Investigation of $^{22}\text{Mg}$ levels via resonant scattering of $^{18}\text{Ne} + \alpha$

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The $\alpha$ resonant scattering on $^{18}\text{Ne}$ was measured in inverse kinematics to understand the $\alpha$-clustering of proton-rich $^{22}\text{Mg}$ nucleus, performed at the CNS Radio-Isotope Beam Separator (CRIIB) of Center for Nuclear Study, University of Tokyo, located at the RIBF of RIKEN Nishina Center. The excitation function of $^{22}\text{Mg}$ was obtained for the excitation energies of $10–16 \text{MeV}$ by adopting the thick-target method. Several resonances were evident in the present work, which implies the existence of energy levels with large $\alpha$ widths. Since energy levels were not clearly observed at the astrophysically important energy range, upper limits on the $^{18}\text{Ne}$ $(\alpha, \alpha)$$^{20}\text{Ne}$ cross section were set. The astrophysical impact was also investigated by estimating the $^{18}\text{Ne}$ $(\alpha, p)$$^{21}\text{Na}$ cross section.

**Keywords**

decomposition cluster, $\alpha$-cluster structure, resonant scattering, energy level properties, thick-target method in inverse kinematics, RI beam, explosive stellar environments, $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$

**1 Introduction**

The $\alpha$-cluster structure in atomic nuclei has been one of the most interesting topics in nuclear physics. The $\alpha$-clustering of self-conjugate ($N = Z$) and $A = 4n$ ($n = 2, 3, 4, \cdots$) nuclei including $^8\text{Be}$, $^{12}\text{C}$, $^{16}\text{O}$, and $^{20}\text{Ne}$ has been studied extensively for decades [1–3]. The strong evidence for the $\alpha$-cluster structure was found through the studies. Observations of a series of levels with large $\alpha$ reduced widths that form a rotational band can provide a
The 22Mg nucleus is to populate in 11C may originate from the negative-parity cluster band, which is analogous to its mirror nucleus. For example, independent analysis. Considering the isobaric invariance of the nuclear force, the characteristics of the α-cluster structure for a proton-rich nucleus are similar to those for its mirror nucleus. For example, experimental results indicate that some of the observed resonances in 11C may originate from the negative-parity cluster band, which is analogous to its mirror nucleus 11B [7, 8].

The α-cluster structure of neutron-rich 22Ne has been extensively investigated both experimentally and theoretically [9–13]. Rogachev et al. observed a splitting of 1+, 3+, 5+, and 9− α-cluster states into doublets [10], which could be theoretically explained by the extended two cluster model (ETCM) calculation assuming the α + 16O two-cluster configuration [11]. Recently, Kimura suggested the presence of two kinds of α-cluster structures in 22Ne using the hybrid-generator coordinate method (GCM) calculation. The first is the molecular orbital bands with the α + 16O core and two valence neutrons, which correspond to the observed α-cluster states below the α + 16O threshold energy reported in [14, 15]. The other is the α + 16O molecular bands, which correspond to the observed states above the threshold energy reported in Ref. [10].

Studies on the α-cluster structure of proton-rich 22Mg are still very rare. The GCM calculation predicted the existence of the 1− and 3− doublet states located at excitation energies of 12–13 MeV, assuming the α + 18Ne two-cluster model [11]. Considering the lower energy level density of proton-rich nuclei than that of neutron-rich nuclei, observing doublets should be easier in the case of the 22Mg nucleus. However, the experimental data obtained by Goldberg et al. [12] show no clear evidence of the doublets. Although the excitation function of mirror nucleus 22Ne has been reported in Ref. [10], the α + 18Ne two-cluster model [11]. Considering the typical X-ray burst temperature of T ~ 2 GK, the Gamow window corresponds to the excitation energy Eα ~ 9.56–10.96 MeV. Therefore, it is important to study the energy level properties of 22Mg in this energy region. The 22Ne (α, p)21Na reaction has been studied by direct measurements [19–21] and time-reversal reaction measurement [29]. The experimental results, however, show a large discrepancy. In the present work, the 22Ne (α, p)21Na reaction cross section was estimated based on the experimental level structure of the 22Mg nucleus.

