STORAGE RINGS FOR RADIO-ISOTOPE BEAMS

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1 INTRODUCTION

In this decade, new era is opened in nuclear physics with use of radioactive nuclear beams. Many new types of structure and new phenomena have been discovered in unstable nuclei, particularly in nuclei near drip lines. Typical example of nuclear structure study, is given in Fig. 1 [1] where rms radii of nucleon distributions are given with radioactive nuclear beam experiments. @The diameter of the circle in the nuclear chart shows (rms-1.47) fm of nuclei, just to enhance the difference of radii. Radii of large isospin isobars are larger than those of stable isobars (radius is not proportional to $A^{1/3}$). Nuclei at the neutron drip line are extremely large, reflecting the neutron halo. Nuclear theory has to be carefully modified to incorporate this new behavior of nuclear density.
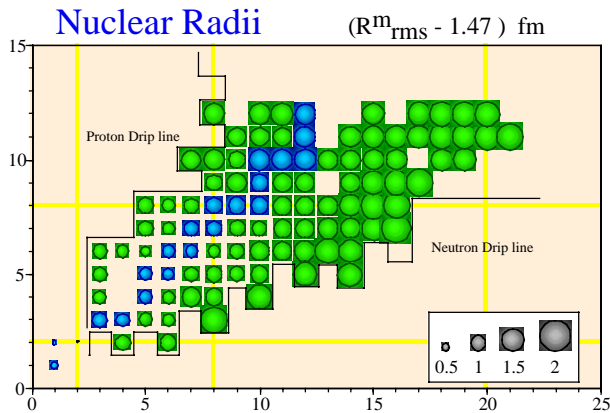

Fig. 1 Rms radii of nucleon distribution in nuclei.

Therefore it has become world-wide effort to use radioactive nuclear beams in a wide range of nuclear physics. Intermediate and high-energy beams(>50 MeV/u) of radioactive nuclei are produced by the fragmentation of high-energy heavy ions and separated by an electromagnetic separator. This method has been widely used because of its simplicity and fast separation time. The separation time is less than several hundred nano-seconds so that all beta-unstable nuclei can be separated. However, this secondary beam has its natural momentum broadening of a few % and emittance of several tens mm mrad. Therefore, it is difficult to carry out high-resolution studies with these beams. A cooler storage ring is considered to be suitable for making the good quality beam and for efficient use of radioactive beams.

With this insight, the Experimental Storage Ring(ESR) was built at GSI, and produced a pioneering works of the nuclear physics and atomic physics. Encouraged by the success at ESR, several cooler storage rings, second generation of RI storage rings, are proposed and under construction. In these proposals, the extreme one is to provide new opportunities of studies such as electron scattering of radioactive nuclei.

In the present paper, key issues @of @proposed RI dedicated storage rings will be discussed as well as the typical experiments envisaged.

2 PHYSICS MOTIVATION

2.1 Electron- RI Collision

Nuclear theories so far established describes experimentally measured nuclear properties such as the mass, size, charge distribution and the current distribution which are fundamental quantities of nucleus. For stable nuclei, there are comprehensive data, however no data is available for unstable nuclei. The purpose of the electron RI beam collider is to determine the not-yet-measured charge distributions of neutron-and proton-rich radioactive nuclei for which exotic structures such as neutron halo and skin are indicated.

The differential cross section for the elastic eA scattering can be written as,

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left|F_c(q)\right|^2$$

where *Mott* is for the scattering cross section from a point-like nucleus that can be calculated exactly and F_c is the charge form factor to be determined. Experimental difficulties are related to have high enough luminosity and to construct a large acceptance high-resolution electron spectrometer. If one can achieve a luminosity of 10^{24} cm²/sec/nucleus for eA collisions, it is possible to determine the charge radii for such RIs as ^{11}Be, ^{39}Ca, and ^{132}Sn, and when one has the luminosity of 10^{26} cm²/sec/nucleus, charge distribution can be measured for ^{15}O, ^{17}F, ^{49}Sc and ^{192}Pb.

