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New ISOL-Based Radioactive Nuclear Beam Facility at INS

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* Invited talk presented at the Fourth International Conference on Radioactve Nuclear Beams, held on June 4 - 7, 1996 in Omiya, Japan.

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An ISOL-based radioactive nuclear beam facility is just about to come into operation at INS. The present status of the INS radioactive nuclear beam project is reported. The capability of the facility and possible experiments are also discussed, including research programs of nuclear physics and nuclear astrophysics.

1. INTRODUCTION

Because of rapid development in nuclear physics of unstable nuclei, radioactive nuclear beams (RNB) are now available for a wide range of energy. They are obtained mostly from heavy-ion induced projectile fragmentation reactions at intermediate and high energies. However, high-intensity and high-quality RNBs at low energies are hardly obtained by this method.

The most feasible way for the purpose is to use Isotope-Separator On-Line (ISOL) with a thick target for radioactive nucleus productions, and accelerate them by a second accelerator. This ISOL-based RNB facility can provide higher intensities of RNB than the intermediate or high energy heavy-ion facilities. This difference is dramatic at low energies. In the ISOL-based facilities, one may use a high-energy proton beam to produce unstable nuclei where thick targets can be used, and the beam emittance to be obtained is as good as for ordinary stable nuclear beams. A pioneering setup was established with a limited capability at Louvain-la-Neuve [1]. Although the primary beam energy is only 30 MeV, the beam current is as high as 500 μA for radioactive nucleus productions. There are at least four projects going on for establishing such facilities in the world, i.e., Oak Ridge National Laboratory [2], GANIL [3], Louvain-la-Neuve, and the Institute for Nuclear Study of the University of Tokyo (INS) [4]. These facilities will be in operation

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within a year or two. There could be some overlaps on the subjects being proposed in these RNB facilities. However, there are clearly different characteristics in each facility, primary beams, ion sources, mass separators, and the post accelerators. These will give complemental and useful efforts for this field.

The RNBs have opened a new page in nuclear astrophysics. As has been emphasized already [4–6], the radioactive nuclei play a crucial role in explosive nucleosynthesis in the universe such as novae and supernovae. To investigate the nuclear reactions in such astrophysical conditions by a direct simulation, radioactive nuclear beams of high-intensity and low beam emittance are the crucial factor for the success of experiments. Such a high quality RNB will be supplied only in ISOL-based RNB facilities, as discussed above. Following the projects mentioned above, another two proposals have been approved recently at TRIUMF [7] and CERN-ISOLDE [8].

In this paper, we will report the present status of the INS-RNB project that involves a construction of an ISOL-based RNB facility, and research programs to be conducted with the RNB provided there. The RNB facility is just about to be operational. Possible experiments to be investigated in this facility are also discussed.

2. OVERVIEW OF THE INS RNB-FACILITY

2.1. Layout

This RNB project is a part of E-Arena in Japanese Hadron Project. Since ISOL-based RNB facility requires a variety of developments in technology for high intensity RNB, our first aim is to develop such technology with a thick target method using the small existing cyclotron that has K = 68, and then study with the RNBs nuclear reactions relevant to nuclear astrophysics as well as to nuclear physics. Thus, the present project at INS is called, in other word, INS R&D project. Figure 1 displays an overall schematic plan of the E-Arena facility. The R&D project covers the left-hand half of the figure. The site for the project, where the post accelerators and the experimental apparatus are installed, is apart from the existing cyclotron facility. There is a 60-m long transport line for the low energy beams of radioactive nuclei produced by proton or ^{3}He beams from the cyclotron. The detailed layout of the facility is provided in Fig. 1 in ref. [4].

2.2. Ion Source

Ion source technology with thick targets [9,10] is the most crucial part for the ISOL based RNB facilities. The achievement of high ionization efficiency critically determines the capability of the facility. Thus, we have been working on development of the ion source in the past years. Two type ion sources are now working with high efficiency for some elements, i.e., the surface ionization ion source and ECR ion source. The Febiad-type ion source is also under development on-line. An interesting and important development achieved in this project is a bunching method, which not only gives a way of efficient extraction of ions but also enables a direct measurement of the ionization efficiency of the ion source [9,10]. Beam bunching is required for an efficient operation in the present facility since the post accelerator, the split-coaxial(SC)-RFQ linac, operates with a duty factor of 30 % for ions of low charge-to-mass ratios. The bunching was simply made by installing an electrode just at the exit of the ion source, and applying an alternative positive and negative voltages relative to the ionizer, which controls to "close" and "open",

