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Direct Measurement of the ^{14}O$(\alpha,\alpha)^{14}$O Cross Section for Astrophysically Important ^{14}O + α Resonances

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For the study of astrophysically important states in ^{18}Ne, the ^{14}O$(\alpha,\alpha)^{14}$O cross section was measured in inverse kinematics using a radioactive ^{14}O beam. This reaction was investigated for properties of resonant states of ^{18}Ne for determining the ^{14}O$(\alpha,p)^{17}$F reaction rate, which is one of the most important reactions for understanding the breakout mechanism from the Hot CNO cycle to the rp-process. Alpha-induced elastic scattering on ^{14}O was performed using the low-energy radioactive ion (RI) beam separator at the Center for Nuclear Study (CNS) in the RIKEN Accelerator Research Facility. The energy range $E_x = 7.2 \sim 13.1$ MeV of ^{18}Ne was scanned with the thick target method. Recoiled alpha particles were measured with Si dE-E telescopes. Spins and widths of three resonances at $E_x = 8.6$, 9.22, and 10.06 MeV were calculated using the R-matrix analysis, and a new state of ^{18}Ne at $E_x = 12.0$ MeV was found in this experiment.

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I. INTRODUCTION

In hot stellar environments such as x-ray bursts, novae, and supernovae, explosive reactions occur at high temperatures. When the temperature rises to more than $\sim$0.5T$_9$ (t$_9$ = 1 × 10^9 K), the rapid proton capture process separated from the Hot CNO cycle is initiated [1]. The α-induced reaction on ^{14}O triggers the synthesis of heavy elements by the ^{14}O$(\alpha$,p$)^{17}$F$(p,\gamma)^{18}$Ne$(\alpha,p)^{21}$Na reaction sequence, which provides a path into the rp-

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process. Therefore, the reaction rate of $^{14}O(\alpha$,p)^{17}F, which is one of the key break-out reactions, at low energy is important astrophysically. However, there are still large uncertainties in the $^{14}O(\alpha$,p)^{17}F reaction rate. Previous estimates were based on indirect measurements due to difficulties of producing a radioactive ^{14}O beam and handling a ^{4}He gas target [2]. People have measured the time-reverse reaction by using a radioactive ^{17}F beam, which provides values for the partial widths related to the resonances connecting the ground states of ^{14}O and ^{17}F [3,4].

In this study, we measured the cross section of $^{14}O(\alpha,\alpha)^{14}O$ for studying the resonant properties of ^{18}Ne. The alpha cluster structure of ^{18}Ne was reported [5] recently, and this can provide α widths of resonance levels in ^{18}Ne that are astrophysically important for certain temperature ranges through an α-induced reaction on ^{14}O. The excitation function of the $^{14}O(\alpha,\alpha)^{14}O$ reaction in the energy range $E_{c.m.}$= 2.1 $\sim$ 8.0 MeV was measured.

II. EXPERIMENTS AND DISCUSSION

The direct measurement of $^{14}O(\alpha,\alpha)^{14}O$ was accomplished using the low-energy CNS RI beam separator (CRIB) [6]. Figure 1 shows the CRIB beam line and experimental set-ups. The 8.35-MeV/u ^{14}N primary beam from the AVF cyclotron was used to produce the secondary beam, ^{14}O, through the (p,n) reaction in inverse kinematics. The maximum primary beam intensity was 170 pnA, and for improving the intensity of the ^{14}O beam, the H_2 gas cell was cooled down to 80 K by using liquid nitrogen. Furthermore, the purity of the ^{14}O beam was increased up to 90% by operating a Wien filter system just before the F3 experimental scattering chamber. The CRIB, as well as the He gas target and detector system in F3, is shown in Fig. 1.

The secondary beam was identified by measuring the time of flight (TOF) between two PPACs (parallel plate avalanche counters) in the F3 chamber and the rf signals from the cyclotron. Figure 2 shows the particle identification of the secondary beams after the Wien filter. The main contaminations of the secondary beams were ^{11}C and ^{14}N, but we obtained a highly-purified ^{14}O beam because we optimized our apparatuses for separating ^{14}O cleanly, as shown in Fig. 2. The produced ^{14}O beam intensity was $\sim 10^5$/s. As we used a relatively-high-energy primary beam, some degraders with Havar foil and aluminium foil with different thicknesses were installed behind the exit window of the production target (H_2 gas cell) to acquire the desired energy of the ^{14}O beam.