2.2 Schottky Mass Spectroscopy

Schottky mass spectroscopy is a novel method of precision nuclear mass spectrometry based on the measurement of revolution frequencies of ions in a storage ring. The measurements are performed by non-destructive detection and frequency analysis of the beam noise, the well established Schottky diagnosis technique. Schottky

mass spectrometry was applied for the first time at the ESR at GSI using electron cooled, highly charged heavy ions at relativistic energies of up to 370 MeV/u[2]. In the experiments, relative accuracy down to 3×10^{-7} were achieved for the measured masses. Presently the method is applicable, so far, to nuclei with half-lives of at least a few seconds due to the required electron cooling time. In future with stochastic pre-cooling the wide range of unstable nuclei with life time of sub second could be measured.

2.3 Internal Target Experiments

The internal gas target increases experimental possibilities for the nuclear physics at the cooler ring. One of the typical experiments at the cooler ring is proton elastic scattering using the H_2 gas target to determine the matter distribution of unstable nuclei. Under the inverse kinematics, the recoiled protons having low kinetic energy are emitted close to relative to the stored RI beam. The internal gas target configuration makes possible to detect such low energy recoiled protons without serious disturbance due to multiple scattering in the target, keeping luminosities reasonably high. This is difficult to be realized in a case of external secondary-beam experiments using a solid hydrogen target. Inelastic scattering, which produces lower energy protons, will be also an example of typical experiments at the cooler ring. One studies the nuclear structure in detail through the excitation of giant resonance, and the measurement of spin-isospin response of unstable nuclei. An example of experiments using other gases, such as D_2 and ^3He, is the measurement of single nucleon transfer reaction, such as (d,p) and (^{3}He,d).

2.4 Merging Beam

The merging beam technique allows the reaction energy to be low, suitable for a nuclear fusion while the energies of the beams in the storage rings are high. It has an additional advantage that the nuclei produced by fusion are emitted at high energy in the direction between two beams. Therefore the separation of fusion products from the beams is easy, and the background can be reduced efficiently. The use of magnetic spectrometer allows the identification of products without referring to their decay modes and lifetimes. As seen from these advantages, the merging beam technique is suitable for the search of super-heavy nuclei with quite low possibilities[3]. Both of the combination, one between two heavy-ion beams and other between heavy-ion and neutron rich nuclei, will provide many possibilities.

3 KEY ISSUES OF STORAGE RINGS FOR RADIO ISOTOPE BEAMS

To attain the specifications of radioisotope storage rings which satisfy the requirements from the physics motivation, described in the preceding chapter, we should solve the following issues relevant to radioisotope storage rings.

Effective RI Beam Production

The high peak current heavy ion source should be developed, which has a pulse width of several tens micro seconds, and good repetition rate. Such a high current beam should be accelerated in the injector synchrotron, linac or cyclotron. The space charge problems at the low energy part in the injector system could be severe problem. The production of RI beams via a projectile fragmentation process should have a good separation, namely good purification, and matched emittance and momentum spread with the acceptance of the storage rings.

Accumulation of RI Beams

Produced RI beams should be injected and accumulated in the phase spaces of the storage rings with several methods, namely multi-turn injection in betatron phase spaces, RF stacking in the longitudinal phase space, and their combinations. The beam cooling should be simultaneously used.

Fast Beam Cooling

The RI beam has a large emittance and momentum spread which is too large value to accumulate many times in the storage ring. The fast beam cooling, typically cooling time of 0.1 sec, is a most crucial issue to perform the accumulation of RI beams in the storage ring, because the interesting RI has a short intrinsic life time. The fast stochastic pre-cooling is a most important subject to be developed. The electron cooling can be used as a subsequent cooling.

Acceleration and Deceleration of RI Beams

Some experiments requires the low energy RI beams, such as tens MeV/u. Then the accumulated and cooled beam should be decelerated and slowly extracted from the storage ring, if necessarily.

High Current Electron Beam Storage

This is a special requirement for the experiments at RI beam and electron collider facility. For this experiment, the energy of electron beam is relatively low, several hundreds MeV, and the electron current of 1 Ampere is required to get a good luminosity. Contrasting to the case of electron positron collider such as B factory, the number of bunch is small in order to achieve a synchronous collision with RI bunch, then the instability problem of electron beam will be a crucial subject.

4 PROPOSED STORAGE RINGS AT IMP, GSI AND RIKEN

IMP

At the heavy ion facility at the Institute of Modern Physics in Lanzhou, a combined facility of two cooler storage rings is under construction.[4] The first Cooler

Storage Ring(CSRm) is planned to store heavy ion beams from the present K=450 separate sector cyclotron. Heavy ions of charge to mass ratio (q/A) equal to 1/2 are accelerated to 900 MeV/u and U-ions are accelerated to 400 MeV/u. The maximum magnetic rigidity is 10.584 Tm. The second experimental Cooler Storage Ring(CSRe) is located after the CSRm and the separator for the radioactive beams. The maximum magnetic rigidity of the ring is 6.4 Tm. The experiments using radioactive nuclear beams with internal target, are planned in CSRe.

