

# Experimental Investigation of the Stellar Reaction $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$ via Coulomb Dissociation

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**Abstract.** Coulomb dissociation of the proton-rich nucleus  $^{31}\text{Cl}$  was studied experimentally using a  $^{31}\text{Cl}$  beam at 58 MeV/nucleon with a lead target. The relative energy spectrum of  $^{30}\text{S}+p$  system was obtained from the measured momentum vectors of the reaction products detected in coincidence by the invariant mass method. The first excited state in  $^{31}\text{Cl}$  was observed which is relevant to the resonant capture in the stellar  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$  reaction. Discussion for another observed state is also given.

## 1. Introduction

A type I X-ray burst takes place when the hydrogen-rich envelope of an accreting neutron star ignites a thermonuclear runaway. In this stellar events, rapid proton capture ( $rp$ ) process synthesizes heavier elements by passing through the nuclide  $^{30}\text{S}$  [1]. This nuclide has been considered to be a waiting point in the  $rp$  process [2] because of the low  $Q$  value (284 keV [3]) for the  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$  reaction and the long  $\beta^+$  decay lifetime (1.178 sec [4]). The low  $Q$  value establishes a  $(p, \gamma)$ - $(\gamma, p)$  equilibrium and blocks the reaction flow at  $^{30}\text{S}$  until  $\beta^+$  decay occurs. Under the low temperature ( $T \leq 0.3$  GK), equilibrium is not achieved and thus the strength of the proton capture on  $^{30}\text{S}$  affects the reaction flow in the  $rp$  process nucleosynthesis.

The  $^{31}\text{Cl}$  formation in the  $rp$  process mainly depends on the resonant capture via the first excited state in  $^{31}\text{Cl}$  at 0.75 MeV [5, 6]. Thus, direct measurements have not been made on the  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$  reaction because the cross section becomes quite small at stellar energies due to

the Coulomb barrier, and the intensities of the radioactive beams are not sufficiently large due to the use of secondary beams.

Through the Breit-Wigner expression for resonant capture via a narrow resonance, the measurement of the resonant strength  $\omega\gamma$  of a state gives the relevant  $(p, \gamma)$  cross section. The strength  $\omega\gamma$  is given by,

$$\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_\gamma \Gamma_p}{\Gamma_{tot}}, \quad (1)$$

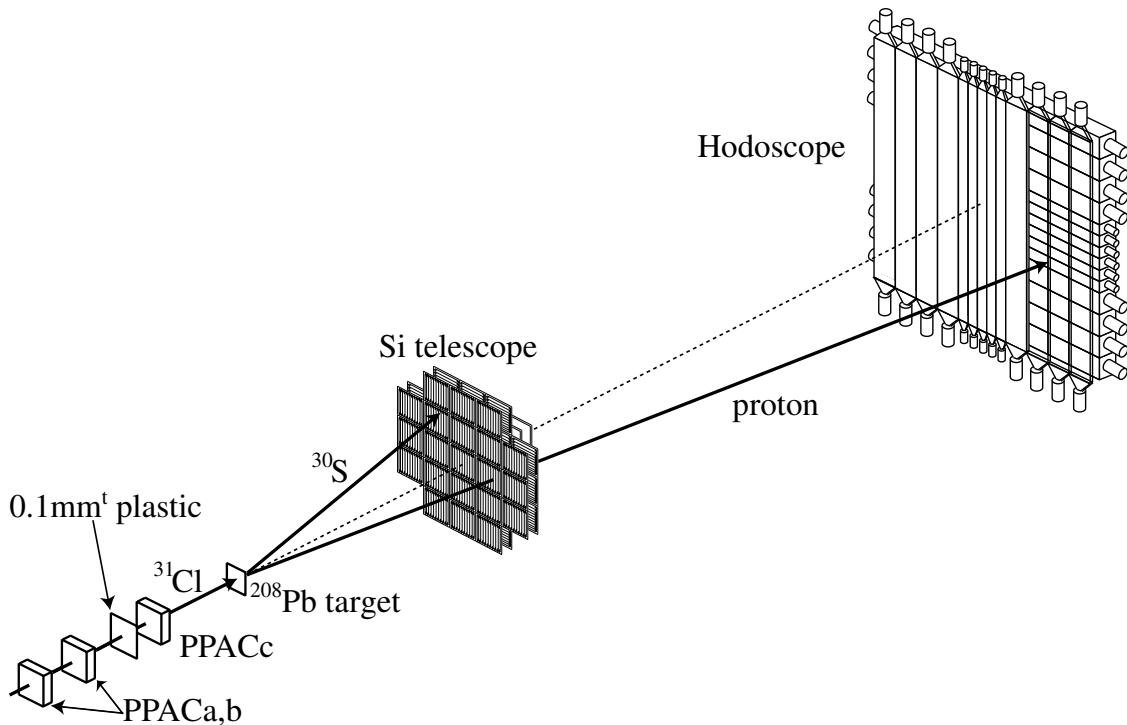
where  $J_1$  and  $J_2$  are the spins of the interacting nuclei,  $J$  is the spin of the resonant state,  $\Gamma_\gamma$  is the radiative width,  $\Gamma_p$  is the proton decay width, and  $\Gamma_{tot}$  is the sum of those two widths. In most cases including the first excited state in  $^{31}\text{Cl}$ , the  $\Gamma_p$  value is much larger than the  $\Gamma_\gamma$  value, thus the strength  $\omega\gamma$  is almost determined by the  $\Gamma_\gamma$  value. Therefore the strength of the resonant proton capture reaction on  $^{30}\text{S}$  via the first excited state in  $^{31}\text{Cl}$  can be obtained by determining the width  $\Gamma_\gamma$ . No direct measurement have been done for  $\Gamma_\gamma$ . Ref. [3] give the estimate of the  $\Gamma_\gamma$  value for the first excited state in  $^{31}\text{Cl}$  based on a lifetime of the mirror state in  $^{31}\text{Si}$ . This estimate may have potential uncertainties, thus the direct measurement is desired.

