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Study of the ^{26}Si(p, γ)^{27}P reaction through Coulomb dissociation of ^{27}P

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Abstract. The Coulomb dissociation of ^{27}P was studied experimentally using ^{27}P beams at 57 MeV/nucleon with a lead target. The $E2$ gamma decay width of the first excited state in ^{27}P was determined to be $(2.8 \pm 0.5) \times 10^{-5}$ eV. The total $(M1 + E2)$ gamma decay width of the state, which is of astrophysical interest, is estimated by combining the experimental result and a shell model calculation. The reaction rate of ^{26}Si(p, γ)^{27}P is deduced from the estimated total gamma decay width. The astrophysical implication derived from estimated gamma decay width is discussed.

PACS. 25.60.-t Reaction induced by unstable nuclei – 25.70.De Coulomb excitation – 26.30.+k Nucleosynthesis in novae, supernovae and other explosive environments – 27.30.+t $20 \leq A \leq 38$

1 Introduction

The mapping of the isotope ^{26}Al in the interstellar medium through the detection of its 1.809 MeV γ line by satellites [1] has increased the interest in ^{26}Al nucleosynthesis. This is a trace of ongoing nucleosynthesis in the universe because lifetime of ^{26}Al (10^6 yr) is much shorter than the timescale of the cosmic evolution. Consequently, the nuclear physics of the isotopes around ^{26}Al is of importance.

The ^{26}Si(p, γ)^{27}P reaction is relevant to the synthesis of ^{26}Al. The nuclide ^{26}Si β decays to the isomeric state of ^{26}Al which subsequently β decays to the ground state of ^{26}Mg, thus no γ-ray is emitted. The characteristic 1.809 MeV γ line is only emitted by the β decay of ^{26}Al in the ground state. Therefore, the synthesis of ^{26}Si was not thought to contribute the γ-ray emission of ^{26}Al. Recently, it has been suggested that high temperature environment with $T_9 \geq 0.4$ is hot enough to establish an equilibrium between the isomeric state and the ground state in ^{26}Al [2]. Therefore, ^{26}Si destruction by proton capture is important to determine the amount of the ground state in ^{26}Al produced by the equilibrium.

Under this high temperature the capture reaction rate, $N_A\langle\sigma v\rangle$, is expected to be dominated by the resonant capture via the first excited state in ^{27}P [3]. Resonant capture rates for isolated, narrow resonances are given by

$$N_A\langle\sigma v\rangle = 1.54 \times 10^{11}(\mu T_9)^{-3/2}\omega\gamma \exp\left[-11.605\frac{E_R}{T_9}\right] \quad (1)$$

with N_A Avogadro's number, μ the reduced mass in amu, T_9 the temperature in unit of GK, $\langle\sigma v\rangle$ the thermally averaged nuclear cross section, and E_R the resonance energy in MeV [4]. The resonance strength $\omega\gamma$ is given by

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

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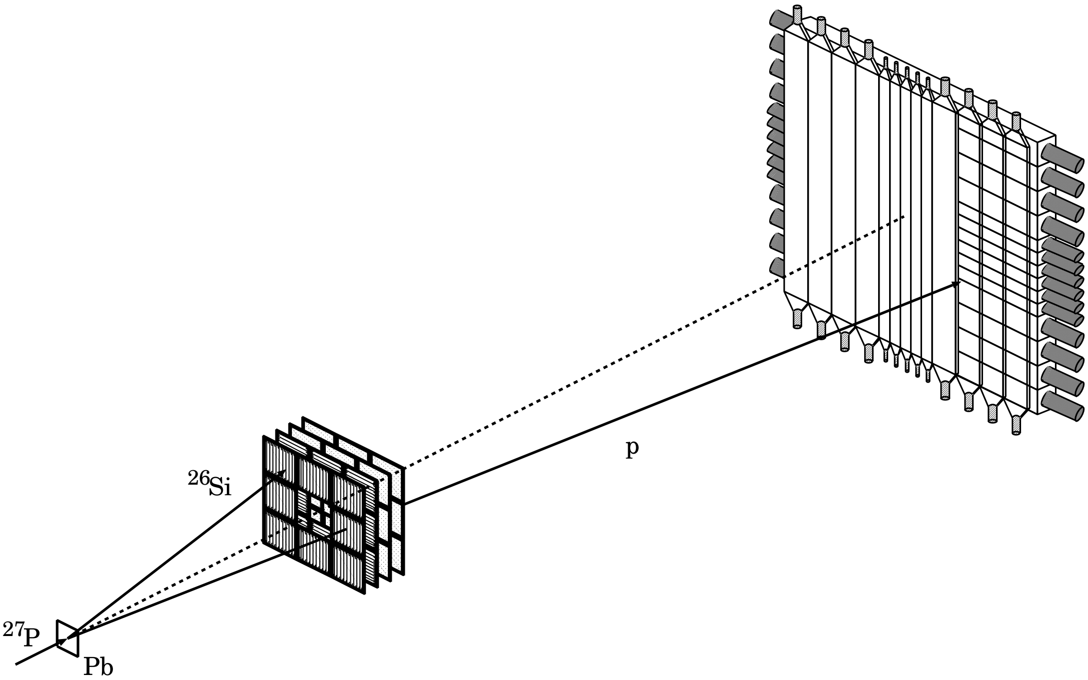

