Nuclear Astrophysics with Radioactive Nuclear Beams

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Nuclear reactions play an important role in the evolution of the universe. Various astronomical observations of nuclear effects provide important clues and tests for understanding of the mechanism of stellar events and the evolution of the universe. The explosive phenomena in the universe inevitably involve radioactive nuclei. Nucleosynthesis in big bang models and stellar models are discussed critically, in particular the key nuclear reactions that involve radioactive nuclei. Also discussed is how new facets recently attained in the nuclear physics of unstable nuclei alter the nucleosynthesis scenarios. The scope of the new research field developed with radioactive nuclear beams in nuclear astrophysics is also discussed.

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Introduction

The universe has recently attracted scientists of various fields because it exhibits phenomena that range from the large scale structure of the universe to the microscopic scale of nuclear physics and particle physics. Nuclear reactions play one of the key roles for the evolution of the universe. Nuclei interact with each other in stars enclosed by the strong gravitational force. The dynamical behavior of nuclei in the universe is, therefore, something like in a gravitational cooking pot. Thus, the investigation of nucleosynthesis is one of the keys to solve the mechanism of the evolution of stars and the universe. Furthermore, the universe gives us a good
testing ground for nuclear physics as well. Because of such interest, nuclear astrophysical programs are now one of the major subjects in nuclear physics; many developments in both experiments and theories are taking place. Specifically, the new current was triggered by a development in nuclear physics of radioactive nuclei. New radioactive nuclear beam facilities are coming into operation, and the next new generation of such facilities is going to be built in the near future. At this stage, it is worthwhile to summarize the present status of the study of nuclear astrophysical problems, especially the problems that involve radioactive nuclei, which is most typical for explosive phenomena in the universe.

§ 1. Observation of nuclear effects in the cosmos

Nuclear reactions are one of the key elements for the evolution of the universe. The first stringent test for nuclear reactions is the so-called solar abundance, which is of course the final result of various sequences of stellar events since the primordial nucleosynthesis just after the big bang. These included a variety of nuclear reactions which produced almost all the elements from the light to the heavy mass region. It appears now possible to make a reasonable estimate of the solar abundance by taking into account the evolution of our galaxy. Of course it is still very controversial to make a detailed model for the big bang and also for the evolution of our galaxy including various events. However, recent observations have been providing very interesting and suggestive information for the chemical evolution of the galaxies. The chemical abundance of stars in the bulge, the disk and the halo is clearly different from each other. The abundance suggests that stars in the bulge region were produced mostly by Type II supernovae, whereas the ones in the disk like our sun has a considerable contribution of Type I supernovae, something like the frequency ratio of SNI/SNII=1/9. Totally different ratios are estimated for the Large Magellanic

![Fig. 1. The solar abundance. The abundance of Si was normalized to $10^6$. This figure is borrowed from Ref. 20).](https://academic.oup.com/ptp/article-abstract/96/2/275/1854128)
These facts clearly indicate that one should be able to learn about the evolution of the galaxies by looking at the elemental abundances, and by having better nuclear inputs for the models of the stellar evolution including the supernovae. Detailed discussions on the chemical evolution may be found in Refs. 18) and 19).

If one looks carefully into solar abundance, one may recognize the following facts. 1) Generally speaking, heavier elements are less abundant, but there is a prominent bump around the Ni and Fe region. 2) There is a clear odd-even staggering as a function of Z in the sd-shell nuclei. This is clearly due to the pairing effect in nuclei. 3) There are some double peaks in the heavy mass region, which are characteristic for the magic numbers of shell closure of stable nuclei and neutron-rich unstable nuclei. These indicate that two possible mechanisms have processed for heavy elements synthesis; one went more or less along the line of stability with a sequence of neutron capture reactions and beta decays over long periods of time, which is called the slow (s) process. The other process, on the other hand, strongly suggests a very rapid nucleosynthesis most probably under an explosive condition, involving successive neutron capture reactions, and going more or less through very neutron-rich nuclear regions far from the stability line. This is called the rapid (r) process. However, the stellar site for the r-process is not identified yet, although the most probable site has been suggested to be the hot bubble region created in Type II supernovae.

The heavy elements are considered to have been produced mostly through the two processes discussed above. However, there is another group of nuclides that cannot be explained by the two processes in the heavy mass region. These nuclei, called p-process nuclei, are located more in the neutron deficient region. This is not only an interesting subject to learn how they were produced, but it also gives another chance to study stellar events. There are a few mechanisms proposed for this production; the photo disintegration reactions could be a source, and the rp-process for the relatively lighter mass region, etc. Among the p-process nuclides, there are some very long-lived nuclei. These give us a good chance to learn about the age of the galaxy.

There are some neutron deficient nuclei that have long half lives, such as $^{22}\text{Na}$, $^{26}\text{Al}$, $^{44}\text{Ti}$, $^{56}\text{Co}$. They also give us an interesting clue for the investigation of the universe. They emit specific gamma rays. Recent gamma ray observation has discovered a presence of massive amounts of $^{26}\text{Al}$ as much as 3M$_{\odot}$ from the central direction of our galaxy. The COMPTEL observation succeeded in mapping the gamma ray source of 1.809 MeV that came from the nuclear decay of $^{26}\text{Al}$ ($T_{1/2}=7.16 \times 10^5$ yr). It is an interesting open question where and how $^{26}\text{Al}$ was synthesized. Precise nuclear physics input will clarify the site condition for this problem. The gamma rays of the decay of $^{56}\text{Co}$ were also observed from the supernova SN1987A, which is discussed below.

These long lived nuclei may be also related to the isotopic anomaly in meteorites, which is also an interesting subject, and could be a good clue for studying stellar events. One of the long standing questions is the so-called Neon-Extraordinary (Ne-E) problem. This was first found in a meteorite in 1972. The abundance ratio of $^{20}\text{Ne}/^{22}\text{Ne}$ was abnormally small as compared to the solar abun-
dance known. The most plausible explanation was that $^{22}\text{Na}$ was produced and ejected in some stellar event and got frozen in a meteorite. Since $^{22}\text{Na}$ has a long half life of 2.6 yr, it decayed afterward, producing $^{22}\text{Ne}$. This problem will be discussed later. These long lived nuclei are considered to have been produced in some stellar events, most probably in explosive nucleosynthesis.

As indicated above, there are many nuclear effects observable in the universe. They give us rich information about the nuclear reactions that have taken place, and thus they provide very critical clues for understanding stellar events. We may discuss in this paper how we can approach the astrophysical problems of the universe from a nuclear physics point of view. Here, it is important to clarify the mechanism of each nuclear reaction process, i.e., nucleosynthesis under cosmological conditions. The astrophysical models will be examined with these nuclear parameters, giving eventually the real picture for the astrophysical event and the site of interest. Nucleosynthesis involving stable nuclei has been studied for a long time. There are still many important nuclear reactions of stable nuclei that are not well examined yet mostly at low temperatures. It is of course obvious at low temperatures that the nuclear reactions in the universe take place over virtually an infinitely long time duration, which is far more than what we can simulate in laboratories with the current technology.

Explosive phenomena such as supernovae and the very early universe just after the big bang inevitably involve

![Fig. 2. The light curve of SN1987A since the explosion. This figure is borrowed from Ref. 28.](https://academic.oup.com/ptp/article-abstract/96/2/275/1854128)

![Fig. 3. Nucleosynthesis scenarios on a schematical nuclear chart.](https://academic.oup.com/ptp/article-abstract/96/2/275/1854128)
radioactive nuclei of very short half lives due to the fast sequence of nuclear reactions before cooling by beta decays, etc. Typical evidence of radioactive nuclei among the stellar events is the light curve of the supernova SN1987A, which is shown in Fig. 2. The light curve observed for the SN1987A is well explained by the nuclear decay of $^{56}$Co.$^{28}$ This is a clear evidence that abundant short-lived nuclei $^{56}$Co were synthesized in the supernova explosion. Here, $^{56}$Co is believed to have been produced from the beta decay of $^{56}$Ni. More directly, the gamma rays of $^{56}$Fe following the beta decay of $^{56}$Co were also observed.$^{29}$ The decay curves of light and the gamma rays give us interesting information about the mixing of core material as well.$^{30}$

Since explosive phenomena which take place in high-density high-temperature sites include successive nuclear reactions, the nucleosynthesis there flows away from the stability line on the nuclear chart.$^{13}$ Figure 3 shows schematically various nucleosynthesis scenarios on the nuclear chart. The pp-chain and some cycles are going more or less around the stability line, as they take place in relatively low density regions at low temperatures. Whereas rapid processes such as the rapid-proton (rp) process,$^{31}$ which is an explosive hydrogen burning process, go through the proton-rich unstable nuclear regions.

The investigation of the nuclear structure and the reactions of the nuclei far from the stability line is one of the most active subjects in nuclear physics today. Therefore, the investigation of the explosive nucleosynthesis was made possible by new technology of radioactive nuclear beams in nuclear physics. In the last several years, a new research field of nuclear astrophysics that uses radioactive nuclear beams has developed. Although the experimental works performed on nuclear reactions that involved radioactive nuclei are still quite limited, I will discuss the results and the problems as well as the scope of the field.

