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Experimental Approach to Explosive Nucleosynthesis*

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Abstract

Recent development of experimental studies on explosive nucleosynthesis, especially the rapid proton process and the primordial nucleosynthesis were discussed with a stress on unstable nuclei. New development in the experimental methods for the nuclear astrophysics is also discussed which use unstable nuclear beams.

1. UNSTABLE NUCLEI AND HIGH TEMPERATURE NUCLEOSYNTHESIS

In the recent years, considerable development has been made in the study of unstable nuclei in nuclear physics, especially by using heavy ion beams. Intermediate and high energy heavy ion beams have produced unstable nuclei efficiently. This feature has provided a new tool for nuclear astrophysics as well. We will discuss some recent developments on the explosive nucleosyntheses. Here, we concentrate on the rapid-proton (rp) process and the primordial nucleosynthesis.

Nucleosynthesis plays a crucial role in the stellar evolutions and also in the early universe just after the big bang. As was shown clearly in the recent super nova 1987A, unstable nuclei play very crucial roles in explosive processes in the universe. Figure 1 displays several nuclear reaction processes which take place in stellar sites, and some of them in the primordial site as well. At low temperatures, some processes undergo for a long duration near the stability line, but the ones at high temperatures go very rapidly involving more the nuclei far from the stability line. For instance, the rapid proton (rp) process[1)] involves very proton-rich unstable nuclei. This process will include successive proton capture reactions before beta decay. Thus, as shown in Fig. 1, the flow goes near the proton drip line more or less, but the actual flow path should be determined by a competition of the beta decay and the proton capture reaction in high-temperature high-density sites. Nuclear physics inputs are very crucial here although this problem of course

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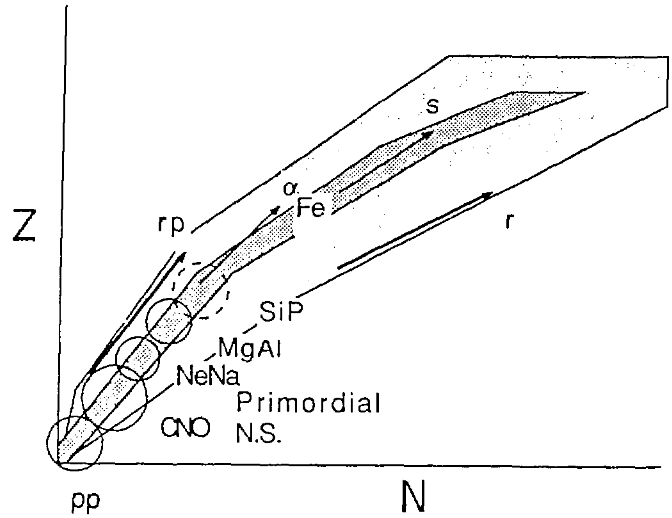

Fig. 1 Nuclear reaction processes shown on the N-Z Plane. Density is also a crucial parameter to be considered here.

depends on the conditions of the stellar sites.

Although the rp-process is expected to involve many proton-rich unstable nuclei possibly near the proton-drip line, the nuclear structures are little known of these nuclei yet. When this process was proposed in 1981 by Wallace and Woosley,[1] the proton drip line was not well known. The scenario of the rp-process then was using many assumptions for the nuclei involved. Actually, the proton drip line in the sd-shell (Z = 8 - 20) region has been experimentally clarified very recently by the GANIL experiments. Similar status can be seen in the neutron-rich side for the rapid-process. Under these circumstances, it should be worthwhile to check experimentally critical nuclear reactions for nucleosynthesis scenarios in nuclear astrophysics.

As an experimental approach to the problems of nucleosyntheses, there would be usually three stages;

1) we first need to know if the nucleus is particle stable or not, then
2) identify levels, the spin-parities and the life times, and finally,
3) we have to know the properties of the nuclear levels relevant to the burning processes, e.g., the total width and the decay widths.