Fig. 1. A schematic view of the experimental setup. The entire system is in vacuum.

where J is the spin of the compound nucleus, and J_p and J_T are the spins of the proton and target, respectively. Γ_p and Γ_γ are the proton widths and the gamma decay widths of the resonance. The total width Γ_{tot} is the sum of the partial widths.

A direct measurement of the relevant capture cross section is the preferable method for determining the proton capture reaction rates. However, the cross section becomes quite small at stellar energies due to the Coulomb barrier and radioactive beams of sufficient intensities are not available. Therefore, indirect methods must be employed to extract the information about the reaction rate.

The Coulomb dissociation at intermediate energies is an alternative method to study the radioactive capture reactions of astrophysical interest at low energies [5,6,7]. The process can be regarded as photodisintegration by virtual photons, which is essentially the inverse of the radiative capture process [8]. The extracted electromagnetic transition probability is directly determines the Γ_γ. The Coulomb breakup process is characterized by a large cross section which helps to compensate for the small capture cross section.

The present paper reports on an experimental study of the dissociation of ^{27}P in the Coulomb field of a Pb nucleus. The Γ_γ values of the first excited state in ^{27}P, which have the largest contribution to the resonant capture rate of $^{26}\mathrm{Si}(\mathrm{p},\gamma)^{27}\mathrm{P}$, has been extracted.

2 Experiment

The experiment was performed at the RIKEN Accelerator Research Facility. A ^{27}P beam was produced via the projectile fragmentation of a 115-A-MeV ^{36}Ar beam incident on a 460 mg/cm^2 thick Be target, and separated by the RIKEN Projectile-fragment Separator (RIPS) [9]. The typical ^{27}P intensity was about 2800 counts per second and the energy was 57 A MeV with an energy spread of about 1.5%. It bombarded a 125 mg/cm^2 thick lead target. The isotopic purity of ^{27}P in the secondary beam is about 1%. The major contributions are ^{26}Si, ^{25}Al, and ^{24}Mg. The particle identification for secondary beams was performed event by event by means of the time-of-flight (TOF)-ΔE method using a 0.5 mm thick plastic scintillator located at the second focal plane of the RIPS. Two sets of parallel plate avalanche counters were also placed at the final focal plane of the RIPS to extrapolate the position and angle of the beam at the target.

The isotope ^{27}P were excited by the lead target and disintegrated to ^{26}Si and proton. Figure 1 shows the detector system for the measurement of breakup products. The emission angles of these products were measured at a position-sensitive silicon telescope located at 48 cm downstream of the target. The silicon telescope consists of four layers of detectors with 0.5 mm thickness. Each layer was of eight silicon detectors with $50 \times 50\,\mathrm{mm}^2$ effective areas on $56 \times 56\,\mathrm{mm}^2$ frames. The eight detectors in a layer formed a 3×3 matrix with a hole in the center. The count rate in the telescope was suppressed to 3000 counts per second by introducing the hole whereas the total beam rate was about 3×10^5 count per second. The detectors in the first and second layers have 5 mm wide strip electrodes, which enables to measure the hit positions of the products. The energy of the ^{26}Si was also measured by the silicon telescope. ^{26}Si was stopped at the fourth layer, and identified using the ΔE-E method.

