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Experimental determination of astrophysical reaction rates with radioactive nuclear beams

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This paper is dedicated to the memory of our friend and the world-leader of RIB science, Jerry Garrett who made a great contribution to the promotion of RIB science.

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1. Introduction

Nuclear astrophysics is one of the basic and indispensable fields for the science of the Universe. Nuclear reactions play an important role in the evolution of the Universe. The large amount of energy stored in atomic nuclei plays a decisive role in the evolution of the Universe [1–3]. 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. The environmental conditions for nuclear burning are dependent on the stellar sites, which characterize the scenario of burning such as the CNO cycle in the hydrogen burning stage in massive stars. Recent progress is summarized for instance in Refs. [4–10].

Observation of elemental abundance, on the other hand, provides important clues for understanding not only various phenomena but also the evolution of the Universe. Detailed abundance ratios have been observed optically for several novae, where heavy elements such as Si and S were observed, which should have been produced in the explosive nucleosynthesis [11]. These allow us to investigate the nucleosynthesis in novae quantitatively. Investigation of isotopic anomalies in meteorites [12,13] also provides interesting information for understanding explosive nuclear burning. Recently,

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X-ray observation from satellites provides the elemental distributions in the outbursts of supernovae [14]. This wealth of observational data allows us to study nucleosynthesis and hence the mechanism of such an explosive event. The solar abundance composition of heavy elements beyond iron is suggesting at least two types of scenarios for the heavy-element nucleosynthesis. One is the rapid neutron capture process (r-process), and the other one is the slow neutron capture process (s-process). There are other complications for heavy element synthesis such as the p-process that is considered to be responsible for production of isolated neutron-deficient nuclei in heavy mass regions. Observation of elements in the oldest objects has a chance that one might study them to understand the primordial nucleosynthesis. When one discusses inhomogeneous Big Bang models [15], one may study the models from the nucleosynthesis point of view. There, both astronomical observations [16] and laboratory experiments, on ^{8}Li(α,n)^{11}B [17–19] for instance, provide stringent tests for the Big Bang models.

Specifically, a new fact realized more widely in the last decade is that observations of isotopic abundances, not only of elements, are very crucial and restrain the models very tightly. Observed nuclear gamma rays [20,21], such as the gamma decay of ^{44}Ti and also the isotopic anomalies in meteorites [12,13] require explanation of the isotopic ratios. Recent observations with high-resolution optical telescopes now also provide isotopic ratios from isotopic shift measurements [22]. Isotopic information has much more importance as it is directly connected to the nuclear reactions.

Research activities in nuclear astrophysics have expanded very rapidly in the last decade because a variety of radio isotope beams (RIB) have become available, which give us a unique opportunity to study the reaction processes involved in explosive burning phenomena in the Universe [4–10]. As mentioned above, various characteristics of nuclear burning define the scenario of nucleosynthesis [2,3]. 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, which is depicted in Fig. 1 [8]. In stellar evolution, there are several sites that have such high-temperature and high-density conditions, which involve unstable nuclei. Here, there are a few important astrophysical problems to be investigated. They include the mechanisms of (i) ignition and (ii) termination processes, which are dependent on the nuclear structure of some specific relevant nuclei. Along the nucleosynthesis pathways, there are some critical reaction steps that would determine the pathway. They are called (iii) bottlenecks and (iv) waiting points. When the nucleosynthesis flow reaches the proton drip line, for instance, there is no way to go further by the (p,γ) reaction. Then, the nucleosynthesis flow needs to wait for the beta decay to find the next (p,γ) reaction path. The same situation can be seen if the (p,γ) cross section is very small, or the reaction Q-value is small so that the inverse reaction becomes important. Sometimes it often has to wait for another beta decay to find the pathway of the next capture reaction. In this case, the last beta decay before the next capture reaction primarily defines the waiting time of the flow. This is called the waiting point. This first capture reaction after the waiting point is also sensitive to the flow rate of the nucleosynthesis, which is called the bottleneck. Since these points are located close to the proton drip line, the level

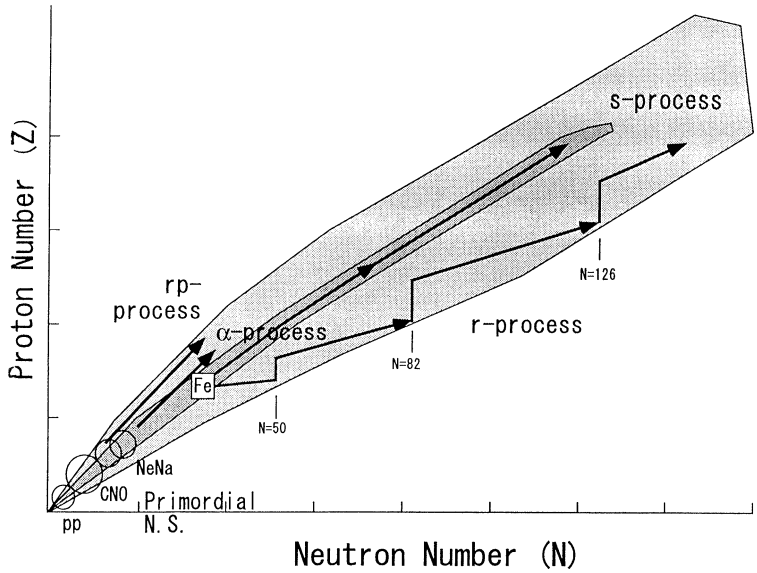

Fig. 1. Typical nucleosynthesis flows of important scenarios for nuclear astrophysics on the nuclear chart.

density at the excitation energy region of interest is low as the threshold energy is low, and the reaction path proceeds through isolated resonances and/or direct capture. This implies precise experimental efforts are needed for studying explosive nucleosynthesis especially on these four points. 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.

In this article, we review experimental methods for determining reaction cross sections at astrophysical energies and their significance, and touch on some new aspects that may lead to new development in nuclear astrophysics. In principle, there are two ways to approach the problem experimentally, the direct method and the indirect methods. Although RIBs are available for many reactions of interest for explosive nucleosynthesis, we need to use both direct and indirect methods for practical reasons. For instance, when one investigates a proton capture reaction $A(\mathrm{p},\gamma)B$ $(= A + \mathrm{p})$, one can study the reaction using a RIB of A on a hydrogen target at the stellar energy. One may investigate first the property of a resonance of $A + \mathrm{p}$, such as E_r, J^π and Γ_tot, and then the cross sections by measuring either the gamma ray or the particle B at the stellar energy. This is called the direct method. All others are called indirect methods. If there is a proton resonance in the Gamow energy region, it would enhance the reaction rate considerably, depending on the property of the resonance. If one investigates the reaction with the RIB of A, there are usually two experimental difficulties for the direct method. The (p,γ) cross sections are usually quite small at the stellar energies and the intensities of RIBs are much less than stable nuclear beams. The difficulty increases when one investigates the reactions along the r-process, where both the target nuclei and neutrons are unstable. One needs to study the

reaction process, with the present technology, using indirect methods, which are discussed in Section 5.

Several nuclear physics parameters have to be determined to deduce the reaction rates for nucleosynthesis as well as the parameters in the stellar site of interest [23,24]. The Gamow energy, which is an optimum temperature for burning, is determined by the temperature of the astrophysical site and the nuclear system, as is given by Eq. (3) in the following section. It is defined for charged-particle induced reactions primarily by two terms, the penetrability of the reaction and the Maxwell–Boltzmann distribution of the site. The Gamow energy is roughly several times larger than the temperature ($E = kT$) of the site. Therefore, the primary interest here is to clarify the nuclear structure in this energy region. If there is a resonance in the region, the reaction rate could be considerably enhanced depending on the decay property of the resonance.

