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ABSTRACT: 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, nuclear astrophysics, and material science.

I. INTRODUCTION

Because of rapid development in nuclear physics for unstable nuclei, radioactive nuclear beams are now available for a wide range in energy. They are obtained mostly from heavy-ion induced projectile fragmentation reactions at intermediate and high energies. However, high-intensity and high-quality beams at low energy 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 unstable nuclei production, and accelerate them by a post accelerator. This ISOL-based radioactive nuclear beam facility can provide one or two orders of magnitude higher beam intensity than the intermediate or high energy heavy-ion facilities do. Of course, 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]. There are at least four projects going on for establishing such a facility in the world, i.e., Oak Ridge National Laboratory, GANIL, Louvain-la-Neuve, and INS, University of Tokyo. These facilities will be in operation in a few years, but each has a different characteristic feature depending on the primary beams, and thus the radioactive ion species to be produced, the post accelerators, and the energy ranges of the radioactive ion beams.

Here, I will make a short status report of the INS project we are working on, and discuss the capability and possible experiments in the facility.

II. OVERVIEW OF THE INS FACILITY

Figure 1 displays the overall plan of the facility under construction. The new site for the project, where the post accelerators and the experimental apparatus will be installed, is apart from the existing cyclotron facility. There will be a 50-m long transport line for the beams of unstable nuclei produced by light ion beams from the sector focusing (SF) cyclotron that is an AVF cyclotron of K = 68.

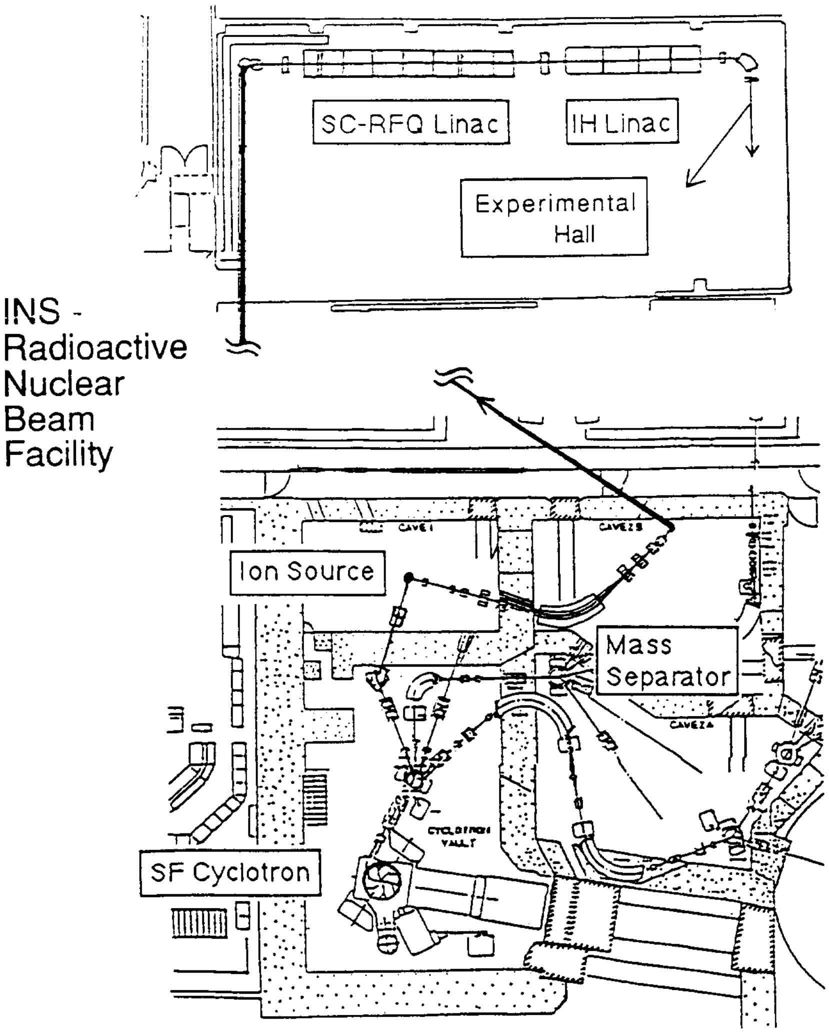

Fig. 1 INS radioactive nuclear beam facility under construction.