2 Experiment

The α resonant elastic scattering of 18Ne was measured in inverse kinematics at the CNS Radio-Isotope Beam Separator (CRIB) [30, 31] of the Center for Nuclear Study, University of Tokyo, located at the RIBF of RIKEN Nishina Center. A schematic of the experimental setup is shown in Figure 1. The 18Ne rare isotope beam was produced by using the in-flight (IF) method. A primary 16O beam with an
energy of 8.026 MeV/u from the AVF cyclotron [32] was delivered to the F0 focal plane of CRIB and bombarded a 3He gas target. Then, a secondary 18Ne beam was produced by the 3He (16O, 18Ne) reaction.

The 3He gas was contained in the cell at a pressure of 360 Torr. The 3He gas atoms were isolated from the beam line kept at a high-level vacuum by using 2.5-μm-thick Havar foils as the entrance and exit windows. To increase the density of the 3He gas target and the intensity of the secondary 18Ne beam, a cryogenic system using liquid nitrogen was used [33]. The areal thickness of the 3He gas target was achieved to be 1.54 mg/cm² by keeping the temperature at T ~ 90 K.

18Ne10+ ions were selected by a double achromatic system with a proper magnetic rigidity (Bp) value of 0.5920 Tm, which is optimized to obtain the maximum 18Ne beam production rate. A slit of ±15 mm was installed at the momentum dispersive focal plane (F1) to remove the beam contaminations produced due to various nuclear reactions, yielding the momentum dispersion Δp/p ~ 1%. The secondary beam particles were further purified using the Wien Filter (WF) system by applying a high voltage of ±59.5 kV. Two delay-line-type PPACs [34] were installed downstream of the WF to measure the time and the two-dimensional position information for each secondary beam particle. By using PPACs, the secondary beam identification after the WF was performed. The 18Ne beam intensity and purity were ~2.6 × 10⁶ pps and ~65%, respectively. The impurities were 17F9+ (~28%) and 16O8+ (~4%), respectively. A small amount of other beam species including 15O8+, 18N8+, and 4He2+ was also observed. These contaminants were clearly excluded by the time-of-flight information in the final analysis.

The F3 target chamber was filled with 3He gas for α scattering measurement. The 3He gas was at a pressure of 470 Torr and was sealed with a 23-μm-thick aluminized Mylar foil as a beam entrance window. The 3He target pressure was selected to stop the 18Ne beam before it reaches the detector. The 18Ne beam energy after passing through the target entrance window was measured as 45.2 ± 1.1 MeV, which is consistent with an energy loss calculation result considering the 3He pressure of 0.5920 Tm and the effective thickness of ~45 μm Mylar foil for the two PPACs and the beam entrance window. By adopting the thick-target method in inverse kinematics [35], a wide range of excitation energies of 22Mg was investigated with a single 18Ne beam energy.

The energy and position of the recoiling α particles were obtained using two sets of ΔE-E silicon detector telescopes. The central telescope (Tel 1) was installed at 430 mm downstream from the entrance window of the target chamber along the beam axis. The other telescope (Tel 2) was located at 10.15° off from the beam axis, as viewed from the center of the entrance window. Tel 1 (Tel 2) consisted of 20-μm-, 496-μm-, and 485-μm-thick (20-μm- and 1500-μm-thick) silicon detectors. The most energetic α particles from the 18Ne (α, α)18Ne reaction could be entirely stopped under these conditions. Each detector had 16 strips and an active area of 50 × 50 mm². Energy calibration of each strip was carried out by using an α-emitting source composed of 146Gd (3.148 MeV), 241Am (5.462 MeV), and 244Cm (5.771 MeV). Since the energy range of recoiling α particles is much wider (0–27 MeV) than that of the α particles from the source, additional energy calibration was required for the high-energy region. α beams at various energies (13, 15, 20, and 25 MeV) were used for this purpose.

Even after the beam purification using the CRIB spectrometer, beam-like α particles were transported to the F3 reaction target chamber. These beam-like α particles were produced at the upstream of the beam line and selected by the Bp value which was set for the 18Ne beam particles of interest. The number of the beam-like α particles was much less than the number of 18Ne beam particles (~< 0.01%); however, an amount comparable to that of the reaction products reached the central telescope. Therefore, the argon gas pressure of about 87 Torr was selected so that the incident particles exhibit energy losses similar to those of 3He gas. By comparing the two α spectra obtained with and without the 3He gas target, the contribution from beam-like α particles was identified.

