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Abstract. Radio-isotope (RI) beams have opened up a new field in nuclear astrophysics in the last decade, especially for investigating explosive nucleosynthesis. Recent astronomical observations also have made a great advance that isotopic abundances rather than elemental abundances are obtained, which clearly indicate the stellar reactions responsible and also tells us exact amounts of radioisotopes synthesized in the stellar event. However, experimental studies of nuclear reactions of astrophysical interest with RI beams are usually quite difficult because of small beam intensities and small cross sections in many cases. New experimental methods have been developed to cope these difficulties in both direct and indirect methods. We will review recent experimental investigations for each nucleosynthesis scenario, which is based on the new experimental methods developed, such as the thick target method and the Asymptotic Normalization Coefficient Method (ANC) as well as the Coulomb dissociation method. The subjects here include nucleosynthetic problems from the primordial nucleosynthesis to the supernova nucleosynthesis. As for the study of the r-process, we discuss on the experiments performed with a heavy ion storage ring for precision mass and half-life measurement. A brief discussion is also made for the outlook of the field, especially possibilities at the up-coming RI beam facilities like the ones at RIBF at RIKEN and the ISOL-type RIB facility at TRIUMF.

I OBSERVATION OF ELEMENTS TO ISOTOPES

The Universe is an interesting and important test ground of nuclear physics because such a dynamic and wide variety of nuclear reactions going on in terms of energy, nuclear species, matter density, etc. which we have never experienced in the laboratories. Nuclear physics, on the other hand, is really needed to understand the evolution of the Universe as well as various astronomical events. The large amount of energy stored in atomic nuclei plays a decisive role in the evolution of the Universe¹⁻³⁾. The origin and the distribution of the elements are other important factors for understanding the Universe and the constituents of our world. Nuclear reactions cause synthesis of a variety of elements from light to very heavy ones in the Universe. There are various nucleosynthesis scenarios depending on the environmental conditions for nuclear burning in the stellar sites, which require various nuclear physics informations to understand the mechanism. Recent progress of nuclear astrophysics is summarized for instance in refs. 4-10).

Observation of elemental abundance has been providing important clues for understanding not only various phenomena but also the evolution of the Universe. Detailed abundance ratios observed optically for novae, such as Si and S which should have been produced in a explosive nucleosynthesis¹¹⁾, are a very important clue for understanding the mechanism of novae. Recently, X-ray observation from satellites also provides the elemental distributions in the outbursts of supernovae¹²⁾. This wealth of observational data allows us to study nucleosynthesis and hence the mechanism of such an explosive event. Observation of elements is the unique clue to study the primordial Universe just after the Big Bang as compared to other means. Therefore, there should be, in the oldest objects, a chance that one might study them to understand the primordial nucleosynthesis. When one discusses inhomogeneous Big Bang models¹³⁾, one may study the models from the nucleosynthesis point of view. There, both astronomical observations¹⁴⁾ and laboratory experiments provide stringent tests¹⁵⁾ for the Big Bang models.

FIGURE 1. Typical nucleosynthesis flows of important scenarios for nuclear astrophysics on the nuclear chart.

In the last decade, a very important progress in astronomical observation is that they can now tell us not only elemental abundance but also isotopic abundance for some elements. Isotopic abundance restrains the models very tightly as it tells us more clearly the stellar reactions responsible for the production, and also give us exact amount of isotopes produced there. First nuclear gamma rays were observed for $^{26}\text{Al}^{16)}$. The origin of ^{26}Al production is still an open question. Gamma rays from the decay of ^{56}Co were also reported from the SN 1987A, which directly indicated a massive production of ^{56}Ni in the explosion¹⁷⁾. Recently, the nuclear gamma decay of $^{44}\text{Ti}^{18)}$ was observed from Cassiopeia A which is a remnant of supernova first observed in 1680. Certain amount of production of these nuclei, Ti and Ni (Co), are qualitatively consistent with the prediction by supernova models¹⁹⁾. The isotopic anomalies in meteorites²⁰⁾ are also an observation of isotopes in presolar grains, which could have been produced in some stellar event. Of course the detection of the solar neutrino is also a direct observation of specific nuclear reactions inside the sun, where one can observe only through neutrinos^{21,22)}.

Recent observations with high-resolution optical telescopes now also provide isotopic ratios from isotopic shift measurements for some elements²³⁾. Observation of isotopic abundance or quantity of nuclides is a new breakthrough for studying the Universe. These observations of radioisotopes also indicate, as a general remark, that unstable nuclei play an important role in such explosive phenomena.

II EXPLOSIVE NUCLEOSYNTHESIS AND UNSTABLE NUCLEI

There are several sites where such explosive conditions are realized along the evolution of the Universe. They include the primordial universe, supernovae, novae, X-ray burst, etc., although the conditions for the nucleosynthesis is totally different each other. Here, unstable nuclei are inevitably involved in explosive nucleosynthesis. Various characteristics of nuclear burning define the scenario of nucleosynthesis^{2,3)}, which is depicted in Fig. 1⁸⁾. A chain of nuclear reactions under explosive conditions leads the nucleosynthesis-flow to the nuclear regions far from the line of stability because successive capture reactions take place before beta decays at high temperature and high density.

Research activities in nuclear astrophysics have expanded very rapidly in the last decade partly because a variety of radio isotope beams (RIB) have become available²⁴⁾, which give us a unique opportunity to study these reaction processes in explosive burning phenomena in the Universe⁴⁻¹⁰⁾. Although these scenarios include many nuclear reactions, beta decays etc, which we do not know yet, there are some critical points to be investigated carefully to

clarify the scenario. Since the nucleosynthesis flow runs through neutron-rich or proton rich nuclear regions away from the line of stability, one needs to study experimentally the following common points along the possible flow path. They include

- (1) ignition process,
- (2) termination process,
- (3) bottlenecks, and
- (4) waiting points.

