Development in Nuclear Astrophysics

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Abstract: A brief review is given on recent developments in nuclear astrophysics, specifically investigations of explosive phenomena in the universe, including recent works on the rapid-proton capture process and the rapid-process. The scope of nuclear astrophysics and the nuclear data compilation for nuclear astrophysics are also discussed.

I. Explosive Phenomena and Radioactive Nuclei

Nuclear reactions are one of the key elements for the evolution of the universe. There are many nuclear effects observable in the universe. These nuclear effects give us rich information about the nuclear processes that have taken place, and thus they are very critical clues for understanding the stellar events. We may discuss in this paper how we can approach the astrophysical problems from a nuclear physics point of view. Astrophysical models together with the nuclear physics information should explain the stellar event of interest. These critical tests will eventually give the real picture for the stellar phenomena. Nucleosynthesis involving stable nuclei has been studied for many years, but there are still many important nuclear reactions that have not been well examined yet mostly at low temperatures.

On the other hand, nuclear reactions that involve radioactive nuclei were much less investigated in the past [1]. Explosive phenomena such as supernovae and the very early universe just after the big bang inevitably involve radioactive nuclei of very short half-lives due to fast successive nuclear reactions before cooling through nuclear decays. A typical example of evidence of radioactive nuclei among the stellar events would be seen in supernova. For instance, the light curve of the supernova SN1987A is well explained by the nuclear decay of ^{56}Co, and the gamma rays of ^{56}Fe following the beta decay of ^{56}Co were also observed [2].

Since explosive phenomena, which take place in high-temperature and high-density sites, include successive nuclear reactions, the nucleosynthesis-flow goes away from the line of stability on the nuclear chart [1]. Figure 1 shows schematically various nucleosynthesis scenarios on the nuclear chart. The pp-chain and some cycles are effective more or less around the line of stability, as they take place in relatively low-density regions at low temperatures. By contrast, rapid processes such as the rapid-proton capture (rp) process [3] that is an explosive hydrogen burning process, go through the proton-rich or neutron-rich unstable nuclear region. The development of physics and technology of radioactive nuclei in nuclear physics stimulated these investigations in the last decade. This provides not only an opportunity for investigations of nuclear astrophysical problems but also new facets for

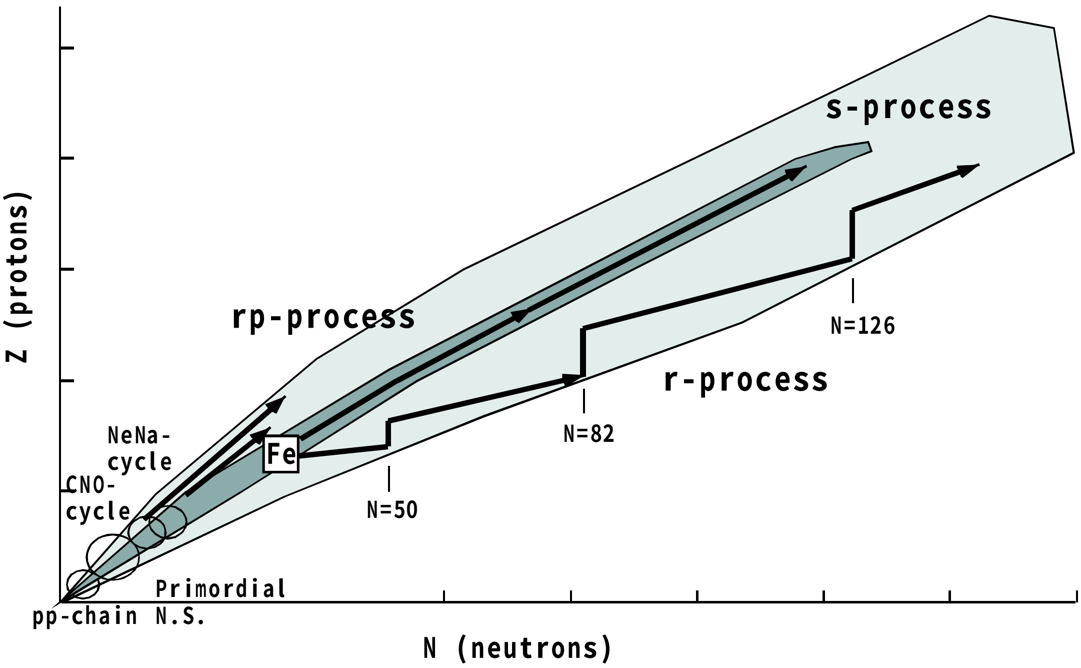

Fig. 1 A schematic view of pathways of explosive nucleosynthesis in the universe, depicted on the nuclear chart.