Or, one needs to know the reaction cross sections instead of 2) and 3). If there is a resonant state at the temperature region of interest, it will enhance the reaction rate considerably. Scenarios of nucleosyntheses of explosive processes are still based on such fragile bases in a sense of nuclear physics. Some parts still need the stage 1) experiment. This consideration is also true for the problem of primordial nucleosynthesis.

Discussions on the rp-process and the primordial nucleosynthesis are given in secs. 2 and 3, respectively. In sec. 4, recent new development in the experimental methods is discussed.

2. DEVELOPMENT IN THE RAPID-PROTON PROCESS

Considerable efforts have been made recently for investigating experimentally the breakout process from the hot-CNO cycle,[1-7] which leads to the onset of the rp-process. The *main sequence of the breakout* process is considered to be $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$.[1,2] For this problem we have investigated the nuclear reactions of the onset process, i.e., $^{19}Ne(p,\gamma)^{20}Na$ and $^{20}Na(p,\gamma)^{21}Mg$ by using an indirect method. The nuclear structure of ^{20}Na was studied through the direct charge-exchange reactions (^{3}He,t) and (p,n) on ^{20}Ne, and many new levels (with excitation energies and the spin-parities) were identified,[4] including the 2.637 MeV 1^+ state which is just 438 keV above the proton threshold. This *new state was found to produce at least two orders of* magnitude larger reaction rate at the temperature region of interest. Consequently, the ignition temperature of this process is found to be lowered roughly by a factor of two. However, the absolute onset temperature is not determined yet because the information of stage 3) is not known yet, i.e., the gamma width of the resonant states in ^{20}Na.

Recently, we have performed an experiment to study the decay property of the levels near the proton threshold in ^{20}Na using the projectile fragment separator RIPS at RIKEN. The secondary beam of

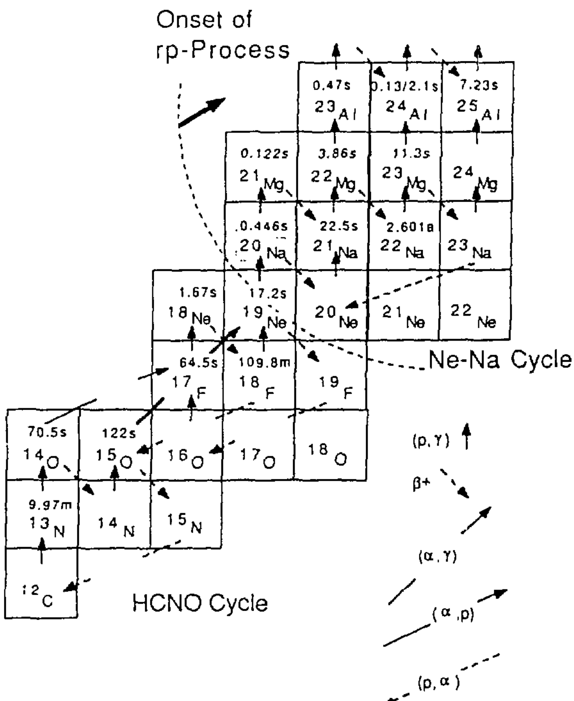

Fig. 2 The hot-CNO cycle and the onset of the rapid-proton process.

