RIKEN RI Beam Factory Plan and R&D Activity

Isao Tanihata

RIKEN(The Institute of Physical and Chemical Research), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

1. The Facility Plan

The RI Beam Factory is under construction to promote science using high-energy beams of radioactive nuclei. A bird-eye view of the planned facility is shown in Fig. 1. RIBF includes three new cyclotrons (fRC, IRC, and SRC) connected to the existing separate sector cyclotron (RRC). The SRC is the main super-conducting ring cyclotron of K=2400 MeV. The IRC and the fRC are booster cyclotrons. The available energy of accelerated beams is shown in Fig. 2. Under the combination of IRC and SRC, the energy of heavy ion is variable.

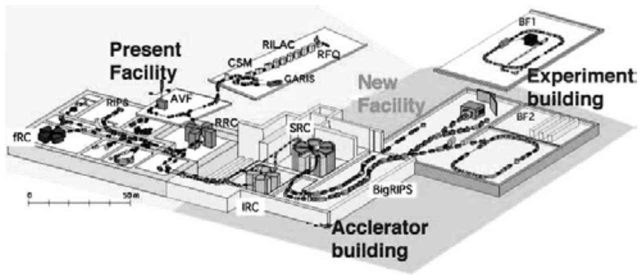

Fig. 1 A bird-eye view of RIBF at RIKEN.

Nuclei up to mass number 40 are accelerated to up to 400*A* MeV but the maximum energy of heavier nuclei gradually decrease. With a use of fRC, 350*A* MeV of energy is available for all the mass range though it is a fixed energy.

Two fragment separators are planned to deliver different RI beams simultaneously. One of the separators consists of normal conducting dipoles and super-conducting quadrupoles to obtain large angular acceptance so that it has high capture efficiency for fission product. The other separator uses only normal conducting magnets but has safficient acceptance for projectile fragments. Both of the separators have two-separation sections so that the trigger of each nucleus can clearly be made.

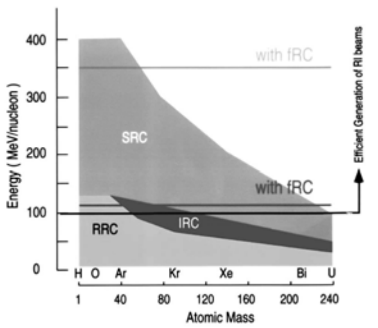

Fig. 2. Primary beam energy at RIBF.

Planned experimental floor is shown in Fig. 3. It is so designed that RI beams from two separators can be delivered to main experimental facilities.

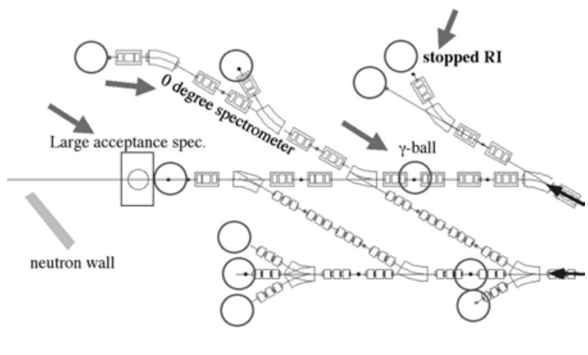

Fig. 3 Planned experimental floor.

We also plan to build a storage ring and an electron scattering ring. The

R&Ds for those are under progress.
The project has been funded for construction of cyclotrons and super-conducting separator. They will be completed in 2006 and experiments are planed to start in 2007.

2. The R&D activities

Presently, R&D activities are mainly on the experimental facilities. Here, I present several of R&D activities that are essential for experiments in RIBF.

2.1 Production target

Power loss of the beam on the production target ranges up to 20 kW in area of 1 mm^2. Although the total power is not as high as an ISOL or a neutron spallation source, the energy-loss density is extremely high, up to 4 MW/cm^3. We have developed a water-cooled rotating target and measured its characteristics. Figure 4 shows the result of the test experiment with 30 cm diameter Carbon target. The extrapolation of the data shows that the target with rotation speed faster than 150 rpm can be operated up to 15 kW of beam. A higher rotation speed is expected to give better result also. This target has also been used in the present RIPS separator in RIKEN and stable operation was achieved with high-intensity ^{48}Ca beam.

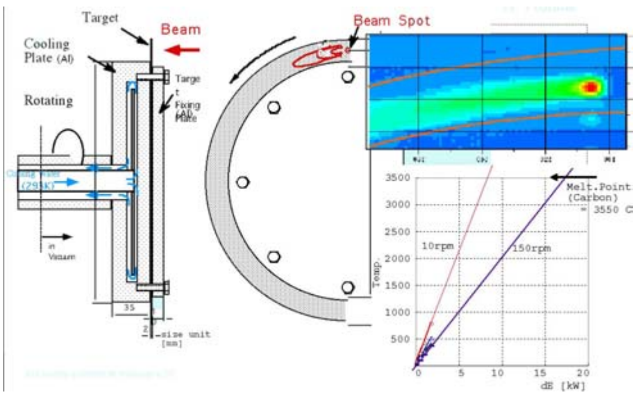

Fig. 4 Rotating target and measured temperature.

