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NUCLEOSYNTHESIS IN THE RAPID-PROTON PROCESS*

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* Invited talk presented at the 18th INS International Symposium on Physics with High-Intensity Hadron Accelerators, Tokyo, March 14 - 16, 1990.

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Abstract: Recent experimental studies on ^{20}Na and ^{21}Mg and the implication to the onset of the rapid-proton process in stellar sites are discussed. A plan of the nuclear reaction studies with using radioactive nuclear beams is also presented.

1. Introduction

Nucleosynthesis generally plays a crucial role in the stellar evolutions and also in the formation process of the universe just after the big bang. In high temperature burning stages nucleosynthesis often includes unstable nuclei. The rapid proton (rp) process[1], which will take place in high temperature, hydrogen rich sites, is expected to involve many proton-rich unstable nuclei, as shown schematically in Fig. 1. However, the nuclear structures are often not well known of these nuclei. Actually, the proton drip line (the limit to hold protons bound in the ground state) in the sd-shell (Z = 8 - 20) region has been experimentally clarified very recently. Under these circumstances it should be worthwhile to check experimentally the key nuclear reactions for nucleosynthesis scenarios in nuclear astrophysics. Some scenarios are still based on rather fragile bases in a sense of nuclear physics.

Recently, considerable efforts have been made for investigating experimentally the breakout process from the hot-

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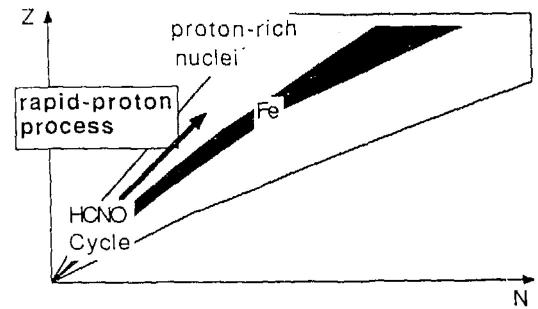

Fig. 1 Nucleosynthesis in the rapid-proton process.

CNO cycle[2], which leads to the onset of the rp-process. The main sequence of the breakout process is said to be $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$[1,3]. Although the nuclear structure of ^{20}Na is so crucial for this process, it was almost unknown until very recently. The properties of nuclear levels near and just above the proton threshold are critical for hydrogen burning, but only one level was suggested[4] previously at around 2.9 MeV in this energy region in ^{20}Na. We have identified[5-7] many new levels by the (^{3}He,t) and (p,n) reactions on ^{20}Ne, including a possible s-wave resonant state (1^+) at 2.637 MeV which is the first excited state above the proton threshold. The stellar reaction rate calculated based on these experimental results is about two orders of magnitude larger than the previous theoretical predictions[1,3], suggesting the onset temperature of the $^{19}Ne(p,\gamma)^{20}Na$ process to be about a factor of two smaller than those predicted before.

Here, we have studied[8] the next process just after the breakout from the hot-CNO cycle, i.e., the $^{20}Na(p,\gamma)^{21}Mg$ process. Nothing was known[9,10] for the nuclear structure of ^{21}Mg near and above the proton threshold. The question here is whether the rp-process flows up to ^{21}Mg quickly, or it goes to ^{20}Ne by a slow beta decay process. The nuclear structure of ^{21}Mg was studied by using the three-neutron pick-up reaction $^{24}Mg(^3He,^6He)^{21}Mg$.

The experimental setup and the experimental results on the nuclear structure of ^{21}Mg are presented in the next section. In sec. III, the implication to the stellar reaction rate of the ^{20}Na(p,γ)^{21}Mg process and the breakout problem from the hot-CNO cycle will be discussed based on the present result together with those previously obtained on ^{20}Na[5-7]. In sec. IV a plan of the experimental studies of the stellar nuclear reactions is presented which uses radioactive nuclear beams, with which one can really investigate directly in the laboratory system the nuclear reactions which take place in stellar sites.