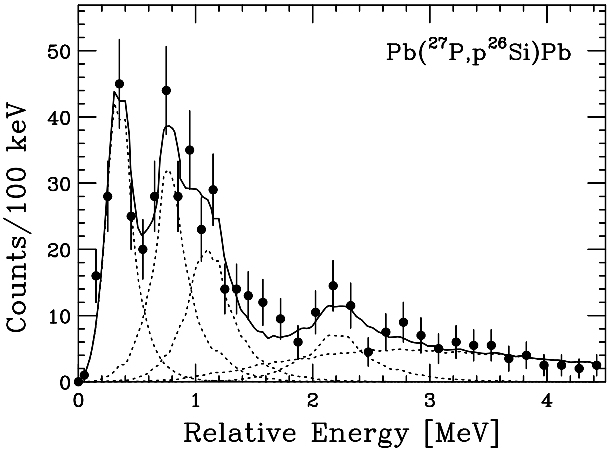

Fig. 2. Relative energy spectrum of the ^{27}P breakup on Pb (full circle). The data was fitted by the detector responses simulated using Geant4 code [10]. The dashed curves and solid curve represent the components and sum of the elements.

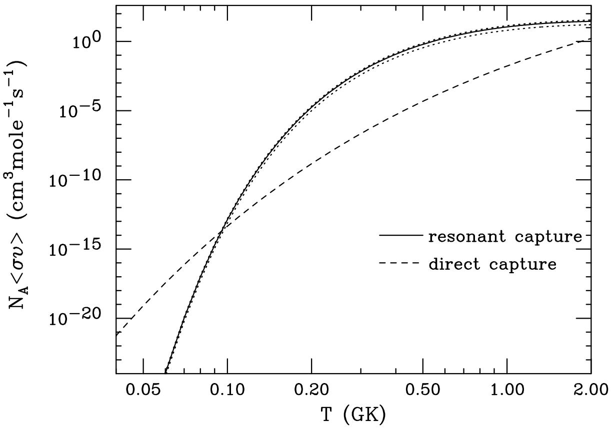

Fig. 3. The reaction rate of ^{26}Si(p, γ)^{27}P as a function of the temperature of stars. The solid and dotted curve represent our result and the range of its error, respectively. The dashed line shows the direct capture component estimated by J.A. Caggiano *et al.* [3].

The energy of the proton, which penetrated the silicon telescope, was determined with a plastic scintillator hodoscope placed at the 2.8 m downstream of the target by measuring the TOF. The hodoscope with an active area of $1 \times 1\,\mathrm{m}^2$, consists of thirteen 5 mm thick ΔE- and sixteen 60 mm thick E-plastic scintillators. The outgoing proton was stopped in the E counters after passing through the ΔE counters. The proton was identified by the TOF-ΔE and TOF-E methods.

The relative energy E_{rel} between ^{26}Si and proton was extracted by combining the positions and energies of the products. The energy E_{rel} corresponds to the center-of-mass energy, and thus the excitation energy of ^{27}P E_x can be expressed as

$$E_x = E_{rel} + E_s, \quad (3)$$

where E_s represents the separation energy for the decay channel (0.859 MeV for ^{27}P). Therefore, by measuring the E_{rel} the excitation energy E_x can be determined.

3 Result and discussion

The relative energy spectrum is shown in fig. 2. The full circles represent the experimental data. The solid curve represents the best fit with five contributions shown by the dashed curves. The detector responses were simulated by the GEANT4 code [10]. The peak at 0.31 MeV corresponds to the known first excited state at 1.2 MeV in ^{27}P. The bump at around 1 MeV may be respectively due to the known second excited state at 1.6 MeV and an unknown one at 2.0 MeV. The peak at 2.2 MeV corresponds to the known state at 3.4 MeV. The direct breakup component, which distributes from 0.8 MeV to 4.5 MeV, corresponds to the non-resonant proton capture process. The cross section σ is related to the astrophysical S-factor

$$S = \sigma E \exp(2\pi\eta), \quad (4)$$

where η denotes the Sommerfeld parameter. We assume that the non-resonant capture is dominated by the $E1$ transition and the astrophysical S-factor is independent of the energies.