2.2 Solid hydrogen target

Proton and deuteron scattering of RI beam are important experiment at RIBF. The development of hydrogen target is thus very important. Usually liquid hydrogen is used in p-p scattering. However at RIBF, all experiment use RI beams and inverse kinematic condition is necessary. Therefore one has to detect a low energy recoil proton into large scattering angle. The container of the liquid hydrogen is thus undesirable. In contrast solid hydrogen can be produced without window in the vacuum if temperature is kept low. This solid target may not be stable under high intensity beam irradiation but RI Beams will never be that strong. It is therefore the most suitable hydrogen target for RI Beam. The solid hydrogen target from 3 to 10 mm thickness has been made and used in the test experiments.[1]

2.3 Polarized proton target

Polarized proton target is the other important in RI beam studies. Several important special requirements exist. Firstly, high magnetic field is undesirable. As already mentioned, one has to detect a low energy recoil proton. A high magnetic field at the target bend the proton track considerably and make it difficult to determine the scattering angle. Secondly, target should be exposed to as much directions as possible so that large detection efficiency can be obtained. This requirement favors not to use low

temperature.
As a material that satisfies such conditions, aromatic molecules has been tested. Using Naphthalene doped with 0.01 mol% pentacene, 36.8 % of proton polarization has been obtained under the temperature at 100K and 3 kG of magnetic field.

2.4 New additional separation method, rf deflector

Presently, a separation of projectile fragments is made by so-called energy-achromat separator that uses magnetic separator with a wedge degrader. However it does not have enough separation power in particular for proton-rich region. In many cases near the proton dripline nucleus, objective nuclide is only a small fraction of the separated beam. Therefore additional separation method is extremely important.

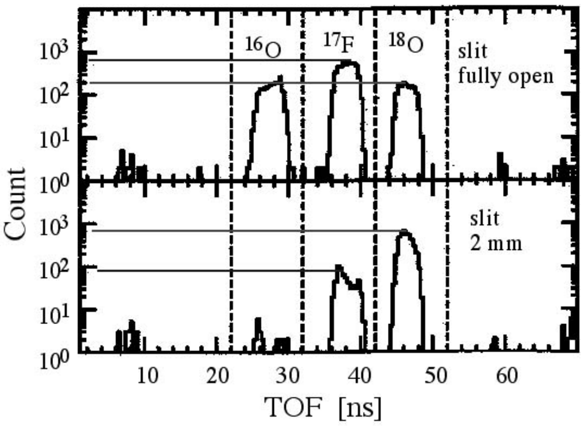

Fig. 5 Effect of rf deflector. The ratio of 18O to other nuclei is 0.2 without the rf deflector (upper figure) and 9 with rf deflector.

When a primary beam has micro-bunch structure, rf deflector can be used as efficient velocity filter. The mixed nuclides after the separator have different velocities and therefore reach to a deflector at different times. If rf electric field is applied, only a selected nuclide can go though the deflector and collimator system. Such a device has been made and tested at the present RIPS facility at RIKEN. Figure 5 shows a result of the test.

2.5 Gas stopping of RI Beams

rf guided Gas stopping has been tested using secondary beam of 100*A* MeV ^{8}Li produced at RIPS facility. The beam was injected into the 2 m long He gas filled chamber and the ions are extracted to the perpendicular direction from the beam. At the end of the chamber two layers of rf carpets. (see Fig. 6) About 1 % of the ^{8}Li extracted from RIPS has been extracted. From the measured energy profile of the injected ^{8}Li, it was estimated that only 7% of ^{8}Li stopped in the gas cell. Therefore 1/7 of ^{8}Li stopped in the cell were extracted. More over, the behavior of extracted amount against the energy profile of the

