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Direct measurement of the astrophysical reaction $^{14}O(\alpha,p)^{17}F$

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The stellar reaction $^{14}O(\alpha,p)^{17}F$, that critically determines the onset of the high-temperature rp-process, has been studied through a direct measurement with a low-energy radioactive ^{14}O beam and a gaseous helium target cooled down to 30 K. The reaction cross section was measured directly by means of a thick target technique in the energy range of $E_{c.m.}(^{14}O+\alpha)$ = 0.8-3.8 MeV. The $^{14}O(\alpha,p)^{17}F^*$ reaction leading to the first excited state in ^{17}F was clearly observed for the first time, suggesting an increase of about 50% for the stellar reaction rate.

1. Introduction

In explosive astrophysical events such as novae and X-ray bursts, the proton-rich nuclei interact further with protons and alpha particles on a short time scale relative to the beta decay. The nucleosynthetic process from the hot-CNO cycle to the heavy elements along the proton-rich side of the valley of stability is called the rp-process. As a starting point of the rp-process, nuclear reactions on the breakout process from the hot-CNO cycle are much interesting in the field of nuclear astrophysics[1]. At high temparature, the ^{14}O(α,p)^{17}F (p,γ)^{18}Ne (α,p)^{21}Na reaction sequence can provide a path into the rp-process. Hydrogen burning of ^{14}O is inhibited since ^{15}F is particle unbound, and significant amount of ^{14}O may be accumulated due to the relatively long half-life of the beta decay ($t_{1/2}$ = 71 s) in the hot-CNO cycle. Thus the ^{14}O(α,p)^{17}F reaction is essential to understand the breakout process.

However, this reaction was studied via mere indirect methods and time-reverse reaction so far. Since the reaction is mainly resonant, it depends on the properties of intermediate states in the compound nucleus ^{18}Ne. The properties of these levels have been investigated[2–6] by measuring the resonance energies with other reactions and by estimating widths and spin assignments from the mirror nucleus ^{18}O. The ^{14}O(α,p)^{17}F reaction rate at low temperatures is believed to be dominated by a resonance arising from a 1^- state at E_x = 6.15 MeV in ^{18}Ne. Several states at E_x = 7.0–7.5 MeV may also contribute to the reaction rate at higher temperatures up to 3×10^9 K, and this topic motivated a novel research via the time-reverse ^{17}F(p,α)^{14}O reaction with a radioactive ^{17}F beam[7,8]. This reaction, however, only provides values for the partial widths for proton decay to the ground states of ^{17}F. Since the proton decay to the first-excited $1/2^+$ state in ^{17}F at E_x = 0.495 MeV would also contribute to the astrophysical yield, these proton widths have to be determined experimentally.

A direct measurement of the cross section for the ^{14}O(α,p)^{17}F reaction is difficult because, in addition to a low-energy radioactive ^{14}O beam, it also requires using a long ^{4}He gas target. This difficulty has been overcome by the combination of a newly-developed low-energy in-flight RI beam separator and a helium gas target cooled to 30 K. The measurement was performed with the thick target method[9,10].

In this paper, we report the results of a direct measurement of the nuclear reaction ^{4}He(^{14}O,p)^{17}F using the ^{14}O beam in conjuction with a cold gaseous helium target. The energy spectrum of protons from the helium target was measured and the reaction cross section for the ^{14}O(α,p)^{17}F was deduced from the spectrum. By comparing with the results in the experiments using time-reversed reaction, the reaction leading to the first excited state in ^{17}F was clearly observed for the first time.

2. Experimental Setup

The experiment was performed using the CNS radioactive ion beam separator (CRIB)[11], which was recently installed by CNS, in the RIKEN accelerator facility. The CRIB has been developed as an extensive low-energy RI beam separator of in-flight type. Figure 1 shows the experimental setup of the measurement. A primary beam of ^{14}N was accelerated up to an energy of 8.4A MeV at the RIKEN AVF cyclotron with K = 70. The maximum intensity of the beam was 300 pnA. The primary beam bombarded a CH_4 gas target with a thickness of 1.3 mg/cm^2. The target gas was confined in a small chamber with entrance and exit windows. The gas pressure was 1.0 atm and Havar foils of thickness of 2.2 μm were used for the windows. A secondary beam of ^{14}O was produced by the ^{1}H(^{14}N,^{14}O)n reaction.

