High-Resolution Measurement of the Time-Modulated Orbital Electron-Capture and of the β^+ Decay of Hydrogen-like ^{142}Pm^{60+} Ions*

P. Kienle[†1,2], *F. Bosch*[3], *P. Bühler*[2], *T. Faestermann*[1], *Yu.A. Litvinov*[3,4,5], *M.S. Sanjari*[3,6,7], *D.B. Shubina*[4,5], *N. Winckler*[3,4], *D. Atanasov*[4,8], *H. Geissel*[3,9], *V. Ivanova*[3], *X.L. Yan*[3,4,10], *D. Boutin*[3,11], *C. Brandau*[3,7,9], *I. Dillmann*[3,9], *C. Dimopoulou*[3], *R. Hess*[3,7], *P.-M. Hillebrand*[3,9], *I. Izumikawa*[12], *R. Knöbel*[3,9], *J. Kurcewicz*[3,8], *N. Kuzminchuk*[3,9], *M. Lestinsky*[3], *S.A. Litvinov*[3], *X.W. Ma*[10], *L. Maier*[1], *M. Mazzocco*[3,14], *I. Mukha*[3], *C. Nociforo*[3], *F. Nolden*[3], *C. Scheidenberger*[3,9], *U. Spillmann*[3], *M. Steck*[3], *Th. Stöhlker*[3,14,15], *B.H. Sun*[3,9,16], *F. Suzaki*[17], *S.Yu. Torilov*[18], *M. Trassinelli*[3,19], *X.L. Tu*[3,10], *M. Wang*[10], *H. Weick*[3], *D.F.A. Winters*[3], *N. Winters*[3], *P.J. Woods*[20], *T. Yamaguchi*[17], *and G.L. Zhang*[16]

[1]Technische Universität München, Garching, Germany; [2]Stefan Meyer Institut, Vienna, Austria; [3]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany; [4]Max-Planck-Institut für Kernphysik, Heidelberg, Germany; [5]Universität Heidelberg, Germany; [6]J.W.-Goethe Universität, Frankfurt, Germany; [7]ExtreMe Matter Institute EMMI, Darmstadt, Germany; [8]CERN, Geneva, Switzerland; [9]Justus-Liebig-Universität Gießen, Germany; [10]Chinese Academy of Sciences, Lanzhou, PR China; [11]CEA-Saclay, Gif-Sur-Yvette, France; [12]Niigata University, Niigata, Japan; [13]INFN, Padova, Italy; [14]Friedrich-Schiller-Universität, Jena, Germany; [15]Helmholtz-Institut Jena, Germany; [16]Beihang University, Beijing, China; [17]Saitama University, Saitama, Japan; [18]St. Petersburg State University, St. Petersburg, Russia; [19]Université Pierre et Marie Curie, Paris, France; [20]University of Edinburgh, Edinburgh, United Kingdom

We report on the re-investigation of the two-body orbital electron-capture (EC) decay of hydrogen-like ^{142}Pm^{60+} ions, stored and cooled in the Experimental Storage Ring ESR of GSI [1]. In a first measurement of this system, a few years ago, a modulation superimposed on the exponential decay has been observed with a period of $T = 7.1$ seconds and an amplitude of about $a = 0.2$ [2]. In the present experiment we benefitted from a newly designed Schottky-noise frequency detector [3]. This device, a 245 MHz pillbox-like resonator, exhibits a signal-to-noise ratio improved by about two orders of magnitude with respect to the capacitive pick-up used in the previous experiment. It reveals in an unprecedented manner hitherto hidden details of the EC decay of a single ion and provides the true decay time as well as the time- and frequency-resolved kinematics and the entire cooling process of the recoiling daughter nucleus just from the moment of its generation, as demonstrated in Fig. 1. In particular, the projection of the recoil velocity onto the beam direction is signalled within 32 ms after the decay by a frequency shift Δf with respect to the revolution frequency of the cooled daughter ion (see Fig.1). From the distribution of these frequency shifts, observed for many thousand EC decays, finally the longitudinal component of the recoil velocity could be figured out and, hence, the momentum of the recoiling daughter ion and of the generated electron neutrino which are equal in magnitude and have opposite direction. Furthermore, the clearly visible onset of the cooling trace of the daughter ion provides an unambiguous signature of the decay time, unlike in the previous experiment, where only the appearance of the cooled daughter ion could be observed [2].

The total of all EC-decays recorded in the present experiment does *not* show significant modulations. However, it happen in part of the time that due to technical failures, "old" ions were not removed from the ESR thus leading to a smearing out the modulation. An uninterrupted series of 7125 consecutive injections of the ions into the ESR without fault was determined and used for the data analysis. This is outlined in detail in [1]. A fit of the data recorded by the 245 MHz resonator yields a modulation with a period of $T = 7.10(11)$ seconds and an amplitude of $a = 0.107(24)$ (see Fig. 2), and for the simultaneously used "old" pick-up detector a period of $T = 7.12(11)$ seconds and an amplitude of $a = 0.134(27)$. Both periods are not only in perfect agreement to each other, but also to the previously reported period of $T = 7.10(25)$ seconds [2]. Both amplitudes are, however, significantly smaller than the previous value of $a = 0.23(4)$.