The method to be used for the nuclear astrophysics experiment changes depending on the type of RIB facility and also on the beams available. There are some simulating methods developed for deducing the reaction rates in the last decade. Coulomb dissociation methods at intermediate and high energies may provide reverse capture cross sections at low energies in some cases. Similarly, direct particle transfer reactions for bound states provide the particle capture cross sections of the direct capture process. The direct particle transfer reactions could also provide, for transitions to unbound states, the particle decay width of the resonance. In Section 5.6, a new instrumentation, heavy-ion storage rings, is discussed that has made a great breakthrough for studying precisely masses and half lives of the nuclei far from the line of stability. These masses and half lives will provide important basic information for estimating very roughly the pathway of explosive nucleosynthesis, although detailed nuclear structure information is needed eventually for determining the reaction rate of interest and the pathway.

2. Physical quantities for reaction rates

The temperature range we are discussing here is around $T_9 = 0.01$–3, that corresponds to 1–a few hundred keV in energy, where we use a convention of temperature defined by $T_9 = T/(10^9\ \mathrm{K})$. Here, we consider a particle capture reaction $A(x,\gamma)B$. Although the effective temperature for nucleosynthesis for charged particles is a few times larger than this energy as discussed below, it is still below the Coulomb barrier. Therefore, many nuclear reactions in astrophysical events proceed via compound reaction mechanism. However, since explosive events involve nuclei near the drip line, as mentioned above, the relevant level density becomes small and the statistical model is not applicable, specifically in the light mass region. Thus, precise experimental data are needed of radioactive nuclei for understanding explosive phenomena in the Universe. This is the main theme of the present paper.

Here, we assume a case of single, narrow resonance for the process. The nuclear reactions between charged particles at low energies are dominated primarily by the Coulomb force. The astrophysical S-factor $S(E)$ is often used for convenience, which is defined as follows:

$$\sigma(E) = \frac{S(E)}{E} \mathrm{e}^{-2\pi\eta}, \tag{1}$$

where the strong energy-dependent terms, the penetrability through the Coulomb barrier and the geometrical factor, are explicitly included, giving roughly a constant value for the S-factor if there is no resonance. 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 follows [23]:

$$\langle \sigma \upsilon \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \mathrm{e}^{\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right)} \mathrm{d}E, \tag{2}$$

where $b = 0.989 Z_x Z_A \mu^{1/2}$ MeV$^{1/2}$. The second term in the bracket is from the Coulomb penetrability, and the first term is from the Maxwell–Boltzmann distribution. In the absence of resonances, the integrand in Eq. (1) exhibits a broad peak that defines the most relevant energy range for charged particle reactions contributing to the stellar rate. The peak energy E_G, which is called Gamow energy, is given by

$$E_\mathrm{G} = \left(\frac{bkT}{2}\right)^{2/3}. \tag{3}$$

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

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \omega \frac{\Gamma_x \Gamma_\gamma}{(E - E_\mathrm{R})^2 + (\Gamma_\mathrm{tot}/2)^2}. \tag{4}$$

The resonance contribution for the reaction rate is thus written as follows:

$$\langle \sigma \upsilon \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega\gamma \mathrm{e}^{-\frac{E_\mathrm{r}}{kT}}, \tag{5}$$

where

$$\omega\gamma = \frac{(2J_\mathrm{r} + 1)}{(2J_x + 1)(2J_A + 1)} \frac{\Gamma_x \Gamma_\gamma}{\Gamma_\mathrm{tot}}.$$

Here, $\omega\gamma$ is called the resonance strength and $\omega = (2J_\mathrm{r} + 1)/((2J_x + 1)(2J_A + 1))$ 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 particle width Γ_x is much larger than the gamma width Γ_γ, the resonance strength is roughly proportional to the gamma width, which is often the case for the explosive nucleosynthesis, whereas it is proportional to Γ_x at low temperatures in hydrostatic nucleosynthesis. The reaction rate involves mainly four terms as follows:

$$\langle \sigma \upsilon \rangle = \langle \sigma \upsilon \rangle_\mathrm{res} + \langle \sigma \upsilon \rangle_\mathrm{direct} + \langle \text{res-dir} \rangle_\mathrm{int} + \langle \sigma \upsilon \rangle_\mathrm{tail}. \tag{6}$$

The interference term of the resonance and the direct terms are also important. The contribution at around the Gamow energy given in Eq. (3), the remaining contributions of tails of other resonances, and the interferences between resonance tails are included in the tail term. The direct term can be obtained by extrapolating the cross sections off

resonance. One may also use, for direct capture reactions, the Asymptotic Normalization Coefficient method, which is discussed in Section 5.3.

In the experimental approach, one needs to know first if there are any resonances in the energy region of interest. New levels will be identified by the direct or indirect methods as discussed in Section 5. The reaction rate in Eq. (6) can be approximately determined from the resonance strength that can be determined by indirect methods. Of course, the best is to measure the reaction cross sections directly, because the cross sections of the direct measurement include not only the resonance contribution but also all other contributions in Eq. (6).

The reaction network calculations are made by solving a series of rate equations,

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \sum_{n_j n_k} n_j n_k \langle \sigma \upsilon \rangle_{jk \to i} - \sum_{n_m} n_i n_m \langle \sigma \upsilon \rangle_{i+m \to n} + \frac{n_h}{\tau_h} - \frac{n_i}{\tau_i}, \tag{7}$$

using the reaction rates in stellar models or Big Bang models. Here, n_x is the number density of particle x, and τ_y is the life time of nucleus y. The nucleus i of interest is produced by a collision of $j + k$ and destructed by a collision of $i + m$. The number of nuclei i also changes by the beta decays. It is clear from Eq. (7) that one needs to know the life time of the relevant nuclei. Here, the life time is not the one measured in the laboratories as all atoms are highly ionized in the high-density and high-temperature sites. To be precise, one needs to include other contributions such as reactions induced by photons and neutrinos as well.

3. Radioactive nuclear beams for experiments

Available nuclear species as a beam depend on the method of production, and the beam quality also depends on it. As discussed in other articles in this book, there are two types in production method of Radio Isotope Beams (RIBs) in principle. They are [25]:

(1) ISOL method with a post accelerator,

(2) in-flight method using heavy ion beams.

The RIB intensities, in general, can be obtained by a transformation factor of about 10^{-3} or less of the primary beam intensity. The ISOL method uses high-energy light ions or neutrons to produce radioisotope nuclides abundantly using target fragmentation processes with a thick target, an on-line ion source to extract the radioactive nuclides and to ionize them, and a post accelerator to obtain RIBs. Thus, this method provides, in principle, a high-intensity and high-quality RIB, but it is limited to nuclei of relatively long half lives ($\gtrsim 0.1$ s) because of the process time of extracting the isotope from the production target. The ISOL technique has a strong chemical selectivity depending on the property of the target material and the transport line to the ion source. This target and ion source technology is a key element that needs to be developed for the ISOL method. Nuclides of half life longer than a few hundred millisecond can be produced with the present technology. These characteristics of the method roughly define the research region on the nuclear chart and the methods to be used in the experiments. This shortcoming of

the ISOL method can be reduced through a new development, such as the proposed gas-trapping method [26], that shortens the process time at the target/ion source and increases the total efficiency. The beam quality of RIBs by the ISOL method is, of course, better than those of the in-flight method as the ISOL method uses an accelerator from zero velocity, the same as for ordinary stable nuclear beams.

The in-flight method has been widely and actively used in many heavy-ion laboratories in the world. They mostly use heavy ion beams of intermediate and high energies, and produce RIBs of quite short half life ($\lesssim 1$ μs) using projectile fragmentation processes. Therefore, the RIBs obtained have a certain spread in energy of the order of the Fermi energy of the nucleons in the projectile. Because of the thick targets available for production at intermediate and high energies, high intensity RIBs can be obtained. Various experimental methods were developed that have large detection efficiencies with high energy resolutions. Because of low intensity of the RIBs in general as compared to stable beams, the detection system needs to have large solid angles. The beam particles are often identified one by one to assure beam-particle identification as well as to determine the beam energy and the incident angle. This method is applicable up to around 10^6 pps. The detector systems include multisegmented elements. A detection method using coincidence measurements of the ejected particles, is also used that enables a good excitation energy determination that is free from the RIB energy spread to the first order. A typical example is the Coulomb dissociation method. The RIBs produced with this method cannot be applied easily to the direct-method experiment of nuclear astrophysics, which requires beam energies of a few MeV or less. The beam quality becomes worse in energy and angle due to a thick degrader to reduce the beam energy from a few tens MeV/u down to a few MeV. As a result, the beam intensity per energy bin becomes very small.

