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Nuclear astrophysics at the east drip line

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Abstract. In the first half of the paper, the nuclear astrophysics activities in Japan, especially in experimental studies are briefly overviewed. A variety of beams have been developed and used for nuclear astrophysics experiments in Japan. The activities include the RI beam facilities at low energies by the in-flight method at the Center for Nuclear Study (CNS), University of Tokyo and by the ISOL-based method at the JAERI tandem facility, and the RI beam facility at intermediate energies at RIKEN. Other activities include a study of the $^{12}C(\alpha,\gamma)^{16}O$ reaction exclusively at the tandem accelerator at the Kyushu University, and studies at the neutron facility at Tokyo Institute of Technology and at the photon facility at AIST (Sanso-ken). Research opportunities in the future at RIBF, J-PARC, and SPRING8 are also discussed. A discussion on the research activities at CNS has been specifically extended in the latter half, including various possibilities in collaboration at the RI beam factory at RIKEN.

PACS. 25.70.Ef Resonances – 25.60.-t Reactions induced by unstable nuclei – 26.30.+k Nucleosynthesis in novae, supernovae and other explosive environments – 29.25.Rm Sources of radioactive nuclei

1 Introduction

The nuclear astrophysics activity in Japan is partially stimulated by the high activities in astronomy in Japan. The Kamiokande detector successfully observed the supernova neutrinos in 1987 for the first time, and the large-scale, high-resolution optical telescope SUBARU has been operational since 1997 in Hawaii. The successful operation of X-ray observatories in Japan is another element. Recently, the radio-observatory activities at Nobeyama have been decided to extend to the ALMA project, that is the next generation of the radio observatories, based on the US-Japan-Europe collaboration. Of course, the nuclear astrophysics activity inversely has stimulated, for instance, astronomical observations of r-process elements as well as the s-process elements in very metal-poor stars, and also observations of isotopic ratios rather than elements. For instance, a recent SUBARU observation has succeeded in determining the isotopic ratios for the element Eu.

Experimental efforts in nuclear astrophysics have been expanded very rapidly in the last two decades since the introduction of RI beams in nuclear physics. One of the major reasons is that the nuclear reactions involved in explosive phenomena in the universe can be directly investigated with RI beams at very low energies. Along the development of nuclear astrophysics several useful methods have been invented for the field. These include indirect methods such as the Coulomb dissociation method, the asymptotic normalization coefficient (ANC) method, and so on. These developments are summarized in ref. [1]. The

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Table 1. Accelerator facilities for nuclear astrophysics in Japan.

Beam	Facility	Affiliation	Subjects
Stable beams	Tandem	Kyushu University	$^{12}C(\alpha,\gamma)^{16}O$
RI beams (low energies, in-flight)	CRIB	Univ. of Tokyo	Primordial NS, rp-process
RI beams (intermediate energies, in-flight)	RIPS	RIKEN	Coul. Dissoc., ANC
RI beams (low energies, ISOL based)	TRIAC	KEK-JAERI	primordial NS, SN-NS
Neutron beams	Pelletron	TIT	s-process, prim. NS
Photon beams	e-ring	Sanso-ken(AIST)	p-nuclei, s-process

early stage of the development was initiated also in Japan that can be seen in refs. [2,3,4,5,6,7,8]. The research activity of nuclear astrophysics is now widely accepted as an important subfield of nuclear physics. It can be easily understood by looking at session names in most large conferences, and also at research propagandas in proposals for large-scale facilities. One never misses subjects related to nuclear astrophysics.

As is well known, there are two ways for RI beam production. In-flight RI beam separation is the most popular way adopted and realized, but ISOL-based method is more powerful in a sense for nuclear astrophysics. These two type facilities are available in Japan. The former method has been adopted at RIKEN at intermediate energies, and at the Center for Nuclear Study (CNS), University of Tokyo at low energies, whereas the latter one is adopted at the KEK-JAERI collaboration. A neutron source is available at the pelletron facility at the Tokyo Institute of Technology. Photon beams, available at AIST (Sanso-ken), were introduced for nuclear astrophysics experiments. On the other hand, a pure, high intensity ^{12}C beam is also realized at low energies at the Tandem facility of the Kyushu University.