The measurement of the $^{14}O+\alpha$ elastic scattering cross section was carried out using the thick target method, which provides a continuous excitation function for a certain energy range because energy loss occurs steadily through thick gas cell filled with ^{4}He. The pressure of the helium target in the F3 chamber was 440 Torr, and the length of the cell was 150 mm, which is equivalent to 1.45 g/cm^2 at room temperature. We performed measurements at two different beam energies by using different sets of degraders. The energies of the ^{14}O beam were 35 MeV and 24 MeV after the entrance window (2.5-μm Havar foil) of the helium target. Consequently, we could scan E_x = 7.2 $\sim$ 10.4 MeV and 10.3 $\sim$ 13.1 MeV of ^{18}Ne ($E_{c.m.}$ = 2.1 $\sim$ 5.3 MeV and 5.2 $\sim$ 8.0 MeV).

The recoiled particles were detected using three sets of dE-E telescopes, which consisted of position sensitive

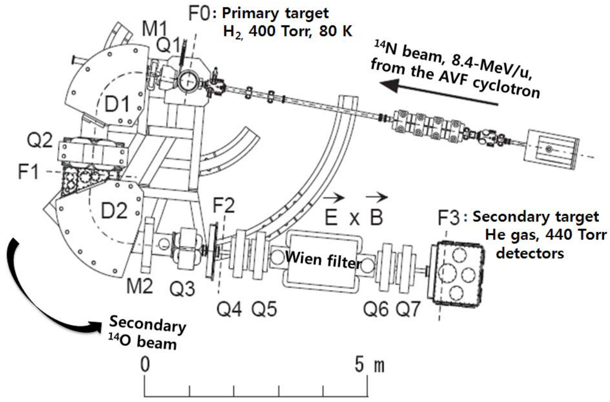

Fig. 1. Schematic view of the RI beam separator of CRIB [7]. This CRIB is composed of two parts, a double achromatic focal system (Q1, M1, D1, Q2, D2, M2, and Q3) and the Wien filter (Q4, Q5, and $\vec{E}\times\vec{B}$).

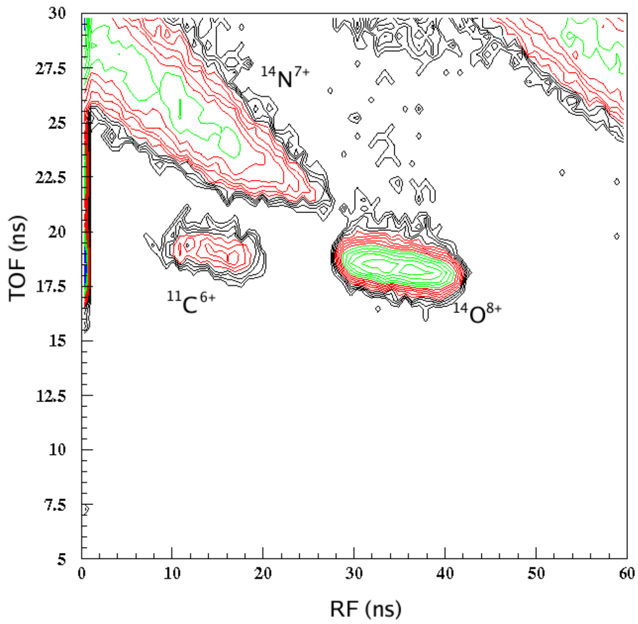

Fig. 2. (Color online) Secondary beam identification. The y axis and the x axis represent the TOF and the RF time, respectively.

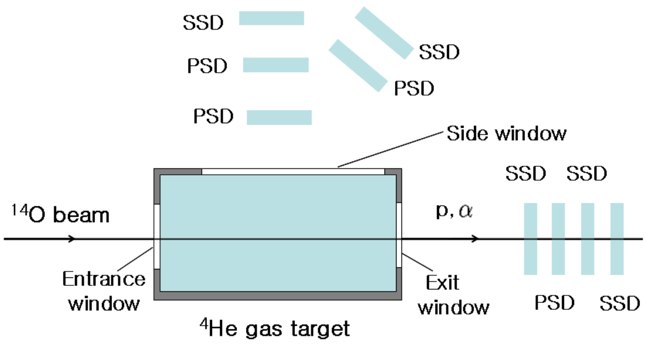

Fig. 3. Experimental setup in the F3 chamber.

Table 1. Resonance parameters of ^{18}Ne above E_x = 7.5 MeV.

