New Precision Measurement of the Orthopositronium Decay Rate: A Discrepancy with Theory

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The vacuum decay rate λ_T of orthopositronium (o-Ps), formed in a gas, has been measured to be $\lambda_T = 7.0516 \pm 0.0013\ \mu s^{-1}$. This result, which is 4 times more accurate than any previous measurement, is 10 standard deviations above the theoretical value. Extensive systematic tests included measurement of λ_T in three different gases, each to an accuracy of at least $\pm 0.0025\ \mu s^{-1}$ (350 ppm), and the use of two entirely different digital timing systems.

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Measurement of the properties of the electron-positron bound state (positronium, Ps) provides a rigorous testing ground for bound-state quantum electrodynamics (QED). The decay rates of the $^1S_0$(p-Ps) and the $^3S_1$(o-Ps) positronium ground states as well as the energy splitting between them ($\Delta\nu$) have been calculated[1,2] including radiative corrections up to order $\alpha^2 \ln\alpha$. Calculations of these quantities to order α^2 are considered to be straightforward, though technically difficult, and the $\Delta\nu$ calculation is nearing completion.[3] The importance of experimentally checking these theoretical calculations goes beyond bound-state QED because the relativistic bound-state formalism used has analogies in calculations of quark-antiquark bound states in QCD. For example, calculation of the decay of the Υ meson into three gluons is closely related in technique to calculation of the o-Ps decay rate.[4] Problems in the theoretical treatment of Ps, particularly if due to the treatment of the bound state, will be amplified in the corresponding QCD calculation where the expansion parameter α_S, is 10 times the size of α in QED.

The theoretical value for the decay rate of o-Ps may be expressed as the sum of decay rates into three photons (λ_3), five photons (λ_5), etc.:

$$\lambda_T = \lambda_3 + \lambda_5 + \lambda_7 + \ldots .$$

The contribution of λ_5 has been calculated[5] to be $\lambda_5/\lambda_3 \sim 10^{-6}$, and is thus negligible. The leading term, λ_3, is given by

$$\lambda_3 = \frac{\alpha^6 mc^2}{\hbar}\frac{2(\pi^2-9)}{9\pi}[1 + A(\alpha/\pi) + \tfrac{1}{3}\alpha^2\ln\alpha + B(\alpha/\pi)^2 + \ldots].$$

The two most recent calculations give $A = -10.266 \pm 0.011$[1] and $A = -10.282 \pm 0.003$.[2] The coefficient B is still uncalculated. If $B = 1$, its contribution to λ_3 is 4 ppm or $3 \times 10^{-5}\ \mu s^{-1}$. Taking A from Ref. 2, one obtains through order $\alpha^2 \ln\alpha$ $\lambda_3 = 7.038\,30 \pm 0.000\,07\ \mu s^{-1}$.

We report in this Letter a new measurement of λ_T with an uncertainty of 200 ppm, a factor of 4 improvement over the best previous measurement. We find that $\lambda_T = 7.0516 \pm 0.0013\ \mu s^{-1}$, in substantial agreement with previous experimental results, the most recent of which[6-9] are $7.056 \pm 0.007\ \mu s^{-1}$, $7.045 \pm 0.006\ \mu s^{-1}$, $7.051 \pm 0.005\ \mu s^{-1}$, and $7.050 \pm 0.013\ \mu s^{-1}$. We note that all of the previous results are 1 to 2.5 standard deviations above the present theoretical value and that the result reported in this paper exceeds the theory by 10 standard deviations.