The bottlenecks and the waiting points have a major effect for the pathway and the time duration of the explosion. Since these points are located close to the proton drip line in the rp-process case, precise experimental efforts are needed for studying explosive nucleosynthesis especially on these four points. There are at higher-temperature and higher-density conditions further complications such as two-proton (2p) capture process and the α p-process set in. The nucleosynthesis flow can go over a non-existing nucleus to a nucleus of $Z+2$ by the 2p-process. The α p-process will play an important role at relatively light mass region, which is not much investigated yet.

Similar arguments can be made for the r-process, although the r-process is considered to run through the region of neutron-rich nuclei that have neutron separation energies of about 2 - 3 MeV where the (n, γ) and (γ ,n) processes equilibrate. Since these waiting points and the bottlenecks are located around the magic numbers or sub-magic numbers of nuclei in the proton-rich and neutron-rich nuclear regions, the shell magicity should be known, which might different from those at the stable nuclear region. The magic numbers of protons will affect to the rp-process and those of neutrons to the r-process. Nuclear physics information in the mass region, including the location of the drip lines, is really needed.

In this talk, we review recent experimental developments for each problem in nuclear astrophysics, performed with RI beams, or tested for RI beam experiments. Here, a specific emphasis was placed on new methods developed for determining reaction cross sections at astrophysical energies.

In principle, there are two ways to approach the problem experimentally²⁵⁾,

- (1) the direct method, and
- (2) the indirect methods.

Here, we consider a stellar reaction of $A(x,y)B$, where A and/or x is an unstable nucleus. Reaction study of $A + x$ at the energy of interest is called the direct method. The reverse geometry, $B(y,x)A$ can be used as well, although the reaction leading to the excited states in y or B cannot be determined in the reverse geometry. All others are called indirect methods. If one has enough knowledge on the nuclear properties of the nuclei relevant, one can make a good estimate for the reaction rate. Experimental derivation on these physical parameters is also called an indirect method. In practice, we need to use both direct and indirect methods although RIBs are available for many reactions of interest for explosive nucleosynthesis. This is due to two difficulties; one is that the intensities of RIBs are much less than stable nuclear beams, and the second is that the cross sections are often quite small at the stellar energies. The difficulty increases when one investigates the reactions along the r-process, where both the target nuclei and neutrons are unstable. Here, one needs to study the reaction process using indirect methods at the present technology.

There are several indirect methods developed or being developed that simulate the direct method, or simulate some part of the process. They include²⁵⁾

- (1) the Asymptotic Normalization Coefficient (ANC) method,
- (2) Coulomb dissociation method, and
- (3) Trojan Horse method.

Here, the Trojan Horse method, being developed recently, is a three-body reaction study under a quasi-free scattering condition. The Coulomb dissociation method has been extensively used for radiative capture reactions at low energies, although this method is not well tested for a case of direct capture process. This method measures the Coulomb-dissociation cross sections, and convert them to the capture cross sections at low energies. Here, the dissociation process should include virtually only the contribution of the Coulomb field, although heavy ion reactions at intermediate and high energies inherently have both nuclear and Coulomb contributions. The capture cross section can be obtained by a detailed balance, where the phase factor enhances the yield for this method. Of course, one can use a thick target and the resolution of the relative energy does not depend very much on the energy resolution of the incident beam. The ANC method has a possibility to study a low-energy direct capture reaction from a direct particle transfer reaction. It will be discussed in the following section.

III FRONTIER OF EXPERIMENTAL STUDIES BY NEW METHODS WITH RI BEAMS

There are many interesting progresses made in the last years in experimental study in nuclear astrophysics. New development in experimental methods²⁵⁾ made a large progress, specifically for the study with RI beams. To overcome the experimental difficulties mentioned above, various efficient methods of high-resolution have been developed both in the direct and indirect methods. Depending on the problem, the method is chosen to deduce the answer. Here, we will discuss important reaction studies made in the past years for each scenario of nucleosynthesis from hydrostatic hydrogen burning to the r-process with a specific emphasis of new experimental methods that enabled the progress.

A Primordial Nucleosynthesis

The Inhomogeneous Big Bang (IBB) models¹³⁾ have been discussed extensively in the past, but it is not clearly concluded in any respect, observations, theories, nor laboratory experiments. The IBB model predicts much more synthesis of heavy elements as well as larger baryonic matter density for the Universe, which is crucial for the problem of cosmology. The primordial nucleosynthesis is quite important to examine back to the early epoch of our Universe. Certainly, observation of heavy elements in the early age would tell us the problem. Nuclear physics inputs are thus quite important to investigate the primordial Universe. Recent measurement of the cosmic microwave background (CMB) shows a power spectrum that can be explained by a large Ω_b , but it cannot be explained within the standard Big Bang model, which is discussed in a contribution to this conference²⁶⁾.

One of the crucial reaction channels of the IBB model is ${}^8\text{Li}(\alpha, n){}^{11}\text{B}$, that would bridge the mass gap at $A = 8$ and 9 for heavy element synthesis. This experiment is still going on by measuring directly the reaction cross sections at the Gamow energy region at RIB facilities such as at TRIUMF. Here, the Gamow energy is the optimum burning temperature defined by two factors²⁷⁾, the Maxwell-Boltzmann distribution of the site and the nuclear penetrability for a charged particle channel, and it is roughly several times larger than the temperature ($E = kT$) of the site. The temperature range we are discussing in this paper is around $T_9 = 0.01 \sim 3$, that corresponds to $10 \sim$ a few hundred keV in energy.

