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ISSN 1343-2230
CNS-REP-44
May, 2002

CNS Report

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submited to European Physical Journal A

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

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Abstract

Differential cross sections of the ^{24}Mg(p,t)^{22}Mg reaction were measured at 34.68 MeV for the states near the proton threshold at 5.502 MeV in ^{22}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}Na(p,γ)^{22}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 $J^\pi = (1^-)$. These two states will also play an important role for ^{22}Mg production in novae.

PACS: 21.10.Hw, 25.40.Hs, 26.30.+k, 27.30.+t

The nuclear structure of the unstable nucleus ^{22}Mg near and above the ^{21}Na+p threshold at 5.502 MeV has been of interest because of the importance of the stellar reaction ^{21}Na(p,γ)^{22}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}Mg. Several transfer reactions, the ^{24}Mg(p,t) [5, 7], the ^{20}Ne(^{3}He,$n\gamma$) [8, 9], the ^{20}Ne(^{3}He,n) [6, 10], and the ^{12}C(^{16}O,^{6}He) reactions [11], were studied in order to obtain information on the excited states in ^{22}Mg, which can be used for an estimate of the ^{21}Na(p,γ)^{22}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}Mg, by the ^{24}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}Mg(p,t)^{22}Mg reaction were measured. A 34.68-MeV proton beam obtained from the CNS-SF cyclotron bombarded a ^{24}Mg metallic foil of 358 ± 12 μg/cm^2 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 msr, 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 photomultiplier tubes on both sides. The gas counter provided position information on the focal plane and energy losses (ΔE) 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 ΔE, E, and TOF for each particle. Energy spectra of 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 degree steps to check the validity of 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 angle. Thus, measurement at a wide angular range is required for distinction of ^{22}Mg peaks from contamination peaks. Table 1 summarizes the excitation energies in ^{22}Mg observed in the present experiment together with the results in Ref.[5]. Although the beam energy was changed from 37.9 MeV to 34.7 MeV, all the states were clearly observed at the same excitation energies in ^{22}Mg. In the present experiment, triton peaks from the 3.35-MeV state in ^{10}C and from the states at 6.27 MeV, 6.59 MeV and 6.79 MeV in ^{14}O were identified as contamination. Since the contamination peaks were the well-known states in ^{10}C and ^{14}O, the yields were estimated by the DWBA calculations, for which optical potential parameters were taken from Refs.[15, 16].

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 a code TWOFNR [14]. 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.[7], 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 angles, whereas the $L = 0$ distribution has a distinct oscillations and a sharp increase near zero degree.

The 5.714-MeV and 6.046-MeV states in ^{22}Mg are considered to play an important role in the ^{21}Na(p,γ)^{22}Mg reaction during novae nucleosynthesis. The 2^+ state is known to be located at around 5.7 MeV from the (^{3}He,n) [6] and the (^{3}He,$n\gamma$) [8] reaction studies. The angular distribution for the 5.714-MeV state is similar to the data for the 2_1^+ state, which was measured for the first time in the (p,t) reaction, and the $L = 2$ DWBA curve rather than the $L = 0$ curve. See Fig. 2. Therefore, the present result supports by the ^{24}Mg(p,t)^{22}Mg reaction the previous assignment that 5.714 MeV state in ^{22}Mg has 2^+.

Previously, only one state of $J^\pi = 0^+$ state was known at around 6.0 MeV from the (p,t) reaction [7] at 41.9 MeV. Since the 6.046-MeV state in the present experiment is more strongly excited than the 5.962-MeV state, roughly by a factor of ten, the 6.046-MeV state should be the one observed in Ref.[7]. In fact, the angular distribution for the 6.046-MeV state is quite similar to the one for the ground state and reasonably well explained by the $L = 0$ DWBA calculation. Thus, $J^\pi = 0^+$ is assigned here for the 6.046-MeV state.

The 5.962-MeV state could be also important for ^{22}Mg production in ONeMg novae as it is located in the middle of the Gamow peak at $T_9 = 0.4$, although nothing is known for the spin and parity of this state. The measured differential cross sections for the state was about $0.1 - 1$ μb/sr. Thus, a high energy resolution was required to distinguish a state nearby, including contaminant peaks. The angular distribution for the state could be explained either by $L = 0$ or 1, although the fit is not so good. In the mirror nucleus, ^{22}Ne, there is a 1^- state at 6.69 MeV, and no other 0^+ state around 6.0 MeV. All other states in this energy region in ^{22}Ne have corresponding states in ^{22}Mg. Therefore, the 5.962-MeV state is reasonable to be assigned to have $J^\pi = 1^-$.

The present spin assignments for the excited states, are summarized in Table 2. The 5.837-MeV state was observed only in Ref.[8]. There was no indication in the present experiment. The last column shows spin and parity assignments adopted here.

In summary, the new states at 5.962 and 6.046 MeV in ^{22}Mg have been confirmed in the present experiment. New spin parity assignments have been also made for the states just above the proton threshold. However, some of the assignments are still tentative, and thus further work is awaited experimentally for spin assignment.

The new states established in the present experiment could be important for ^{22}Mg production in novae. The states at 5.714, 5.813, 5.962 and 6.046 MeV are recommended to be included in the nova model calculations. The 5.962-MeV(1^-) state should be a p-wave resonance in ^{22}Mg and be effective in the vicinity of the top temperature of ONeMg novae. The reaction rate including a 1^- state was discussed in Ref.[5], although the spin assignment there was only an assumption. The contribution of the 5.96-MeV state is estimated to be about 10% of the total reaction rate at $T_9 = 0.4$. Further information on the 5.96-MeV state, especially the resonance strength, is definitely required for a precise estimate of the ^{21}Na$(p,\gamma)^{22}$Mg reaction rate.