Table 1 summarizes the major beam facilities now available for nuclear astrophysics in Japan. Details will be described for each facility in sect. 2. There are some other facilities relevant to nuclear astrophysics. Nuclear reaction mechanisms at very low energies have been investigated at Tohoku University, and some stellar reactions are under investigation at the Research Center of Nuclear Physics, Osaka University by an indirect method. We specifically discuss the detail of the low-energy in-flight RI beam separator CRIB [9] at CNS in sect. 3, and the experimental results in sects. 4 and 5. A short summary is given in sect. 6.

2 Experimental facilities in japan

There are two-type RI beam facilities known, and both of them are available in Japan, as mentioned above. In-flight type RI beam separators include RIPS at RIKEN at intermediate energies and CRIB at CNS. In-flight separation mostly uses inverse kinematics to obtain the kinematical focusing effect. Unstable nuclei can be produced with heavy-ion induced reactions, separated in-flight and focused at the double-achromatic focal plane. A detail of RIPS will be explained in the contribution by Togano to this symposium. The most typical activities for nuclear astrophysics with RIPS are the investigation of stellar reactions using the Coulomb dissociation method. The low-energy separator CRIB will be discussed in detail in the next section. The RI Beam Factory (RIBF) at RIKEN, which is under construction, will begin delivering RI beams in 2006 or 2007, which will enable us to investigate the pathway of the r-process for the cosmochronology, first generation stars, and the supernova mechanism. The detail of the RIBF project may be found at `http://www.rarf.riken.go.jp/index-e.html`.

The ISOL-based facility, called TRIAC, very recently has been established at the Tandem laboratory in JAERI, Tokai by a collaboration of JAERI and KEK. Most part was transferred from the E-arena of the old INS (Institute for Nuclear Study, University of Tokyo). They are going to place their emphasis on acceleration of fission products for nuclear physics as well as for nuclear astrophysics. The facility may be operational for routine use from the fall of 2005. They also have a plan to increase the RI beam energies by the existing super-conducting Linac up to 8 MeV/u for ions of $q/A \geq 1/4$. A detailed introduction to the facility can be found at `http://triac.kek.jp/en/`.

Neutron capture reactions play a crucial role specifically for heavy element synthesis. The neutron facility at the Tokyo Institute of Technology has been running for more than ten years for nuclear astrophysics. The group headed by Nagai introduced large-volume NaI crystals to measure directly the capture-gamma rays, which made the measurements more reliable than the activation method. They have found an important contribution of p-wave under a certain condition even at very low energies, indicating breakdown of the $1/v$ rule. A proposal of an extensive neutron facility plan for nuclear astrophysics has been approved in the J-PARC project, the large hadron project by the joint venture of KEK and JAERI, although the proposal is not funded yet.

Another interesting beam for nuclear astrophysics is the real photon beam, which can be obtained by backscattering of the laser beam from stored electron beams. A beautiful experiment was demonstrated by Utsunomiya, which can be explained in detail in this volume of the proceedings. A new-generation photon beam facility is under preparation at Spring8 in Harima, Japan.

