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New low-energy RIB separator CRIB for nuclear astrophysics

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Abstract. An in-flight RIB separator at low energies, which is the first extensive separator at low energies, called CRIB, is just under construction at CNS. This consists of a double-achromatic magnetic separator, a window-less gas target, and a Wien filter. Some characteristics of the CRIB are described. Possible experimental plans are also discussed in our nuclear astrophysics project for the study of the explosive hydrogen burning process, especially on the onset mechanism.

PACS. 28.60.+s Isotope separation and enrichment – 26.30.+k Nucleosynthesis in novae, supernovae and other explosive environments – 25.60.-t Reactions induced by unstable nuclei

1 Introduction

Low-energy radio-isotope beams (RIB) are very useful for nuclear spectroscopy as well as for nuclear astrophysics experiments. Mostly, the low-energy RIBs are produced by heavy-ion–induced fragmentation reactions at a few tens of MeV/u or higher, separated by a fragment separator such as RIPS in RIKEN, and degraded down to low energies of interest. Because of the large degradation of the RIB, the RIB quality is very poor. ISOL-based RIB facilities, on the other hand, are now providing high-quality RIBs of some limited nuclides at Louvain-la-Neuve and Oak Ridge National Laboratory. Of course, the beam quality there is as good as ordinary stable beams because one uses a post accelerator for RIB acceleration. Facilities of this type, however, need extensive installation of ISOL system and a post accelerator. It also requires extensive development of ion source for each element for high-efficiency extraction. If one can obtain low-energy RIBs of reasonable energy resolution with an in-flight separator, it should be very useful. This will give an opportunity of RIB science to the facilities of small machines. Here, one can avoid extensive installation of ion sources and a post accelerator, and also the ions source development. Such an in-flight RIB separator at low energies, which is called CRIB, is now under construction in the E7 experimental hall in the RIKEN accelerator facility as a part of CNS(Center for Nuclear Study)-RIKEN collaboration.

First, we briefly describe in sect. 2 the CNS-RIKEN collaboration, that has enabled the installation of the CRIB. This includes the extensive installation of experimental facilities as well as upgrading the accelerator and the ion sources. In sect. 3, we explain the feature of the CRIB. In sect. 4, we present our research programs on nuclear astrophysics, and discuss possible experiments to be performed with the low-energy RIBs from the CRIB.

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2 CNS-RIKEN collaboration projects

Several new projects have been initiated under the new research contract between CNS and RIKEN, and the CRIB project is one of them. Figure 1 illustrates the plane view of a part of RIKEN accelerator facility. Under the CNS-RIKEN contract, there are several projects going on including the activities of 1) accelerator technology as well as 2) nuclear physics experiments. As for the accelerator technology, one major aim is to deliver high-intense heavy-ion beams from the AVF cyclotron to the CRIB. This activity includes development of ECR ion source such as super-conducting ECR source and the AVF cyclotron, installation of new beam lines and the Hyper ECR which was transferred from the old CNS campus at Tanashi. A flat-top RF system will be installed for the AVF cyclotron for the acceleration of heavy-ion beams with better energy resolution. Four new linear accelerator segments were also installed to accelerate the heavy-ion beams up to 6 MeV/u, at the end of the existing Linac injector. This enables one to use the Linac beams for nuclear reaction studies such as synthesis of super-heavy elements. Thus, the GARIS system was moved to the experimental hall

