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Astrophysical reaction rate of ^{30}S$(p,\gamma)^{31}$Cl studied by Coulomb dissociation

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The Coulomb dissociation of the proton-rich nucleus ^{31}Cl was studied experimentally using a ^{31}Cl beam at 58 MeV/nucleon with a lead target. The relative energy spectrum between ^{30}S ions and protons 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}Cl was observed which is relevant to the resonant capture in the stellar ^{30}S$(p,\gamma)^{31}$Cl reaction. Discussion for another observed state is also given.

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PoS(NIC XI)228

1. Introduction

The rapid proton capture (*rp*) process in a type I X-ray burst synthesizes heavy elements ($A \sim 100$) through stellar reactions of proton-rich nuclei [1]. In this process, the nuclide ^{30}S has been considered to be a waiting point [2] because of the low Q value (284 keV [3]) for the ^{30}S$(p,\gamma)^{31}$Cl reaction and the long β^+ decay lifetime (1.178 sec [4]). The low Q value establishes a (p,γ)-(γ,p) equilibrium and blocks the reaction flow at ^{30}S until β^+ decay occurs. At low temperatures, (T $\leq$ 0.3 GK), equilibrium is not achieved and thus the strength of the proton capture on ^{30}S affects the reaction flow in the *rp* process nucleosynthesis under T $\leq$ 0.3 GK conditions.

The ^{31}Cl formation in the *rp* process mainly depends on the resonant capture via the first excited state in ^{31}Cl at 0.75 MeV [5, 6]. Thus far, direct measurements have not been made on the ^{30}S$(p,\gamma)^{31}$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,γ) cross section. The strength $\omega\gamma$ is given by,

$$\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_\gamma\Gamma_p}{\Gamma_{tot}}, \tag{1.1}$$

where J_1 and J_2 are the spins of the interacting nuclei, J is the spin of the resonant state, Γ_γ is the radiative width, Γ_p is the proton decay width, and Γ_{tot} is the sum of those two widths. In most cases including the first excited state in ^{31}Cl, the Γ_p value is much larger than the Γ_γ value, thus the strength $\omega\gamma$ is almost determined by the Γ_γ value. Therefore the strength of the resonant proton capture reaction on ^{30}S via the first excited state in ^{31}Cl can be obtained by determining the width Γ_γ.

In order to extract the Γ_γ value, the Coulomb dissociation method was applied for the present study. The Coulomb dissociation with intermediate energy beams is an alternative method to to study the proton capture reactions of astrophysical interests at low energy [7]. The reaction process can be regarded as a photodisintegration induced by virtual photon absorption, the inverse process of the proton capture reaction. Thus we can convert the Coulomb dissociation cross section to the proton capture cross section using detailed balance. The Coulomb dissociation cross section is much ($\sim 10^5$ times) larger than the proton capture cross section because of the large phase volume of the Coulomb dissociation reaction.

In this paper we aimed at determining the Γ_γ value of the first excited state in ^{31}Cl to investigate the stellar ^{30}S$(p,\gamma)^{31}$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}Cl was produced by fragmentation of a 115-MeV/nucleon ^{36}Ar beam incident on a 531 mg/cm^2 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}Cl intensity was about 500 counts per

