A pilot experiment for mass measurement at CSRe*

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Abstract A pilot experiment of mass measurement was performed at CSRe with the method of isochronous mass spectrometry. The secondary fragments produced via RIBLL2 with the primary beam of 400 MeV/u ^{36}Ar delivered by CSRm were injected into CSRe. The revolution periods of the stored ions, which depend on the mass-to-charge ratios of the stored ions, were measured with a time-of-flight detector system. The results show that the mass resolution around 8×10^{-6} for $\Delta m/m$ is achieved.

Key words radioactive ion beam, mass resolution, isochronous mass spectrometry

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1 Introduction

As one of the fundamental properties of the nucleus, the atomic mass is of primary interest for the nuclear structure, astrophysics models and theoretical mass models improvement. The determination of nuclear masses has attracted a great deal of interest from both experimentalists and theoreticians for many years. Different methods for determining the masses of nuclei, such as the $B\rho$-TOF method, the TRAP method and so on have been developed[1, 2]. The masses of most stable and long-lived nuclides have been well determined, while the experimental data on the masses of exotic nuclei far from the valley of β-stability are scarce. Thanks to the radioactive ion beam (RIB) facilities developed recently, the determination of the masses for short-lived nuclides is becomeing a rapidly developing field in nuclear physics. For reviews please refer to[3, 4].

The experimental results from the experimental storage ring (ESR) at the Gesellschaft für Schwerionenforschung (GSI) prove that the combination of the in-flight separator[5], which can provide RIB with half-lives shorter than microseconds, and the cooler storage ring, is an efficient method for direct mass measurements for short-lived exotic nuclides[6]. With the commissioning of the cooler storage ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR)[7], a pilot experiment under operating CSRe in the isochronous mode to test the capability of HIRFL-CSR for measuring the mass of short-lived nuclides was performed in December 2007. Mass resolution around 8×10^{-6} for $\Delta m/m$ was achieved.

2 The scheme of the mass measurement in CSRe

Figure 1 shows the layout of the Heavy Ion Research Facility at the Lanzhou (HIRFL) complex. The cooler storage ring (CSR) is the post-acceleration

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system of the HIRFL, which consists of a main ring (CSRm) and an experimental ring (CSRe). The CSRe is a high accurate spectrometer for mass/decay measurement, which is interconnected to CSRm by a secondary beam line named RIBLL2.

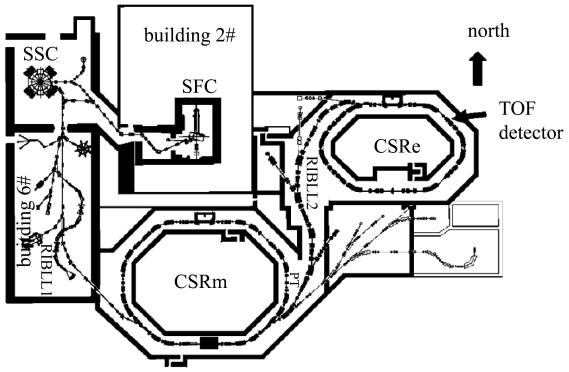

Fig. 1. The layout of HIRFL-CSR.

For measuring the mass of short-lived nuclides at CSRe, the RIBLL2 is operated in the mode of producing RIBs, through bombarding a production target located at the entrance of the RIBLL2 with high energy heavy ions extracted from CSRm. In this experiment, the RIBLL2 is operated as a pure magnetic rigidity filter in order to simultaneously transmit several ions with close mass-to-charge ratios into CSRe. Usually, the nuclides to be measured are purified furthermore by the RIBLL2 with the $B\rho$-ΔE-$B\rho$ technique and then injected into CSRe.

In an ion storage ring, the revolution frequencies f of the circulating ions can be related to their mass-to-charge ratios (m/q) in the first-order approximation, as the following:

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{(m/q)} + \left(1-\frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta\nu}{\nu}, \qquad (1)$$

where γ and ν are the Lorentz factor and the velocity of the ions, respectively. γ_t is the transition point of the storage ring. The measured revolution frequencies reflect directly the mass-to-charge ratios of the stored ions if the contribution of the second term in relation (1) is negligible. This can be achieved either by cooling the stored ions to make their velocity spread down to the order of 10^{-7} or by making γ as close to γ_t as possible by running the storage ring in the isochronous mode. The first case is called Schottky Mass Spectrometry (SMS)[8] where the revolution frequencies of the stored ions are usually measured with the Schottky spectrometer. The second case is called Isochronous Mass Spectrometry (IMS)[9], which makes the one species ions with different velocities reaching an identical revolution period in the ring. Since the cooling of the stored ions is not necessary, the IMS is suitable for the mass measurements of exotic nuclides with half-lives of several tens microseconds.