E_x[MeV]	$E_{c.m.}$[MeV]	Γ_α[MeV]	Γ_p[MeV]	J^π
8.60 ± 0.10	3.50 ± 0.10	0.615 ± 0.024	0.166 ± 0.020	(1^-)
9.22 ± 0.04	4.10 ± 0.04	0.365 ± 0.018	0.124 ± 0.012	3^-
10.06 ± 0.04	4.95 ± 0.04	0.207 ± 0.030	0.095 ± 0.010	1^-
10.48 ± 0.02	5.37 ± 0.02			
11.60 ± 0.09	6.49 ± 0.09			
12.0 ± 0.10	6.9 ± 0.10			
12.4 ± 0.09	7.29 ± 0.09			
12.85 ± 0.25	7.70 ± 0.25			

and surface barrier silicon detectors. The telescopes can covered the laboratory angle range of 0 to 70 degrees. The number of α particle reaching the side telescopes was too small to be analyzed due to the fact that α particles from the reactions are strongly forward peaked. Therefore, only the data collected by the telescope at 0 degrees were used for this study. The 0 degrees telescope consists of 20-μm silicon strip detector (SSD), 73-μm position sensitive detector (PSD), 1.5-mm silicon strip detector (SSD) and 1.5-mm silicon strip detector (SSD). Figure 3 shows the final detector and target set-ups in the F3 chamber.

The identification of an α particle was made using the dE-E method by measuring the energy loss of the particles produced from the reactions. Since the recoiled alpha particles were positioned as a clean line in the dE-E plot of Fig. 4, we extracted them easily. However, because we need to confirm whether all or some of them originated from the reactions with ^{4}He inside the target, we considered both the dE-E information and the timing signals between the PPAC and the detectors. As real α particles from a reaction formed on a specific line in the TOF-E plot, we could distinguish them cleanly from background α particles. The right plot in Fig. 4 shows alpha particles obtained by using 2-dimensional gate conditions of dE-E and TOF-E. For more accurate subtraction of the background, empty target runs were carried out with the same experimental conditions, except for the pressure of the gas target.

Figure 5 shows the excitation function of the ^{14}O$(\alpha,\alpha)^{14}$O reaction measured at the 0 degrees telescope. The energy resolution of the excitation function was 0.04 MeV. The strong resonance peak was positioned at 9.22 MeV of ^{18}Ne, which corresponds with the previous measurement [5]. Table 1 shows the measured resonance states of ^{18}Ne and the properties of the first three resonance states. The values of Γ_α and Γ_p are from an R-matrix calculation. Figure 6 presents the R-matrix fit using the spins and the parities $J^\pi = 1^-$, 3^-, and 1^- for the 8.60-, 9.22-, and 10.06-MeV states in ^{18}Ne, respectively. The spin values are chosen when the chi-square of R-matrix fit is least and the energies of the peaks from the experimental data agree with the peak energies of the resonance states calculated from the R-matrix. Our spin and parity assignments, $J^\pi = 3^-$ and 1^- for the E_x = 9.22 MeV and E_x = 10.06 MeV states, and their energies agree with previously reported values [5]. However, as shown in Fig. 6, the first 1^- state was identified at 8.60 MeV in ^{18}Ne more easily, and the value of the excitation energy is 0.1 MeV lower than that in Ref. 5. $J^\pi = 0^+$ as well as 1^- for the 8.60-MeV state were suggested in Ref. 8, and the data of Ref. 5 could not exclude 0^+. When we include 0^+ instead of 1^-, the strong resonance at 9.22 MeV was destroyed, and the position of the peak was changed greatly. This suggests that the 1^- assignment is more probable.

For the energy region $E_x \geq 10$ MeV, we have seen a newly-observed peak at 12.0 MeV ($E_{c.m.}$= 6.90 MeV) as well as several resonances reported by previous studies. Further analysis for high energy resonances including the new peak will be reported elsewhere [9]. The resonances in the lower energy range ($E_x \leq 7$ MeV, $T_9 = 1$) in this study contribute significantly to the reaction rate for the breakout process from the HCNO cycle. However, for extreme temperatures, $T_9 \geq 3$, higher-lying states ($E_x \geq 7$ MeV) are astrophysically important for determining the reaction rate in stellar explosions such as x-ray bursts [3]. Therefore, our measurements, including a newly found peak, can be useful for better determining the astrophysically important ^{14}O$(\alpha,p)^{17}$F reaction rate.

