Short Note

Measurement of the $^{24}\text{Mg}(p, t)^{22}\text{Mg}$ reaction for the states near the $^{21}\text{Na} + p$ threshold

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Abstract. Differential cross-sections of the $^{24}\text{Mg}(p, t)^{22}\text{Mg}$ reaction were measured at 34.68 MeV for the states near the proton threshold at 5.502 MeV in $^{22}\text{Mg}$. Among them, the new states at 5.962, 6.046, 6.246 and 6.323 MeV, which were reported previously, have been confirmed. Angular distributions for these states were analyzed by distorted-wave Born-approximation calculations to deduce the spins and parities. The angular distribution for the 5.714 MeV state, which is considered to be most crucial for the stellar reaction $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$, has been found to be consistent with $J^\pi = 2^+$ assignment. The 6.046 MeV state is newly assigned to have $J^\pi = 0^+$, and the 5.962 MeV state is tentatively assigned to have $J^\pi = (1^-, 2^+)$. These two states will also play an important role for $^{22}\text{Mg}$ production in novae.


The nuclear structure of the unstable nucleus $^{22}\text{Mg}$ near and above the $^{21}\text{Na} + p$ threshold at 5.502 MeV has been of interest because of the importance of the stellar reaction $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ [1, 2]. In ONeMg novae, the top temperature is typically $T_9 = 0.3$–0.4, which corresponds to Gamow energy at 280–340 keV above the proton threshold [3, 4]. Thus, the excited states at around 5.5–6.0 MeV would make major contributions to produce $^{22}\text{Mg}$. Several transfer reactions, the $^{24}\text{Mg}(p, t)$ [5, 6], the $^{20}\text{Ne}(^3\text{He}, t)^{17}\text{O}$ [7, 8], the $^{20}\text{Ne}(^3\text{He}, n)$ [9, 10], and the $^{12}\text{C}(^8\text{O}, ^6\text{He})$ reactions [11], were studied in order to obtain information on the excited states in $^{22}\text{Mg}$, which can be used for an estimate of the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ reaction rate.

In our previous work, we observed new levels at 5.962, 6.046, 6.246 and 6.314 MeV and precisely determined the excitation energies of the levels, which are located near the proton threshold in $^{22}\text{Mg}$, by the $^{24}\text{Mg}(p, t)$ reaction at 37.925 MeV [5]. However, the spins and parities were not assigned for these states. We extended our study to confirm the new levels by changing the incident energy and also measuring at a wider angular range. We measured the angular distributions for the states of possible importance for the hydrogen burning, including the new states, and made spin assignments for the states.

The experiment was performed at the Center for Nuclear Study (CNS), University of Tokyo. Differential cross-sections for the $^{24}\text{Mg}(p, t)^{22}\text{Mg}$ reaction were measured. A 34.68 MeV proton beam obtained from the CNS-SF cyclotron bombarded a $^{24}\text{Mg}$ metallic foil of 358±12 µg/cm² enriched to 99.9%. The beam current on the target was monitored by a Faraday cup placed just after the target. The typical current was about 100 nA. Outgoing particles were analyzed by a high-resolution magnetic spectrograph, PA [12]. The solid angles for tritons were defined by an aperture of 5.0 mrad, which was installed at 350 mm downstream from the target position. Along the focal plane, a detector system was placed, which consisted of a hybrid-gas counter [13] and a plastic scintillator with

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photomultiplier tubes on both sides. The gas counter provided position information on the focal plane and energy losses ($\Delta E$) of the particles in the counter. The plastic scintillator gave energies ($E$) and the timing for time-of-flight (TOF) measurement from the target to the scintillator. The start time was obtained from the RF signal of the cyclotron. Particle identification was made using $\Delta E$, $E$, and TOF for each particle. Energy spectra of the triton were obtained from the position information given by the gas counter. Triton spectra near the proton threshold were obtained at nine angles, 13.0, 20.0, 23.5, 27.0, 34.0, 44.5, 48.0, 55.0, and 62.0 degrees in the laboratory system. Overall energy resolution observed was about 37.5 keV FWHM for tritons. We also measured angular distributions for the ground state and the first excited state in $^{22}$Mg at 10.0–80.0 degrees in 5.0 degrees steps to check the validity of the distorted-wave Born-approximation (DWBA) and to determine the optical potential parameters for DWBA analysis.

Excitation energy in $^{22}$Mg was determined by a mean value of excitation energies obtained at each measured angle. We can identify reacting target nuclei from kinematical shifts of triton momenta as a function of the angle. Thus, measurement at a wide angular range is required for the distinction of the triton momenta as a function of the angle. We can identify reacting target nuclei from kinematical shifts of triton momenta as a function of the angle.

The state at 5.962 MeV was observed again in the present experiment. Triton momenta from the state, which was measured at angles from 13 degrees to 62 degrees, were consistent with the one from $^{24}$Mg(p, t)$^{22}$Mg reaction. The excitation energy obtained is 5.960 MeV in $^{22}$Mg from the calibration with an uncertainty of 8 keV. Thus, the new state at 5.962 MeV has been confirmed in the present experiment. The doublet states at 6.250 MeV and 6.323 MeV have also been confirmed here by the same way.

Spin assignments have been made using the DWBA analysis for the angular distributions, where the analysis is made with the code TWOFNR [16]. Figures 1 and 2 show the experimental angular distributions for the $^{24}$Mg(p, t)$^{22}$Mg reaction together with the lines predicted by the DWBA calculations.

As for the optical potential parameters of the initial and the final channels, we adopted those in ref. [6], which roughly reproduce the measured angular distributions for the ground and the first excited state in $^{22}$Mg. A Woods-Saxon form factor with $r = 1.25$ fm and $a = 0.65$ fm was used for the bound-state potential, where the depth was determined to reproduce the separation energy.

Typical shapes of $L=0$ and 2 angular distributions can be seen in the transitions to the ground state in fig. 1 and to the $2^+_1$ state in fig. 2, respectively. Although the oscillation phases of $L=0$ and 2 are similar to each other, the $L=2$ distribution has a smooth increase at forward

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Table 1. Experimental excitation energies in $^{22}$Mg. The first column implies the results in the present experiment, and the second the ones in ref. [5]. The last column shows the excitation energies adopted by the present experiment. The energies in italic characters were used for the energy calibration.

<table>
<thead>
<tr>
<th>Present (keV)</th>
<th>Bateman [5]</th>
<th>Adopted (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5713.9</td>
<td>5713.9</td>
<td>5713.9(1.2)²</td>
</tr>
<tr>
<td>5960(8)</td>
<td>5961.9(2.5)</td>
<td>5961.7(2.4)</td>
</tr>
<tr>
<td>6045.8</td>
<td>6045.8(3.0)</td>
<td>6045.8(3.0)</td>
</tr>
<tr>
<td>6253(5)</td>
<td>6246.4(5.1)</td>
<td>6249.8(3.6)</td>
</tr>
<tr>
<td>6324(10)</td>
<td>6322.6(6.0)</td>
<td>6323.0(5.1)</td>
</tr>
</tbody>
</table>

² Ref. [7].