NEW SCHEME FOR PRECISION MASS MEASUREMENTS OF RARE ISOTOPES PRODUCED AT RI BEAM FACTORY*

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For precision mass measurements of short-lived rare isotopes, a new experimental apparatus, named "Rare-RI Ring", has recently been proposed. A unique possibility of the project is discussed, comparing with other experimental techniques. The current status is presented.

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1. Introduction

Nuclear masses are one of the most essential quantities for understanding nuclear properties. Mapping the mass surface over the nuclear chart provides a crucial test of nuclear models. Nuclear masses also play an important role as basic input for network calculations of element synthesis of the r-process in supernovae. Since the r-process path has not yet been solved, systematic measurements of the nuclear masses for neutron-rich nuclei far from the β-stability (*i.e.*, short-lived rare isotopes) are indispensable. The masses can impose strict restrictions on the neutron capture rates and the β-decay rates that affect the r-process path. The challenge is to precisely measure the masses of such nuclei. Since it is difficult to increase the statistics of rare isotopes, a device that specializes in mass measurements for such a region is required.

The RI beam factory (RIBF) [1] aims to establish nuclear structure physics and nuclear astrophysics research programs. The facility consists of a cyclotron complex and a fragment separator, BigRIPS [2]. Various kinds of rare RI can be produced via the in-flight fission process of a high-energy uranium beam up to 350 MeV/nucleon. The primary beam intensity will eventually reach up to 1 $p\mu$A, which would allow us to study exotic nuclei at and near the driplines, and therefore to stimulate direct mass measurements of such nuclei. The first commissioning experiments of the BigRIPS using ^{86}Kr and ^{238}U beams have already been successfully performed since March, 2007.

We have proposed a new experimental apparatus, named "Rare-RI Ring", for measuring the masses with an order of 10^{-6} precision [3, 4]. This new apparatus is suitable for mass measurements of short-lived rare isotopes, including the r-process region. It will be located as one of the major experimental installations at RIBF [1].

2. Principle of mass measurements

The principle of mass measurements is based on the cyclotron frequency (f_{C}),

$$f_{\mathrm{C}} = \frac{1}{2\pi}\frac{q}{m}B\,, \tag{1}$$

where q/m is the charge-to-mass ratio and B is a magnetic field. The revolution time ($T_0 = 1/f_{\mathrm{C}}$) of a reference m_0/q particle with an isochronous mode ($B = B_0\gamma_0$) is expressed as

$$T_0 = 2\pi\frac{m_0}{q}\frac{1}{B}\gamma_0 = 2\pi\frac{m_0}{q}\frac{1}{B_0}\,, \tag{2}$$

where γ_0 is a relativistic factor, defined as $\gamma_0 = 1/\sqrt{(1-\beta_0^2)}$ and $\beta_0 = v/c$.

Under such a condition, we measure the revolution time (T_1) of an unknown mass, m_1/q particle (rare isotope to be measured), which may have a slightly different mass-to-charge ratio (*i.e.*, $m_1/q{=}m_0/q{+}\ \Delta(m_0/q)$),

$$T_1 = 2\pi\frac{m_1}{q}\frac{1}{B}\gamma_1 = 2\pi\frac{m_1}{q}\frac{1}{B_0}\frac{\gamma_1}{\gamma_0}\,, \tag{3}$$

where $\gamma_1 = 1/\sqrt{(1-\beta_1^2)}$. Thus, the isochronism is no longer fulfilled for an unknown mass particle. In this case, m_1/q can be expressed as

$$\frac{m_1}{q} = \frac{m_0}{q}\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \frac{m_0}{q}\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}\,. \tag{4}$$

The relative differential value of m_1/q is expressed as

$$\frac{\delta\left(\frac{m_1}{q}\right)}{\frac{m_1}{q}} = \frac{\delta\left(\frac{m_0}{q}\right)}{\frac{m_0}{q}} + \frac{\delta\left(\frac{T_1}{T_0}\right)}{\frac{T_1}{T_0}} + k\frac{\delta\beta_1}{\beta_1}\,, \tag{5}$$

where

$$k = -\frac{\beta_1^2}{1-\beta_1^2} + \left(\frac{T_1}{T_0}\right)^2\frac{\beta_1^2}{1-\left(\frac{T_1}{T_0}\beta_1\right)^2}\,. \tag{6}$$

The coefficient k is on the order of 10^{-2} for $\Delta(m_0/q) \sim 1\%$. To evaluate the mass of a non-isochronous particle, a correction for the velocity β_1 is required. The mass of a non-isochronous particle within a m/q difference of 1% can be determined with an order of 10^{-6} precision by measuring $T_{0,1}$ with an accuracy better than 10^{-6} and β_1 with an accuracy better than 10^{-4} independently, under the condition that the isochronous magnetic field inside the ring is tuned with a precision better than 10^{-6}.

3. New scheme of mass measurements

A new scheme of mass measurements is described as follows. Rare isotopes produced at the BigRIPS are delivered through a long injection beam line, which determines the velocity with an accuracy better than 10^{-4}, and are injected into an isochronous storage ring using a fast kicker system one by one. The injected particles revolve for about 1 ms in the ring, and are ejected by the same kicker system. Particle identification is performed upstream (BigRIPS) and downstream of the storage ring using the $B\rho$-ΔE-TOF and $B\rho$-TOF-ΔE-E methods, respectively. The total revolution times are precisely measured between the entrance and the exit of the storage ring using fast-timing time-of-flight detectors with an accuracy better than 10^{-6}.