In order to extract the  $\Gamma_\gamma$  value experimentally, the Coulomb dissociation method was applied for the present study. The Coulomb dissociation with intermediate energy beams is an alternative method to study proton capture reactions of astrophysical interest at low energy [7]. The reaction process can be regarded as a photodisintegration induced by the virtual photon absorption. Thus the electromagnetic transition probability can be obtained, which can be convert to the width  $\Gamma_\gamma$ .

In this paper we aimed at investigating the resonances in  $^{31}\text{Cl}$  for the study of the stellar  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$  reaction using the Coulomb dissociation method.

## 2. Experimental Setup

The experiment was performed using the RIBF accelerator complex operated by RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. The secondary beam of  $^{31}\text{Cl}$  was produced by fragmentation of a 115-MeV/nucleon  $^{36}\text{Ar}$  beam incident on a 531 mg/cm<sup>2</sup> thick Be target. The secondary beams were selected by the RIKEN Projectile-fragment Separator (RIPS) [8] with the help of a RF-deflector system [9]. The typical  $^{31}\text{Cl}$  intensity was about 500 counts per second and the energy was 58 MeV/nucleon with a momentum spread of 0.5 %. The isotropic purity of  $^{31}\text{Cl}$  in the secondary beam was about 8%. The major contaminants were  $^{30}\text{S}$  and  $^{24}\text{Na}$ . The beam of  $^{31}\text{Cl}$  bombarded a  $^{208}\text{Pb}$  target whose thickness was 104 mg/cm<sup>2</sup>. The particle identification for the secondary beams was performed event-by-event by means of the time of flight (TOF) -  $\Delta E$  method using the RF signal of the cyclotrons, a 0.1 mm thick plastic scintillator and a 0.1 mm thick silicon detector located at the final focal plane of the RIPS. Three sets of parallel plate avalanche counters (PPACs) were also placed at the final focal plane to extrapolate the position and angle of the beams at the target position. The reaction products, i.e.,  $^{30}\text{S}$  ions and protons, were measured by the detectors located downstream of the target as shown in Fig. 1. The emission angles of these products were measured by a position sensitive silicon telescope located 62 cm downstream of the target. The kinetic energy of  $^{30}\text{S}$  was also measured by the telescope. The telescope consisted of four layers of detectors arranged in a  $5 \times 5$  matrix without 4 detectors at the corners for the first and second layers, and a  $3 \times 3$  matrix for the third and fourth layers. Each layer was composed of silicon detectors with an effective area of  $50 \times 50$  cm<sup>2</sup> and with a thickness of 500, 500, 325, and 500  $\mu\text{m}$ , respectively.  $^{30}\text{S}$  was stopped at the fourth layer, and identified using the  $\Delta E$  and  $E$  information. The energy of protons, which penetrated the silicon telescope, was determined with a plastic scintillator hodoscope placed 2.95 m downstream of the target by measuring the TOF. The hodoscope had an active area of  $1 \times 1$  m<sup>2</sup>, consisting of thirteen 5-mm-thick  $\Delta E$ - and sixteen 60-mm-thick  $E$ -plastic scintillators. The protons were identified by TOF,  $\Delta E$ , and  $E$  information. The relative energy  $E_{rel}$  between



