STORI'24: A novel method of half-life determination for highly-charged ions based on the isochronous mass spectrometry*

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Abstract: The lifetime of the isomeric state in fully stripped $^{94}Ru^{44+}$ ions has been measured using isochronous mass spectrometry (IMS) at the experimental Cooler Storage Ring (CSRe) of the Heavy Ion Research Facility in Lanzhou (HIRFL). Previously, the isomeric lifetime was determined by analyzing the decay time points of individual decay events. In this work, we present a novel approach to determine the isomeric lifetime based on the survival time of ions in the IMS. The survival lifetime of the ground and isomeric states of $^{94}Ru^{44+}$ were measured to be 270(9)μs and 121(4)μs in the laboratory frame, respectively. Given that the ground state of $^{94}Ru^{44+}$ has a natural lifetime of approximately 75 minutes, its survival lifetime in the experimental setup was predominantly determined by beam-loss lifetime, including interactions with residual gas in the storage ring and the carbon foil of detector. In contrast, the survival lifetime of the $^{94m}Ru^{44+}$ was governed by both its intrinsic nuclear lifetime and additional beam-loss effects. The nuclear decay lifetime of $^{94m}Ru^{44+}$ was extracted through differential survival lifetime analysis between ground and isomeric state, under the assumption that the beam-loss lifetimes for both quantum systems are identical. Using this novel methodology, the laboratory-frame lifetime measurement yielded 221(14)μs. After relativistic time-dilation corrections, the corresponding rest-frame half-life was calculated to be 118(7)μs. This result demonstrates excellent consistency with previous experimental results, validating the reliability of the new method. This method is suitable for determining half-lives of highly-charged ions in the range of about several tens of microsecond to milliseconds using IMS.

Keywords: Highly Charged Ions, Lifetime Measurement, Isomeric State, Isochronous Mass Spectrometry

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I. INTRODUCTION

The decay characteristics of highly charged ions (HCIs) serve as sensitive probes for nuclear-electron coupling effects, tests of collective nuclear models, and constraints for astrophysical nucleosynthesis pathways in stellar environments [1−3]. In bare ions, the absence of atomic electrons eliminates competing decay channels such as internal conversion (IC) and orbital electron capture (EC), permitting direct measurement of γ-decay branching ratios [4−8]. Therefore, HCIs offer a unique object for investigating the nuclear structure of excited states.

Storage-ring based experiments employing Schottky mass spectrometry (SMS) have successfully investigated long-lived isomers ($\tau > 1$ s) through characteristic frequency shifts [9−13], particularly confirming the existence of high-K isomers. These studies provided direct evidence for nuclear deformation effects in heavy nuclei. A milestone achievement was the lifetime measurement for hydrogen-like $^{192m}Os^{75+}$, where the observed lifetime extension compared to neutral atoms validated relativistic Dirac-Fock calculations of internal conversion coefficients in HCIs [14, 15]. Recent developments in Schottky-isochronous mass spectrometry (S+IMS) [16, 17] have reduced the measurable half-life threshold down to approximately 24 ms [17]. However, microsecond-scale

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decays remain challenging due to necessary electron cooling and limited signal to noise ratio of the Schottky resonator.

To overcome these challenges, an innovative method for identifying the in-ring decay using isochronous mass spectrometry (IMS) was proposed in the experimental storage ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [8]. In that experiment, a sudden change in the revolution time of the fully-stripped $^{94m}Ru^{44+}$ was recognized as the fingerprint of the isomer decay when stored in the ring. The advantage of this method is that the revolution times of stored ions in an IMS experiment are measured in time intervals shorter than μs. Consequently, it is sensitive enough to observe nuclear decays occurring on a time scale from a few μs to a few hundred μs, establishing $^{94m}Ru^{44+}$ as the shortest-lived nuclear state with directly-measured mass.

However, in the previous data analysis, only decay events of the $^{94m}Ru^{44+}$ were used, leading to a relatively large error of the determined half-life. In this work, we propose a refined methodology to determine the half-life of $^{94m}Ru^{44+}$ using beam-loss constants individually evaluated for its ground and isomeric states. With the new method, all events of the decay and non-decay isomers were used, and thus the precision of half-life of short-lived HCIs determined in the IMS was improved.