1) Ion Sources

Ion source technology with thick targets is the most crucial part for the ISOL based facilities. The achievement of high ionization efficiency critically determines the capability of the facility. Therefore, we have been working on development of the ion source for more than four 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 high bunching gains but also enables a direct measurement of the ionization efficiency of the ion source[2,3]. Beam bunching is required for an efficient operation in the present facility since the post accelerators, linacs, operate with a duty factor of 30 % for ions of low charge-to-mass ratios. The bunching method developed was simply realized 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", respectively, the exit of the ion source.

Figure 2 shows the bunching gains obtained for the ions denoted, including ^{38}K ions tested on-line. K ions are clearly extracted with more than 90 % efficiency even for 20 % duty factor at high repetition rates. This efficiency directly related to the ionization efficiency[3], and thus it is a very useful tool for ion source diagnosis.

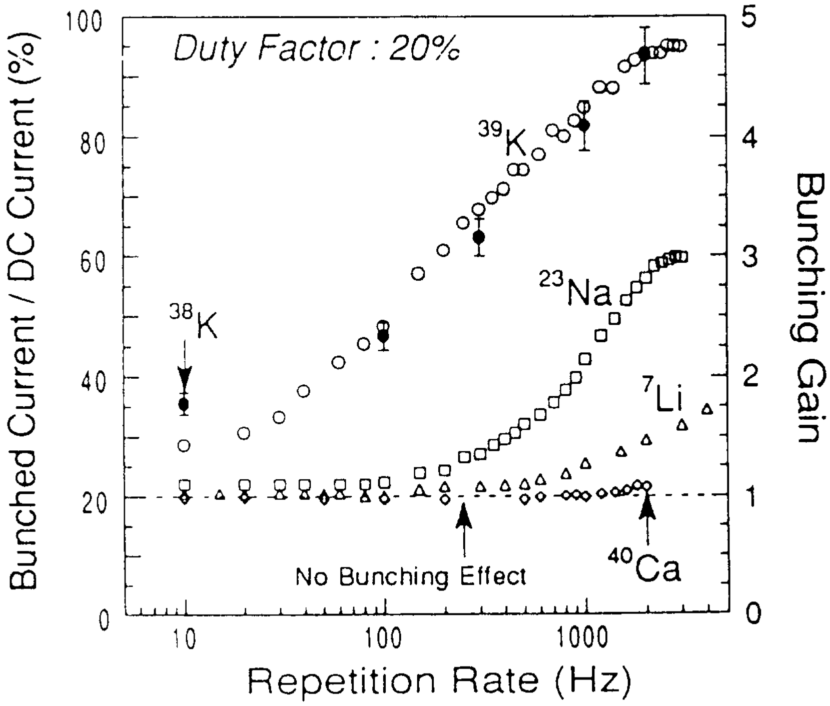

Fig. 2 Bunching gains as a function of repetition rate for 20 % duty factor for the ions denoted.

2) High Resolution Mass Separator and the 50-m Low-Energy Beam Transport Line

A schematic view of the high resolution mass separator is shown in Fig. 3. This separator has a mass resolution of $m/\Delta m = 9000$ and has three nice features; one is that the first magnetic quadrupole doublet is movable so that it can adjust the source point even for the ECR ion source, and the second is that an arbitrary negative potential can be applied for separation because the whole system is insulated from the ground potential and thus a full extraction voltage can be used for a good separation. The third point is that there is a rough mass separator at the beginning and it can be operated with a different potential, which gives another purification of the beam of interest. 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 linac.

The 50-m long low-energy transport line is composed of about 50 sets of electric quadrupole doublets and 7 deflectors. They are now in manufacturing stage, and will be installed in the first half of the next year.