Another possible leakout path for heavy element synthesis is ${}^8\text{Li}(n, \gamma){}^9\text{Li}$. This reaction was investigated by a dissociation of intermediate-energy ${}^9\text{Li}$ in the electromagnetic field of the targets to get better estimate of the contribution²⁸⁾.

B The pp-Chain and the Solar Model

Although the pp-chain²⁷⁾ is not an explosive nucleosynthesis, we will discuss it here as it involves unstable nuclei and also there are many works made in the last few years. Since the sun is the nearest star, it is a good target to investigate in detail. The main energy source is known to come from the nuclear burning, called the pp-chain, which is a typical hydrostatic nuclear burning process of hydrogen. Only a few reactions were studied at the Gamow energy region among the pp-chain. Some of the reactions are too difficult to study experimentally at the Gamow energy in the laboratories. The observation of neutrinos produced from nuclear reactions inside the sun, is the unique way to observe the reaction rate directly. However, the measured intensities of the neutrinos from the sun are too low roughly by a factor of two as compared to the standard model prediction²⁹⁾. There are three possibilities for this problem; (1) the neutrinos produced in the sun change the flavor along the travel to the detector on the earth^{21,22)}, (2) the nuclear reaction cross sections relevant are wrong, or (3) the solar model²⁹⁾ is wrong. Very recently, the Sudbury Neutrino Observatory (SNO) project reported from their measurement that they confirmed that the neutrino changes the flavor on the way to the earth, and the total intensity of neutrinos does hold²²⁾. The Super-Kamiokande experiment succeeded to obtain accurate and enough data of the atmospheric neutrinos, which also strongly suggests the flavor change of the neutrinos²¹⁾. These results would explain the major part of deficit of the neutrino flux observed.

However, the uncertainties in the experimental cross sections are not precise enough yet to discuss the solar model in detail. Those of the reaction cross sections involved in the pp-chain, especially those related to ${}^8\text{B}$ production affect very much to the uncertainty of ${}^8\text{B}$ production. Here, the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction is the critical reaction for high energy neutrinos to be detected at Super-Kamiokande for instance. The ${}^8\text{B}$ production yield is roughly proportional to the reaction cross sections of ${}^3\text{He}({}^4\text{He}, \gamma){}^7\text{Be}$ and ${}^7\text{Be}(p, \gamma){}^8\text{B}$, and approximately inversely-

TABLE 1 Astrophysical S-factors obtained experimentally. Here, the S-factor is defined as $\alpha(E)=S(E)/E \text{ e}^{-2\pi\eta}$.

S₁₇(0) (eV · b)	Method	Ref.
22.4	Summary	33)
19 +4-2	Summary	30)
17.3 ± 1.8	ANC summary	36)
20.6 ± 1.2(exp.) ± 1.0(th.)	Coulomb diss. 254 MeV/u	35)
S (1.09) = 22.7 ± 1.2	Direct method	37)
S (1.29) = 23.8 ± 1.5	Direct method	37)
18.8 ± 1.7	Direct method	38)
22.7 ± 0.6	Direct method	39)
17.8 +1.4-1.2	Coulomb dissociation	34)

proportional to the root of the cross section of $^3\text{He}(^3\text{He},2p)^4\text{He}^{29)}$. The uncertainty of ^8B production accumulates these uncertainties. The second reaction has about 10 % uncertainty according to the recommendation of 1998 by Adelburger and his collaborators³⁰⁾. The $^3\text{He}(^3\text{He},2p)^4\text{He}$ reaction was extensively studied in the past in the LUNA project³¹⁾, and also recently at the RCNP, Osaka University³²⁾, giving cross-sections consistent with each other. However, the cross sections in both experiments are not conclusive yet as the uncertainties are too large at the Gamow energy region.

Table 1 summarizes new experimental works reported since the recommendation³⁰⁾ for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction in the solar model. The recommended value for $S_{17}(0)$ is $19 +4-2 \text{ eV} \cdot \text{b}$, whereas the previous recommendation was $22.4 \text{ eV} \cdot \text{b}$ ³³⁾. Three methods, already mentioned, were applied for the reaction study. The Coulomb dissociation method at intermediate and high energies gives 17.8 ³⁴⁾ and $20.6 \text{ eV} \cdot \text{b}$ ³⁵⁾, respectively, which agree with each other within the uncertainties. The ANC method gives slightly smaller S-factor³⁶⁾. The three direct-method experiments³⁷⁻³⁹⁾ also give smaller uncertainties, and in principle the results are consistent with the recommendation³⁰⁾. The work reported by Junghans³⁹⁾ in this conference has a small uncertainty by reducing systematic uncertainties. The result is a little larger than $19 \text{ eV} \cdot \text{b}$, but consistent within the uncertainties. Here, the important fact is that the cross sections in Table 1 appear still not converging well, although they mostly agree within the uncertainties. Note that all the values were measured at much higher energies than the Gamow energy, which is roughly 18 keV, and extrapolated using a theoretical curve. However, the extrapolation should be made carefully because a new broad resonance has been identified at $3.5 \pm 0.5 \text{ MeV}$ that has a width of $8 \pm 4 \text{ MeV}$ in ^8B ⁴⁰⁾.

We will go over each experimental effort listed in Table 1 for this problem, which were performed recently with different methods.