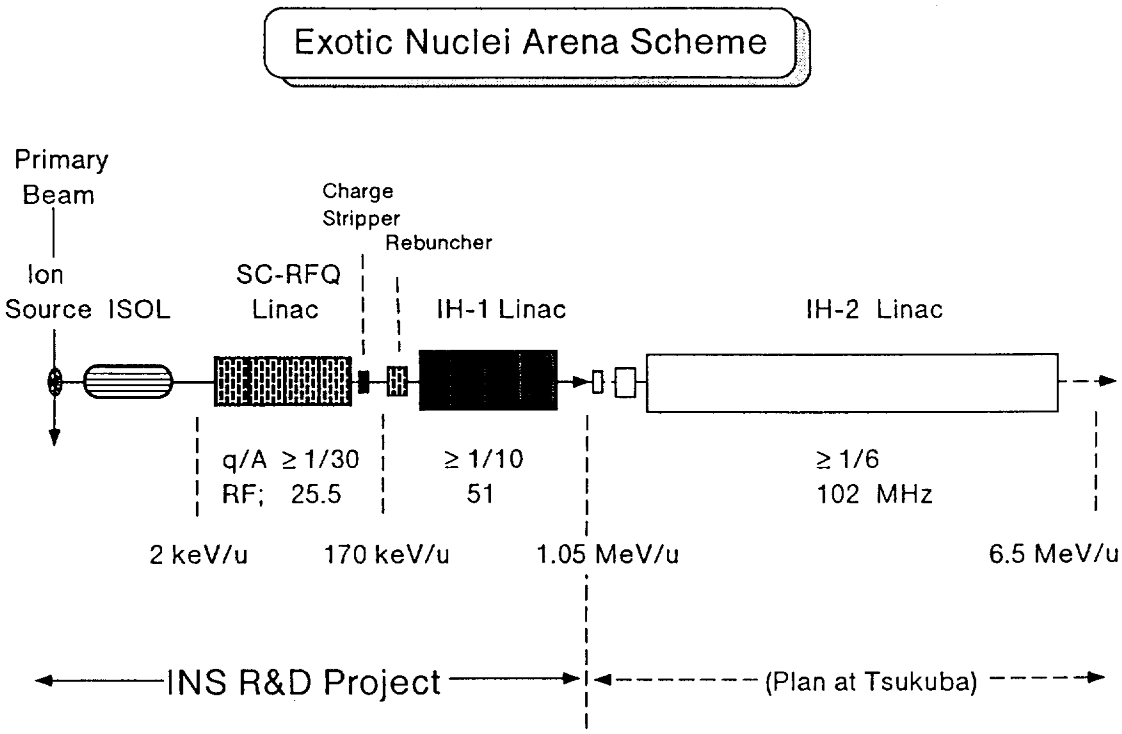

Figure 1. Scheme of the Exotic Nuclei Arena in Japanese Hadron Project. The INS R&D project, the left hand half, is the present RNB facility at INS.

respectively, the exit of the ion source. The ions of high ionization efficiency seem to be stored in the ion source region when "closed". Thus, the bunching gains obtained for ^{38}K ions, tested on-line, are as high as nearly a factor of five for an operation of 20 % duty factor at high repetition rates. This means that almost all the ions produced are extracted without a major loss. Since this bunching gain is directly related to the ionization efficiency [10], it is a very useful tool for ion source development.

2.3. High resolution mass separator

A schematic view of the high resolution mass separator is shown in Fig. 2. This separator has a mass resolution of $m/\Delta m = 9000$ and has four nice features. One is that the first magnetic quadrupole doublet is movable so that different type of ion sources can be set in, and the second is that an arbitrary negative potential can be applied for mass separation because the whole system is insulated from the ground potential and thus a full extraction voltage can be used for a good mass separation. The third point is that there is a rough mass separator at the beginning and it can be operated with a slightly different potential, which gives another purification of the beam of interest. The last point is that one can extract the RNBs at very low velocity. It will be ideal for injecting radioactive nuclei into an ion trap, for instance. The whole setup is now in the tuning stage. The energy of the ions extracted by the separator is set to 2 keV/u to match the velocity to be accepted by the SC-RFQ linac. It was already tested for ^{19}Ne beam and gave a high