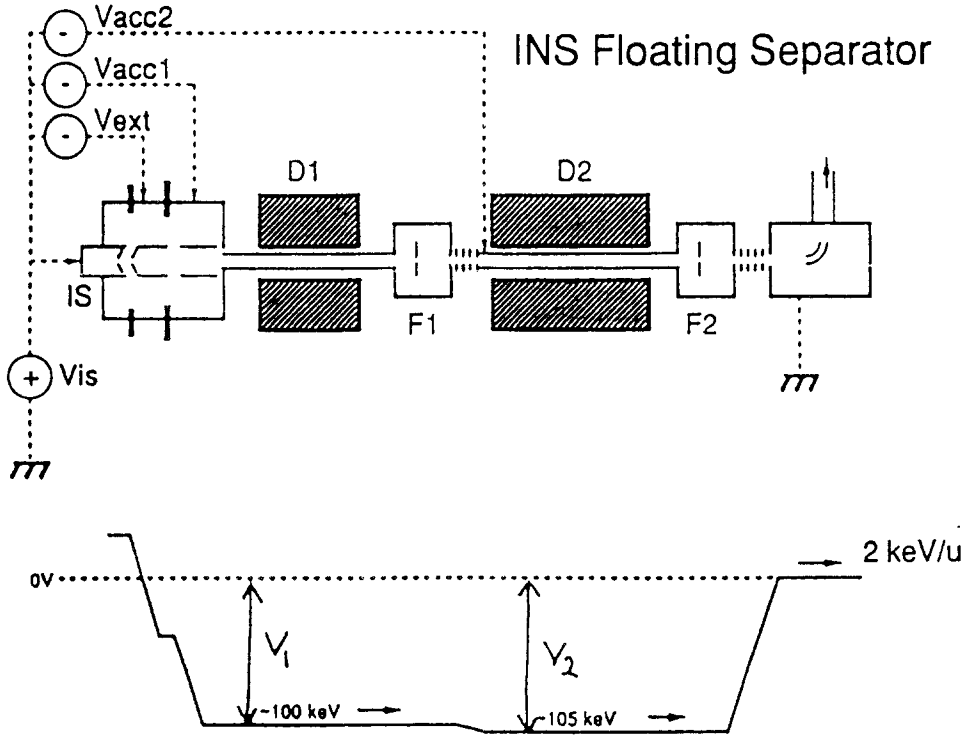

Fig. 3 Schematic layout of the INS-type on-line isotope separator, which is floated to negative voltages.

3) Accelerators

Two types of linac were adopted for acceleration of the radioactive nuclear beams[4]. The first linac is a split-coaxial RFQ(SC-RFQ) linac that operates at 25.5 MHz and accelerates ions of $q/A \geq 1/30$ from 2 keV/u to 170 keV/u. The second accelerator is interdigital H-type linac that operates at 51 MHz and provides variable energies up to 1.05 MeV/u for the ions of $q/A \geq 1/10$.

The SC-RFQ has been designed and built based on a previous test of a proto-type machine that successfully had accelerated N^+ ions with about 90 % transmission. This machine has been already assembled in the position. The tuning work has just started. The second part, IH linac, was also designed based on a cold model. This has a separate function of acceleration by the linac and focusing by triplet Q magnets. This linac can accept beams of three-times larger emittance than those of the SC-RFQ linac so that it can accept ions through a charge stripper. This is under construction, and will be installed next spring.

Between the two linacs, we have a charge stripper and a rebuncher that retunes the time structure, resulting in a wide capture of the beam injected to the IH linac. The energy resolution of the accelerated beams will be improved by tuning the rf power and the phase.

