Accurate velocity determination of stored ions in CSRe by resolving the non-isochronicity of time-of-flight detectors

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Abstract

Accurate velocity determination of stored ions in storage rings plays a key role for nuclear mass measurements using the technique of Bρ-defined isochronous mass spectrometry (B -IMS). However, the accuracy and precision of the ion's velocity are seriously deteriorated by the non-isochonicity of the time-of-flight (TOF) detectors. In this paper, the non-isochonicity is described by a correlation function between the time-delay difference, t_d, of the two TOF detectors and the orbital length, C, of the stored ions. The obtained correlation functions, t_d C, allow for accurate determination of the ion's velocity which is then used for mass calibration in the B -IMS technique. The present data analysis method is proved to be capable of resolving the effects of the non-isochronicity of TOF detectors.

Full Text

Accurate velocity determination of stored ions in CSRe by resolving the non-isochronicity of time-of-flight detectors

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Abstract

Accurate velocity determination of stored ions in storage rings plays a key role for nuclear mass measurements using the technique of B -defined isochronous mass spectrometry (B -IMS). However, the accuracy and precision of the ion's velocity are seriously deteriorated by the non-isochronicity of the time-of-flight (TOF) detectors. In this paper, the non-isochronicity is described by a correlation function between the time-delay difference, td, of the two TOF detectors and the orbital length, C, of the stored ions. The obtained correlation functions, td   C, allow for accurate determination of the ion's velocity which is then used for mass calibration in the B -IMS technique. The present data analysis method is proved to be capable of resolving the effects of the non-isochronicity of TOF detectors.

Keywords: ion velocity determination, B -IMS, mass calibration, TOF detector

I. INTRODUCTION

The mass or binding energy of an atomic nucleus is a fundamental physical property, reflecting the summed effects of all interactions in the nucleus. Precise measurement of nuclear masses plays an important role in various research fields, such as nuclear structure and nuclear astrophysics [1–3]. The magnetic rigidity-defined isochronous mass spectrometry (B -IMS), recently established at the heavy-ion storage ring CSRe, provides a method for accurate nuclear mass measurements [4–6].

In B -IMS experiments, two identical time-of-flight (TOF) detectors are employed for accurate measurements of velocity (v) and revolution time (T) of the stored ions. The detectors are installed in the straight section of CSRe as shown in Fig. 1 [Figure 1: see original paper] [4, 7, 8]. Each TOF detector consists of a carbon foil of 20 μg/cm^2 thickness and a set of microchannel plates (MCP). Ions stored in the ring pass through the carbon foil periodically and induce secondary electrons (SEs) from the foil surface. These SEs are guided by perpendicular electric and magnetic fields to the MCP. The signals are then recorded by a digital oscilloscope [9]. In this way, two time sequences from the two TOF detectors, tTOF1(N) and tTOF2(N) as a function of the revolution number N, are obtained for each stored ion [8, 10]. By analyzing these time sequences, the ions' revolution times and velocities can be determined [8].

For an ion species with well-known mass-to-charge ratio m/q, the magnetic rigidity B and the orbital length C are obtained directly using the experimentally measured T and v according to the relation $C = v \cdot T$, where $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor of the ion. In principle, the measured B and C values of any stored ion should be around the curve of B versus C determined by the beam optical settings of the storage ring [11]. The key of the B -IMS technique is to establish the B (C) function using the experimentally deduced (B , C) data of known-mass nuclei. Once the B (C) function is known, the B values of any stored ions can be obtained according to its orbital length C = T • v. Subsequently, the m/q of these ions can be derived.

The B -defined IMS has been successfully used in mass measurements of short-lived nuclides [12–15]. However, in the event-by-event data analysis, it is found that the obtained individual mass values are, in some cases, related to the corresponding orbital lengths, leading to a larger uncertainty for the mean mass value. In this paper, we report a novel data analysis method to resolve this problem. The new method is used to analyze the data from a mass measurement experiment, and its successful application is demonstrated.

II. ORBITAL DEPENDENCE OF VELOCITY DETERMINATIONS FOR STORED IONS

The experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL) [16]. A ^{86}Kr primary beam with an energy of E = 420 MeV/u bombarded a ^{9}Be target. The projectile fragments were selected by the fragment separator RIBLL2 and injected into CSRe, which was tuned in the isochronous mode with γt = 1.34. The central magnetic rigidity of the RIBLL2-CSRe system was set at B = 7.2 T • m.

Figure 2 [Figure 2: see original paper] shows the ions observed in this experiment in the revolution-time range of 600–640 ns. The ion species were identified in the plot of Ū versus T, with   and Ū representing the ion's detection efficiency and the average signal amplitude of the ion, respectively [17]. The ion species used for calibration are marked in red, while others are shown in black.