The Coulomb dissociation cross section for the first excited state in ^{27}P was determined to be 14.8 ± 2.7 mb from the yield of the peak. The error includes the statistical one and ambiguity of the detection efficiency. Supposing the spin and parity of the state is $3/2^+$ from the level scheme of the mirror nucleus ^{27}Mg [11], the transition between the first excited state and ground state ($1/2^+$) is induced by the $M1$ and $E2$ multipolarities. This means that the Γ_γ is a sum of a $E2$ component ($\Gamma_\gamma(E2)$) and an $M1$ component ($\Gamma_\gamma(M1)$). Since the Coulomb dissociation is highly sensitive to the $E2$ component compared with the $M1$ transition [12], the experimental cross section is expected to be exhausted by the $E2$ excitation. $\Gamma_\gamma(E2)$ is determined to be $(2.8 \pm 0.5) \times 10^{-5}$ eV form the measured cross section.

To deduce the $\Gamma_\gamma(M1)$, the $E2/M1$ mixing ratio δ of the first excited state in ^{27}P was estimated by the combination of the known mixing ratio [13] of the mirror nucleus ^{27}Mg and the double ratio R defined as $R = \delta_{Tz+}/\delta_{Tz-}$, where δ_{Tz+} and δ_{Tz-} represent the mixing ratios of the mirror pair. To estimate the ratio R, we performed shell model calculations using the USD effective interaction [14] with conventional values of the effective charges in the sd-shell region, $e_p = 1.3e$ and $e_n = 0.5e$ [15]. The reliability of the R calculated by the shell model was evaluated to be 60% (2σ) by comparing with the experimentally known values. From the calculated R and the known δ of ^{27}Mg, the mixing ratio for ^{27}P was estimated to be 0.020 ± 0.012. The $\Gamma_\gamma(M1)$ was derived from the mixing ratio and thus the total Γ_γ estimated to be $(3.7 \pm 2.2) \times 10^{-3}$ eV. The error includes the experimental error and ambiguity come from the estimation of $M1$ contribution. This value is consistent with the previous estimation [3].

The reaction rate of the ^{26}Si(p, γ)^{27}P was calculated using the extracted Γ_γ value. Figure 3 shows the temperature dependence of the reaction rate. The resonance

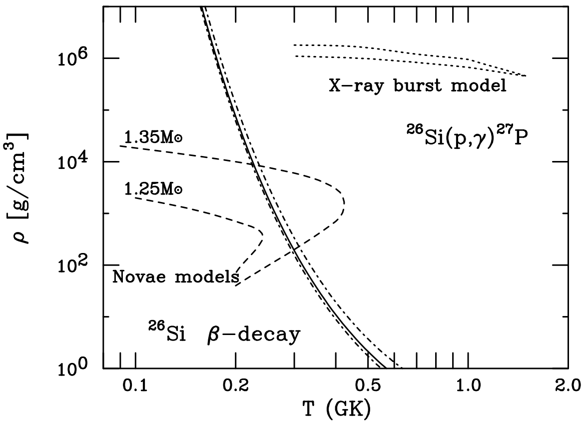

Fig. 4. Temperature-density boundary (solid line) at which the ^{26}Si(p, γ)^{27}P reaction and the competing β decay are of equal strength assuming a hydrogen mass fraction $X_{\mathrm{H}} = 0.5$. Dot-dashed curves represent the range of error. The dashed curves and dotted line indicate T-ρ profiles of two novae sequences and an X-ray burst, respectively.

parameters are taken from ref. [3] except for Γ_γ. The solid and dotted curves represent the present result of the reaction rate and range of its error. The dashed line denotes the direct capture component of reaction rate calculated by J.A. Caggiano *et al.* [3] based on a shell model. This figure indicates that the resonant capture is the dominant process above 0.1 GK, the temperature region of novae and X-ray bursts temperature [16].