§ 2. Nucleosynthesis of radioactive nuclei

Before beginning the discussion of various nucleosynthesis scenarios that involve unstable nuclei, it should be emphasized again that the nuclear physics of unstable nuclei has been expanding rapidly on the nuclear chart towards the limit of nuclear particle stability,$^{71-11}$ i.e., the proton and neutron drip lines and also to the super heavy mass region, but the knowledge of nuclear physics is still restricted to about half of the nuclei near the stability line, out of about 6000 nuclei predicted, as is shown schematically in Fig. 3. The new nuclear physics will alter some classes of reaction rates considerably, such as the $(n, \gamma)$ cross sections$^{32-34}$ that are related to the s-process nucleosynthesis, as we discuss below. The magic numbers of shell closure known near the stability line also would not hold for the nuclei far from the stability line, which might also change the r-process route. Namely, the nuclear physics of unstable nuclei itself is a very active research field, being developed in the last decade and revealing new facts that could alter the nucleosynthesis scenarios in some aspects. The r-process pathway predicted is still mostly outside the accessible region in the laboratory. As is sketched here, the study of the explosive nucleosynthesis is a challenging subject for both nuclear astrophysics and nuclear physics.

As an example, we just overview the recent development of the $(n, \gamma)$ reaction
study at stellar temperature. Nagai and his collaborators have measured the $(n, \gamma)$ cross sections at 30 keV on some light nuclei, finding tremendously larger cross sections than expected with the ordinary $1/v$ rule for low-energy neutron capture reactions.\cite{32,33} This fact is clearly explained\cite{34} by the new concept of nuclear structure, i.e., the relevant nuclear levels of $1/2^+$ are characterized by an anomalously extended tail, which is called the nuclear halo,\cite{35} and thus the neutron capture reactions that take place far outside the nuclei have a large overlap with the nuclei, i.e., the p-wave component of the scattering is very much enhanced since the residual state has the halo structure and the capture reaction can have an El transition. This fact results in a totally different energy dependence, giving an enhancement of the cross sections about by two orders of magnitude for the $^{16}\text{O}(n, \gamma)^{17}\text{O}$ reaction at 30 keV,\cite{33} for instance. This nuclear halo structure was first discovered in $^{\text{11}}\text{Li}$ and is now widely accepted to be one of the features of nuclear structure of neutron-rich nuclei far from the stability line. This enhancement of the $(n, \gamma)$ cross sections will have a significant consequence for the s-process scenario of heavy element synthesis as this reaction could be a poison of the neutron flux, where the neutrons for the s-process are considered to be provided mainly by the $^{13}\text{C}(a, n)^{16}\text{O}$ and $^{22}\text{Ne}(a, n)^{25}\text{Mg}$ reactions in the He burning stage.\cite{36}

We now begin to discuss the role of the radioactive nuclei in the nucleosynthesis and the crucial physical parameters to be investigated. Experiments have been made only in the last several years except for some cases using long lived nuclear targets, and the most important points have to be studied yet, as was discussed in the last section. There are usually key problems to be solved, but they are different from subject to subject. The difficulties are sometimes due to the limits in experimental technique, and sometimes due to the physics difficulties such as extremely small cross sections.

In an explosive process there are common problems to which we should direct our experimental efforts. The nucleosynthesis-flow goes very rapidly through unstable nuclear region skipping slow beta decays, but would compete with beta decays of very short half lives near the particle drip lines on the nuclear chart. Or, it would be stopped by having no stable next nucleus. This is called the waiting point of the process. Figure 4 shows a sketch of the idea. For the case of explosive hydrogen burning, competition between proton capture reactions and beta decays determine the flow pathway under high temperature and high density conditions.

The second critical point we should learn is the so-called bottle neck which is also defined by the particle stability of...
the nuclei, i.e., a vertical flow (proton capture reaction) right next to the line indicated in the figure is not allowed due to the lack of a particle stable nucleus. The rate going through the bottle neck is also one of the key factors that decide the explosion time scale. If the rate is too small, then the explosion will be stopped there, or will be slowed down by detouring through more stable nuclear regions in which nuclei have much longer half lives. Eventually, this would result in less energy production.

Another reason for the need of experiments studying the explosive nucleosynthesis is that these processes pass through more or less unstable nuclear regions near the particle drip lines where the particle threshold is getting very small, and thus the level density near the threshold is also small. Therefore, statistical models for the nuclear levels are not applicable at all. The reaction rates would be very much influenced by a single or a few resonances. Nuclear theories, however, are not yet reliable to predict precisely the excitation energy and the other properties in detail.

There are two experimental approaches in nuclear astrophysics. One way is the direct method, i.e., one measures the thermal reaction cross sections at the temperature of interest. This is possible for the case of stable nuclear reactions and also for the reactions that include unstable nuclei in explosive conditions as it requires the knowledge at higher excited states from the threshold. The second method is the indirect method. One may use simulated processes, or measure the physical parameters separately and calculate the reaction rate using Eq. (5) described below. The Coulomb dissociation method recently developed and the direct particle-transfer reactions belong to the simulated method. The indirect method is complementary to the direct method and is the only way to approach a reaction rate near the threshold, where direct measurements are not possible due to the extremely small cross sections.

The temperature we are discussing here is \( T = 0.01 \to a \) few, that correspond to \( 1 \to a \) few hundred keV in energy, where we use here a convention of temperature defined by \( T = T_e \times 10^9 \text{K} \). Although the effective temperature for nucleosynthesis for charged particles is a few times larger than this energy as discussed below, it is still far below the Coulomb barrier. The nuclear reactions between charged particles at very low energies is dominated primarily by the Coulomb force. The astrophysical \( S \)-factor is often used for discussion, and is defined as

\[
\sigma(E) = S(E)/E \cdot \exp(-2\pi\eta),
\]

where the energy dependence of the penetrability through the Coulomb barrier and the geometrical factor are explicitly removed for the \( S \)-factor.

The reaction rate is obtained by averaging the cross section over the velocity of the Maxwell-Boltzmann distribution. Using Eq. (1), the reaction rate is written as

\[
\langle \sigma v \rangle = \left( \frac{8}{\pi \mu^2} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left[ -\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE,
\]

where \( b = 0.989Z_1Z_2\mu^{1/2} (\text{MeV})^{1/2} \). The second term in the bracket is from the Coulomb penetrability, and the first term is from the Maxwell-Boltzmann distribution. If there is no resonance, the reaction rate is simply determined by the direct capture process, which has a broad peak at the Gamow energy defined by
\[ E_\text{c} = (bkT/2)^{2/3}. \] (3)

The cross section for a narrow resonance will be expressed by a single-level Breit-Wigner formula,

\[ \sigma(E) = \pi \lambda^2 \omega \frac{\Gamma_1 \Gamma_2}{(E - E_\text{c})^2 + \left( \frac{\Gamma_\text{tot}}{2} \right)^2}. \] (4)

The resonance contribution for the reaction rate will be written for a proton capture reaction as

\[ \langle \sigma v \rangle = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \omega \gamma \exp(-E_\gamma/kT), \] (5)

where

\[ \omega \gamma = (2J_1 + 1)/(2J_1(2J_2 + 1)) \cdot \Gamma_\gamma \Gamma_\text{p}/\Gamma_\text{tot}. \]

Here, \( \omega \gamma \) is called the resonance strength and \( \omega \) is the spin factor. The precise excitation energy of the resonance, the spin-parity and the decay widths are needed to deduce the reaction rate. If the proton width \( \Gamma_\text{p} \) is much larger than the gamma width \( \Gamma_\gamma \), the resonance strength is roughly proportional to the gamma width, which is often the case for the explosive nucleosynthesis, but it is proportional to \( \Gamma_\gamma \) at low temperature. The reaction network calculations are made in stellar models and big bang models by solving a series of rate equations using the reaction rates obtained above.

§ 3. Nucleosynthesis in the primordial universe and big bang models

Light elements such as \(^4\text{He}\) and \(^7\text{Li}\) were believed to have been produced just after the big bang in the primordial universe. This nucleosynthesis took place of course at the very high temperature and high density conditions. The abundance of light elements is a strong constraint for the big bang models. The standard model explains the light elements,\(^{37,38}\) but the nucleosynthesis was limited up to mass 7 because of the \( A=5 \) and \( 8 \) gaps in the nuclear chart. On the contrary, inhomogeneous big bang (IBB) models, discussed in the last decade,\(^{38-41}\) have predicted a considerable production of elements of heavier masses. These models have inhomogeneities of protons and neutrons due to the quark-hadron phase transition. If protons and neutrons were distributed unequally, there would have been considerable production of heavier elements through mostly the neutron-rich unstable nuclear region. Thus, production of heavy elements can be a stringent test. There have been extensive astronomical observations made that looked for the abundances of Be and B of the primordial origin in the old stars in the halo region.\(^{42}\) Although there is some possibility reported, it is still not clear if they really came from the primordial universe.

The IBB models involve several unknown nuclear reactions associated with the unstable nuclei, which are on the pathway to heavier elements. This model may be critically examined by studying these unknown reactions. Some of them were stud-
ied during the last several years. The postulated dominant flow path, which bypasses the $A=8$ gap in the models for heavy element synthesis, is

$$^4\text{He} (t, \gamma)^7\text{Li} (n, \gamma)^{11}\text{B}$$

$$(n, \gamma)^{12}\text{B} (\beta^- \nu)^{12}\text{C}$$
as shown in Fig. 5. The reaction rates relevant to $^8\text{Li}$ are crucial for heavy element synthesis, but are not yet determined experimentally. The $^8\text{Li}(a, n)^{11}\text{B}$ reaction was completely unknown when this scenario was proposed. The reason was that the target nucleus $^8\text{Li}$ has a short half life of 0.8 sec., and thus the experiment is possible only by using a $^8\text{Li}$ beam in the inverse kinematics.