In this pilot experiment, CSRe was operated as an IMS. The revolution periods of the stored ions were measured by a fast time pick-up detector with a thin foil in their revolving path of the ions. The transition point γ_t of CSRe in isochronous mode is 1.3951 which corresponds to the energy about 368 MeV/u for the ions with atomic number-to-charge ratio A/q=2. For the ions with rigidities fulfilling the isochronous window of CSRe, the revolution time is about 615.7 ns.

3 Experiment procedure

3.1 Fast verification of the isochronous mode of CSRe

As the first step of the experiment, the magnetic rigidity of both the RIBLL2 and CSRe was set at $B\rho$ = 6.03956 Tm. The RIBLL2 was set as a beam transport line and CSRe as an IMS for the ions with A/q = 2. The high intensity $^{36}Ar^{18+}$ beam of 368.022 MeV/u form CSRm, corresponding to $B\rho$ = 6.03956 Tm and γ = 1.3951, was directly injected into CSRe to confirm the isochronism of CSRe. The revolution frequency of the stored $^{36}Ar^{18+}$ ions in CSRe was measured with the beam position monitor, which is used for non-destructive beam diagnostics and the revolution frequency spectrum was obtained using the Fourier transformation. The measured frequency dispersion $\delta f/f$ is about 8×10^{-7} (shown in Fig. 2), which is much smaller than the momentum dispersion of the order of 10^{-4} in normal operation of the CSRe mode. This was taken as strong evidence that the isochronism of CSRe was achieved.

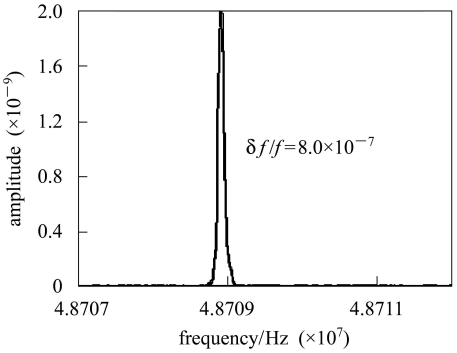

Fig. 2. The revolution frequency spectrum of the circulating $^{36}Ar^{18+}$ ions with the energy of 368.022 MeV/u when CSRe operated as an IMS.

3.2 Measurement of the revolution periods of the stored radioactive ions

Keeping the optical setting of the CSRe and RIBLL2 unchanged, the energy of the primary beam $^{36}Ar^{18+}$ was increased up to 400 MeV/u and bombarded the production target made of Al_2O_3 with the thickness of 2.828 mm inserted at the entrance of RIBLL2 to produce the secondary beams. The fragments with $A/q = 2$ and velocities fulfilling the isochronous condition of CSRe were selected with the $B\rho$ setting of RIBLL2, and injected into CSRe and then stored. The primary beam was rejected by limiting the $B\rho$ acceptance of RIBLL2 with slits.

The revolution periods of stored ions were measured using a detector (shown in Fig. 3 and the details will be described elsewhere[10]), which consists of a carbon and a multi-channel plate (MCP). The carbon foil with a thickness of 20 μg/cm^2 and a diameter of 40 mm was positioned in the circulating path of the stored ions. The secondary electrons emitted from the foil induced by the ions were guided isochronously to the MCP as an electron amplifier with perpendicular electrostatic and magnetic fields. The detector has been tested with α particles from the ^{241}Am radiation source, and a time resolution of (197±10) ps (FWHM) was obtained with a detection efficiency of 61%.

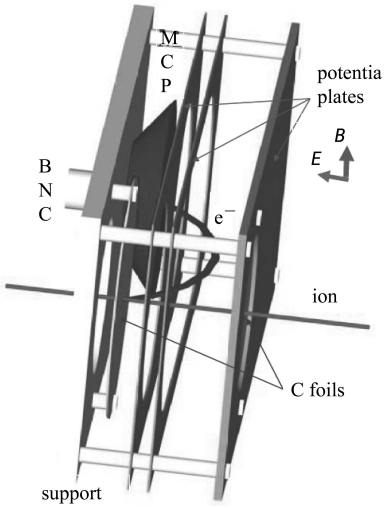

Fig. 3. The configuration of the MCP-based time-of-flight detector.

