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Abstract

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Full Text

Accurate Velocity Determination of Stored Ions in CSRe by Correcting 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

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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 researches, 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 the 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 (SE) from the foil surface. These SEs are guided by perpendicular electric and magnetic fields to the MCP. Then, the signals are recorded by a digital oscilloscope [9]. In this way, two time sequences from 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 $C = v \cdot T$ where γ 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 B -IMS technique is to establish the B (C) function using the experimentally deduced (B , C) data of known-mass nuclei via Eq. (1). Once the B (C) function is known, the B values of any stored ions can be obtained according to its orbital length $C = T \cdot v$. 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 an improved 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]. In this experiment, the ^{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 $\gamma_t = 1.34$. The central magnetic rigidity of the RIBLL2-CSRe system was set at $B\rho = 7.2$ Tm. Fig. 2 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 $\bar{U}\eta$ versus T, with η and $\bar{U}$ representing the ion' s detection efficiency and the average signal amplitude of the ion, respectively [17].

At first, 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 in the same way as described in [4, 6] according to $v = L/(t_s - t_d)$ where t_s is the mean time of flight extracted from the measured time sequences $t_{TOF1}(N)$ and $t_{TOF2}(N)$, L is the flight length of the ion in the straight section, and t_d is the time delay difference between the two timing signals [8]. Assuming the parameters L and t_d are constant, $L = 18.049$ m and $t_d = 139$ ps were determined using the method described in [6] (the $(B\rho, C)$ data for diverse ions will overlap when appropriate values of L and t_d are assigned).

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 value obtained from each of the ^{64}Fe events 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 the L and t_d are constant is based on perfect conditions. In fact, the carbon foils of the two TOF detectors may not be perfectly parallel to 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 t_d is affected by the hitting positions which depends on the orbitals of the ions.

Therefore, both t_d and L are functions of the orbital length C. Then Eq. (3) should be re-written as $v(C) = L(C)/(t_s - t_d(C))$. In the following, we show that $t_d(C)$ and $L(C)$ can be determined from the experimental data. Assuming t_d 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:

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

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

Then K_{ts} becomes:

$$K_{ts} = \frac{dt_s}{dT}\bigg|_{T=T_0} = \frac{\gamma^2}{\bar{\gamma}^2 - \gamma^2} \cdot \frac{L_0}{C_0} + \frac{\bar{\gamma}^2}{\bar{\gamma}^2 - \gamma^2} \cdot t'_d$$

which is a function of mean revolution times, T_0, of different ion species. Other parameters in Eq. (6) can be obtained by fitting the data. These parameters include the mean orbital length C_0, the ratio of the straight-section flight distance to the mean orbital length L_0/C_0, the mean value of transition energies γ_t of CSRe, and t'_d, L' of the TOF detector.

We extracted the $K_{ts} = \frac{dt_s(T)}{dT}\Big|_{T=T_0}$ by fitting the (t_s, T) data for the ion species with statistics of more than 600 counts using a cubic polynomial $t_s(T)$. The experimentally determined K_{ts} versus T_0 is shown in Fig. 5 [Figure 5: see original paper]. Then we used Eq. (6) to fit the (K_{ts}, T_0) data. In the fitting procedure, $\bar{\gamma}^2$ is approximated by $\bar{\gamma}^2 = (1 - \beta^2)^{-1} = [1 - (C_0/T_0 c)^2]^{-1}$ with $C_0 \approx 128.8$ m [16] 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 t_s 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 t_s and T, and the slopes, K_{ts}, are different for different ion species.

The fit result is shown by the red line in Fig. 5. The corresponding fit parameters are $\gamma_t = 1.346$, $L_0/C_0 = 0.140057$, $L' = 0.000469$, $t'_d = 163$ ps • m ^{1}, respectively. Using the fit parameters L' and t'_d, the variation in L is evidently very small with a change of $\Delta C \approx \pm 20$ cm for the stored ions. Instead, the variation in t_d is quite significant. For example, at $(L_0, t_{d0}) = (18.034$ m, 98 ps$)$, the relative change of L is only $\Delta L/L \approx \pm 5 \times 10^{-6}$, while the relative change of t_d is as large as $\Delta t_d/t_d \approx \pm 30\%$. Considering the flight time between the two TOF detectors is 80–90 ns for various ions, the derived velocity can be changed by 10^{-4}.

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

In our analysis, we used $L_0 = 18.038$ m and $t_{d0} = 184$ ps which were determined using the previous method. These two parameters are compatible with the directly measured values in [7]. Then the linear correlation functions, $L(C)$ and $t_d(C)$, were established and demonstrated in Fig. 6 [Figure 6: see original paper]. One sees that the relative variations of $L(C)$ and $t_d(C)$ are in the order of $\sim \pm 10^{-6}$ and $\sim \pm 0.3$, respectively.

III. Velocity Determination for Individual Stored Ions

Combining Eqs. (1) and (4), we have:

$$v = \frac{L_0 + L' \cdot (C - C_0)}{t_s - t_{d0} - t'_d \cdot (C - C_0)}$$

In this equation, all parameters are known except the orbital length C. By solving the equation, C is obtained as:

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

from which, the orbital length C of each stored ion is determined by its T and t_s. Then $t_d(C)$ and $L(C)$ of the individual ions are extracted directly using Eq. (5). Using the velocity derived from Eq. (4), we can determine $B\rho$ via Eq. (1). As an example, Fig. 7 [Figure 7: see original paper] shows the scattering plot of $B\rho$ versus C for all the reference ion species, which will be used for mass calibration.

