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Constraining the rp-process by measuring ^{23}Al(d,n)^{24}Si with GRETINA and LENDA at NSCL

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Abstract. The ^{23}Al(p,γ)^{24}Si stellar reaction rate has a significant impact on the light-curve emitted in X-ray bursts. Theoretical calculations show that the reaction rate is mainly determined by the properties of direct capture as well as low-lying 2^+ states and a possible 4^+ state in ^{24}Si. Currently, there is little experimental information on the properties of these states.

In this proceeding we will present a new experimental study to investigate this reaction, using the surrogate reaction ^{23}Al(d,n) at 47 AMeV at the National Superconducting Cyclotron Laboratory (NSCL). We will discuss our new experimental setup which allows us to use full kinematics employing the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) to detect the γ-rays following the de-excitation of excited states of the reaction products and the Low Energy Neutron Detector Array (LENDA) to detect the recoiling neutrons. The S800 was used for identification of the ^{24}Si recoils. As a proof of principle to show the feasibility of this concept the Q-value spectrum of ^{22}Mg(d,n)^{23}Al is reconstructed.

1 Introduction

X-ray bursts are produced when a neutron star accretes H- and He-rich material from a companion star. During infall of the material onto the neutron star gravitional energy is released which produces a constant X-ray flux. Observations of accreting neutron stars show that on top of the constant flux occasionally bright peaks occur with typical duration of 10-100s and a recurrence time of hours to days. While the neutron star accretes, the material gets compressed and heats up. At a certain point

the temperature of this thin layer gets high enough for the layer to become thermonuclear unstable. What follows is a thermonuclear runaway, involving (α,p) ,(α,γ) and (p,γ)-reactions and beta-decays, which produces the characteristic light curve. It has been shown that this light curve can be used to extract stellar parameters [1]. In order to extract information of the underlying system, one needs to correctly simulate the X-ray bursts behavior using nuclear physics information such as masses and reaction rates. Recent extensive burst simulations show that the uncertainty in the ^{23}Al(p,γ)^{24}Si-rate has a large impact on the overall light curve [2].
The ^{23}Al(p,γ)^{24}Si reaction has a relatively low Q-value of only 3.29 (20) MeV, and it is therefore mainly determined by resonant capture into low-lying resonances in ^{24}Si. Earlier attempts to reconstruct the structure of ^{24}Si are not conclusive. A low-lying 2^+ resonance has been identified at 3.441 (10) MeV [4] and 3.410 (16) MeV in [4] and [5], respectively. According to the mirror nucleus ^{24}Ne and USD shell model calculations [5], another low-lying resonance between 150-200 keV might exist, which has not been observed yet and could potentially have a significant effect on the reaction rate. We therefore performed an experiment in inverse and complete kinematics to study the surrogate reaction ^{23}Al(d,n)^{24}Si to populate the ^{24}Si states of interest in the astrophysically relevant ^{23}Al(p,g)^{24}Si reaction. First preliminary results will be presented in the next sections, proving the feasibility of this novel technique.