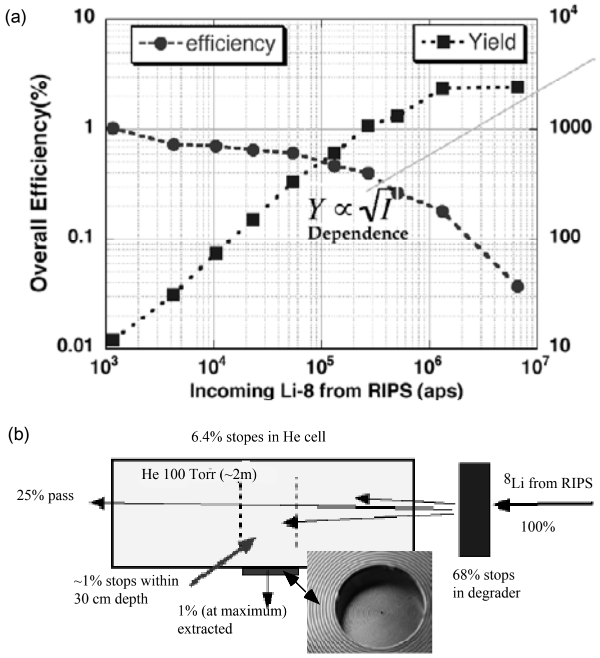

Fig. 6. ^{8}Li extraction efficiency from an rf-gas stopping cell. (a) the measured efficiency as a function of intensity of the incident ^{8}Li. (b) shows where other ^{8}Li escape.

beam indicates that only the ions stopped near (within 30 cm in depth) the extraction nozzle were extracted in high efficiency.
The test result shows that it is extremely important to make the energy spread of the ions small so that they stops in a small volume.
The intensity dependence of the extraction efficiency has also been measured. The extraction efficiency rapidly decreases when the intensity of injected ions become larger than 10^5 per seconds. Intensity (I) dependence proportional to $\sqrt{I}$ is consistent with the behavior of ion recombination in a gas.

2.6 Storage ring

A storage and cooler ring provides many additional opportunities in usage of RI beams. In particular high-resolution studies and mass measurements are promising research possibility among others. Another extremely important use is to eliminate isomers in the RI beams. After the RI beam separator, the ground state and isomers in a nucleus may be mixed. Because a separation time in fragment separator is short (<100 ns), isomers with life time longer than that are also transmitted. If isomer is mixed in the beam it is impossible to identify a reaction from the ground state and that from an isomer. Only the possible method to get out of this problem is to eliminate isomers in beams. A storage ring provides this possibility.

Special requirement of the storage ring for RI beam is as follows;

1. Faster cooling time down to 1 ms range is desirable. However this cooling is not necessary to cool the beam to very small momentum spread but just need to cool beam enough to the beam in the ring for the lifetime of the beam nuclide.
2. We would like to use as thick target as possible.
3. Sometime the intensity of RI is extremely small and thus an injection process may not put any nucleus in the ring. Quick method to detect whether nuclei are in or not helps faster accumulation of data.

Simulations and R&D are going on to optimize the luminosity of storage ring for internal target studies. One of the interesting possibilities is a use of very thick target such as a foil of 1 μm that correspond to 10^{19} atoms/cm^2. In particular this is necessary for study of nuclei far from the stability line because they are very weak in intensity. However their lifetime is short (<10 s) so that it is not necessary to keep the beam long time in the storage ring.
Let see the back of the envelope estimation whether it is possible to operate under such a condition. Suppose just one particle is in the ring, the available luminosity is 10^{24} cm^2 if one can use 10^{19} atoms/cm^2 thick target. In this case, a stored nucleus reacts with target nucleus with an average rate higher than 1 per second. Therefore is it necessary to keep the beam only for seconds. The energy loss of the particle per turn is $0.2Z^2$ keV and the necessary acceleration voltage per turn is $0.2Z$ kV and is easily available. The emittance growth of the beam can be compensated by the acceleration of the beam. The beam energy become broader as number of turn increases. However it may not be necessary if beam is kept in the ring only for seconds.

2.7 Electron scattering ring development

The conventional design of electron-RI beam collider has been already made. Now we are working on the new principle for electron-ion collision. It is based on an ion trapping in the electron orbit. Once ions are trapped in the electron ring it stays in the electron orbit captured by the electron's electric field. This is the phenomenon observed in electron storage rings and is the important factor to determine the beam lifetime. If we can positively inject RI ions in the electron orbital and keep them in the confined region by additional longitudinal potential, extremely high luminosity can be obtained. For example 10^{27} /cm^2•s of luminosity can be achieved if one can store 10^8 /s of ions in a 500 mA electron beam.

3. Conclusion

With those R&D activities, part of RIBF facility, accelerators and one super-conducting separator with minimum following beam line, will be completed in FY2006. The first stage experiments are planned to start in 2007. The planned experiment at the beginning of the operation are;

1. expansion of nuclear chart by projectile fragmentations and fission in flight.,
2. lifetime measurements of R-process path nuclei,
3. interaction- and fragmentation- cross section of heavy unstable nuclei,
4. proton elastic scattering of exotic nuclei,
5. Coulomb excitation of exotic nuclei,
6. Gamma decay of excited state of exotic nuclei.

[1] S. Ishimoto, T. Kobayashi, K. Morimoto, et al., Nuclear Instruments and Methods in Physics Research A **480**, 304 (2002).