ImprovedB -defined isochronous mass spectrometry for mass measurements of exotic nuclei

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Abstract

The technique of B -defined isochronous mass spectrometry (B -IMS), established at a storage ring, serves as a valuable tool for determining the masses of short-lived nuclei. In the previous B -IMS experiments, the effects of magnetic field drifts have to be corrected in order to improve the mass resolving power of B -IMS [Eur. Phys. J. A 59, 27 (2023)]. The correction procedures are complicated and require multiple reference ions with well-known masses in each injection, which may not be the cases in the measurements of exotic nuclei with tiny production yields. In this study, we propose a novel approach of B -IMS that requires only one reference ion for mass determination in an individual injection, avoiding the tedious and complicated correction procedures. This approach achieves the mass precision comparable to that of previous B -IMS results, and is approved to be suitable for future mass measurements of exotic nuclei with extremely low production yields.

Full Text

Preamble

Improved B -defined isochronous mass spectrometry for mass measurements of exotic nuclei

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The technique of B -defined isochronous mass spectrometry (B -IMS), established at a storage ring, serves as a valuable tool for determining the masses of short-lived nuclei. In previous B -IMS experiments, the effects of magnetic field drifts had to be corrected to improve the mass resolving power of B -IMS [**?**]. The correction procedures are complicated and require multiple reference ions with well-known masses in each injection, which may not be feasible in measurements of exotic nuclei with tiny production yields. In this study, we propose a novel approach to B -IMS that requires only one reference ion for mass determination in an individual injection, avoiding tedious and complicated correction procedures. This approach achieves mass precision comparable to that of previous B -IMS results and is proven suitable for future mass measurements of exotic nuclei with extremely low production yields.

Keywords: Storage ring, B -defined isochronous mass spectrometry, Double time-of-flight (TOF) detectors, Nucleus mass measurement

INTRODUCTION

Mass spectrometry of nuclei or ions has wide applications in nuclear physics [**?**] and other areas [**?**, **?**]. Isochronous mass spectrometry (IMS) conducted at the Cooler Storage Ring for experiment (CSRe) at Lanzhou, China, has emerged as a pivotal technology for nuclear mass determination. This method has yielded numerous new mass values \cite{4–10}, establishing itself as an essential tool in nuclear mass spectrometry \cite{11–13}.

Early IMS experiments relied on measurements of revolution times (T) of stored ions, achieving high resolving power only for ion species with limited mass-to-charge ratios (m/q) that fulfilled the isochronous condition $\gamma = \gamma_t$ [**?**]. Here, γ is the relativistic Lorentz factor of the ion, and γ_t is the transition point, an ion-optical quantity of the ring. However, for most ion species with $\gamma \neq \gamma_t$, time resolutions are inevitably deteriorated depending on how far their γ values differ from γ_t [**?**].

To make IMS broadband, great efforts have been made [**?**, **?**], and an additional velocity (v) measurement at the straight section of the ring was also proposed [**?**, **?**]. The velocity measurement was finally realized at the CSRe [**?**, **?**], enabling determination of both orbit length, $C = vT$, and magnetic rigidity, $B\rho = m/q\gamma v$, for reference ions with well-known masses. Consequently, the universal calibration function $B\rho(C)$ is constructed, enabling $B\rho$ determination for non-reference ions using their measured C values—thereby realizing B -defined IMS (or B -IMS) [**?**, **?**]. Using this technique, mass measurements with remarkable precision down to 5 keV were achieved [**?**], and numerous new mass values were determined for the first time \cite{24–26}.

However, to obtain an accurate $B\rho(C)$ function, one must eliminate the effect

of magnetic field drifts during the experiment, which can exceed $\sim 10^{-5}$. Thus, a complicated correction procedure was developed, requiring multiple reference ions to correct for magnetic field changes in each injection [**?**]. This requirement is unfavorable for mass measurements of exotic nuclei, as the number of reference ions per injection can be quite low. Furthermore, the correction process may potentially introduce improper mass uncertainty assignments for both reference and non-reference ions (a similar example can be found in Ref. [**?**]).