The last facility is the Tandem accelerator facility at Kyushu University. They have constructed an extensive recoil separator exclusively for the measurement of the stellar $^{12}C(\alpha,\gamma)^{16}O$ reaction at the He burning temperature region. They have succeeded to modify the Tandem

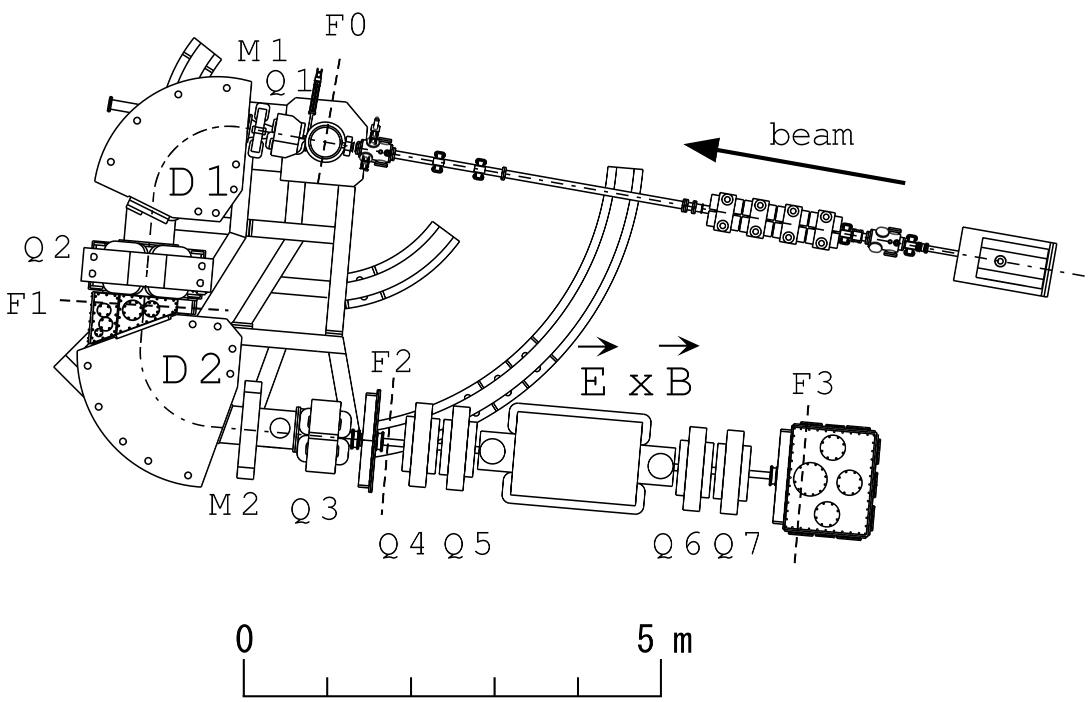

Fig. 1. Plane view of CRIB. Primary low-energy heavy-ion beams are provided from the AVF cyclotron of RIKEN.

Table 2. Intensities of RI beams below 10 AMeV obtained at CRIB.

RI beam	Primary beam	Reaction	Intensity (pps)	Purity (%)
^{7}Be	^{7}Li	^{1}H(^{7}Li, ^{7}Be)	1×10^6	90
^{8}Li	^{8}Li	^{2}H(^{7}Li, ^{8}Li)	1×10^6	100
^{10}C	^{10}B	^{1}H(^{10}B, ^{10}C)	1.6×10^5	90
^{14}O	^{14}N	^{1}H(^{14}N, ^{14}O)	1.6×10^6	90

operation for high intensities at very low energies. Currently, they are fighting to attain the beam suppression factor of 10^{-19} by improving the whole system by one order of magnitude.

As we overviewed above, we have a variety of opportunities for experimental nuclear astrophysics in Japan as well as great possibilities in the years to come.

3 The CRIB project at CNS

The CNS shut down their own cyclotron in 2000, and moved to the RIKEN campus, and immediately initiated a joint venture with RIKEN at the RIKEN Accelerator Research Facility (RARF). CRIB [10] is one of the major facilities that CNS introduced to RARF. In order to maximize the capability, we set a CNS-RIKEN joint project, AVF-Up Grade Project, under which we had decided to establish an extensive low-energy RI beam separator. Figure 1 displays the plane view of CRIB which consists of a double-achromatic magnetic section and a Wien Filter section. The configuration is F0-QMDQ-F1-DMQ-F2-QQ-WF-QQ-F3, where Fi is the i-th focal plane of the optics, D a dipole magnet, Q a quadrupole magnet, and M a multipole magnet. One may use a degrader at F1, which is a momentum dispersive focal plane, for a better separation of the RI beam of interest.