GSI

The future plan of GSI accelerator system is under discussion.[5] They are planning to construct a high intensity synchrotron named SIS 200, where 60 GeV high intensity protons, 30 GeV/u Ne[10+], and high intensity 1GeV/u U[7+] beams will be obtained. With a installation of new separator, new experimental storage ring, the collider of electron with RI beam is planned. Also the 14 GeV anti-proton ring is proposed to prepare a next generation anti-proton facility. Optionally, bunch compression ring is conceived to perform a fundamental experiments of heavy ion inertial fusion.

RIKEN

The RI Beam Factory is under construction at RIKEN for the use of ion beams for nuclear physics and other areas of basic science and applications. The accelerator system consists of two cascade cyclotrons(IRC and SRC), and Multi-Use Experimental Storage rings(MUSES).[6]A beam from the existing ring cyclotron(RRC) is injected into the IRC and SRC. Light nuclei are accelerated to 400 MeV/u and the heaviest nuclei are accelerated to 150 MeV/u with the highest intensity 1particle μA. The heavy ion beams obtained from the SRC will be converted into radioactive nuclear beams by a separator complex called the Big RIPS.

The MUSES has four rings; Accumulator Cooler Ring(ACR), Booster Synchrotron Ring(BSR), and Double Storage Rings(DSR). The ACR accumulates and cools radioactive nuclei. Internal target experiments can be carried out in the ACR. After cooling in the ACR, ions are injected into the BSR and accelerated to 1400 MeV/u. Then they are transferred to DSR where various collision experiments can be performed. Electrons are accelerated by the BSR to 2.5 GeV and brought into the DSR.

One of the key studies planned at the DSR is a colliding experiment involving an electron beam with radioisotope beam. The number of stored electrons amounts up to 2.7×10^{12}, and the typical colliding luminosity is estimated to be $5.6 \times 10^{26}/cm^2/s$, provided that 1×10^7 ions are stored and synchronouly collided with electron bunches.

5 PRODUCTION OF UNSTABLE NUCLEI

The features of fragmentation process are given as follows. The nuclear cross sections are almost independent of projectile beam energy, but the target thickness can be enlarged for higher energy which results in larger yield. The central momentum of the fragments is almost equal to the incident nucleus. The width of momentum spread $\sigma(p_l)$ is independent of target mass and beam energy but depend upon the mass number of projectile (A_p) and the fragment(A_f).

The dependence of $\sigma(p_l)$ on A_p and A_f is expressed as

$$\sigma(p_l) = \frac{150}{\sqrt{3}} \sqrt{A_p - A_f} \quad (MeV/c)$$

The width of transverse momentum distribution of the fragment is found to be roughly equal to $\sigma(p_l)$. If one use a projectile energy higher than 200 MeV/nucleon, the momentum spread is less than 3 % in all mass range. The angular spread is several degrees. From theses values, one can see that the high transmission efficiency can be obtained by a recoil separator which has a momentum acceptance larger than a few % and an angular acceptance of a few degrees.

Production rates of RI beams can be estimated with the code INTENSITY2 [7]. In the code, the physical feature of the projectile-fragmentation process is treated as empirical way. The primary beam and the thickness of the Be production target are optimized so as to obtain the maximum production rate. In the calculation, the intensity of the primary beam is assumed to be 100 particle μA. Fig. 2 shows the result of the calculation with the assumption of the acceptance of the separator as 10 mrad in angle and 1 % in momentum.
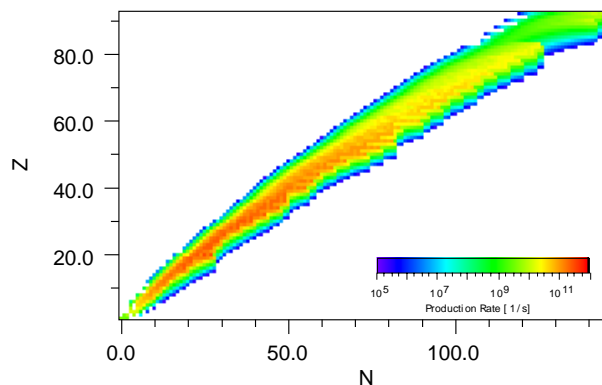

Fig. 2   Production rate of RI beams at MUSES project.

