resolved in our experiment that has resolution of better than 100 keV. The ^{32}S beam energy was 1.4 MeV/u and the ^6LiF target thicknesses were between 20-35 $\mu\text{g}/\text{cm}^2$ on 5-10 $\mu\text{g}/\text{cm}^2$ C foil. The idea was to impinge the ^{32}S beam on the ^6LiF target and to measure the deuterons at 0° in the MDM spectrometer in coincidence with α -particles measured with a silicon array (covering an angular range of about 10° - 60° in the lab) positioned in the scattering chamber. This way we are able to determine the spin and ANC of the states simultaneously.

We performed DWBA calculations to estimate the cross sections assuming a small spectroscopic factor of 0.1. Since the spin of the states are not known we performed the calculations using different momentum transfer, in order to estimate a lower limit of the expected rates. We estimated a conservative cross section of about 10 $\mu\text{b}/\text{sr}$. Therefore, we requested a ^{32}S beam intensity of 30 pA in order to achieve significant statistics in 6 days.

To perform this experiment we adopted the following plan:

1. To measure Rutherford scattering at 6° on ^{197}Au to calibrate the Faraday cup.
2. Measure $^6\text{Li} + ^{32}\text{S}$ elastic scattering in order to determine the ^6LiF thickness more precisely.
3. To measure the energy of the beam from the field settings.
4. To perform a wire position calibration.

5. Then to position the MDM spectrometer at 0° for the physics measurement.

For step 1 we started with low intensities of ^{32}S (about 50 pA). We successfully calibrated the Faraday cup by comparing the Rutherford scattering cross section and the reading in the Faraday cup. We found that Faraday cup reading was consistent with Rutherford scattering cross section. To proceed to step 2 we requested an increase on the ^{32}S beam intensity however we were not able to increase the beam intensity any further. Since the beam intensity was too low we were not able to proceed. It was later found that the beam intensity was low due to poor vacuum condition in the beam line leading to the MDM spectrometer. Several vacuum leaks have been eliminated since the time of experiment and vacuum has been improved by one order of magnitude. We plan to repeat this experiment after we verify the intensity of at least 10 pA can be achieved for the 1.4 MeV/u ^{32}S beam.

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