The Wien filter section gives a capability of better particle separation and also provides some interesting features for other studies. The velocity separation section has 1.5 m-long electric parallel plates that have the maximum voltages of ±200 kV for a gap of 8 cm, giving 50 kV/cm. The maximum velocity dispersion designed was about 0.8 cm/%. The separation capability was verified with an ^{14}O beam produced from the ^{1}H(^{14}N, ^{14}O) reaction at F0. It gave almost 100% purity at F3. Another favorable feature of the RI beam from the filter is the beam quality. Under some condition, one may need only the Wien filter without the degrader, to obtain a small beam spot since the major factor for the RI beam size is due to the straggling at the degrader.

For example, an ^{14}O beam of 1.6×10^6 pps was obtained from the ^{1}H(^{14}N, ^{14}O) reaction with a moderate beam intensity of 200 pnA of the primary beam at F0. We have succeeded to eliminate most contamination by the Wien filter. The RI beam size at F3 is still as large as $7 \times 7\,\text{mm}^2$ without degrader. Since this can be improved by correcting for the higher order aberration of the beam optics, a new sextupole magnet was installed. This work is in progress. The RI beam intensities (table 2) are limited

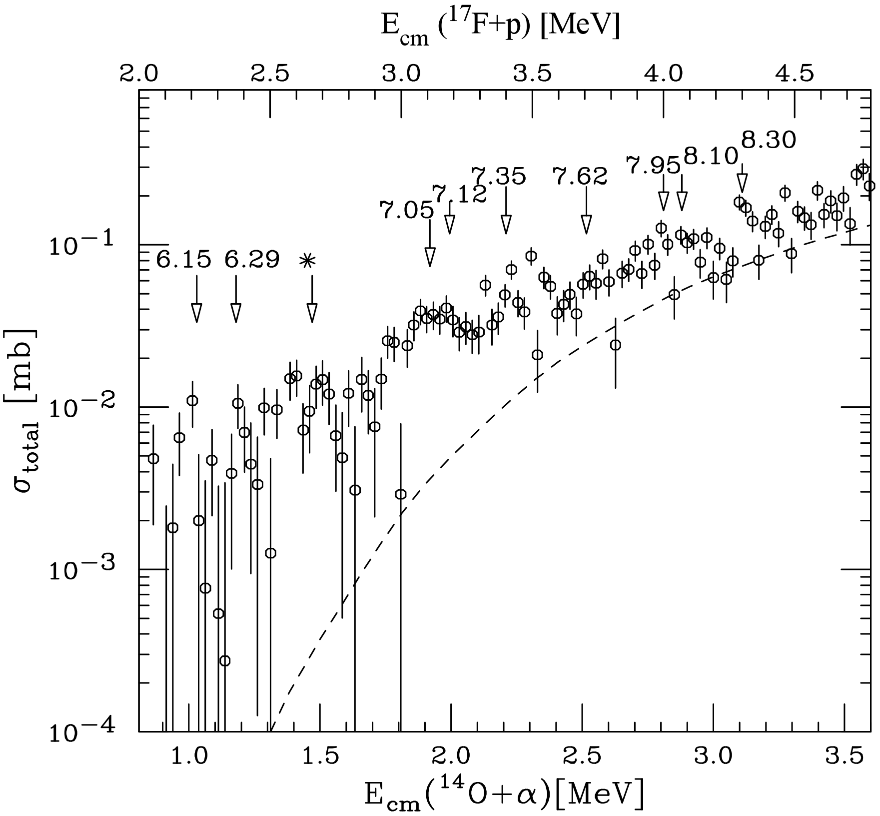

Fig. 2. Proton spectrum from the $^{14}O(\alpha,p)^{17}F$ reaction measured at $\Theta_{Lab} = 0°$. The asterisk indicates a transition to the 0.495 MeV first excited state in ^{17}F.

