Measurement of the Decay Rate of the Negative Ion of Positronium (Ps^-)

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A new determination of the decay rate of the negative ion of positronium (Ps^-), using a beam-foil method and a stripping-based detection technique, is reported. The measured result of $\Gamma = 2.089(15)\ ns^{-1}$ is a factor of 6 more precise than the previous experimental value of $\Gamma = 2.09(9)\ ns^{-1}$, and is in excellent agreement with the theoretical value of $\Gamma = 2.086(6)\ ns^{-1}$.

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Consisting of a positron and two electrons ($e^+e^-e^-$), the negative ion of positronium (Ps^-) is one of the simplest three-body systems with a bound state. In contrast to other fundamental three-body systems like H^-, H^{2+}, or He, its constituents are pointlike particles of equal mass, which are only subject to the electroweak force. This, together with its unique mass ratio, makes it an interesting object to study the quantum-mechanical three-body problem. In addition, Ps^- can annihilate on and off shell into n photons and an electron, which results in characteristic QED contributions to its bound state properties and, in particular, in a finite lifetime of the ion of about 0.5 ns. Despite numerous theoretical investigations [see, e.g., [1] and references therein], however, experimental results on this elusive ion are so far limited to the proof of existence made almost 25 years ago [2], and to a subsequent decay rate measurement resulting in $\Gamma = 2.09(9)\ ns^{-1}$ [3]. While these pioneering experiments nicely confirmed the early considerations of Wheeler [4], more precise results are required to challenge theoretical predictions. We have therefore initiated an experimental program to study the negative positronium ion in more detail, and started our investigations with a new decay rate measurement employing a beam-foil method together with a stripping-based detection technique.

The total decay rate of the $^1S^e$ ground state of Ps^-, which is bound by 0.326 eV [1] and the only state stable against autoionization, is dominated by the 2γ decay and is commonly calculated using a formula given by [5],

$$\Gamma = 2\pi\alpha^4 \frac{c}{a_0}\left[1 - \alpha\left(\frac{17}{\pi} - \frac{19\pi}{12}\right)\right]\langle\delta(r_{1p})\rangle, \qquad (1)$$

where a_0 is the Bohr radius and $\langle\delta(r_{1p})\rangle$ is the expectation value of finding the positron and one of the electrons at the same position. The correction term of first order in α includes only the leading term of the 3γ decay and the leading radiative correction to the 2γ-decay constant, while other terms of order α are still missing [5]. Using this expression and a numerical wave function obtained by variational methods [6], the calculated decay rate is $\Gamma = 2.086(6)\ ns^{-1}$, where the uncertainty is conservatively assumed—in lack of any estimate in the theoretical literature—to be of the order of the correction term itself. A more precise evaluation of the accuracy of the calculated Γ value is highly desirable, but so far even this accuracy is more than an order of magnitude beyond the precision of the only previously available experimental value.

In the present measurement of the Ps^- decay constant the beam-foil technique already employed by Mills [2,3] has been used: Ps^- ions are produced by a beam of slow positrons traversing an ultrathin foil, where they eventually pick up two electrons. The Ps^- ions leaving the surface of the production foil are then accelerated via a gap of adjustable width d. Recording the number of ions surviving the acceleration across the gap as a function of d allows us to deduce Γ once the relation between the distance d with the time of flight t' (measured in the rest frame of the ions) is known. A straightforward relativistic calculation yields

$$t' = \frac{d}{\Lambda c}\ln[1 + \Lambda + \sqrt{\Lambda^2 + 2\Lambda}](1 - \sqrt{\Lambda_0/\Lambda}), \qquad (2)$$

with $\Lambda_0 = T_0/(3m_ec^2)$ and $\Lambda = eU/(3m_ec^2)$, where T_0 denotes the longitudinal kinetic energy of the positronium ion when leaving the production foil and U the acceleration voltage across the gap. It follows from Eq. (2), which is correct up to terms of order $\Lambda^{3/2}$ and Λ_0/Λ, that the proper time needed for crossing the gap is strictly proportional to its width d. Therefore, the measured rate $R(d)$ of the positronium ions surviving the acceleration across the gap decreases exponentially with increasing d, $R(d) = r_0\exp(-\mu d)$, and μ is related to Γ by

$$\Gamma(1 - \sqrt{\Lambda_0/\Lambda}) = \mu[\Lambda c/\ln(1 + \Lambda + \sqrt{\Lambda^2 + 2\Lambda})]. \qquad (3)$$

