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Abstract

The isochronous mass spectrometer at the Heavy Ion Research Facility in Lanzhou Cooling Storage Ring is an ideal facility for conducting studies on the decay of short-lived, high charge state nuclear isomeric states. In the lifetime measurement experiment of the short-lived, high charge state ion $^{94m}\text{Ru}44+$, we directly observed the decay process of the $8+$ isomeric state of ^{94}Ru to the ground state. Within the observation time window (20 s, 180 s), 49 decay events were identified. To identify more decay events, this paper investigates a method for identifying decay events based on spectral amplitude. Based on simulation results, this method can effectively identify decay events within (15 s, 185 s). Applying the new identification method to experimental data processing, 54 decay events were identified within (15 s, 185 s). Based on these 54 decay events, the lifetime of $^{94m}\text{Ru}44+$ in the moving reference frame was calculated to be 194(121) s. The new lifetime result is consistent with the previous result of 218(148) s within uncertainties and exhibits higher precision.

Full Text

Preamble

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An Effective Method for Identifying Decay Events in Storage Rings and Its Application to the Lifetime Measurement of $^{94m}\text{Ru}44+$

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Abstract

The Isochronous Mass Spectrometry (IMS) facility at the Heavy Ion Research Facility in Lanzhou – Cooling Storage Ring (HIRFL-CSR) provides an ideal platform for investigating the decay of highly charged, short-lived nuclear isomers. In the lifetime measurement experiment for the short-lived, highly charged ion $^{94m}\text{Ru}44+$, we directly observed the decay process from the $8+$ isomeric state of ^{94}Ru to its ground state, identifying 49 decay events within the observation time window of (20 s, 180 s). To enhance the identification of additional decay events, this paper investigates a novel method based on spectral amplitude analysis. Simulation results demonstrate that this approach can effectively identify decay events within an extended window of (15 s, 185 s). Applying this new identification method to experimental data processing yielded 54 decay events within (15 s, 185 s). Based on these 54 events, the lifetime of $^{94m}\text{Ru}44+$ in the rest frame was determined to be 194(121) s. This new result is consistent with the previous value of 218(148) s within experimental uncertainties, while offering improved precision.

Keywords: HIRFL-CSR; fully stripped ions; ^{94m}Ru ; lifetime measurement; observation time window

Introduction

Isochronous Mass Spectrometry (IMS) based on the Heavy Ion Research Facility in Lanzhou – Cooling Storage Ring (HIRFL-CSR) represents a recently developed technique for studying the decay of short-lived, highly charged ions. In the lifetime measurement experiment for the highly charged ion $^{94m}\text{Ru}44+$, the isomeric species were produced via projectile fragmentation reactions. The primary beam $^{112}\text{Sn}35+$ was accumulated in the CSRm main ring to an intensity of approximately 150 A and accelerated to 376.42 MeV/u before fast extraction onto a 10.0 mm thick ^9Be target at the entrance of the Radioactive Ion Beam Line in Lanzhou (RIBLL2). The resulting secondary fragments were subsequently selected by RIBLL2 and injected into the experimental storage ring CSRe for storage and measurement.

The Time-of-Flight (TOF) detectors installed on CSRe continuously recorded and stored timing signals for each ion passage. Each injection cycle was recorded for 200 s, corresponding to approximately 300 revolutions of the ions in the ring. When an ion decays during circulation, its mass changes, causing a corresponding shift in its revolution period of approximately 11.9 ps. Since most ions can complete over 1000 revolutions in the storage ring—corresponding to a

TOF variation of about 20 ps—the daughter nucleus $^{94}\text{Ru}44+$ remains stored in CSRe without loss following the decay of $^{94\text{m}}\text{Ru}44+$. Moreover, because both $^{94\text{m}}\text{Ru}44+$ and $^{94}\text{Ru}44+$ are isochronous central ions, the TOF of $^{94}\text{Ru}44+$ is minimally affected by energy loss after decay. Consequently, even after the parent nucleus $^{94\text{m}}\text{Ru}44+$ decays, the daughter nucleus $^{94}\text{Ru}44+$ continues to circulate for a sufficiently long duration to enable precise measurements.