Very recently, a new facility was built using the concept of the in-flight method for low energy RIB production [27]. This facility uses high-intensity heavy ion beams at low energies of up to about 10 MeV/u for production. This method was not considered so seriously before because the effective target thickness usable for RIB production is too thin. However, recent development of ion source technology for heavy ions enables one to produce RIBs of reasonably high intensity. This facility has been installed at the Center for Nuclear Study, University of Tokyo (CNS), under the CNS–RIKEN joint project. It is the first extensive installation of this type, which is a double achromatic spectrometer system including a water-cooled high-power Faraday cup of a few kW, a windowless gas target system, and a Wien-filter to purify the RIBs. One may obtain RIBs of 10^{8-9} aps for some nuclei near the line of stability if one uses a target of 1 mg/cm^2 and a heavy-ion beam of 1 pμA. This method should be very useful for small scale laboratories because it does not require any development like the ion source work for the ISOL method. The RIBs using this method can have reasonably good beam quality at around 10 MeV/u, where well established methods of nuclear spectroscopy can be applied to deduce spectroscopic information. Particle transfer reactions can be used for determining the direct capture cross sections and also the particle decay widths, which are discussed in Section 5. Nuclear structure studies with in-beam gamma ray spectroscopy in the present energy region are also very useful, because nuclear fusion reactions have large cross sections.

Since nuclear phenomena in the universe involves 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, it is not practical in many cases. Therefore, there is a wide window of opportunity for indirect methods.

At the intermediate and high energy heavy ion facilities, nuclear properties such as masses and half lives of the relevant nuclei, or identification of new resonances can be studied with a beam intensity of as low as 10^4 aps. There are also efficient methods developed at high energies such as the Coulomb dissociation method. Some specific problems can be investigated uniquely at high energies like the bound state beta decay process.

The research capability using RIBs are discussed in the following sections.

4. Direct measurement of astrophysical cross sections

As discussed in the last section, the best way to determine the reaction rate is to measure directly the reaction cross sections at the stellar energies, because the direct method includes all the terms in Eq. (6). The reaction rate of the $A(x, y)B$ reaction can be derived best by the direct method except for the electron screening effect [23] which is different in the laboratory from the one in astrophysical sites.

There are two ways for measuring directly the cross sections of $A(x, y)B$. One is to measure immediately the reaction product or products, y and/or B. It can be also measured by the reverse reaction $B(y, x)A$. The other one is to measure the subsequent decay from the product B in the $A(x, y)B$ reaction, which is the direct evidence of the reaction. For instance, if the nucleus B β-decays to a state in nucleus C, which subsequently decays through alpha particle emission, this alpha decay with a specific energy and with a certain half-life will be a measure of the reaction cross section of $A(x, y)B$. However, the reaction time of $A(x, y)B$ is not directly connected to the alpha detection time. This possibly introduces higher background in the measurement.

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 has 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.

An experiment adopting the inverse kinematics was already made [28] for a study of $^{12}C(^4He, \gamma)^{16}O$ in the He-burning stage, which is a critical stellar reaction that influences

seriously the stellar models [29,30], although this stellar reaction does not involve any unstable nuclei. This method made it possible to measure the cross sections less than 1 pb/sr by measuring both the gamma and ^{16}O particle in coincidence.

As was discussed in Section 3, RIBs which become available depend on the type of facility. Very short-lived RIBs are available at the in-flight separators, whereas ISOL-type facilities provide RIBs of high quality such as the beam energy resolution at low energies. Thus, experiments with the direct method are suited at the ISOL-type facilities, whereas several indirect methods can be studied at the in-flight type facilities.

4.1. Activity measurements

If one measures the subsequent decay of the residual nucleus B from the reaction $A(x, y)B$, the decay yield of the nucleus B gives the reaction cross sections of $A(x, y)B$. After bombardment of A with the beam x or vise versa, the number of B to be produced is [23]

$$N_r = \sigma(E)\mathrm{e}^{-\lambda t_1} \int_0^{t_1} I(t)N(t)\mathrm{e}^{\lambda t}\,\mathrm{d}t, \tag{8}$$

where $1/\lambda$ is the lifetime of nucleus B, $I(t)$ is the beam current and $N(t)$ is the target thickness. Here, the production rate of the activity $P(t)$ is given as $P(t) = \sigma(E)I(t)N(t)$. If the residual nucleus B decays subsequently to $z + C$ following a beta decay, one can measure the reaction cross sections by detecting either z or C. In this case, the decay is characterized by a specific particle z and the decay energy. This method has a great advantage that one can make a measurement with large efficiency under good detection condition that has less background by avoiding the beam bursts. However, if one applies this method to a reaction study of extremely small cross sections, it would suffer from natural radioactivity background. One can attack this problem by detecting the two particles, z and C, in coincidence. The disadvantage of this method is that the subsequent decay particle arrives with a time delay due to the half life of the nucleus B. One needs also to assure that all of the nuclei B produced remain in the target for the activity measurement. Of course, the background originating from the contamination in the beam or in the target should be also carefully checked. Therefore, the activity measurement should be used with much care, although this method is a convenient one. The results should provide an upper limit for the problem.

Here for example, we may consider the reaction study of ^{7}Be(p, γ)^{8}B, which is crucial for the solar neutrino problem [31–38]. Many reaction studies were made previously using a radioactive target of ^{7}Be [32–35,37]. The prompt gamma-ray measurement from this reaction is quite difficult since the radioactive target produces more than 10^7 gamma rays on the detector in addition. Instead of measuring the direct γs from the reaction ^{7}Be(p, γ)^{8}B, one may detect the alpha particles from the decay of the excited states in ^{8}Be following the beta decay of ^{8}B(g.s.), as shown in Fig. 2. A thin silicon detector was used for measurement of the decay alphas thus minimizing the energy deposit by the beta rays. As discussed in

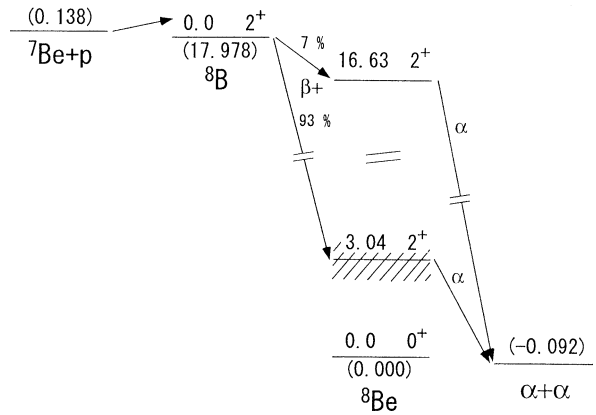

Fig. 2. The ^{7}Be(p, γ)^{8}B reaction and the subsequent decays. Here, the reaction cross section can be measured by the activation measurement with detecting the alpha decay of ^{8}Be.

the following subsection, the reaction study with inverse kinematics, ^{1}H(^{7}Be, γ)^{8}B offers a better condition that the detector does not see the intense gamma source of ^{7}Be.