Several experiments were made to study this process. The first experiment was made using the inverse reaction $^{11}\text{B}(n, a)^8\text{Li}$. The astrophysical $S$-factor obtained is about 8400 MeV·b near the Gamow peak of $T_9=1$, which is a typical temperature for heavy element synthesis in the primordial site. This value accidentally agrees with that assumed in the IBB model calculation in Ref. 40). However, it is peaked at $n=1$, whereas it was assumed to be a constant value in the original model calculations. This measurement, however, includes only the neutrons from the $^8\text{Li}(a, n)^{11}\text{B}$ reaction to the ground state in $^{11}\text{B}$.

The cross sections of the $^8\text{Li}(a, n)$ reaction to the excited states in $^{11}\text{B}$ were estimated by an indirect method next. The properties of the resonance, such as the partial decay widths, were studied using the direct three-nucleon transfer reaction $^9\text{Be}(a, p)^{12}\text{B}$, which was found to excite the present resonant states with reasonable cross sections as expected. The most important state for the $^8\text{Li}(a, n)^{11}\text{B}$ reaction (at around $T_9=1$) is the one at 10.572 MeV, with the $^8\text{Li}+a$ threshold lying at 10.000 MeV in $^{12}\text{B}$. This state was excited in the $(a, p)$ reaction, and was assigned tentatively to have $J^\pi=2^+$ from the Distorted Wave Born Approximation (DWBA) analysis, together with the angular correlation function analysis of the neutron decay.

The branching ratios for the particle decays from these states were also determined by measuring the decay neutrons. The experiment was made using a 50-MeV $a$ beam at the Institute for Nuclear Study, the University of Tokyo (INS). The sum of the intensities of the neutron decays to the excited states are found to be roughly the same as the yield for the ground state. Thus, the reaction rate of the $^8\text{Li}(a, n)^{11}\text{B}$ process was found to be increased roughly by a factor of two at least as compared to the previous estimate. The branching ratios obtained are approxi-
mately $\Gamma_{\alpha}/\Gamma_{\text{tot}}=1/3$, $\Gamma_{\alpha_g}/\Gamma_{\text{tot}}=1/3$ and
$\Gamma_\alpha/\Gamma_{\text{tot}}=1/3$. The $\alpha$-branching ratio is
much larger than expected. However, this is consistent with the fact
that the entrance channel of the thermal $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction could be an
$s$-wave resonance. The same experiment was made later at 35 and
40 MeV, revealing larger $n$-decay widths. The reaction at low energies
would have some difficulties in the reaction mechanism, and could be
exciting different states, resulting in a different decay widths.

The cross sections of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction were measured
directly down to $E_{\text{cm}}=1.6$ MeV using the low-energy unstable beam of $^8\text{Li}$
from the RIKEN fragment separator (RIPS), which is a typical radioactive
beam separator used in heavy ion facilities, as shown in Fig. 6. The $^8\text{Li}$
beam was produced by the projectile fragmentation process of a $^{14}\text{N}$ beam,
degradated down to the energy range of 10–20 MeV, and then introduced to an ioniza­
tion chamber, MUSIC, which had an admixture of $^4\text{He}$ as a target. The experiment
was successful even with the limited quality of the $^8\text{Li}$ beam, because of the large cross
sections. The cross sections obtained are larger than the previous values from the
$^{11}\text{B}(n, \alpha)$ reaction roughly by a factor of 5 at $E_{\text{c.m.}}\geq 1.6$ MeV. This experiment was
extended recently down to $E_{\text{c.m.}}=0.64$ MeV at the Tandem Accelerator Facility of
the University of Notre Dame. They observed a result similar to that of the RIKEN
experiment.

Therefore, the cross sections of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction appear to be larger than
the value assumed in the IBB models by a factor of two to five at $T_9=1$. However,
the uncertainties of the two experiments of $^8\text{Li}(\alpha, n)$ are very large for a quantitative
discussion. The cross sections should be measured down to 0.3 MeV to cover the
Gamow window of $T_9=1$, and also the uncertainties of the cross sections in the direct
method discussed above need to be improved.

Recently, an interesting suggestion was made from a direct reaction theory
analysis of the $^8\text{Li}(\alpha, n)^{11}\text{B}$ reaction. This reaction was analyzed by one-step
DWBA calculations, where a triton cluster transfer was assumed for the reaction.
The result suggests that the direct transfer reaction cross section is comparable to the
cross sections of $^{11}\text{B}(n, \alpha)^{9}\text{Li}$ even at $E_{\text{c.m.}}=0.5$ MeV. This contribution should be
further checked, as the direct transfer contribution is neglected so far for nucleosyn­
thesis, and it would bring in a serious modification for the reaction rates in general.
In the primordial nucleosynthesis, neutron-induced reactions are also very crucial. Recently, one of the key reactions $\rho(n, \gamma)d$ was measured for the first time between 10 and 80 keV, the energy relevant to the primordial nucleosynthesis. The experiment was performed at the Pelletron Facility of the Tokyo Institute of Technology. The result has proved the previous theoretical predictions. Another interesting development made for the primordial nucleosynthesis is the $^7\text{Li}(n, \gamma)^{8}\text{Li}$ 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. The cross section obtained is $39.3 \pm 6.0 \text{mb}$, which is about a factor of two larger than the value reported before. The present value is consistent with the thermal reaction cross section. Similarly, the $^8\text{Li}(n, \gamma)^{9}\text{Li}$ reaction would be also important for the IBB model. Ieki and his collaborators are investigating this reaction using the Coulomb dissociation method with a $^9\text{Li}$ beam.

A flow of $^7\text{Li}(t, n)^{9}\text{Be}(t, n)^{11}\text{B}$ could also be an important pathway for heavy element synthesis. Some experiments were made to study the first step, and the second step. Coc reported an experiment that used a radioactive target of tritium together with a $^7\text{Li}$ beam, and determined the S-factor. The result gave a factor of 3-7 smaller value for the S-factor of $^7\text{Li}(t, n)^{9}\text{Be}$ than predicted, but it is consistent with the previous measurement. Therefore, the experiments have confirmed the importance of the reaction for heavy element synthesis, specifically for the production of $^9\text{Be}$, which is actively studied in astronomical observation because of its primordial origin. The second step, $^9\text{Be}(t, n)^{11}\text{B}$, has not yet been studied by a direct method. This reaction is important as it leads to $^{12}\text{C}$ and heavier element synthesis.

As discussed above, the most critical nuclear reactions need to be investigated further for the primordial nucleosynthesis to learn about the big bang and the primordial universe.

§ 4. Nuclear reactions in the sun

Our sun is a good testing ground for stellar models; it has arrived at the stage of the main sequence in its evolution. Although the sun is in a static hydrogen burning state, the relatively long-lived unstable nuclei are involved in the $pp$-chain that is a typical nucleosynthesis in this stage of evolution of the stars. The solar neutrinos, which have been observed and investigated theoretically for many years, bring us directly nuclear reaction information from inside the sun. All the observations, however, indicate less neutrino flux, 46-65 % than the standard solar model prediction, although there seem to be some discrepancies among the data. These ratios are different depending on the type of the detectors, which have different energy thresholds for neutrino detection. This problem is called the solar neutrino problem. There are three possibilities in principle; i) the nuclear reaction data could be wrong, ii) the neutrino flux could be changed on the way to the detectors on earth, and iii) the solar model itself could be incorrect. Although the term ii) is favorably discussed recently, the origin of the problem is not yet clear. Neutrino oscillation may be tested better in the near future for instance by a long base line experiment at
KEK-KAMIOKANDE\textsuperscript{60} in Japan. The nuclear physics cross sections, on the other hand, also have large ambiguities\textsuperscript{61} in the various stages of the $pp$-chain, and have to be determined better.

A possible problem with the nuclear physics side is the large cross section uncertainties of the reactions involved. The measured cross sections are not determined better than 30\%, which is serious enough for the neutrino problem. They can be $^4\text{He}(^4\text{He}, 2p)^6\text{He}$, $^4\text{He}(^4\text{He}, \gamma)^7\text{Be}$ and $^7\text{Be}(p, \gamma)^8\text{B}$. The first reaction is being investigated at the underground laboratory at Gran Sasso\textsuperscript{62} where the experiment is almost free from the background due to cosmic rays. Among the three reactions, the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction, of which beta decay produces high energy neutrinos to be measured by the neutrino detectors underground, was investigated using a radioactive $^7\text{Be}$ target in the past. Here, the problem of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction is two-fold. One is to determine the S-factors with smaller uncertainties at $E_{\text{c.m.}} \geq 100$ keV, where the data so far obtained are scattered by more than 40\%. The second is to measure cross sections at the energy as low as possible towards 10–20 keV, which gives more reliable extrapolation for the S-factor at 10–20 keV, which is the Gamow energy inside the core of the sun. The problem here is a non-resonant radiative proton capture reaction at extremely low energies.

The reaction $^7\text{Be}(p, \gamma)^8\text{B}$ was reinvestigated recently at RIKEN by the Coulomb dissociation method mentioned in § 2. Before discussing the experimental result, we briefly describe the Coulomb dissociation method here.