The conversion factor depends on the acceleration voltage U and—via the correction factor on the left-hand side—on the initial average longitudinal kinetic energy T_0 of the Ps^- ions. Both Γ and T_0 can be determined when performing the decay rate measurements at different values of the acceleration voltages U: plotting the uncorrected decay

rate $\Gamma^* = \Gamma(1 - \sqrt{\Lambda_0/\Lambda})$ versus $\Lambda^{-1/2}$, the decay constant Γ can be deduced by extrapolating Γ^* for $\Lambda^{-1/2} \rightarrow 0$, while a finite T_0 value is reflected by a negative slope of Γ^* with $\Lambda^{-1/2}$.

In an exploratory investigation [7] we have tried out the method first used by Mills [2,3] to detect the number of ions surviving the acceleration across the gap. It is based on detecting the annihilation photons from the in-flight decay of the fully accelerated positronium ions by making use of the Doppler-shift seen by a high-resolution gamma detector in forward direction, which allows us to distinguish the Ps^- decays from other electron-positron annihilations. However, given the unfavorable signal-to-background ratio, which is caused by the copious amounts of positrons annihilating in the vicinity of the production foil, a significant improvement in the precision of Γ seemed to be hardly possible within this approach. We therefore developed a new detection method based on a stripping technique [8].

The setup used in the present decay rate measurements is shown schematically in Fig. 1. The experiment utilizes positrons from a 40 mCi ^{22}Na source, which are moderated in a 4 μm thick tungsten foil and reaccelerated to 30 eV to form a beam of 7 mm diameter with a flux of $1.5 \times 10^5 e^+/\mathrm{s}$. These positrons are guided by a longitudinal magnetic field to the experiment chamber, where they are accelerated towards a 5 to 8 nm thin DLC (diamondlike carbon) foil of 12 mm diameter [9] mounted on a copper grid of 86% transmission. When adjusting the foil voltage U_e such that about half of the positrons are transmitted, the Ps^- production probability was measured to be maximal and to amount to about 1×10^{-4} [7], in agreement with Ref. [2]. Thus about 15 Ps^- ions were produced per second. After leaving the foil, the negative ions are accelerated (while any transmitted positron is being repelled) by a grid of the same type as the supporting grid of the production foil, which is biased at a voltage U_a such that the total acceleration voltage is $U = U_a - U_e$. In order to allow for a precise variation of the distance d between the production foil and the acceleration grid, the grounded entrance grid and the DLC foil are mounted on top of a high-precision piezoelectric translation stage with a position reproducibility of ≤ 1 μm.

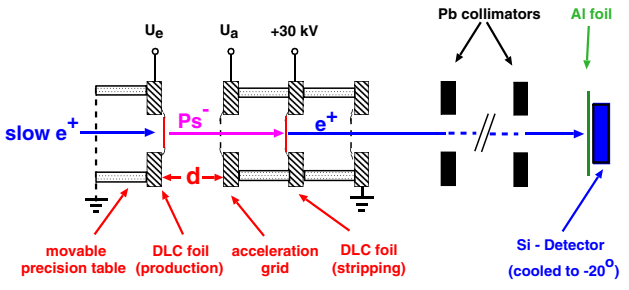

FIG. 1 (color online). Schematic view of the setup used for measuring the decay rate of Ps^-. Typical voltage settings are $U_e = -800$ V and $U_a = +3.1$ kV.

