An improvement of isochronous mass spectrometry: Velocity measurements using two time-of-flight detectors

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ABSTRACT

Isochronous mass spectrometry (IMS) in storage rings is a powerful tool for mass measurements of exotic nuclei with very short half-lives down to several tens of microseconds, using a multicomponent secondary beam separated in-flight without cooling. However, the inevitable momentum spread of secondary ions limits the precision of nuclear masses determined by using IMS. Therefore, the momentum measurement in addition to the revolution period of stored ions is crucial to reduce the influence of the momentum spread on the standard deviation of the revolution period, which would lead to a much improved mass resolving power of IMS. One of the proposals to upgrade IMS is that the velocity of secondary ions could be directly measured by using two time-of-flight (double TOF) detectors installed in a straight section of a storage ring. In this paper, we outline the principle of IMS with double TOF detectors and the method to correct the momentum spread of stored ions.

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1. Introduction

Isochronous mass spectrometry at heavy-ion storage rings plays an important role in mass measurements of short-lived nuclei far from the valley of β-stability [1]. Many important results in nuclear physics and nuclear astrophysics have been obtained in recent years based on the accurate determination of mass values by applying IMS at Gesellschaft für Schwerionenforschung (GSI) and Institute of Modern Physics (IMP), Chinese Academy of Sciences [1,2]. The basic principle of IMS describing the relationship between mass-over-charge ratio (m/q) and revolution period (T) can be expressed in first order approximation [3]

$$\frac{dT}{T} = \alpha_p \frac{d(m/q)}{m/q} - \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{dv}{v}, \qquad (1)$$

where v is the ion velocity. The momentum compaction factor α_p is defined as:

$$\alpha_p = \frac{dC}{C} \Big/ \frac{dB\rho}{B\rho}. \qquad (2)$$

It describes the ratio between the relative change of orbital length C of an ion stored in the ring and the relative change of its magnetic rigidity $B\rho$. γ_t, defined as $\alpha_p \equiv 1/\gamma_t^2$, is the transition energy of a storage ring. By setting the Lorentz factor γ of one specific ion species to satisfy the isochronous condition $\gamma = \gamma_t$, the revolution period of the ions is only related to its mass-over-charge ratio m/q, and independent of their momentum spreads. Obviously, this property can only be fulfilled within a small mass-over-charge region, which is called the isochronous window [4]. However, for other ion species beyond the isochronous window, or even for the ions within the isochronous window, the isochronous condition is not strictly fulfilled. As a result, the unavoidable momentum spread due to the nuclear reaction process will broaden the distribution of revolution period, and thus, lead to a reduction in mass resolving power.

To decrease the spread of revolution period, it is obvious that the magnetic rigidity spread of stored ions should be corrected for. However, the magnetic rigidity of each ion can presently not

be measured directly, especially for the ions with unknown mass-to-charge ratio, according to the definition of magnetic rigidity:

$$B\rho = \frac{p}{q} = \frac{m}{q}\beta\gamma c. \tag{3}$$

We note that, as shown in Eq. (2), ions with the same magnetic rigidity will move around the same closed orbit, regardless of their m/q. Therefore, the correction of magnetic rigidity of the stored ions can be established via the correction of their corresponding orbit.

To realize this kind of correction, one recently-proposed method is to measure the ion's position in the dispersive arc section by using a cavity doublet, which consists of a position cavity to determine the ion position and a reference cavity to calibrate the signal power [5,6]. However, the establishment of this method may strongly depend on the sensitivity of the transverse Schottky resonator.

Another possible method, which will be described in detail below, is to measure the ion velocity by using the combination of the two TOF detectors installed in a straight section of a storage ring. The original idea was first proposed at GSI [7], and has recently been tested in on-line IMS experiments at IMP [8] and studied by simulations [9]. Fig. 1 illustrates the schematic view of the setup of the double TOF detectors at the experimental cooler storage ring (CSRe). By employing this additional velocity information of stored ions to correct the momentum spread, the mass resolving power of IMS will significantly be improved.

2. Formulation and method

In typical IMS experiments, the primary beam is accelerated and then bombards a target to produce the secondary particles. After in-flight separation, several secondary ions are injected and stored in the ring simultaneously. When the stored ions penetrates a thin carbon foil of the TOF detector, secondary electrons are released from the surface of the foil and are guided by perpendicularly arranged electrostatic and magnetic fields to a set of microchannel plate detectors (MCP). The timestamps of each ion penetrating the TOF detector are recorded by a high-sampling-rate oscilloscope and are analyzed to determine the revolution periods of all stored ions. After correcting for instabilities of magnetic fields of the storage ring, all revolution periods of stored ions are superimposed to a revolution period spectrum, which can be used to determine the unknown masses and the corresponding errors [11–13].