This method was proposed as an alternative method to determine low-energy capture cross sections from inverse reactions. A successful application of the method was first made for a study of a stellar reaction of $^{13}\text{N}(p, \gamma)^{14}\text{O}$\textsuperscript{63}. The radioactive beam of $^{14}\text{O}$ at 87.5 MeV/u, produced from the $^{16}\text{O}$ fragmentation at 135 MeV/u, was incident on a heavy target $^{208}\text{Pb}$, and broken up into $p + ^{13}\text{N}$ by absorbing the virtual photons in the very strong Coulomb field of $^{208}\text{Pb}$. The two particles were measured in coincidence at small relative energies. If the scattering is nearly due to the Coulomb interaction, the breakup cross section can be converted by detailed balance to the low energy capture cross section of $^{13}\text{N}(p, \gamma)^{14}\text{O}$. The result was consistent with the direct measurement\textsuperscript{64} that used the accelerated radioactive $^{13}\text{N}$ beam, as will be discussed in § 6.1. The advantage of the Coulomb dissociation method is that i) the kinematical factor for conversion in the detailed balance equation is large, and ii) one can use a thick target since the resolution of the final relative energy is relatively insensitive to the $^{14}\text{O}$ beam energy spread. These facts give an en-

![Fig. 7. The $S$-factors of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction. The closed circles are from Ref. 66).](https://academic.oup.com/ptp/article-abstract/96/2/275/1854128)
hancement of the yield of about 5 orders of magnitude. This will allow one to approach lower energies than allowed by the direct method if other complications discussed below are negligible. There are several problems to be checked carefully in applying the method. First, there should be no significant nuclear contribution. Second the resonant state of interest should not be strongly coupled to other states except for the ground state in the projectile nucleus. The direct reaction analysis for the incident excitation process brings in ambiguities. The two projectiles will get different post accelerations when leaving the $^{208}$Pb target region, which needs proper corrections.

The Coulomb dissociation method was applied recently to the study of the $^7$Be $(p, \gamma)^8$B reaction at low energy, where a $^8$B beam was obtained from RIPS at RIKEN, and dissociated on a $^{208}$Pb target. Figure 7 displays the preliminary results of the S-factor of $^7$Be$(p, \gamma)^8$B together with previous measurements. The results are consistent with the previous ones, although the errors are quite large. There will also be an E2 contribution in addition to the E1 component. It seems promising to arrive at a meaningful result for the astrophysical S-factor, since the contribution of the nuclear interaction and the final state interaction was estimated to be small. Thus, this method may be limited to a certain relative energy higher than that requested for the problem, as discussed above. This method should be critically tested in the case of a typical non-resonant capture reaction at low energy. It should be also noted that there is no reason that the Coulomb dissociation method is superior to the direct method except the fact that the method has a larger efficiency.

The direct approach to the problem is to measure the cross section by using a $^7$Be beam or target. So far, there is no experiment that has used a $^7$Be beam, which provides a better experimental condition than a $^7$Be target. These experiments are now being prepared at several laboratories.

The nucleosynthesis at relatively low temperatures, as discussed here, involves very low energy nuclear reactions, which is quite difficult to study in the laboratory due to the small cross sections. The requirement is a better detector system that has a good signal-to-noise ratio, such as the one in the LUNA project, mentioned above. Furthermore, there could be some other complexity at very low energies for the capture process such as the electron screening effect. These require further experimentation.

§ 5. Cluster nucleosynthesis and $^{16}$O synthesis

We will discuss in this section the nucleosynthesis in the He-burning and the subsequent C- and O-burning processes. Along the stellar evolution process, the most crucial and long-standing problem is the $^{16}$O production rate by the $^{12}$C$(a, \gamma)^{16}$O reaction in He burning. This reaction rate plays a decisive role in the later half of the stellar evolution scenario, and also to the cosmic abundance. The mass ratio of C and O in massive stars should be changed according to this rate, which finally leads to a different scenario for the remnant of a supernovae, for instance. Although this reaction involves stable nuclei, we will discuss it because of the importance of the problem and also because recent experiments were made by using a radioactive
nuclear beam of $^{16}$N.

Figure 8 displays the Cluster-Nucleosynthesis(CN) diagram\textsuperscript{70} that sketches the relation of stellar evolution and energy generation. This explains stellar evolution from He burning to the stage of Fe core formation in massive stars, and also the relation to the energy generation in nucleosynthesis point of view. In the universe, $^4$He, $^{12}$C and $^{16}$O, are the most abundant nuclides other than hydrogen, and they frequently participate in the nucleosynthesis, where nuclear cluster states above the cluster threshold play a crucial role. The clustering is favored to minimize locally the energy of the nuclear systems because of the large binding energies of these nuclei. The nucleosynthesis in nature of course goes through a synthesis flow-path that obeys the same principle under the site condition of interest. This CN-diagram is similar to the so-called cluster diagram in nuclei, but includes the dynamics of nucleosynthesis. As can be seen in the CN-diagram, nucleosynthesis in the stars is a process to crush clusters one by one leading to synthesis of heavier nuclei and simultaneously release the energy to the stellar site. Thus, the ordinate measures the released energy per nucleon, and thus more energy will be released as the nucleosynthesis develops by going to the right-lower level until Fe. In nuclear physics studies on the contrary, one usually discusses the development of clustering by putting excitation energies to the nuclear system, although the underlying physics is the same. This CN-diagram also gives a good guide for investigation of nucleosynthesis.

The first step of He burning after the pp-chain is the synthesis of $^{12}$C by the triple $\alpha$-process, and then the $^{12}$C($\alpha$, $\gamma$) reaction to produce $^{16}$O, but it would not go much beyond because of the nuclear structure at the energy region of interest above the $\alpha$ threshold in $^{20}$Ne. Although the $^{12}$C($\alpha$, $\gamma$) reaction is very important in the He-burning stage as discussed above, the reaction cross section is not determined yet directly at the temperature region of interest,\textsuperscript{71)−79} i.e., $\sim 2 \times 10^8$ K or 300 keV above the threshold since the cross section is expected to be extremely small, and it will be
Table I. The S-factors of the $^{12}$C($a, r$)$^{16}$O reaction in units of keV·b.

<table>
<thead>
<tr>
<th>$S_n(300$ keV)</th>
<th>$S_{sp}(300)$</th>
<th>$S_{sw}(300)$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiments;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140(three-level R.)</td>
<td></td>
<td></td>
<td>a) Ref. 72)</td>
</tr>
<tr>
<td>80(R. + optical M.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>180</td>
<td>430</td>
<td>b) Ref. 73)</td>
</tr>
<tr>
<td>200</td>
<td>96</td>
<td>296</td>
<td>c) Ref. 74)</td>
</tr>
<tr>
<td>≤140</td>
<td></td>
<td></td>
<td>d) Ref. 75)</td>
</tr>
<tr>
<td>1</td>
<td>40</td>
<td></td>
<td>e) Ref. 70)</td>
</tr>
<tr>
<td>57(K-matrix)</td>
<td></td>
<td></td>
<td>f) Ref. 78)</td>
</tr>
<tr>
<td>79(Global R-matrix)</td>
<td></td>
<td></td>
<td>g) Ref. 79)</td>
</tr>
<tr>
<td>95(R-matrix)</td>
<td></td>
<td></td>
<td>h) Ref. 68)</td>
</tr>
<tr>
<td>69(Global R-matrix)</td>
<td></td>
<td></td>
<td>i) Ref. 69)</td>
</tr>
</tbody>
</table>

Star models;

| 250            |              |              |           |
| 170            |              |              |           |

a) Ref. 72), b) Ref. 73), c) Ref. 74), d) Ref. 75),
e) Ref. 70), f) Ref. 78), g) Ref. 79), h) Ref. 68),
i) Ref. 69)

determined by an interference of the tails of the resonances at higher energy and sub-threshold states nearby.

The astrophysical S-factors at 300 keV were estimated by extrapolation of the experimental reaction cross section of $^{12}$C($a, r$)$^{16}$O at $E_{c.m.} \geq 0.94$ MeV, by measuring the singles gamma rays$^{72\text{-}75,77}$ or the gamma rays coincident with the recoil product of $^{16}$O$^{76}$. They are summarized in Table I. Here, the E1 and E2 strengths were separated by measuring angular distributions. The extrapolation procedures, which were made using K-matrix or R-matrix theory, have a large ambiguity. Recently, extensive measurements were made for the $\beta$-delayed $a$ decay of $^{16}$N, which is sensitive predominantly to the E1 component$^{71}$ and has a large phase space to the lower energy in $^{16}$O. These facts give a better efficiency for deducing the S-factor(E1) at low energies. Buchmann et al.$^{78}$ and Zhao et al.$^{79}$ reported S-factors estimated from their data, which are consistent with each other. Since these data were fitted together with other data of $^{12}$C($a, r$) and $^{12}$C($a, a$), the estimate of S(E1) is relatively well determined. The results, shown in Table I, are slightly smaller than the previous data except for the one in Ref. 77). These are, however, roughly a factor of two smaller than the values of 170 - 250 keV·b currently used for the stellar models.$^{68,69}$

The E2 part is very poorly estimated yet, and the E1 part also needs more experimentation. Therefore, it should be concluded that the estimated values are still very uncertain, and thus this is still one of the most important open problems to be solved by experiment.

There are some on-going experiments related to this subject. One possibility is to use the Coulomb dissociation method$^{65}$, which is sensitive to the E2 component in this case, but it appears quite difficult$^{60,61}$ to apply the method. One has to deal carefully with the nuclear-force contribution and final-state interaction effects in a continuum region. An extensive coupled-channel calculation, including coupling to
the continuum states, has been made by Hirabayashi\textsuperscript{81}) for the inelastic excitation, revealing that the nuclear excitation contribution is comparable to the Coulomb excitation. If the breakup process is fully understood, there would be a chance that one might be able to derive the Coulomb contribution separately by measuring detailed correlations between the $\alpha$ and $^{12}$C particles. These require both theoretical and experimental development.

