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High Resolution Study of ^{24}Mg(p,d)^{23}Mg for the Ne-E Problem

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Abstract: Nuclear levels of ^{23}Mg near and above the proton threshold were investigated with high resolution. A new level has been identified at 7.643 MeV (66 keV above the proton threshold) with a possible $J^{\pi} = (3/2, 5/2)^{+}$. Some other spin-parity and excitation-energy assignments are also made. These results enable the reaction rate estimate of $^{22}Na(p,\gamma)^{23}Mg$ with much smaller uncertainties, which is critical for the Ne-E problem in nuclear astrophysics.

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One of the interesting subjects in nuclear astrophysics would be so called Ne-E problem [1], where very high ^{22}Ne enrichments were observed in some meteorites. Most plausible explanation is that the meteorites were ejected from some stellar event with high temperatures. All the inert gas would have been lost by evaporation, but Na would have been frozen in them. The nucleus ^{22}Na, which has a long half-life time of 2.6 y, would have beta decayed afterward, giving a strong enrichment of ^{22}Ne in the meteorites. Thus, the nuclear astrophysical problem here is to know the reaction rates which are associated to ^{22}Na [1-3].

The main production processes of ^{22}Na would be $^{21}Ne(p,\gamma)$ and $^{22}Mg(\beta^{+}\nu)$, and they are known rather well. However, the destruction process, $^{22}Na(p,\gamma)^{23}Mg$, was not well studied. Above 290 keV this reaction was investigated by using a radioactive target of ^{22}Na [4,5]. Nevertheless, the reaction rate had a very large uncertainty, several orders of magnitudes, especially at low temperatures [2].

We report here the result of a high resolution study of the $^{24}Mg(p,d)^{23}Mg$ reaction to learn about the nuclear levels (excitation energy and spin-parity) near and just above the proton threshold in ^{23}Mg. A doublet suggested before [3] at 7.63 MeV was resolved experimentally and studied separately.

The experiment was performed with a 34.945 MeV proton beam from the sector-focusing cyclotron of the Institute for Nuclear Study, University of Tokyo. The reaction products were momentum analyzed by a high resolution magnetic spectrograph [6], and detected by a hybrid type gas-proportional counter [7] backed up with a plastic scintillator behind. A metallic foil of ^{24}Mg (enriched to more than 99.9 %) of about 130 $\mu g/cm^2$ was used to separate the doublet at around 7.63 MeV in ^{23}Mg for the whole run. The excitation energy was obtained by using the

$^{12}C(p,d)^{11}C$ reaction as well as the energies obtained by the $^{25}Mg(p,t)$ reaction [8]. The uncertainty in the excitation energies are within 10 keV for all the states observed. The uncertainty of the absolute cross sections is about 20 %.

Figure 1 displays a typical momentum spectrum of deuterons from the $^{24}Mg(p,d)^{23}Mg$ reaction observed at 66°. The doublet structure at around 7.63 MeV was barely resolved, and so at most measurements at other angles. The differential cross sections were obtained by a peak fitting procedure.

Figure 2 shows the angular distributions for the doublet states. The two distributions have quite different shapes each other. Distorted wave Born approximation calculations [9] were performed for the data with two models. The one is a conventional DWBA calculation, and the other one is an adiabatic model calculation, where the proton and neutron in the deuteron are assumed to go through independently the target nucleus since the binding energy of deuteron is so small. This model explains better

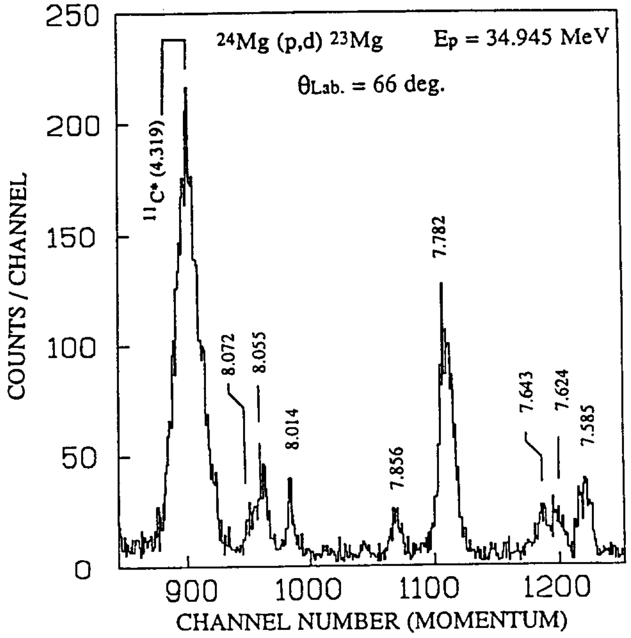

Fig. 1 A typical spectrum of deuterons from the $^{24}Mg(p,d)^{23}Mg$ reaction at $\Theta_{Lab} = 66°$.