The secondary ^{14}O particles were separated in the CRIB. An energy degrader of 10-μm thick Mylar foil was installed at the momentum dispersive focal plane (F1) to remove background light ions from the secondary beam. A holizontal slit was set to separate the ^{14}O particles at a mean energy of 6.40A MeV after the degrader with the momentum acceptance of 1%.

At the achromatic focal plane (F2) of CRIB, a series of detectors and a secondary target were installed after an energy degrader of 7.5-μm thick tantalum foil in a vacuum chamber. The setup consisted of two parallel-plate avalanche counters (PPAC's)[12], a secondary target of helium gas with a thickness of 3.57 mg/cm^2, and a silicon-detector stuck with thicknesses of 0.02, 0.07, 1.5 and 1.5 mm. The secondary beam was monitored with two PPAC's during the data taking. Particle identification was performed for each event on the basis of time of flight (TOF) between the two PPAC's. The purity of the ^{14}O beam was 85% at F2.

The ^{14}O beam bombarded a novel helium gas target, which was designed which operates at 30 K, offering ten times larger density than at room temperature. This design results in exceedingly compactness and this makes it possible to effectively apply the thick target method. The helium gas was confined in a 50-mm long gas cell with two windows of 2.2-μm thick Havar foils, where were kept at a pressure of 0.6 atm. The effective thickness of ^{4}He was about 3.1 mg/cm^2. The target was chosen as thin as possible, being large enough to stop the ^{14}O nuclei in it. The reaction products emitted from the helium target were identified by the ΔE-E method, using the telescope of four silicon detectors located at 0°. The energy deposit in each detector was measured, where the energy of each detector was calibrated using proton beams produced through the CRIB facility.

3. Result and Discussion

The ^{4}He(^{14}O,p)^{17}F reaction was measured with a ^{14}O beam at the incident energy of 43 MeV on the helium gas target by using a thick target method. Protons from the helium target were detected by the silicon telescope. From the proton spectrum, the cross sections for the ^{14}O(α,p)^{17}F reaction were obtained in the region of $E_{\rm c.m.}(^{14}{\rm O}+\alpha) = 0.8$–$3.8$ MeV. The measured cross sections are presented in Fig. 2 as a function of the center-of-mass energy. Eight resonances are evident in the data which correspond to previously observed states in ^{18}Ne at 6.15, 6.29, 7.05, 7.12, 7.35, 7.62, 7.95 and 8.30 MeV[2,3]. The four arrows at the bottom side in Fig. 2 indicate the location of 6.15, 7.05, 7.37 and 7.60 MeV. The rate for the breakout reactions is dominated by the resonance parameters for the 1^- state at 6.15 MeV at around the temparature $T_9 = 1$, while the contributions from the three higher-lying resonances start to dominate the reaction rate in the temparature range $T_9 \geq 3$[13]. In addition, we newly observed a peak related to the ^{14}O(α,p)^{17}F* reaction leading to the $1/2^+$ first-excited state in ^{17}F, which goes through a resonance at around $E_x = 7.1$ MeV in ^{18}Ne. The ^{18}Ne levels in the energy region have been investigated by means of indirect method, however, the peak observed newly in our experiment has not been observed. Thus we could not conclude the transition through a new level in ^{18}Ne.

The new peak would be a transition to the excited state in ^{17}F. Figure 3 shows the level scheme of ^{18}Ne. The first excited state of ^{17}F could be observed at excitation energy of 0.495 MeV from the ground state. On the other hand, the new peak was observed at the excitation energy to be 0.5-MeV lower than the 7.10-MeV level. Thus one could understand it to be the $^{14}O(\alpha,p)^{17}F^*$ reaction leading to the $1/2^+$ first-excited state in ^{17}F, which goes through a resonance at around 7.1 MeV. The dashed arrow shows the transition to the excited state in ^{17}F.

The result of this experiment demonstrated the usefulness of the low-energy radioactive ^{14}O beam and the cold helium gas target for a direct measurement of the $^{14}O(\alpha,p)^{17}F$ reaction. Due to the contribution from the excited state in ^{17}F, the reaction cross sections were found to differ from even that obtained by the time-reverse reaction[7,13]. This branch may be significant astrophysically and increase the $^{14}O(\alpha,p)^{17}F$ reaction rate [8]. For instance, a calculation of the stellar reaction rate has been performed in Ref. [13]. The contribution from the 7.05 MeV becomes the main component of total reaction rate over the temperature of $T_9 = 2.0$ K. The result of this paper would change the result of calculation. From the yield ratio of the ground state to the excited state of ^{17}F in the measured proton number, this result would suggest an increase of 50% for the $^{14}O(\alpha,p)^{17}F$ reaction rate.

