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Institute for Nuclear Study, University of Tokyo (INS), Midori-cho, Tanashi, Tokyo, 188 Japan
[a] Physics Department, Yamagata University, Yamagata, 990 Japan
[b] Cyclotron and Radioisotope Center, Tohoku University, Aoba, Sendai, 980-77 Japan
[c] Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo, 152 Japan
[d] Department of Physics, Osaka University, Toyonaka, Osaka, 560 Japan
[e] Theory Division, National Astronomical Observatory, Mitaka, Tokyo, 181 Japan

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A series of experiments were made to investigate the early stage of the rapid-proton process. Specifically, the nuclear reaction chain at N=11 was discussed, including a recent result on ^{25}Si. A discussion with nova model calculations using the present experimental results is also made.

1. Introduction

Light proton-rich nuclei play a crucial role in the explosive hydrogen burning process (rapid-proton process) [1], especially for the early stage of the process. According to the rp-process scenario, the nucleosynthesis-flow just after the breakout off the Hot-CNO(HCNO) cycle goes through nuclei of which structure is not known well or totally unknown. It is quite interesting to understand the early stages of the rp-process because it is directly related to the production of the elements observable in novae. The breakout from the HCNO cycle and the first step after the breakout were studied before, which include a successive nuclear reactions, ^{19}Ne(p,γ)^{20}Na(p,γ)^{21}Mg . . . [2–4].

A series of experimental studies were extended to the possible subsequent second flash at N = 11 on the rp-process by indirect methods, and a nova model study has been made to learn about the explosive process, using the reaction rates obtained here. The nuclei on the path way from ^{22}Na through ^{25}Si were studied here experimentally. These led us discoveries of new resonances near and above the proton thresholds in all nuclei studied, giving considerable changes for the stellar reaction rates.

The experimental works were made using a high resolution spectrograph at the cyclotron facility of the Institute for Nuclear Study (INS), University of Tokyo.

2. ^{22}Na(p,γ)^{23}Mg

The first step was the ^{22}Na(p,γ)^{23}Mg reaction. This process is a depletion process of ^{22}Na, which is of great importance in two fold; so called the Ne-E problem [5,6] and

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the gamma ray observations. The Ne-E problem is a long standing problem of isotopic anomaly of Ne isotopes in meteorites. High ^{22}Ne enrichments have been observed in some presolar grains, which are believed to have been produced in some stellar event. The nucleus ^{22}Na trapped in a meteorite would have beta decayed afterward, giving an enrichment of ^{22}Ne, since ^{22}Na has a long half life of 2.6 y. This depletion process, ^{22}Na(p,γ)^{22}Mg, was almost totally unknown below 290 keV, although the reaction at higher energies was investigated previously using a radioactive target of ^{22}Na [7,8]. In the low temperature region, a resonance was suggested at around 7.6 MeV by the (^{3}He,α) reaction [9].

The nuclear levels near the proton threshold in ^{23}Mg were investigated by the direct neutron-pickup reaction ^{24}Mg(p,d)^{23}Mg [10] with high resolution at the cyclotron. A new resonance was discovered at 7.643 MeV, and the spin-parity assignment of $J^{\pi} = (3/2,5/2)^{+}$ was made through a Distorted-Wave-Born- Approximation analysis for the angular distribution measured. The newly discovered state clearly dominates the reaction rate below 1.0 x 10^{8} K of the Gamow energy.

Very recently, this new resonance at 7.643 MeV was reconfirmed by Bohum group using the direct proton transfer reaction ^{22}Na(^{3}He,d)^{23}Mg [11], giving the multipolarity of the resonance to be d-wave and the proton partial decay width. In fact, this resonance enhances the reaction rate by several orders of magnitude at around 0.5 x 10^{8} K. Since the spin of the state is not uniquely determined yet, there still remains some ambiguity for the rate. Since the half life of ^{22}Na is quite long as mentioned above, there will be a chance that the gamma rays from the decay of ^{22}Na are observed in novae which occur in our neighborhood. This is an interesting challenge for the gamma ray observations. So far, there is only some upper limit set for the ^{22}Na gamma rays from Nova Cyg 1992 [12] in a recent gamma ray observation [13].