understanding scenarios of nucleosynthesis in the universe. For instance, neutron halo structures will dramatically alter the reaction rates of (n,γ) cross-sections, which are related to the s-process nucleosynthesis. The magic numbers of shell closure known near the line of stability would not hold necessarily for the nuclei far from the line of stability, which may change the r-process route.

In this short report, we will review briefly recent development specifically on the experimental works on the rp-process and the r-process.

II. Rapid-Proton Capture Process

Hydrogen burning is one of the basic scenarios of stellar nuclear burning. Specifically, the hydrogen burning under a condition of high temperature and high density, which is called the rp-process, has attracted many investigators in the last decade since they could be related to the explosive phenomena, such as novae and X-ray burst. Here, one can discuss the observations with the stellar models quantitatively in terms of the energy, the elemental abundances and the evolution.

The rp-process was proposed in 1981 by Wallace and Woosley [3]. Because of lack of nuclear physics information for the nuclei relevant, the pathway of breakout from the Hot-CNO cycle, which leads to the onset of the rp-process, was not identified clearly in the original paper. The suggested pathway of the onset and early stage of the rp-process is,

$$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na(p,\gamma)^{21}Mg(\beta)^{21}Na(p,\gamma)^{22}Mg(\beta)^{22}Na(p,\gamma)^{23}Mg(p,\gamma)^{24}Al(p,\gamma)^{25}Si \ldots$$

Along this pathway suggested for the rp-process, a series of experiments were performed to clarify the onset mechanism at the cyclotron of the Center for Nuclear Study (CNS), University of Tokyo [1]. Many new resonances were discovered above the proton thresholds in the nuclei relevant. The summary of the works is presented in Fig. 2, which shows ignition temperature of each process along the pathway mentioned above. Here, the estimated temperature of the first process, $^{15}O(\alpha,\gamma)^{19}Ne$, is taken from refs. [4,5]. As to the reaction of $^{22}Na(p,\gamma)^{23}Mg$, the S-factor was taken from ref. [6]. A new resonance was first identified at 7.643 MeV in the present experiment of $^{24}Mg(p,d)^{23}Mg$ just around $T_7 = 5$ for the Gamow window [7], where there was no estimate made before for the reaction rate.

Figure 2 suggests that the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is limiting the onset of the rp-process. However, note that none of the values in the figure is definitive because the decay properties of the critical levels for the nucleosynthesis are not known yet. These are one of the hottest subjects being or to be investigated with radioactive nuclear beams. So far, the ignition temperature of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction seems too high to give a condition that leads to a major flow-out of CNO material to heavier mass elements under ordinary nova conditions [8]. Therefore, this reaction should be of great importance to study nucleosynthesis in novae. Of course, the nova models also need to be developed to conclude the speculation above. For instance, a measurement of the α decay widths of the crucial resonant states in ^{19}Ne is underway at CNS using the reaction of $^{19}F(^{3}He,t)\,^{19}Ne(4.033)(\alpha)\,^{15}O$.

The second possible reaction sequence for the breakout off the HCNO cycle, which leads to an onset of the rp-process [3], more likely at stellar sites under higher temperatures and higher densities, is $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$… . Here, a new type reaction (α,p) sets in at the explosive burning. The reaction rate of $^{14}O(\alpha,p)^{17}F$ was investigated theoretically before [9,10]. However, there still is a large uncertainty in the rate, although many experimental efforts were also made [11,12]. The second

