Multichannel R-matrix analysis for an alpha scattering in inverse kinematics using a $^{21}\text{Na}$ radioisotope beam

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1. Introduction

Nucleosynthesis of $^{22}\text{Na}$ is an astronomically interesting subject because of potential Galactic $\gamma$-ray observation [1–3], and isotopic abundance anomalies of $^{22}\text{Ne}$ in presolar grains [4]. In the stellar environment, $^{22}\text{Na}$ would be mainly produced through the hot NeNa cycle from the seed nucleus $^{20}\text{Ne}$, and the $\beta$-decay ($T_1/2 \approx 2.6 \text{ yr}$) leads to the first excited state in $^{22}\text{Ne}$, which de-excites to its ground state by emitting a characteristic 1275 keV $\gamma$-ray [1]. A few observational searches for this $\gamma$-ray signal have been performed utilizing satellite observatories, but this $\gamma$-ray has not been observed yet [5]. It is pointed out that the Ne-E problem, which is very high enrichment of $^{22}\text{Ne}$ in certain meteorites, would originate from $^{22}\text{Na}$ [4]. The $^{21}\text{Na}(\alpha, p)^{24}\text{Mg}$ stellar reaction is a break-out process from the NeNa cycle to the MgAl cycle. It could bypass $^{22}\text{Na}$, resulting in reduction of $^{22}\text{Na}$ production. We performed for the first time the measurement of the $^{21}\text{Na} + \alpha$ scattering and a direct measurement of the $^{21}\text{Na}(\alpha, p)$ reaction in inverse kinematics with the thick target method [6, 7] using a $^{21}\text{Na}$ RI beam. In this paper, we discuss only the alpha scattering experiment result and an application of a multichannel R-matrix method to extract resonance parameters.

2. Experiment and Data Analysis

The $^{21}\text{Na}$ beam used in the experiment was produced by the CNS low-energy in-flight separator (CRIB) [8] which consists of a cryogenic gas production target, a double-achromatic magnetic separator, a Wien filter, and a scattering chamber [9]. The experimental setup was set in the scattering chamber. There are two parallel-plate avalanche counters (PPACs) [10] to track the beam direction and to deduce fast timing information. Followed by a semi-cylinder gas target with a length of 15 cm which contained helium gas at a pressure of 580 Torr. $\Delta\text{E} - \text{E}$ telescopes were mounted downstream of the gas target at three different scattering angles ($0^\circ$, $16^\circ$ and $26^\circ$) with respect to the beam line. The reaction products, which were mainly alphas and protons, were measured by three $\Delta\text{E} - \text{E}$ telescopes. The alpha and proton particles were clearly identified by the $\Delta\text{E} - \text{E}$ method and the E - TOF method, where, the TOF is a flight time of particles measured from the first PPAC to the Si telescope.

The energy region in the center of mass system covered by the experiment was from 1.6 MeV to 6.2 MeV. The data were analyzed event-by-event. The incident energy of $^{21}\text{Na}$ at the interaction and the scattering angle were determined by solving the kinematics equation with energy loss correction. The excitation functions were deduced for three different scattering angular regions, $0^\circ - 5^\circ$, $5^\circ - 10^\circ$ and $10^\circ - 15^\circ$. The data were separated into low and high energy parts by an energy gap due to the dead layer of the $\Delta\text{E}$ detector. The low energy part mainly contained Coulomb scattering, and there could be a resonance at about 3.3 MeV. All these resonances have been observed for the first time. In the high energy part, four resonances have been observed clearly. The uncertainties in the resonance energies mainly resulted from the energy resolution of the detectors themselves, the angular resolution due to the finite size of strip (3 mm) of detectors, and the energy straggling of the alpha particles through the gas target and the exit window foil. In total, the energy resolution obtained was 50 – 80 keV depending on the scattering angles and the resonance energies.

3. Multichannel R-matrix Analysis and Results

Resonance parameters were assigned using the multichannel R-matrix analysis method [11] with the SAMMY code [12]. The effect of other decay channels than the alpha channel were considered. According to a Q-value consideration, proton and $\gamma$ channels are opened with high positive Q-values. Since the decay width of the $\gamma$ channel ($\Gamma_\gamma$) is much smaller than those of the alpha ($\Gamma_\alpha$) and proton ($\Gamma_p$) channels, $\Gamma_{tot} \approx \Gamma_\alpha + \Gamma_p$, and the proton decay channel could mainly affect the alpha scattering cross section. The energies and total widths of resonances were derived by fitting the experimental data with a Lozientzian function. In order to vary the alpha and proton widths within the total width, we proposed to vary a ratio between proton reduced width within a standard deviation, corresponding to certain range of $\theta_p^2/\theta_\alpha^2$ value, as shown in Fig. 1.
to calculate the $^{21}\text{Na}(\alpha,p)\text{Mg}^{24}$ cross section, this cross section should be larger than that of the $^{21}\text{Na}(\alpha,p)\text{Na}^{22}$ reaction cross section from the time-reversed reaction study. Under this condition, two configurations in the high energy region were eliminated, since their calculated cross sections were smaller than that of the time-reversed cross section around the resonance at 5.97 MeV.

Figure 2 shows the best case by combining the best fittings of the separate low and high energy parts which had the smallest $\chi^2$ values. The result of the R-matrix analysis is summarized in Table 1. The obtained resonance parameters can use to calculate a rate of the $^{21}\text{Na}(\alpha,p)\text{Mg}^{24}$ reaction, it is important to understand experimentally a contribution of this reaction to the production of $^{22}\text{Na}$. A detail of this discussion is not represented in this report.

Table 1. Resonant states in $^{25}\text{Al}$ observed in the present work.

<table>
<thead>
<tr>
<th>$E_r$ (MeV)</th>
<th>$\Gamma_\alpha$ (MeV)</th>
<th>$\Gamma_p$ (MeV)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.32 ± 0.07</td>
<td>0.05 – 0.12</td>
<td>0.15 – 0.23</td>
<td>$5/2^+,7/2^+$, $9/2^+11/2^+$</td>
</tr>
<tr>
<td>4.10 ± 0.08</td>
<td>0.15 – 0.19</td>
<td>0.10 – 0.22</td>
<td>9/2</td>
</tr>
<tr>
<td>4.57 ± 0.09</td>
<td>0.12 – 0.19</td>
<td>0.05 – 0.13</td>
<td>5/2</td>
</tr>
<tr>
<td>5.33 ± 0.06</td>
<td>0.17 – 0.19</td>
<td>0.05 – 0.13</td>
<td>7/2</td>
</tr>
<tr>
<td>5.97 ± 0.07</td>
<td>0.22 – 0.24</td>
<td>0.05 – 0.12</td>
<td>$3/2^-$ $(3/2^-, 5/2^-)$</td>
</tr>
</tbody>
</table>

References