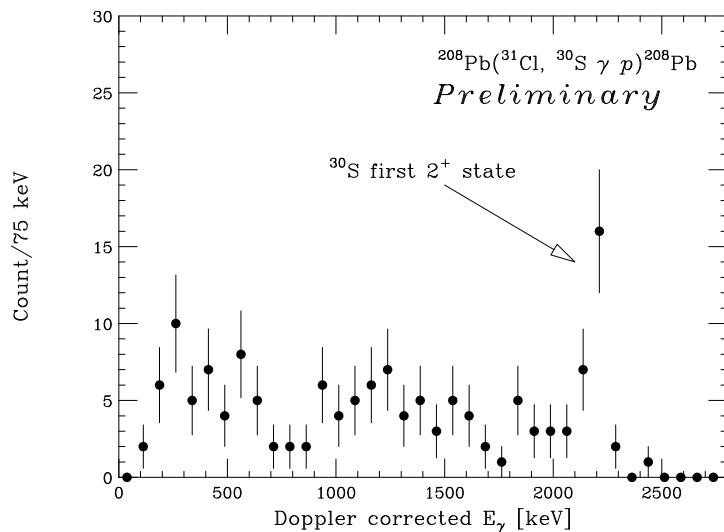
**Figure 1.** A Schematic view of the experimental setup. The entire system was in vacuum.

the  $^{30}\text{S}$  ions and proton was obtained using the measured emission angles and energies of the products. The excitation energy  $E_x$  in  $^{31}\text{Cl}$  is the sum of  $E_{\text{rel}}$  and the one proton separation energy of  $^{31}\text{Cl}$ . An array of 160 NaI(Tl) scintillator DALI2 [10] was placed around the target to measure de-excitation  $\gamma$  rays from the reaction products. The high granularity of the DALI2 provides a measurement of the  $\gamma$  emission angle enabling corrections of the Doppler shifts.

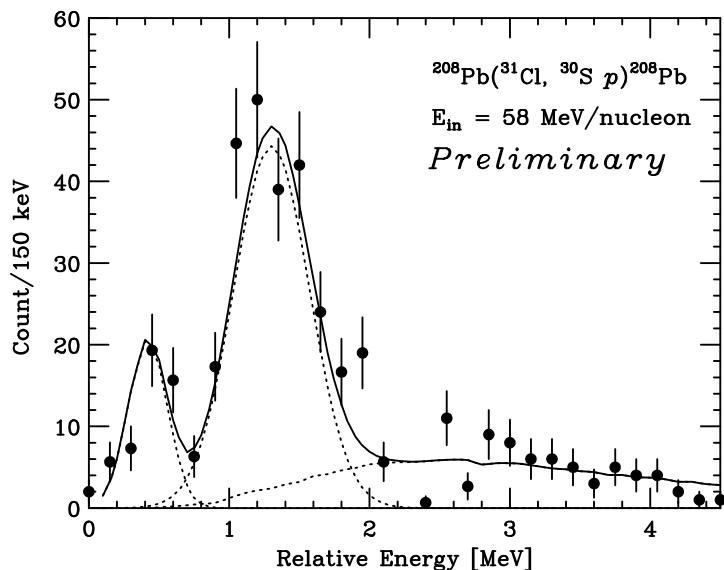
### 3. Results and Discussions

Figure 2 shows the preliminary Doppler-shift corrected energy spectrum of the  $\gamma$  ray for  $^{31}\text{Cl} \rightarrow ^{30}\text{S} + p$  events. To suppress the background event due to Compton scattering events, the events with multiplicity of the NaI(Tl) detectors equal to 1 were selected. A peak at 2.2 MeV, which corresponds to the de-excitation from the known first excited state to the ground state in  $^{30}\text{S}$  [11]. This 2.2 MeV  $\gamma$  ray was the indication that  $^{31}\text{Cl}$  was excited to the excited state higher than 2.2 MeV + one proton separation energy of  $^{31}\text{Cl}$ . These events were excluded from the analysis by taking the detection efficiency of the 2.2 MeV  $\gamma$  ray into consideration to subtract the contribution of highly excited events which decays to  $^{30}\text{S}(2^+)$  and proton. The photo-peak efficiency of the DALI2 was estimated from a Monte-Carlo simulation to be 12% for a 2.2 MeV  $\gamma$  ray.