After having passed the acceleration grid, the surviving Ps^- ions enter the detection part of the setup. Here they are first post-accelerated across a gap of 16.8 mm towards another thin DLC foil by a positive voltage of +30 kV. By passing through the foil the electrons are stripped off, and the bare positrons are further accelerated towards a grounded grid while the electrons are decelerated. The positrons, having acquired a kinetic energy of 39.5 keV, are magnetically guided towards a Si charged-particle detector with an active surface area of 300 mm^2 and a depletion depth of 100 μm, which is kept at a temperature of $-20\,^\circ$C. Two layers of 0.75 μm aluminum foil had to be placed directly in front of the detector surface to prevent positive ions from hitting the detector; while being sufficient to stop all ions in the relevant energy range, the positrons lose only about 800 eV. Another background contribution was found to be caused by Compton electrons which are produced by the 511 keV annihilation radiation at the inner surface of the beam line tubing. A sizable improvement of the signal-to-background ratio was achieved by means of two lead collimators mounted in the detector beam line. Finally, the detector section was surrounded by a lead house of 5 cm lead bricks with an inner lining of 5 mm copper to shield the detector against environmental radiation. In the detection part of the setup all distances and voltages are fixed, thus the detection probability for a positronium ion reaching the acceleration grid is constant and independent of the value of d. The overall detection probability was found to be about 1%. We attribute the main loss in efficiency to the scattering of the positrons in the stripper foil, which can result in transversal energies too large to be compensated by the magnetic transport field of 160 G.

To allow for a determination of the decay constant Γ as well as of the initial longitudinal kinetic energy T_0, the decay rate measurements were performed for different acceleration voltages U, namely 985, 1285, 1882, 3875, 3973, and 4766 V. This was accomplished by adjusting the grid voltage U_a while keeping the foil voltage U_e constant. For each value of U, a set of distances d was chosen, covering roughly a full decade of the exponential decay; the largest usable distance of $d = 28.0$ mm was included in all runs for the purpose of background determination. To minimize uncertainties due to possible drifts in the positron flux and to account for the decaying source activity, the measurements at different acceleration gap widths d were done in short cycles. Within each cycle, the order of the single measurements at different distances was set randomly, and the respective data-taking time Δt was chosen (with the exception of the background runs at $d = 28.0$ mm) such as to reach a comparable number of Ps^- counts at every individual value of d; at the smallest distance used, $d = 2.7$ mm, Δt was set to 10 min.

Because of the long duration of the experiment, which was performed over a period of eight months, the first run performed at an acceleration voltage of 3875 V was repeated near the end of the experiment to check the reproducibility of the results.

As an example, Fig. 2 displays positron energy spectra recorded with the Si detector at four different values of d for an acceleration voltage of $U = 3875$ V (run #1). The background spectrum was deduced from the spectrum measured at $d = 28.0$ mm by iteratively correcting for the residual Ps^- contribution. After fitting a linear combination of the corrected background spectrum and an empirical positron line shape to the individual spectra, the fitted background was subtracted and the number of detected Ps^- ions was determined from the background-corrected spectra by summing up the counts in the interval $[90, 135]$. Together with the dead-time corrected measuring times these data yielded the Ps^- rates $R(d)$ for a given acceleration voltage U. The individual errors of $R(d)$ were calculated by error propagation from the square-root counting errors for the signal and the scaled background; uncertainties in the determination of the measuring times are negligible. The decay constant μ was then obtained from the best fit of the measured rates using the function $R_0 \exp(-\mu d)$ with R_0 and μ as free parameters, and the 1σ error of the resulting μ was finally deduced from a plot of χ^2 in the parameter plane μ versus R_0. An example of such a fit is shown in Fig. 3.

Several tests were performed in order to check for the consistency of the deduced decay constants μ. It was verified that a change of the peak integration interval changes μ only well within the statistical errors. By confining the analysis of the runs performed at a given acceleration voltage to subruns and to subsets of the set of distances d, significant changes of μ were observed only for the run at $U = 4766$ V, where variations of up to 4σ were detected. As this voltage was only about 100 V below the breakdown voltage and unusually high noise contributions were found in several individual run files, the data recorded at this acceleration voltage were disregarded in the final analysis.

Using Eq. (3), the decay rates Γ^* were calculated from the slope parameters μ; the results are plotted in Fig. 4 as a function of $1/\sqrt{U}$. Uncertainties due to the accuracy of the acceleration voltage settings of ± 5 V are more than an order of magnitude smaller than the one caused by the statistical error of μ, and can therefore be neglected. Note that the two measurements performed at $U = 3875$ V at the beginning and the end of the experimental campaign agree well within their accuracies.

