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[3,7,12], I. Dillmann[3,9], C. Dimopoulou[3], R. Hess[3,7], P.-M. Hillebrand[3,12], I. Izumikawa[13], 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[3,15,16], B.H. Sun[3,9,17], F. Suzaki[18], S.Yu. Torilov[19], M. Trassinelli[3,20], X.L. Tu[3,10], M. Wang[10], H. Weick[3], D.F.A. Winters[3], N. Winters[3], P.J. Woods[21], T. Yamaguchi[18], and G.L. Zhang[17]

[1]Technische Universität München, 85748 Garching, Germany; [2]Stefan Meyer Institut für subatomare Physik, 1090 Vienna, Austria; [3]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany; [4]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany; [5]Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany; [6]J.W.-Goethe Universität, 60438 Frankfurt, Germany; [7]ExtreMe Matter Institute EMMI, 64291 Darmstadt, Germany; [8]CERN, 1211 Geneva 23, Switzerland; [9]II Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany; [10]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, PR China; [11]Service de physique nucléaire CEA-Saclay, F 91191 Gif-Sur-Yvette Cedex, France; [12]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany; [13]Radio Isotope Center, Niigata University, Niigata-951-8510, Japan; [14]Dipartimento di Fisica, INFN, 135131 Padova, Italy; [15]Institute of Physics, Friedrich-Schiller-Universität Jena, 07743 Jena, Germany; [16]Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany; [17]School of Physics and Nuclear Energy Engineering, Beihang University, 100191 Beijing, China; [18]Graduate School of Science and Engineering, Saitama University, Saitama 338-8570, Japan; [19]St. Petersburg State University, 198504 St. Petersburg, Russia; [20]INSP, CNRS and Université Pierre et Marie Curie, UMR 7588, 75005 Paris, France; [21]School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, 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 couple of 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 modulus 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 entangled by momentum- and energy conservation. Furthermore, the clearly visible onset of the cooling trace of the daughter ion provides an unambiguous signature of the decay time, in strict contrast to the previous experiment, where only the appearance of the cooled daughter ion could be observed [2].

The whole of all EC-decays recorded in the present experiment does *not* show significant modulations. However, it could happen that due to technical failures, "old" ions were not removed from the ESR thus leading to washing out the modulation. An uninterrupted series of 7125 consecutive injections of the ions into the ESR 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,
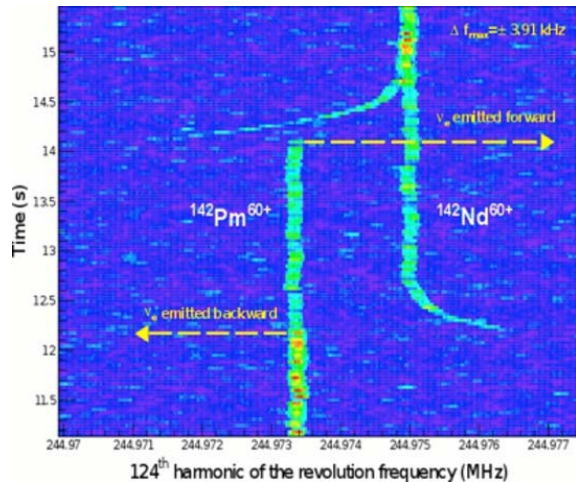
Figure 1: Time traces of two cooled ^{142}Pm^{60+} parent ions, recorded at the 124th harmonic of the revolution frequency by the 245 MHz resonator vs the the time after injection, with time-and frequency binning of 32 ms and 31.25 Hz, respectively. The arrows indicate the true decay times, as unambiguously 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.

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 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 literature, is that the modulations reflect – like the well-known quantum beats – the interference of two coher-
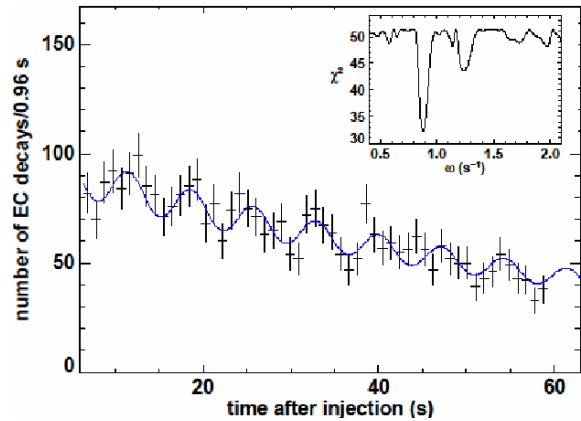

Figure 2: Number of EC decays per 0.96 s of hydrogen-like ^{142}Pm^{60+} ions, recorded by the 245 MHz resonator, vs. the time t after injection of the ions into the storage ring ESR. Displayed is also the modulation fit. The inset shows the χ^2 values vs. the angular frequency ω, for a fixed total decay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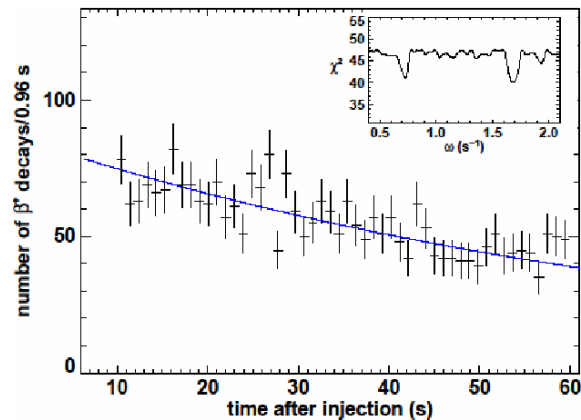

Figure 3: Number of β^+ decays per 0.96 s of hydrogen-like ^{142}Pm^{60+} ions, recorded by the 245 MHz resonator, vs. the time t after injection of the ions into the storage ring ESR. Displayed is also the exponential fit. The inset shows the χ^2 values vs. the angular frequency ω, for a fixed total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

ent 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, significantly higher decay statistics.

References

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