IV. Application of the Velocity

In order to obtain accurate $B\rho(C)$ function for the mass calibration, we selected the 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 $B\rho(C)$ function to fit the $(B\rho, C)$ data of the selected reference ions. The standard deviations of the fitting residuals, $\sigma(B\rho_{\mathrm{exp}} - B\rho_{\mathrm{fit}})$, were deduced. Fig. 8 [Figure 8: see original paper] shows the final fitting residuals of ^{25}Na ions which is flat along C, i.e., independent of the orbital length, and distributed approximately at zero. These results indicate that the selected 3rd-order polynomial describes well the $(B\rho, C)$ data and thus can be used as the $B\rho(C)$ function for mass calibration.

As a summary, t'_d and L' were extracted by analyzing the correlations between t_s and T for the stored ions (see Fig. 4). In this step, no particle identification is required. We used the L_0 and t_{d0} values determined from the experiment data [6]. With the known parameters t'_d, L', L_0, and t_{d0}, the accurate C and the correlation functions, $t_d(C)$ and $L(C)$, were obtained via Eq. (9) and Eq. (5) in the event-by-event data analysis. Finally, the accurate $B\rho$ values of the ions were determined via Eq. (1).

Theoretically, when the ion velocities are determined accurately, the experimental $(B\rho, C)$ data for all ion species should follow the same curve determined by the optical setting of CSRe. If the ion velocities are inaccurate, the $(B\rho, C)$ data for different ion species would not be perfectly overlapped, which can be reflected in the fitting residuals, $\Delta B\rho = B\rho(C) - B\rho_{\mathrm{exp}}$.

To check the correctness of velocity determination mentioned above, we calculated the velocities of stored ions using Eq. (3) and Eq. (4), respectively. Then two $(B\rho, C)$ data sets from all reference ions were deduced using Eq. (1) and Eq. (9). Fig. 9 Figure 9: see original paper and (b) show the $(B\rho, C)$ data for ^{64}Fe and ^{39}Cl, respectively. One observes that the two $(B\rho, C)$ data sets are not perfectly overlapped (see Fig. 9(a)) if Eq. (3) was used for velocity determination. To see the details, we fit the $B\rho \sim C$ data using the 3rd-order polynomials, and show the fitting residuals, $\Delta B\rho = B\rho(C) - B\rho_{\mathrm{exp}}$, in Fig. 9(c) and Fig. 9(d). It is evident that the residuals for the two ion species in Fig. 9(c) are not overlapped, having a small dependence on the orbital length, while the fitting residuals in Fig. 9(d) are well overlapped and symmetrically distributed around zero, indicating that the $B\rho(C)$ function can well describe the $(B\rho, C)$ data for all reference ion species. We thus conclude that the $(B\rho, C)$ data obtained using Eq. (4) for velocity determinations are independent of ion species, consistent with theoretical expectations.

Using the $B\rho(C)$ function, the magnetic rigidity $B\rho(C_i)$ of any ion (both reference ions and non-reference ions) can be directly obtained, then, the m/q value for M ions is deduced through:

$$\left(\frac{m}{q}\right)_i = \frac{B\rho(C_i)}{T_i}$$

where $i = 1, 2, ...M$. The individual m/q values are converted into atomic mass excess $\{ME_i, i = 1, 2, ..., M\}$. Fig. 10 [Figure 10: see original paper] shows the differences, $\Delta ME = ME_{\text{exp}} - ME_{\text{AME20}}$, as red points.

To demonstrate the impact of our new method of velocity determination via Eq. (4), the same procedure is performed using Eq. (3) (with $L = 18.049$ m and $t_d = 139$ ps) for velocity determination. The obtained individual mass values are also shown in Fig. 10 as blue points. The Pearson correlation coefficients, r' s, are deduced and indicated in the figures. It is evident that the correlation between masses and the orbital lengths (the blue points) are removed using the new method (the red points).

The histograms in Fig. 10 show the distributions of mass differences, $\Delta ME = ME_{\text{exp}} - ME_{\text{AME20}}$, for ^{64}Fe and ^{39}Cl. One sees that, using Eq. (4) for velocity determination, ΔME has a narrow distribution with a mean value close to zero ($\mu \sim 16$ keV for ^{64}Fe). This result is much better than that using Eq. (3) for velocity determination, which yields a broad ΔME distribution with the mean value of $\mu \sim 210$ keV as demonstrated in Fig. 10(a). Same improvement is also observed for ^{39}Cl, see Fig. 10(b).

V. Conclusion

Accurate velocity determination of stored ions in storage rings plays a key role in mass measurements using the B -defined isochronous mass spectrometry. However, we found that the accuracy and precision of the ion' s velocity are considerably 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 determinations. In this approach, two functions describing the detector' s non-isochronicity, $t_d(C)$ and $L(C)$, were constructed from experimental data.

In this way, a significant improvement on the velocity accuracy of stored ions has been achieved. Based on the accurate velocities, the $(B\rho, C)$ data of all the reference ion species are well overlapped, which allow precise determination of the $B\rho(C)$ 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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