The direct measurement of $^7\text{Be}(p,\gamma)^8\text{B}$

A ^7Be target can be produced, as the half-life of ^7Be is about 53.3 d. The direct measurements were made previously using a ^7Be target. But, experiments with this method were carried out again with much care to reduce the statistical and systematic errors³⁷⁻³⁹⁾. The measurement was made by detecting the decay α particles from ^8Be .

A better method to measure directly the cross section has been successfully tested using the inverse kinematics, i.e., a ^7Be beam bombards a hydrogen target, and ^8B can be detected directly or the gamma ray from the reaction. There are two merits in this geometry. The detectors do not see the active target, thus one can reduce the count rate. It is much easier to detect the residual nucleus ^8B in the inverse kinematics. The experiment of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction was made at Naples⁴¹⁾, using a RIB of ^7Be that was produced in Karlsruhe, Germany and LLN, Belgium and transported to Naples. A $^7\text{Be}^{4+}$ beam was obtained from a sputter ion source and a Tandem accelerator, and impinged on a window-less gas target of ^1H . The reaction products ^8B were identified in a mass separator complex. Since the reaction yield is very small, the signal-to-noise ratio needs to be very high. The heavy residue ^8B were measured by a combined system of a magnetic analyzer and a Wien filter system, with a beam suppression factor of better than 10^{-10} . It is an interesting challenge to realize a mass separator system with extremely good beam suppression. If one measures the gamma rays from $^1\text{H}(^7\text{Be},^8\text{B})\gamma$ in coincidence, it will help to reduce further the background.

Coulomb dissociation method

There are three experiments reported^{34,35,42)} on ${}^7\text{Be}(p,\gamma)$ using the Coulomb dissociation method since the recommendation of 1998³⁰⁾, although this method is not fully tested for the case of non-resonant breakup process. A discussion on this method can be found in ref. 43). The $S_{17}(E1)$ values obtained are listed in Table 1, which are consistent with previous measurements within the experimental uncertainties. Since the dissociation process here is non-resonant, it needs to be carefully checked. The E2 component was separated by measuring the angular distribution in a wider angular range and fitting the shape with the DWBA calculation. The choice of the optical potential sets has an effect less than a few %, which gives a minor contribution to the result. The other contributions such as the nuclear contribution were not yet determined quantitatively. The same experiment was made also at low energies⁴²⁾, giving a consistent result with the recommendation.

The Asymptotic Normalization Coefficient (ANC) Method

Direct particle transfer reactions at relatively low energies, around 5 - 20 MeV/u, are an immensely useful tool for nuclear spectroscopy. They can be used for identifying nuclear levels and for studying the nuclear properties. Using a particle transfer reaction, one may deduce spectroscopic information using Distorted-Wave Born Approximation (DWBA) analysis of the angular distribution for the transfer reaction. If one investigates a transition to an unbound state, one may deduce a particle partial width Γ_i from the DWBA analysis⁴⁴⁾ for a narrow and symmetric resonance.

One important use of direct particle transfer reactions is the ANC method for deducing low-energy direct-capture cross sections. This method has been developed recently by the Texas A&M group⁴⁵⁾.

Direct capture reactions $A + x \rightarrow B + \gamma$ at stellar energies take place on the nuclear tail region far outside the nucleus. If a direct particle (x)-transfer reaction also takes place predominantly on the peripheral region, one may deduce from the transfer reaction the overlap function for $(B|A+x)$, with which one can derive the direct capture cross sections at stellar energies. Such conditions could be found at very forward angles in the angular distributions of the direct transfer reactions at certain incident energies, which are not too high to avoid the contribution inside the nucleus, but not too low to preserve the direct nature for the reaction.

This method was successfully tested for the proton capture reaction ${}^{16}\text{O}(p,\gamma){}^{17}\text{F}$ ⁴⁶⁾ with the ${}^{16}\text{O}({}^3\text{He},d){}^{17}\text{F}$ reaction at 29.8 MeV and also for the neutron capture reaction ${}^{12}\text{C}(n,\gamma){}^{13}\text{C}$ with the ${}^{12}\text{C}(d,p){}^{13}\text{C}$ reaction at 11.8 MeV⁴⁷⁾, recently. The cross sections for the direct capture reactions can be written as

$$\sigma = \lambda |\langle I_{Ax}^B(r) | \hat{O}(r) | \Psi_i^{(+)}(r) \rangle|^2, \quad (1)$$

where I_{Ax}^B is the overlap function of $A + x$ and B , $\hat{O}$ is the electromagnetic transition operator, and $\Psi_i^{(+)}$ is the incident wave. For a reaction that takes place far outside the nucleus, the overlap function can be expressed as

$$I_{Ax}^B(r) \equiv C \frac{W_{-\eta, \ell+1/2}(2\kappa r)}{r} \quad r > r_N, \quad (2)$$

where C is the ANC that defines the amplitude of the overlap function, W is the Whittaker function, and η is the Coulomb parameter for the bound state.

If a direct particle(x)-transfer reaction $A(a,b)B$, where $a = b+x$, takes place well outside the nucleus, the cross section can be expressed by the DWBA including the overlap function above as follows;

$$\frac{d\sigma^{\text{exp}}}{d\omega} = \sum_{j_B j_a} \left(\frac{C_{Ax}^B}{b_{Ax} j_B} \right)^2 \left(\frac{C_{bx}^a}{b_{bx} j_a} \right)^2 \frac{d\sigma^{\text{DWBA}}}{d\omega} \quad (3)$$

where b s denote the asymptotic normalization coefficients for the single particle wave functions used in the DWBA calculations, which are defined as follows:

$$\phi_{nj}(\mathbf{r}) \equiv b_{ij} \frac{W_{-\eta, \ell+1/2}(2\kappa r)}{r} \quad r > r_N \quad (4)$$

FIGURE 2. The solid line is the $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction cross sections derived by the ANC method⁴⁷⁾, and the dashed lines the uncertainties discussed in text. The main uncertainty for the estimate comes from the choice of optical potential and the bound state potential parameters. The experimental data points by the direct method were obtained from ref. 48) .