Averaging over numerous data points effectively reduces the influence of ion emittance-induced fluctuations on revolution periods. By averaging over approximately 30 revolutions (~ 20 s), the uncertainty in revolution time is estimated to be ~ 2 ps, corresponding to a mass resolution of $\sim 8 \times 10^{-4}$. This establishes an observation time window of (20 s, 180 s) after data acquisition begins, within which decay events can be reliably identified. In previous data analysis approaches, decay events were identified by monitoring changes in revolution periods. If a $^{94\text{m}}\text{Ru}44+$ decay occurred outside this observation window, the corresponding event could not be effectively identified and was consequently excluded from analysis. Additionally, by fitting the relationship between ion flight time and revolution number with a straight line, the residuals from this linear fit could be obtained. When $^{94\text{m}}\text{Ru}44+$ underwent decay, the revolution period changed, causing a kink-like distortion in the residual plot; no such distortion appeared for non-decaying ions. Using this method, the effective observation window for decay events was (20 s, 180 s), yielding 49 identified decay events.

To further extend the observation window and identify additional decay events, this study investigates the frequency spectrum of linear fit residuals through simulation. By examining the relationship between spectral amplitude and revolution number at decay, a new identification method was developed.

2.1 Fourier Transform

This section presents the derivation of the Fourier transform formula for a non-periodic asymmetric triangular wave. The transformation from time domain to frequency domain is given by:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} dt$$

where $f(t)$ is the time-domain expression and $F(\omega)$ is the frequency-domain expression.

Assuming the piecewise function for a non-periodic triangular wave is $f(t)$:

$$f(t) = \begin{cases} a(t - t_1), & t \in [t_1, z] \\ b(t_2 - t), & t \in (z, t_2] \\ 0, & t \in (-\infty, t_1) \cup (t_2, +\infty) \end{cases}$$

where a , b , t_1 , and t_2 are constants.

Performing the Fourier transform on Eq. (2) yields:

$$F(\omega) = e^{-j\omega z} \left(\frac{-j\omega z(at_1 - az) - a}{\omega^2} \right) - e^{-j\omega z} \left(\frac{-j\omega z(bt_2 - bz) - b}{\omega^2} \right) - \frac{e^{-j\omega t_1} - e^{-j\omega t_2}}{-j\omega}$$

The intersection point of the two lines is $z = \frac{a \cdot t_1 + b \cdot t_2}{a + b}$. Substituting this into the above expression and rearranging terms gives:

$$F(\omega) = \frac{1}{\omega^2} [(a + b) \cdot e^{-j\omega z} - a \cdot e^{-j\omega t_1} - b \cdot e^{-j\omega t_2}]$$

Using Euler's formula $e^{-jx} = \cos(x) - j \sin(x)$, the double-angle formula $\cos(x) = 1 - 2 \sin^2(x/2)$, and the sampling function expression $Sa(x) = \sin(x)/x$, Eq. (4) can be written as:

$$F(\omega) = -\frac{z^2(a + b)}{\omega^2} \cdot Sa^2\left(\frac{\omega z}{2}\right) - j \frac{(a + b)z}{\omega} \cdot Sa(\omega z) + j \frac{at_1}{\omega} \cdot Sa(\omega t_1) + j \frac{bt_2}{\omega} \cdot Sa(\omega t_2)$$

From Eq. (5), the relationship between the magnitude of $F(\omega)$ and frequency ω can be obtained, which yields the simulation results shown in Figure 1: see original paper and Figure 1: see original paper.

[Figure 1: see original paper] illustrates the time-domain and frequency-domain plots for cases with and without noise under otherwise identical conditions. As shown in Figure 1: see original paper and Figure 1: see original paper, when a kink appears in the time-domain plot, a corresponding maximum appears in the frequency spectrum. Figure 1: see original paper demonstrates that when noise is considered—resulting in a jagged kink in the time-domain plot—the corresponding frequency spectrum in Figure 1: see original paper also exhibits a maximum, which remains essentially unchanged compared to the noise-free case in Figure 1: see original paper. Therefore, the maximum value of the frequency spectrum can be used to identify decay events of 94mRu44+. Based on this method, we validated the approach using simulated data.