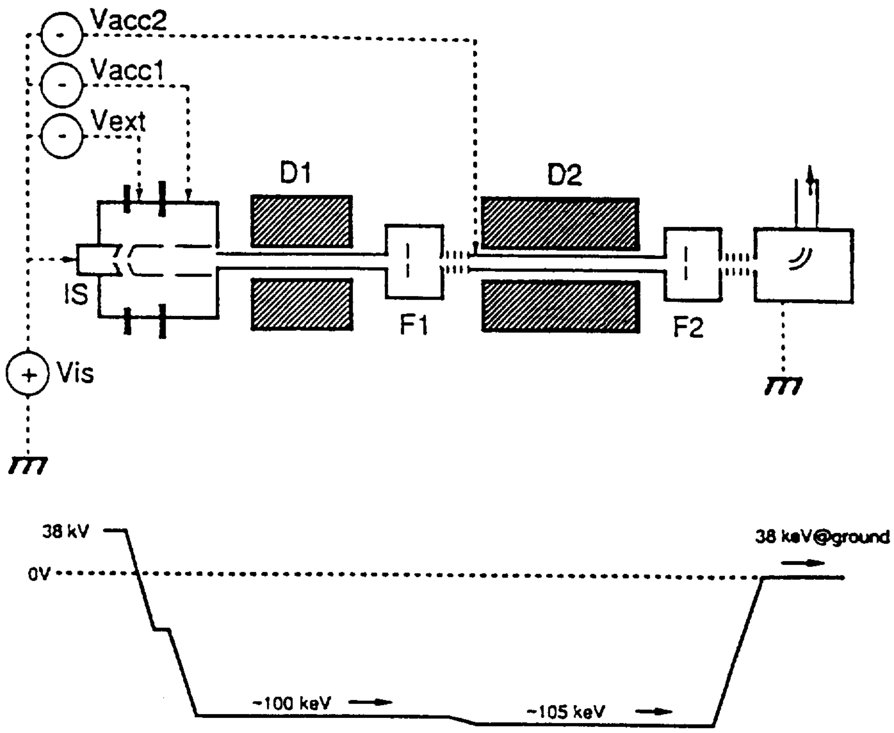

Figure 2. High resolution mass separator and the high-voltage potentials to be applied for high-resolution and good-purification operation.

transmission, about 90 %. The mass resolution was not fully tested, but so far about m/Δm = 3000 was obtained for the beam from the Febiad source. It will be tested soon by putting high voltages to the whole system, and applying the multipole elements for the high resolution operation of m/Δm = 9000 as designed.

2.4. Low-energy RNB transport line

The 60-m long low-energy transport line is composed of about 50 sets of electric quadrupole doublets and 7 electric deflectors. It was already assembled and is being tested with a $^{20}Ne^{+}$ beam of 2 keV/u, the designed energy for the line and the SC-RFQ linac. The vacuum of the most parts of the line is in the range of 10^{-7} Torr that was designed for high transmission for the very low energy RNBs. A high transmission of the beams is the goal of this part. This is the last part to be completed in the facility.

2.5. Accelerators

Two types of linacs were constructed for acceleration of the radioactive nuclei [11]. The first linac, SC-RFQ linac that operates at 25.5 MHz, has already succeeded in acceleration of $^{14}N^{+}$ ions up to the designed value of 170 keV/u with an efficiency more than 95 %. This linac is capable of accelerating the ions of $q/A \geq 1/30$.

The second accelerator is an interdigital H-type (IH) linac that operates at 51 MHz and provides variable energies up to 1.05 MeV/u for the ions of $q/A \geq 1/10$. This