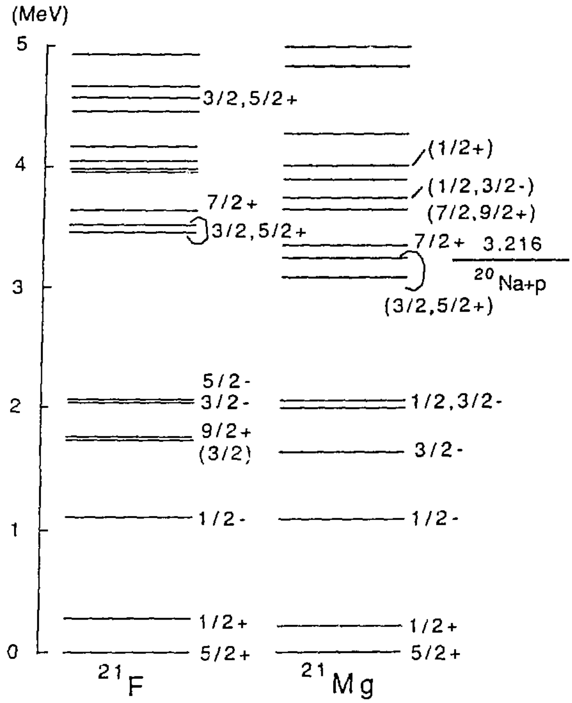

Fig. 3 Nuclear levels of ^{21}Mg identified in the present experiment and the levels of the mirror nucleus ^{21}F.

^{20}Mg was obtained by using a 100-MeV/u primary beam of ^{24}Mg from the RIKEN ring cyclotron. Only the proton decays were observed so far, as expected for the states in ^{20}Na.[2,5] Here, the gamma width is the subject of near-future experiment.

The next process ^{20}Na(p,γ)^{21}Mg predicted by the scenario was also examined by studying ^{21}Mg with the reaction ^{24}Mg(^{3}He,^{6}He)^{21}Mg at INS-cyclotron of the University of Tokyo. Here, it was known that the nucleus ^{21}Mg has about $\tau_{1/2}$ = 90 ms, but the nuclear levels were completely unknown near and above the proton threshold in ^{21}Mg. In the previous calculations of the rp-process, the nuclear levels same as those of the mirror nucleus ^{21}F were assumed for ^{21}Mg. Figure 3 displays the level scheme of ^{21}Mg identified in the present experiment.[6,7] The states near the proton threshold show considerable level shifts to lower energy. The s-wave resonant state postulated just above the proton threshold was found to be a bound state. Thus, this state gives almost no effect to the reaction rate in the nucleosynthesis. In total, the thermal reaction rate in the temperature region of T_9 = 0.1 - 1.0 (T_9 = T/(10^9 K)) was found to be a few orders of magnitude

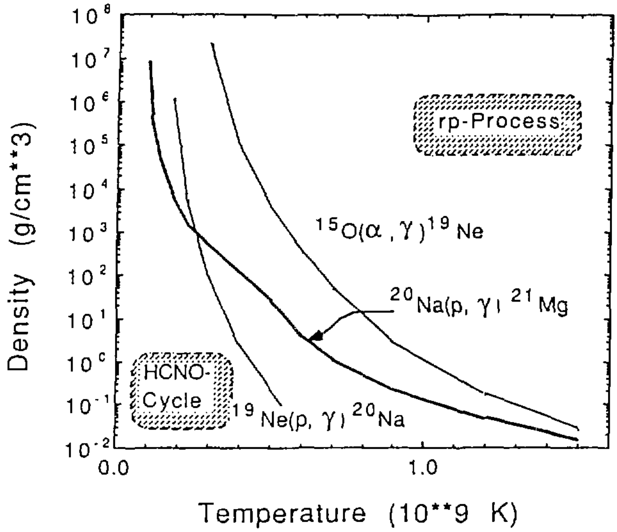

Fig. 4 The thermal reaction rates of the three successive reactions in the breakout process from the Hot-CNO cycle.

overestimated in the previous predictions.[1,3] This could be an instructive example for the necessity of nuclear physics experiment for the astrophysical problems. These level shifts are very serious as far as one measures the shifts from the threshold.

From these two experiments discussed above, the estimated reaction rates suggest that the rp-process begins at around $T_9 = 0.4$ for a typical density of nova $\rho = 5x10^5$ g/cm^3, and the limiting reaction process for the breakout seems to be the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction, as shown in Fig. 4. However, it should be noted that they are not conclusive since the stage 3) experiments are not made yet which determine the absolute temperatures.

