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Precision isochronous mass measurements at the storage ring CSRe in Lanzhou

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ABSTRACT

Direct mass measurements of ^{78}Kr projectile fragments have been performed in the recently commissioned storage ring CSRe employing the isochronous mass spectrometry method. A new data-analysis technique has been developed to correct the drifts in the revolution frequencies caused by instabilities of the magnetic fields in the CSRe, thus yielding a mass resolving power of $R = m/\Delta m \approx 1.7 \times 10^5$ (sigma). Masses for ^{45}V, ^{47}Cr, ^{49}Mn and ^{51}Fe nuclei are determined with a relative mass precision of $\delta m/m \approx 2 \times 10^{-7}$ (sigma) which is an improvement by a factor of ~ 2 compared to the literature values.

1. Introduction

Nuclear mass is a fundamental property of the nucleus. The complex interplay of strong, weak and electromagnetic interactions in a nucleus contributes to the difference between its mass and the sum of the masses of its constituent nucleons. Nuclear masses find their applications in nuclear structure, nuclear astrophysics, as well as in testing the standard model and fundamental symmetries [1,2]. Owing to the broad range of applications, mass spectrometry is an intensively developing field in nuclear physics.

In recent years, the majority of new data stem from Penning trap and storage ring mass spectrometry [3–8]. Both techniques are based on the accurate determination of revolution frequencies (or equivalently revolution times) of stored nuclides [1,9]. However, due to instabilities of the magnetic fields, the revolution frequencies may drift, thus deteriorating the power of resolution (see, e.g., Refs. [6,7]). In Penning trap spectrometry, magnetic fields are calibrated by measuring revolution frequencies of nuclides with well-known masses (reference nuclides), ideally of ^{12}C-clusters [10]. The nuclides of interest are investigated in between such calibration measurements and the magnetic field strength value is interpolated [1]. Recently, a novel "double-pan" balance method, where the reference and the measured ions are stored simultaneously in a Penning trap, has been developed. By that method the effects of magnetic field drifts are suppressed allowing the relative uncertainties to be smaller than 1×10^{-11} (sigma) for the first time in a mass measurement [11]. In storage ring mass spectrometry, one usually groups the data acquired in a short-time measurement, then, mass values and associated errors are determined using a correlation-matrix approach [5,6]. This method was developed and used first in the data analysis of the Schottky Mass Spectrometry (SMS) experiments at GSI [5]. A similar procedure was also used in the

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Isochronous Mass Spectrometry (IMS) in GSI [12], leading to a mass resolving power of $R \approx 2 \times 10^5$ (FWHM). An obvious advantage of the storage ring spectrometry is that the reference nuclides and the nuclides of interest can be easily stored simultaneously in the ring. Thus the reference nuclides can be used to correct the frequency drifts due to the instabilities of magnetic fields or due to other instabilities.

The recent commissioning of the Cooler Storage Ring (CSR) at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [13] has enabled direct mass measurements at the Institute of Modern Physics in Lanzhou (IMP), Chinese Academy of Sciences. In a test experiment [14], masses of three proton-rich nuclei, ^{63}Ge, ^{65}As, and ^{67}Se were measured for the first time. However, due to the instabilities of the magnetic fields in experimental cooler storage ring (CSRe), only a moderate mass resolving power of $R \approx 5 \times 10^4$ (sigma) was obtained. Here we report on a new data-analysis technique which is applied to the present experiment performed at CSRe. Our new technique can efficiently correct the effects of magnetic field drifts in CSRe. High precision masses of ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr nuclides have been obtained and reported in our recent publication [15]. Details of data analysis and systematic error estimations are described in this article. We present also the improved mass values for ^{45}V, ^{47}Cr, ^{49}Mn, and ^{51}Fe, the uncertainties of which have been reduced by a factor of ~ 2 compared to the previous Atomic Mass Evaluation [16]. These nuclides have all half-lives of the order of 0.5 s [17].

2. Experiment

In this experiment we aimed at measuring the masses of short-lived $A=2Z-1$ nuclei. For this purpose, a primary $^{78}Kr^{19+}$ beam at 4 MeV/u was provided by the sector focusing cyclotron (SFC). The beam was stripped to $^{78}Kr^{28+}$ in the beam transportation line and then injected into the main storage ring (CSRm). Several bunches of $^{78}Kr^{28+}$ ions were accumulated in CSRm reaching up to $\sim 1 \times 10^8$ stored particles. The accumulated beam was then accelerated to a relativistic energy of 483.4 MeV/u. The high-energy ^{78}Kr beam was fast-extracted and focused upon a 15 mm thick beryllium target placed at the entrance of the radioactive beam line (RIBLL2). Exotic nuclei were produced via the projectile fragmentation. At this high energy, the reaction products emerged from the target predominantly as bare ions. The $A=2Z-1$ nuclides were separated in flight with RIBLL2, which was operated as a pure magnetic rigidity filter, and injected into the experimental cooler storage ring for mass measurements. The magnetic rigidities of both RIBLL2 and CSRe were set to a fixed value of $B\rho = 5.9493$ Tm throughout the entire experiment.