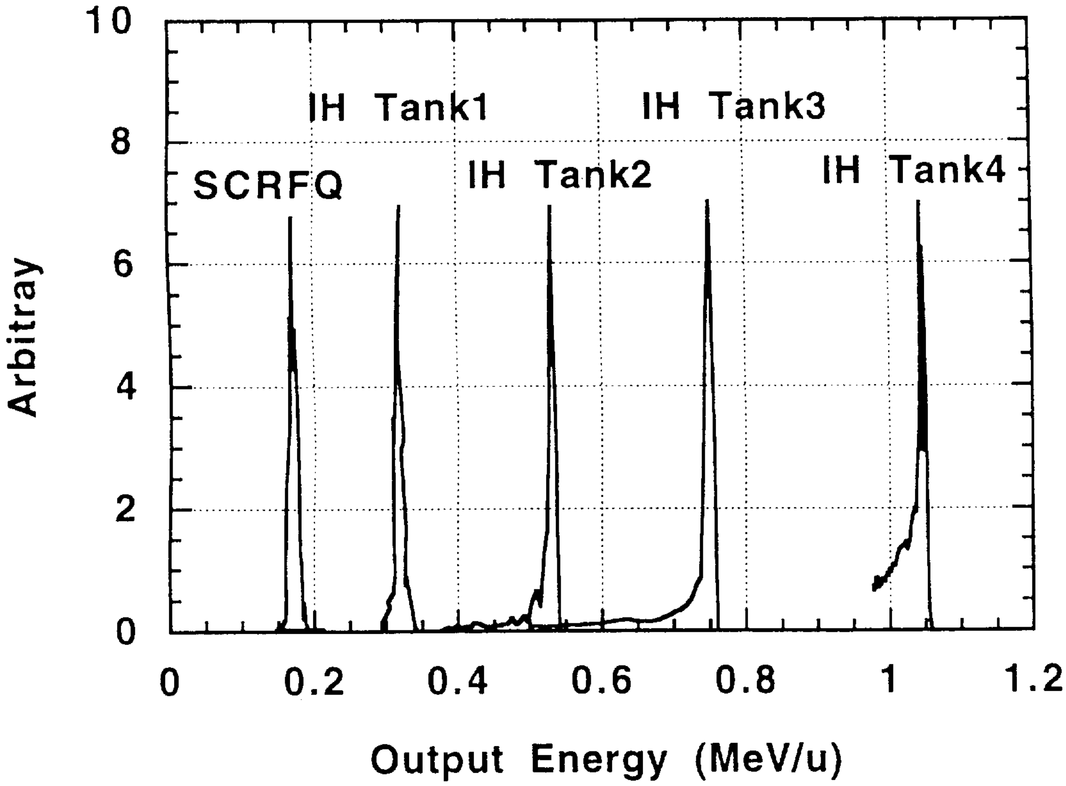

Figure 3. The beam current from the IH linac observed after the first dipole magnet. The RF power was applied to each tank of the IH linac one by one.

linac consists of four accelerator tanks, and has a separate function of acceleration by the linac parts and focusing by triplet Q magnets in between. It can accept beams of three-times larger emittance than those of the SC-RFQ linac so that it can capture most ions through a charge stripper. The IH linac successfully accelerated $^{14}N^{2+}$ beam end of March, 1996, and the first beam of stable nuclei was transported to the target of the recoil mass separator for nuclear astrophysics experiments. The beam energy can be changed roughly by turning on a proper number of the RF powers, and then tuned precisely by changing the power and the acceleration phase. Figure 3 shows beam currents from the IH linac, observed after a dipole magnet.

Between the two linacs, there are a charge stripper and a rebuncher that retunes the time structure, resulting in a large capture efficiency of the beam injected to the IH linac. The energy resolution of the accelerated beams will be also improved to an order of 1 % or better by tuning the RF power and the RF phases of the IH linac tanks, which will be tested soon.

2.6. Radioactive nuclear beams

Radioactive nuclides will be produced by a 40-MeV proton beam or a 90-MeV ^{3}He beam obtained from the INS SF-cyclotron. The primary intent of the project is to accelerate unstable nuclides of A $\leq$ 30. Although the intense production of unstable nuclei is very

Table 1
On-line test results of ISOL ion source.

Radioactive Ion	Half Life	Target Material	Ion Source	Primary Beam (MeV)	RIB Yield (aps@10eμA)	Efficiency (%)
$^{38}K^+$	7.64 min	CaF_2	Surface	^3He 70	3.2E9	67
$^{21}Na^+$	22.5 sec	CaF_2	Surface	^3He 70	1.3E7	2.0
$^{20}Na^+$	0.45 sec	CaF_2	Surface	^3He 80	6.2E5	0.2
$^{19}Ne^+$	17.2 sec	CaF_2	Febiad	p 20	1.5E8	1.0
"	"	LiF	ECR	p 30	1.0E9	3.8
$^{19}Ne^{2+}$	"	LiF	ECR	p 30	2.2E8	0.9
$^{18}Ne^+$	1.67 sec	CaF_2	Febiad	p 35	5.0E6	0.3

much limited near the line of stability, we may produce very easily 10^9 atoms or more for these nuclear species. Table 1 shows some of radioactive nuclear species extracted from the ion source, where the intensities are normalized to the case of a primary beam of 10 μA. There are, of course, a considerable beam loss in various stages from the ion source to the experimental target. The most crucial part is the ion source, as mentioned earlier. The easiest elements such as alkali metals could be obtained with an overall efficiency of 10 % from the production to the target. This ratio is dependent on the efficiencies of ionization, transport, and acceleration.