Let me keep going on the discussion on the rp-process. In Fig. 2, we do not know how the rp-process flows after ^{21}Mg. The current scenario[3] says that it should go to ^{21}Na by a slow beta decay process. However, our recent shell model calculation[8] suggests that there would be some resonances which have large s-wave components just above the proton threshold in ^{22}Al. This would favor a nucleosynthesis-flow up to ^{22}Al. Here, experiments are definitely needed.

Another interesting subject among the rp-process is the termination process. The rp-process is considered to run over the mass region of Fe-Ni way up to somewhere A = 100. However, it is not known how far and where it will go. There were some unknown nuclei through which the rp-process runs in the scenario.[9] A beautiful experimental result was reported[10] very recently from MSU group. The critical nuclei ^{65}As, ^{69}Br, etc have been identified by using the newly installed secondary beam line at MSU. This result supports that the rp-process goes through these nuclei. This is clearly the experiment of stage 1), and thus further experimental works of stage 2) and 3) are needed.

3. *PRIMORDIAL NUCLEOSYNTHESIS*

One of the key issues in the primordial nucleosynthesis is if the metals (^{12}C and heavier elements) were produced in the very early universe. Inhomogeneous big bang (IBB) models,[11-15] which introduced inhomogeneities in baryon density in the quark-hadron phase transition, have succeeded in predicting nucleosynthesis of finite metallicity, although there is a difficulty with ^{7}Li overabundance. The postulated dominant flow path,[14] which bypasses the A = 8 gap in the IBB models, is $^{4}He(t,\gamma)^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B(n,\gamma)^{12}B(\beta^{-}\nu)^{12}C$. These scenarios, however, assumed several important reaction rates which were unknown then. Especially, the $^{8}Li(\alpha,n)^{11}B$ reaction was completely unknown since the target ^{8}Li is unstable.

An experiment[16] on this process was recently made which used the reverse reaction $^{11}B(n,\alpha)^{8}Li$. Figure 5 shows the astrophysical S-factor obtained. *It is about 8400 MeV·b near the Gamow peak of* $T_9 = 1$, which is the value used in the IBB model calculation by Malaney and Fowler.[14] However, it is clearly not a constant S-factor (energy independent) as was assumed in the IBB models. This measurement, however, includes only the neutrons to the ground state in ^{11}B, and it

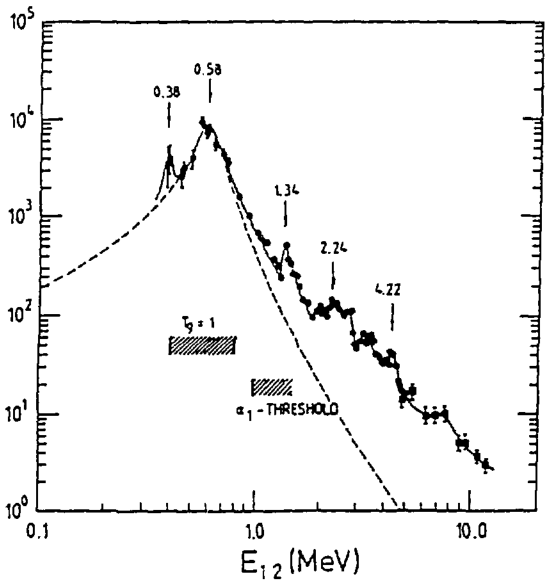

Fig. 5 The astrophysical S-factor of the $^{8}Li(\alpha,n_0)^{11}B$ reaction.[16]