The competition between ^{26}Si(p, γ)^{27}P reaction and ^{26}Si β decay can be discussed by using the extracted reaction rate. The competition depends on the density, temperature, and mass fraction of proton in stars. The solid line in fig. 4 represents the temperature and density condition for which (p, γ) reaction and the competing β decay are of equal strength. The dot-dashed lines show the error of the present estimate. The solid curve was calculated using our result and assuming a hydrogen mass fraction of $X_H = 0.5$. In the region above the solid curve the proton capture reaction dominates, while below the solid line the nuclei ^{26}Si are exhausted by β decay. The dashed lines denote temperature-density profiles for the two novae sequences, whose masses are 1.25 $M_\odot$ and 1.35 $M_\odot$ [17,18], and the dotted line shows one for an X-ray burst [19] of a 1.4 $M_\odot$ neutron star. The novae sequence evolves in time from larger to smaller densities, on the other hand the one for X-ray burst evolves from smaller to larger densities. It can be seen that the (p, γ) reaction dominates in the heavy novae when they are at around the peak temperature, whereas the reaction hardly occurs in the light novae. On the other hand, the X-ray burst is dominated by the (p, γ) reaction in their all phases.

4 Summary

The Coulomb dissociation of ^{27}P was experimentally studied to investigate the ^{26}Si(p, γ)^{27}P reaction in explosive hydrogen burning in novae and X-ray bursts. The first excites state in ^{27}P, which has the largest contribution among the resonances of ^{27}P to the reaction rate, was observed by measuring the relative energy between ^{26}Si and proton.

The $E2$ component of Γ_γ for first excited state was experimentally determined to be $(2.8 \pm 0.5) \times 10^{-5}$ eV. We estimated the total Γ_γ to be $(1.3 \pm 0.8) \times 10^{-3}$ eV by the measured $E2$ component together with the $E2/M1$ mixing ratio estimated by the one for the mirror nuclei ^{27}Mg with the help of a shell model calculation. This is consistent with the previously estimated value by J.A. Caggiano *et al.* [3]. The present result indicates non-negligible effects of the ^{26}Si(p, γ)^{27}P reaction to the nuclear burning in heavy novae and X-ray bursts.

Analysis for higher excited states, which may affect the reaction rate at high temperature, is in progress.

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References

1. R. Diehl *et al.*, Astron. Astrophys. Suppl. Ser. **97**, 181 (1993).
2. A. Coc *et al.*, Phys. Rev. C **61**, 015801 (1999).
3. J.A. Caggiano *et al.*, Phys Rev. C **64**, 025802 (2001).
4. W.A. Fowler *et al.*, Annu. Rev. Astron. Astrophys. **5**, 525 (1967).
5. T. Motobayashi *et al.*, Phys. Rev. Lett. **73**, 2680 (1994).
6. N. Iwasa *et al.*, Phys. Rev. Lett. **83**, 2910 (1999).
7. T. Gomi *et al.*, Nucl. Phys. A **734**, E77 (2004).
8. G. Baur *et al.*, Nucl. Phys. A **458**, 188 (1986).
9. T. Kubo *et al.*, Nucl. Instrum. Methods B **70**, 309 (1992).
10. S. Agostinelli *et al.*, Nucl. Instrum. Methods A **506**, 250 (2003).
11. P.M. Endt, Nucl. Phys. A **521**, 1 (1990).
12. K. Langanke *et al.*, Phys. Rev. C **49**, 1771 (1994).
13. M.J.A. de Voigt *et al.*, Nucl. Phys. A **186**, 365 (1972).
14. B.H. Wildenthal, Prog. Part. Nucl. Phys. **11**, 5 (1984).
15. B.A. Brown *et al.*, Annu. Rev. Nucl. Sci. **38**, 29 (1988).
16. C. Iliadis *et al.*, Astrophys. J. **524**, 434 (1999).
17. J. Jose *et al.*, Astrophys. J. **520**, 347 (1999).
18. C. Iliadis *et al.*, Astrophys. J. Suppl. **142**, 105 (2002).
19. O. Koike *et al.*, Astron. Astrophys. **342**, 464 (1999).