The ions of $1/10 > q/A \geq 1/30$ need a charge exchange between the two linacs, which induces a considerable beam emittance increase and a spread of charge state distribution. These result in a significant beam loss. If we can get intense q = 2+ ions from the ion source instead, we can avoid this problem. This will also open a way to acceleration of ions of A = 31 - 60. This is also a subject we are working on. Some $^{19}Ne^{2+}$ ions were already extracted in the on-line test. More details are described elsewhere [4,11,12].

3. RESEARCH PROGRAMS

There are three research subjects that we are planning to study in this facility, i.e., nuclear astrophysics, nuclear physics, and material science. In fact, extensive preparations were made for two subjects; 1) the recoil mass separator together with a low-background, high efficiency gamma detector of NaI for nuclear astrophysics, and 2) the ion-trap spectroscopy facility primarily for nuclear physics.

3.1. Nuclear astrophysics

Three beam lines are prepared for experiments after the IH linacs. One line has a recoil mass separator (RMS) together with the low-background gamma ray detector system. Figure 4 shows the experimental setup of the RMS and the gamma detector.

The RMS is designed for low-energy capture reaction study for nuclear astrophysics. It

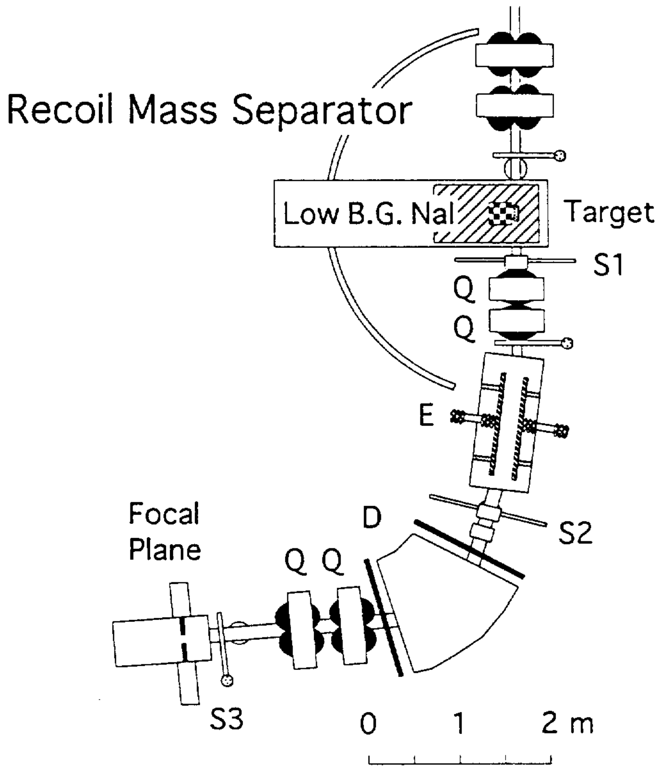

Figure 4. The setup of the recoil mass separator and the low-background gamma detector for nuclear astrophysics experiments.

has a mass resolving power of about 60, and the beam-energy acceptance of 5 %, which allows us to use the beam through a charge stripper between the two accelerators. The RMS should help to reduce the accidental gamma rays for the capture-gamma measurements. Since the event rate expected is quite small because of small cross sections at very low energies and the low beam intensity, the NaI(Tl), the main part of the gamma detector, is made with low-background material, and the same for the lead and Cu shield. Further, an extensive setup also is being prepared, a window-less gas target of differential pumping with a blow-in geometry [13]. This has good advantages for this kind of experiments. As compared to polyethylene target for ^{1}H, 1) the effective target thickness increases roughly by a factor of two, 2) high purity ^{1}H can be used, 3) unnecessary scattering of the beam particles that cause a high background in the target region will be absent, and 4) there is no reaction background from C target.