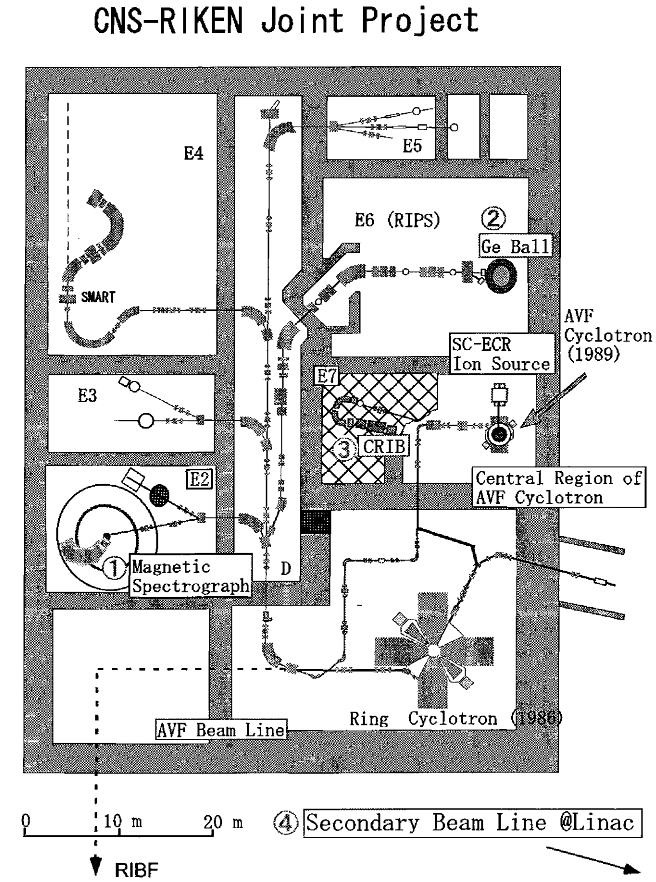

Fig. 1. New installations of the CNS-RIKEN collaboration.

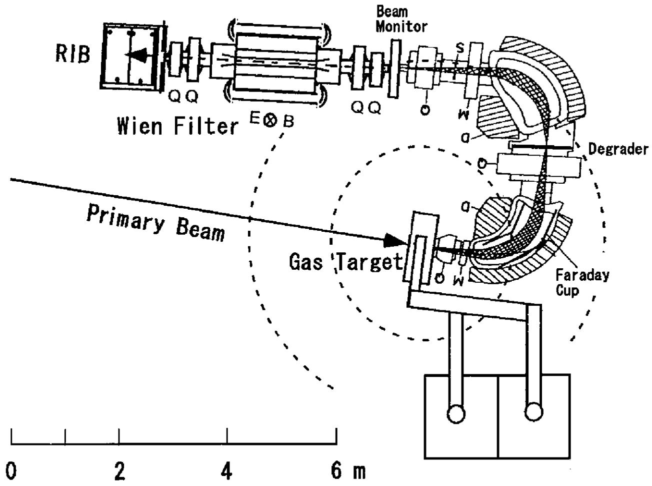

Fig. 2. The low-energy in-flight RIB separator CRIB under construction at CNS.

Table 1. Characteristics of the CRIB.

Orbit Radius	84–98 cm
Maximum energy	110 Q^2/A MeV
Energy range	30%
Solid angle	6.4 msr
Momentum resolution (at F1)	1/850
Momentum dispersion (at F2)	0

of the Linac. There is also a new CNS beam line of RIBs there.

Another effort of the CNS-RIKEN collaboration is an installation of a new beam line that delivers the AVF beams directly to all the existing experimental facilities in RIKEN. This new beam line enables one to use the AVF beams separately from the RIBF operation, that uses the Linac injector and the Ring cyclotron.

As for the experimental programs of the collaboration, there are four experimental facilities installed by the CNS; 1) the CRIB in the experimental hall E7, 2) a high-resolution QDD magnetic spectrograph transferred from the old CNS facility to the E2 room, and 3) the Linac beam line for RIB experiments and other applications, as mentioned above. The CNS effort includes also 4) a Ge ball project that can be used for both low- and high-energy heavy-ion experiments. This has a Doppler-shift correction capability. The collaboration will extend to many other parts of the research activities in the future.

3 Low energy in-flight RIB separator CRIB

The present method of low-energy in-flight production of RIBs is now practical because of the recent development of the ion source technology. Because of thin target thicknesses usable for RIB production at low energies, the production yields were limited. However, recent heavy-ion ECR sources provide very high intense beams. For light heavy ions, they produce more than 100 pμA, for instance. This will enable one to produce RIBs with $10^{8\text{-}9}$ aps, which are comparable to those obtained by other methods. This method was examined experimentally at the old cyclotron facility of CNS. The CRIB is now under construction in the RIKEN accelerator facility. The plane view is shown in fig. 2. A window-less gas target is also installed for such high-intensity beams, and large-area water-cooled beam stoppers inside the first dipole magnet. There is a momentum-dispersive focal plane (F1) just after the first dipole magnet, and a double achromatic focal plane at F2. A Wien filter is also installed to eliminate unwanted nuclear species. Of course, one can use a degrader at F1 for better particle separation. Table 1 summarizes briefly the characteristics of the CRIB.