3 Data analysis

3.1 Kinematics reconstruction

The particle identification was performed by the standard energy loss techniques. A typical particle identification plot obtained at the central telescope is shown in Figure 2. The total energy deposition of the particles is plotted as a function of energy deposition in the ΔE detector. As shown in the figure, α particles were clearly separated without significant contamination from other charged particle groups. The α particles with Eα ~ 13 MeV were observed in the background run with argon gas, as shown in Figure 2B, indicating that those α particles were contaminants in the secondary beams. The beam-like α particles were clearly distinguished by using the time-of-flight information between the PPAC and the second layer of the telescope, as shown in Figure 3.

The α particles in coincidence with the 18Ne beams incident in the target chamber were selected for further analysis. The measured energy of the α particle (Eα) was converted to the center-of-mass energy of 18Ne + α system (Ecm) by assuming the elastic scattering kinematics using

\[ E_{cm} = \frac{M_{18Ne} + M_{\alpha}}{4M_{18Ne}} \cos^{2}\theta_{lab} E_{\alpha}, \]

where \( M_{18Ne} \) and \( M_{\alpha} \) are the nuclear masses of the 18Ne and α particle, respectively, and \( \theta_{lab} \) is the scattering angle in the laboratory frame. The value of \( \theta_{lab} \) was determined using the trajectories of the recoiling α particle and corresponding 18Ne beam particle at the reaction vertex. The reaction vertex in the extended gas target was reconstructed by considering the energy losses of the 18Ne beam and recoiling α particle in 3He gas. The energy loss functions were obtained using the SRIM code [36]. Direct measurement of the energy loss of the 18Ne beam at six different target pressures in the present study was in good agreement with the SRIM calculation result.

3.2 Excitation function of 18Ne + α elastic scattering

The differential cross section of 18Ne + α resonant elastic scattering in the center-of-mass frame was calculated by
\( \frac{d\sigma}{d\Omega} \text{cm} = \frac{1}{4 \cos \theta_{\text{lab}}} \left( \frac{d\sigma}{d\Omega} \right)_{\text{lab}} \frac{Y}{N \Delta\Omega_{\text{lab}}} \)  

where \( Y \) is the yield of recoiling \( \alpha \) particles, \( \theta_{\text{lab}} \) is the scattering angle in the laboratory frame, \( I \) is the number of \(^{18}\text{Ne}\) beam particles incident on the target, \( N \) is the number of \(^4\text{He}\) target atoms, and \( \Delta\Omega_{\text{lab}} \) is the solid angle covered by the detector.

The number of incident \(^{18}\text{Ne}\) beam particles was counted using two F3 PPACs. To obtain the precise number of beam particles entering into the target chamber through the entrance window, an additional cut was applied to the \(^{18}\text{Ne}\) beam events. The positions of the beam particles at the target entrance were reconstructed event-by-event by extrapolating the beam trajectory obtained at two F3 PPACs, and then \(^{18}\text{Ne}\) beam events falling in the diameter of the entrance of the target chamber were selected. A total of \( \sim 1.33 \times 10^{10} \) \(^{18}\text{Ne}\) beam ions impinged on the target during the runs.

The excitation function of \(^{18}\text{Ne} + \alpha\) resonant elastic scattering was extracted by selecting \( \alpha \) events with an angular range of \( 0^\circ \leq \theta_{\text{lab}} \leq 7^\circ \) \( (166^\circ \leq \theta_{\text{c.m.}} \leq 180^\circ) \). The solid angle was calculated using the known detector geometry and reaction vertex of each event as a function of \( E_{\text{c.m.}} \). Due to the finite angular range of \( \theta_{\text{lab}} \), an average value of solid angle at the reaction vertex \( (\text{or } E_{\text{c.m.}}) \) was used. The areal number density of \(^4\text{He}\) atoms was obtained by considering the effective target thickness as a function of \( E_{\text{c.m.}} \). The uncertainty in \( E_{\text{c.m.}} \) was measured to be approximately 50–100 keV, depending on the energy. The uncertainty originates from the energy resolution of a silicon detector (30–90 keV) and energy straggling of the \(^{18}\text{Ne}\) beam and \( \alpha \) particles in the gas (20–60 keV).