As discussed in the context of Eq. (3), a finite average initial longitudinal kinetic energy T_0 of the Ps^- ions should be reflected by decreasing values of Γ^* with $1/\sqrt{U}$, a trend which is not supported by the data. Fitting $\Gamma^* = \Gamma(1 - \sqrt{T_0/U})$ under the constraint $T_0 \geq 0$ eV to the data, the best fit is obtained for $\Gamma = 2.089$ ns^{-1} and $T_0 = 0$ eV with a χ^2 of 5.24 at 4 degrees of freedom. Using the procedure suggested by the Particle Data Group [10], the 90% confidence limit of T_0 was determined to be $T_0 < 0.12$ eV. The standard deviation of Γ was deduced from the $\Delta\chi^2 = 1$ contour in the Γ versus T_0 plane to be ± 0.013 ns^{-1}.

Interpreting the result obtained for T_0, one should keep in mind that this quantity might not only depend on the still unexplored Ps^- formation process but also on details of the foil surface and the local electric fields at the surface. The only comparable information on T_0 is from the previous

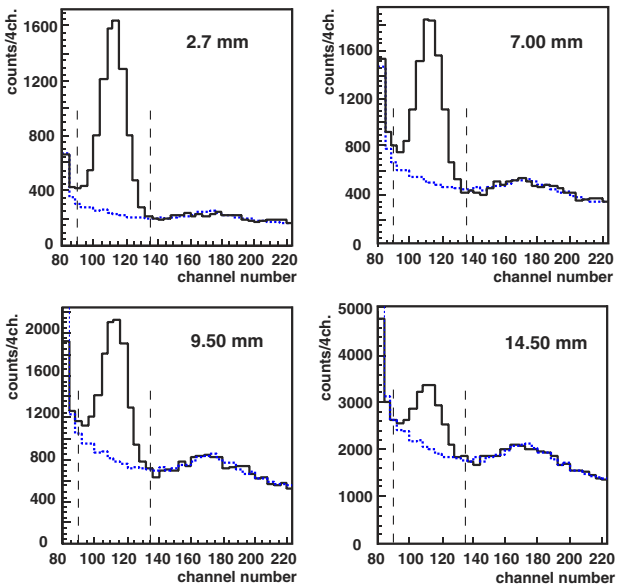

FIG. 2 (color online). Positron energy spectra resulting from the stripping of Ps^- ions which survived the acceleration by $U = 3875$ V across four different gap widths d. The dotted histograms represent the appropriately scaled background spectrum determined as discussed in the text. The broken vertical lines mark the integration interval used to evaluate the Ps^- rates.

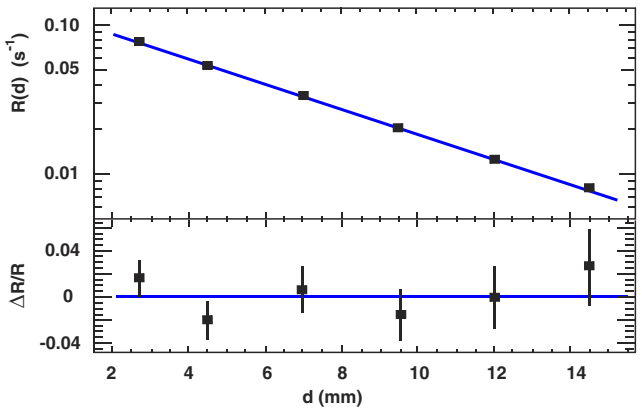

FIG. 3 (color online). Upper panel: rate of surviving Ps^- ions as a function of the gap width d, measured at an acceleration voltage of $U = 3875$ V. The solid line represents the best fit by an exponential $\exp(-\mu d)$. Lower panel: residuals $\Delta R/R$ after subtraction of the fitted function from the data.