As for a current problem in the explosive hydrogen burning [39] (rp-process) problem [8, 39–42], a crucial stellar reaction is ^{19}Ne(p, γ)^{20}Na, which is the breakout point from the hot-CNO cycle to the rp-process. Especially, the 2.654 MeV state in ^{20}Na, which is the first excited state above the proton threshold, would play a decisive role for the synthesis [41]. This reaction was investigated by several methods, but only an upper limit has been set experimentally [43–47]. This is probably due to a small gamma width, and thus the yield of the ^{19}Ne(p, γ)^{20}Na reaction is very small. Since the detection efficiency is also small for the gamma detection, the activation method was applied for the measurement to increase the detection efficiency [47]. Here, the specific alpha decay to ^{16}O(g.s.) from the 7.424 MeV state in ^{20}Ne, following the beta decay of ^{20}Na(g.s.)($\beta^+\nu$), was measured. The branching ratio of the beta decay to this state is known to be 16%. This decay rate should be proportional to the cross section of interest. In the experiment, the alpha decay was not clearly observed. Instead, the spectrum was dominated by the background of natural radioactivities. An upper limit of 18 meV was set for the gamma width of the 2.654-MeV state.

This method should be very useful, but needs to be improved concerning background.

4.2. In-beam measurements

The excitation 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. The direct-method studies have been made for many years using high-intensity stable nuclear beams for the problems of hydrostatic nuclear burning. Excitation functions were measured by changing the incident energy step by step. The detailed experimental techniques and methods for stable beam experiments are described in Ref. [23].

When one studies nuclear reactions that involve short-lived nuclei, which is often the case for explosive nucleosynthesis, one needs to use unstable nuclei as a beam. Thus, a thick target method [48] with a beam of A will be applied, as discussed above. The yield curve $Y(E)$ 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:

$$Y(E) = I(E) \int_{E-\Delta E/2}^{E+\Delta E/2} \frac{\sigma(E_i)}{\varepsilon(E_i)} \, \mathrm{d}E_i, \quad E = E_1 - E_2, \tag{9}$$

where $I(E)$ is the number of the beam particle A, and $\varepsilon(E_i)$ 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 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 the energy loss of x is small in the target material. This is just a process scanning the reaction with varying the relative energy. Thus, the excitation functions $\sigma(E)$ of elastic scattering of $x + A$ can be obtained very simply from a singles energy-spectrum by the thick target method.

To make a scan, the RIB of A bombards a thick target of x, and the recoil nucleus x should be measured at forward angles. As the kinetic energy of A decreases in the target, A reacts with other target nuclei x at a less kinetic energy. The recoil particle x carries the information about the resonance parameters like the width and kinetic energy at the resonance. The 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. Thus, the precise excitation function 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 carry out a high-resolution measurement. 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.

Fig. 3 shows an example of the thick target method, where the energy spectra of the recoil protons from $^1\mathrm{H}(^{19}\mathrm{Ne},\mathrm{p})^{19}\mathrm{Ne}$ and $^1\mathrm{H}(^{19}\mathrm{F},\mathrm{p})^{19}\mathrm{F}$, detected at 0° with a thick polyethylene target [45,49], can be essentially identical to the excitation functions of elastic scattering of $\mathrm{p} + {}^{19}\mathrm{Ne}$ and $\mathrm{p} + {}^{19}\mathrm{F}$. In another case, a missing 3^+ proton resonance [50] was recently discovered by the same techniques using RIB of $^{17}\mathrm{F}$ [51]. This resonance could be an s-wave resonance, and thus will affect the ignition condition for the high-temperature rp-process [52], through a reaction chain of $^{14}\mathrm{O}(\alpha,\mathrm{p})^{17}\mathrm{F}(\mathrm{p},\gamma)^{18}\mathrm{Ne}(\alpha,\mathrm{p})^{21}\mathrm{Na}$.

The first successful experiment with a short-lived RIB to measure the reaction cross section was made by the direct method at Louvain-la-Neuve for the $^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}$ stellar reaction [53], which was a crucial reaction for determining the onset condition of the hot-

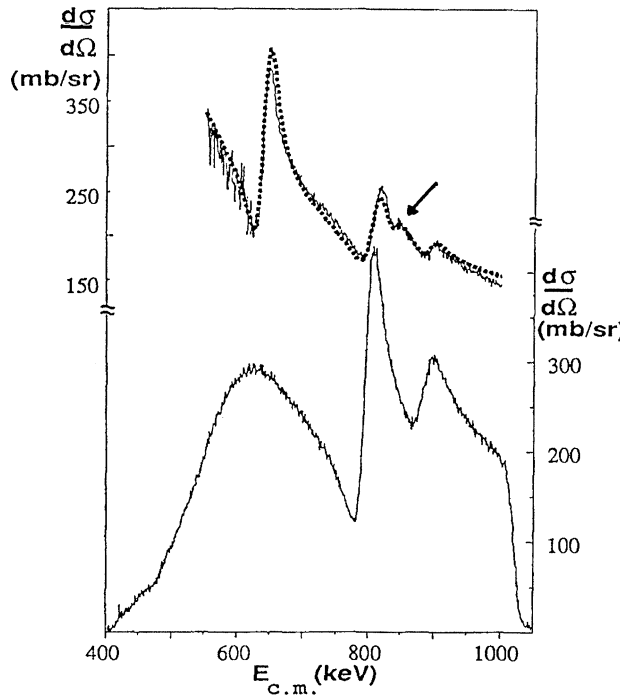

Fig. 3. Proton energy spectra measured at 0°, from the ^{19}Ne + p and ^{19}F + p scattering [49]. Here, a thick polyethylene target was used.

CNO cycle. The ^{13}N beam of 10^8 aps was used for the experiment, where radioactive nuclei ^{13}N were produced by the ^{13}C(p, n) reaction with a proton beam of a few hundred μA from a first cyclotron, ionized by an ECR ion source, and then accelerated by a second cyclotron, which worked simultaneously as a mass separator in the acceleration phase. A singles gamma ray measurement determined the gamma width $\Gamma_\gamma = 3.8 \pm 1.2$ eV for the 1^- resonance at 5.173 MeV, which is 527 keV above the proton threshold.

Another success of determining the stellar reaction rate by the direct method with RIB is ^{18}F(p, α)^{15}O [54–56]. 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 novae [57].

For nuclear astrophysics experiments with RIBs, it is very important to measure the heavy partner B, as mentioned earlier. Detection of heavy ions at low energy have inherently less background than gamma ray detection. Here, we consider a proton capture reaction ^{1}H$(A, B)\gamma$ in inverse kinematics. Mass separators are the best suited for this purpose, and thus many laboratories working for nuclear astrophysics have such a separator. Detection of heavy ions will be contaminated much less than gamma detection. However, if one measures the nucleus B alone, one needs to have a high beam-suppression factor of the mass separators mainly because the cross section of interest is very small. One such successful experiment using an unstable nuclear beam is reported for the study of ^{7}Be(p, γ)^{8}B at Naples [58,59]. They used a RIB of ^{7}Be which was produced in Karlsruhe,

Germany and LLN, Belgium and transported to Naples. A $^{7}Be^{4+}$ beam was obtained from a sputter ion source and a Tandem accelerator, and impinged on a window-less gas target of ^{1}H. The reaction products ^{8}B were identified in a mass separator complex. Here, the detection efficiency is very high, nearly 100% due to focusing of the inverse kinematics of the $^{1}H(^{7}Be,^{8}B)\gamma$ reaction. However, since this is basically a singles measurement, the analyzer system needs to have an extremely high background suppression. It consists of magnetic elements and a Wien filter. It requires high vacuum as well to minimize the scattering of the beam with the residual gas. A gas ion chamber detector was used at the focal plane, which can identify the particles unambiguously. Here, the beam suppression factor of about 10^{-10} was achieved. It is an interesting challenge to realize a mass separator system with an extremely good beam suppression. In addition, if one measures the gamma rays from $^{1}H(^{7}Be,^{8}B)\gamma$ in coincidence, it will reduce further the background. However, the detection efficiency will decrease simultaneously. Therefore, the detector system should be optimized considering each element and the total efficiency.