II. EXPERIMENTAL SETUP

The experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL) [18]. A primary beam of $^{112}Sn^{35+}$ was accelerated to an energy of 376.42 MeV/u with an intensity of 7×10^7 particle per pulse, and subsequently fast-extracted to impinge on a ^{9}Be target located at the entrance of the Radioactive Ion Beam Line in Lanzhou (RIBLL2) fragment separator. The resulting projectile fragments were selected and purified via RIBLL2, and a carbon stripper foil placed at the exit further ionized the fragments before they were injected into the experimental Cooler Storage Ring (CSRe).

For optimal isochronous mass spectrometry conditions, the CSRe was tuned to a transition point of $\gamma_t = 1.302$ with a magnetic rigidity of $B\rho = 5.5294$ Tm. The storage ring was operated in the isochronous mode, ensuring a revolution time nearly independent of the ions' velocity for the nuclei of interest, $^{94}Ru^{44+}$.

The revolution times of the stored ions were measured using a time-of-flight (TOF) detector based on a micro-channel plate (MCP) [19]. The TOF detector incorporated a carbon foil with a thickness of approximately 19 μg/cm^2 and a diameter of 40 mm, mounted at the geometric center of the beam line. As ions passed through the carbon foil, secondary electrons were emitted. These electrons were accelerated by an electric field (130 V/mm) and deflected by a perpendicular magnetic field (~80 Gs) toward the MCP detector. Upon reaching the MCP, the electrons were amplified, producing signals that were transmitted through high-frequency coaxial cables to a Tektronix DPO71254 digital oscilloscope, operating at a 50 GHz sampling rate, for offline analysis. Additional experimental details are available in Ref. [8].

III. DATA ANALYSIS

For each particle circulating in the ring, a time sequence, the time stamps when passing the TOF detector as a function of the revolution number was extracted from the recorded signals. As mentioned in the previous study[20], only the isomeric states decayed in the observation window [15 μs, 185 μs] can be identified.To determine the beam lost constant, all ions that circulated for more than 15 μs were considered in the analysis with the procedures described in Ref. [19, 21, 22]. In the revolution spectrum, the events with revolution times between 670.90 and 670.98 ns were identified as $^{94}Ru^{44+}$. All these events can be classified into three categories: ground state, isomeric state, and decayed isomeric state. The decayed isomeric state event refers to cases where the isomer decays to the ground state within the observation window. After decay, the ion continues circulating in the CSRe as a ground state. These decayed events were identified using the method described in Ref. [20]. Next, we need to identify the remaining events as either ground state or isomeric state. Based on the excitation energy of ^{94m}Ru and the optical parameters of CSRe, the revolution time difference between the isomeric and ground states is 11.9 ps.

In the revolution time spectrum obtained by directly accumulating revolution times into a histogram, the ground and isomeric states of $^{94}Ru^{44+}$ cannot be resolved due to magnetic field instabilities, which also induce shifts in revolution times across different injections. By leveraging the fact that multiple ions are stored simultaneously in the CSRe and assuming identical shifts for all ions within a single injection, we applied the method described in Ref. [23] to correct for magnetic field instabilities. This correction resulted in a higher-resolution revolution period spectrum, as shown in Fig. 1. The events whose revolution times are smaller than 670.958 ns are marked as ground states and the others are identified as isomeric states.

For each ion circulating in the IMS, the TOF detector tracked it turn by turn. The last timing signal of each ion in the observation window was pinned as the decay point for the ground state of ^{94}Ru. As the half-life of the ground state of ^{94}Ru is about 75 minutes, which is much longer than the observation window, they would be lost due to non-radiation decay, the interaction with the residual gas in the CSRe and the carbon-foil of the TOF detector. The last timing signal of it was determined as the decay point.