The technique used in this experiment is similar to that discussed in Refs. 6 and 8. Positrons from a 10-μCi radioactive ^{22}Na source pass through a 0.115-mm-thick scintillator and form Ps in a gas in a magnetic field of 6.8 kG (Fig. 1). The end-point energy of ^{22}Na is 0.54 MeV which is low enough to stop a large fraction of the positrons in the 14-cm-long gas chamber. This results in a considerably increased signal rate compared to Refs. 6 and 8 which used ^{68}Ge (end-point energy 1.89 MeV). The scintillator is coupled via a 45-cm Lucite light pipe to an Amperex XP2020 photomultiplier tube (PMT). The pulse from this PMT provides a start signal to a digital timing system. The magnetic field causes all positrons with a forward momentum component to spiral into the chamber. The positrons then slow down in the gas to energies of order 10 eV and some fraction of these (roughly 25%) form Ps. The magnetic field mixes the $m = 0$ singlet and triplet magnetic substates of Ps resulting in perturbed triplet (and perturbed singlet) states that decay with lifetimes of 13 nsec (0.12 nsec) at 6.8 kG. The $m = \pm 1$ triplet states are unperturbed and continue to decay with a rate λ_T. When Ps decays, the annihilation γ rays are detected by an annular plastic scintillator coupled via light pipes to four Hamamatsu R1250 PMT's. These provide the stop timing signal. One data run consists of a histogram of start-stop delay times. A decay rate, λ, at the given gas density is extracted from the histogram (as discussed below) and λ_T

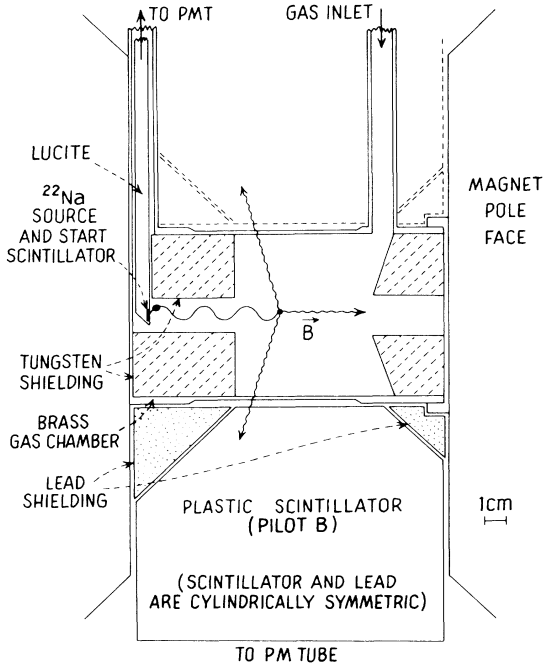

FIG. 1. Ps formation chamber and detector arrangement.

is assumed to be the intercept after extrapolation to zero gas density. To check this assumption we have measured λ at gas densities differing by more than a factor of 10 for each gas used, and we have made separate extrapolations in three different gases (nitrogen, isobutane, and neopentane), each to at least an accuracy of ± 0.0025 μs^{-1}.

The electronics for this experiment were based on two independent digital timing systems. The use of two entirely different electronic timing systems, both of which gave results in agreement with each other within their standard errors, renders essentially negligible the possibility of any electronics-based systematic error. One system used a Hewlett Packard model 5345A time counter; the other used a LeCroy model 4204 time-to-digital converter (TDC) with LeCroy model 3588 histogramming memory. The LeCroy TDC (with 1-MHz start-rate capability) permitted a very simple timing system in which the 2 PMT signals (start and stop) were discriminated and sent directly to the TDC inputs. Start rates as high as 100 kcps were used in this "fast system." The Hewlett Packard TDC was much slower (5 kcps) and thus required a rejection system to filter out as many unwanted events as possible. We required that any start be followed by no other start and by a stop delayed by at least 40 ns. In addition, a deadtime of 1 μs was imposed on the stop. The start rate in this "slow system" was thereby reduced to approximately 1–2 kcps. Thus (98–99)% of the starts were rejected before reaching the TDC. In spite of its increased complexity, the slow system had the advantage of reducing random background events in the lifetime histogram by a factor of about 2.

The two TDC's were calibrated to an absolute accuracy of 10^{-5} by comparing them to a Monsanto model 3100A frequency synthesizer and to an Ortec model 462 time calibrator. Bin-width variations in the histogram were also checked. The Hewlett Packard TDC showed no variations in its 8-ns-wide bins at the 0.01% level. The LeCroy TDC had variations of order 0.3% units 10-ns bins. These variations were measured and found to be stable over 6-month time intervals. The measured widths were used to correct the data. The LeCroy TDC also showed a slope of 0.04% over a 1-μs interval as measured in runs with background only and no signal. This effect necessitated a correction of +0.001 to +0.002 μs^{-1} (depending on noise rates) on the fitted decay rate.