There are only a few cases where the reaction rate is determined in the Gamow energy region. One of the major sources of background is cosmic rays in laboratories on the surface of the earth. To measure extremely small cross sections directly at the energies of interest for charged-particle induced reactions, one has to try to eliminate the natural background in the laboratory 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 laboratory [60,61]. The $^{3}He(^{3}He, 2p)^{4}He$ 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 ^{3}He away from the branch that produces ^{8}B, which is the source of high energy neutrinos to be detected at SuperKAMIOKANDE. Thus, if the $^{3}He(^{3}He, 2p)$ reaction rate is higher than accepted at present, the flux of the high-energy neutrinos will be reduced accordingly. Currently, the experimental uncertainty needs to be reduced to conclude the problem. A similar underground laboratory has been established for investigating low-energy nuclear reactions of astrophysical interest at Oto in Osaka [62].

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.

Another important direct method being developed is reverse reaction studies with real photon beams for radiative-capture reactions $A(x,\gamma)B$. High-quality photon beams of small energy spread at a few MeV can be obtained by laser-induced Compton back scattering (LC) with high-energy electron beams, where the LC photon energy and the width can be changed by tuning the electron beam. This provides high quality, high intensity photon beams as compared to the traditional photon sources such as photons by bremsstrahlung. This is a new development being made with stored, high-energy electron beams and lasers. These photon beams of a few MeV should be very powerful for studying radiative capture reactions in the reverse reaction, $B(\gamma,\chi)A$. So far, there are not many

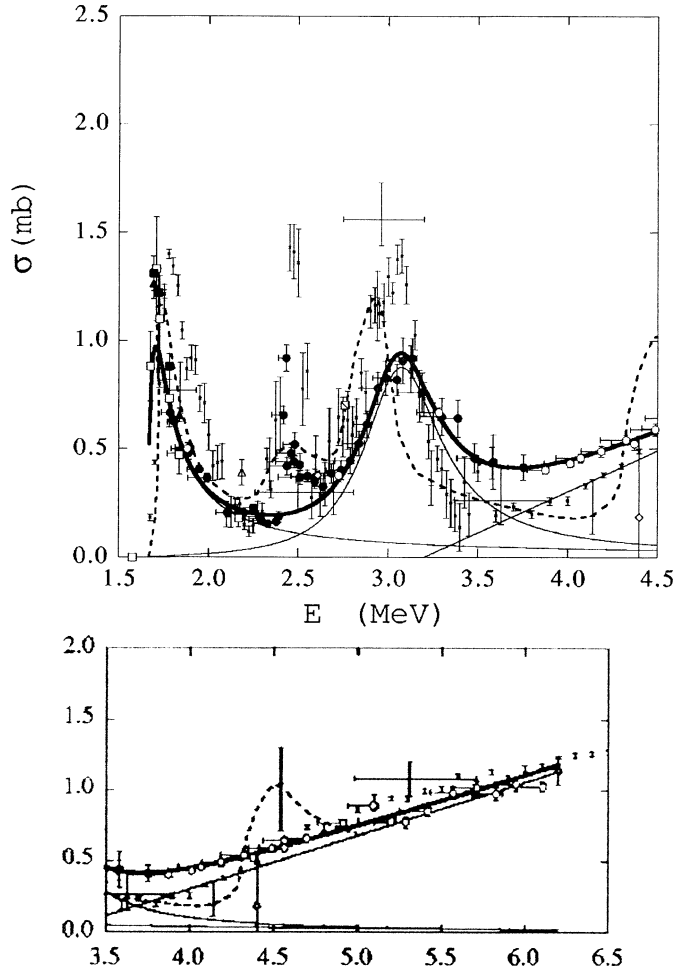

Fig. 4. The cross sections of the ^{9}Be(γ,n)$\alpha\alpha$ reaction, measured with the polarized LC photons (solid circles) and the unpolarized LC photons (open circles) [63], compared with those obtained by other methods.

application of this beam to nuclear astrophysics because of the limited beam intensities of about 10^5 photons/s. One beautiful example [63] using this method was reported recently on the study of $\alpha(\alpha n,\gamma)^9$Be, which is considered to bridge the mass gaps at $A = 8$ and 9 at the initial stage of the r-process in type II supernovae. See Fig. 4. The experiment was performed in the inverse reaction, ^{9}Be(γ,n)$\alpha\alpha$ using a photon beam of about 2.1 MeV with a flux of about 10^4 photons/(s mm^2) from the electron storage ring TERAS of the Electrotechnical 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 in Section 5.4, that uses virtual photons with possible complications inherent in high-energy heavy-ion reactions.

There are some projects and plans of LC photon beams for higher beam intensities [64].

These will open a new field in nuclear astrophysics. It should be of great interest to use LC photon beams with RIB for the problem of nuclear astrophysics in the future, although for the moment it is not feasible due to the low luminosity.

5. Indirect measurements of reaction cross sections

5.1. Fundamental physical parameters for nucleosynthesis

Along the evolution of the Universe, there are various sites that involve almost all states of matter. The physical conditions vary from extremely high-temperature and density to very low temperature and low density. Therefore, various features of nuclear matter are involved in the stages of evolution, and a large amount of nuclear physics inputs are required for nuclear astrophysics. As to the nucleosynthesis, the basic information needed for the problem is limited but still includes many physical parameters like particle stability, masses, beta decay rates, fission probabilities, level densities, giant resonances, etc. One of the challenging, unexplored subject is the investigation of the r-process pathway at around $A = 190$, which can be roughly determined by nuclear masses in the region. There is no method realized yet for production of nuclides there. Experiments can be made using RIBs of these nuclei with intensity as low as a few aps if one has such a beam. Specifically, masses and half-lives can be determined with high precision by using a storage ring, as discussed in detail in Sections 5.5 and 5.6.

To evaluate the rates of stellar reactions, one needs to know a certain number of physical parameters. The first step is to search for resonances in the relevant energy region of the nuclei and study the properties. Several methods are available to identify resonances. Two-body reactions such as the (^{3}He,t) reaction can be used for such a search. All the resonances are not necessarily observed in two body reactions. Of course, resonance search by measuring the excitation function of elastic scattering can be used for identifying a wide resonance of about $\Gamma \gtrsim 1$ keV, as was the case for the 3^+ state in ^{18}Ne, discussed above [50,51]. It should be, however, cautioned that resonances that have smaller total widths can not be observed in elastic scattering, even though they may play a decisive role for determining the reaction rate. In-beam gamma spectroscopy and beta decay studies are also powerful tools in searching resonances, although they are also restricted by the selection rules, etc. One has to pay attention to this point, as some of the levels would not be excited above the background level of the experiment.

5.2. Direct transfer reactions for particle decay widths

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 a spectroscopic factor (S) and the spin–parity assignment using Distorted-Wave Born Approximation (DWBA) analysis of the angular distribution for the transfer reaction. The shapes of the angular distribution are usually well characterized by the transferred

angular momentum of the reaction. The cross sections of the direct transfer reaction for unbound states can be expressed as follows [65]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega}^{\mathrm{exp}} = \left(\frac{\Gamma_l}{\Gamma_{\mathrm{s.p.}l}}\right)\frac{\mathrm{d}\sigma}{\mathrm{d}\omega}^{\mathrm{DWBA}} \quad \text{with} \tag{10}$$

$$\Gamma_l = \Gamma_{\mathrm{s.p.}l} C^2 S_l, \tag{11}$$

where Γ_l is the width of the resonance, $\Gamma_{\mathrm{s.p.}l}$ the single particle width of angular momentum l, and C the isospin Clebsch–Gordan coefficient. The S factor is well-defined for the transitions to bound states, but not for the transitions to unbound states. If the resonance is narrow and symmetric, the differential cross section measured should be proportional to the particle partial width Γ_l, according to the method for unbound states in Ref. [65]. Using DWBA analysis that includes this option, $\Gamma_{\mathrm{s.p.}l}$ is also calculated from the analysis. As was discussed with Eq. (5), the reaction rate should be primarily determined by the particle width if the resonance has a width that is much smaller than the gamma width. This is the case when nuclear burning takes place hydrostatically at low temperatures. Namely, the resonance lies very close to the decay threshold for charged particles. Determination of the resonance strength is quite difficult under this condition by any other method. This method can be also very useful with RIBs.