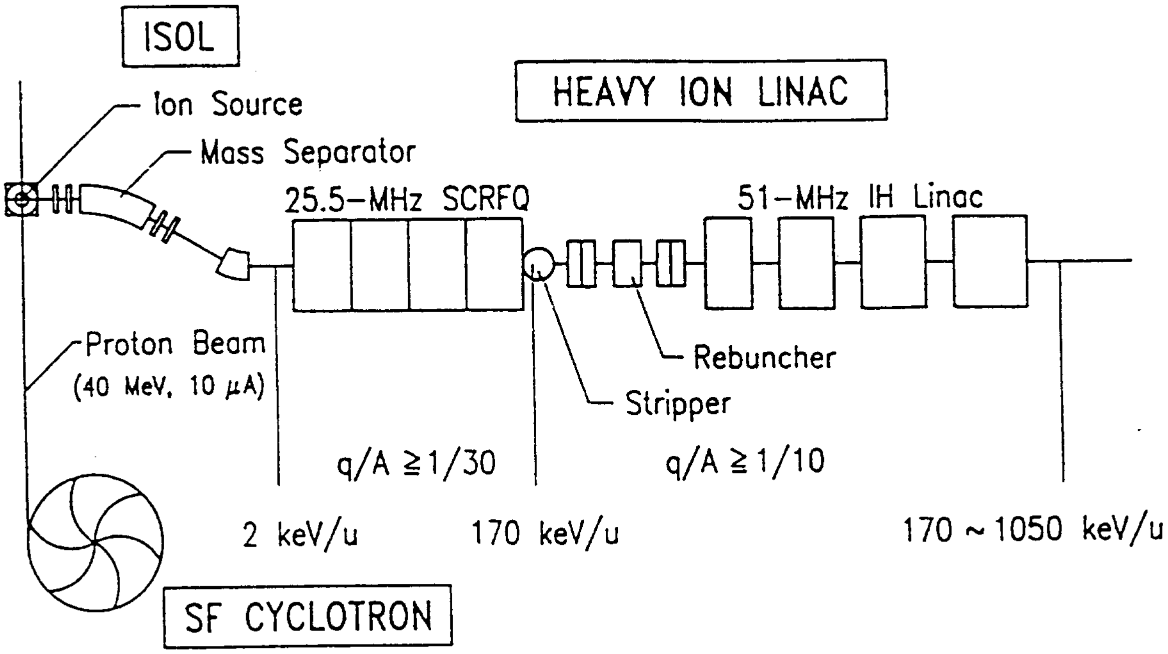

Fig. 4 The post accelerator scheme for radioactive ions from the ISOL system. This brings up the ion energy from 2 keV/u to 1.05 MeV/u.

4) Experimental Apparatus

Three beam lines will be prepared for experiments after the linacs. One line has a recoil mass separator(RMS) together with a low-background gamma ray detector system, specifically designed for nuclear astrophysics experiments [5]. The second line has a scattering chamber for nuclear physics and astrophysics, and the third line is for the studies of material science and hyperfine interaction. There is also a beam line and an extensive laser setup just after the ISOL for ion trap spectroscopy [6].

The RMS is designed for low-energy capture reaction study for nuclear astrophysics. It has a mass resolving power of about 60, and the beam spread acceptance of 5 %, which can allow to use the beam through a charge stripper between the two machines. The RMS should help to reduce the accidental gamma rays. Since the event rate expected is quite small because of small cross sections 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.