To address these challenges, a new approach for B -IMS is needed. Given the short storage time of ions in the ring (a few hundred microseconds) per injection, magnetic field drifts become negligible over this brief duration. Therefore, if the $B\rho$ value of non-reference ions can be directly determined via a single reference ion within the same injection, the need for correcting magnetic field drifts using multiple reference ions would be eliminated.

According to the definition of γ_t [**?**], which connects the $B\rho$ and C differences between two ions within the same injection, the $B\rho$ determination of a non-reference ion based on a single reference ion becomes possible in principle. In this paper, we propose a novel method for B -IMS that utilizes well-characterized γ_t values [**?**] for $B\rho$ and mass determination. This method demonstrates two key advantages: (1) it requires only a single reference ion per injection, and (2) it naturally reduces the effects of magnetic field drifts, thereby obviating the need for extra correction procedures. In Sect. II, we outline the principle of this method. In Sect. III, we exemplify its performance through an experiment [**?**, **?**] using $^{58}Ni^{19+}$ as the primary beam. In Sect. IV, the discussion is presented, followed by a summary and outlook in Sect. V.

II. PRINCIPLE OF THE NEW METHOD

According to the fundamental equation $B\rho = m/q\gamma v$, the mass-to-charge ratio m/q of a stored ion can be expressed as $m/q = B\rho \cdot \sqrt{1 - v^2/c^2}/v$, where v is the velocity of the ion and c is the speed of light in vacuum. Since v is measured directly by the double time-of-flight (TOF) detectors installed in the straight section of the storage ring [**?**], the challenge in determining unknown mass lies in the $B\rho$ determination.

In previous B -IMS works [**?**, **?**], $B\rho$ and C were assumed to follow a $B\rho(C)$ curve characterized by an analytic function, which was used to determine the $B\rho$ values of non-reference ions based on their measured C values. However, the $B\rho(C)$ curve varies with time due to magnetic field drifts. To obtain an accurate $B\rho(C)$ function, a complicated method was utilized to mitigate the effect of field drifts, as detailed in Ref. [**?**].

In this work, we propose a more straightforward approach to determine the $B\rho$ value of non-reference ions in each injection. For ions circulating in the ring, the relative changes in $B\rho$ and C satisfy the following equation: $d(B\rho)/B\rho = \gamma_t^2 \cdot dC/C$, where the parameter γ_t serves as a bridge connecting the relative

variations in $B\rho$ and C. Although γ_t is often considered constant with respect to C, it actually varies with C, forming a $\gamma_t(C)$ curve [**?**].

For simplicity, consider two ions simultaneously stored in the ring: one is a reference ion with known mass, and the other is a non-reference ion with unknown mass. Let $B\rho_0$ and C_0 represent the magnetic rigidity and orbit length of the reference ion, respectively, while $B\rho_x$ and C_x denote those of the non-reference ion. Note that $B\rho_0$, C_0, and C_x can be determined by measuring T and v for both ions. According to the equation above, one has: $\int_{B\rho_0}^{B\rho_x} d(B\rho)/B\rho = \int_{C_0}^{C_x} \gamma_t^2(C) \cdot dC/C$. By defining $K = \int_{C_0}^{C_x} \gamma_t^2(C) \cdot dC/C$, the relationship can be derived as: $B\rho_x = B\rho_0 \cdot e^K$. Through this equation, $B\rho_x$ of the non-reference ion is obtained via a single reference ion in the same injection, and then the mass value is directly determined via the mass-to-charge ratio equation. Consequently, the effect of magnetic field drifts between injections is expected to be effectively eliminated.

III. THE γ_t, $B\rho$ AND MASS DETERMINATION

Several methods have been developed to measure the γ_t values [**?**, **?**], and their results are in excellent agreement. In this work, we employ the method using energy loss to calculate the $\gamma_t(C)$ values due to its simplicity. Details regarding this method can be found in Ref. [**?**].

Figure 1 [Figure 1: see original paper] illustrates the scatter plot of γ_t values obtained from all ions measured in the experiment using $^{58}Ni^{19+}$ as the primary beam [**?**, **?**]. The unreasonable scattered points are primarily attributed to the low detection efficiency of the TOF detector for light ions [**?**]. To obtain more accurate averaged γ_t values, only ions with mass number $A > 18$ are adopted. The averaged γ_t values within approximately 3 mm intervals are presented as the red curve. The γ_t value at any C within the specified range can be determined via linear interpolation.