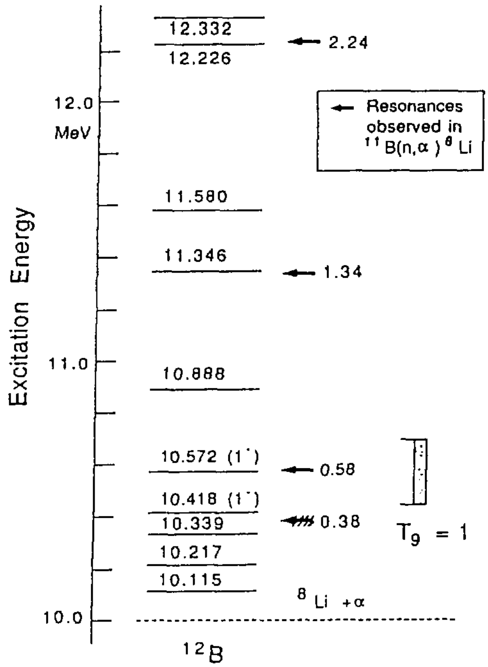

Fig. 6 Nuclear Levels of ^{12}B observed in the present experiment, and the resonances seen in the $^{11}B(n,\alpha)$ reaction.[16]

was discussed that the neutrons to the excited states would be less than 10 %.[16] Here, crucial physical parameters such as particle decay widths and the spin-parities were not determined for the resonances in ^{12}B.

These properties were studied[17] further by using the direct reaction $^{9}Be(\alpha,p)^{12}B$, which was found to excite the present resonant states with reasonable cross sections as expected.[18] Figure 6 shows a clear correspondence between the levels observed in the $^{9}Be(\alpha,p)^{12}B$ reaction and the resonances,[16] where the $^{8}Li + \alpha$ threshold lies at 10.000 MeV in ^{12}B. The lowest resonance was not well determined in the (n,α) measurement. The most important state for the $^{8}Li(\alpha,n)^{11}B$ reaction at around $T_9 = 1$ is the one at 10.572 MeV, which is strongly excited in the (α,p) reaction. The (α,p) angular distribution measured for the 10.572-MeV state was fitted reasonably well by an exact finite-range Distorted Wave Born Approximation[19] calculation assuming the angular momentum transfer $L_{tr} = 0 - 2$. This gives a tentative assignment of $J^{\pi} = (0^+, 1^-, 2^+, 3^-)$.

The branching ratios for the particle decays from these states were determined by measuring the decay neutrons. Figure 7 shows a typical time-of-flight spectrum of the neutrons from the 10.572 MeV state in ^{12}B, measured at 30° with $E_{\alpha} = 50$ MeV. The sum of the intensities of the neutron decays to the excited states are almost the same as the yield

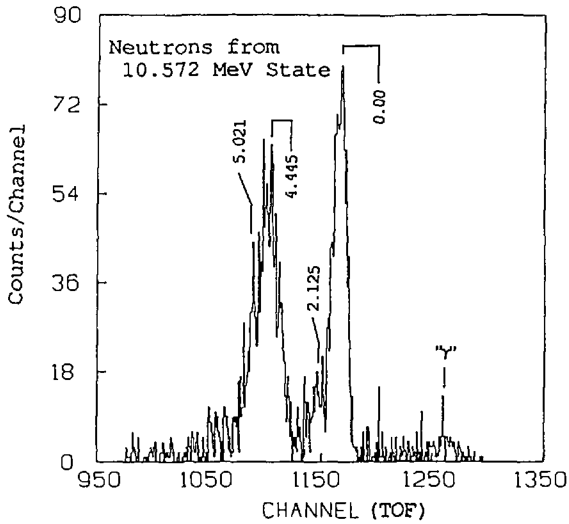

Fig. 7 Time-of-flight spectrum of neutrons from the 10.572 MeV state in ^{12}B excited by the $^{9}Be(\alpha,p)^{12}B^{*}$ reaction, measured at 30°.

for the ground state. Thus, the reaction rate of the $^{8}Li(\alpha,n)^{11}B$ process should be increased roughly by a factor of two at least as compared to the previous estimate.[16] The angular correlation functions of the neutrons for the first four states are reasonably well fitted with a square of the Legendre polynomial of the order of 1, 1, 3 and 1, respectively. By taking into account the tentative assignment discussed above, this state has most probably $J^{\pi} = 2^{+}$. The branching ratios obtained are approximately $\Gamma_{n_0}/\Gamma_{tot} = 1/3$, $\Gamma_{n_{ex}}/\Gamma_{tot} = 1/3$, and $\Gamma_{\alpha}/\Gamma_{tot} = 1/3$. The α-branching ratio is much larger than expected.[16] However, this is consistent with the fact that the entrance channel of the thermal $^{8}Li(\alpha,n)^{11}B$ reaction can be an s-wave resonance.