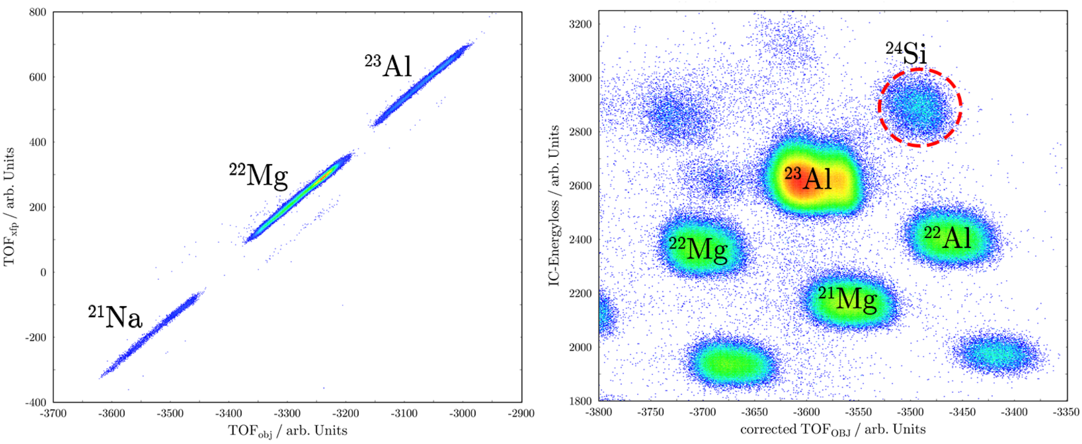

Figure 1. Incoming particle identification (ToF between the extended focal plan scintillator of the A1900 (xfp) plotted against ToF for fragments between the object scintillator of the S800) of runs without CD_2 target inserted (left). Reactions products identified in the S800 focal plane after the ^{23}Al beam hit the CD_2 target (right).

2 Experimental Details

Spectroscopic information of states in ^{24}Si near the proton separation energy is needed for ^{23}Al(p,γ) rate calculations. Thus, the main challenge in the experiment is to measure these quantities for all states up to 4 MeV in ^{24}Si, using a transfer method to populate the sates of interest (see [3] for more information).
Our new experimental concept combines the state-of-the-art γ-ray detector GRETINA [6, 7] with the neutron detector LENDA [8, 9]. This setup gives us the opportunity to perform a measurement in full kinematics and obtain very precise level energies from the gamma data and the properties of the

states from the angular distribution of the recoiling neutrons. The experiment was carried out at the National Superconducting Cyclotron Laboratory (NSCL). A primary beam of ^{22}Mg at 180 MeV/A impinged on a ^{9}Be target producing ^{23}Al via multi-particle exchange reactions. The ^{23}Al beam was then selected using the A1900 fragment separator and transported to the S800 vault. The experiment setup at the target location included GRETINA at its pivot point and LENDA at backward angles. The beam was focused on a 110.5 mg/cm^2 CD_2 target in the center of GRETINA to produce ^{24}Si by the desired ^{23}Al(d,n)-reaction. Due to the fact that half of the hemisphere was covered by the support structure of GRETINA a new double row holding structure for LENDA was used to cover an angle from 115-175 degree with respect to the beam axis. The first and second row with 12 LENDA bars each were placed at 1 and 1.1 m distance to the target, respectively. This was the best compromise between a good time of flight resolution and a high angular coverage of the 24 30x4.5x2.5cm bars for high detection efficiency.
Due to reactions on carbon atoms in the CD_2 target, runs with a 78 mg/cm^2 thick C target were used to substract background. During 7.5 days of beam time we were able to collect 96 h of data with beam on the CD_2 target and 35 h of data with the carbon target.

3 Beam production and particle identification

Figure 1 shows the incoming particle identification plot for the runs without the CD_2 target inserted. The beam composition was dominated by ^{22}Mg, resulting in a purity of ^{23}Al of only 13 %. Using the time of flight dependency between this two scintillators in the runs with target allows us to gate only on incoming ^{23}Al isotopes. The right side of Figure 1 shows the outgoing particle identification diagram gated on incoming ^{23}Al when using the CD_2 target. During the experiment we detected 11400 ^{24}Si isotopes when using the CD_2 target and 3400 ^{24}Si isotopes when using the C target.