II. Experimental Study of ^{21}Mg

Nuclear levels of ^{21}Mg have been studied through the ^{24}Mg(^{3}He,^{6}He)^{21}Mg reaction at 73.71 MeV. A ^{3}He beam of 0.5 - 1 μA was obtained from the sector-focussing cyclotron of the

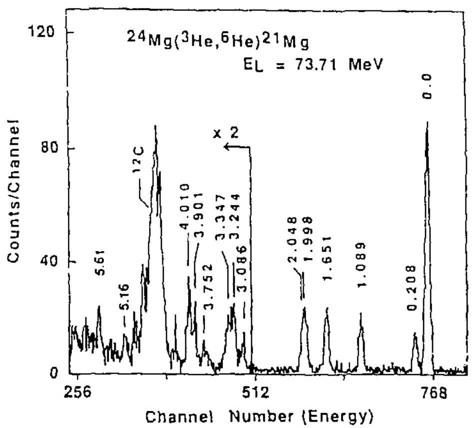

Fig. 2 A momentum spectrum of ^{6}He from the ^{24}Mg(^{3}He, ^{6}He)^{21}Mg reaction measured at $\Theta_L = 10^{o}$.

Institute for Nuclear Study, University of Tokyo. Metallic foils of enriched ^{24}Mg (99.92 %) of about 890 and 390 $\mu g/cm^2$ were bombarded and the reaction products ^{6}He were measured with a hybrid-type gas counter on the focal plane of the QDD type magnetic spectrograph. The high-resolution momentum spectrum of ^{6}He from the reaction was calibrated by using the ^{12}C(^{3}He,α)^{11}C reaction with using the same beam and the setup in the run. The experimental details will be found elsewhere[8].

Figure 2 shows a typical spectrum of ^{6}He from the ^{24}Mg(^{3}He,^{6}He)^{21}Mg reaction. In general, the cross sections of the reaction are very small, e.g., the peak for the 3.086 MeV state corresponds roughly to 17 nb/sr. The experimental results are summarized in Fig. 3 together with the data for ^{21}F from refs. 9 and 10). The errors in the excitation energies are estimated to be about 10 keV, most of which come from the uncertainty in the

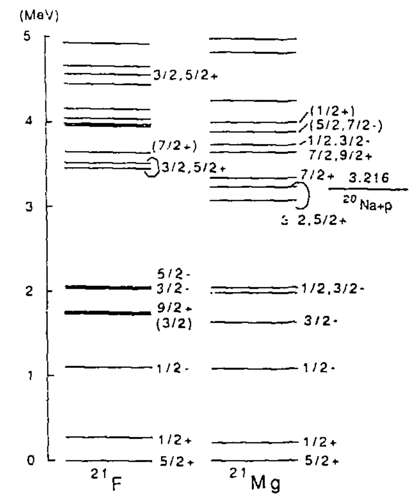

Fig. 3 Nuclear level schemes of ^{21}Mg obtained here and the mirror nucleus ^{21}F from refs. 6 and 7).

peak fitting of the levels in ^{11}C for calibration. The old data[9]) which suggested bound states at 0.0, 0.22, 1.3, 1.62, and 1.89 MeV seem to be consistent with the present results within their large errors. All levels above 1.998 MeV are the states identified for the first time in the present experiment. The first excited state above the proton threshold (3.216 MeV) is at 3.244 MeV, which is 28 keV above the threshold. Figure 3 also compares the level structures of ^{21}Mg and the mirror nucleus ^{21}F. One interesting observation is that some states near and just above the proton threshold in ^{21}Mg show considerable Coulomb shifts, and one state (at 3.086 MeV) is found to be a bound state.

We also have measured the angular distributions for the reaction to determine the spin-parities of these states. The shapes of the measured angular distributions especially at forward angles are found to be very much characteristic to the transferred angular momenta (L), e.g., L = 2, 0, 1, and 4 for the transitions to the states at 0.00, 0.208, 1.086, and 3.347 MeV, respectively. These characteristics are well reproduced by exact-finite range Distorted-Wave-Born-Approximation calculations[11]). The experimental angular distributions for the states at 3.086 and 3.244 MeV have rather similar shapes to that of the ground state, whereas the angular distribution for the 3.347 MeV state shows a clear L=4 shape as mentioned above, indicating $J^\pi = 7/2^+$ or $9/2^+$ for this state. Therefore, the first two states should be the analog states of the states at 3.45 and 3.51 MeV in ^{21}F, both of which have $J^\pi = (3/2, 5/2)^+$, and the third state to be the one at 3.63 MeV which has $J^\pi = (7/2^+)$. All the spin-parity assignments for ^{21}Mg in Fig. 3 are the present experimental result.