Of course one could approach the problem by lowering the energy with the direct measurement of $^{12}$C($\alpha$, $\gamma$)$^{16}$O using a higher-intensity beam with an improved detector of better efficiency and signal-to-noise ratio, although it is almost impossible with the current experimental technology to measure the cross section directly at 300 keV. However, it will give us a more reliable extrapolation to the energy region of interest. This subject still deserves further investigation in experiment.

Another interesting nucleosynthesis problem along the main sequence of stars, as can be seen in the CN-diagram in Fig. 8, is the Carbon and Oxygen burning, which eventually lead to Si burning to reach the iron core formation just before the supernovae. These burning processes also play a crucial role in Type I supernovae. In the latter case, they take place even in higher temperature conditions ($T_\odot \geq 1$) since the burning processes are explosive. However, the nuclear data do not exist at the temperature region of interest. These also require devoted experimental efforts with very high intensity beams and a low-background detector system. These data will improve the supernova models.

\section*{§ 6. Hot-CNO Cycle and the rapid-proton process}

\subsection*{6.1. Hot-CNO cycle}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig9}
\caption{The HCNO cycle and the onset of the rp-process. The gray area are stable nuclei.}
\end{figure}
From the early works, CO material was considered to form a catalytic cycle of nucleosynthesis, called the CNO cycle, that burns hydrogen with higher efficiency for energy production than the \( pp \)-chain. This CNO cycle is a sequence of nuclear reactions of

\[
^{12}\text{C}(p, \gamma)^{13}\text{N}(\beta^-)^{13}\text{C}(p, \gamma)^{14}\text{N}(p, \gamma)^{15}\text{O}(\beta^-)^{15}\text{N}(p, a)^{12}\text{C},
\]

where four hydrogens are converted to a nucleus of \(^{4}\text{He} \) together with an energy release of about 25 MeV. The CNO cycle is limited by a slow beta decay of \(^{13}\text{N} \), which has a half life of about 10 min. The cycle will be extended to a high temperature cycle, the Hot-CNO (HCNO) cycle, that bypasses the \(^{13}\text{N} \) beta decay by going to \(^{14}\text{O} \) i.e., the new cycle is

\[
^{12}\text{C}(p, \gamma)^{13}\text{N}(p, \gamma)^{14}\text{O}(\beta^-)^{14}\text{N}(p, \gamma)^{15}\text{O}(\beta^-)^{15}\text{N}(p, a)^{12}\text{C}.\]

This new extended route accelerates the cycle, resulting in much higher energy production rate. Figure 9 shows the HCNO cycle together with the breakout process to be discussed later.

The least known process among the cycle was the \(^{13}\text{N}(p, \gamma)^{14}\text{O} \) reaction, as it involves the short-lived unstable nucleus \(^{13}\text{N} \). This process was investigated as the first successful experiment that used an accelerated beam of radioactive nuclei, which was produced on-line. As we discuss later, accelerated radioactive nuclear beams at low energies have properties much superior to the radioactive beams from the heavy-ion induced projectile fragmentation process. This pioneering work was made at Louvain-la-Neuve by using the radioactive beam of \(^{13}\text{N} \) of more than \( 10^8 \) aps. Here, \(^{13}\text{N} \) was produced by the \(^{13}\text{C}(p, n)^{13}\text{N} \) reaction with a proton beam of a few hundred \( \mu \text{A} \) from a first cyclotron, ionized by an ECR ion source, and then accelerated by a second cyclotron, which also worked as a mass separator in the acceleration phase. This experiment determined a gamma width \( \Gamma_\gamma = 3.8 \pm 1.2 \text{ eV} \) for the \( 1^- \) resonance at 5.173 MeV, which is 545 keV above the proton threshold.

As was discussed in §4, the Coulomb dissociation method was also applied successfully for the first time in nuclear astrophysics. The experiment was performed using an \(^{14}\text{O} \) unstable nuclear beam of 87.5 MeV/\( \mu \text{A} \). The cross sections of the capture reaction \(^{13}\text{N}(p, \gamma)^{14}\text{O} \) at the stellar energies was derived from the dissociation cross sections with the help of a DWBA analysis for the inelastic excitation to the resonance at 5.173 MeV. This provided the excitation strength, i.e., the Coulomb deformation parameter, which was then converted to the radiative width by using the detailed balance equation for the inverse reaction. The result obtained is \( \Gamma_\gamma = 3.1 \pm 0.6 \text{ eV} \), in agreement with that obtained directly, as discussed above. The present application was successful because the excitation is mainly an E1 transition since it is the transition from \( 0^+ \) to \( 1^- \) states, and the gamma width of the state is unusually large. Here, all the complications discussed in §4 are small. Therefore, the experimental result defines well the ignition temperature and the hydrogen density of the site for the HCNO cycle.

The HCNO cycle has a side flow at around \( 10^8 \text{ K} \) to \(^{15}\text{N}(p, \gamma)^{16}\text{O}(p, \gamma)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\beta^+)^{18}\text{F}(p, a)^{15}\text{O} \). The reaction \(^{18}\text{F}(p, a)^{15}\text{O} \), that involves the unstable nucleus \(^{18}\text{F} \) with
$T_{1/2}=110$ min., was investigated by the direct method recently.\cite{84,85} This reaction is also important in the accelerated bypass of the HCNO cycle as follows: $^{14}\text{O}(a, p)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\beta^+)^{18}\text{F}(p, a)^{15}\text{O}$. This process skips the beta decay of $^{14}\text{O}(70.6$ sec), the slow process in the cycle. This bypass begins at some stage because the most abundant nuclides in the primary HCNO cycle are $^{14}\text{O}$ and $^{18}\text{O}$ since the beta decays of these nuclei are limiting the cycle speed. Further, the stellar site gets a higher temperature and a larger $^4\text{He}$ abundance due to the catalytic synthesis of hydrogen into He. The third importance of the reaction is that this reaction is in the competing reaction process against the possible leakout from the HCNO cycle to the rp-process, i.e., $^{14}\text{O}(a, p)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\alpha)^{18}\text{F}(p, \gamma)^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$.

This reaction study of $^{18}\text{F}(p, a)^{15}\text{O}$ was the second successful experiment performed using an accelerated radioactive beam of short lived nuclei at Louvain-la-Neuve,\cite{84} and also at Argonne National Laboratory.\cite{85} At Louvain-la-Neuve, the radioactive $^{18}\text{F}$ ions produced were chemically processed to a stable molecular form of CH$_3$F for an efficient transport to the ECR ion source, and fed into the ion source for ionization, and then accelerated by the second cyclotron. The experiment determined the resonance parameters, $\Gamma_{\text{tot}}=37$ keV and $\omega\gamma=5.6$ keV, for the $3/2^+$ resonance at 638 keV above the proton threshold. This result has confirmed clearly the previous reaction rate estimate with much better reliability at $4 \times 10^8$ K and higher. The lower excitation energy region should be investigated further.\cite{86}

Along the breakout process from $^{14}\text{O}$ mentioned above, the $^{17}\text{F}(p, \gamma)^{18}\text{Ne}$ stellar reaction is very important but yet to be investigated. This reaction will also lead to another leakout at higher temperature through $^{14}\text{O}(a, p)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(a, p)^{21}\text{Na}$... For this problem the resonant states in $^{18}\text{Ne}$ near and above the proton and alpha thresholds were investigated by an indirect method, i.e., multi-nucleon transfer reactions at high energies.\cite{87} One of the key issues for the reaction is that there is a missing $3^+$ resonance in $^{18}\text{Ne}$ above the proton threshold. This state is predicted to be around 640 keV above the proton threshold, and could possibly be an $s$-wave resonance since the ground state of $^{17}\text{F}$ has $J^\pi=5/2^+$. This should be one of the challenging reactions to be investigated with a radioactive beam of $^{17}\text{F}$.

Another experiment relevant to the HCNO cycle was reported recently\cite{88} that used a radioactive beam of $^{12}\text{N}$ for the $^{11}\text{C}(p, \gamma)^{12}\text{N}$ stellar reaction study. This process is important in the hypothetical nucleosynthesis scenario of the hot pp-chain\cite{89} that could take place in the hydrogen burning phase of massive zero-metal stars. This process may bypass the triple $\alpha$-process for heavy element synthesis, and thus it will decide the flow rate from the hot pp-chain to the HCNO cycle. The Coulomb dissociation method was applied for this experiment by using a $^{12}\text{N}$ beam of 65.6 MeV/\text{u} at GANIL. The two fragments, p and $^{11}\text{C}$, were detected at small correlation angles. There are two important resonances at $E_{\text{c.m.}}=0.359$ and 0.489 MeV above the proton threshold in $^{12}\text{N}$. The resonance strength $\omega\gamma=3.75$ meV was obtained for the second resonance at $E_{\text{c.m.}}=0.489$ MeV. The most crucial resonance at $E_{\text{c.m.}}=0.359$ MeV is being investigated at RIKEN.\cite{90}

6.2. Onset of the rp-process

A high-temperature and high-density hydrogen burns explosively in stellar sites.
This could be the case most typically in novae and X-ray bursts. A similar situation could have occurred at the supernovae and the primordial site just after the big bang. This nucleosynthesis is called the rapid-proton (rp)-process.\(^{31}\) In this scenario the rp-process starts by breaking out one cycle going to the next starting from the HCNO cycle, i.e., HCNO cycle → NeNa cycle → MgAl cycle → ... where each cycle was closed at low temperatures. This process gives a higher energy production as well as heavier element synthesis. The first step, at moderately high temperature, supposedly begins by breaking out from the HCNO cycle through a reaction chain of

\[
^{15}\text{O}(a, \gamma)^{19}\text{Ne}(p, \gamma)^{20}\text{Na}(p, \gamma)^{21}\text{Mg} \ldots
\]

at a few \(\times 10^8\) K,\(^{91}\) as shown in Fig. 9. However, none of the reactions involved are well determined experimentally yet.\(^{92-102}\) Thus, the onset mechanism of the rp-process is not clarified well, and is still one of the hottest issues in nuclear astrophysics.