Here, it is important to check if the reaction, especially at the forward-angle scattering, is sensitive mostly to the peripheral part of the nucleus. An example is shown in Fig. 2 for the direct capture reaction $^{12}\text{C}(n,\gamma)^{13}\text{C}$, studied with the $^{12}\text{C}(d,p)^{13}\text{C}$ reaction at 11.8 MeV⁴⁷⁾, at the Center for Nuclear Study (CNS), University of Tokyo. Precise measurement at very forward angles and a careful analysis for the ambiguities of a choice of the potential parameters lead to a reasonable agreement with the data measured directly⁴⁸⁾.

This method was applied to the stellar reaction $^7\text{Be}(p,\gamma)^8\text{B}$ using the direct, one-proton transfer reaction ($^7\text{Be},^8\text{B}$) on ^{10}B and ^{14}N at 84 MeV⁴⁹⁻⁵¹⁾, since the stellar reaction primarily goes through a direct capture process. The extracted value, 17.3 ± 1.8 eVb, reasonably well agrees with the recommended value³⁰⁾, where a careful analysis was made especially for the potential ambiguities.

Trojan Horse Method

Although this method⁵²⁾ was not applied to the stellar reaction study relevant to the solar model, I will briefly discuss here, as it could be an interesting alternative for studying low energy reactions. This method was proposed to derive also a low energy reaction cross sections by using an approximate method to get larger cross sections under a quasi-free scattering condition. For a study of the $t(p,a)b$ reaction at the stellar energy of interest, one may realize a similar condition in a quasi-free scattering of $A(=t+s)(p,ab)s$ at higher energies. Here, the target nucleus A should have a good cluster configuration of t and s , and s should not participate in the reaction like a spectator. Another important point is that the reaction between t and p channel should be induced at relatively small energies which can be compensated by the Fermi motion in the nucleus A . This method was tested⁵³⁾ for the $^{12}\text{C} + \alpha$ elastic scattering study using the $^{12}\text{C}(^6\text{Li},\alpha)^{12}\text{C} \rightarrow ^2\text{H}$ reaction. The result agrees reasonably well with the elastic scattering data at the sub Coulomb barrier energy region.

Underground laboratory experiments

There are only a few cases where the reaction rates are determined in the Gamow energy region. One of the major sources of background for measurements of extremely small event rates is the cosmic rays in the laboratories

on the surface of the earth. To measure such cross sections directly at the energies of interest for charged-particle induced reactions, one has to try to eliminate the natural background in the laboratories and in the detector materials. A large improvement can be achieved in underground laboratories. Such a pioneering project for nuclear astrophysics has been made at the Gran Sasso underground laboratory³¹⁾. The ${}^3\text{He}({}^3\text{He},2p){}^4\text{He}$ cross sections were measured down to 22 keV in the LUNA project, which corresponds to the Gamow energy in the center of the sun. This is a crucial reaction that defines the outflow of ${}^4\text{He}$ away from the branch that produces ${}^8\text{B}$, which is the source of high-energy neutrinos to be detected at Super-Kamiokande²¹⁾. Thus, if the ${}^3\text{He}({}^3\text{He},2p)$ reaction rate is higher than accepted at present, the flux of the high-energy neutrinos will be reduced accordingly, as discussed earlier. Currently, the experimental uncertainty needs to be reduced to conclude the problem. The new facility Oto in Osaka³²⁾ is also providing a similar background level in their measurement of the ${}^3\text{He}({}^3\text{He},2p)$ reaction.

Generally speaking, for the study of astrophysical reactions at very low energies, one has to overcome the difficulties of very low cross sections as well as of low beam intensities of RIBs. This suggests that the RIB facility should be better made underground for nuclear astrophysics. New detector technology of high efficiency with less background must be developed.

C The CNO Cycle and the rp-process

The most remarkable progress on this subject is the extensive use of RI beams accelerated or obtained by in-flight method to learn the stellar reactions.

To investigate the reaction $A(x,y)B$, where nucleus A is a short-lived nucleus, A is provided as a beam with much smaller beam intensity as compared to stable nuclear beams. Experiments with RIBs of short-lived nuclei need to be made inevitably through inverse kinematics, which enables one to use a thick target method for experiment. RIB experiments with a thick target method have some good features as follows:

- 1) A thick target can be used for investigating the reaction over a wide incident energy range.
- 2) The detector does not have to face the strong target activities when the inverse kinematics is employed.
- 3) One can measure completely the reaction kinematics, i.e., detect both y and B, enabling a redundant measurement for less background.

RI beams that become available depend on the type of facility. Very short-lived RIBs are available only at the in-flight separators, whereas ISOL-type facilities provide RIBs of high beam quality for the nuclei of relatively long half-lives. Thus, experiments with the direct method are suited at the ISOL-type facilities, whereas indirect methods can be used at the in-flight type facilities. The stellar reactions among the extended CNO cycle were most extensively investigated in the past year using RI beams accelerated, at Louvain-la-Neuve, Oak Ridge National Laboratory, and Argonne National Laboratory. Available RIBs in these laboratories include ${}^{13}\text{N}$, ${}^{17,18}\text{F}$ and ${}^{18,19}\text{Ne}$ for this subject.