This work is partly supported by a Grant-in-Aid for Science Research from the Japanese Ministry of Education, Culture, Sports, and Technology under the contract no. 13440071.

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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 does the ones in Ref.[5]. The last column is adopted excitation energies by the present experiment. The energies in italic characters were used for the energy calibration.

Present [keV]	Bateman[5] [keV]	adopted [keV]
5713.9	*5713.9*	5713.9(1.2)[1]
5960(8)	5961.9(2.5)	5961.7(2.4)
6045.8	6045.8(3.0)	6045.8(3.0)
6253(5)	6246.4(5.1)	6249.8(3.6)
6324(10)	6322.6(6.0)	6323.0(5.1)

[1] Ref.[8].

Table 2: Spin and parity assignments for the states in ^{22}Mg near and above the proton threshold in the present experiment together with previous experimental results.

<table>
<tr><th>Ex
[keV]</th><th>Present
(p,t)</th><th>Paddock[7]
(p,t)</th><th>Rolfs[8]
(^{3}He,nγ)</th></tr>
<tr><td>5713.9(1.2)</td><td>2^+</td><td></td><td>1, 2</td></tr>
<tr><td>5837(5)</td><td></td><td></td><td>≥ 2</td></tr>
<tr><td>5961.7(2.4)</td><td>(1^-)</td><td rowspan="2">}0^+</td><td></td></tr>
<tr><td>6045.8(3.0)</td><td>0^+</td><td></td></tr>
</table>

<table>
<tr><th>Ex
[keV]</th><th>Alford[10]
(^{3}He,n)</th><th>Endt[17]
—</th><th>adopted
—</th></tr>
<tr><td>5713.9(1.2)</td><td>$L = 2$</td><td>2^+</td><td>2^+</td></tr>
<tr><td>5837(5)</td><td></td><td>(0 – 5)</td><td></td></tr>
<tr><td>5961.7(2.4)</td><td rowspan="2">}$L = 0$</td><td rowspan="2">}0^+</td><td>(1^-)</td></tr>
<tr><td>6045.8(3.0)</td><td>0^+</td></tr>
</table>

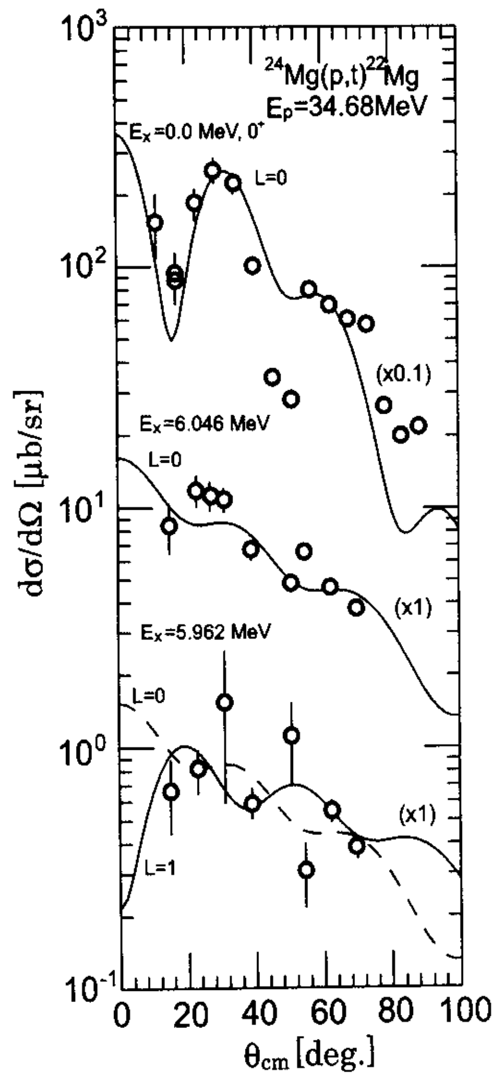

Figure 1: Angular distributions of the tritons from the ^{24}Mg$(p,t)^{22}$Mg reaction for the ground state and excited states in ^{22}Mg at 6.046 MeV and 5.962 MeV together with the DWBA calculations. The lines are the calculations for the transferred angular momenta L denoted.

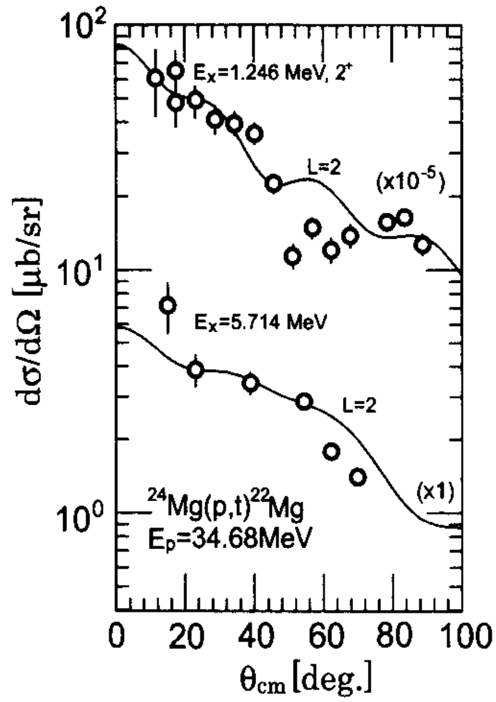

Figure 2: Angular distributions of the tritons from the $^{24}Mg(p,t)^{22}Mg$ reaction for the excited states in ^{22}Mg at 1.246 MeV and 5.714 MeV together with the DWBA calculations. The lines are the calculations for the transferred angular momenta L denoted.