In order to assess the significance of these results evidence criteria in favour of a certain model have been used. We compared the reliability of a strictly exponential distribution (model M_0) of the data on the one hand, and of a periodical modulation superimposed on an exponential distribution (model M_1) on the other hand, according to the "Akaike Information Criterion (AIC)" which is based on a maximum likelihood analysis. For the data recorded

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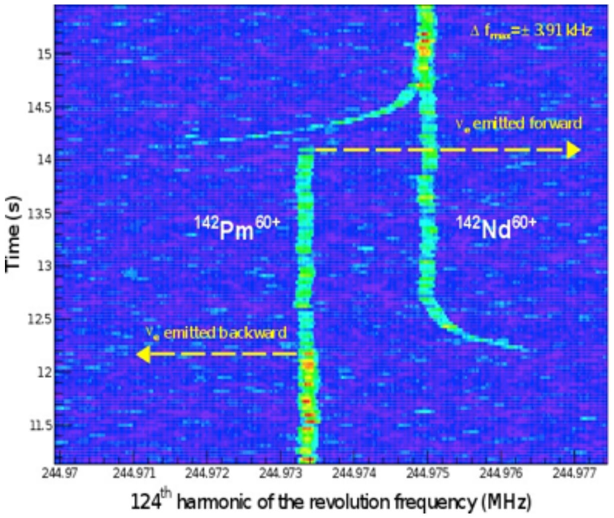

Figure 1: Time traces of two cooled $^{142}\mathrm{Pm}^{60+}$ parent ions, recorded at the 124$^{\mathrm{th}}$ harmonic of the revolution frequency by the 245 MHz resonator vs the time after injection, with time-and frequency binning of 32 ms and 31.25 Hz, respectively. The arrows indicate the true decay times, as unambiguously identified by the onset of the trace of the recoiling daughter ion. It starts at a revolution frequency shifted by Δf with respect to the frequency of the cooled daughter ion, where Δf reflects the projection of the recoil velocity onto the beam direction immediately after the decay.

by the 245 MHz resonator we get a "weight of evidence" of $w_1 = 0.998$ for model M_1 and $w_0 = 0.002$ for model M_0 and of $w_1 = 0.9998$, $w_0 = 1.8 \cdot 10^{-4}$ for the data of the capacitive pick-up. These weights of evidence lead to the conclusion that the reported modulation period of $T = 7.1$ s has been confirmed by the new experiment, although with significantly smaller amplitude.

For the three-body β^+ decays observed in the same data set *no significant modulation* was found, as shown in Fig. 3. This might point to a weak-interaction origin of the modulation which is observed in connection with the (almost) monoenergetic electron-neutrinos from the two-body EC decays, but absent for the continuous neutrino spectrum of the three-body β^+ decay branch. Any conclusive and commonly accepted explanation of the modulation is (still) missing. One of the proposed suggestions, strongly disputed in the literature, is that the modulations reflect – like the well-known quantum beats – the interference of two coherent states, separated in the ion rest frame by an energy difference $\Delta E = h\gamma/T = 8.3 \cdot 10^{-16}$ eV, for $T = 7.11$ s and the Lorentz factor $\gamma = 1.43$ of the stored ions. To be able to confirm or disprove this suggestion, further experiments are mandatory which exploit other systems, different magnetic fields acting on the stored ions and which provide, first of all, higher statistical significance.

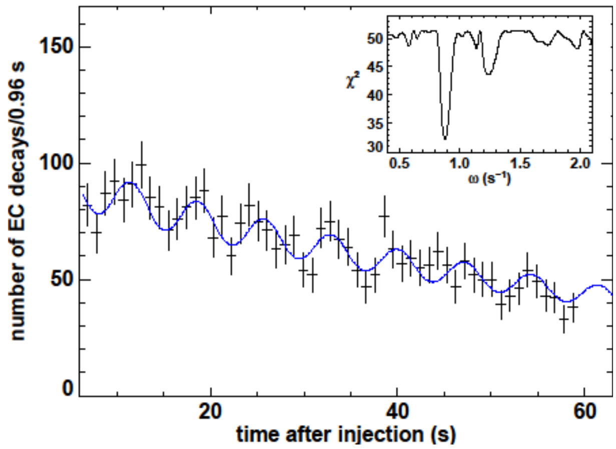

Figure 2: Number of EC decays per 0.96 s of hydrogen-like $^{142}\mathrm{Pm}^{60+}$ ions, recorded by the 245 MHz resonator, vs. the time t after injection of the ions into the storage ring ESR. Displayed is also the modulation fit. The inset shows the χ^2 values vs. the angular frequency ω, for a fixed total decay constant λ and a variation of amplitude a and phase ϕ.

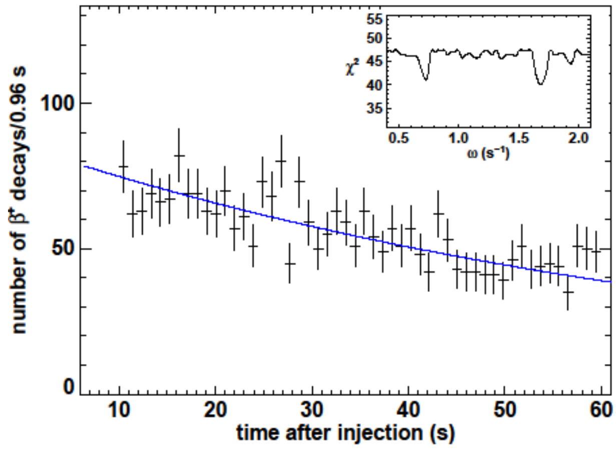

Figure 3: Number of β^+ decays per 0.96 s of hydrogen-like $^{142}\mathrm{Pm}^{60+}$ ions, recorded by the 245 MHz resonator, vs. the time t after injection of the ions into the storage ring ESR. Displayed is also the exponential fit. The inset shows the χ^2 values vs. the angular frequency ω, for a fixed total decay constant λ and a variation of amplitude a and phase ϕ.

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