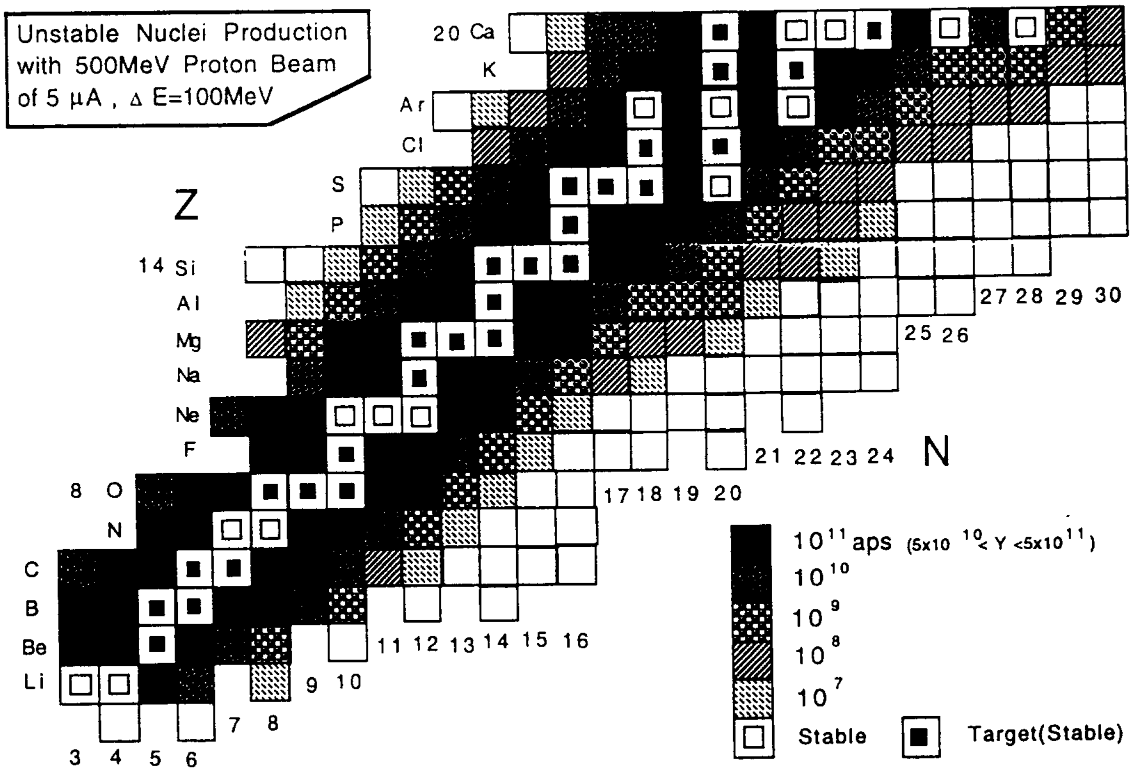

Fig. 5 Predicted unstable nuclei produced by a 40-MeV protons of 10 μA.

III. CAPABILITY AND POSSIBLE EXPERIMENTS

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 = 30 or less. Although the intense production of unstable nuclei is very much limited near the stability line, we may produce very easily 10^9 atoms or more for these nuclear species. Figure 5 shows the predicted production yields for 10 μA of 40-MeV protons. 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 part, 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 q/A between 1/10 and 1/30 need a charge stripper between the two linacs, which produces 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 is a subject we have to develop in the near future.

There are three major research subjects that we are planning to study in this facility, i.e., nuclear astrophysics, ion-trap spectroscopy, and material science, as mentioned before.

Table 1 Possible unstable-nuclear-beam induced reactions to be studied in this project.

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

One of the main programs is the nuclear astrophysical problems [5]. As was sketched in the previous section, we are now preparing an extensive instrument for this purpose. Many nuclides of interest for nuclear astrophysics are within the range of dark 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. Table 1 shows a short list of possible experiments we may pursue in this facility. There could be some overlap on the subjects being proposed in other facility. However, there are clear different characteristics in each facility. These will give a complemental effort for the subject of interest. Since the present facility also provides low-energy and high intensity stable beams, some critical stellar reactions of stable nuclei can be studied such as the $^{12}C(\alpha,\gamma)^{16}O$ reaction.

Extensive setups also are being prepared, including an RF trap, a Penning trap, and a UV laser, for the laser spectroscopy of unstable nuclei. Bohr-Weisskopf effect (hyperfine anomaly) will be systematically investigated by a laser-microwave double resonance experiments [6].

As is intended by the organizers of this meeting, we would like to encourage international collaborations in this facility.

REFERENCES:

1) P. Decrock, et al., Proc. Int. Workshop Unstable Nuclei in Astrophysics, ed. S. Kubono and T. Kajino, World Scientific, 1992, p. 75.
2) Y. Shirakabe, N. Ikeda, S. Ohkawa, T. Nomura, and T. Shinozuka, Nucl. Instr. Method, A337 (1993) 11.
3) T. Nomura, Y. Shirakabe, N. Ikeda, and T. Shinozuka, Nucl. Instr. Method, B93 (1994) 492.
4) S. Arai, et al., Proc. 17th International Linac Conf., Tsukuba, Japan, 1994, and .M. Tomizawa, et al., ibid., to be published.
5) See for example, S. Kubono, Comm. on Astrophys. 16 (1993) 287.
6) I. Katayama, et al., Proc. Second China-Japan Nuclear Physics Symp. "Recent Topics on Nuclear Physics", Beijing, 1994, to be published.