In first order, a relation between revolution times T (revolution frequencies f) of the stored ions, their mass-to-charge ratios m/q, and the velocity spreads $\Delta v/v$ is given by [9]

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

where γ is the relativistic Lorentz factor of the stored ions and γ_t denotes the transition point of the storage ring. The second term on the right hand side of this equation is zero if the condition $\gamma = \gamma_t$ is fulfilled. In this case the revolution times reflect directly the mass-to-charge ratios of the ions, independent of their velocity spread. In the present Isochronous Mass Spectrometry (IMS) mode, which was pioneered at the ESR facility of GSI [9,12,18–20], the differences in velocities of different species were compensated by the lengths of their closed orbits. The γ_t value of CSRe is 1.395, therefore, the primary beam energy was selected to ensure the mean kinetic energies of desired fragments to be 368 MeV/u at the injection into CSRe.

The revolution times were measured using a timing detector [21] equipped with a 19 μg/cm^2 thin carbon foil of 40 mm in diameter. Each stored ion passed through the timing detector at every revolution in CSRe. Secondary electrons released from the foil due to the passing ions were guided isochronously by perpendicularly arranged electrostatic and magnetic fields to a set of micro-channel plates. The time resolution of the detector was about 50 ps (sigma), and the detection efficiency varied from 20% to 70 % depending on the ion type and the number of the ions stored. The signals from the detector were sampled with a digital oscilloscope Tektronix DPO 71254 [22] at a sampling rate of 50 GHz. The recording time, triggered by the start pulse of the CSRe injection kicker, was set to 200 μs for each injection corresponding to ~ 320 revolutions of the ions in CSRe. A part of a typical trace acquired in real time is shown in Fig. 1(a).

In the projectile fragmentation of ^{78}Kr, fragments inevitably have broad energy distributions of a few percent. All nuclides within the acceptance of the RIBLL2-CSRe system should be transmitted and stored in CSRe. Typically, more than ten ions were stored simultaneously in one injection. On average, two $A=2Z-1$ nuclides were stored at CSRe for each ejection.

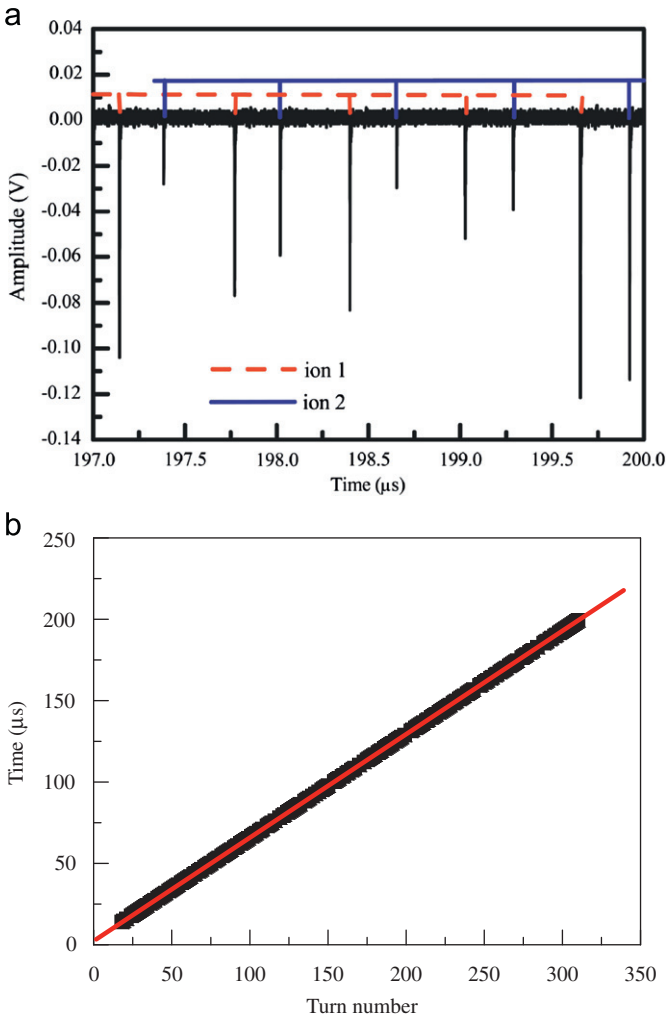

Fig. 1. (a) A part of the timing signals from the MCP detector recorded by the digital oscilloscope Tektronix DPO 71254. Two ions are indicated as ion 1 and ion 2 (see text for details). (b) The extracted passing times of an ion as a function of the revolution turns. The solid red line corresponds to the fit using a second order polynomial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)