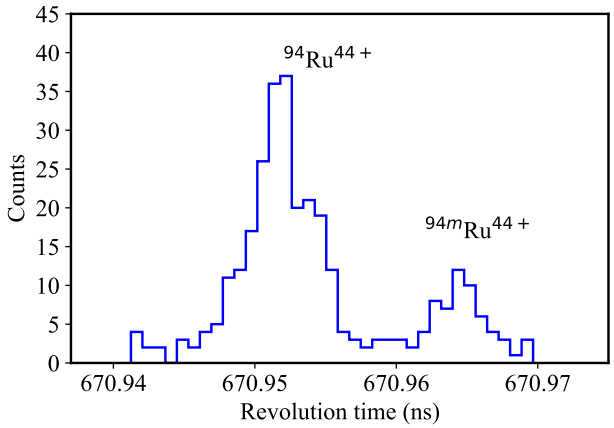

Fig. 1. (color online) The revolution time spectrum of the ground state and isomeric state of $^{94}Ru^{44+}$ after the magnetic field correction.

The distribution of the survival time of the ground state of ^{94}Ru was shown in Fig. 2(a). For the events in isomeric state, it would decay both due to the radiation, gamma decay, and non-radiation decay. For the events which could still circulate in the CSRe after decay occurred, its decay time point was determined by the approach introduced in ref[20]. For the other isomeric events, the decay time point in the observation windows was also determined as the last timing signal. The distribution of the survival time of the isomeric state of ^{94}Ru was shown in Fig. 2(b).

The normalized survival ratio (R) for i^{th} bin ground (isomeric) state of ^{94}Ru was defined by the following equation,

$$R_i = \frac{Sum - \sum_{j=1}^{i-1} Count_j}{Sum}, \quad (1)$$

where *Sum* is the total count of the ground (isomeric) state and $Count_j$ is the count in the j^{th} bin in Fig. 2. As the observation window starts from 15μs after the trigger of DAQ, the normalized survival ratio at 15 μs was set as 1. The normalized survival ratio as a function of the time after the trigger is shown in Fig. 3. Thus the decay constants for both the ground state and isomeric state of ^{94}Ru, $\lambda_{g.s.}$ and $\lambda_{i.s.}$, were determined by fitting the normalized survival ratio as a function of the time after the trigger, T, with a single exponential function:

$$R = R_0 e^{-\lambda_{g.s(i.s)}T}, \quad (2)$$

separately. The corresponding values of goodness of fit are 0.983 for the ground state and 0.984 for the isomeric state. The decay constant of the ground state, $\lambda_{g.s.}$, was determined to be 0.00371(12) μs^{-1}, while that of the isomeric state, $\lambda_{i.s.}$, was measured as 0.00824(26) μs^{-1}.

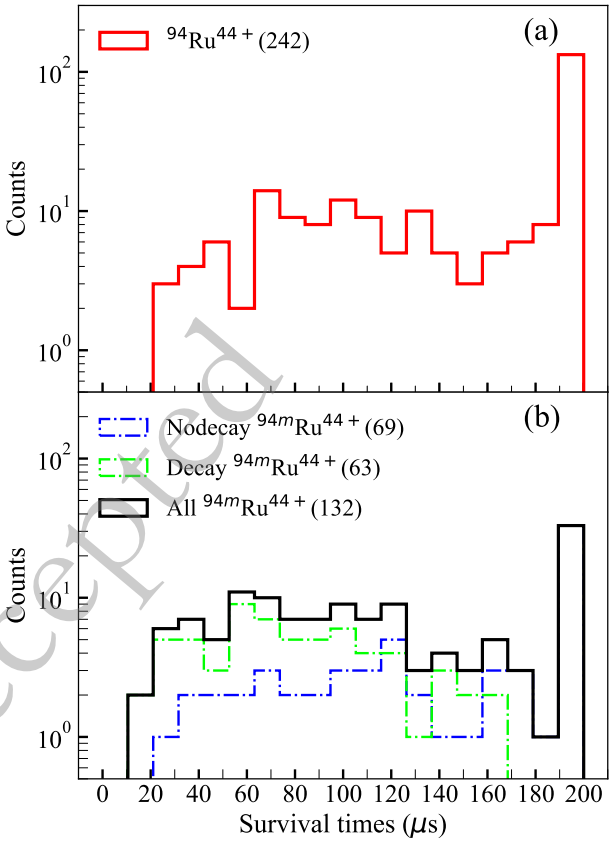

Fig. 2. (color online) The distribution of last point time of the ions for (a) ground state of $^{94}Ru^{44+}$ and (b) isomeric state of it. The numbers in parentheses within the legend denote the counts of corresponding events.

