STUDY OF ^{23}Na AND ^{24}Mg USING ($^3He, d$) SPECTROSCOPY

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The production of sodium in the NeNa cycle is regulated by the rates of the ^{22}Ne$(p,\gamma)^{23}$Na, ^{23}Na$(p,\alpha)^{20}$Ne, and ^{23}Na$(p,\gamma)^{24}$Mg reactions. An anticorrelation between the observed abundances of sodium and oxygen in the atmospheres of globular cluster giant stars is believed to result from mixing between the stellar atmosphere and the hydrogen-burning shell. The sodium-to-oxygen abundance ratio may be used to establish the mixing depth; however, such a determination is uncertain owing to uncertainties in the reaction rates that produce and destroy ^{23}Na.

The ^{22}Ne$(p,\gamma)^{23}$Na, ^{23}Na$(p,\alpha)^{20}$Ne, and ^{23}Na$(p,\gamma)^{24}$Mg reaction rates are dominated by contributions from resonances corresponding to states in the compound nuclei just above the proton threshold. The rates of these reactions are uncertain because the proton partial widths for the states near threshold are poorly constrained by experiment. There are 13 known states in ^{23}Na between the proton threshold and the lowest-energy (p,γ) resonance that has been measured directly. Two of these states at $E_x = 8.862$ and 8.894 MeV may dominate the ^{22}Ne$(p,\gamma)^{23}$Na reaction rate, but their contribution is uncertain by as much as a factor of 10^4. The uncertainties in the ^{23}Na$(p,\alpha)^{20}$Ne and ^{23}Na$(p,\gamma)^{24}$Mg reactions are not as severe, but a state at $E_x = 11.727$ MeV may have significant influence on the ^{23}Na$(p,\alpha)^{20}$Ne rate at low temperatures, and a state at $E_x = 11.828$ MeV contributes a factor of 2 uncertainty to the ^{23}Na$(p,\gamma)^{24}$Mg rate.

We have measured angular distributions of differential cross sections for the ^{22}Ne$(^3He,d)^{23}$Na and ^{23}Na$(^3He,d)^{24}$Mg reactions at Triangle Universities Nuclear Laboratory. A 20-MeV beam of ^{3}He was used, and deuterons detected in the TUNL Enge split-pole magnetic spectrometer. Targets of ^{22}Ne implanted into a carbon foil were used in measurements of the ^{22}Ne$(^3He,d)^{23}$Na reaction. Targets of sodium or sodium-bromide evaporated onto carbon backings were used in measurements of the ^{23}Na$(^3He,d)^{24}$Mg reaction. Absolute cross sections were determined by normalizing the deuteron yield to ^{3}He elastic scattering measured in the splitpole. Elastic scattering of ^{3}He was also measured using charged-particle detectors at fixed angles in the target chamber in order to monitor the target composition. Proton spectroscopic factors for the states of interest were determined by fitting the measured differential cross sections to theoretical cross sections predicted from DWBA. The desired proton partial widths were obtained by scaling the corresponding single-particle widths by the proton spectroscopic factors.

For states where previous data exist, we generally find agreement between spectroscopic factors determined from this and previous measurements.[2,3,4] We

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[2]J. Görres *et al.*, *Nucl. Phys.* A408, 372 (1983).

[3]W. A. Childs *et al.*, *Nucl. Phys.* A203, 133 (1973).

[4]J. R. Powers *et al.*, *Phys. Rev. C* 4, 2030 (1971).

find no evidence at any angle for the 8.862- and 8.894-MeV states seen in a previous ($^3He, d$) measurement.[4] An example spectrum from the ^{22}Ne($^3He, d$)^{23}Na reaction measured at a laboratory angle of 10 degrees is shown in Fig. 1. We have established upper limits on the proton spectroscopic factors for the 8.862- and 8.894-MeV states which indicate that both of these states are too weak to contribute substantially to the ^{22}Ne(p, γ)^{23}Na reaction rate. Below a temperature of 0.2×10^9 K, the reaction rate is dominated by the contribution from the state at 8.828 MeV. We determine a proton spectroscopic factor of 0.026 for the 8.828-MeV state, which is in agreement with previous results from both ($^3He, d$) and direct capture; however, the proton-partial width we extract for this state is 30% smaller than that previously recommended. The single-particle widths should be more reliable in this case since they were calculated in a self-consistent manner using the same radial wave functions as from the DWBA calculations. Our results imply that the ^{22}Ne(p, γ)^{23}Na reaction rate is near to the lower limit as given in El Eid and Champagne[5] for $T > 8 \times 10^7$ K but for lower temperaures, the rate is somewhat lower than the lower limit given in this compilation.