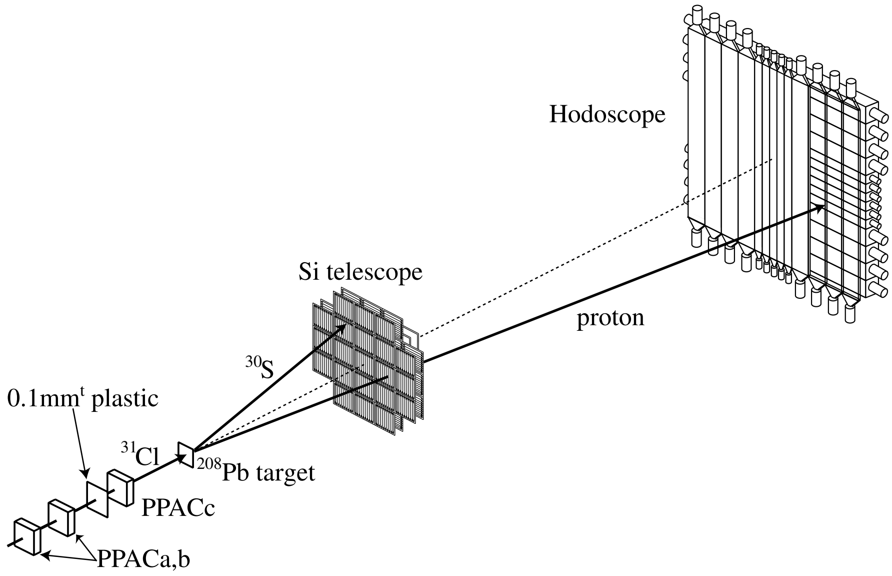

Figure 1: A Schematic view of the experimental setup. The entire system was in vacuum.

second and the energy was 58 MeV/nucleon with a momentum spread of 0.5 %. The isotropic purity of ^{31}Cl in the secondary beam was about 8%. The major contaminants were ^{30}S and ^{24}Na. The beam of ^{31}Cl bombarded a ^{208}Pb target whose thickness was 104 mg/cm^2. The particle identification for the secondary beams was performed event-by-event by means of the time of flight (TOF) - ΔE 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}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}S was also measured by the telescope. The telescope consisted of four layers of detectors arranged in a 5×5 matrix without 4 detectors at the corners for the first and second layers, and a 3×3 matrix for the third and fourth layers. Each layer was composed of the silicon detectors with an effective area of 50×50 cm^2 and with a thickness of 500, 500, 325, and 500 μm, respectively. ^{30}S was stopped at the fourth layer, and identified using the ΔE 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 1×1 m^2, consisting of thirteen 5-mm-thick ΔE- and sixteen 60-mm-thick E-plastic scintillators. The protons were identified by TOF, ΔE, and E information. The relative energy E_{rel} between the ^{30}S ions and proton was obtained using the measured emission angles and energies of the products. The excitation energy E_x in ^{31}Cl is the sum of E_{rel} and the one proton separation energy of ^{31}Cl. An array of 160 NaI(Tl) scintillator DALI2 [10] was placed around the target to measure de-excitation γ rays from the reaction products. The high granularity of DALI2 provides a measurement of the γ emission angle enabling corrections of

PoS(NIC XI)228

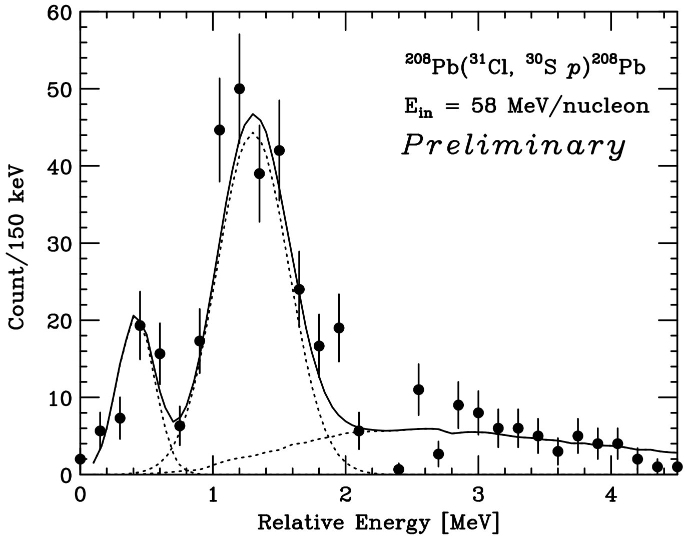

Figure 2: Preliminary relative energy spectrum of ^{31}Cl dissociation on ^{208}Pb (circles). The data was fitted by assuming two resonances and a direct capture components. The dashed curves and the solid curve represent each component and sum of them, respectively.

the Doppler shifts.

3. Results and Discussions

The preliminary spectrum of the relative energy E_{rel} between the ^{30}S ions and protons is shown in Fig. 2. 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. Each component is shown by the dashed curves. The peak at E_{rel} =0.45 MeV corresponds to the known first excited state at E_x =0.75 MeV in ^{31}Cl [5]. The peak at E_{rel} =1.3 MeV may be attributed to the known state at $E_x = 1.75$ MeV [5]. The widths of the two peaks were consistent with the experimental resolution. The broad component from 0.8 MeV to 4.5 MeV corresponds to the direct proton capture process. The direct capture was assumed to be dominated by the E1 transition and the astrophysical S-factor to be independent of the relative energy.

