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A. Akber *et al.*

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A. Akber,[1] M. W. Reed,[1] P. M. Walker,[2] Yu. A. Litvinov,[3,4] G. J. Lane,[1] T. Kibédi,[1] K. Blaum,[3] F. Bosch,[4] C. Brandau,[5,6] J. J. Carroll,[7] D. M. Cullen,[8] I. J. Cullen,[2] A. Y. Deo,[2] B. Detwiler,[9] C. Dimopoulou,[4] G. D. Dracoulis,[1,*] F. Farinon,[4] H. Geissel,[4,10] E. Haettner,[10] M. Heil,[4] R. S. Kempley,[2] R. Knöbel,[4] C. Kozhuharov,[4] J. Kurcewicz,[4] N. Kuzminchuk,[4] S. Litvinov,[4] Z. Liu,[11] R. Mao,[12] C. Nociforo,[4] F. Nolden,[4] W. R. Plaß,[10] Zs. Podolyák,[2] A. Prochazka,[4] C. Scheidenberger,[4,10] D. Shubina,[3] M. Steck,[4] Th. Stöhlker,[4,13] B. Sun,[14] T. P. D. Swan,[2] G. Trees,[9] H. Weick,[4] N. Winckler,[3,4] M. Winkler,[4] P. J. Woods,[11] and T. Yamaguchi[15]

[1] *Department of Nuclear Physics, R.S.P.E., Australian National University, Canberra ACT 0200, Australia*
[2] *Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[3] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[4] *GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[5] *ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[6] *Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, 35392 Giessen, Germany*
[7] *US Army Research Laboratory, 2800 Powder Mill Road, Adelphi MD, USA*
[8] *Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[9] *Youngstown State University, One University Plaza, Youngstown, Ohio 44555, USA*
[10] *II Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany*
[11] *School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[12] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, PR China*
[13] *Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany*
[14] *School of Physics and Nuclear Energy Engineering, Beihaug University, 100191 Beijing, PR China*
[15] *Graduate School of Science and Engineering, Saitama University, Saitama 338-8570, Japan*

An excited metastable nuclear state of ^{192}Os in a hydrogen-like charge state has been studied for the first time. It was populated in projectile fragmentation of a ^{197}Au beam on a ^{9}Be target with the UNILAC-SIS accelerators at GSI. Fragmentation products in the region of interest were passed through the Fragment Separator (FRS) and injected into the Experimental Storage Ring (ESR). Cooling of the injected beam particles enabled Schottky Mass Spectrometry (SMS) to be performed. Analysis shows the lifetime of the state to be considerably longer than that of the neutral ion ($\tau_{neut} = 8.5(14)$ s); this change is attributed to hindrance of internal conversion in hydrogen-like ^{192}Os. Calculations have been performed to estimate the lifetime, and has been compared with that measured experimentally. There is good agreement between the expected ($\tau_{H-like} = 13.0(24)$ s) and measured lifetimes ($\tau_{rest} = 15.1^{+1.5}_{-1.3}$ s) from the internal decay of ^{192m}Os. This provides a test for the reliability of the values obtained from internal conversion coefficient calculations in highly-ionised systems and is the first measurement of its kind to be performed using the ESR setup.

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Heavy mid-shell nuclei are understood to be favourable for the existence of high-energy, long-lived isomers arising from their deformed shape and underlying shell structure [1–3]. In these cases, highly-excited isomeric states occur when nucleon pairs are broken and re-coupled, forming high-spin states known as yrast traps that often decay via either internal conversion or γ-decay [2]. The underlying physics of these processes is well studied in neutral atoms. However, particularly for internal conversion, the reliability of calculations to extract internal conversion coefficients for nuclei in highly-charged ionic states is undetermined. This is largely due to the difficulty in creating an excited nuclear state as a highly-charged ion and storing it for long enough to observe its decay.

Nuclei in the neutron-deficient region are relatively straightforward to populate using fusion evaporation reactions. However, to produce nuclei beyond the line of stability on the neutron-rich side, only a few methods can currently be employed. In this experiment relativistic projectile fragmentation was used to populate ^{192}Os. Atoms of ^{197}Au were accelerated by the UNILAC and SIS-18 heavy-ion accelerators to a beam energy of 478-492 MeV/u (dependent on the required products) and impinged on a ^{9}Be target. A 221 mg/cm^2 thick Nb foil was placed behind the target to provide additional stripping of atomic electrons, producing nuclei in exotic charge states: bare, hydrogen-like, helium-like, lithium-like, etc.. The resulting reaction products were then separated by both Z and A using the FRagment Separator (FRS) [4] and injected into the Experimental Storage Ring (ESR) [5] for prolonged observation and measurement. Other results of the present work have been published in [6, 7].