6 BEAM COOLING

Up to now, three beam cooling methods are developed for ion beam cooling, namely, stochastic cooling, electron cooling and laser cooling. The stochastic cooling is effective for large momentum spread and large emittance beam, because such a hot beam can produce a strong feedback signals. As a first approximation, the cooling time of stochastic cooling is independent of ion energy, and is proportional to the number of ions to be cooled. It is inversely proportional to the system band-width. Thus the stochastic cooling is efficient for the pre-cooling of small

number fragments in the storage ring. On the other hand, the electron cooling is effective for low energy, high charge state ion beams with small emittance and small momentum spread. Thus the electron cooling is used to cool down the relatively cold beam. The laser cooling is applicable to the ions which has a specific electron configurations. Presently the laser cooling is used for low energy Be, Mg, and meta-stable Li ions at several laboratries.

6. 1 Stochastic Pre-cooling

The stochastic cooling system will be used to get a fast cooling of injected RI beams which occupy initially large phase space. The typical emittance is several tens π mm.mrad, and the momentum spread is 10^{-3}. They should be cooled down as early as possible to several π mm.mrad, which beam can be cooled down with subsequent electron cooling.

The cooling rate of emittance or momentum deviation is given by,

$$\frac{1}{\tau} = \frac{W}{N}\left[2g\left(1 - M_u^{-2}\right) - g^2\left(M + U/Z^2\right)\right]$$

where N the number of ions in the coasting beam, W the system band width, g the gain parameter, M the desired mixing factor from kicker to pickup, M_u the undesired mixing factor from pickup to kicker. U the noise to signal ratio, and Z the charge number of ions. Clearly it is desirable to use the large band width to get a short cooling time. But there is a severe limitation of band width, one is the RF technological problem and the other is the mixing problem[8]. A first technological limit is the fact that beyond cut off frequency of vacuum chamber, the vacuum chamber pipe acts like waveguide. Then the closed loop is composed with a pickup, amplifier, kicker and vacuum chamber. From this point of view the maximum frequency is around 10 GHz.

The mixing problem is another strong limitation of band width. Up to now, the existing all rings are designed to have slipping factor from kicker(K) to pickup(P) is equal to the slipping factor from P to K, namely they are equal to the slipping factor of a whole ring. In this cooling case, the ratio of M and M_u is unit roughly, and the cooling rate with optimum gain, is given by

$$\frac{1}{\tau} = 0.29 N / W$$

On the other hand, to get a fast cooling, an ideal case, there should be no mixing from P to K($M_u \gg 1$), and full mixing from K to P($M=1$). In this case, the cooing rate is

$$\frac{1}{\tau} = N / W$$

where we assume no noise. The ideal design of lattice is that the path from P to K is isochronous, whereas the path K to P is strongly dispersive. To meet the other requirements as a storage ring, ideal lattice design should be abandoned and the "semi-isochronous" and "semi-dispersice" lattice is studied. As cooler ring at the RIKEN and GSI projects, such a new generation stochastic cooling oriented lattice is studied.[9, 10]

The simulation study of stochastic cooling in such a asymmetric lattice configuration shows[11], that the cooling time is much shorter than that in the normal lattice structure. The other important result of the simulation study is that the stochastic cooling system should change the band width during the process of cooling , for example, initially 100-200 MHz, while it is changed to 400-800 MHz at the end of cooling. With this dynamic change of band width, beam cooling is faster by a factor 2 than the fixed band system.

6.2 Electron Cooling

The cooling force and the cooling time are estimated from a binary collision models with ions and electrons. It turns out that quite different scaling law are valid depending upon whethere the ion velocity, in the electron rest frame, is smaller or larger than the rms electron velocity. The energy of radioactive beam produced via fragment separation is several hundreds MeV/nucleon and have a large emmitance and momentum spread. Then normally cooling time of radioactive beam is several tens to several seconds. As a result, it is turned out that the stochastic cooling is always much faster than the electron cooling

7 COLLIDER

7.1 Accumulation of Unstable Nuclei

There are several ways to accumulate the RI beams in the storage rings. The one is the multi-turn injection in horizontal and vertical betatron phase spaces, the second is the RF stacking, and the third is the combination of these two methods. The selection of way of the ion accumulation is largely dependent upon the pulse shape and the repetition rate of the injector accelerators. Here we will show the example of the case of RIKEN MUSES project where the injector is a cyclotron, and has a good repetition rate. The accumulation of RI beam is performed by using the combination of multi-turn injection with RF stacking. RI beam is injected into the ring by means of multi-turn injection and then that beam will be RF stacked. The time interval of the repetition of this process is adjusted to the beam cooling time.