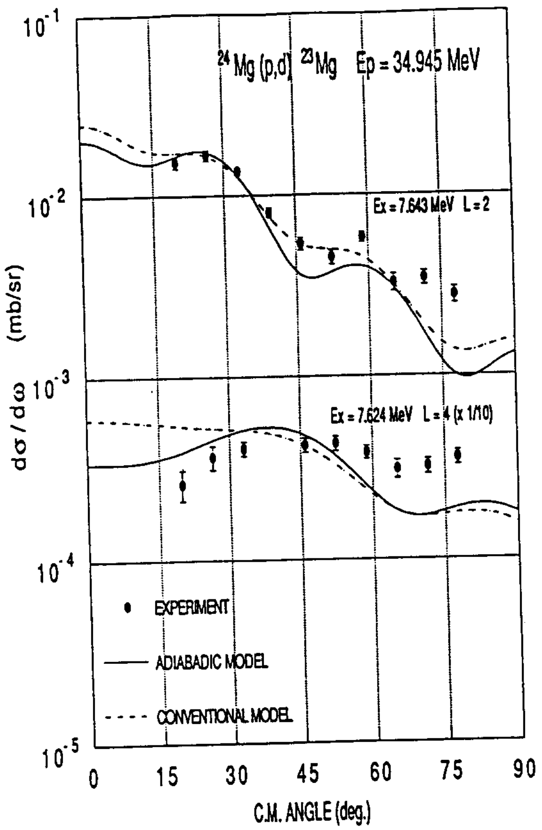

Fig. 2 Angular distributions for the doublet states denoted. The experimental cross sections for the 7.624 MeV state are displayed by dividing the data by a factor of 10. The dashed lines are conventional DWBA calculations with L = 2 and 4, and the solid lines are the calculations with the adiabatic model discussed in the text.

the (p,d) reactions at this energy region. The optical potentials were taken from refs. [10,11] for the incident, and exit channels, respectively, for the conventional model calculations, and those from ref. [12] for the adiabatic model calculations. The angular distribution for the 7.643 MeV state is reasonably well explained by the DWBA calculations with the two models by assuming the transferred angular momentum L = 2, and the one for the 7.624 MeV state by L = 4. Here, we simply compared the peak and valley angles, and did not try to fit best. The dashed lines are conventional

DWBA results, and the solid lines are the adiabatic model results.

From this DWBA analysis, the possible spin parity assignment made is $J^{\pi} = (3/2,5/2)^+$ for the new state at 7.643 MeV, and $J^{\pi} = (7/2,9/2)^+$ for the 7.624 MeV state. The 7.624 MeV state was observed before by the reactions, ^{25}Mg(p,t) [8], ^{24}Mg(p,d) [13], and ^{24}Mg(^{3}He,α) [3], and the spin-parity was assigned to be $(7/2,9/2)^+$, which is consistent with the present result. However, a possible state at around 7.643 MeV was suggested only by the (^{3}He,α) reaction [3], although there was no spin assignment.

The new state of $(3/2,5/2)^+$ at 7.643 MeV could be an s-wave or d-wave resonance in the p + ^{22}Na scattering since the ground state of ^{22}Na has 3^+. The ^{22}Na(p,γ)^{23}Mg reaction rate was estimated previously [2] by allowing a large range of possible spin-parities for the most states above the proton threshold in ^{23}Mg, 7.577 MeV. Although they showed a general trend for the reaction rate, the estimate of course includes very large ambiguities of 3 ~ 4 orders of magnitudes. Since the doublet structure was not known well then, they assumed a $9/2^+$ state at 7.647 MeV. The calculation predicted that this state dominates the reaction rate at the temperature region of $1 \sim 10 \times 10^8$ K.

The present experimental result will considerably reduce the ambiguity for the reaction rate, and provides an important information for the Ne-E problem.

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