An example is the study of the $^{22}\mathrm{Na}(\mathrm{p},\gamma)^{23}\mathrm{Mg}$ stellar reaction. A new resonance was discovered at very low energy, 65 keV above the proton threshold at 7.643 MeV with a possible spin–parity assignment of $J^\pi = (3/2, 2/5)^+$ by using the $^{24}\mathrm{Mg}(\mathrm{p},\mathrm{d})^{23}\mathrm{Mg}$ reaction [66]. Since this resonance is located very close to the proton threshold, the proton width is expected to be much smaller than the gamma width. Thus, the resonance strength of this state should be determined primarily by the proton width of the state. Here, the direct proton transfer reaction $^{22}\mathrm{Na}(^3\mathrm{He},\mathrm{d})^{23}\mathrm{Mg}$ was used at 30 MeV to deduce the proton width of the state [67]. The measured angular distribution was analyzed by DWBA analysis, deducing the spectroscopic factor of $S_{l=2} = 0.34$, which corresponds to the proton width $\Gamma_\mathrm{p} = 2 \times 10^{-8}$ meV. This result clarifies the reaction rate of the $^{22}\mathrm{Na}(\mathrm{p},\gamma)^{23}\mathrm{Mg}$ stellar reaction especially at low temperatures $T_8 < 1$.

There are many other works made using this method to determine the particle widths. The α width for the analog of the 4.033-MeV state in $^{19}\mathrm{Ne}$, which is critical for the breakout of the Hot-CNO cycle was investigated, for instance [68].

There are some points to be cautioned for the accuracy of this method. One needs to calculate the single-particle decay width, which clearly affects the derived particle width. The definition of the channel radius for the decay width is not necessarily the same as the effective radius for the S-factor defined in the DWBA calculation. However, there are certain regions where the indirect method is the unique way for reaction rate determinations.

5.3. Direct transfer reactions for direct-capture cross sections

Another important use of direct particle transfer reactions is the so-called Asymptotic Normalization Coefficient (ANC) method for deducing low-energy radiative capture cross

sections. This method has been developed recently by the Texas A&M group [69].

Radiative capture reactions $A + x \to B + \gamma$ at stellar energies take place on the nuclear tail region far outside the nuclei. If a direct particle(x)-transfer reactions also take place predominantly on the peripheral region, one may deduce the overlap function for $(B|A+x)$, with which one can derive the radiative 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 $^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}$ [70] at 29.8 MeV and also for the neutron capture reaction $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}$ at 11.8 MeV [71], recently. The cross sections for the direct capture reactions $A + x \to B + \gamma$ can be written as

$$\sigma = \lambda \left| \left\langle I_{Ax}^{B}(r) \middle| \widehat{O}(r) \middle| \Psi_i^{(+)}(r) \right\rangle \right|^2, \tag{12}$$

where I_{Ax}^{B} is the overlap function of $A + x$ and B, $\widehat{O}$ 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

$$I_{Ax}^{B}(r) \cong C \frac{W_{-\eta,l+1/2}(2\kappa r)}{r}, \quad r > r_N, \tag{13}$$

where C is the asymptotic normalization coefficient (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:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{j_B j_x} \left(\frac{C_{Axl_B j_B}^{B}}{b_{Axl_B j_B}} \right)^2 \left(\frac{C_{bxl_a j_a}^{a}}{b_{bxl_a j_a}} \right)^2 \frac{\mathrm{d}\sigma}{\mathrm{d}\omega}^{\mathrm{DWBA}}_{l_B j_B l_a j_a}, \tag{14}$$

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

$$\varphi_{nlj}(r) \cong b_{lj} \frac{W_{-\eta,l+1/2}(2kr)}{r}, \quad r > r_N. \tag{15}$$

Here, it is important to check that the reaction, especially the forward-angle scattering, is sensitive mostly to the peripheral part of the nucleus. The incident energy should be chosen to meet the peripherality condition, and should be high enough to assure a direct process.

This method was tested for derivation of the low-energy cross sections of the $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}$ capture reaction using the $^{12}\mathrm{C}(\mathrm{d},\mathrm{p})^{13}\mathrm{C}$ reaction. The incident energy was chosen to be 11.8 MeV to meet the criteria above. The angular distribution for the $^{12}\mathrm{C}(\mathrm{d},\mathrm{p})^{13}\mathrm{C}(3.089\ \mathrm{MeV},\ 1/2^+)$ reaction shows a characteristic shape of angular momentum transfer $l = 0$. The cross sections at very forward angles are most sensitive to the contribution from the reaction at far distance. The DWBA calculations show very small change, specifically at very forward angles, by cutting off the contribution in the

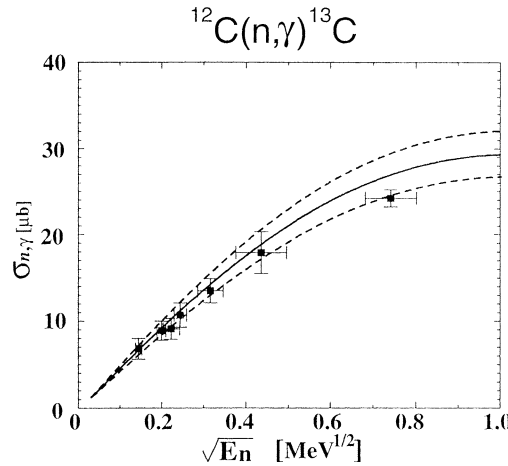

Fig. 5. The lines are the ^{12}C(n, γ)^{13}C reaction cross sections derived by the ANC method [71]. The main uncertainty for the estimate comes from the choice of optical potential and the bound state potential parameters. The experimental data points were obtained from Ref. [72].

inside region of the nucleus for integration in the DWBA analysis. Fitting to this part, one obtains quite stable results for the ^{12}C(d, p)^{13}C($1/2^+$) cross sections. DWBA calculations for several different types of potential sets, both for the distorted waves and for the bound state, were made, showing only small deviations of the forward-angle cross sections. The deduced (n, γ) capture cross sections are compared to the experimental cross sections [72] in Fig. 5. The cross sections derived from the ANC method agree with the data of ^{12}C(n, γ)^{13}C within the uncertainty of the analysis. This suggests that the ANC method can be a good alternative way to deduce the cross sections of capture reactions at low energies with the uncertainty of about 15%. The ANC method was also successfully applied to the study of the ^{7}Be(p, γ)^{8}B reaction using the ^{7}Be(d, n)^{8}B reaction at 5.8 MeV [73]. The astrophysical $S_{17}(0)$ factor obtained is 27.4 ± 4.4 eV b, roughly consistent with other values.

5.4. Coulomb dissociation method

Radiative capture reactions $A(x, \gamma)B$ take place through the electromagnetic interaction, and play an important role in nucleosynthesis. The cross sections are usually quite small at low energies. These low energy capture reactions could be investigated by reverse reactions with a real photon beams discussed in Section 4.2. There can be a similar situation of virtual photons, under some conditions, in the Coulomb dissociation reactions $\gamma(B, x)A$, at high energies. Thus, this method can be applicable, in practice, provided the reverse reactions primarily proceed via Coulomb interaction. This method was proposed originally by Baur and his collaborators [74]. The experiments with this method have some advantages, which are well fitted to the experiments with RIBs.

The Coulomb dissociation cross sections can be enhanced by the phase volume difference in the detailed balance. The capture reaction can be expressed by the reverse,

dissociation reaction as follows:

$$\sigma(A+x \to B+\gamma) = \frac{3(2j_B+1)}{(2j_A+1)(2j_x+1)} \frac{k_\gamma^2}{k^2} \sigma(B+\gamma \to A+x). \tag{16}$$

Here, the phase factor k_γ^2/k^2 is quite small as it involves the ratio of the square of the momentum transfers. Thus, the reverse cross section should be enhanced by the inverse of this factor as compared to the capture process. In addition, if one uses an intermediate or high-energy beam of B, a thick target of ^{208}Pb can be used, which provides a strong Coulomb field giving a large number of virtual photons. This will also enhance the count rate of the dissociation events.