The beam accumulated in ring is decaying with its own intrinsic life-time. The maximum number of the nuclei stored in the ring is determined by the balance of the supply rate and the decay rate.

The space charge limit of the ion number is also considered in the estimation of the maximum number of the nuclei stored in the ring. However the space charge limit is important only for the high production rate nuclei such as stable nuclei and their neighbors.

7.2. *Luminosity*

Luminosity L of the collision of beams with Gaussian distribution in space is numerically calculated.

Bunch lengths $\sigma_{z_{1,2}}$ are determined by the RF voltage of the collider ring and to be 50 cm for nucleus beam and 2 cm for electrons. The electron current is assumed as 500 mA and in order to make a synchronous collision of electrons and nuclei, bunch number of electrons are varied from 30 to 45 according to the beam energy of nuclei from 300MeV/u to 3.5 GeV/u.

In Fig. 3, luminosity of e-RI collision at the MUSES is plotted for various nuclei in an *N-Z* plane. In the figure plotted ones are only the nuclei whose luminosity $L \geq 10^{27}\ cm^2/s$, the value corresponds to the minimum luminosity required to measure the charge distribution from the e-RI elastic scattering. Those nuclei are their live times longer than about 1 min.
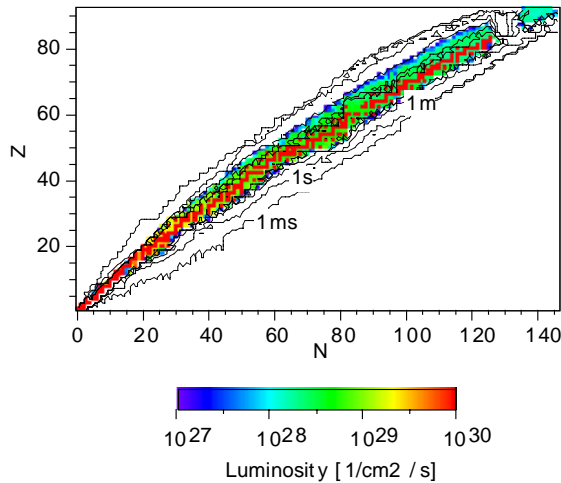

Fig. 3   Luminosity of e-I collision

8 SUMMARY

In the present paper, we discussed on the physics motivation for the radioactive storage rings, and on the various accelerator aspects to realize a storage rings which satisfy the requirements. Especially the possibility of RI and electron collider is described. Conclusively we can summarize the key subjects to attain such a next generation RI beam storage rings as follows.

High peak current, such as 100 pμ Ampere heavy ion beam acceleration could be obtained in the linac and cyclotron injector. In that case, high peak current ion source such as laser ion source(LIS), electron beam ion

source(EBIS) or a metal vapor vacuum arc ion source(MEVVA) will be good candidates. The selection of the ion source depends upon the kind of injector system. Beam loading effects are the subjects to be studied theoretically and experimentally, especially at the cyclotron injector.

The stochastic pre-cooling is key subject to realize a fast cooling time less than 0.1 sec. The lattice structure of the accumulator cooler should be optimized to have a good mixing condition as well as the other requirement from the ring design such as wide dynamic aperture, long straight section for the experiments. With electron cooling, cooling time will be more than seconds. It will be useful for the cooling stacking of stable or quasi-stable RI beams and to suppress the ion beam instabilities in the ring.

When the electron-RI beam collider is designed, the luminosity of 10^{27} to 10^{31}/cm².sec could be obtained for the head-on collision, if the intrinsic lifetime of the RI beam is larger than 1 min. The electron current of 500 mA is obtained when the careful design of the vacuum chamber and environment with a small impedance.

Beam-beam effects will be limiting term for luminosity as well as the space charge limit for the long life RI beams. Beam cooling to compensate the beam-beam non-linear effects will be useful to increase the luminosity of order of magnitude.

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