3. ^{23}Mg(p,γ)^{24}Al

The second process was ^{23}Mg(p,γ)^{24}Al. This process is sitting on the breakout point from the NeNa cycle to the next MgAl-cycle in the rp-process. Here, an interesting question is the breakout condition from the NeNa cycle, which should take place from ^{23}Mg to ^{24}Al at moderately high temperature. This is very similar to the situation of the breakout from the HCNO cycle. The nuclear levels in ^{24}Al were investigated by the ^{24}Mg(^{3}He,t)^{24}Al reaction [14]. Several new states were identified above the proton threshold including a resonance at 917 KeV above the proton threshold, and the crucial resonance at 2.521 MeV assumed before has been confirmed. There are significantly large level shifts observed as compared to the mirror nucleus ^{24}Na. The reaction rate estimated based on the new experimental result is about a factor of five larger than the previous estimate, resulting in a reduction of the onset temperature of the ^{23}Mg(p,γ)^{24}Al process roughly by 10 %. A network calculation clearly indicates that a sharp onset of the leakout from the NeNa cycle takes place through the ^{23}Mg(p,γ)^{24}Al reaction at around 2.3 x 10^{8} K, although a small leakout begins through the ^{23}Na(p,γ)^{24}Mg reaction at lower temperatures. The critical physical parameters, the resonance strengths, should be determined for these states. This is an interesting subject to be investigated with an unstable nuclear beam of ^{23}Mg in radioactive nuclear beam facilities.

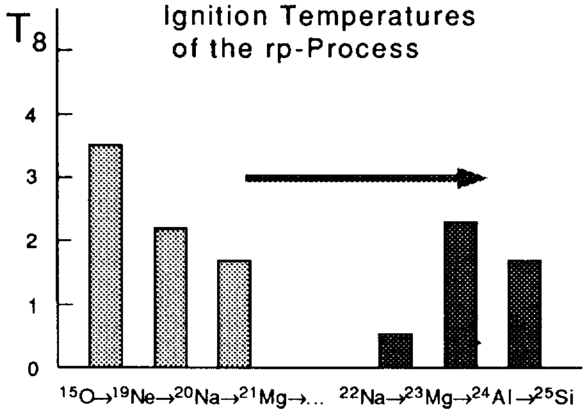

Figure 1. The iginition temperatures of the early stage of the rp-process estimated here, together with the ones for the onset of the rp-proess [3].

4. ^{24}Al(p,γ)^{25}Si

Recently, the possible next process ^{24}Al(p,γ)^{25}Si was investigated by the ^{28}Si(^{3}He,^{6}He)^{25}Si reaction. This process is also of great interest since the half life of ^{24}Al is 2.07 sec. which is long enough to retard the explosion. If this process is favored, then the flow goes up to the heavier mass region without the delay. This reaction may be related to the nucleosynthesis of Si and S observed in nova ejecta [12,15], but is least investigated among the three reactions discussed here. There was only one level suggested previously at 3.8 MeV just above the proton threshold, and spin-parities were not known for most levels in ^{25}Si. The (^{3}He,^{6}He) reaction is very useful for a spectroscopy of proton-rich nuclei, although the reaction has very small cross sections, i.e., it may determine not only the excitation energies but also the spin-parity of the residual states [16]. The experiment was performed with a 73-MeV ^{3}He beam from the cyclotron. The observed oscillation phases at forward angles in the angular distributions enabled us spin-parity assignment for each level. Four resonances have been identified within 0.8 MeV above the proton threshold in ^{25}Si, including three new resonances. These resonances are within a Gamow window of 3 - 10 x10^8 K, and the estimated reaction rate of the ^{24}Al(p,γ)^{25}Si process is dominated by a new resonance at 3.7 MeV at all the temperature region up to 10^9 K.

5. The rp-Process in Novae

Figure 1 summarizes the ignition temperatures estimated for each reaction from the present works except for the $^{15}O(\alpha,\gamma)^{19}$Ne process which was taken from ref. [17]. The influence of the present experimental results on the nucleosynthesis for a typical nova is studied using a quasi-analytical nova model [18,19] that involves only two parameters, the mass of the white dwarf M_{WD} and the envelope mass M_{env}. The time evolution of the envelope is calculated by solving the energy equation, with the nuclear energy produced from the network calculations. Here, we assumed neon-rich novae that have mainly ^{16}O, ^{20}Ne and ^{24}Mg. A detail of the model is discussed by Wanajo in this proceedings. In the present analysis, we set M = 1.3 $M_\odot$ and M_{env} = 1 x10^{-4}, which are close to a condition of a recently observed nova, Nova Cyg 1992 [12], that showed considerable abundances of Ne and heavier elements in the ejecta. The initial abundance is assumed to be a mixture of the solar abundance and the white dwarf material at the surface. Considerable increases are observed in production of ^{27}Al and ^{28}Si, but almost none for ^{26}Al. There is also some depletion seen for ^{22}Na production.

Since the successive proton capture reactions discussed here is a bridge between ^{22}Na and ^{26}Al, both of which are of great interest for isotope anomalies and the gamma ray observations. The most crucial physical parameter, the resonance strengths, are not measured yet for most resonances relevant to the onset and the early stage of the rp-process. These remain to be further investigated experimentally. Specifically, they will be directly investigated in near future using radioactive nuclear beams at new ISOL-based radioactive nuclear beam facilities such as the one at INS, which is just about to come into operation.

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