Analysis of the data from the ^{23}Na($^3He, d$)^{24}Mg reaction is currently in progress. No evidence for the 11.727-MeV state was seen, but the 11.828-MeV state, which dominates the uncertainty in the ^{23}Na(p, γ)^{24}Mg rate was cleanly observed. The data analysis will be completed next year, and the results of these measurements will significantly reduce the uncertainties in the ^{22}Ne(p, γ)^{23}Na, ^{23}Na(p, α)^{20}Ne and ^{23}Na(p, γ)^{24}Mg reaction rates.

[5] M. F. El Eid and A. E. Champagne, *Astrophys. J.* 451, 298 (1995).

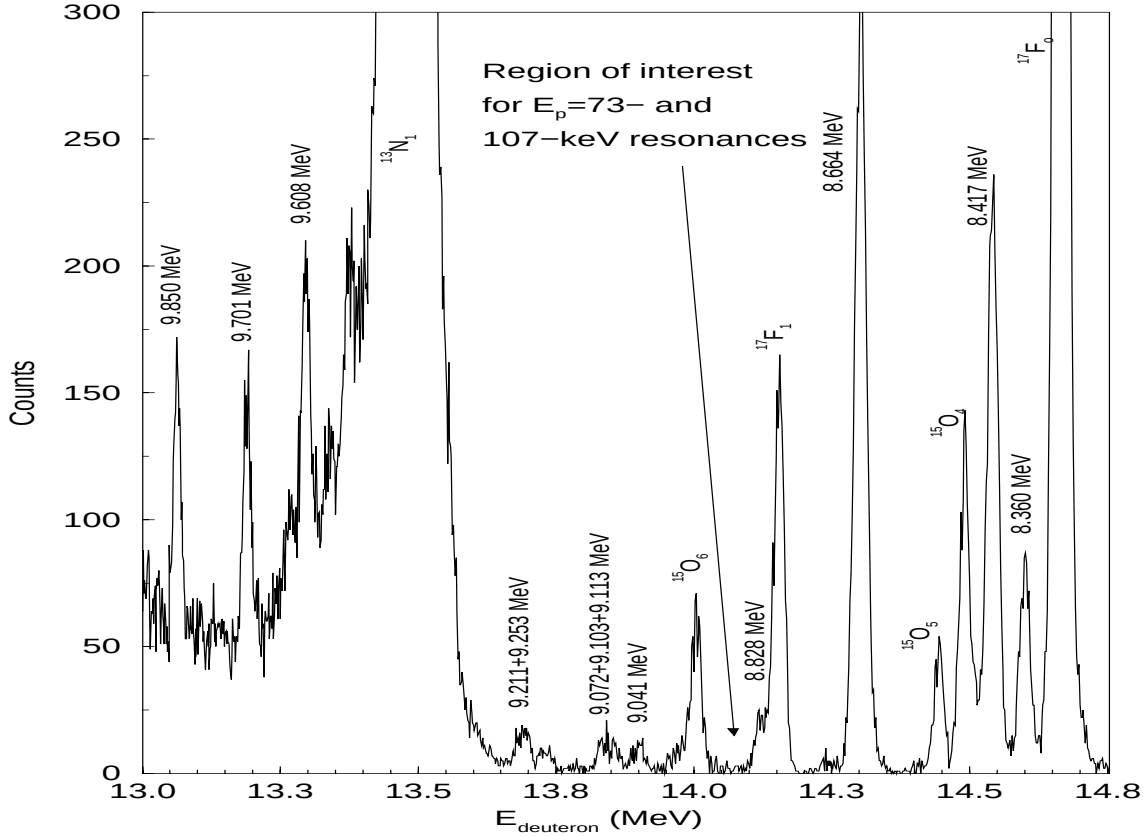

Figure 1: Deuteron spectrum from ^{22}Ne($^3He, d$)^{23}Na at $E_{He} = 20$ MeV and $\theta = 10°$.