Experimental Challenges of the First Mass Measurement Campaign at the Rare-RI Ring

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Abstract. With the recent commissioning of the Rare-RI Ring (R3), nuclear mass measurement of rare isotopes (RIs) produced at the RI Beam Factory (RIBF) at RIKEN has become possible. The R3 spectrometer is based on the Isochronous Mass Spectrometry technique that allows for reaching a mass measurement precision of $10^{-6}$ within less than 1 ms. With the newly established self-triggered individual injection method, R3 is specialized in mass measurements of extremely short-lived nuclei with low production yields.

In this paper, we report the first mass measurement campaign conducted at the R3 addressing nuclei in the vicinity of N=50 and N=82 neutron magic numbers, with a particular focus on the challenges of this new facility.

1. Introduction

The Rare-RI Ring (R3) is a storage ring at the RIBF/RIKEN facility that is dedicated for mass measurement of Rare Isotopes (RIs). We have conducted mass measurement of neutron-rich nuclides far from stability produced at RIBF. We measured nuclear masses of $^{74,76}$Ni isotopes, which have implications for the weak $r$-process nucleosynthesis. In this same campaign, we also measured masses of heavier neutron-rich nuclides, namely $^{122}$Rh, $^{123,124}$Pd and $^{125}$Ag, which are mostly relevant for the main $r$-process nucleosynthesis [1, 2].

In this contribution, we report the experimental details of this first mass measurement campaign at the R3, focusing on two major challenges that were not discussed previously.
2. Description of the experimental setup

The basis of the R3 measurement is the Isochronous Mass Spectrometry to determine nuclear masses of RIs [3, 4]. The ring is located at the end of the beam-line at the RIBF facility, behind BigRIPS separator, OEDO and SHARAQ spectrometers. The R3 is the only storage ring placed at a cyclotron-based facility. The advantage of having the R3 at RIBF is to measure nuclear masses of RIs that are very far from stability and cannot be reached elsewhere. However, this configuration raises a difficult issue of operating a pulsed machine (R3) with a quasi-continuous beam provided by the cyclotron. To inject a particle into a storage ring, a fast kicker magnet system is required, which can be operated only periodically. To solve this issue we developed the self-triggered individual injection method [5–7]. First, particle identification (PID) is performed upstream of the beam-line from energy loss in an ion chamber and time-of-flight measurement using plastic scintillators. The particle timing signal when passing through an upstream detector is then sent to activate the kicker magnets. The particle could thus be injected with the kicker magnets triggered by its own timing signal. We can therefore track the injected particles event-by-event at all times using their PID. To activate the kicker magnets, we used the timing signal from a plastic scintillator placed at the focal plane F3 on the BigRIPS separator, as shown in Fig. 1. The kicker magnets are activated shortly before the particle reaches the kicker magnets position inside the R3. The particle is injected into the R3 and revolved for about 700 $\mu$s, then extracted by employing the same kicker magnets set.

In the following, we will describe the challenges faced during the first mass measurement campaign with R3.

2.1. Extraction of Rare Isotopes

Since particles have different mass-to-charge ratio ($m/q$), they accomplish different number of turns within 700 $\mu$s and have slightly different time-of-flights inside the ring when extracted. The kicker magnets effective pulse duration ($\sim 100$ ns) is narrower than the average revolution time ($\sim 400$ ns). The extraction time should be then carefully adjusted to be able to extract all
kinds of particles of interest. In figure 2, we show one example of the kicker timing window adjusted to extract the reference particles (\(^{128}\)Sn, \(^{127}\)In and \(^{126}\)Cd) and particles of interest (\(^{125}\)Ag and \(^{124}\)Pd). The time-of-flight is estimated at the kicker position at the extraction. The estimation of time-of-flight requires the determination of the revolution times and turn numbers, which will be detailed in the next section. Particles at the tail of the kicker magnetic field will have a smaller kick angle and might get lost before the extraction at ELC (see Fig. 1.). We therefore used several kicker delay times to extract all particles. Only two of the kicker delay times are shown in Fig. 2 for one particular setting.

In figure 3, we show all extracted events (in pink), compared to all events (yellow) recorded upstream at F5 of BigRIPS for all nuclides measured in this first mass measurement campaign. Due to the acceptance of the R3, only isotones can be injected into the R3 for a particular magnetic field setting. We had thus four settings. Each of them aimed at different target nuclei (circled in green) and several extraction times were used for each setting to extract reference particles (circled in black) together with the particles of interest.

2.2. Revolution time determination
For mass determination of an unknown \(m/q\), we use the following formula [3]:

\[
\frac{m}{q} = \left( \frac{m}{q} \right)_0 \frac{T}{T_0} \sqrt{1 + \frac{1 - (T_0/T)^2}{\left( \frac{(m/q)_0}{B\rho} \right)^2}},
\]

with \(T\) and \(T_0\) the revolution times inside the ring of the particle of interest with \((m/q)\) and the reference particle with \((m/q)_0\), respectively. The determination of the magnetic rigidity \(B\rho\) is detailed in a separate publication in this proceeding [8]. In the following, we concentrate on the determination of the revolution times \(T\) and \(T_0\).
**Figure 3.** Particle Identification (PID) showing the energy loss in the Ionization Chamber (IC) at F3 of BigRIPS and time-of-flight (ToF) from F3 to F5 (see Fig. 1). In yellow are shown all events recorded at BigRIPS. In pink are shown extracted events after the R3 at ELC. Particles of interested are circled in green, while reference particles are circled in black.