III. The Onset of the rp-Process

The $^{20}Na(p,\gamma)^{21}Mg$ process is expected to take place just after breakout via the main sequence $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$. The stellar reaction rate of this process has been evaluated here based on the experimental results to clarify how the dominant flow of the rp-process goes just after the breakout. If it goes through by a β^+ emission as mentioned in sec. I, the onset temperature would be increased because of the slowness of the decay process (0.446 sec).

In the p + ^{20}Na scattering, proton unbound states of $J^\pi = 3/2^+$ or $5/2^+$ could be s-wave resonances in ^{21}Mg since the ground state of ^{20}Na has $J^\pi = 2^+$. Previously, the stellar reaction rate of the $^{20}Na(p,\gamma)^{21}Mg$ process was evaluated by Wallace and Woosley[1]), and Wiescher et al.[12]), where both of the works assumed the same level scheme as that of ^{21}F[9]) for ^{21}Mg. However, one of the possible s-wave resonant states expected from the level structure of ^{21}F is now found to be a bound state. For the reaction rate calculation of the $^{20}Na(p,\gamma)^{21}Mg$ process, the resonance, the tail of resonance, and the direct capture processes are included. The excitation energies and the spin-parities are the present experimental results, and for other parameters the same values were used as in the previous estimate[12]) with corrections for penetrability. Here, a typical density $\rho = 5\times10^5$ gr/cm^3 of novae was assumed. Figure 4 shows the result, together with theoretical predictions by Wallace and Woosley[1])(WW), and Wiescher et al.[12]) All the results are plotted against the calculated rate by Wallace and Woosley. The present result shows

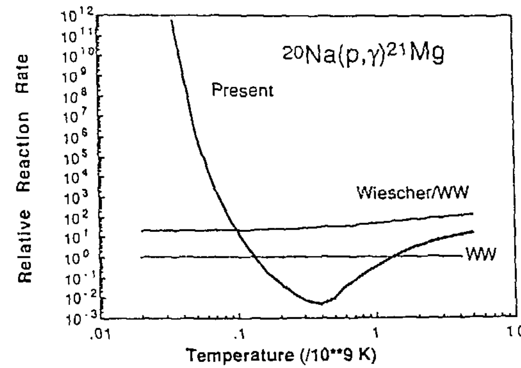

Fig. 4 The stellar reaction rate of the $^{20}Na(p,\gamma)^{21}Mg$ process evaluated based on the present experimental results. Here the rates are plotted against the prediction by Wallace and Woosley[1]).

a tremendous increase of the $^{20}Na(p,\gamma)^{21}Mg$ rate at $T \leq 1x10^8$ K as compared to the previous estimates, and a little decrease at the intermediate temperature region.

Therefore, the present calculation indicates at relatively low temperatures a very fast leakout through the $^{20}Na(p,\gamma)^{21}Mg$ process, which is the first stage of the rp-process just after breakout from the hot-CNO cycle.

The rp-process is considered to begin by breaking out from the hot-CNO cycle as mentioned earlier. As described in sec. I, we have suggested that the stellar reaction rate of the $^{19}Ne(p,\gamma)^{20}Na$ process should be enhanced by more than two orders of magnitudes as compared to the previous theoretical predictions. This enhancement primarily comes from the fact that the excitation energy of the 1^+ state observed is lower than expected[1,3] and it comes close to the threshold. Figure 5 shows the present stellar reaction rate of the $^{20}Na(p,\gamma)^{21}Mg$ process and our previous result on the $^{19}Ne(p,\gamma)^{20}Na$ process[5-7], where they

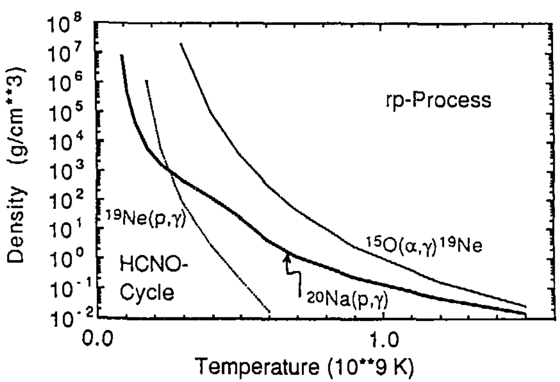

Fig. 5 The temperature-density plot of the breakout process from the hot-CNO cycle. The stellar reaction rate of the $^{20}Na(p,\gamma)^{21}Mg$ process is the present result and that of the $^{19}Ne(p,\gamma)^{20}Na$ process is our previous result[2,3].

are plotted on the temperature-density (of hydrogen) plane. In the original scenario by Wallace and Woosley[1], the $^{19}Ne(p,\gamma)^{20}Na$ process was the critical process for the onset of the rp-process, but now the $^{15}O(\alpha,\gamma)^{19}Ne$ process seems to be the critical reaction for this problem. Therefore, the onset temperature of the rp-process will be possibly lowered considerably. However, it should be noticed that the most important physical parameters are not yet determined experimentally[5-7], i.e., the gamma widths of the nuclear levels associated in both nuclei. Experimental works are under way in some laboratories including our project at RIKEN.