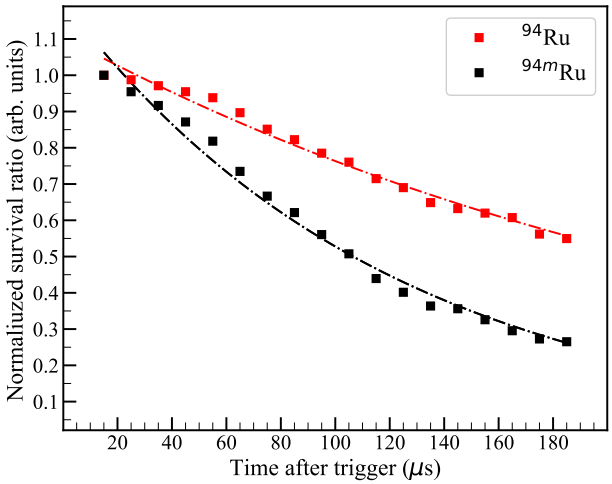

Fig. 3. (color online) Normalized survival ratios of the ground and isomeric states of $^{94}Ru^{44+}$ after the trigger of DAQ. The dash-dotted lines represent the results of exponential function fitting.

Accordingly, the survival lifetimes of the ground and isomeric states of $^{94}Ru^{44+}$ in the laboratory frame were deduced to be 270(9)μs and 121(4)μs, respectively. The de-

cay constant of the ^{94m}Ru, $\lambda_{i.s.}$ is a sum of three components: the internal conversion (IC) decay constant λ_{IC}, the γ decay constant λ_γ, and the beam-loss constant λ^*_{loss} due to collisions with residual gas atoms or carbon foil in TOF detector,

$$\lambda_{i.s.} = \lambda_{IC} + \lambda_\gamma + \lambda_{loss} \quad (3)$$

It is obvious that for the fully stripped ion ^{94m}Ru, $\lambda_{IC} = 0$ due to the absence of bound electrons. The beam loss constants depend typically only on Z and thus the beam-loss constant for ground state and isomeric state of ^{94}Ru would be identical. As already being mentioned in the previous part, the decay half-life of the ground state of ^{94}Ru is 75 minutes, which is much longer than its survival time in the CSRe. Thus the λ_{loss} would be equal to the $\lambda_{g.s}$. Then the λ_γ for ^{94m}Ru was calculated to be 0.00453(28) μs^{-1}. Taking into account the Lorentz factor γ = 1.302, deduced from the magnetic rigidity of CSRe, $T_{1/2}(^{94m}Ru^{44+}) = 1/\lambda_\gamma \times \ln(2) /\gamma$ = 118(7) μs in the rest frame, which was in good agreement with previous measurements.

IV. SUMMARY

The survival time of ions stored in the experimental Cooler Storage Ring (CSRe) can be determined using the isochronous mass spectrometry (IMS) technique. By analyzing the distribution of survival ratios within a defined observation window, the decay constant can be extracted with relatively high precision.

In this work, we determined the beam loss constants for both the ground and isomeric states of ^{94}Ru. The beam loss associated with the ground state was dominated by non-radioactive processes. The non-radioactive loss rate for the isomeric state was assumed to be the same as that of the ground state. By subtracting the non-radioactive component from the total beam loss constant of the isomer, we derived the half-life of fully stripped $^{94m}Ru^{44+}$ to be 118(7)μs. This result is in good agreement with the previously reported value of 102(17)μs [8], and features an uncertainty that is half of the earlier value. This substantial improvement confirms both the validity and the enhanced reliability of the revised analysis method presented in this work.

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