The signals from the detector were sampled with a digital oscilloscope Tektronix DPO 7254 at a sampling rate of 40 GHz and recorded for 200 μs for one injection. The revolution time of the stored ions is around 615.7 ns and 200 μs corresponds approximately to 324 turns in the ring. The energy loss of the stored ions on the carbon foil is inevitable and acceptable in the measuring periods (200 μs) since the energy loss rate is only $\sim 10^{-7}$per turn. The velocity difference of the ion in different turns can be compensated for by circulating in the shorter orbit based on the principle of the isochronicity of CSRe. The sampled data were transported from the oscilloscope to the computer for off-line analysis.

4 Data analysis

A typical spectrum from the detector after one injection into CSRe is shown in the left panel of Fig. 4 as an example. The data were analyzed following the technique developed by the ESR group[11, 12].

At first, the signals were sorted with some certain requirements set on the amplitude and the rising time. Then the arriving time information of each signal was determined with the constant fraction triggering technique to eliminate the influence of amplitude fluctuation. The parameters for the constant fraction method were optimized to get the least uncertainty of the time.

By comparing the time intervals between different turns, the signals generated by the same particle can be assigned. An example is shown in the right panel of Fig. 4. The revolution periods for a certain particle can be obtained by investigating the time dependence on the number of turns. As shown in the left panel of Fig. 5, for a single particle these times are approximately proportional to the number of turns since injection. By fitting these datum points, the revolution period was finally extracted for this particle. In this pilot experiment, the slope of a linear fit was assigned as the revolution period since the influence caused by the energy loss of the ion passing through the carbon foil is negligible. The final revolution time spectrum for all measured particles in the pilot experiment is shown in the right panel of Fig. 5, which was accumulated with the extracted slope value of each particle. The peaks indicate different particles with their own m/q ratios. The mean revolution time of each peak in the revolution time spectrum was calculated and then the corresponding nuclides identification were performed according to relation (1).

Assuming the masses of the radioactive nuclides ^{34}Cl and ^{30}P are not known, the masses of the stable nuclei ^{32}S, ^{28}Si, ^{24}Mg, ^{26}Al were used as references for calibration to determine the masses of ^{34}Cl and ^{30}P, where ^{34}Cl and ^{26}Al have isomeric states with low excitation energy of 146.36 keV and 228.305 keV[13],

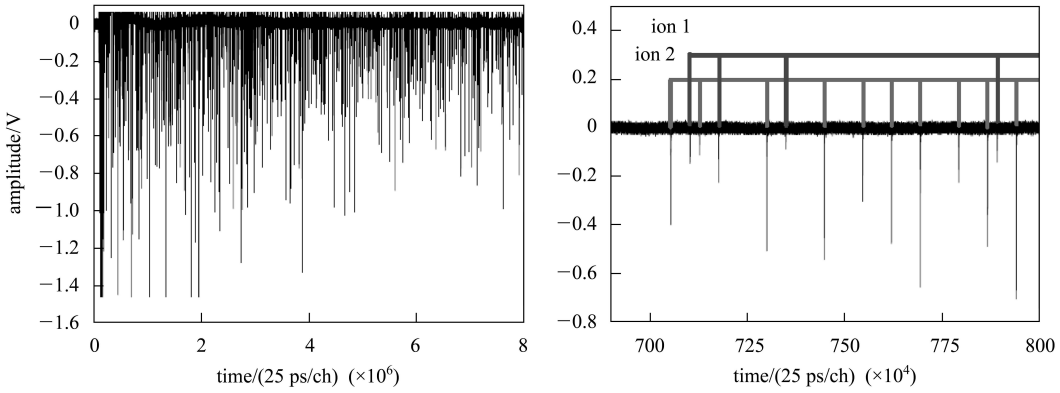

Fig. 4. (left) The original time spectrum measured with the detector for one injection into the CSRe. (right): The enlarged one which shows two particles stored in the ring simultaneously.