### 3.3 Upper limits on the cross section

The \(^{18}\text{Ne} (\alpha, \alpha)\) \(^{18}\text{Ne}\) cross section extracted in the present work is rather smooth in the energy region below \( E_{\text{c.m.}} < 3\text{ MeV} \). In this region, however, two small bumps were observed at \( E_{\text{c.m.}} \sim 2.6\text{ MeV} \) and 2.7 MeV in the cross section spectrum. Several resonances in \(^{22}\text{Mg}\) have been identified in the energy range through the previous \(^{18}\text{Ne} (\alpha, p)\) \(^{21}\text{Na}\) reaction study as reported in [20]. For instance, two energy levels located at the resonance energies of \( E_r = 2.52 \pm 0.14\text{ MeV} \) and \( E_r = 2.72 \pm 0.14\text{ MeV} \) have been reported in the previous direct measurement by Groombridge et al. [20]. However, the existence of these resonances is not obvious in our data, possibly due to the insufficient statistics. Therefore, the upper limits on the cross section were set to indicate the possible maximum resonant cross section that is consistent with our experimental spectrum. Figure 4 shows the obtained upper limits by assuming hypothetical levels located at \( E_{\text{c.m.}} = 2.63\text{ MeV} \) (top) and \( E_{\text{c.m.}} = 2.75\text{ MeV} \) (middle). The upper limit with both hypothetical levels is also plotted in the figure (bottom). The black circles represent the empirical cross sections obtained at \( 0^\circ \leq \theta_{\text{lab}} \leq 7^\circ \). The blue solid lines represent the best fit curves for the observed bumps. The
investigated. The cross section of the 18Ne ($^\alpha p$)21Na reaction relevant to a temperature of $T \sim 2$ GK. Therefore, the upper limit was not evaluated for this resonance.

4 Discussion

4.1 Astrophysical implication

Two small bumps observed in the present work fall within the Gamow window at $T \sim 2$ GK. The contribution of the observed bumps to the 18Ne ($^\alpha p$)21Na reaction was then investigated. The cross section of the 18Ne ($^\alpha p$)21Na reaction was calculated using the Breit–Wigner formula [37].

![FIGURE 4](image)

The upper limits of the 18Ne ($^\alpha p$)21Na cross section calculation are summarized. Two sets of parameters ("COM1" and "COM2") are used in the calculation to illustrate the sensitivity of the $\Gamma_\alpha$ for the reaction cross section. All energies are expressed in MeV.

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>$J^\pi$</th>
<th>$\Gamma_\alpha$</th>
<th>$\Gamma_p$</th>
<th>$\Gamma_{tot}$</th>
</tr>
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<tr>
<td>COM1</td>
<td>2.63</td>
<td>0$^+$</td>
<td>0.015</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0$^+$</td>
<td>0.015</td>
<td>0.01</td>
</tr>
<tr>
<td>COM2</td>
<td>2.63</td>
<td>0$^+$</td>
<td>0.015</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0$^+$</td>
<td>0.015</td>
<td>0.195</td>
</tr>
</tbody>
</table>

\[ a_{BW}(E) = \frac{\lambda^2}{4\pi} \frac{(2J_\pi + 1)}{(2J_{\alpha} + 1)} \frac{\Gamma_\alpha \Gamma_p}{(E - E_\gamma)^2 + (\Gamma_{tot}/2)^2} \]

where $\lambda$ is the de Broglie wavelength, $E_\gamma$ is the resonance energy; $J_\pi$, $J_{\alpha}$, and $J_\pi$ are the spins of resonance, 18Ne, and 4He, respectively. $\Gamma_\alpha$, $\Gamma_p$, and $\Gamma_{tot}$ are the $\alpha$ partial width, proton partial width, and total width, respectively. $\Gamma_{tot} = \Gamma_\alpha + \Gamma_p$ was assumed in the calculations. Two hypothetical levels used in the upper limit calculation were considered to be the resonances for the 18Ne ($^\alpha p$)21Na reaction, where the resonance energies were adopted as $E_\gamma = 2.63$ and 2.75 MeV. $\Gamma_\alpha$ values of both resonances were determined by further analyzing with the R-matrix code SAMMY [38, 39], where the experimental energy increase of $\sim 50$ keV was assumed. The best fit yielded values of $\Gamma_\alpha = 15$ keV for both resonances.