by two factors at this moment, the primary beam intensities and the production target. An intensive program is under way for the first part by installing the Hyper ECR source, and by upgrading many parts of the AVF cyclotron for the acceleration efficiency. This includes successful installation of a flat-top acceleration mode, a new deflector, new DC power supplies, etc. The accelerator energy factor K is now about 80, which was about 45 in practice before. As for the second part, a cooled gas target system is being developed that has a higher target density and can stand high beam currents. These efforts are in progress so that in the near future we may begin to study the stellar (p,γ) reaction directly with CRIB. This project should be a nice demonstration that a small accelerator facility can make a great contribution for RI beam physics.

4 The direct measurement of the $^{14}O(\alpha,p)^{17}F$ reaction

A series of reaction studies with low-energy RI beams has been undertaken at CRIB, specifically, for the onset and the early stage of the explosive hydrogen burning (rp) process.

The high-temperature (high-T) rp-process may typically take place in an X-ray burst, which is considered to be an event on the surface of a neutron star with accretion of hydrogen from the companion star in the main sequence phase. Here, one of the most critical stellar reactions is $^{14}O(\alpha,p)^{17}F$ for the ignition of the high-T rp-process. There are many experiments performed by indirect methods [11,12] for the problem, but not by the direct method with an ^{14}O beam. Two experiments were made previously using the time-reverse reaction $^{17}F(p,\alpha)^{14}O$. Only some transitions through resonances above $E_{cm} = 3$ MeV in ^{18}Ne were reported [13,14]. Note that the most critical energy region is around $E_{cm} =$ 1–2 MeV for the present problem. This reaction has been successfully investigated for the first time using a high intensity ^{14}O beam from CRIB.

A low-energy ^{14}O beam was produced by the $^{1}H(^{14}N,^{14}O)$ reaction at 8.4 MeV/u, and separated. The intensity and the purity of the beam was 1.6×10^6 pps and 85%, respectively, at F2. The momentum spread of the beam was defined to 1% by setting an aperture at F1, the momentum dispersive focal plane. The secondary target of He was cooled down to about 30 K, so that the target length was shortened roughly by a factor of 10, which made the present experiment possible. This is described in detail in ref. [15].

For the measurement of the $^{14}O(\alpha,p)^{17}F$ cross section, we applied the thick-target method [1], which has been developed in the last decade for low-energy RIB experiments and applied for proton elastic scattering experiments. This method was successfully used in the present case. Figure 2 displays a proton spectrum measured at 0° with a

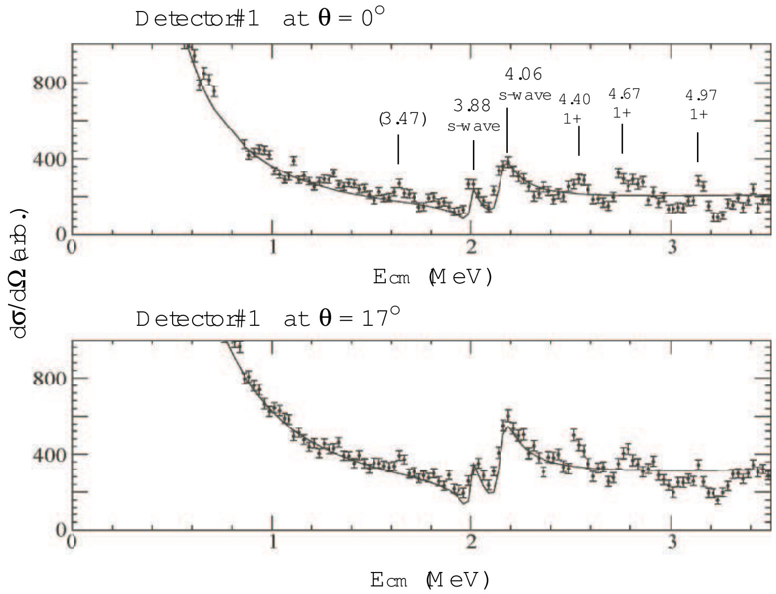

Fig. 3. Elastic scattering of ^{23}Mg+p measured at $\Theta_{Lab} = 0°$ and 17°. The solid line is an *R*-matrix fit. Possible states are indicated by the excitation energies in ^{24}Al.

