Direct radiative proton capture $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$ studied via one-proton nuclear breakup of $^{24}\text{Si}$

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Abstract. We present the results of an experimental work that studied the direct component of the radiative proton capture reaction $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$ for its relevance in X-ray burst nucleosynthesis. The experiment was performed at GANIL using one-proton nuclear breakup reaction at intermediate energies to determine the Asymptotic Normalization Coefficient (ANC) of the system $^{24}\text{Si} \rightarrow ^{23}\text{Al} + p$. Using the ANC, we evaluated the corresponding astrophysical $S$ factor and reaction rate.

1. Motivation

X-ray bursts are among the energetic events ($\sim 10^{40}-10^{42}$ ergs) observed in cosmos. It is thought that X-ray bursts are thermonuclear explosions occurring in binary systems consisting of a neutron star that accretes matter from a main sequence companion star. The extreme density found near the neutron star surface provides the environment for explosive Hydrogen and Helium burning allowing radioactive nuclei far from stability to be synthesized.

With a better understanding of the mechanism governing the explosive X-ray bursts, it is possible to determine the final abundance distribution that falls back onto the neutron star crust. To understand this explosive mechanism of X-ray burst production, it is necessary to determine reaction rates for the nuclear processes that occur during these events.

The nuclear astrophysics process considered as the onset for the explosive X-ray bursts is the rp-process (rapid proton capture). In the rp-process, proton capture is favored compared to $\beta$-decay until a nucleus with a small $(p,\gamma)$ Q-value is reached. At that point, the thermo-equilibrium between $(p,\gamma)$ radiative capture and its inverse reaction $(\gamma, p)$ photodisintegration is established.

An example of such a radiative capture reaction with a small Q-value (only 142 keV) is the reaction $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$ which is thus in thermoequilibrium with its inverse reaction $^{23}\text{Al}(\gamma,p)^{22}\text{Mg}$ at X-ray burst temperature and density conditions. To allow to break out from the $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$ -
$^{23}\text{Al}(\gamma,p)^{22}\text{Mg}$ equilibrium, it requires a fast $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$ reaction rate. The influence of the fast sequential two-proton capture reactions on $^{22}\text{Mg}$ forming $^{24}\text{Si}$ becomes important during X-ray bursts [1]. Moreover, recent sensitivity studies on X-ray burst nucleosynthesis [2] have identified the radiative proton capture $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$ among the influential reactions affecting the total energy output by more than 5%.

Following we describe a measurement performed recently at GANIL to determine with an indirect method the astrophysical $S$ factor and the reaction rate for $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$.

2. Experiment and Method

It has been demonstrated that the momentum distributions of the core fragments measured in one-nucleon breakup reactions are powerful spectroscopic tools to determine single-particle structure of the nuclei far from stability [3]. The shapes (widths) of these momentum distributions provide information on the orbital angular momentum $l$ of the removed nucleon [4], whereas the nuclear breakup cross section determines the Asymptotic Normalization Coefficient (ANC). This ANC is used to calculate the direct (non-resonant) component of the astrophysical $S$ factor of radiative capture reactions [5].

To accomplish this for the radiative proton capture $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$, we have performed an experiment [6] at the GANIL coupled cyclotron facility that measured the longitudinal momentum distributions of the $^{23}\text{Al}$ fragments resulted from the nuclear breakup of a $^{24}\text{Si}$ secondary beam. As a matter of fact, a cocktail of secondary beams was produced via the fragmentation of an intense 95 MeV/nucleon $^{32}\text{S}$ primary beam on a thick carbon target. Fourteen ion species, among which was also $^{24}\text{Si}$, with energies between 20 and 60 MeV/nucleon and intensities ranging from 30 and 7000 pps, were obtained. We had about 30 pps of $^{24}\text{Si}$ at 61 MeV/nucleon. A secondary reaction target of carbon, 175 mg/cm$^2$ thick, was used. To measure the breakup fragment momentum distributions, the SPEG energy-loss spectrometer was employed.

Ion identification at the focal plane of SPEG was achieved using the energy loss from a gas ionization chamber and the time-of-flight between a thick plastic stopping detector and the cyclotron radio frequency. Two large-area drift chambers straddling the focal plane of SPEG allowed the focal plane position spectra to be reconstructed. The longitudinal momentum of each particle was derived from the reconstructed focal plane position taking into account the beam central magnetic rigidity in SPEG. The momentum of the core fragments relative to the incident projectiles in the laboratory frame was transformed in the projectile rest frame using Lorentz transformation. To compare the measured momentum distributions with the theoretical ones, all broadening effects inherent in the measurement have been considered through Monte Carlo simulations. These effects include the energy spread in the beam, the differential energy losses of the projectiles and the fragments in the secondary target, the energy and angular straggling in the target, and the detector and spectrometer resolutions.

The reaction target was surrounded by eight EXOGAM Germanium clover detectors set up in a new configuration, for the first time in association with SPEG. This enabled us to measure also the coincidences with $\gamma$-rays from core fragments, left excited after the nuclear breakup occurred. However, this was not the case for the breakup of $^{24}\text{Si}$ because the core fragment, $^{23}\text{Al}$, does not have bound excited states.

3. Results

Figure 1 shows the experimental momentum distribution of the $^{23}\text{Al}$ core fragments, in the center-of-mass reference frame, compared with extended Glauber-type theoretical calculations, which are explained in detail in Ref. [4]. For the calculations (full curve in figure 1), we used $^{24}\text{Si}$ mid-target energy of 53 MeV/nucleon. The single-particle wave functions are calculated in a Woods-Saxon proton binding potential with a set of radius and diffuseness parameters $r_0 = 1.18$ fm and $a = 0.60$ fm.
The comparison between the experimental momentum distribution and the calculated distribution enabled us to extract the ANC for the system $^{24}\text{Si}_{gs} \rightarrow ^{23}\text{Al}(5/2^+) + p$, and an experimental spectroscopic factor with a value of 2.5, which agrees reasonably [6] with a spectroscopic factor of 3.5 obtained from large-scale shell model calculations made with modern effective interactions. The squared value of the ANC for the $^{24}\text{Si}$ ground state configuration $|5/2_{gs}^+ \otimes \pi l d_{5/2}^- \rangle$ is found to be $C^2(^{24}\text{Si}_{gs}) = 62.2 \pm 7.1 \text{ fm}^{-1}$.

Using this ANC, the direct component of the astrophysical $S$ factor and the reaction rate for $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$ can be evaluated. These results and their implication for X-ray burst nucleosynthesis are presented in a forthcoming paper. This is the first measurement of the direct (non-resonant) capture component of the radiative proton capture reaction $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$.

Figure 1. Experimental momentum distribution of $^{23}\text{Al}$ core fragments in the center-of-mass frame, compared with a theoretical calculation (see text for details).

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