Article ID: 1007－4627(2009)Suppl.－0185－05

The First Isochronous Mass Measurements at CSRe*

TU Xiao-lin[1,2], XU Hu-shan[1,#], WANG Meng[1], XIA Jia-wen[1], MAO Rui-shi[1], YUAN You-jin[1], HU Zheng-guo[1], LIU Yong[1], ZHANG Hong-bin[1], ZANG Yong-dong[1,2], ZHAO Tie-cheng[1], ZHANG Xue-ying[1], FU Fen[1], YANG Jian-cheng[1], MAO Li-jun[1], XIAO Chen[1,2], XIAO Guo-qing[1], ZHAO Hong-wei[1], ZHAN Wen-long[1]

(1 *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou* 730000, *China*;
2 *Graduate School of Chinese Academy of Sciences, Beijing* 100049, *China*)

Abstract: With the commissioning of the Cooler Storage Ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR), a pilot experiment operating the CSRe in isochronous mode to test the power of HIRFL-CSR for measuring the mass of the short-lived nucleus was performed in December of 2007. The fragments with $A/q = 2$ of ^{36}Ar were injected into CSRe and their revolution frequencies were measured with a fast time pick-up detector with a thin foil in the circulating path of the ions. The preliminary result is presented. The result shows the potential of CSRe for mass measurements of short-lived nuclei.

Key words: radiotive ion beam; mass; time-of-flight; HIRFL-CSR

CLC number: O571.22 **Document code**: A

1 Introduction

The mass of a nucleus, i.e. its binding energy, reflects all the interactions between its constituent. It is of the primary interests for nuclear structure, for astrophysics models and for theoretical mass models improving. The determination of the masses of the nuclei has attracted the great interests of both the experimentalists and the theoreticians for many years. After almost one century's work, the masses of the most stable and long-lived nuclides have been well determined, while the experimental data on the masses of the exotic nuclei far from the valley of β-stability are scarce, due to the low production rates and very short lives. Thanks to the radioactive ion beam (RIB) facilities developed recently, the determination of the masses of the short-lived nuclei becomes a rapidly developing field in nuclear physics[1,2].

Contrast to the stable nuclides, usually the exotic nuclides are produced in nuclear reactions with a large amount of contaminants, therefore two main complementary separation methods are applied in the RIB facilities: the isotope separation on-line (ISOL)[3] and the in-flight separation[4]. An in-flight separator can provide RIB with half-lives shorter than microseconds, while lifetimes of RIB from ISOL system are limited by the diffusion processes and are longer than several milliseconds.

The experimental results from the ESR at the Gesellschaft für Schwerionenforschung (GSI) prove that the combination of the in-flight separator and the cooler storage ring is an efficient meth-

---

* Received date: 31 Oct. 2008

* Foundation item: National Natural Science Foundation of China(10635080, 10221003); State Key Development Program of Basic Research of China(2007CB815000); Knowledge Innovation Project of Chinese Academy of Sciences(CXTD-J2005-2, KJCX2-SW-N18)

Biography: Tu Xiao-lin(1992－), male(Han Nationality), Chongqing, Doctor Candidate, working on experimental nuclear physics; E-mail: tuxiaolin@impcas.ac.cn

Corresponding author: Xu Hu-shan, E-mail: hushan@impcas.ac.cn

od for direct mass measurements for the short-lived exotic nuclides[5]. With the commissioning of the Cooler Storage Ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR)[6], mass measurements are possible at CSRe with similar scheme.

Fig. 1 shows the layout of the HIRFL-CSR complex. CSR is the post-acceleration system of the HIRFL. It consists of a main ring (CSRm) and an experimental ring (CSRe). The heavy ion beam from the HIRFL cyclotron(s) can be accumulated, cooled and accelerated in CSRm. A secondary beam line named RIBLL2 interconnects the CSRm and CSRe. The extracted beam from CSRm can produce radioactive ion beams (RIBs) or highly charged ions through the RIBLL2. Those secondary beams can be accepted and stored in the CSRe for the mass/decay measurement or the internal-target experiments.