Table 2 shows a short list of possible experiments of nuclear astrophysics we may pursue in this facility. Many nuclides of interest for nuclear astrophysics locate close to the stable nuclear region, the shaded area in Fig. 5, and the beam energies needed is also less than 1 MeV/u. Thus, the present facility is well suited for this purpose. Specifically, the ignition mechanism of the explosive hydrogen burning is of great interest, which include reaction chains of ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na, and ^{14}O(α,p)^{17}F(p,γ)^{18}Ne(α,p)^{21}Na. Since the present facility also provides low-energy and high intense stable beams, some critical stellar reactions of stable nuclei can be studied such as the ^{12}C(α,γ)^{16}O reaction.

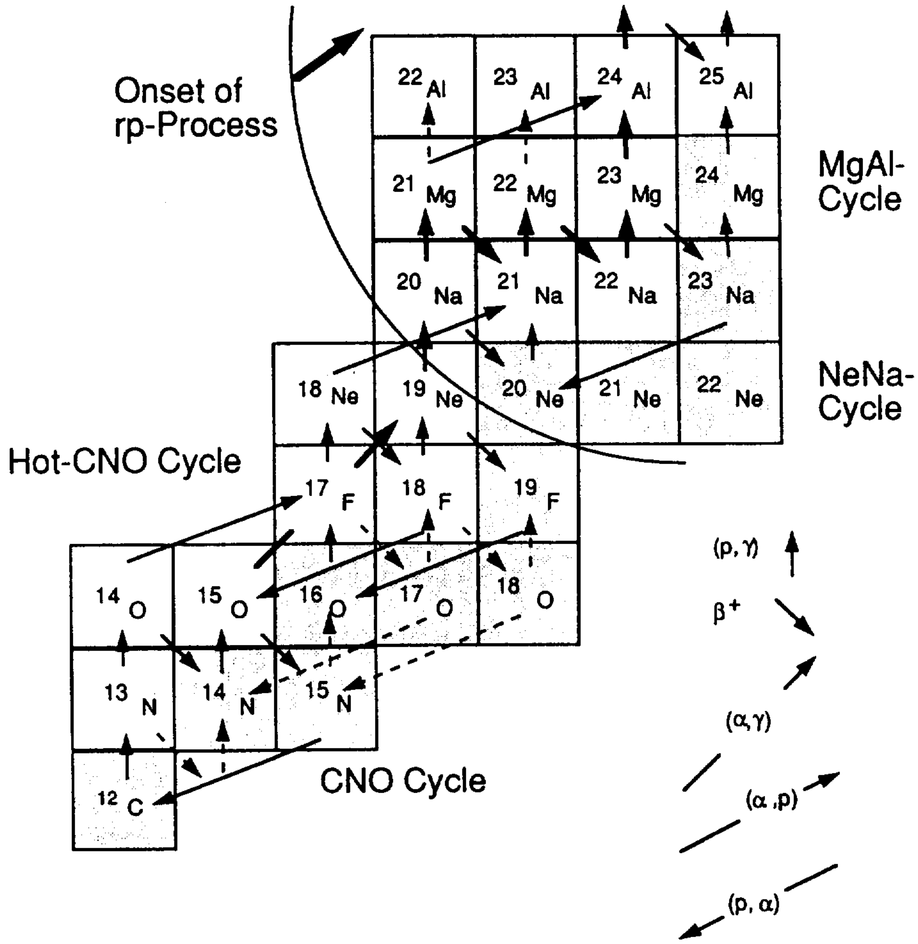

Figure 5. The nucleosynthesis flow diagram of the Hot-CNO cycle and the early stage of the rapid-proton process. The shaded area indicates stable nuclei.

3.2. Ion trap spectroscopy

An extensive setup is also being prepared for learning property of short-lived nuclei with very high accuracy, that includes an RF trap, a Penning trap, and a UV laser. This is a combination of ion trap and laser spectroscopy. A laser-microwave double resonance method was achieved for studying hyperfine anomaly. One of the key factors for this setup is to realize a short cooling time to confine ions in a trap. Laser cooling was successfully applied to Ca ions into a linear RF trap, giving a cooling time of about 3 sec. A detailed discussion is given in ref. [14].

4. PROSPECT OF THE E-ARENA PROJECT

The E-arena project will be fully realized at the new campus in Tsukuba site, where INS will be reborn next year, April, 1997. Figure 6 indicates the plan being discussed for the arena, where the building is the existing E-counter hall at the KEK proton-synchrotron in Tsukuba. In the new site, the primary beam is a 3-GeV proton of 10 μA from the

Table 2
Possible unstable-nuclear-beam induced reactions to be studied in this project.