The shape of the histogrammed time spectrum, to sufficient accuracy for this work, has the following form[10] for $t > 150$ ns:

$$N(t) = (A e^{-\lambda t} + B) e^{-Rt}. \quad (1)$$

Here, λ is the decay rate of o-Ps in the gas at a particular gas density and R is the total stop rate at the TDC for the fast system. The magnetically perturbed triplet state (with a 13-ns lifetime) has decayed away sufficiently by 150 ns to be excluded from Eq. (1). The spectrum was fitted by use of a maximum-likelihood routine to extract the parameters A, B, and λ. The parameter R can be measured independently when no rejection electronics are used. For the slow system (with rejection and dead times) R is identically zero.

In the data runs the detected positron rate was typically 60–100 kcps and the γ-ray stop rate was between 6 and 12 kcps. The total o-Ps rate in the $m = \pm 1$ states ranged from 200 to 500 cps, and the ratio A/B in Eq. (1) ranged from 5 to 20. Thus, in a 1-d run 4×10^7 o-Ps events are detected and histogrammed. Roughly ten such runs permit a determination of the decay rate at one value of the gas density to about ± 0.002 μs^{-1} (300 ppm). During the run the gas pressure is measured by a Baratron model 170m-6B capacitive manometer. Temperature and pressure were monitored on an hourly basis and the density was computed with the use of the ideal gas low with (when necessary) a first virial correction. The gas in the chamber was pumped and replaced daily to prevent contamination from any minor leaks and chamber degassing.

We have measured the o-Ps decay rate as a function of density in three different gases: isobutane, neopentane, and nitrogen with a small admixture of isobutane. For isobutane, $CH(DH_3)_3$, the pressure ranged from 100 to 1200 Torr (corresponding to densities of 5.4×10^{-3}–67.1×10^{-3} moles/l) and the virial coefficient[11] used was -0.55 ± 0.05 l/mole. Similarly in neopentane, $C(CH_3)_4$, pressures ranged from 100 to 800 Torr (5.4×10^{-3}–44.8×10^{-3} mole/l) with a virial coefficient

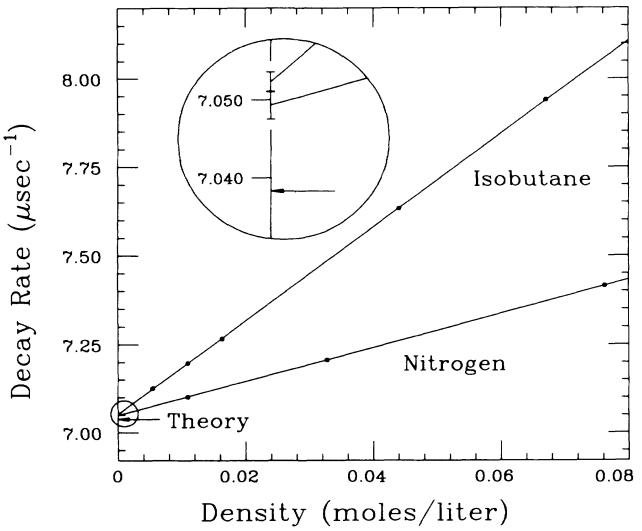

FIG. 2. o-Ps decay rate vs gas density for isobutane and nitrogen. Error bars are approximately 3 times smaller than the plotting symbol. The neopentane data, omitted for clarity, fall on nearly the same line as the isobutane data.

of -0.90 ± 0.09 l/mole. For the nitrogen runs at pressures of 200–1600 Torr (10.8×10^{-3}–76.2×10^{-3} moles/l) a 20-Torr admixture of isobutane was used to quench low-energy positrons.[12] The virial coefficients for this gas mixture are sufficiently small that the gas can be considered ideal. These data were extrapolated in nitrogen density after each value was first corrected for the effect of 20 Torr of isobutane (0.0144 ± 0.0003 μs^{-1}). The nitrogen and isobutane results are graphed in Fig. 2 and the zero-density intercepts for all three gases are summarized in Table I. For each gas we have averaged the fast- and slow-system measurements to get a measured decay rate. We then perform a weighted average of these results to get a final value. Since we consider the three different gas measurements as systematic tests, the error that we assign to the weighted average is not the error of the mean but rather the smallest error of the individual runs (isobutane, $\Delta\lambda = \pm 0.0012$ μs^{-1}) as the final statistical error in our measurement.