Initially, we analyzed the experimental data using the same method established in earlier works [6, 12]. In this case, the velocity of each stored ion was derived according to $v = L/(t_s - t_d)$, where ts is the mean time of flight extracted from the measured time sequences tTOF1(N) and tTOF2(N), L is the flight length of the ion in the straight section, and td is the time delay difference between the two timing signals [8]. Assuming the parameters L and td are constant, values of L = 18.049 m and td = 139 ps were determined using the method described in [6].

The mass values were obtained following the procedures described in [4, 6]. However, in the event-by-event analysis, a noticeable correlation between the individual mass values and the orbital lengths was observed. A typical example is shown in Fig. 3 [Figure 3: see original paper], where the individual mass obtained from each ^{64}Fe event is plotted as a function of its corresponding orbital length. The Pearson correlation coefficient is obtained as r = -0.63. Obviously, such a correlation will certainly enlarge the standard deviation of the mean mass value of ^{64}Fe.

We have analyzed the possible causes of this correlation. The assumption that L and td are constant is based on perfect conditions. In fact, the carbon foils of the two TOF detectors may not be perfectly parallel with each other, thus the flight length L might change for ions with different orbital lengths. More importantly, the time delays of the timing signals in each TOF detector vary depending on the hitting position on the carbon foil, i.e., the TOF detectors are not exactly isochronous [9]. Thus, the time delay td is affected by the hitting positions which depend on the orbitals of the ions. Therefore, both td and L are functions of the orbital length C.

The velocity determination equation should then be re-written as:

$$v(C) = \frac{L(C)}{t_s - t_d(C)}$$

Assuming td and L are continuous functions of C, they can be expressed as a Taylor expansion at the average orbital length C_0. In the first-order approximation, one has:

$$L(C) = L_0 + L' \cdot (C - C_0)$$

$$t_d(C) = t_{d0} + t'_d \cdot (C - C_0)$$

where L_0 and td_0 are the time delay and flight length at the mean orbital length C_0, and t'd = dtd(C)/dC and L' = dL(C)/dC.

III. VELOCITY DETERMINATION FOR INDIVIDUAL STORED IONS

The parameter $K_{ts} = dt_s/dT|_{T=T_0}$ can be extracted by fitting the (ts, T) data for ion species with statistics of more than 600 counts using a cubic polynomial ts(T). The experimentally determined Kts versus T_0 is shown in Fig. 5 [Figure 5: see original paper].

We used the theoretical expression for Kts to fit the (Kts, T_0) data. In the fitting procedure, $\bar{\gamma}^2$ is approximated by $\bar{\gamma}^2 = (1 - \beta^2)^{-1}$ with C_0 128.8 m and c being the speed of light in vacuum. For a stored ion, the change in C is only $±$0.2 m, leading to a variation of γ of just $±$0.2%. Therefore, this approximation affects the values of L' and t'd at a level below $±$1%.

First, we show in Fig. 4 [Figure 4: see original paper] the plots of ts versus T for ^{25}Na and ^{64}Fe ions in the event-by-event analysis. It is evident that there is a clear correlation between ts and T, and the slopes Kts are different for different ion species.

The fit result for Kts(T_0) is shown by the red line in Fig. 5 [Figure 5: see original paper]. The corresponding fit parameters are γt = 1.346, L_0/C_0 = 0.140057, L' = 0.000469, and t'd = 163 ps $\cdot$ m^{-1}, respectively. Using these fit parameters, we find that the variation in L is evidently very small. For a change of ΔC $±$20 cm for the stored ions, the relative change of L is only ΔL/L $±$5 $\times$ 10^{-6}. In contrast, the variation in td is quite significant, with a relative change as large as Δtd/td $±30^{-4}$ level.

With the correlation functions established, the magnetic rigidity B can be determined using the velocity derived from the corrected equation. As an example, Fig. 7 [Figure 7: see original paper] shows the scattering plot of B versus C for all the reference ion species, which will be used for mass calibration.

IV. APPLICATION OF THE VELOCITY

In order to obtain an accurate B (C) function for mass calibration, we selected reference ion species with more than 300 counts and mass uncertainties below 15 keV in AME20 [18–20]. We used a polynomial as the expected B (C) function to fit the (B , C) data of the selected reference ions. The standard deviations of the fitting residuals, σ(B _{exp} - B _{fit}), were deduced. To check the goodness of the fitting, Fig. 8 [Figure 8: see original paper] shows σ(B _{exp} - B _{fit}) as a function of the polynomial order. One sees that the standard deviations converge when the polynomial order reaches 8.

Fig. 9 [Figure 9: see original paper] shows the final fitting residuals for ^{25}Na ions, which are flat along C (i.e., independent of the orbital length) and distributed approximately around zero. These results indicate that the selected 8th-order polynomial describes the (B , C) data well and thus can be used as the B (C) function for mass calibration.

We note that there is no significant tilt angle between the parallel carbon foils of the two detectors [7], while the isochronicity of the detectors lacks validation. On the one hand, the detectors are unable to provide identical time responses for ions on different orbits due to manufacturing precision limitations. On the other hand, there exists instability of the voltages applied to the carbon foils and electrode plates of the TOF detectors during the experiment. These factors lead to differences in td when ions hit different positions on the carbon foils.