The preliminary spectrum of the relative energy  $E_{\text{rel}}$  between the  $^{30}\text{S}$  ions and protons is shown in Fig. 3. The circles are the experimental data. The solid curve represents the best fit with two Gaussian functions for the two peaks and a broad distribution for the direct capture component. The single components are shown by the dashed curves. The peak at  $E_{\text{rel}} = 0.45$  MeV corresponds to the known first excited state at  $E_x = 0.75$  MeV in  $^{31}\text{Cl}$  [5]. The peak at  $E_{\text{rel}} = 1.3$  MeV may correspond to the  $E_x = 1.7$  MeV state. Our result is 0.15 MeV smaller than the previously obtained resonance energy. The widths of the two peaks were



**Figure 2.** Preliminary Doppler-shift corrected energy spectrum of the  $\gamma$  ray in coincidence with inelastically scattered  $^{31}\text{Cl}$  followed by decay to  $^{30}\text{S}$  and proton. The peak at 2.2 MeV corresponds to the de-excitation from the first  $2^+$  state to the ground state of  $^{30}\text{S}$ .



**Figure 3.** Preliminary relative energy spectrum of  $^{31}\text{Cl}$  dissociation on  $^{208}\text{Pb}$  (circles). The data was fitted by assuming two resonances and a direct capture component. The dashed curves and solid curve represent each component and sum of them, respectively.

consistent with the experimental resolution. The component which distributes broadly from 0.8 to 4.5 MeV corresponds to the direct proton capture process. The direct capture was assumed to be dominated by the E1 transition with an astrophysical S-factor independent of the relative energy.

The Coulomb dissociation reaction is more sensitive to the electric quadrupole (E2) transition than the magnetic dipole transition (M1) at the beam energies of several tens of MeV/nucleon

[7]. This makes measurement of M1 transition strength difficult when the E2 transition is also allowed. E2 and M1 transitions are allowed between the first excited state ( $1/2^+$ ) and the ground state ( $3/2^+$ ) in  $^{31}\text{Cl}$ . The shell model with the USDB effective interaction [12] predicts the M1 transition probability is 400 times larger than E2 probability. The number of virtual photon which emits in a single collision for E2 transition is about 5000 times larger than the one for M1 transition [7]. Thus the contribution of the E2 component is almost dominant to the Coulomb dissociation cross section, whereas M1 component is dominant in the  $(p, \gamma)$  reaction. However, it is possible to decompose the M1 component from the total cross section using the angular distribution of the scattered  $^{31}\text{Cl}$  because the M1 component distributes at the forward angle, whereas the E2 component is almost flat distribution [13]. The  $\Gamma_\gamma$  value of the first excited state in  $^{31}\text{Cl}$  will be obtained by decomposing the M1 component from the analysis of the angular distribution.

#### 4. Summary

The stellar reaction  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$ , which is relevant to the  $rp$  process on the accreting neutron star, was experimentally investigated using the Coulomb dissociation of  $^{31}\text{Cl}$ . The relative energy spectrum between the  $^{30}\text{S}$  ion and proton were obtained using measured momentum vectors of the reaction products. In the spectrum, we observed the first excited state at  $E_{\text{rel}} = 0.45$  MeV, which is important in the stellar resonant proton capture reaction  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$ . We also observed the resonance at  $E_{\text{rel}} = 1.3$  MeV for the first time. It may be the mirror state of the 1.7-MeV state in the mirror nucleus  $^{31}\text{Si}$ . Since the spins and parities of the ground and first excited state in  $^{31}\text{Cl}$  are  $3/2^+$  and  $1/2^+$ , respectively, E2 and M1 transitions can contribute to the cross section to the first excited state. The angular distribution of the scattered  $^{31}\text{Cl}$  which was excited to the first excited state is under analysis to obtain the E2 and M1 component of the  $\Gamma_\gamma$  value.

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