Using the $\gamma_t(C)$ curve, the parameter K defined above is obtained through numerical integration: $K = \int_{C_0}^{C_x} \gamma_t^2(C) \cdot dC/C$, which can be calculated as long as $\gamma_t(C)$ is known. Here, $C_i = C_0 + i\Delta C_s$ and $\Delta C_s = (C_x - C_0)/n$, with n representing the number of intervals. By choosing a large n, or equivalently, a sufficiently small ΔC_s (e.g., 0.3 mm), the $\gamma_t(C)$ value within each interval can be regarded as constant during integration.

With the calculated K value, $B\rho_x$ is determined according to $B\rho_x = B\rho_0 \cdot e^K$ based on the $B\rho_0$ value of the reference ion. If there are multiple reference ions in the same injection, the same number of $B\rho_x$ values will be yielded. All these $B\rho_x$ values are averaged to obtain a mean $B\rho_x$ value. Then, the m/q value is obtained via the mass-to-charge ratio equation.

In this work, ions with mass uncertainties below 50 keV are selected as references to determine the mass values of non-reference ions. However, to validate

the mass determination, the mass of each reference ion is first assumed to be unknown and then re-determined using the other reference ions in the same injection. As shown in Fig. 2 [Figure 2: see original paper], all the obtained m/q values are combined, forming distinct m/q peaks.

Figure 3 [Figure 3: see original paper] compares the standard deviation $\sigma(m/q)$ of m/q peaks (in units of keV/e) from three methods: this work, previous B -IMS, and transformed from the original T peaks without any post-processing procedure like magnetic field correction. Here, the transformed m/q peaks are obtained via the mass-to-charge ratio equation, where $v = C/T$, and the $B\rho$ and C are fixed as 128.86 m and 5.4758 Tm, respectively (see Ref. [**?**] for details). It can be observed that $\sigma_{m/q}$ from this work is significantly lower than that transformed from the original T peaks but is comparable to that obtained from previous B -IMS. This indicates that the impact of magnetic field drifts on mass determination has been effectively eliminated by this new method. We note that this is achieved without any additional magnetic field correction procedures. Nevertheless, $\sigma_{m/q}$ obtained from this work is slightly (approximately 1 keV/e) larger than that from previous B -IMS results. This may be attributed to variation of the $\gamma_t(C)$ curve caused by magnetic field drifts during the experiment. Further discussion is provided in Sect. IV.

Assuming that each m/q value contributes equally, the final determined m/q and its uncertainty are calculated as follows: $\langle m/q\rangle = \frac{1}{N}\sum_{j=1}^{N}(m/q)_j$ and $\sigma_{\langle m/q\rangle} = \sigma_{m/q}/\sqrt{N-1}$, with N being the number of counts.

For each nuclide, the comparison of mass excess (ME) with literature values (e.g., the previous B -IMS result [**?**]) is illustrated in Fig. 4 [Figure 4: see original paper], showing good agreement between them.

To further quantitatively evaluate the agreement, the normalized χ_n defined as $\chi_n = \sqrt{\frac{1}{N_c}\sum_{i=1}^{N_c}\frac{(ME_i^{\rm exp}-ME_i^{\rm lit})^2}{\sigma_{\rm exp}^2+\sigma_{\rm lit}^2}}$ is employed. Here, N_c is the total number of nuclides for comparison, $ME_i^{\rm exp}$ and $ME_i^{\rm lit}$ are the mass excesses determined in this work and from the literature, respectively, and $\sigma_{\rm exp}$ and $\sigma_{\rm lit}$ represent the corresponding mass uncertainties.

The obtained χ_n values of 0.80 and 0.53 for reference and non-reference nuclides indicate that the mass results from the two methods are in good agreement. However, the mass uncertainties in this work are slightly larger than those from previous B -IMS work, consistent with the slightly larger $\sigma_{m/q}$ observed in this work, as shown in Fig. 3.