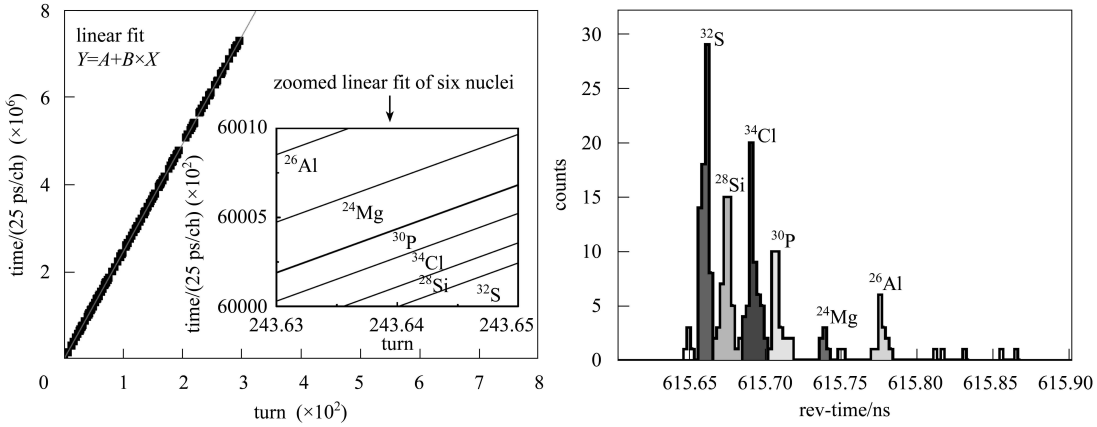

Fig. 5. (left) The slope of a linear fit was assigned as the revolution. (right) The final revolution time spectrum for all measured particles in the pilot experiment.

respectively, but the mean revolution time of the ground state has not been influenced significantly since the isomer population should not be high[14]. The m/q ratios of the reference nuclides were fitted by a second-order polynomial as a function of the revolution time T,

$$\frac{m}{q}(T) = a_0 + a_1 T + a_2 T^2 \,. \qquad (2)$$

The error of m/q of the reference nuclide from the literature and the contributions of the dispersion of the revolution time were treated as weight factors for fitting. The results are shown in Fig. 6. The atomic mass excesses of the radioactive nuclei ^{34}Cl and ^{30}P obtained from the measurement are -24447 ± 79 keV and -20135 ± 97 keV, and they deviate by about 7 keV and -66 keV from the literature values[15], respectively. The final errors were obtained by the quadratic combination of three contributions: (1) the contribution of the revolution time error $\sigma/\sqrt{N}$, where σ is the standard deviation of each peak and N is the number of counts in the peak; (2) the extrapolation error obtained using the covariance matrix of the fit function; (3) the systematic error which reflects the deviations of reference masses obtained by the second-order polynomial fitting from their literature values.

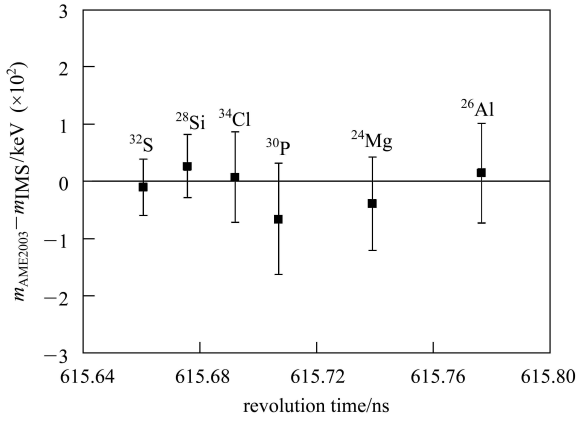

Fig. 6. The measured masses comparing with the data from AME2003[15].

5 Summary

A pilot experiment of mass measurement was performed at CSRe with the method of isochronous mass spectrometry. The fragments from the ^{36}Ar projectile were injected in CSRe and stored. Their revolution periods were measured with a time-of-flight detector system. Mass resolution around 8×10^{-6} for $\Delta m/m$ is achieved. The results show that CSRe has a strong potential for the mass measurements of short-lived nuclides.

The present TOF detector whose signal width is about 7 ns, which limits the number of ions accepted and the time resolution of about 197 ps will contribute $\sim$1 ps to the revolution time uncertainty. The upgrade of the detector to get a narrower signal width, a faster rising time and a higher detection efficiency is undertaken. The mass measurements for the nuclides of physical interest will be performed soon.

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