The first important finding among the experiments performed was the discovery of the first excited state at 2.64 MeV, i.e., 0.44 MeV above the proton threshold with a tentative spin-parity assignment of \(1^+\) in \(^{20}\text{Na}\)\(^{93}\) by the \((\alpha, n)\), \((p, n)\) and \(2\alpha\) reactions. This is a typical example of demonstrating the necessity of nuclear physics experiments for astrophysics. There was only one broad level suggested at 2.9 MeV in this energy region in \(^{20}\text{Na}\) before the experiment was performed. Since this new resonance is just in the middle of the Gamow window of \(T_{\text{S}}=0.1-1.0\), it enhanced the estimated reaction rate by at least two orders of magnitude at this temperature region. It is to be noted that the spin-parity of the state is still uncertain. The estimated reaction rate is plotted in Fig. 10. This finding gives a possible new route for transmutation of CO material into Ne and heavier elements in the rp-process. The enhancement is simply due to the fact that the new resonance is at a much lower energy than thought before in \(^{20}\text{Na}\).

To measure the resonance strength, which is the key parameter that determines the rate, several experimental efforts were made for the 2.64 MeV state in \(^{20}\text{Na}\). The gamma decays from the 2.64 MeV state were searched in the beta delayed gamma spectra of \(^{20}\text{Mg}\) which were produced in the projectile fragmentation process of \(^{24}\text{Mg}\) at RIKEN,\(^{95}\) MSU,\(^{96}\) and GANIL,\(^{97}\) no feeding was observed to this state in \(^{20}\text{Na}\). The charge-symmetric reaction \(^{20}\text{Ne}(t, 3\text{He})^{20}\text{F}\)\(^{98}\) did not populate the postulated analog state in \(^{20}\text{F}\), but excited the 2.97 MeV \(3^+\) state with a reasonable cross section, suggesting a spin-parity of \(3^+\). This spin assignment is consistent with a recent experimental result for this state in the \(^{20}\text{Na}(p, n)^{20}\text{Na}\) reaction at 135 MeV.\(^{100}\) An experiment to measure directly the gamma decay was performed at Louvain-la-Neuve\(^{99}\) using a radioactive nuclear beam of \(^{18}\text{Ne}\) accelerated up to the resonance energy of \(\beta + {^{15}}\text{Ne}\). So far, only an upper limit of 18 MeV was set for the gamma decay width of the 2.64 MeV state. An experimental effort was also made for the gamma branching ratio by the \(^{20}\text{Ne}(\alpha, t\gamma)^{20}\text{Na}\) reaction.\(^{101}\) Further experimental works on this subject are being prepared at various radioactive beam facilities, e.g., the facility at INS,\(^{103}\) which is just coming into operation.

The best estimated reaction rates related to the breakout off the HCNO cycle are
plotted in Fig. 10. As mentioned already, none of the rates in the figure has been determined definitively, because the critical physical parameters for the reaction rates of the capture processes are not yet measured. They are more or less estimated from the values of the analog states in mirror nuclei. As is shown here, it is quite difficult to make a good estimate theoretically for the excitation energy near the proton threshold and the resonance strength. There are always level shifts which often result in a large change to the astrophysical reaction rates. This implies that experimental investigations are really needed for the study of the rp-process, as discussed in § 2.

As can be seen in Fig. 10, the present best estimate suggests that the most critical reaction process is the $^{15}$O($\alpha$, $\gamma$)$^{19}$Ne process. None of the reaction rates is definitive as was stated already. Recent optical observations of nova ejecta show considerable amounts of Ne and Mg in some events. Some show even heavier elements such as S and Ar. It is an interesting question if CO material is really transmuted into heavier elements such as Ne, Mg, etc. in novae. If this path is open in the nova conditions, classical novae involving a CO white dwarf could be a candidate for heavy element synthesis. The other possibility is that it is a Ne-rich nova on a ONeMg white dwarf, which is more massive than the CO white dwarfs. This does not necessarily require the transmutation of CO material. The key question here is if the breakout of the CNO cycle really takes place under nova conditions. In any case, the necessity of the nucleosynthesis of Si and S indicates an explosive condition for these stellar events.

Nova model calculations have been made using a hydrodynamic model together with a full reaction network that includes the reaction rate or the beta decay data for each process. Figure 11 displays the result of the time sequence of the temperature and the density of the nova together with the experimental estimate of the $^{15}$O($\alpha$, $\gamma$)$^{19}$Ne reaction rate. Here, only CO material was assumed for the core, and the mass of the dwarf and the accretion rate are also designated in the figure. The curve of $(M/M_\odot, \Delta M/M_\odot) = (1.3, 10^{-4})$, where $\Delta M$ is the accretion rate and $M_\odot$ is the solar
mass. This condition is close to the nova Cyg 1992\(^{106}\) which has about 10\% of Ne in the ejecta. This curve and the reaction rate of \(^{15}\Omega(a, \gamma)^{19}\text{Ne}\) are about to cross each other in the figure. This result indicates that both the nova model and the reaction data should be critically improved in order to draw conclusions about the possible transmutation of CO material in novae. The crossing temperature could be as high as \(T_9=0.4-0.5\), which is approaching the condition of the ignition of the new mechanism at high temperature, i.e., the \((a, p)\) process\(^{109},^{110}\). This process opens a new route for the breakout off the HCNO cycle. This point will be discussed further in § 6.4.

The detailed investigation of the mechanism of the breakout off the HCNO cycle and the ignition of the rp-process will improve the nova and X-ray burst models.

6.3. Early stage of the rp-process

According to the rp-process scenario, the nucleosynthesis-flow just after the breakout off the HCNO cycle goes through nuclei of which the nuclear structure is not known well or totally unknown. It is quite important to understand the early stages of the rp-process because these are strictly related to the production of the elements observable in novae.

We look here at the experimental studies of nuclei along the postulated flowpass. The first step after \(^{20}\text{Na}\) is supposed to go to \(^{21}\text{Mg}\). The nuclear levels of \(^{21}\text{Mg}\) were totally unknown near and above the proton threshold. Many new levels were identified near and above the proton threshold by the \(^{24}\text{Mg}(^{3}\text{He}, ^{6}\text{He})^{21}\text{Mg}\) reaction, and the spin-parity assignments were made by measuring the angular distributions, which gave a unique determination for the transferred orbital angular momentum\(^{111}\). Here, the \((^{3}\text{He}, ^{6}\text{He})\) three-neutron pickup reaction has been developed\(^{112}\) as a useful spectroscopic tool for nuclei near the proton drip line in the light mass region.

The stellar reaction rate of the \(^{20}\text{Na}(p, \gamma)^{21}\text{Mg}\) process has been estimated for the first time based on experiment. The \((p, \gamma)\) rate is a few orders of magnitude smaller than the previous estimates\(^{113}\) at \(T_9=0.2-1.0\), but exceeds the beta-decay rate at \(T_9 \geq 0.1\) in typical nova conditions. It is concluded that the nucleosynthesis-flow of the rp-process will run up at least to \(^{21}\text{Mg}\) as soon as breakout from the HCNO cycle occurs. However, the decay widths of proton and gamma for the resonances remain to be determined experimentally.

The next possible process is to go through another \((p, \gamma)\) reaction to \(^{22}\text{Al}\). There are some resonances expected from our shell model calculation, but the proton threshold energy is as low as about 110 keV\(^{108}\). Thus, the reverse reaction becomes dominant, suggesting that \(^{21}\text{Mg}\) is the waiting point and the nucleosynthesis flow will have to await the beta decay to \(^{21}\text{Na}\). By the same reasoning, the flow from \(^{21}\text{Na}\) will stop at \(^{22}\text{Mg}\), which leads to \(^{22}\text{Na}\) and then \(^{23}\text{Mg}\).

Therefore, an interesting question next is the breakout condition from the NeNa cycle to the MgAl-cycle, which will take place from \(^{23}\text{Mg}\) to \(^{24}\text{Al}\) in an explosive hydrogen burning condition. This is very much the same situation as the breakout from the HCNO cycle. This problem was also investigated through an indirect method. The nuclear levels in \(^{24}\text{Al}\) were investigated by the \(^{24}\text{Mg}(^{3}\text{He}, t)\) reaction\(^{114}\). Several new states were identified above the proton threshold, and the crucial reso-
nance at 2.521 MeV assumed before has been confirmed. There remains, however, a possibility of an alternative assignment to the analog states for the first two levels above the threshold. There are significantly large level shifts observed, compared to the mirror nucleus $^{24}$Na. The reaction rate estimated based on the above experimental result is about a factor of five larger than the previous estimate. This rate also suggests a reduction of the onset temperature of the $^{23}$Mg($p, \gamma$)$^{24}$Al process roughly by 10%. Figure 12 shows the result of a simple model calculation of the nucleosynthesis. Here, 100% of $^{23}$Mg was assumed, and the nucleosynthesis-flow was calculated with present reaction rate estimates till the final products after 1000 sec. The result clearly indicates that a sharp onset of the leakout from the NeNa cycle takes place through the $^{23}$Mg($p, \gamma$)$^{24}$Al reaction at around $2.3 \times 10^8$ K. The critical physical parameters, the proton and gamma widths of the resonances just above the proton threshold should be determined. This is an interesting subject to be investigated with an unstable nuclear beam of $^{23}$Mg.