REACTION	SUBJECT
$^{7}Be(p,\gamma)^{8}B$	Solar model
$^{8}Li(p,\gamma)^{9}Be$	Primordial nucleosynthesis
$^{8}Li(\alpha,n)^{11}B$	Primordial nucleosynthesis
$^{14}C(\alpha,\gamma)^{18}O$	Primordial nucleosynthesis
$^{14}O(\alpha,p)^{17}F$	HCNO
$^{15}O(\alpha,\gamma)^{19}Ne$	HCNO
$^{17}F(p,\gamma)^{18}Ne$	HCNO
$^{19}Ne(p,\gamma)^{20}Na$	HCNO and rp-process
$^{20,21}Na(p,\gamma)^{21,22}Mg$	NeNa and rp-process
$^{21}Mg(p,\gamma)^{22}Al$	NeNa and rp-process
$^{24,25}Al(p,\gamma)^{25,26}Si$	MgAl and rp-process
$^{28}P(p,\gamma)^{29}S$	SiP and rp-process
$^{12}C(\alpha,\gamma)^{16}O$	Stellar model

high intensity proton synchrotron to be built in the JHP program, and will provide us with a variety of short-lived nuclear species far from the line of stability. This energy is much superior to 500 MeV in production of light elements by multifragmentation process. A third linac will be added to boost up the RNBs over 6.5 MeV/u for nuclear reaction and structure study. The IH structure, the same as that for the second linac, will be adopted, but the minimum q/A value will be increased up to something like 1/6 for cost performance. The construction of the whole E-arena facility will take another 5 years. Therefore, we will use the present facility at the INS site for the first two or three years, and move it to the new campus when other parts are ready. The most critical part is the radiation safety and the remote handling of high radioactivities. These will require more developmental works. More versatile ion sources will be the key point for the development.

The experimental works in this pioneering project is just about to start, and is totally open to anyone who has interest to work with.

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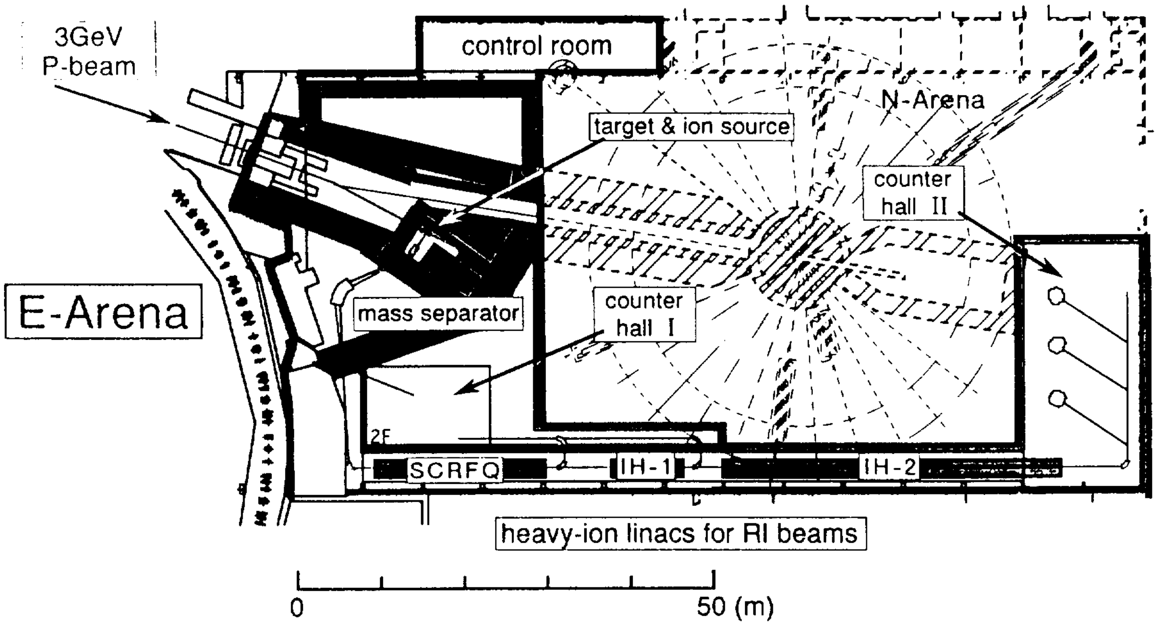

Figure 6. A plan of the new site for the E-arena in Tsukuba.

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