Thick target method with RIBs

The energy range of a few MeV or less above the particle threshold, which correspond to the temperatures of $T_9 = 3$ or less, is the energy range in which one studies nuclear reactions $A(x,y)B$ by the direct method. When one studies nuclear reactions that involve short-lived nuclei in explosive nucleosynthesis, one can use the thick target method³⁴⁾ with an RI beam of A. The excitation function $Y(E)$ for a certain energy range ($E_1 - E_2$) will be obtained by a one-shot run with an energy bin of ΔE as follows;

$$Y(E) = I(E) \int_{E-\Delta E/2}^{E+\Delta E/2} \frac{\sigma(E_1)}{\epsilon(E_1)} dE_1 \quad ; \quad E = E_1 - E_2 \quad , \quad (5)$$

where $I(E)$ is the number of the beam particle A, and $\epsilon(E_1)$ is the stopping cross sections of the ion A in the target material. Here, a thick target should be used to scan from E_2 to E_1 , the beam energies of A. The effective target thickness is small because of large energy loss of A at low energies. The kinetic energy of nucleus A changes quickly as it travels through the target material. If one applies this method to elastic scattering of $x + A$, the light recoil nucleus x will be detected at forward angles with nearly the recoil energy at the scattering if x is a light particle. This is just a process scanning the reaction with varying the incident energy. Here, the recoil particle x carries the information about the resonance parameters like the width and kinetic energy at the resonance. The kinetic energy of the detected particle x may be slightly distorted by the difference in travel distance in the target, which is due to the spread of the RIB in energy and angle. This effect, however, is small and can be corrected for.

FIGURE 3. Proton energy spectra measured at 0° , from the $^{19}\text{Ne}+p$ and $^{19}\text{F}+p$ scattering⁵⁶⁾. Here, a thick polyethylene target was used.

Thus, the precise excitation function $Y(E)$ can be obtained simply by a one-shot measurement of the kinetic energy of x at very forward angles. The scattering of x at very forward angles corresponds to nearly 180° in the center of mass system, where resonant effects can be seen most prominently above the Coulomb and hard-sphere scattering in elastic scattering. Here, the particle energy can be measured by a Silicon detector, which allows one to derive a high-resolution excitation function. This is because the heavy ion A is incident on light nucleus x , and thus the energy in the center of mass system is small.

Figure 3 shows an example of the thick target method, where the energy spectra of the recoil protons from $^1\text{H}(^{19}\text{Ne},p)^{19}\text{Ne}$ and $^1\text{H}(^{19}\text{F},p)^{19}\text{F}$, detected at 0° with a thick polyethylene target^{55,56)}, can be essentially identical to the excitation functions of elastic scattering of $p + ^{19}\text{Ne}$ and $p + ^{19}\text{F}$.

The first successful experiment with a short-lived RIB to measure the reaction cross section of astrophysical interest was made by the direct method at Louvain-la-Neuve for the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ stellar reaction⁵⁷⁾. There are some other experiments reported on the extended CNO cycle. The direct method with RIB of ^{18}F was applied for studies of the stellar reaction $^{18}\text{F}(p,\alpha)^{15}\text{O}$ ⁵⁸⁻⁶⁰⁾. This process is important for burning of ^{16}O to ^{15}N and also for burning of ^{18}F in ONeMg novae. The rate will affect the production of nitrogen in novae⁶¹⁾.

Critical reactions along the high-temperature rp-process

The high-temperature rp-process takes place most typically at X-ray burst, where the accreted hydrogen, from the accompanying main-sequence star, burns explosively on a surface of a neutron star. This process produces nuclides at around $A = 70 - 100$, but there are so many uncertain parts in this scenario to be clarified for nuclear physics. Nuclear physics information near the proton-drip line at $A = 70 - 100$ is still very scarce. As discussed in sec. II, there are four critical points that have to be investigated along the possible rp-process path⁶²⁾. The ignition process

FIGURE 4. The normalized proton yields as a function of the averaged ^{17}F beam energy in the target⁶⁴⁾. The heavy solid line is a fit to the data with three fit parameters: the normalization, the resonance energy, and the width of the 3^+ state. The thin solid line shows the excitation function expected if the only resonances in this region were the previously observed 1^- and 0^- states in ^{18}Ne . The dotted line shows the excitation function if the width of the 1^- state were 20 keV instead of the expected 0.1 keV.

of the high-temperature rp -process is considered to be a reaction chain of $^{14}\text{O}(\alpha, \text{p})^{17}\text{F}(\text{p}, \gamma)^{18}\text{Ne}(\alpha, \text{p})^{21}\text{Na}$. A beautiful and important result was obtained with the direct method for the ignition process. A missing 3^+ proton resonance⁶³⁾ was recently discovered using a RIB of ^{17}F ⁶⁴⁾. See Fig. 4. This was a long standing problem, as it could be an s -wave resonance, and thus it would enhance the reaction rate of the $^{17}\text{F}(\text{p}, \gamma)^{18}\text{Ne}$ reaction considerably. There is a 3^+ state at 5.3 MeV in the mirror nucleus ^{18}O , but the analog state was not known in ^{18}Ne despite of many experimental efforts⁶³⁾. The breakout reaction of this reaction sequence, $^{18}\text{Ne}(\alpha, \text{p})^{21}\text{Na}$, was also investigated at Louvain-la-Neuve using a ^{18}Ne beam, identifying some new resonances in ^{22}Mg ⁶⁵⁾.

The αp -process will play an important role under a high-temperature and high-density condition at relatively low-mass region, as mentioned in sec. II. This process should be investigated but only very few cases were studied so far.