IV. A Plan of Nuclear Reaction Studies with Using Radioactive Nuclear Beams

Explosive burning stages in stellar sites will involve radioactive nuclides as shown in Fig. 1. Such nuclear reactions have been investigated indirectly by using stable beams and targets to some extent. The experimental study described in sec. II was a typical case. However, if one really likes to study directly the reaction $^{19}Ne + p \rightarrow \gamma + {}^{20}Na$[1,3,5-7], for instance, in the laboratory system, unstable nucleus ^{19}Ne is needed as a beam or a target. Very few works have been reported so far which

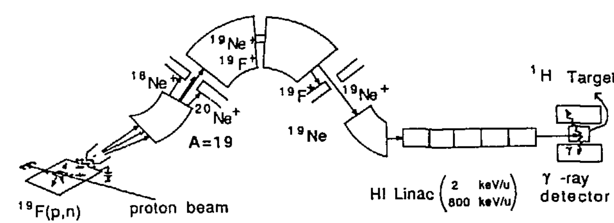

Fig. 6 A plan of the sudy of the $^{19}Ne(p,\gamma)^{20}Na$ reaction in the R & D of the Exotic Nuclei Arena in Japanese Hadron Project.

used unstable nuclei for the reaction studies. However, such studies will be made rather easily and systematically for a wide region of the nuclear chart in the recent development in experimental nuclear physics. Actually, a radioactive beam factory, which is called Exotic Nuclei (E) Arena, is planned in Japanese Hadron Project which is the major project of the nuclear physics community in Japan. In the R&D study of the E arena, we are constructing a pilot station where we can produce limited number of radioactive nuclear beams with low energies. However, such a nuclear reaction mentioned above can be investigated. The plan is shown in Fig. 6, where ^{19}Ne will be produced in the ion source part by using a proton beam from the INS Cyclotron. Then, it will be isotopically separated by a high resolution mass separator and injected to a heavy ion linac, which accelerates ^{19}Ne up to 0.8 MeV per nucleon. The high resolution mass separator ($M/\Delta M \gtrsim 10^4$), which is in the design stage, will remove ^{19}F contamination from the ^{19}Ne beam. The first step of the linac has been completed which will be reported in this symposium by Arai[13]. This energy is high enough to cover the first excited state above the threshold, the 1^+ resonant state[5-7] in ^{20}Na.

This kind of nuclear reaction study with radioactive nuclear beams will open up a new frontier in the experimental nuclear astrophysics.

REFERENCES

1) R. Wallace and S. E. Woosley, Astrophys. J. Suppl. 45 (1981) 389.
2) R. R. Caughlan and W. A. Fowler, Nature Phys. Sci. 238 (1972) 23.
3) K. Langanke, M. Wiescher, W. A. Fowler, and J. Görres, Astrophys. J. 301 (1986) 629.
4) F. Ajzenberg-Selove, Nucl. Phys., A475 (1987) 1.
5) S. Kubono, et al., Z. Phys. A331 (1988) 359.
6) S. Kubono, et al. Astrophys. J. 344 (1989) 460.
7) S. Kubono, et al., Proc. International Symposium on Heavy Ion Physics and Nuclear Astrophysical Problems, World Scientific Pub. (Singapore), ed. S. Kubono, M. Ishihara, and T. Nomura, 1989, 83.
8) S. Kubono, et al., Z. Phys. A334 (1989) 512.
9) P. M. Endt and C. van der Leun, Nucl. Phys. A310 (1978) 1.
10) D. E. Alburger, C. J. Lister, J. W. Olness, and D. J. Millner, Phys. Rev. C23 (1981) 2217.
11) M. Igarashi, exact-finite range DWBA code TWOFNR, unpublished.
12) M. Wiescher, J. Görres, F. -K. Thielemann, and H. Ritter, Astr. Astrophys. 160 (1986) 56.
13) S. Arai, see the paper in this proceedings.