The Coulomb dissociation reaction is sensitive specifically to electric dipole (E1) and quadrapole (E2) transitions at beam energies of several tens of MeV/nucleon [7]. E2 and M1 transitions are allowed between the first excited state (1/2$^+$) and the ground state (3/2$^+$) in ^{31}Cl. The M1 transition probability of the first excited state of ^{31}Cl may be much larger than the E2 probability, because M1 transition is dominant for the mirror transition in ^{31}Si [12]. Thus the contributions of the M1 and E2 transitions to the cross section can be comparable, and then the decomposition of them is required to obtain the E2 and M1 transition probabilities. To decompose them, the angular distribution of the scattered ^{31}Cl, which was excited to the first excited state, is under analysis because the distributions are different for E2 and M1 transitions [13].

The M1 component is dominant in the Γ_γ value of the first excited state in ^{31}Cl, thus obtaining the M1 component through the analysis of the angular distribution is important.

4. Summary

The stellar reaction ^{30}S(p,γ)^{31}Cl, which is relevant to the *rp* process in a type I X-ray burst, was experimentally investigated using the Coulomb dissociation of ^{31}Cl. The relative energy spectrum between the ^{30}S ion and proton were obtained using measured momentum vectors of the reaction products. In the spectrum, we observed the first excited state at $E_{rel} = 0.45$ MeV, which is important in the stellar resonant proton capture reaction ^{30}S(p,γ)^{31}Cl. We also observed a resonance at $E_{rel} = 1.3$ MeV for the first time. It may be the mirror state of the 1.7-MeV state in the mirror nucleus ^{31}Si. Since the spins and parities of the ground and first excited state in ^{31}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}Cl which was excited to the first excited state is under analysis to obtain the E2 and M1 component of the Γ_γ value.

References

[1] H. Schatz *et al.*, *End Point of the rp Process on Accreting Neutron Stars, Phys. Rev. Lett.* **86** (2001) 3471.

[2] J. L. Fisker, F. K. Thielemann, and M. Wiescher, *The Nuclear Reaction Waiting Points ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar and Bolometrically Double-peaked Type I X-ray Bursts, Astrophys. J.* **608** (2004) L61.

[3] C. Wrede *et al.*, *Thermonuclear ^{30}S(p,γ)^{31}Cl reaction in type 1 X-ray bursts, Phys. Rev. C* **79** (2009) 045808.

[4] P. H. Barker, N. Drysdale, and W. R. Phillips, *The Beta Decays of ^{22}Mg, ^{30}S and ^{34}Ar, Proc. Phys. Soc. (London)* **91** (1967) 587.

[5] L. Axelsson em et al., *Beta Decay of ^{31}Ar Nucl. Phys. A* **634** (1998) 475.

[6] C. Iliadis *et al.*, *Proton-induced Thermonuclear Reaction Rates for A=20-40 Nuclei Astrophys. J. Suppl. Ser.* **134** (2001) 151.

[7] G. Baur, C. A. Bertulani, and H. Rebel, *Coulomb dissociation as a source of information on radiative capture processes of astrophysical interest Nucl. Phys. A* **458** (1986) 188.

[8] T. Kubo *et al.*, *The RIKEN radioactive beam facility Nucl. Instr. and Meth. B* **70** (1992) 309.

[9] K. Yamada *et al.*, *RF deflector system for proton-rich RI beams in RIKEN Nucl. Phys. A* **746** (2004) 156c.

[10] S. Takeuchi *et al.*, *Development of NaI(Tl) detector array for in-beam γ-ray spectroscopy RIKEN Accel. Prog. Rep.* **36** (2003) 148.

[11] T. K. Alexander *et al.*, *Lifetimes of Levels of ^{30}S and the Variation of E2 Transition Strength with $T(z)$ and A Phys. Rev. Lett.* **49** (1982) 438.

[12] P. M. Endt and R. B. Firestone, *Supplement to energy levels of A=21-44 nuclei Nucl. Phys. A* **633** (1998) 1.

[13] C. A. Bertulani and G. Baur, *Electromagnetic processes in relativistic heavy ion collisions Phys. Rep.* **163** (1988) 299.