Obviously, the uncertainty of the revolution period, which directly relates to the error of the determined mass value, takes into account the contributions of momentum spread of stored ions.
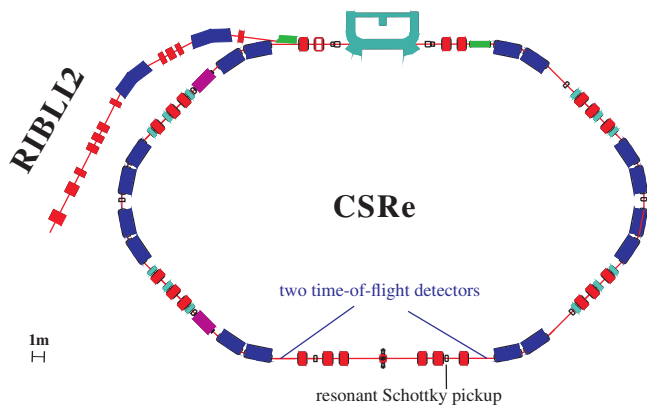

Fig. 1. Schematic view of the arrangement of the double TOF detectors at the experimental cooler storage ring (CSRe) in IMP [10].

In order to correct for such effects, we should think about the basic relationship of the revolution period (T) versus the velocity (v) of an individual ion, or the relationship of the orbital length ($C = T \cdot v$) versus the velocity.

In an IMS experiment, we can assume that when an ion was injected into the storage ring, its initial orbit and magnetic rigidity are C_{init} and $B\rho_{init}$, respectively. After penetrating the carbon foil of the TOF detector for many times, the ion's orbit and magnetic rigidity change to C and $B\rho$, due to the energy loss in the carbon foil. Because the relative energy loss after each penetration is tiny (in the order of 10^{-6}), the change of the orbit can be regarded to be continuous. Therefore, the relationship between the orbit and the magnetic rigidity can be obtained by integration of Eq. (2):

$$\int_{C_{init}}^{C} \frac{dC}{C} = \int_{B\rho_{init}}^{B\rho} \alpha_p \frac{dB\rho}{B\rho}. \tag{4}$$

It is clear that the knowledge of α_p is crucial for solving this problem. In reality, the momentum compaction factor α_p is a function of the magnetic rigidity of the ring. For an ion stored in the ring, it can be expressed as [14]:

$$\alpha_p(\beta\gamma) = \alpha_{p0} + \alpha_{p1}\frac{\delta\beta\gamma}{\beta\gamma} + \alpha_{p2}\left(\frac{\delta\beta\gamma}{\beta\gamma}\right)^2 + \cdots, \tag{5}$$

where α_{p0} is the constant part of the momentum compaction factor determined by the dispersion function, and α_{p1} is related to the perturbation of the momentum compaction factor, which has contributions from the slope of the dispersion function [14]. To clearly express the principle of IMS with double TOF detectors, firstly we ignore all the higher order components of α_p and consider the simplest approximation of $\alpha_p = \alpha_{p0}$. The effect of higher order components of α_p will be discussed in the Section 4.

The result of the integration of Eq. (4) yields the relationship of the orbital length versus the velocity

$$\frac{C}{(\beta\gamma)^{\alpha_{p0}}} = \frac{C_{init}}{(\beta_{init}\gamma_{init})^{\alpha_{p0}}} \equiv K. \tag{6}$$

We emphasize that K is only determined by the kinetic parameters of a given ion, and keeps constant after the ion is injected into the ring, despite of its energy loss in the carbon foil of the TOF detectors. According to Eq. (6), we can calculate the revolution period of each ion corresponding to any arbitrary orbital length, if we can measure the revolution period and the velocity of each ion simultaneously. Therefore, by correcting the revolution period of each ion to a certain orbital length (equivalent to a certain magnetic rigidity for all ions), the corrected revolution periods can superimpose a spectrum with just higher-order contributions of momentum spread. This is the cornerstone of our methodology.

Let us define a reference orbit with a certain length C_0, and the kinetic parameters of that ion circulating in this orbit are $\{T_0, v_0, \beta_0, \gamma_0\}$. As discussed before, the reference orbit C_0 and the real orbit C can be connected by the constant K:

$$\frac{C_0}{(\beta_0\gamma_0)^{\alpha_{p0}}} = \frac{C}{(\beta\gamma)^{\alpha_{p0}}} = K. \tag{7}$$

Since the orbital length of a stored ion is: $C = T \cdot v$, the parameter C can be determined experimentally. The revolution period T of the ion can be extracted from the timestamps of either of the two detectors using the previous method as described in Ref. [12], and the velocity of the ion v in any revolution can be directly measured by the double TOF detectors:

$$v = \frac{L}{t_{TOF1} - t_{TOF2}}, \tag{8}$$

where L is the straight distance between the double TOF detectors, and t_{TOF1}, t_{TOF2} are the timestamps recorded by them respectively [9].