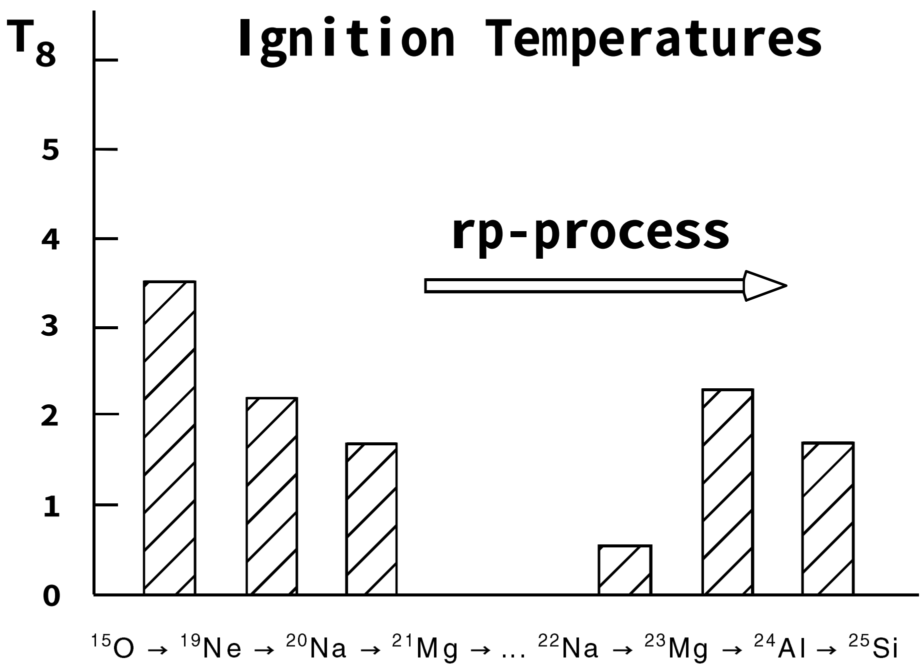

Fig. 2 The estimated ignition temperatures of the nuclear reactions along the possible rp-process under nova conditions.

and the third reactions of the sequence also are not known yet.

Recently, proton and alpha resonances in ^{18}Ne were investigated at CNS, revealing properties of some crucial resonances for the problem [13]. There is a long-standing question about the presence of a 3^+ state around the proton threshold in ^{18}Ne. However, there was no evidence observed here even with a high precision measurement, but some assignments of spin parity and excitation energies as well as the natural widths were made successfully for some critical resonant states. These values give better estimates for the reaction rates of ^{14}O(α,p)^{17}F and ^{17}F(p,γ)^{18}Ne. For the present problem, the resonance strength of the ^{14}O(α,p) reaction is needed to be determined eventually by the direct simulation method.

The second process, ^{17}F(p,γ)^{18}Ne, is now being investigated with a radioactive nuclear beam of ^{17}F at Oak Ridge National Laboratory. The third process is also under investigation at Louvain-la-Neuve with a ^{18}Ne beam. Specifically, the (α,p) process should be investigated systematically to clarify the role of the process under high temperature conditions. So far, most estimates were made with statistical model calculations.

There are some other critical problems to be investigated for the rp-process. They include waiting points, bottlenecks, and the termination of the rp-process. The waiting points determine the time duration of the explosion, and the bottlenecks restrict the pathway of the rp-process. The termination defines the total energy release of the process as well as the elemental production.

III. Rapid-Process

Although nucleosynthesis of heavy elements is not so important for the evolution of the universe and energy generation, they are very useful for understanding the mechanism of stellar events and also for cosmochronology. Figure 1 suggests two different mechanisms for heavy element synthesis, the slow (s)- and rapid (r)- processes.

The r-process should take place in a very high neutron-density region ($n_n \sim 10^{21}$ cm^{-3}) at high temperature ($T_9 \sim 2$ - 3) with a very short time scale, suggesting a nucleosynthesis flow-path far away from the line of stability. The path may be around the nuclear region that have a neutron separation-energy of 2 - 3 MeV, where the half-lives of the beta decays and the neutron capture rates balance. The peaks in the r-process nuclei suggest magic numbers of neutron shell in the very neutron rich region. The most plausible site for the r-process is considered to be in the hot bubble region in Type II supernovae [14], although it is not confirmed yet.

The nucleosynthesis of the r-process is least known experimentally among the nucleosynthesis scenarios since the nuclei on its possible path are quite difficult to produce in the laboratories. Only some nuclei around the possible waiting points at N = 50 and 126 were observed so far. The nucleus ^{130}Cd$_{82}$ was produced and first investigated [15] at CERN-ISOLDE by a high-energy spallation reaction; the half life was determined to be 203 ms, whereas the nucleus ^{80}Zn$_{50}$ was produced as a fission product of ^{238}U, and studied at the high-flux reactor at Brookhaven National Laboratory, giving $T_{1/2}$ = 550 ms [16]. Therefore, the r-process time scale should be not less than 550 ms, since ^{80}Zn is considered to be one of the waiting points of the r-process.