Measurements of stored ions were performed as they pass through two electrostatic plates known as 'Schottky pick-ups'; details of these can be found in refs [8, 9]. Both

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electron [10, 11] and stochastic [12] cooling are operated to reduce the velocity spread of the injected ion beam to a sufficient level that peaks in Schottky spectra can be resolved. In the ESR, stochastic cooling uses a fixed ion energy of 400 A·MeV, and the revolution frequency of the ions at this energy is $\sim$ 2 MHz. By performing a Fast Fourier Transform (FFT) on the measured data, a frequency spectrum for an orbiting ion can be recovered; this is known as a 'Schottky frequency spectrum'. The intensity of the peaks in the Schottky spectrum reflects directly the number of stored ions at that frequency [13]. In this experiment the 30th harmonic revolution frequency was analysed [14, 15], and hence all figures showing a Schottky frequency spectrum are relative to that harmonic ($\sim$ 60 MHz).

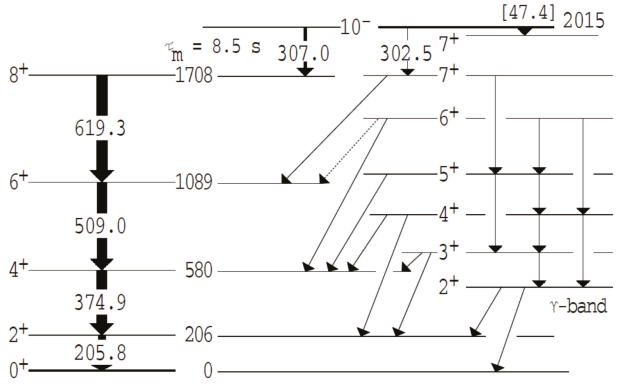

FIG. 1: Partial decay scheme of ^{192}Os, including the 8.5 s isomer, figure adapted from Ref. [19]. The square brackets denote implied transitions, and for clarity some γ-ray energies have been omitted.

An 8.5 s, 10^- isomer with an excitation energy of 2015 keV has previously been identified in ^{192}Os [16, 17] (Figure 1). Our new measurement probes the decay of this isomer when in a hydrogen-like charge state. This was performed by examining over 400 injections where a hydrogen-like isomer was observed, and these data were then sorted into 3.5 s time slices ready for analysis. For clarity, only when a single ion was observed after an arbitrary cooling time were the data accepted and analysed. The in-ring lifetime for each single ion was measured from T_0 = 31.5 s after the injection (Figure 2), the point at which cooling of the ion beam had clearly finished. Although generally there are lower statistics, performing a measurement in this way can greatly improve the precision of the experiment (discussed below) and in Ref. [18], and in this regard it is actually preferential to have a low production and injection probability. With this method it is possible to deduce the survival of ions observed in each time slice over the course of the entire experiment, and, additionally when each ion decayed. This is different from the usual decay curves produced by γ-ray spectroscopy, where the number of decays observed are plotted versus time. Instead in this case, the number of

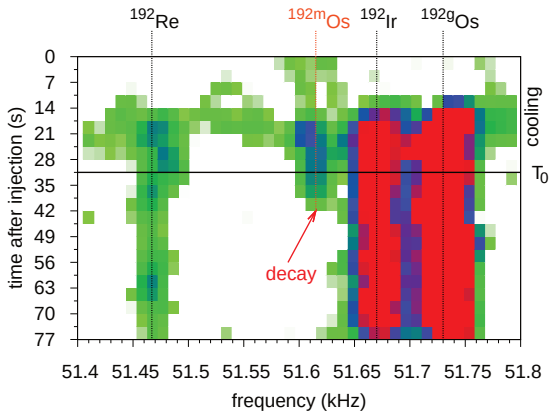

FIG. 2: Colour online - A typical example of a Schottky frequency spectrum with 3.5 s time slices. Large amounts of background noise are observed before adequate time is allowed for cooling. The isomer ^{192m}Os is resolved from the ^{192g}Os state. The sudden absence of the previously observed isomer corresponds to the nuclear decay of the excited state. At 31.5 s after injection, in all analysed injections the background noise was sufficiently low to use this as a start time for lifetime measurements.

observed ions in each time slice can be plotted directly.

The data have been analysed with the following observations: Each individual injection is statistically independent from the previous and subsequent spills. Therefore, each injection can be classed as a separate experiment. Taken across the whole ensemble of nuclei that are analysed, it is possible to know exactly how many of these ions are observed at a specific time by tracking each individually across all time bins. This is an absolute number, with no statistical uncertainty.

Some possible systematic uncertainties have been identified. The decision to select only a set of injections that appear to show a single ion could potentially introduce some selection bias, in that it is possible to miss some valid ions. However, it does not seem likely that we could preferentially miss an ion in such a way that it would bias the subsequent lifetime measurement. In addition, we have assumed that the ion disappearing is due to the isomer decay, however, there are other potential processes that could change the orbital frequency of the ion. The atomic survival time of an ion in the ring has been measured [7], and is large ($\sim$ 45 mins) compared to the known isomer lifetime, therefore this is a negligible effect over the measured time period. Thus, it is possible to assume that the number of ions observed in each time bin has no or at least small uncertainty associated with it.