In our analysis, we used L_0 = 18.038 m and td_0 = 184 ps, which were determined using the previous method. These two parameters are compatible with the directly measured values in [7]. The linear correlation functions L(C) and td(C) were established and are demonstrated in Fig. 6 [Figure 6: see original paper]. One sees that the relative variations of L(C) and td(C) are on the order of

$±10^{-6}$ and $±$0.3, respectively.

Combining the fundamental relations, the orbital length C of each stored ion can be determined from its measured T and ts by solving:

$$C = \frac{t_s + t'_d C_0 - TL' - t_{d0} \pm \sqrt{(TL' - t_s + t_{d0} - t'_d C_0)^2 - 4Tt'_d \cdot (L_0 - L' C_0)}}{2t'_d}$$

From this solution, the orbital length C of each stored ion is determined by its T and ts. Then td(C) and L(C) of the individual ions are extracted directly using the linear correlation functions.

As a summary, t'd and L' were extracted by analyzing the correlations between ts and T for the stored ions (see Fig. 4). In this step, no particle identification is required. We used the L_0 and td_0 values determined from the experimental data [6]. With the known parameters t'd, L', L_0, and td_0, the accurate C and the correlation functions td(C) and L(C) were obtained via event-by-event data analysis. Finally, the accurate B values of the ions were determined.

Theoretically, when ion velocities are determined accurately, the experimental (B , C) data for all ion species should overlap and scatter along the same curve determined by the optical setting of CSRe. If the ion velocities are inaccurate, the (B , C) data for different ion species would not perfectly overlap, which can be reflected in the fitting residuals ΔB = B (C) - B _{exp}.

To check the correctness of the velocity determination, we calculated the velocities of stored ions using both the old method (Eq. 3) and the new method (Eq. 4). Two (B , C) data sets from all reference ions were then deduced. Fig. 10 Figure 10: see original paper and (b) show the (B , C) data for ^{64}Fe and ^{39}Cl, respectively, derived using different velocity determination methods. One observes that the two (B , C) data sets are not perfectly overlapped when Eq. (3) is used for velocity determination. To see the details, we fit the B C data using 8th-order polynomials and show the fitting residuals ΔB = B (C) - B _{exp} in Fig. 10(c) and (d). It is evident that the residuals for the two ion species in Fig. 10(c) are not overlapped, having a small dependence on the orbital length, while the fitting residuals in Fig. 10(d) are well overlapped and symmetrically distributed around zero, indicating that the B (C) function can well describe the (B , C) data for all reference ion species. We thus conclude that the (B , C) data obtained using Eq. (4) for velocity determination are independent of ion species, consistent with theoretical expectations.

Using the B (C) function, the magnetic rigidity B (Ci) of any ion (both reference and non-reference ions) can be obtained. The individual m/q values are converted into atomic mass excess values {MEi, i = 1, 2, …, M}. Fig. 11 [Figure 11: see original paper] shows the differences ΔME = ME_{exp} - ME_{AME20} as red points.

To demonstrate the impact of our new velocity determination method via Eq. (4), the same procedure was performed using Eq. (3) (with L = 18.049 m and td = 139 ps) for velocity determination. The obtained individual mass values are also shown in Fig. 11 as blue points. The Pearson correlation coefficients are indicated in the figures. It is evident that the correlation between masses and orbital lengths (blue points) is removed using the new method (red points).

The histograms in Fig. 11 show the distributions of mass differences ΔME = ME_{exp} - ME_{AME20} for ^{64}Fe and ^{39}Cl. Using Eq. (4) for velocity determination, ΔME has a narrow distribution with a mean value close to zero (17 keV for ^{64}Fe). This result is much better than that using Eq. (3) for velocity determination, which yields a broad ΔME distribution with a mean value of 207 keV as demonstrated in Fig. 11(a). The same improvement is also observed for ^{39}Cl, see Fig. 11(b).

V. CONCLUSION

Accurate velocity determination of stored ions in storage rings plays a key role in mass measurements using B -defined isochronous mass spectrometry. However, we found that the accuracy and precision of the ion's velocity are seriously influenced by the non-isochronicity of the time-of-flight detectors. To eliminate the non-isochronous responses of the TOF detectors, we developed a novel method for velocity determination. In this approach, two functions describing the detector's non-isochronicity, td(C) and L(C), were constructed from experimental data. In this way, a significant improvement in the velocity accuracy of stored ions has been achieved.

Based on the accurate velocities, the (B , C) data of all reference ion species are well overlapped, which allows precise determination of the B (C) function for mass calibration. Consequently, the significant correlation between mass value and orbital length was eliminated. These results demonstrate that the non-isochronicity of the TOF detectors has been largely removed using the present approach for velocity determination, and the reliability of the B -IMS is substantially enhanced. This novel approach will be applied to B -IMS data analysis in future nuclear mass measurement experiments.

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Note: Figure translations are in progress. See original paper for figures.