silicon counter telescope. Several peaks are clearly seen that correspond to the (α, p) reaction mostly leading to the ground state in ^{17}F. The transitions through the 6.15 and 6.29 MeV states in ^{18}Ne were seen for the first time. These transitions were considered to be the main contributions to the stellar reactions under the X-ray burst condition [11]. The cross sections are roughly the same as predicted in ref. [11], thus confirming the primary importance of the two contributions. The transitions through the states at 7–8 MeV are also clearly observed. The peak around 6.5 MeV is considered to be the transition through the state at 7.1 MeV in ^{18}Ne decaying to the first excited state at 0.495 MeV in ^{17}F. Since there is no state of large proton width in the ^{17}F+p scattering [14] and the states in this energy region in ^{18}Ne cannot have a large α width as it is so close to the α threshold, the peak around 6.5 MeV cannot be explained by a state in ^{18}Ne. This implies that the transition through the 7.1 MeV state in ^{18}Ne increases the reaction rate roughly by 50%. Note that the reaction study with the time-reverse reaction cannot access this process.

5 Search for proton resonances relevant to the early stage of the rp-process

The mechanism of the early stage of the rp-process is of great interest. Previously, we studied by indirect methods the excited states near and above the proton threshold in the proton-rich nuclei, relevant to the early stage of the rp-process [16], where many new states were identified. However, the reaction rates are not determined yet because the resonance properties are not known. Thus, we have started to investigate the properties of these proton resonances by the direct method. So far, we studied the proton resonant scattering of ^{21}Na+p, ^{22}Mg+p, ^{23}Mg+p, ^{25}Al+p and ^{26}Si+p as well as ^{24}Mg+p for testing the thick target method [1] with the present experimental setup. The present data of ^{24}Mg+p are very well reproduced by the *R*-matrix calculation [17] with known resonance parameters, confirming the validity of the method. Preliminary results on ^{25}Al+p and ^{26}Si+p are presented elsewhere [18].

Figure 3 displays the proton excitation functions of ^{23}Mg+p. This is the first experiment to investigate ^{24}Al by proton resonance scattering. No resonance parameters were known before for the states in ^{24}Al [19]. We can see clearly two resonances at 3.88 and 4.06 MeV, and they are fitted well by *s*-wave resonances and are in agreement with previously known states at 3.885 and 4.059 MeV [19]. We can also see three resonances that probably correspond to the 1^+ states known by the beta decay study of ^{24}Si [20]. Detailed analysis is in progress.

6 Summary

Experimental facilities for nuclear astrophysics in Japan are briefly overviewed together with their research activities. Most of the interesting beams are available and the future scope is also bright for this field. These include high-energy RI beams of very short-lived, very neutron-rich nuclei at RIKEN, extensive photon beams at Spring8, and high-intensity neutron beams at J-PARC.

In contrast to these grand scale facilities, small machine facilities also can make great contributions to nuclear astrophysics. Our extensive low-energy RI beam facility, CRIB, demonstrates such feasibility. We may investigate stellar reactions of the rp-process very efficiently at CRIB. We have shown that an in-flight RI beam production method at low energies is very useful, and has a possibility to obtain RI beam intensity of the order of 10^8 pps for light nuclides near the line of stability. The Wien filter gives a better condition for the property of RI beams because one does not always have to use the degrader that deteriorates the RI beam quality considerably. The present work demonstrates that even small accelerator laboratories can devote to extensive RI beam programs including nuclear astrophysics.

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