4. Conceptual design and R&D ongoing

Three major parts of the project: a long injection beam line, a fast kicker system and a precisely-tuned isochronous storage ring, are described. The main parameters for a design study are summarized in Table I. More details can be found in [4].

TABLE I

Main parameters of the Rare-RI Ring.

$B\rho$ (max.)	6.43 Tm
transition energy ($\gamma_{\rm t}$)	200 MeV/u (1.214)
Injection beam line	230 m
Sector number	6
Circumference	56.13 m
TOF (storage)	1 ms
$\Delta B/B$ (magnetic field)	$< 10^{-6}$
$\Delta P/P$ (momentum accept.)	1 %
$\Delta\beta/\beta$ (velocity)	$< 10^{-4}$
$\Delta T/T$ (revolution time)	$< 10^{-6}$
$\Delta m/m$ (mass)	$\sim 10^{-6}$

A long injection beam line from the BigRIPS is necessary to measure β with the required accuracy. A start counter for the β measurements will be located at the F3 achromatic focus of BigRIPS, and a stop counter will be located upstream of the entrance of the isochronous storage ring. A thin plastic scintillator [5] or a micro channel plate [6, 7], which has a timing resolution better than 100 ps, will be used for start and stop counters. The distance between them is about 180 m, which gives more than a 1 μs flight time for nuclei of 200 MeV/nucleon. Therefore, the long injection beam line allows us to measure β with an accuracy better than 10^{-4}.

The injection method is based on the individual injection method [8]. The combination of a long injection beam line and a fast kicker system enables us to inject particles into the isochronous storage ring one by one. A trigger signal to fire the kicker will be generated with a plastic scintillation counter at the F3 focus of BigRIPS. The trigger signal must be transmitted to the kicker system faster than the particle, itself. The transmission time of the trigger signal is estimated to be about 1.3 μs from the signal start to the completion of injection preparation, based on R&D using the model kicker magnet. On the other hand, it takes about a 1.35 μs flight time at a distance of about 230 m in the case of a 200 MeV/nucleon. Thus, the present conditions satisfy individual injection.

The isochronous storage ring is a unique device having the features of both a cyclotron and a storage ring. The ring consists of six sector magnets with straight sections. The transition energy (γ_t) is designed to be 200 MeV/nucleon. The isochronism is satisfied in the first order by an edge angle correction in the sector magnets. The second order is corrected by the harmonic fields using trim coils installed in the sector magnets. The isochronous magnetic field should be tuned with a precision better than 10^{-6} at a large momentum acceptance ($\delta P/P = \pm 1$ %). We are developing a simulation code based on the 4th-order Runge–Kutta algorithm. Figure 1 shows a simulation result of the emittance dependence on the isochronism in the ring. The simulation was performed in the hard edge approximation without any imperfection of the magnets. The isochronism $\delta T/T$ is estimated to be less than 10^{-6} for an emittance of less than 46 πmm-mrad.

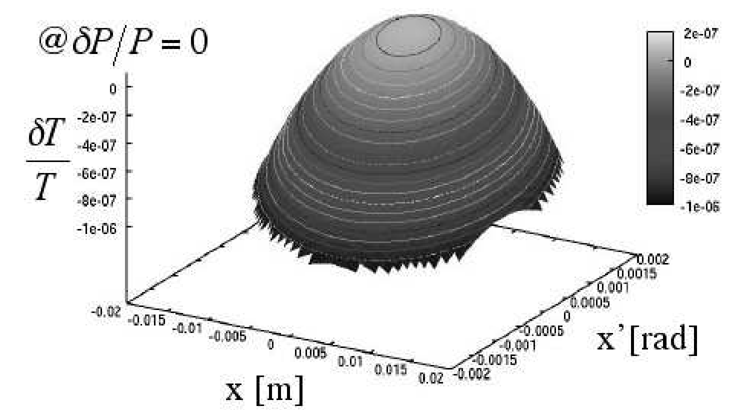

Fig. 1. Simulation result of the emittance dependence on the isochronism in the Rare-RI Ring.

5. Comparison with other techniques

To measure the masses of such short-lived rare isotopes, we have adopted a direct mass measurement method using isochronous optics. This method was originally applied to the TOFI spectrometer [9, 10] at LAMPF. After that, an isochronous optics was applied to the storage ring ESR [11] at GSI to measure the masses of short-lived exotic nuclei (IMS: Isochronous Mass Spectrometry) [6, 12–15]. Here, we compare our method with the IMS at ESR, as summarized in Table II. The advantage of our method is on-line particle identification at the BigRIPS due to the cyclotron-based system, while simultaneous measurements of known and unknown masses have been realized at the IMS based on the synchrotron-based system. The

TABLE II

Comparison of Rare-RI Ring with ESR-IMS.

Facility	ESR-IMS	Rare-RI Ring
$B\rho$ acceptance	$2{\times}10^{-3}$ [14]	10^{-2}
In-flight identification	impossible	possible
Calibration run time	simultaneous	separate
$\Delta m/m$	10^{-5} [15]	10^{-6}

overall mass precision in the Rare-RI Ring will reach an order of 10^{-6} due to event-by-event velocity corrections. It should also be noted that a recently developed $B\rho$ tagging method at ESR has improved the mass precision to an order of 10^{-6} [16]. The IMS will also be upgraded at the future FAIR facility. Detailed calculations of isochronism have been performed and the acceptance will also be increased [17]. Finally, both of the ring systems at the RIBF and the FAIR will do complementary work for precision mass measurements.

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