Some works concentrated on the $^{21}\text{Na}(\text{p}, \gamma)^{22}\text{Mg}$ stellar reaction⁶⁶⁻⁶⁸⁾ in the last few years. Some new resonance were identified with a high resolution (p, t) reaction on ^{22}Mg at CNS⁶⁶⁾. This reaction is important in novae and also for ^{22}Na production, which is an interesting candidate of gamma ray observation, because the half-life of ^{22}Na , 2.6 y, could be long enough to be detected.

There are some experiments reported on the critical nuclei along the possible high-temperature rp -process. One is a study of the $^{56}\text{Ni}(\text{p}, \gamma)^{57}\text{Cu}$ reaction, which is a possible bottleneck around $A = 56$. The experiment was made by measuring the decay width of the analog state by the direct transfer $^{56}\text{Ni}(\text{d}, \text{p})^{57}\text{Ni}$ reaction using a ^{56}Ni beam accelerated. A better estimate for the reaction rate was obtained, which is about 10 times larger than the previous estimate⁶⁹⁾ for the flow rate that goes through the bottleneck at $A = 56$.

The half-lives of nuclei close to the proton drip line are also important to determine the flow rate especially at waiting points and bottlenecks, since the flow will be very much influenced by their properties. The time scale of the explosion would be also determined largely by these nuclei. The flow would terminate there, or the flux would be much reduced there. There are two measurements reported for such nuclei. One is ^{70}Kr that could be reached only by the 2p -capture process from ^{68}Se ⁷⁰⁾. The measured half-life is smaller than the value used previously in the explosion model, and thus giving a reaction rate that runs through this nucleus faster by a factor of 2.5. The half-life of ^{80}Zr was also determined experimentally to be shorter than thought before, suggesting more flux for the rp -process for heavier mass synthesis⁷¹⁾.

D Nucleosynthesis in Supernovae and the r-Process

Low-energy radiative capture reaction study with laser-induced Compton-backscattering photons

Roughly a half of heavy elements is considered to have been produced by the r-process. This process requires a condition of high temperature and a high neutron flux to explain the r-process nuclei including U and Th, which are of great importance for cosmo-chronology. However, the astrophysical site for the r-process is not determined yet. The most plausible site is considered to be in the hot bubble in Type II supernovae⁷²⁻⁷⁴⁾, and another possibility discussed is a neutron-star mergers⁷⁴⁾. In Type II supernovae, due to the strong neutrino wind, the r-process could begin from ${}^4\text{He}$ together with neutrons, like an Fe seed in the classical r-process. The first process of this scenario is ${}^4\text{He}(\alpha, \gamma){}^9\text{Be}$ and ${}^4\text{He}({}^3\text{H}, \gamma){}^7\text{Li}$.

This reaction ${}^4\text{He}(\alpha, \gamma){}^9\text{Be}$ was investigated recently with an innovative method for the reverse reaction ${}^9\text{Be}(\gamma, \alpha\alpha){}^5\text{He}$ ⁷⁵⁾. High-quality photon beams of a small energy spread at a few MeV was obtained by laser-induced Compton back scattering (LC) from a high-energy electron beams, where the LC photon energy and the width can be changed by tuning the stored electron beam. The experiment was performed using the LC photon beam of a few MeV with a flux of about 10^4 photons/sec/mm² from the electron storage ring TERAS of the Electro-Technical Laboratory, Japan. The cross sections derived agree with the ones from other methods, indicating this method to be a powerful tool for nuclear astrophysics. This method should be compared with the Coulomb dissociation method discussed above, which uses virtual photons with possible complications inherent in high-energy heavy-ion reactions.

${}^{44}\text{Ti}$ production in supernovae

Several years ago, the half-life of ${}^{44}\text{Ti}$ was a big issue to estimate the amount of ${}^{44}\text{Ti}$ at the time of the supernova of CAS A, back 1680¹⁸⁾. There are many experiments reported, and they seem to converge to a value of 60 ± 3 y⁷⁶⁾. There are two experiments reported for the ${}^{44}\text{Ti}$ problem since then. One is a reaction study of ${}^{44}\text{Ti}(\alpha, p){}^{47}\text{V}$ which is a destruction process of ${}^{44}\text{Ti}$ ⁷⁷⁾, and the other one is the ${}^{40}\text{Ca}(\alpha, \gamma){}^{44}\text{Ti}$ reaction which could be the main production process⁷⁸⁾. The total cross sections of the ${}^{44}\text{Ti}(\alpha, p){}^{47}\text{V}$ reaction was measured at $E_{\text{cm}} = 6 - 9$ MeV, using a radioactive beam of ${}^{44}\text{Ti}$. The cross sections were roughly a factor of two larger than the previous calculation. The main production process, ${}^{40}\text{Ca}(\alpha, \gamma){}^{44}\text{Ti}$, was investigated by an activation method. A gas target of ${}^4\text{He}$ was bombarded by a ${}^{40}\text{Ca}$ beam, and the amount of ${}^{44}\text{Ti}$ production was determined by the AMS method. The resonance strength of about 10 meV can be measured, because the sensitivity of the AMS is 10^{-14} .

Coulomb fission process for neutron-rich nucleus production

A new production method of very neutron-rich nuclei was developed that uses the Coulomb fission process of an accelerated ${}^{238}\text{U}$ beam at 780 MeV/u at GSI. The very neutron rich "doubly closed shell" nucleus, ${}^{78}_{28}\text{Ni}_{50}$ was produced and identified for the first time, together with many new neutron-rich nuclides⁷⁹⁾. Since the fissioning nucleus ${}^{238}\text{U}$ passed through the strong Coulomb field, the fission fragments were ejected mostly to the very forward angles, and thus they were collected efficiently. Further experimental information such as the half-lives and the masses are needed for ${}^{78}\text{Ni}$ and the nuclei nearby to clarify whether the r-process really passes through. Of course, to determine the reaction rate of each process on the r-process, one needs to know the detail of the nuclear structure, or one needs to know the neutron-capture cross section. New experiments using this method will expand the frontier of knowledge in neutron-rich nuclei toward the possible r-process pathway. The masses and the half-lives of the new isotopes will be determined using a storage ring technology, which is discussed next.