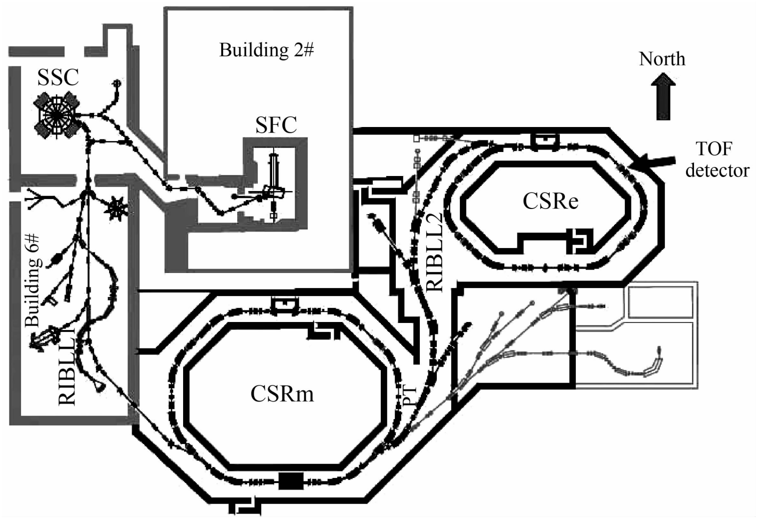


Fig. 1 The layout of the HIRFL-CSR complex.

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

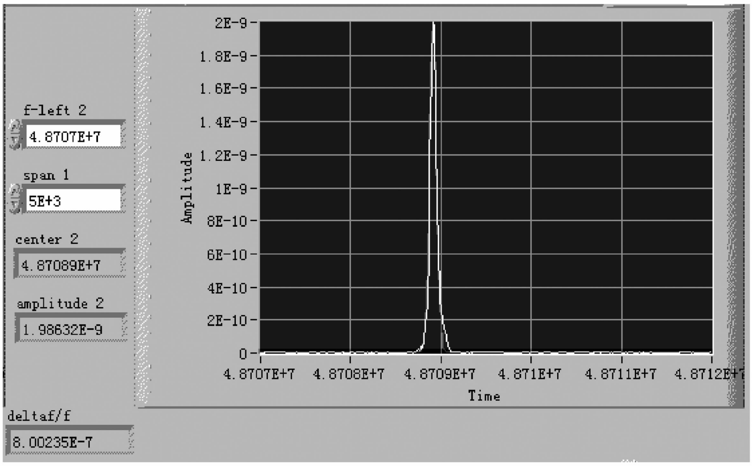
$$\frac{\Delta f}{f}=-\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{(m/q)}+\left(1-\frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}, \qquad (1)$$

where γ and v are the Lorentz factor and the velocity of the ion, 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) goes to zero. 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 and running the storage ring in isochronous mode. The first case is called as Schottky Mass Spectrometry (SMS)[7] where the revolution frequencies of the stored ions are usually measured with Schottky spectrometer. The second case is called Isochronous Mass Spectrometry (IMS)[8] which makes the ions of one species with different velocities reaching an identical revolution period in the ring. Since the cooling of the stored is not necessary, the IMS is suited for the mass measurement of exotic nuclei with half-lives of several tens of microseconds.

2 Pilot Experiment for Mass Measurement

To test the power of HIRFL-CSR for measuring the mass of the short-lived nuclei, a pilot experiment was performed in December of 2007. In this pilot experiment, CSRe was operated in isochronous mode. The transition point γ_t of CSRe in isochronous mode is 1.395 which corresponds to the energy about 368 MeV/u for the ions with $A/q = 2$. For the ions with magnetic rigidities fulfilling the isochronous window of CSRe, the revolution period is about 616 ns since the circumference of CSRe is 128.8 m.