The data have been fitted using a χ^2 fitting procedure that contains no experimental uncertainties. This is used to derive the lifetime and the number of ions originally measured (N_0) together with their uncertainties. Best fit

values for each data point and the associated propagated uncertainties are presented in Fig. 3 compared to the histogram of number of ions observed in each time bin. The extracted in-ring lifetime of $21.6^{+2.2}_{-1.8}$ s is then Lorentz corrected using $\gamma \approx 1.43$ to give an at-rest lifetime of $15.1^{+1.5}_{-1.3}$ s.

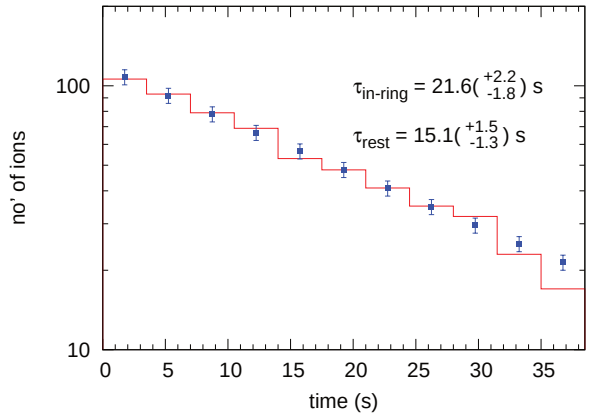

FIG. 3: Colour online - Top: The histogram shows the experimentally measured number of ions observed in each time bin. The points are the number of ions expected within each bin derived from a χ^2 fit to the data, with an uncertainty evaluated from the error in the fit.

The lifetime of the highly-ionised ^{192m}Os is longer than that of the neutral charge state, as the hydrogen-like charge-state hinders the decay due to internal conversion. Examining the known decay transitions from the isomer (see Fig. 1 and Table I), the 47-keV E3 transition is forbidden as the transition energy is below that of the K-shell electron binding energy. More detailed calculations for the internal conversion coefficients for the known transitions in the neutral and hydrogen-like atoms have been performed and are presented in Tab. I. The internal conversion coefficients for neutral atoms were evaluated using the BrICC software [20]. The BrICC software does not allow for evaluations of internal conversion coefficients for ionised atoms, so we have performed direct calculations of conversion coefficients for hydrogen-like ions using the relativistic Dirac-Fock code, RAINE [21]. The high degree of ionisation, with only one electron in the K-shell, when compared to 76 electrons occupying the K to P1 shells, will affect electron wave functions significantly. Perhaps the most extreme example is the K-shell binding energy; in the neutral atom this is 73.87 keV, whereas for a hydrogen-like ion it is 85.7 keV. This change in binding energy has a significant effect on the K-shell conversion when comparing the neutral to hydrogen-like atom.

Experimentally, the neutral isomer decays with a lifetime of 8.5(14) s [16] with three decay paths as shown in Fig. 1. The measured γ-ray intensities [19] of these transitions were used in-conjunction with the neutral lifetime and conversion coefficients to gauge the hindrance due to

TABLE I: Known transitions of ^{192m}Os [19] with internal conversion coefficients for the neutral and hydrogen-like isotopes calculated using BrICC [20] and RAINE [21].

Energy (kev)	I_γ	$\sigma\lambda$	α_T^{neut}	α_T^{H-Like}
47.4	0.0031(6)	E3	7760	0
302.6	100(6)	E3	0.433	0.084
307.0	13.3(3)	M2	0.975	0.374

the hydrogen-like charge state. The evaluated hydrogen-like lifetime is $\tau_{H-like} = 13.0(24)$ s, in good agreement with our measured value of $\tau_{rest} = 15.1^{+1.5}_{-1.3}$ s.

With this technique it is possible to observe a single charged ion undergoing nuclear decay. The storage ring enables observations of highly-ionised, long-lived isomeric states and the identification of their decay paths, from which it is possible to measure the effect of atomic structure on the decay of the nucleus. We have presented the case of hydrogen-like ^{192}Os and the decay of a 2015 keV, 10^- state. With the exceptions of measurements of conversion in highly charged Fe and Te, where, bound internal conversion was observed [22–24], this present measurements is the first storage-ring measurement of the decay of an hydrogen-like isomer. Previously, there have been only measurements of isomers in fully ionised states [25, 26]. In the present case of ^{192}Os, the neutral lifetime measurement has been observed to be 8.5(14) s [16], whereas, our measurement of $15.1^{+1.5}_{-1.3}$ s for hydrogen-like ions is in stark contrast. The difference is explained due to hindering of internal conversion. We have evaluated both neutral and ionised conversion coefficients and hence calculated the theoretical lifetime of a hydrogen-like ion. Our experimental measurement is in agreement with that predicted from the evaluation of conversion coefficients.

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