Although proton resonant scattering on the 21Na nucleus has been measured in literatures [22–24], $\Gamma_p$ in the corresponding energy
region has not been reported so far. To approximate $\Gamma_p$ values for the resonances, the Wigner limit for the proton was calculated by $\Gamma_p = 2h^2/\mu R^2 p$, where $\mu$ is the reduced mass, $R$ is the interaction radius, and $p$ is the penetrability of a given orbital angular momentum $l$. An interaction radius of $R = 1.35 (1 + 211/3) \text{ fm}$ [24] was adopted in the calculation. By considering the global mean reduced proton width $\bar{\Gamma}_p = 0.0045$, suggested in [40], $\Gamma_p$ was estimated to be $-10$ keV for the resonances at $E_x = 2.63$ and 2.75 MeV, which is summarized as “COM1” in Table 1. To illustrate the sensitivity of the proton widths for the $^{18}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section, another set of $\Gamma_p$ values for the resonances was approximated by assuming $\Gamma_p = \Gamma_{\text{tot}} - \Gamma_a$ (“COM2” in Table 1). We adopted $\Gamma_{\text{tot}} = 0.1$ MeV ($\Gamma_{\text{tot}} = 0.21$ MeV) for the resonance at $E_x = 2.63$ MeV ($E_x = 2.75$ MeV), as reported in the previous direct measurement by Groombridge et al. [20].

The calculation results for the $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section are shown in Figure 5, in comparison with the previous experimental results. The cross sections deduced by the Breit–Wigner formula using two sets of $\Gamma_p$ values are shown as the green dashed and black solid lines, respectively. The blue region has not been reported so far. To approximate $\Gamma_p$ values for the resonances, the Wigner limit for the proton was calculated by $\Gamma_p = 2h^2/\mu R^2 p$, where $\mu$ is the reduced mass, $R$ is the interaction radius, and $p$ is the penetrability of a given orbital angular momentum $l$. An interaction radius of $R = 1.35 (1 + 211/3) \text{ fm}$ [24] was adopted in the calculation. By considering the global mean reduced proton width $\bar{\Gamma}_p = 0.0045$, suggested in [40], $\Gamma_p$ was estimated to be $-10$ keV for the resonances at $E_x = 2.63$ and 2.75 MeV, which is summarized as “COM1” in Table 1. To illustrate the sensitivity of the proton widths for the $^{18}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section, another set of $\Gamma_p$ values for the resonances was approximated by assuming $\Gamma_p = \Gamma_{\text{tot}} - \Gamma_a$ (“COM2” in Table 1). We adopted $\Gamma_{\text{tot}} = 0.1$ MeV ($\Gamma_{\text{tot}} = 0.21$ MeV) for the resonance at $E_x = 2.63$ MeV ($E_x = 2.75$ MeV), as reported in the previous direct measurement by Groombridge et al. [20].

The calculation results for the $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section are shown in Figure 5, in comparison with the previous experimental results. The cross sections deduced by the Breit–Wigner formula using two sets of $\Gamma_p$ values are shown as the green dashed and black solid lines, respectively. The blue triangles represent the experimental data obtained by Salter et al. [29], which were determined from the time-reversal reaction measurement. The $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section was inferred by using the principle of the detailed balance theorem [41]; therefore, their data can provide a lower limit for the cross section. The red squares represent the $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ cross section derived from the resonance parameters reported by Groombridge et al. [20]. The black squares represent the recent direct measurement results by Anastasiou et al. [21], which shows a lower cross section by almost an order of magnitude compared with that of Groombridge et al. As shown in the figure, our calculation results indicate that the $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section depends critically on the proton widths of the resonances in the astrophysically important energy region. Thus, experimental studies of the $\Gamma_p$ are highly required for a conclusive understanding of the $^{14}\text{Ne} (\alpha, p)^{21}\text{Na}$ reaction cross section.

### 4.2 R-matrix analysis and $\alpha$-cluster structure

The excitation function of $^{14}\text{Ne} + \alpha$ elastic scattering obtained at the higher excitation energy region $E_x \sim 11$–16 MeV is shown in Figure 6. The black circles represent the differential cross sections of the $^{18}\text{Ne} (\alpha, a)^{40}\text{Ca}$ obtained at $0^\circ \leq \theta_{\text{lab}} \leq 7^\circ$. Several peaks were evident in the spectrum, which implies the existence of resonances with large $\Gamma_a$. Since the strength of the $\alpha$-clustering feature of a resonance state is reflected by its $\alpha$ width, observed peaks in the present work are possible candidates of $\alpha$-cluster states. To constrain the energy level properties of $^{22}\text{Mg}$ including $^{18}\text{Ne}$, an analysis using the $R$-matrix calculation code SAMMY8 [38, 39] has been in progress. A channel radius of $R_c = 5.0$ fm was adopted in the calculation, which is the same value used in the GCM calculation [11]. We calculated the excitation function at an average angle of $\theta_{\text{lab}} = 173^\circ$, and the result was then broadened considering the experimental energy resolution.