In the first step of the pilot experiment, the isochronism of CSRe was verified. CSRe was set as an IMS for the ions with $A/q = 2$ and the magnetic rigidity of the RIBLL2 was set at $B\rho = 6.0395$ Tm, same as CSRe. To confirm the isochronism of CSRe, the primary beam of $^{36}\mathrm{Ar}^{18+}$ of 368 MeV/u, corresponding to $B\rho = 6.0395$ Tm, was directly injected into it. Taking the advantage of the high intensity of the primary beam, the revolution frequency of the stored $^{36}\mathrm{Ar}^{18+}$ ions in CSRe was measured with the beam position monitor, which is used for non-destructive beam diagnostics. The $^{36}\mathrm{Ar}^{18+}$ ions circulating in the ring induced mirror charges on the electrostatic pick-up electrodes. By using the Fourier transform, the revolution frequency spectrum was obtained. By optimizing the optical setting of CSRe, the dispersion of the frequency was reduced. Finally the dispersion of the frequency $\delta f/f$ of about 8×10^{-7} was obtained (shown in Fig. 2), which is much smaller than the momentum dispersion of the order of 10^{-4} to operate the CSRe in normal mode. This was taken as strong evidence that the isochronism of CSRe was achieved.


f-left 2: 4.8707E+7

span 1: 5E+3

center 2: 4.87089E+7

amplitude 2: 1.98632E-9

deltaf/f: 8.00235E-7

Fig. 2 The revolution frequency spectrum of the circulating 368.022 MeV/u $^{36}\mathrm{Ar}^{18+}$ ions in CSRe operating as an IMS.

The optical setting of the CSRe and RIBLL2 kept unchanged in the following step. The energy of the primary beam $^{36}\mathrm{Ar}^{18+}$ was increased up to 400 MeV/u and a production target made of $\mathrm{Al_2O_3}$ with the thickness of 2.83 mm was inserted at the entrance of RIBLL2. By bombarding the production target with the primary beam extracted from CSRm, the secondary beams were produced. The fragments with $A/q = 2$ and velocities fulfilling the isochronous condition were selected with the $B\rho$ setting of RIBLL2, injected into CSRe and then stored. The energy of the primary beam after the production target was reduced to 373.7 MeV/u, which corresponds to $B\rho = 6.0936$ Tm. By limiting the $B\rho$ acceptance of RIBLL2 with the slits, the primary beam can be rejected, despite of the identical $A/q = 2$. In this setting, the RIBLL2 is operated as a pure magnetic rigidity filter in order to transmit several ions with close mass-to-charge ratios into CSRe simultaneously. Usually, the nuclei to be measured are purified furthermore with $B\rho$-ΔE-$B\rho$ technique to reduce the contaminations from other nuclides, and then injected into CSRe.

A time-of-flight (TOF) detector[9] was then inserted into the CSRe to measure the revolution frequencies of the stored ions. A carbon foil with the thickness of 20 μg/cm^2 and the 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 a multi-channel plate (MCP) as an electron amplifier with perpendicular electrostatic and magnetic fields. The detector was tested with α particles of 5.486 MeV from a radiation source, and a time resolution of 197 ±10 ps (FWHM) was obtained with the detection efficiency of 61% in the laboratory.

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 616.2 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 ~10^{-7} per turn. The velocity difference of the ion in different turn can be compensated by circulating in the shorter orbit based on the principle of the isochronism of CSRe. The sampled data were transported from the oscilloscope to the computer on site for off-line analysis.

3 Data Analysis

A typical spectrum from the detector after one injection into CSRe is shown in the left panel of Fig. 3 as an example. The data were analyzed following the technique developed by ESR group[10].

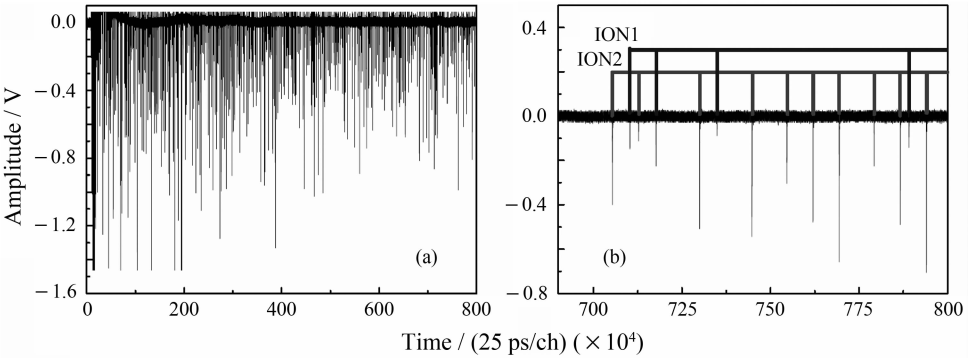


Fig. 3 (a) the original time spectrum measured with the TOF detector for one injection into the CSRe; (b) the enlarged one which shows two particles stored in the ring simultaneously.