The measurement of the breakup process of nucleus B requires determination of the relative energy and angle between x and A, and the scattering angles of the ejectile system of x and A. For detecting two particles in coincidence, a segmented detector setup is needed for measuring x and A. This means the resolution of the result is not dependent, to the first order, on the energy resolution of the incident beam. This is another advantage for experiments with RIBs, which usually possess a large energy spread. The detectors and the segmentation size as well as the entire experimental arrangement should be determined depending on the precision needed. Here, one may use various types of detectors like CsI, NaI, plastic scintillator, Si detectors, etc., or a combination of those.

The energy dependence of the virtual photon numbers for E1, M1 and E2 is shown in Fig. 6, which was calculated for the dissociation of ^{8}B [75]. Since the stellar (p,γ) reactions take place predominantly by the E1 transition, the contributions of E2 and M1 needs to be removed from the Coulomb dissociation cross sections. If one studies the Coulomb dissociation process at low energies, it will have a large contribution of the E2 transition, whereas the M1 component will be more effective at high energies, as can be seen in the figure. To apply this method, one should measure the breakout process at very forward angles, where the E1 cross sections are relatively large. Then, one may use DWBA calculations to fit the inelastic scattering data in order to deduce the gamma width of interest.

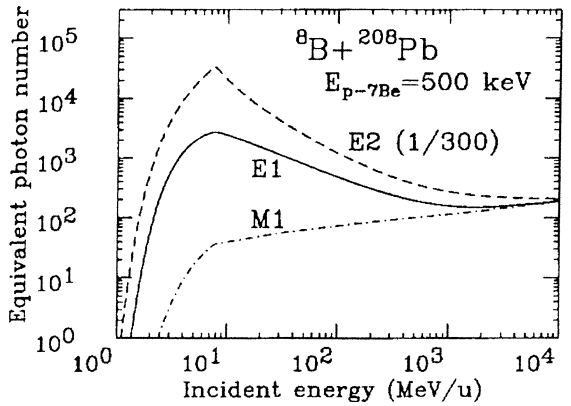

Fig. 6. Virtual photon numbers plotted as a function of the incident beam energy of ^{8}B for M1, E1, and E2 transitions [75].

Although this method was applied for both resonant breakup and nonresonant breakup reactions, it is not well tested yet especially for nonresonant breakup processes. Since the capture reactions take place by the electromagnetic interaction, the reverse reaction should also involve only the electromagnetic interaction, as repeated above. However, heavy ion reactions at intermediate and high energies generally involve not only the Coulomb interaction but also the nuclear interaction. Thus, there are some points to be checked carefully before applying this method:

(1) the nuclear contribution should be negligibly small, although less nuclear contribution is found at very forward angles. This depends also on the multipolarity of the transition;
(2) the final-state interactions should be negligibly small;
(3) the channel coupling to other channels such as the inelastic scattering to the continuum states, should be small;
(4) mixing of other multipolarities of the Coulomb dissociation should be known for nonresonant breakout processes.

These points need to be carefully checked experimentally.

The first experiment of this method was applied to a study of the stellar reaction ^{13}N(p, γ)^{14}O [76,77], which is a key reaction for the onset of the hot-CNO cycle. The reaction is considered to go through the 5.17 MeV 1^- state, which is the first excited state above the proton threshold in ^{14}O. The gamma width for the state was determined to be $\Gamma_\gamma = 3.1 \pm 0.6$ eV, which is in good agreement with the value obtained by the direct measurement with the ^{1}H(^{13}N, γ)^{14}O reaction, as discussed in Section 4.2. The stellar reaction ^{7}Be(p, γ)^{8}B, which is crucial for the solar neutrino problem, was also investigated [78] by the Coulomb dissociation method, resulting in the S_{17}(E1) values consistent with previous measurements within the experimental uncertainties. Since the dissociation process here is nonresonant, 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 percent, which gives a minor contribution to the result. The other contributions such as the nuclear contribution were not yet determined quantitatively. All other points mentioned above needs to be fully examined. The details are discussed in the article by Motobayashi in this special volume.

5.5. Approach to the r-process nuclei

Although heavy elements are not so important for the evolution of the universe and for energy generation, they are very useful for understanding the mechanism of stellar events and also for cosmo-chronology. Various heavy elements such as Ba are observed in old halo stars, and give a stringent test for the stellar models. There are two major mechanisms suggested for heavy element synthesis; the s-process and the r-process [2,3], as mentioned in Section 1. The s-process goes more or less along the line of stability by (n, γ) reactions and beta decays, over long periods of time. The r-process, on the other hand, should occur

in a very high neutron-density region ($n_n \sim 10^{21}$ cm^{-3}) at high temperature ($T_9 \sim 2$–3) on a very short time scale, strongly suggesting a nucleosynthesis flow-path far away from the line of stability. The location of the r-process path is characterized by neutron separation energies of 2–3 MeV, as mentioned before. Beta decays are the waiting points in the path because an isotopic chain with increased Z can only be reached by beta decay which is much slower than the (n, γ)–(γ,n) reactions. The broad abundance peaks below the magic number at stability in the mass distribution are a result of the r-process path encountering closed shell nuclei far from the line of stability, where they are located at lower mass number A. See Fig. 1. The most plausible site for the r-process is considered to be in the hot bubble in type II supernovae [79,80], although that is not definitive yet.

The nucleosynthesis of the r-process is least known experimentally since the nuclei on its possible path are mostly quite difficult to produce in the laboratory. This problem is one of the most challenging subjects in nuclear astrophysics. Only some nuclei around the possible waiting points at $N = 50$ and 82 were observed so far. The nucleus ^{130}Cd was produced and first investigated [81] at CERN-ISOLDE by a high energy spallation reaction; the half life was determined to be 203 ms, whereas the nucleus ^{80}Zn [82,83] was produced as a fission product of ^{235}U, and studied at the high-flux reactor at Brookhaven National Laboratory, giving $T_{1/2} = 550$ ms. Therefore, the half lives of possible waiting points of the r-process would influence considerably the abundance production beyond these nuclei. To identify the r-process path, detailed nuclear structure information such as level densities and giant dipole strengths is needed as well as basic parameters, half lives and masses. Nevertheless, these basic physical parameters very roughly determine the pathway of the r-process. Thus, it should be the first target for investigation of the r-process.

A new production method of very neutron-rich nuclei was developed that uses Coulomb fission of an accelerated ^{238}U beam at 780 MeV/u at GSI. See Fig. 7. The long-standing desire of nuclear physicists was realized by this method, i.e., a very neutron rich "doubly closed shell" nucleus, $^{78}_{28}$Ni$_{50}$ was produced and identified [84]. Since the fissioning nucleus ^{238}U passes through the strong Coulomb field, the fission fragments are ejected mostly to the very forward angles, and thus they can be collected efficiently. Further experimental information such as the half-lives and the masses are needed for ^{78}Ni and the nuclei nearby to answer the question whether the r-process really passes through ^{78}Ni. Of course, to clarify 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 region of the possible r-process pathway. The masses and the half lives of the new isotopes will be determined using the storage ring technology, as discussed in the following subsection.