We note that the two parameters L and Δt_d (see Ref. [**?**] for details) used to determine the velocity of each ion were optimized to minimize the χ^2 value. The literature ME values used for this optimization are taken from Ref. [**?**]. The obtained optimal values of $L = 18.046$ m and $\Delta t_d = -147.0$ ps agree well with those ($L = 18.046$ m and $\Delta t_d = -146.83$ ps) from previous B -IMS work [**?**].

IV. DISCUSSION

A. Effects of magnetic field (or γ_t) drifts

According to the study presented in Ref. [**?**], the $\gamma_t(C)$ curve is affected by magnetic field drifts. For example, it can be shifted horizontally, vertically, or rotated by varying the dipole, quadrupole, and sextupole magnetic fields, respectively. Given that the utilized $\gamma_t(C)$ value in this method is an averaged value over the entire experiment [**?**, **?**], for each injection the $\gamma_t(C)$ value may vary from this averaged value due to magnetic field drifts, introducing potential uncertainties in $B\rho$ and mass determination.

To quantitatively evaluate the effect of γ_t variation, we first assume that γ_t is independent of C. Considering that $\Delta C = C_x - C_0$ is much smaller than C_x or C_0, the parameter K can be approximated as: $K \simeq \gamma_t^2 \cdot \Delta C/C_0$. Since γ_t is close to one, the K value is on the same order of magnitude as $\Delta C/C_0$, which is significantly less than one. Consequently, $B\rho_x$ can be estimated as: $B\rho_x \simeq B\rho_0 \cdot (1+K) \simeq B\rho_0 \cdot (1+\gamma_t^2 \cdot \Delta C/C_0)$.

Assuming that magnetic field drift induces a variation $\delta\gamma_t$ in γ_t, the corresponding variation in the calculated $B\rho_x$ is denoted as $\delta(B\rho_x)$. From the approximation, we obtain: $\delta(B\rho_x)/B\rho_x \simeq 2\gamma_t \cdot (\Delta C/C_0) \cdot \delta\gamma_t$.

Combining the mass-to-charge ratio equation with the above result yields: $\delta(m/q)/(m/q) \simeq 2\gamma_t^2 \cdot (\Delta C/C_0) \cdot \delta\gamma_t$. This equation clearly indicates that the effect of γ_t variation on the final mass value is significantly reduced by the small factor $\Delta C/C_0$, which is generally on the order of 10^{-4} in B -IMS. In this experiment, the average $\Delta C/C$ ratio is approximately $\simeq 5 \times 10^{-4}$.

To further support this conclusion, we present a specific example from the ^{58}Ni experiment. The variation of the dipole magnetic fields over injection numbers is illustrated in Fig. 5 Figure 5: see original paper (one injection every 25 seconds; see Fig. 7(a) and the accompanying text in Ref. [**?**] for details).

Firstly, to examine the effect of magnetic field drifts on the $\gamma_t(C)$ curve, two injection groups marked in red and blue in Fig. 5(a) are selected. The corresponding $\gamma_t(C)$ curves are shown in Fig. 5(b), demonstrating horizontal shifts between the two groups, which is consistent with the conclusion drawn from Ref. [**?**]. The maximum relative change in the γ_t value at a certain C is on the order of 10^{-3}.

Secondly, to quantify the impact of such $\gamma_t(C)$ variation, we examined a simplified scenario in which all $\gamma_t(C)$ values were systematically decreased by 10^{-3}, corresponding to a downward shift of the $\gamma_t(C)$ curve (Fig. 1) by this amount. The resulting $\sigma_{m/q}$ values are presented as triangles in Fig. 5(c). These values are significantly smaller than the original ones (squares) but are still approximately 1 keV/e larger than the normal values (circles) obtained using the unshifted $\gamma_t(C)$ curve. Notably, this magnitude of increase matches the discrepancy observed between our normal results (this work) and previous B -IMS

results (see Fig. 3). This suggests that variations in the $\gamma_t(C)$ curve, caused by dipole magnetic field drifts, may be responsible for the observed discrepancy in $\sigma_{m/q}$ between the two methods.