The revolution time of a particle circulating in the R3 is determined from the total time-of-flight (ToF) inside the ring divided by the number of accomplished turns:

\[
T = \frac{ToF_{\text{ring}}}{\text{turn number}} = \frac{ToF_{\text{ring}}}{N} \quad (2)
\]

Unfortunately, we cannot measure the ToF\text{ring} since it requires a detector inside the ring. However, we measured the total time-of-flight (ToF\text{S0–ELC}) of the particle from SHARAQ’s focal plane S0 to the extraction at ELC (see Fig. 1). The start timing signal at S0 is measured using the E-MCP detector [9], while the stop timing signal at ELC is measured with a plastic scintillator. The distance from S0 to the kicker magnets and to ELC is about twice the circumference of the ring. We can then determine the revolution time from the ToF\text{S0–ELC} by adding two turns as follow:

\[
T = \frac{ToF_{\text{S0–ELC}}}{\#N + 2} = \frac{ToF_{\text{S0–ELC}}}{N'} \quad (3)
\]

To estimate the turn number \#N', we rely on a separate measurement of the revolution time. Before tuning the extraction time we insert a movable E-MCP detector inside the ring to measure a rough revolution time of each species. The precision and accuracy of the revolution time are limited by the timing resolution of the detector as well as the considerable energy loss due to low beam energy (160MeV/u) compared to the detector thickness (Carbon foil of 60µg/cm²).
Figure 4. (Left) Time-of-flight spectrum of $^{126}$Cd from the E-MCP detector placed inside the ring to measure the revolution time. (Right) DFT analysis of $^{126}$Cd time-of-flight spectrum from the E-MCP detector, shown for the 70th harmonic. The main peak is fitted with a Lorentzian function.

Typically, the particles are lost after a few tens of revolutions. The precision of the measured revolution time is thus not sufficient for mass determination in equation (1), but is sufficient for the determination of the turn number. The time-of-flight spectrum of $^{126}$Cd recorded with the E-MCP inside the ring is shown in figure 4 (left). To extract the revolution time with the highest accuracy, we perform a Discrete Fourier Transform (DFT) analysis at higher harmonics as shown in figure 4 (right). The DFT spectrum is then fitted with a Lorentzian function on top of a Gaussian function to fit the background. From the frequency of the DFT spectra, the revolution times of all reference particles were determined and the turn number deduced as shown in table 1. This turn number can thus be used in eq. (3) to deduce the revolution time, which is finally used for the mass determination in eq. (1).

Table 1. Revolution times extracted from the DFT analysis of the E-MCP detector data. These revolution times are used to determine the turn number $#N'$ (see Eq. (3)).

| Nucleus | DFT Rev. T [ns] |ToF S0–ELC [ns] | #N' |
|---------|-----------------|----------------|-----|
| $^{128}$Sn | 393.9660±0.0268 | 725781.69±0.98 | 1842 |
| $^{127}$In | 397.6030±0.0387 | 725726.56±1.07 | 1825 |
| $^{126}$Cd | 401.4275±0.0108 | 725835.75±0.13 | 1808 |
| $^{125}$Ag | 405.4414±0.0353* | 725747.62±0.40 | 1790 |
| $^{124}$Pd | 409.6077±0.0356* | 725830.25±1.61 | 1772 |

* These numbers are deduced from eq. (4) using $B\rho$ and $L$ parameters (see text for more details).

Due to the limited beam-time and the low production yield of the particles of interest, their revolution times inside the ring could not be measured with the E-MCP detector. In order to determine the turn number of particles of interest, we used the following formula\(^1\) to deduce

\[ L = \beta c \cdot T \quad \text{and} \quad B\rho = \frac{m}{q} \cdot \gamma\beta \]
their rough revolution times:

$$T = \frac{L}{c} \sqrt{1 + \left(\frac{m}{q} \right)^2 B\rho^2},$$  \hspace{1cm} (4)

where $L$ is the path length inside the ring, which should be constant for all particles [3], $B\rho$ the mean magnetic rigidity inside the R3 and $c$ the speed of light. To determine the two parameters $L$ and $B\rho$, we fit eq. (4) using the revolution times determined from eq. (3) and $m/q$ of the reference particles ($^{128}$Sn, $^{127}$In, $^{126}$Cd). These parameters are then used to calculate the rough revolution times from eq. (4) of the particle of interest by using $m/q$ estimation from the Atomic Mass Evaluation (AME) [10]. The turn number is finally deduced from eq. (3) (see table 1).

3. Outlook

We reported here the first mass measurement campaign with the Rare-RI Ring at the RIBF, where masses of neutron-rich nuclei in two key regions of the nuclear chart were measured. We addressed some of the challenges encountered during the experiment, namely the extraction from the R3 and determination of the revolution time. Due to the short time window of the kicker pulse, several extraction times had to be used in order to cover all particles of interest. To overcome this issue, we are planning to upgrade the kicker magnets system to operate for longer time. Concerning the revolution time determination method, we relied on the assumption that all particles spend exactly two turns outside the ring. We used the estimated $m/q$ values from the AME to determine the turn number of the particles of interest. We are investigating the systematic uncertainties of the method and their impact on the final mass accuracy. Alternative methods are also being explored to minimize systematic uncertainties.

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