2.2 Simulation Data Generation

First, we estimate the initial revolution times $RevT_{g,1}$ and $RevT_{m,1}$ for 94Ru44+ and 94mRu44+ in this experiment. Assuming the masses of 94Ru44+ and 94mRu44+ are M_g and M_m , respectively:

$$M_g = A \cdot M_u - Q \cdot M_e + ME_g + B_e(Z)$$

$$M_m = A \cdot M_u - Q \cdot M_e + ME_g + B_e(Z) + E_X$$

where $A = 94$ is the mass number; $M_u = 931.494$ MeV is the nucleon mass; $M_e = 0.511$ MeV is the electron mass; $ME_g = -82.584$ MeV is the mass excess of $^{94}\text{Ru}44+$; B_e is the total binding energy of all electrons; and $E_X = 2.644$ MeV is the isomeric excitation energy.

From the masses M_m and M_g , along with the initial magnetic rigidity $B\rho_g = 5.5294$ Tm for $^{94}\text{Ru}44+$ and the corresponding orbit length $L_0 = 128.8$ m, and assuming the initial Lorentz factor γ_0 , relativistic velocity β_0 , and energy per nucleon E/A are identical for both ions upon entering the experimental ring, their expressions are:

$$\gamma_0 = \frac{B\rho_g \cdot M_g}{Q \cdot c}$$

$$\beta_0 = \sqrt{1 - \frac{1}{\gamma_0^2}}$$

$$E/A = M_g \cdot (\gamma_g - 1)$$

where $Q = 44$ is the charge state of the fully stripped ion and $c = 2.9979 \times 10^8$ m/s is the speed of light in vacuum.

From these equations, the initial magnetic rigidity $B\rho_m$ for $^{94}\text{mRu}44+$ can be obtained:

$$B\rho_m = \frac{M_m \cdot \beta_0 \cdot \gamma_0}{Q \cdot c}$$

The orbit length L_m at $B\rho_m$ is then calculated as:

$$L_m = L_0 \cdot \left(1 + \frac{B\rho_m/B\rho_g - 1}{\gamma_t^2}\right)$$

where $\gamma_t = 1.302$ is the transition energy of the experimental ring [2]. Therefore, the initial revolution times $RevT_{g,1}$ and $RevT_{m,1}$ for $^{94}\text{Ru}44+$ and $^{94}\text{mRu}44+$ are:

$$RevT_{g,1} = \frac{L_0}{\beta_0 \cdot c}$$

$$RevT_{m,1} = \frac{L_m}{\beta_0 \cdot c}$$

Subsequently, we calculate the revolution times $RevT_{g,i}$ and $RevT_{m,i}$ for $94Ru44+$ and $94mRu44+$ at the i -th turn. When stored ions pass through the carbon foil in CSRe, they lose energy. The estimated energy loss E_{al} over 300 revolutions is 36.695 MeV, giving an average energy loss per turn E_l of $36.695/300 = 0.1223$ MeV. The change in Lorentz factor per turn $\Delta\gamma$ is $E_l/M_m = 1.3986 \times 10^{-6}$. Thus, after i revolutions, the Lorentz factor γ_i becomes:

$$\gamma_i = \gamma_0 - (i - 1) \cdot \Delta\gamma$$

The corresponding relativistic velocity β_i is:

$$\beta_i = \sqrt{1 - \frac{1}{\gamma_i^2}}$$

At the i -th turn, the magnetic rigidities $B\rho_{g,i}$ and $B\rho_{m,i}$ for $94Ru44+$ and $94mRu44+$ are:

$$B\rho_{g,i} = \frac{M_g \cdot \beta_i \cdot \gamma_i}{Q \cdot c}$$

$$B\rho_{m,i} = \frac{M_m \cdot \beta_i \cdot \gamma_i}{Q \cdot c}$$

The orbit lengths $L_{g,i}$ and $L_{m,i}$ at the i -th turn are:

$$L_{g,i} = L_0 \cdot \left(1 + \frac{B\rho_{g,i}/B\rho_g - 1}{\gamma_i^2} \right)$$

$$L_{m,i} = L_0 \cdot \left(1 + \frac{B\rho_{m,i}/B\rho_g - 1}{\gamma_i^2} \right)$$