4 Nuclear astrophysics programs at CNS and possible experiments with CRIB

Explosive hydrogen burning, which is called the rapid-proton capture process (rp-process) [1], has been investigated at CNS using direct and indirect methods. Specifically, the mechanism of the onset of the rp-process was studied extensively. In the rp-process under a condition of novae, the CNO material would be transmuted to heavier elements. The first step of the process is considered to be $^{15}O(\alpha,\gamma)\,^{19}Ne$ in the scenario [1], and could be followed by a chain of the reactions $^{19}Ne(p,\gamma)\,^{20}Na(p,\gamma)\,^{21}Mg(\beta^+)$

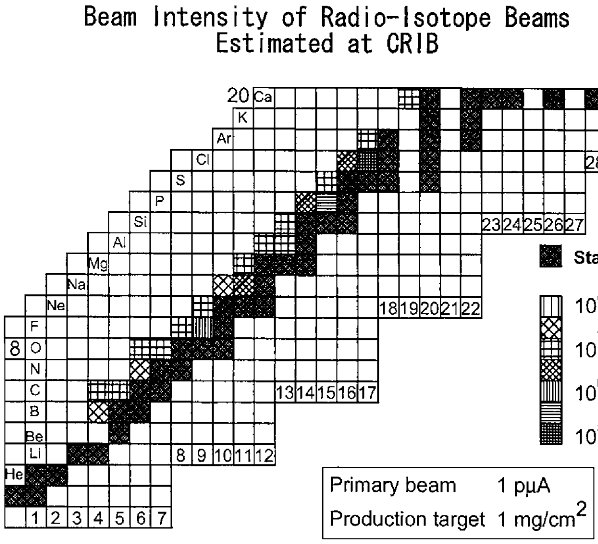

Fig. 3. RIB yield estimates by the CRIB. Here, the target thickness of 1 mg/cm^2 and the primary beam intensity of 1 pμA are assumed for production.

Table 2. Nuclear reactions of astrophysical interest to be investigated with the RIBs from the CRIB.

Reaction	Process
^{7}Be(p,γ)^{8}B	pp-chain
^{7}Be(α,p)^{10}B	Hot pp-chain
^{8}Li(p,γ)^{9}Be	Primordial nucleosynthesis
^{8}Li(α,n)^{11}B	Primordial nucleosynthesis
^{14}C(α,γ)	Primordial nucleosynthesis
^{14}O(α,p)^{17}F	Hot-CNO cycle
^{15}O(α,γ)^{19}Ne	Hot-CNO cycle
^{18}Ne(α,p)^{21}Na	rp-process
^{19}Ne(p,γ)^{20}Na	rp-process
^{20,21}Na(p,γ)^{21,22}Mg	NeNa cycle and rp-process
^{20}Na(α,p)^{23}Mg	rp-process
^{21}Mg(p,γ)^{22}Al	NeNa cycle and rp-process
^{24,25}Al(p,γ)^{25,26}Al	MgAl cycle and rp-process
^{28}P(p,γ)^{29}S	SiP cycle and rp-process

^{21}Na(p, γ) ^{22}Mg(β^+) ^{22}Na(p, γ) ^{23}Mg(p, γ) ^{24}Al(p, γ)^{25}Si ... [1–3]. Here, most of the nuclear reactions in the chain were studied by indirect methods in our project, and many resonances near and above the proton thresholds were discovered [2]. Consequently, most of the reaction rates from ^{19}Ne to ^{25}Si are enhanced, resulting in the reduction of the ignition temperature of the processes.

Many of the stellar reactions in the reaction sequence mentioned above involve proton-rich unstable nuclei that are not far from the line of stability, and can be produced with the CRIB efficiently (see fig. 3). Table 2 displays such nuclear reactions of astrophysical interest. Some nuclear species can be produced here more efficiently than in ISOL-based systems, because the present method involves only a physical process, whereas ISOL-based systems need to handle chemical processes.