The next process, $^{24}$Al($p, \gamma$)$^{25}$Si, is another interesting problem 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. This reaction may be related to the nucleosynthesis of Si and S observed in nova ejecta.\textsuperscript{106,107} This problem was studied recently using the $^{28}$Si($^3$He, $^6$He)$^{25}$Si reaction at INS. Very little was known about the resonances above the proton threshold in $^{25}$Si. Many new levels were identified, including the ones shown in Fig. 13. These resonances certainly increase the reaction rates. The preliminary result suggests that this process may be ignited once the breakout from the NeNa cycle begins.

6.4. High temperature rp-process

Another site of explosive hydrogen burning could be X-ray bursts or supernovae,
where the hydrogen will burn at higher temperature ($\geq 10^9$ K) with higher density ($\geq 10^8$ g/cm$^3$). Since there would be no ejecta from the X-ray bursts, the nucleosynthesis is not so important for the chemical evolution of the universe, but is critical for the energy generation and the burst period for instance. This process, called the high temperature rp-process, involves successive proton capture reactions together with the beta decays, and runs up to heavier mass region. However, now it also includes other mechanisms such as $(\alpha, p)$ reactions in the light mass region, which accelerate the nucleosynthesis-flow and bring the flow back toward the stability line, skipping some waiting points of the rp-process at lower temperatures. As was touched upon already in § 6.1, the $(\alpha, p)$ reactions take place on proton-rich unstable nuclei.\textsuperscript{109} The breakout process from the HCNO cycle will change to a reaction sequence of

$$^{14}\text{O}(\alpha, p)^{17}\text{F}(p, \gamma)^{18}\text{Ne}(\alpha, p)^{21}\text{Na} \ldots.$$ 

Although these $\alpha$-induced reactions on unstable nuclei would be a competing processes at higher temperatures, no experimental information exists. The $(\alpha, p)$ reaction rate estimated by a statistical model suggests that this reaction will dominate the leakout at $T \geq 5 \times 10^8$ K, although the statistical model is not accurate enough to predict the cross section better than a factor of two at best. This new possible route would be a next challenging subject of investigation, using radioactive nuclear beams. The statistical models also need to be improved.

Another interesting subject among the rp-process is the termination process. The high-temperature rp-process is considered to run through the mass region of Fe and Ni way up to somewhere $A=100$. Some p-process nuclei could have been produced by this process. However, it is not clear how far and where it will pass through the neutron deficient mass region of the nuclear chart. There are many unknown nuclei through which the rp-process runs in this scenario.\textsuperscript{109,115} The critical nuclei such as $^{65}$As and $^{69}$Br, which lie on the postulated rp-process, have been identified using heavy-ion induced fragmentation reactions.\textsuperscript{116,117} This result supports that the rp-process goes up to around $A=70$. There are still many nuclei unknown in this mass region. Further, the pathways may be strongly influenced by the proton threshold energies, which become smaller as one goes toward the proton drip line, and the reverse reaction, i.e., the photo-disintegration process dominates the flow, bringing the flow towards the stability line. Further experiments dealing with the nuclear structure near and just above the proton thresholds will clarify the pathway and the termination point. Many of the important nuclei along the possible process have reasonably long half lives to accelerate in ISOL-based radioactive beam facilities for experiments.

§ 7. Isotopic anomalies and gamma ray observations

The long-lived nuclei such as $^{22}$Na, $^{26}$Al, $^{44}$Ti, $^{56}$Co play an interesting role. They emit specific gamma rays, and/or decay to specific products, giving isotopic anomalies in meteorites.

Isotopic abundance gives us another clue for understanding the stellar events of
interest. Of interest are the isotopic anomalies observed in meteorites.\(^26\) One of these is the so-called Ne-E problem,\(^27\) corresponding to high \(^{22}\)Ne enrichments, compared to the solar abundance, observed in some meteorites. These anomalies are usually found in presolar grains, which are believed to have been produced in some stellar event. The most plausible explanation for this problem is that the meteorites were produced from the ejecta of some stellar event at high temperatures. The nucleus \(^{22}\)Na trapped in a meteorite would have beta decayed afterward, giving an enrichment of \(^{22}\)Ne. Here, \(^{22}\)Na has a long half life of 2.6 yr. Thus, the nuclear astrophysical problem is to know the reaction rates which are associated with \(^{22}\)Na.\(^11\)\(^8\),\(^11\)\(^9\) The main production processes of \(^{22}\)Na would be \(^{21}\)Ne(\(p\), \(\gamma\)) and \(^{22}\)Mg(\(\beta^-\nu\)), and these are known rather well. However, the depletion process, \(^{22}\)Na(\(p\), \(\gamma\))\(^{23}\)Mg, has not been well determined. Above 290 keV this reaction was investigated directly by using a radioactive target of \(^{22}\)Na,\(^12\)\(^0\),\(^12\)\(^1\) which was produced by a high energy proton beam and collected by ISOL at ISOLDE of CERN. The reaction rate at low temperatures,\(^11\)\(^9\) however, had a very large uncertainty, several orders of magnitudes, mainly because of the small cross section of \(^{22}\)Na(\(p\), \(\gamma\))\(^{23}\)Mg. A possible way is to study it by indirect methods.

The nuclear resonances near the proton threshold in \(^{23}\)Mg were investigated by the direct pickup reaction \(^{24}\)Mg(\(p\), \(d\))\(^{23}\)Mg.\(^12\)\(^2\) 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 DWBA analysis. Previously, a state was suggested at around this energy by the \(^{(3}\)He, \(d\)) reaction.\(^12\)\(^3\) The newly discovered state determines the reaction rate at low temperatures since it locates just about \(0.5-1.0\times10^8\) K of the Gamow energy.

Very recently, this process was further investigated by the direct proton transfer reaction \(^{22}\)Na\(^{(3}\)He, \(d\))\(^{23}\)Mg reaction.\(^12\)\(^4\) This is an indirect method, but is a kind of simulated method that gives the multipolarity of the resonance angular momentum and the proton partial decay width as follows. The DWBA analysis provides the spectroscopic factor \(S_I\), which is related to the proton partial width \(\Gamma_p\) of the level as

\[
\Gamma_p = \Gamma_sp C^2 S_I ,
\]

where \(\Gamma_sp\) is the calculated single particle width. The experiment reconfirmed the presence of the state at 7.643 MeV, and identified the resonance to be \(d\)-wave. This resonance enhances the reaction rate by several orders of magnitude at around \(0.5 \times 10^8\) K. Since the spin of the state is not uniquely determined yet, there remains some ambiguity. The derived proton partial decay width is about \(10^{-8}\) meV, which is almost impossible to measure by the direct method.

Since the half life of \(^{22}\)Na is very long, there is a chance that the gamma rays from the decay of \(^{22}\)Na are observed in novae which occur in our neighbourhood.

Similarly, \(^{26}\)Al is an interesting nucleus observed in gamma ray observations as well as in isotopic anomaly of \(^{26}\)Mg which is the decay product of \(^{26}\)Al.\(^12\)\(^5\) Discrete gamma rays from \(^{26}\)Al were observed emerging from the galactic plane.\(^24\),\(^23\) Recent gamma ray observations revealed the presence of a large amount of \(^{26}\)Al from the direction of our galactic center, as discussed already in § 1. The origin is still an
open question. The reaction rates relevant to $^{26}$Al and also those to nearby nuclei need to be studied to understand this phenomenon. A recent nova model analysis suggests that such amount of $^{26}$Al can hardly be produced, although the distribution of the novae is similar to the map of $^{26}$Al. The fundamental question about the site itself is still an open question. It is most possibly in some explosive event.

The gamma rays of the decay of $^{56}$Co were observed from SN 1987A, as discussed in § 1. The decay curve of this gamma line as a function of days after the explosion provides us rich information for the mechanism. Since a considerable amount of $^{44}$Ti, the half life of 47.3 yr, should have been produced in SN 1987A, the gamma rays from the decay of this nucleus could be possible when the gas is cleared. The nucleosynthesis between $^{40}$Ca and $^{56}$Ni is very little studied. Specifically, nuclear reactions at the possible bottle necks near $^{40}$Ca and $^{56}$Ni would be of great importance for the astronomical gamma rays of $^{44}$Ti and $^{56}$Co, and thus for stellar models.

§ 8. Heavy element synthesis and cosmochronology

Heavy elements are not particularly important for the evolution of the universe and energy generation, but 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 nucleosynthesis flow of the s-process goes more or less along the stability line by $(n, \gamma)$ reactions and beta decays, over long periods of time. The mechanism of the $(n, \gamma)$ reaction in the keV energy region needs to be reinvestigated thoroughly as was discussed in § 2. The nuclear halo states change the $(n, \gamma)$ cross sections dramatically in some situations. Although the s-process supposedly takes place in the core He burning stage of massive stars for instance, it is not clear which nuclear reactions produce enough neutrons for the s-process. The $^{13}$C$(\alpha, n)^{16}$O and $^{22}$Ne$(\alpha, n)^{25}$Mg reactions are the main candidates as discussed in § 2, but due to the difficulties of these experiments there is not yet a conclusive answer. This is another important subject for investigation of the s-process for heavy element nucleosynthesis.