The revolution times $RevT_{g,i}$ and $RevT_{m,i}$ at the i -th turn are then:

$$RevT_{g,i} = \frac{L_{g,i}}{\beta_i \cdot c}$$

$$RevT_{m,i} = \frac{L_{m,i}}{\beta_i \cdot c}$$

The total flight times $t_{g,n}$ and $t_{m,n}$ for $94Ru44+$ and $94mRu44+$ over n turns are:

$$t_{g,n} = \sum_{i=1}^n RevT_{g,i}$$

$$t_{m,n} = \sum_{i=1}^n RevT_{m,i}$$

If $94mRu44+$ decays into $94Ru44+$ at the s -th turn, the total flight time $t_{d,n}$ for this ion sequence over n turns is:

$$t_{d,n} = \sum_{i=1}^s RevT_{m,i} + \sum_{i=s+1}^n RevT_{g,i}$$

The TOF detector has a time resolution of 50 ps (standard deviation). To make the simulation more realistic, a Gaussian-distributed random number $N(0, 50^2)$ was added to the total time $t_{d,n}$ at the n -th turn. Thus, the simulated total flight time $t'_{d,n}$ can be expressed as:

$$t'_{d,n} = t_{d,n} + X$$

where X represents the generated random number simulating the TOF detector's time resolution.

Figure 2: see original paper shows the simulated flight time versus revolution number, with blue points representing experimental data and the red line indicating the linear fit. Figure 2: see original paper displays the residuals from this linear fit.

2.3 Decay Event Identification Method

When an ion decays within the observation time window, a distinct distortion appears in the linear fit residuals. This distortion arises from the change in revolution period before and after decay, which formed the basis for intuitive decay time identification in previous work. The new identification method presented here builds upon these residuals through further analysis. The primary approach involves performing a Fourier transform on the linear fit residuals to convert the time-domain signal into frequency domain, followed by decay event identification through spectral amplitude analysis, with additional verification using the period difference before and after decay.

We simulated flight time versus revolution number for both decaying and non-decaying events, fitted these data with straight lines, and obtained the corresponding fit residuals, as shown in Figure 3: see original paper and Figure 3: see original paper. Fourier transforms of these residuals yield the frequency spectra displayed in Figure 3: see original paper and Figure 3: see original paper.

[Figure 4: see original paper] illustrates the variation of maximum spectral amplitude with decay turn number for both decaying and non-decaying events. For decay events, the maximum amplitude exhibits a trend of increasing then decreasing with decay turn number, with all values exceeding 2.0. For non-decaying events, the maximum spectral amplitudes are mostly below 2.0. Therefore, this threshold value can serve as a preliminary criterion for decay event identification.

To further confirm decay events, we calculated the revolution period differences before and after the decay point. [Figure 5: see original paper] shows these period differences for both decaying and non-decaying events. All period differences for $94\text{mRu}44+$ decay events exceed 6 ps. Consequently, in subsequent experimental data analysis, a period difference threshold of 6 ps was established as the standard for identifying decay events.

Assuming all $94\text{mRu}44+$ ions do not decay in the TOF detector and that each injection records data for 200 s, ions can complete approximately 300 revolutions in the CSRe experimental ring. When the linear fit residuals exhibit a shape resembling a non-periodic asymmetric triangular wave, as shown in Figure 3: see original paper, and the corresponding frequency spectrum Figure 3: see original paper displays a prominent peak, the $94\text{mRu}44+$ ion is considered to have decayed into $94\text{Ru}44+$ at that turn. Conversely, when no kink appears in the residual plot Figure 3: see original paper and the frequency spectrum Figure 3: see original paper oscillates around zero, the $94\text{mRu}44+$ ion is considered stable. To maximize the identification of decay events, we simulated decay scenarios at every turn from 20 to 280. Each simulated decay event was processed through linear fit residual analysis and Fourier transformation, from which the maximum spectral amplitude was extracted.