High-precision mass measurements with a storage ring

Heavy ion storage rings have various capabilities for studies of nuclear physics and nuclear astrophysics. Basic properties of unstable nuclei can be studied precisely in a storage ring. There are two kinds of experiments reported that used a heavy ion storage ring in the last decade.

Half-life measurements were demonstrated using the experimental storage ring (ESR) at GSI^{80,81)}. The half-lives of the bound state beta decays of ${}^{163}_{66}\text{Dy}^{66+}$ and ${}^{187}_{75}\text{Re}^{75+}$ were successfully measured. Specifically, the latter one has an important significance to the cosmo-chronology⁸²⁾.

Very recently, a beautiful experiment was reported that determined the masses of many unstable nuclei of $56 < Z < 85$, whose masses were not known before⁸³⁾. A 930-MeV/u ${}^{209}\text{Bi}$ ions were fragmented on a thick Be target.

FIGURE 5. Schottky spectra of stored and cooled fragments measured for 160 s with $B\rho = 7.1$ Tm at the Experimental Storage Ring of GSI⁸³⁾. The masses were determined for the first time for the isotopes indicated, using the known masses of the nuclides indicated by the bold letters.

and the fragments were stored in the ESR. The circulating ions were detected by the Schottky noise, which gives precise mass information of each nuclide. Figure 5 displays Schottky spectra that show many new masses as denoted. The mass resolving power achieved was nearly 10^7 . They clearly separated the isomeric state at 316 keV from the ground state in ¹¹⁷Te. Mass measurements of neutron-rich nuclides at the possible r-process path should be of great interest, as it will clarify roughly the pathway of the r-process.

Detailed nuclear properties will be further investigated using internal targets or colliding beams such as electrons and photons in a storage ring of RI beams. These new progress will be realized in the RIBF project at RIKEN, and RIA proposal in the USA.

IV OUTLOOK OF THE FIELD

Astronomical observation of isotopes has opened a new era for nuclear astrophysics. They directly indicate the stellar nuclear reaction responsible for the production, and also tell us exact amount of unstable nuclides produced in the event. These give stringent information for understanding the stellar event. In the last few years, there are many interesting experimental and theoretical works made. The discussion here was made mainly for the experimental development with RIBs with a specific emphasis on new technological developments.

The ISOL-based RIB facility at ORNL started operation and made successful runs for nuclear astrophysics for a problem of the extended CNO cycle. This is the first extensive ISOL-based facility. A thick target method has been developed for efficient direct-method measurement with low-energy RIBs. Another interesting development is a direct method using a few-MeV photon beams of well defined energies, obtained from laser-induced Compton back scattering from high-energy electron beams, to study the astrophysical capture reactions such as (p,γ) and (n,γ) reactions in the reverse reactions. This should be a promising probe for nuclear astrophysics although a

technological development is required to increase the photon beam intensity. It should be very interesting to use this method in the RIB storage ring projects in the future.

Since nuclear phenomena in the Universe involve various aspects of nuclear physics that are not fully investigated yet, one may study the problem by different approaches. Although the direct method is the most powerful tool to investigate the reaction rates, there is a wide window of opportunity for indirect methods with unstable nuclear beams as well as with stable beams, which are not accessible with the direct method in practice.

At the intermediate and high-energy heavy ion facilities, nuclear properties such as masses and half-lives of the relevant nuclei were investigated with high precision at the heavy ion storage ring ESR. Some specific problems were also investigated uniquely at high energies like the bound state beta decay process, which is of importance for cosmo-chronology. There are also efficient simulating methods developed such as the Coulomb dissociation method and the ANC method. Particle transfer reactions at a few – 10 MeV/u were shown to be useful to derive the direct capture cross-sections by the ANC method.

Nuclear astrophysics has expanded in the last decade in particular through the advent of RIBs for explosive nuclear burning. New RIB facilities both of ISOL type and in-flight type are coming up in TRIUMF, MSU, GANIL, RIKEN, and so on. They will advance the experimental study of nuclear astrophysics with wider steps. Although direct measurements with RIBs were made mostly at the ISOL-based facilities, there is a possibility for low-energy in-flight separator facilities such as CRIB, a new facility built at CNS, under the CNS-RIKEN joint project⁸⁴⁾. Because of the recent development of ion source technology one may produce RIBs of reasonably good energy resolution with high intensity of about 10^{8-9} aps for nuclei near the line of stability at relatively low energies. This method would be very useful for small-scale accelerator facilities.

The second phase of the RIBF project at RIKEN and possibly the RIA project in the USA will have much greater capabilities in the future, where heavy ion storage rings will be installed in addition to fragment separators. They may provide research opportunities of fundamental physical parameters needed for heavy element synthesis in the r-process. The RIBs will be merged in the ring with stable nuclear beams as well as with an electron beam. These will provide not only information on nuclear properties but also new possibilities for indirect methods in nuclear astrophysics.

Most part of the research discussed here is clearly in an early stage, and much more effort is awaited to understand various astronomical events and the evolution of the Universe as well as the origin of the elements. New RIB facilities and new methods to enhance the efficiency and the resolution will open a new era for nuclear astrophysics in the coming years.

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