5.6. *Heavy-ion storage rings*

Heavy ion storage rings have various capabilities for studies of nuclear physics and nuclear astrophysics. Basic properties of unstable nuclei can be studied precisely by storing

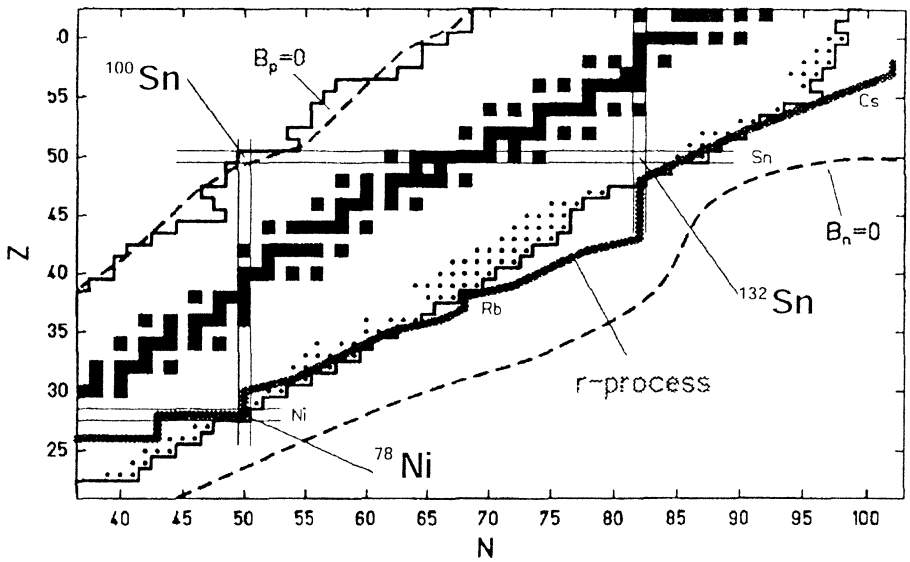

Fig. 7. New isotopes discovered by the Coulomb fission process of ^{238}U at 780 MeV/u [84]. The data are presented by the small dots. A predicted r-process flow path is indicated by a gray belt, and the possible neutron-drip line by the dashed line.

them in such storage rings. The stored beams can also be used for studies of reactions with an internal target or with a colliding beam such as an electron beam and a photon beam. There are two new kinds of experiments reported that used a heavy ion storage ring in the last decade. One is a measurement of bound state beta decays, which is essentially a half-life measurement of nuclei, and the other one is a precise mass measurement of unstable nuclides far from the line of stability. Both experiments were performed at the Experimental Storage Ring (ESR) at GSI. Since both experiments have a large impact on nuclear astrophysics, the results and the consequence are discussed briefly below.

Unstable nuclei under terrestrial condition have constant and well-defined half lives for the beta decays, but the half lives change in principle when ionized. Specifically, if all electrons are stripped off, which is the case under very high-temperature and high-density stellar conditions, the half-lives would change considerably. Such a possibility was suggested for some nuclides that are important for cosmo-chronology [85]. A pioneer work of applying a storage ring to this problem was made for a bound state beta decay. Some nuclei become unstable against weak decay when all the electrons are removed if the Q-value is very small. This was first demonstrated experimentally for the decay of $^{163}_{66}\mathrm{Dy}^{66+} \rightarrow {}^{163}\mathrm{Ho}$ [86]. Here, the fully ionized $^{163}\mathrm{Dy}^{66+}$, which has a slightly positive Q-value for the weak decay, were stored in the ESR. The data clearly indicates a decrease in number of $^{163}\mathrm{Dy}^{66+}$ and an increase of $^{163}\mathrm{Ho}^{66+}$ as a function of time, indicating the $^{163}\mathrm{Dy}^{66+}$ decay to $^{163}\mathrm{Ho}^{66+}$. The half-life of $^{163}_{66}\mathrm{Dy}^{66+}$ was determined to be 47 days.

The ^{187}Re–^{187}Os pair is a good cosmo-chronometer since it is almost independent of the assumed r-process scenario. However, if the decay rate of ^{187}Re to ^{187}Os is influenced by the atomic charge state, the ratio of $^{187}\mathrm{Re}/^{187}\mathrm{Os}$ will be changed, resulting in

a modification for the chronometry. The bound state beta decay of $^{187}Re^{75+}$ was measured at the ESR [87], resulting in a half life of about 32.9 ± 2.0 y which is many orders of magnitude shorter than the one under normal conditions of the ^{187}Re atom, $T_{1/2} = 4.23 \times 10^{10}$ y. This will influence the estimate of the galactic age. This method should be very useful also for investigating such beta-decay that is related to the problem of the p-process [88] and cosmo-chronology [85].

Another powerful application of the storage ring is a precision mass measurement. A beautiful measurement was reported that determined the masses of many nuclei of $56 < Z < 85$, whose masses were not known before [89]. A 930 MeV/u ^{209}Bi ions were fragmented on a thick Be target, and stored in the ESR. The circulating ions were detected by the Schottky noise, which gives a precise mass information of each nuclide. Fig. 8 displays Schottky spectra that show the mass of each nuclide denoted. The resolving power achieved was 3.5×10^5. Mass measurements of neutron-rich nuclides near the possible r-process path should be of great interest. That will clarify roughly the pathway of the r-process.

Nuclear properties, not only the half lives and masses, will be investigated using internal targets or colliding beams such as electrons and photons. These new progress will be realized in the RIBF project at RIKEN, and RIA proposal in the USA.

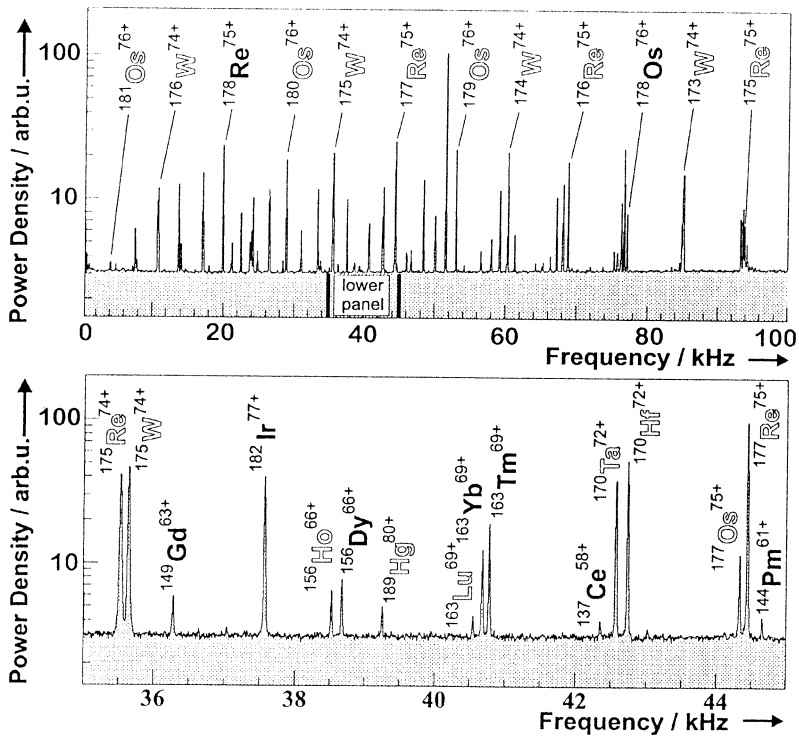

Fig. 8. Schottky spectra of stored and cooled fragments measured for 160 s with $B\rho = 7.1$ Tm at the Experimental Storage Ring of GSI [89]. The masses were determined for the first time for the isotopes indicated, using the known masses of the nuclides indicated by the bold letters.

6. Summary and outlook

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, and RIKEN. They will advance the experimental study of nuclear astrophysics. The second phase of the RIKEN project and possibly the RIA project in the USA will have much greater capabilities. Heavy-ion storage rings will be installed in addition to fragment separators there. They may provide fundamental physical parameters needed for heavy element synthesis in the r-process. The RIB 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. Another interesting development touched in the text is a direct method using a few-MeV photon beams of well defined energies, obtained from laser-induced Compton back scattering with high-energy electron beams, to study the astrophysical capture reactions such as (p, γ) and (n, γ) reactions in the reverse reactions. This could be coupled to RIB storage ring projects in the future.

Direct measurements of reaction cross sections with RIBs' for astrophysical interest will be investigated at ISOL facilities and possibly also at low-energy in-flight separator facilities such as the one at CNS. Although these works will be limited to the nuclei not so far from the line of stability, they will provide rich information that can only be obtained by the direct method.

The indirect methods, which were discussed extensively in this article, also provide a wealth of information needed for nuclear astrophysics with unstable nuclear beams as well as with stable beams, which are not accessible with the direct method in practice.

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