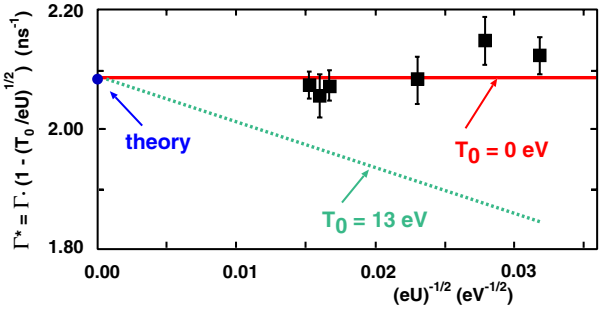

FIG. 4 (color online). The uncorrected decay rate Γ^* as a function of $1/\sqrt{U}$ (in order to show the results more clearly, the three data points at $U = 3875$ V and $U = 3973$ V are drawn at slightly shifted positions along the $1/\sqrt{U}$ axis). The best fit of the data by $\Gamma^* = \Gamma(1 - \sqrt{T_0/U})$ under the constraint $T_0 \geq 0$ eV results in $T_0 = 0$ eV and $\Gamma = 2.089$ ns^{-1} (solid line). To exemplify the sensitivity to the average initial longitudinal energy T_0 of the Ps^- ions, the slope expected for $T_0 = 13$ eV [3] is shown by the broken line.

decay rate measurement of Mills [3], who used standard carbon instead of DLC foils and deduced a T_0 value of 13^{+19}_{-10} eV, which is considerably larger but statistically still compatible with our upper limit of $T_0 < 0.12$ eV. In case the Ps^- ions are formed in the foil and the emission into the accelerating field is governed by kinematics only, one expects T_0 to have values between thermal energies and the binding energy of the second electron, i.e., 0.025 eV $< T_0 < 0.3$ eV, which would be in accord with our findings.

Several sources of systematic errors that could influence the decay rate measurement have been investigated besides T_0; among those are (i) the positron beam flux, (ii) the quality of the linear translation stage, and (iii) the geometrical imperfections of the production foil and acceleration grid setup [11]. (i) Because of the organization of the measurement process, the positron beam could affect the experiment only by short-term fluctuations of the positron flux or by a misalignment between the beam axis and the chamber axis, which would lead to gap-width dependent losses of the e^+ and Ps^- beams. Both effects have been carefully investigated and found to be negligibly small compared to the statistical errors; in particular, flux changes due to a possible misalignment were shown to be $<0.25\%$ when varying d by 40 mm. (ii) The position reproducibility and the angular errors (pitch and yaw) of the linear translation stage used for setting the width d of the acceleration gap contribute less than 0.15% to the error budget of Γ. (iii) While the alignment between the acceleration grid and the production foil as well as the flatness of the latter do not affect the decay rate measurement in first order, the grid structure and deformation of the foil can lead to small modifications of the planar acceleration process assumed in the derivation of Eq. (2). To estimate the size of such effects, numerical simulations based on classical, nonrelativistic particle trajectories have been performed for different configurations. The analysis of the resulting time-of-flight distributions show that such effects may contribute at most on the level of 0.8% for acceleration voltages of $U \approx 1000$ V and on the level of 0.2% for runs at $U \approx 3900$ V to the individual decay rate measurements.

Including the systematic error estimates in the total error budget for Γ, we finally obtain

$$\Gamma = 2.089(15)\ \text{ns}^{-1}$$

for the decay rate of Ps^-. This result is a factor of 6 more precise than the previous experimental value of $\Gamma = 2.09(9)$ ns^{-1} determined by Mills [3], and is in excellent agreement with the theoretical value of $\Gamma = 2.086(6)$ ns^{-1}.

Judging from the discussion of the systematic errors given above, a further 4–5 fold improvement seems feasible with our present setup using the more than 1000 times larger flux of moderated positrons available now at the NEPOMUC source at the FRM-II reactor in Munich [12]. Moreover, once the NEPOMUC source will have reached its design value of $10^9 e^+/\text{s}$ such that Ps^- rates of up to 10^5 s^{-1} can be expected, measurements of the $3\gamma/2\gamma$ branching ratio as well as photo-detachment and photo-excitation experiments of doubly excited, autoionizing Ps^- states will become feasible, allowing further tests of our present understanding of the quantum-mechanical 3-body problem.

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