III. CONCLUSIONS

We successfully performed a direct measurement of the ^{14}O$(\alpha,\alpha)^{14}$O cross section for studying astrophysically important ^{14}O + α resonances. The purity of the produced ^{14}O beam was very high, and the identification of recoiled particles from ^{4}He gas target was clean. The cross sections of both previously known resonances ($E_x = 7.2 \sim 13.1$ MeV) and a newly found resonance at E_x = 12.0 MeV in ^{18}Ne were acquired. In addition, the resonant properties, including J^π, Γ_α, and Γ_p of the first three resonances, were studied through an R-matrix calculation, and our results agree with previous measure-

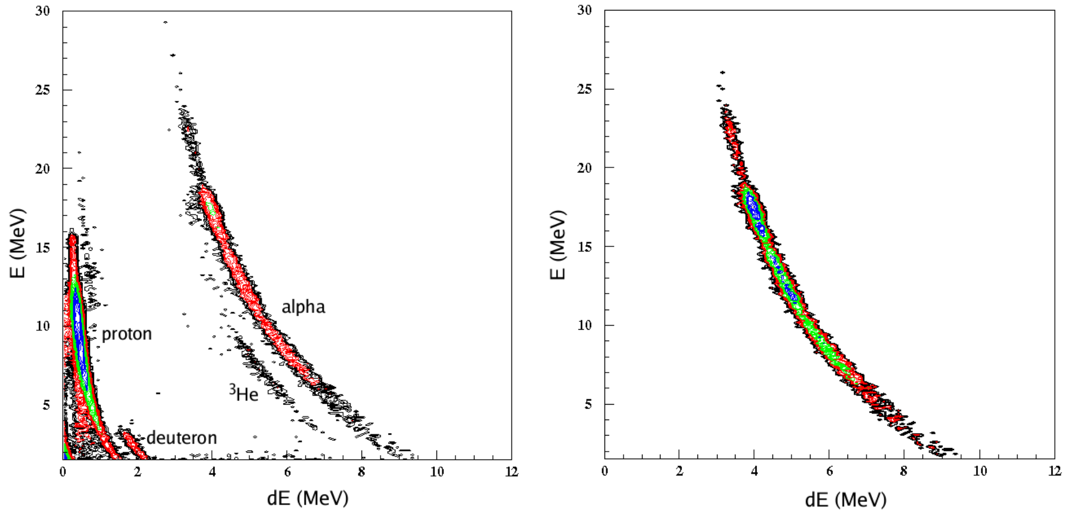

Fig. 4. (Color online) Plot of the dE-E in the Si detectors. The left panel shows all particles from the reaction, and the right panel shows alpha particles gated by TOF and dE-E.

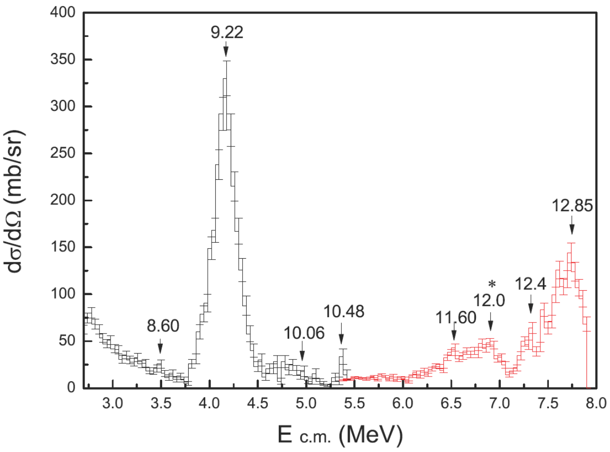

Fig. 5. (Color online) Excitation function of the ^{14}O$(\alpha,\alpha)^{14}$O reaction at the 0 degrees telescope. The level marked by $*$ has not been seen before.

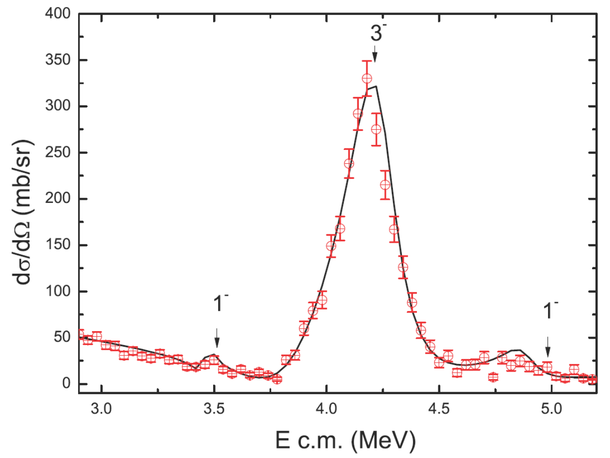

Fig. 6. (Color online) R-matrix fit at low energy ($E_{c.m.} < 5$ MeV). The details are explained in the text.

ments. However, our analysis suggests a spin assignment of $J^{\pi} = 1^{-}$ for the 8.60-MeV state, compared to J^{π}=(1^{-}, 0^{+}) in other studies. Our results can be useful for calculating the ^{14}O$(\alpha,p)^{17}$F reaction rate, which is astrophysically important at a temperature T $\approx 3 \times 10^{9}$ K.

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