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. By comparing the time intervals between different turns, the signals generated by same particle can be assigned. An example is shown in the right panel of Fig. 3. The revolution periods for a certain particle can be obtained by investigating the time dependence on the number of turns. 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 analysis of the data is still in progress and the preliminary result of revolution time spectrum was obtained as shown in Fig. 4. The mean revolution time of each peak in the revolution time spectrum was calculated, which reflects different particles with the unique m/q ratios. According to Eq. (1) and the relative position of the peaks, the peaks were assigned to the corresponding particles as marked in Fig. 4.

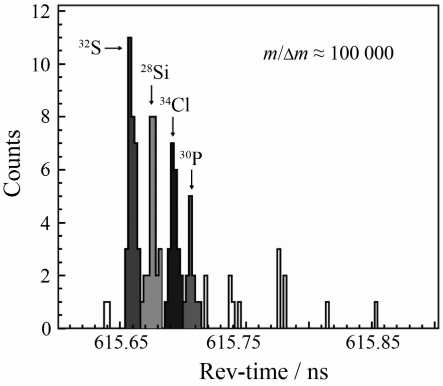


Fig. 4 The preliminary revolution time spectrum of stored nuclei in the experiment.

The data are still under analysis, while two conclusions can be still drawn: 1) the radioactive nuclear beams of ^{34}Cl and ^{30}P were produced and injected in the CSRe. This is the first time for RIBLL2 to provide radioactive ion beams; 2) The differences of mass-to-charge ratios between the neighbors of the four nuclei in Fig. 4 are in the scale of 5×10^{-5}, and they can be separated clearly. The peaks were fitted with Gaussian form and the frequency deviation of about 6.5×10^{-6} was obtained. The error of the experimental result still needs to be understood, while the mass resolution of better than 10^{-5} for $\Delta m/m$ can be achieved.

4 Summary and Discussion

A pilot experiment of mass measurement was performed at CSRe with the method of isochronous mass spectrometry. The fragments of ^{36}Ar were injected in CSRe and stored. Their revolution frequencies were measured with a TOF detector system. The preliminary result shows the potential of CSRe for the mass measurements of short-lived nuclei.

The data are still under analysis. We are improving the procedure of data analysis and investigating the uncertainties of the experimental results. Then the nuclear masses will be extracted and compared with literature values. The mass measurements for the nuclei of physical interests will be performed soon.

References:

[1] Lunney D, Pearson J M, Thibault C. Rev Mod Phys, 2003, 75 : 1 021.

[2] Klaus Blaum. Phys Rep, 2006, 425: 1.

[3] Mark Huyse. Nucl Phys, 2002, A701: 265.

[4] Hans Geissel, Gottfried Münzenberg, Helmut Weick. Nucl Phys, 2002, A701: 259.

[5] Geissel H, Litvinov Yu A, Beckert K, *et al*. Eur Phys J, 2007, 150: 109; Litvinov Yu A, Geissel H, Beckert K, *et al*. Nucl Phys, 2007, A787: 315c.

[6] Xia J W, Zhan W L, Wei B W, *et al*. Nucl Instr and Meth, 2002, A488: 11.

[7] Radon T, Kerscher Th, Schlitt B, *et al*. Phys Rev Lett, 1997, 78: 4 701.

[8] Hausmann M, Attallah F, Beckert K, *et al*. Nucl Instr and Meth, 2000, A446 : 569.

[9] Tu Xiaolin, Wang Meng, Hu Zhengguo, *et al*. to be published.

[10] Hausmann M, Stadlmann J, Attallah F, *et al*. Hyperfine Interactions, 2001, 132: 291; Stadlmann J, Hausmann M, Attallah F, *et al*. Phys Lett, 2004, B586: 27.