The equation for γ_t variation indicates that a 10^{-3} shift in the $\gamma_t(C)$ curve introduces a relative m/q uncertainty: $\delta(m/q)/(m/q) \simeq 2 \times 1.362 \times (5 \times 10^{-4}) \times 10^{-3} \simeq 2 \times 10^{-6}$. This corresponds to an expected additional uncertainty of ~ 4 keV/e in m/q, leading to an approximate 1 keV/e increase in $\sigma_{m/q}$. This estimation is in agreement with the observed 1 keV/e increase in $\sigma_{m/q}$ in Fig. 5(c), thereby confirming the validity of the uncertainty equation.

Finally, to demonstrate the effect of the $\gamma_t(C)$ curve with and without the artificial shift on the final mass determination, the differences in ME values resulting from both cases are presented in Fig. 5(d). Most of these differences lie within a narrow range of ± 5 keV (see the shaded area in Fig. 5(d)), supporting the robustness of this method.

B. The advantage of requiring only one reference ion in each injection

Nowadays, nuclides with well-known masses have been extended to quite exotic regions, characterized by short half-lives and very low production yields. When measuring mass-unknown nuclides using the B -IMS technique, the number of stored ions per injection can become remarkably low.

Figure 6 [Figure 6: see original paper] presents the statistics of the number of ions per injection for a B -IMS experiment using ^{36}Ar as the primary beam, which aims to measure the mass value of the very exotic nuclide ^{22}Si. In this experiment, the magnetic rigidity of beam lines was optimized to maximize transport efficiency for the extremely exotic ion $^{22}Si^{14+}$. Consequently, the most frequently observed number of stored ions per injection was reduced to approximately three. Under such conditions, the previous B -IMS method, which requires as many reference ions as possible for magnetic field correction, encounters significant challenges. One potential solution is to discard injections containing fewer than, for example, three reference ions to ensure successful magnetic field correction. However, this approach leads to a significant loss of statistics (28%) and may introduce biases in mass uncertainty assignments for both reference and non-reference ions. Alternatively, one could use the $B\rho$-C curve without magnetic field correction, but this would allow magnetic field fluctuations between injections to directly affect mass measurements at the 10^{-5} level, significantly degrading mass precision.

In such challenging scenarios, the method proposed in this paper effectively overcomes all these difficulties. It requires only one reference ion to determine unknown mass values and achieves high precision without the need for magnetic field correction. Using this method, the re-determined ME value of ^{23}Si, which is 23365(16) keV [**?**], is fully confirmed by the LEBIT Penning trap result of 23362.9(5.8) keV [**?**], demonstrating the efficiency and reliability of this important improvement for B -IMS.

V. SUMMARY AND OUTLOOK

In this work, we propose a novel method relying on the $\gamma_t(C)$ curve for B -IMS to determine nuclear mass values. This method significantly reduces the need for correcting the effects of magnetic field drifts and requires only at least one reference ion with known mass value for determining the masses of ions of interest. Remarkably, the achieved mass precision, without any correction procedure, is still comparable to that of previous B -IMS methods. Consequently, it not only simplifies the data analysis procedure for B -IMS but is also suitable for future IMS experiments involving very exotic nuclei with extremely low yields.

Nonetheless, further improvements of this method are possible. First, while this method significantly reduces the influence of variations in the $\gamma_t(C)$ curve (or magnetic field), residual effects cannot be entirely neglected, especially as the mass precision of B -IMS is expected to continue improving. From this perspective, a stable magnetic field environment remains essential. However, given that absolutely stable magnetic fields are technically unachievable, and considering that drifts of the dipole magnetic field induce only a horizontal shift in the $\gamma_t(C)$ curve, a flatter $\gamma_t(C)$ curve would further minimize the impact of dipole magnetic field drifts on final mass determinations and is thus highly desirable. Second, the current mass determination of this method relies on averaging all obtained m/q values under the assumption of equal contribution. In reality, each individual m/q value has different uncertainty, and this simple assumption may introduce deviations, particularly when statistics are limited. Future refinements should incorporate uncertainty quantification for individual m/q values of each nuclide to enable a weighted mean value and uncertainty.

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