4. Summary

In summary, the astrophysical $^{14}O(\alpha,p)^{17}F$ reaction, which is important in various steller environments such as X-ray bursts, has been measured directly for the first time, by using a radioactive ^{14}O beam. The present experiment has shown that the combination of a low-energy RI beam and cold helium gas target can be used for the study of (α,p) reactions. The measured cross section was found to differ from a prediction based on an indirect measurement, and a direct measurement with time-inverse reaction since the observed channel was limited to the branch to the ^{17}F ground state alone. A proton decay from the ^{18}Ne levels at $E_x = 7.05$ and 7.12 MeV to the first-excited state in ^{17}F has been measured. This result would suggest an increase of 50% for the $^{14}O(\alpha,p)^{17}F$ reaction rate and might affect the senario of ignition phase of X-ray burst.

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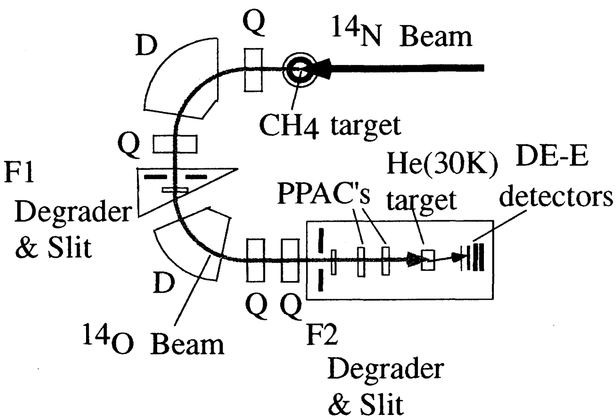

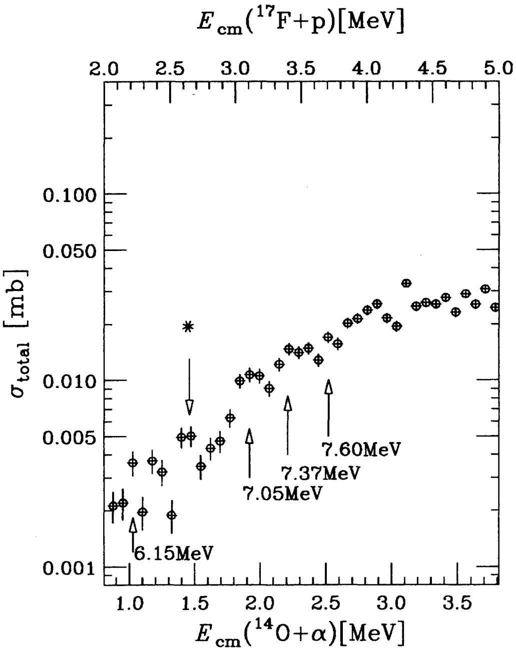

Figure 1. Schematic view of the experimental setup used for the measurement of the $^{14}O(\alpha,p)^{17}F$ reaction cross section.

Figure 2. Measured cross sections for the $^{14}O(\alpha,p)^{17}F$ reaction. The asterisk mark is the new peak.

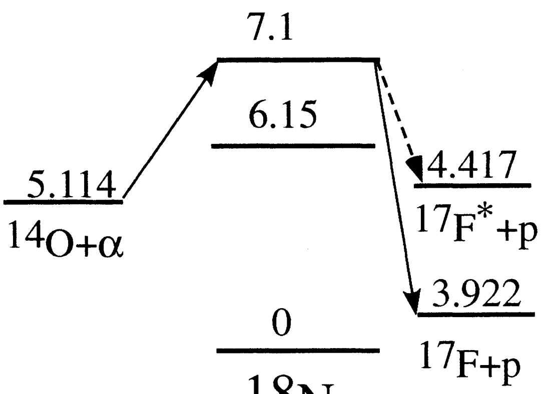

Figure 3. Level Scheme of ^{18}Ne. The dashed line arrow shows a transition to the excited state of ^{17}F