The r-process, on the other hand, should have taken place in a very high neutron-density region ($n_n \sim 10^{21}$ cm$^{-3}$) at high temperature ($T \sim 2-3$) with a very short time scale, suggesting a nucleosynthesis flow-path far away from the stability line. The path may be around the nuclei that have a neutron separation energy of 2–3 MeV, where the beta decays balance the neutron capture rates. The peaks, such as at mass 128 in the mass distribution in Fig. 1, show 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 in Type II supernovae, although this is far from certain yet.

The nucleosynthesis of the r-process is least known experimentally since the nuclei on its possible path are all quite difficult to produce in the laboratory. Only some nuclei around the possible waiting points at $N=50$ and 126 were observed so far. The nucleus $^{130}$Cd was produced and first investigated at CERN-ISOLDE by a high energy spallation reaction; the half life was determined to be 203 ms, whereas the

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* This value has not been confirmed yet, and is a subject of current experimental programs, E. B. Norman, private communication.
nucleus $^{80}$Zn$^{130,131}$ was produced as a fission product of $^{235}$U$^{130}$ and studied at the high-flux reactor at Brookhaven National Laboratory, giving $T_{1/2} = 550$ ms. Therefore, the r-process time scale could be at least 550 ms, since $^{80}$Zn is considered to be one of the waiting points in the r-process. Further experiments on very neutron rich nuclei are really needed for the study of the r-process.

Very recently, a new production method of very neutron-rich nuclei was developed that uses Coulomb fission of an accelerated $^9$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, $^{28}$Ni$^{130}$ was produced and identified.$^{132}$ Further experimental information such as the half life, beta decay $Q$ value, mass are needed for $^{78}$Ni and the nuclei nearby to answer the question if the r-process is really going through $^{78}$Ni.

The 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 when the $Q$-value is very small.$^{133}$ This was first demonstrated experimentally for the decay of $^{163}$Dy$^{66+} \rightarrow ^{163}$Ho.$^{134}$ The half life of $^{163}$Dy$^{66+}$ was determined to be 47 days. Here, the fully ionized $^{163}$Dy$^{66+}$ has a slightly positive $Q$-value for the weak decay. Such a condition of full ionization and storage of the ions was realized for the first time using the high energy heavy ion accelerator and the storage/cooler ring ESR at GSI. This enabled the half life measurement of $^{163}$Dy$^{66+}$. Figure 14 displays change of number of ions of $^{163}$Dy$^{66+}$ and $^{163}$Ho$^{66+}$ in the storage ring, indicating the $^{163}$Dy$^{66+} \rightarrow ^{163}$Ho$^{66+}$ decay.

The $^{187}$Re-$^{187}$Os pair is a good cosmochronometer since it is almost free from the r-process scenario.$^{133}$ However, if the decay rate of $^{187}$Re-$^{187}$Os is influenced by the atomic charge state considerably, the ratio of $^{187}$Re/$^{187}$Os will be changed, resulting in a modification for the chronometry. The bound state beta decay of $^{187}$Re$^{75+}$ was beautifully measured very recently at GSI,$^{135}$ resulting in a half life of about 12 yr that is many orders of magnitude shorter than under normal condition of $^{187}$Re, $T_{1/2} = 4.23 \times 10^{10}$ yr. The cosmochronological significance is being evaluated.$^{136}$ This method can be very powerful for investigating such beta-decay in learning p-process and cosmochronology. The storage ring will be also used to determine the mass of short-lived radioactive nuclei as well as their half lives. These are also very important inputs for the study of the r-process.
There are many other interesting developments for the problems in nucleosynthesis, which were not discussed here. Many crucial problems have been studied little and await both experimental and theoretical investigations.

§ 9. Prospects of nuclear astrophysics with radioactive nuclear beams

9.1. The new technology of radioactive nuclear beams

As we have discussed in the preceding sections, a variety of radioactive nuclei are involved in astrophysical nuclear reactions. It is evident from the discussion above that new technological developments open new research fields in science. Since the beginning of the radioactive nuclear beam development at Berkeley by the INS-LBL collaboration in 1980's, the most popular method has been the heavy-ion induced projectile fragmentation process at intermediate and high energies, as shown in Fig. 6. This relies on the fragment separator technique developed by the collaboration. The second generation separators give good isotope separation with better efficiency. These facilities are operational in the major heavy ion laboratories. Projectile fragments produced at high energies can be stored due to relatively smaller emittance since the fragments have a spread of about Fermi momentum regardless of the incident beam energy for production. A storage ring equipped with a cooling function, which was used for the bound state beta-decay of $^{187}$Re as discussed in the previous section, enables precise mass and half life measurements of unstable nuclei, which was realized for the first time at GSI in Germany. This technique is very powerful in investigating nuclei far from the stability line, because a single nucleus is detectable non-destructively. Extensive applications are possible with the storage/cooler ring. This kind of extensive third generation radioactive beam facility is planned at RIKEN. The radioactive nuclear beams will be stored and merged parallel or anti-parallel with stable nuclear beams or electron beams for nuclear structure and the reaction study of unstable nuclei.

The second method for radioactive nuclear beams, which is called the ISOL + post-accelerator scheme, has been established recently at the cyclotron facility of Louvain-la-Neuve. Here, radioactive nuclei are produced by a primary beam and separated on-line (ISOL), and accelerated by the second cyclotron. This is a first pioneering setup with limited capability. A successful measurement was made for the $^{13}$N($p, \gamma$)$^{14}$O stellar reaction as discussed in § 6.1. An intense beam of radioactive nuclei $^{13}$N was produced by the $^{12}$C($p, n$) reaction, ionized with the ECR ion source, and then accelerated by the second cyclotron up to the energy of the resonance of interest. Of course, the experiment was performed with a hydrogen target using inverse kinematics. This method provides radioactive nuclear beams of high intensity with high quality since the production can be made by high energy protons with a thick target and the quality of the accelerated beams is as good as that of ordinary stable beams, in contrast with the poor beam quality and low intensity at low energies in heavy ion facilities.

New radioactive nuclear beam facilities based on this ISOL + post accelerator scheme will soon come into operation at least in three laboratories in the world.
They include INS, University of Tokyo, Oak Ridge National Laboratory in the U.S.A., and GANIL in France. Similar projects also have been approved recently at TRIUMF and CERN-ISOLDE. The major concern here may be the absolute efficiency of ionization and acceleration of the radioactive products, which is currently under development. There are several similar plans under discussion in Europe and Russia. Figure 15 displays the facility being constructed at INS, University of Tokyo. The whole system will be operational late in 1996. This is the first extensive facility that includes a construction of secondary beam accelerators, a new type of RFQ, Split-Coaxial (SC)-RFQ linac and an interdigital H type linac, both of which are now operational. Specifically, the SC-RFQ linac can accelerate ions of $q/m \geq 1/30$, which will give a high absolute efficiency for radioactive nuclei. Because of the diverse applicability of radioactive nuclear beams in science, second generation facilities are being planned by international collaborations. These include the Isospin Laboratory planned for North America, a similar laboratory planned in Europe, and the Exotic Nuclei Arena of the Japanese Hadron Project in Japan.

9.2. Scope of the physics with radioactive nuclear beams

We here summarize the crucial nuclear reactions for nuclear astrophysics to be studied that mostly involve radioactive nuclei. As was stressed already, experimental studies in general are still in a quite early stage in many subjects in nuclear astrophysics.

For the solar model problem, the $^4\text{He}(^3\text{He}, \gamma)^7\text{Be}(p, \gamma)^8\text{B}$ as well as the $^3\text{He}(^3\text{He}, 2p)^4\text{He}$ reactions are of great importance for the temperature region of interest. The $^{12}\text{C}(a, \gamma)^{16}\text{O}$ reaction still remains to be further investigated for the He burning process in the stellar model. The $^{12}\text{C}$ and $^{16}\text{O}$ burning process are also to be studied.

There are several important reactions for the HCNO cycle, the onset of the
rp-process and the early stage of the rp-process that require radioactive beams. They include $^{18}\text{O}(a, \gamma)^{20}\text{Ne}$, $^{14}\text{O}(a, p)^{17}\text{F}(p, \gamma)^{20}\text{Ne}(a, p)^{21}\text{Ne}$, etc. The real pathway from the HCNO to the rp-process is important for learning the transmutation of CO 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 which showed the presence of considerable excess of Si and S. The reactions around $^{40}\text{Ca}$ and $^{56}\text{Ni}$ could be a bottle neck 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 are crucial for learning the termination of the rp-process and possible production of the p-process nuclei at $A = 60-100$. These works will improve the stellar models.

For the Ne-E problem, the reactions associated with $^{22}\text{Na}$ should be carefully studied for understanding its origin. Similarly, the reactions around $^{26}\text{Al}$ are critical for the study of $^{26}\text{Al}$ gamma rays. So far, the large amount $^{26}\text{Al}$ seems quite difficult to explain by the existing nova models.

A more 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 awaited here.

Although I emphasized the importance of reaction studies with unstable nuclei that simulate exactly the reactions at the stellar energies, 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 to get information related to astrophysical problems.

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