By introducing three resonances in the $R$-matrix calculation, the fitting curve was obtained at $E_x \leq 12.3$ MeV, which is plotted as red solid line in Figure 6. The resonance parameters are summarized in Table 2. Since the spectroscopic information of $^{22}\text{Mg}$ nucleus in this energy region is very limited, an intensive $R$-matrix analysis with all possible spin and natural parity combinations for observed resonances should be carefully performed until the experimental excitation function is well-reproduced. The resonance parameters with best fitting result will be provided in the future. The $\chi^2$ analysis will be performed to deduce possible parameters for each peak. The dimensionless partial width $\bar{\Gamma}_p$ for each level will be calculated by $\bar{\Gamma}_p = \Gamma_p / \Gamma_W$, where $\Gamma_W$ is the Wigner limit of $\Gamma_a$, which can provide a direct comparison with theoretical predictions in [11]. More detailed calculations would be necessary to reveal the nature of those levels, if they are shell-model-like or cluster-like states.

**Table 2** Resonance properties of $^{22}\text{Mg}$ extracted from the present work are summarized. Results from the previous works are listed for comparison.

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_a$ (keV)</th>
<th>$J^+$</th>
<th>$E_x$ (MeV)</th>
<th>$J$</th>
<th>$E_{\text{GCM}}$ (MeV)</th>
<th>$J^+$</th>
<th>$\theta_{\text{GCM}}$ (%)</th>
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<tr>
<td>11.49</td>
<td>7</td>
<td>1</td>
<td>11.462</td>
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<td></td>
<td>3</td>
<td>11.7</td>
</tr>
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</table>
5 Summary

We measured $\alpha$ resonant elastic scattering on $^{18}\text{Ne}$ using the thick-target method in inverse kinematics technique to improve our knowledge of the $\alpha$-cluster structure of proton-rich $^{22}\text{Mg}$ nucleus. The excitation function for $^{18}\text{Ne}\left(\alpha,\alpha\right)^{18}\text{Ne}$ in the energy range of $E_\gamma$ = 10–16 MeV was obtained at $0^\circ \leq \theta_{\text{lab}} \leq 7^\circ$. Several levels with large $\alpha$ widths were evident in our result, which can be candidates for the $\alpha$-cluster states. To clarify the energy level properties of $^{22}\text{Mg}$ and to investigate $\alpha$-clustering features, the $R$-matrix analysis is in progress. The resonance parameters will be extracted considering all possible combinations of spin and parity for observed peaks. The first experimental constraints on spectroscopic information of $^{22}\text{Mg}$ above $E_\gamma$ = 13 MeV will be provided. To better understand the experimental results, complete theoretical descriptions are required in the future.

No levels were evident at $E_\gamma < 11$ MeV in the present work, even though two small bumps were observed in the cross section spectrum. Therefore, we set upper limits on the $^{18}\text{Ne}\left(\alpha,\alpha\right)^{18}\text{Ne}$ cross section, which indicate the possible maximum resonant cross section assuming the hypothetical levels at $E_\gamma$ = 10.772 and 10.892 MeV ($E_{\text{res}} = 2.63$ and 2.75 MeV). We also estimated the astrophysically important $^{18}\text{Ne}\left(\alpha,\alpha\right)^{21}\text{Na}$ reaction cross section based on our experimental data. The calculation indicates that the $^{18}\text{Ne}\left(\alpha,\alpha\right)^{21}\text{Na}$ cross section depends on the proton widths of the resonances as well. Experimental studies on $\Gamma_p$ are necessary to evaluate the $^{18}\text{Ne}\left(\alpha,\alpha\right)^{21}\text{Na}$ reaction cross section conclusively.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

KC was the spokesperson of the experiment. All authors contributed to the setup of the experiment and the measurements. SMC wrote the first draft, the revised versions, and the final version of the manuscript. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References