We also have tested to measure the cross sections of this $^{8}Li(\alpha,n)^{11}B$ reaction directly by using the low energy secondary beam of ^{8}Li from the RIPS at RIKEN. The beam was produced by projectile fragmentation process, degraded to the energy range of 10 - 20 MeV, and then introduced to the ionization chamber, MUSIC, which has an admixture of ^{4}He as a target. As will be discussed in detail in the following talk by Boyd, this method seems to be promising for the measurement of α-induced thermal reaction cross sections. The cross sections obtained seem to be much larger than the previous values.[16]

Another interesting development made[20] for the primordial nucleosynthesis was an experiment with a low energy neutron beam for the $^{7}Li(n,\gamma)^{8}Li$ reaction. This is the problem of the trigger reaction for heavy element synthesis in the primordial site. The radiative capture cross section of neutrons was measured at 30 keV at the pelletron facility of the Tokyo Institute of Technology. We have measured directly the prompt gamma rays from this reaction. The cross section obtained is 39.3 $\pm$ 6.0 μb, which is about a factor of two larger than the value reported before.[21] However, the present value is consistent with the extrapolation from a thermal reaction cross section.

A flow of $^{7}Li(t,n)^{9}Be(t,n)^{11}B$ could be also an important pass way for heavy element synthesis.[22] Coc reported in this conference an experimental work for the first step, which reproduced the previous measurement,[23] supporting the importance of this process.

4. NEW EXPERIMENTAL METHODS FOR NUCLEAR ASTROPHYSICS

As we sketched in the preceding sections, there are new methods developed or being developed for nuclear astrophysics. Specifically, unstable nuclear beams become available from very low to high energies. Although the quality of the secondary beams from the projectile fragmentation processes is limited, there are many interesting experiments to be made for nuclear astrophysics. We made three different types of such experiments at RIKEN by using the projectile fragment separator RIPS. The decay property of ^{20}Na, and the cross sections of the $^{8}Li(\alpha,n)^{11}B$ reaction were measured as discussed above. Another important development we made is a Coulomb dissociation measurement of unstable nucleus ^{14}O. The gamma width of the 1^{-} state just above the proton threshold in the $^{13}N(p,\gamma)^{14}N$ reaction was determined to be 3.1 $\pm$ 0.6 eV, which is quite consistent with the values obtained by other methods. This was reported by Motobayashi[24] in the poster session in this conference.

More promising method could be the unstable nuclear beams accelerated. This includes an ISOL system to produce intense unstable nuclei and an accelerator to boost the kinetic energy to the region of astrophysical interest. A pioneer work was reported by Arnould in the previous talk. The gamma width of the 1^{-} state in ^{14}O was successfully measured by using the unstable nuclear beam of ^{13}N accelerated by a cyclotron. Extensive unstable nuclear beam factories are being planned in the world including the proposal of Exotic Nuclei Arena in Japan Hadron Project, as will be discussed by Nomura in this conference.

In summary, nuclear physics inputs are very crucial and valuable, and being awaited in nuclear astrophysics. Unstable nuclear beams seem to be opening a new field in nuclear astrophysics, especially for the problem of explosive nucleosynthesis. Study of nuclei near the drip lines is really research field for both nuclear physics and nuclear astrophysics. It should be, however, noted that the experimental works for the nucleosynthesis problems by a small machine and/or stable beams are also valuable and needed.

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