4 Test case: ^{22}Mg(d,n)^{23}Al

In order to understand and test this new experimental technique, a reaction with higher statistics was investigated: ^{22}Mg(d,n)^{23}Al. The structure of ^{23}Al offers other advantages: there is only one excited state at 1616 keV that decays via γ-ray emission, all other states have a 100% proton-decay branching, since the proton separation threshold is very low (140 keV) and the first excited state is observed at 550 keV. The γ data of GRETINA show that the population of the state at 1616 keV via the (d,n)-reaction is negligible. All other excited states decay to ^{22}Mg before arriving at the spectrograph. Thus, only the ground state of ^{23}Al is populated through the (d,n) reaction when gating on outgoing ^{23}Al fragments in the S800 focal plane.
Figure 2 shows the angle of the detected neutrons of the ^{22}Mg(d,n)^{23}Al as a function of the kinetic energy which was determined using time-of-flight. For comparison the expected kinematics line range are also shown. The kinematic line range is a consequence of the thick target. This results in a large spread of different reaction energies in the target, which can not be reconstructed uniquely. Nevertheless, the good agreement with the experimental data shows that the employed technique is successful and we are able to investigate the transfer reaction with this method.
The Q-value spectrum can be reconstructed by:

$$(Q - Ex_{out}) = E^{N}_{kin}(1 + \frac{m_N}{m_{out}}) - E^{in}_{kin}(1 - \frac{m_{in}}{m_{out}}) - 2\sqrt{\frac{m_N m_{in} E^{in}_{kin} E^{N}_{kin}}{m^2_{out}}} \cos\theta_{lab} \tag{1}$$

where m_N, m_{in} and m_{out} are the mass of the neutron, incoming and outgoing fragment. E^{in}_{kin}, E^{N}_{kin} are the kinetic energies of the incoming fragment and the neutron and Ex_{out} is the excitation energy of the outgoing fragment. By using the energy E_{kin}^{in}, which we expect in the middle of the target, the reconstructed Q-value spectrum is rather wide (Figure 2 red line), because of the large energy loss through the target. Using event-by-event reconstruction of the isotope trajectories in the S800, a more precise determination of the energy loss in the target was obtained. This, in turn, permits the extraction of the reaction vertex in the target and results together with an approximation of the incoming beam energy by a time-of-flight measurement of each fragment between two scintillators before the target in a much more precise E_{kin}^{in} value event-by-event. With this approach, we managed to obtain a resolution of 1.1 MeV (Figure 2 blue line). A GEANT4 simulation shows that this resolution is dominated by the time resolution of the time-of-flight measurement of the neutrons which is about 951 ± 12 ps (FWHM). Analysis of the ^{24}Si data is currently under-way.

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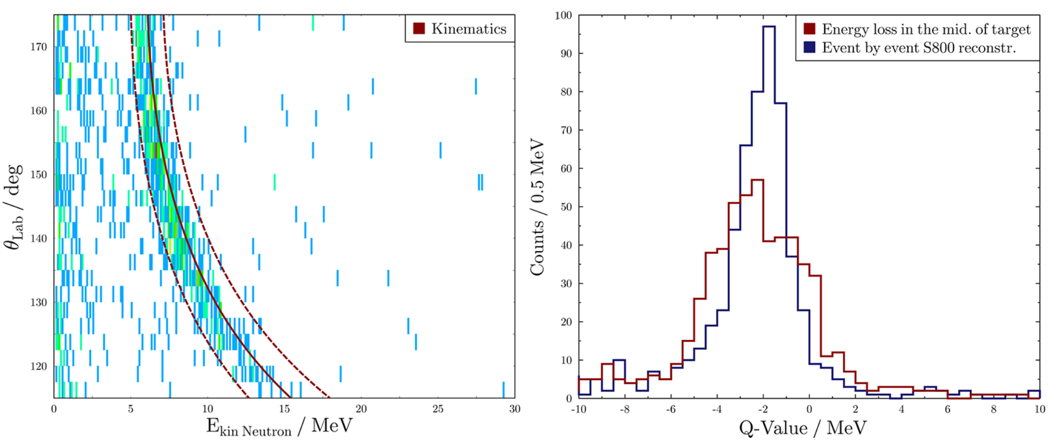

Figure 2. Left: Kinetic energy as a function of detection angle for ^{22}Mg(d,n)^{23}Al-reaction cuts. Expected kinematics line of this reaction is shown in red. Right: Reconstructed Q-value spectra of this reaction before and after the additional correction.

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