3. Application to $94\text{mRu}44+$ Lifetime Measurement Experiment

Based on simulation results, decay of $94\text{mRu}44+$ can be identified when the maximum amplitude of the Fourier-transformed residuals exceeds 2 and the period difference at the decay turn is greater than 6 ps. The specific procedure is as follows.

The revolution periods of $94\text{Ru}44+$ and $94\text{mRu}44+$ ions range from 670.9 ns to 671.0 ns. For all events within this period range, we extracted the maximum amplitude of the frequency spectrum from the linear fit residuals, yielding 235 preliminary decay candidates. The decay times for all candidates were then extracted using the method described in [7]. The revolution period differences before and after decay were calculated, and 54 candidate events exhibited period differences exceeding 6 ps. Finally, experimental and simulated data were compared, as shown in [Figure 6: see original paper] and [Figure 7: see original paper].

[Figure 6: see original paper] reveals that for these 54 decay events, the maxi-

imum spectral amplitude from Fourier-transformed residuals follows a trend of increasing then decreasing with decay turn number. The experimental data points follow the pattern of simulated data, clustering around the simulation curve. [Figure 7: see original paper] shows that the period differences for decay events also cluster around the simulated values, fluctuating around 11.9 ps.

To calculate the ion lifetime, we employed a maximum likelihood method constrained to a limited time range, detailed in [6]. The lifetime estimator and its uncertainty are given by:

$$\hat{\tau} = \frac{\sum_{i=1}^n t_i}{n} - T_1$$

$$\sigma(\hat{\tau}) = \frac{\hat{\tau}^2}{\sqrt{n(T_2 - T_1)}}$$

where $\hat{\tau}$ and $\sigma(\hat{\tau})$ are the maximum likelihood estimate and its error, n is the number of decay events, t_i are the individual decay times, and $T = T_2 - T_1$ is the observation time window size. Using the average decay time of 71.7 s for the 54 events and an observation window of $T = 170$ s, we obtain a lifetime of 194(121) s for 94mRu44+ in the relativistic frame.

Since this method identified 54 decay events (increasing n), Eq. (28) shows that the error of the maximum likelihood estimator is inversely proportional to the square root of the number of decay events. Thus, the increased event count reduces the uncertainty and improves precision.

The theoretical half-life of the neutral atom isomer 94mRu in the rest frame is 71(4) s [8]. 94mRu decays to the ground state through γ cascade or internal conversion. When all atomic electrons are stripped, the internal conversion channel is closed, and the fully stripped isomeric ion can only decay via the γ cascade channel [9]. The BRICC code [10] calculates an internal conversion coefficient of 0.335 for 94mRu, yielding a theoretical prediction of 178(10) s for the lifetime of fully stripped 94mRu44+ in the laboratory frame ($\gamma = 1.302$).

This paper presents a new, accurate method for identifying ion decays. By measuring the revolution periods and flight times of fully stripped 94mRu44+ ions and their decay products 94Ru44+ in CSRe, we obtain the frequency spectrum of linear fit residuals. Based on the maximum spectral amplitude, decay events are preliminarily identified. The decay time is then extracted to calculate the period difference before and after decay, enabling efficient and rapid identification of 94mRu44+ decay events while extending the decay observation time window. The previous method provided an observation window of (20 s, 180 s), whereas the new method extends this to (15 s, 185 s). While the original method identified 49 decay events, analysis using the new approach revealed 54 events—five additional decays. Recalculating the lifetime using these 54 events

yields $194(121)$ s for $94\text{mRu}44+$ in the laboratory frame, consistent with the previous result of $218(148)$ s [6] but with enhanced precision.

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