Following our previous studies, the most critical reaction for the problem of novae is considered to be the ^{15}O(α,γ)^{19}Ne stellar reaction, as it seems to define the ignition of the rp-process, but the reaction rate is not well known. For this reaction, we made two experiments of indirect methods: 1) study of the single-particle nature of the resonances, and 2) measurement of the alpha-decay branching ratios for these states using a coincidence measurement for ^{19}F(^{3}He, t) ^{19}Ne(α). In the following, I will briefly explain these experiments first, and then discuss possible experiment using the ^{15}O beam from the CRIB.

The property of the threshold states in ^{19}Ne was studied with the charge symmetric reactions, ^{20}Ne(d, t) ^{19}Ne and ^{20}Ne(d, ^{3}He) ^{19}F [4]. One could identify the analog states by comparing the angular distribution shapes, because all related states are analog states. We identified the mirror relation, and also obtained spectroscopic information on the states of interest. Since the peak temperature of novae is somewhere around $T_9 = 0.2$–0.4, the nuclear levels relevant are those below 5 MeV in ^{19}Ne. The main contribution of the ^{15}O(α,γ) ^{19}Ne stellar reaction is considered to come from the 4.033 MeV $3/2^+$ state. This state was very weakly excited by the (d, t) reaction, suggesting that there is very little $d_{3/2}$ single-particle component. A DWBA analysis explains well the angular distribution for the 4.033 MeV state with the angular momentum transfer $l = 2$, confirming the spin assignment of $3/2^+$. The spectroscopic factor derived for the state is as small as $S = 0.04$. This state, however, was excited strongly by the ^{21}Ne(p, t) ^{19}Ne reaction before [5]. These suggest that this state has a 5-particle 2-hole nature. The stellar reaction, ^{15}O(α,γ)^{19}Ne, would proceed only through a small component of 2p-3h in ^{15}O. This is very much consistent with the very small α width, $(9.9 \pm 1.5)\,\mu$eV, estimated by an α-transfer reaction leading to the analog state in ^{19}F [6].

In the present ^{15}O(α,γ)^{19}Ne stellar reaction, the resonance strength $\omega\gamma$ should be dominated by the α-decay width, because the critical state at 4.033 MeV sits close to the α-threshold. Thus, we tried to measure the α branching ratio of this state. This state was excited with a reasonable cross-section by the (^{3}He, t) reaction at 30 MeV. The experiment was performed by a coincidence measurement of tritons and α's from ^{19}F(^{3}He, t) ^{19}Ne*(α) ^{15}O, where tritons were momentum analyzed by the QDD magnetic spectrograph. The decay α-particles were measured at backward angles in coincidence with the tritons by four strip-Si detectors which cover about 11% of 4π. The α branching ratios were determined with a little better statistics in the present experiment than in the previous experiment [7], but are consistent with them for the high-lying states. However, the branching ratios of the levels at 4.033 and 4.379 MeV were not determined in the present experiment because of the very small α yield.

The most interesting experiment for the problem is to study the ^{15}O(α,γ)^{19}Ne stellar reaction directly using an ^{15}O beam. However, it seems quite difficult because the yield rate expected would be extremely low. An alternative way is to use a semi-direct method for the reaction, *i.e.*, a direct α-transfer reaction to deduce the α width of the critical state in ^{19}Ne. The secondary beam of ^{15}O can be produced efficiently with the CRIB, using the (p, n) reaction at an energy just above the threshold in the inverse kinematics. The energy spread of the ^{15}O beam should be reasonably small, about 1%, and the beam spot size of a few mm diameter at the focal plane. If one can use an ^{15}O beam of 10^9 aps on target, one could measure the angular distribution for the ^{6}Li(^{15}O, ^{19}Ne*(4.033))d reaction either measuring deuterons at backward angles or ^{19}Ne particles at forward angles with a reasonable count rate, something like a few events per hour or more.

In summary, the CRIB is the first extensive low-energy in-flight RIB separator. Although the production of nuclear species is very much limited to the nuclei close to the line of stability, the production rate can be very high because of the inverse kinematics we adopt here and also the large cross-sections for production, although the available target thickness is small. This weak point will be compensated with very high beam intensities from ECR ion sources. This method for low-energy RIB production should be, thus, very useful in practice.

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