Further experiments on very neutron rich nuclei are really needed for the study of the r-process.

Recently, a new production method of very neutron-rich nuclei was developed, which uses Coulomb fission of an accelerated U beam at very high energy at GSI. The long-standing desire of nuclear physicists was realized by this method, i.e., a very neutron-rich "doubly closed shell" nucleus, $^{78}_{28}Ni_{50}$ was produced [17]. Further experimental information such as the half-lives, beta-decay Q values, and masses are needed for the neighboring nuclei around ^{78}Ni.

New developments in experimental technology open a new research field that was not accessible before. Such new achievement was attained for bound-state beta decay measurements. Some nuclei become unstable against weak decay when all the electrons are removed if the Q-value is very small. Such condition of fully ionization and storage of the ions was realized using the high-energy heavy ion accelerator and the storage/cooler ring ESR at GSI. The bound state beta decay of $^{187}Re^{78+}$ was beautifully measured [18], resulting in a half-life of about 12 years that is many orders of magnitude shorter than those under normal condition of ^{187}Re, $T_{1/2} = 4.23 \times 10^{10}$ yr. This will influence on the s-process scenario. This method is very powerful for investigating such beta-decay relevant to the p-process and cosmochronology. The ring is also being used to determine the masses of short-lived radioactive nuclei as well as their half-lives. These are also very important inputs for the study of the r-process.

IV. Prospects

There are many other interesting developments for the problems of nucleosynthesis, which were not discussed here, although experimental study in general is still in a quite early stage in many subjects in nuclear astrophysics.

For the solar model problem, the $^{7}Be(p,\gamma)^{8}B$ reaction is still a crucial reaction to be investigated. Especially, an experiment with a ^{7}Be beam should be of great interest. There are also some other reactions relevant to the pp-chain such as the $^{3}He(^{4}He,\gamma)^{7}Be$ reaction. As for stellar models, the reaction rate of $^{12}C(\alpha,\gamma)^{16}O$ still remains a critical subject to be further studied. The ^{12}C and ^{16}O burning processes are also of great importance.

There are several important reactions for the HCNO cycle and the early stage of the rp-process that require radioactive beams. They include $^{15}O(\alpha,\gamma)$ $^{19}Ne(p,\gamma)$ $^{20}Na(p,\gamma)^{21}Mg$, $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Ne$, etc. The real pathway from the HCNO to the rp-process is important for learning the transmutation of CNO material to the heavier elements, and also the energy generation in novae and x-ray bursts. The reactions around Si are also needed for investigating the mechanism of recent novae that showed a presence of considerable amounts of Si and S. The reactions around ^{40}Ca and ^{56}Ni could be a bottleneck for the rp-process, and need to be investigated. The mapping of the proton-drip line, and the study of the reaction and the structure of the related nuclei near the proton drip line at $A > 60$ are crucial for learning the termination of the rp-process and possible production of the p-process nuclei.

The most challenging subject is the investigation of the r-process. Coulomb fission processes at high energy, as demonstrated at GSI, could be a possibility for the production of very neutron-rich nuclei along the postulated r-process pathway. The technical development of a highly efficient production method at the ISOL-based facilities is really awaited here.

Although we did not discuss on the nucleosynthesis of long-lived nuclei such as ^{22}Na, ^{26}Al and ^{44}Ti, they are of great interest as their amounts will be quantitatively determined from line-gamma observations [1]. The nuclear reactions associated to these nuclei should be carefully investigated.

These nuclear reactions will be investigated experimentally at the RIKEN facility and the radioactive beam facility of KEK. Further opportunity will be provided in the RIB project at RIKEN in a few years. Although I emphasized in this report the importance of reaction studies with radioactive nuclear beams, it should be mentioned that the indirect method is also indispensably important for nuclear astrophysics. Since the cross sections become extremely small at low temperature, the indirect method is often the only possible way that gives information relevant to astrophysical problems.

Nuclear data work is also quite important, but the current situation is very serious. There is no organization that takes care of it systematically after the Fowler's effort. This requires worldwide effort by the nuclear physicists and astrophysicists working for the astrophysical problems. This should be one of the urgent subjects to be solved.

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