We consider the agreement of the three measurements of λ_T in different gases to be the single most important systematic test that we performed, because the agreement of the results excludes a wide range of gas- or pressure-dependent effects which, if present, would produce differences in the extrapolated decay rate. The most significant of these gas-dependent effects is associated with the possibility that the velocity distribution of the Ps changes, i.e., the Ps "thermalizes" on a time scale similar to λ_T^{-1}. This would mean that λ in Eq. (1) could be decreasing throughout the lifetime spectrum and thus the fitted decay rate would be artificially high, especially at low pressures where thermalization would be slower. In fact, we observe a trend consistent with thermalization in the fitted decay rate at the lowest pressures used for each gas. As the start channel of the fitting program is successively stepped out beyond $t = 150$ ns the fitted decay rate decreases by roughly 1000 ppm before asymptotically approaching a constant value at 175–275 ns, depending upon the gas. Upon doubling of the gas pressure, and hence of the Ps–gas-molecule collision rate, the effect disappears and λ is observed to be constant beyond 150 ns. We conclude that Ps thermalization effects are negligible at all but the lowest gas pressures used and that, at these low pressures, we have correctly accounted for such effects by selecting the asymptotic value of λ. We therefore expect no pressure-dependent shift in the extrapolated value of λ_T. The agreement of the measured values of λ_T for the three different gases (for which the Ps thermalization rates would not be expected to be identical) strongly supports this conclusion. Systematic errors due to other gas-related effects, such a chemical interactions of Ps with gas molecules or any other effects that are nonliner in the gas density, are ruled out on the same grounds.

TABLE I. Values of λ_T (in μs^{-1}) measured in three gases with the use of two separate timing systems (statistical errors in parentheses). Note that the timing systems acquired data simultaneously and thus are not statistically independent.

Gas	Slow system	Fast system	Average
Isobutane	7.0525(12)	7.0520(15)	7.0523(12)
Nitrogen	7.0493(17)	7.0492(20)	7.0493(17)
Neopentane	7.0537(25)	7.0533(29)	7.0535(25)

The other systematic tests conducted in this experiment were done to rule out effects which would alter the observed decay rate in the same way for all gases. As mentioned above, the use of two very different timing systems and their accurate time calibration strongly supports the accuracy of the digital electronics. We have also acquired data using a positron source that is 5 times weaker than the usual 10-μCi source. The resulting lower rates increase A/B in Eq. (1) (thus reducing systematic effects due to nonflat backgrounds) while reducing pile-up effects in the detectors and PMT's. The decay rates measured in this way agree at the 200-ppm level with those measured with the stronger source. In addition we have raised signal discriminator levels without affecting the measured decay rate, conducted background runs to check the background component in Eq. (1), and demonstrated reproducibility in measurements separated in time by a year or more.

The only systematic effect that cannot be shown by direct experiment to be below 100 ppm is an effect associated with the presence of long-lived excited states of Ps (Ps*) which could introduce extra components into Eq. (1). Direct analysis of the data indicates that there are no such components present with an intensity and lifetime which would cause a 3σ (± 0.0039 μs^{-1}) change

TABLE II. Contributions to the error in units of μs^{-1}.

	Isobutane	Nitrogen	Neopentane
Statistics	0.0012	0.0017	0.0025
Pressure measurement	0.0004	0.0003	0.0007
Virial coefficient	0.0003	Negl.	0.0008
Correction for isobutane admixture	...	0.0003	...
TOTAL	0.0013	0.0018	0.0027

in the fitted value of λ. However, we expect that Ps* is quickly collisionally deexcited in the polyatomic gases we use since the analogous process of collisional deexcitation of excited-state atoms in polyatomic gases occurs with large cross sections[13] of order 10^{-15} cm^2. It is generally understood that long-range dipole-dipole interactions are responsible for the deexcitations and the same mechanism will cause the collisional deexcitation of P-state Ps (kinetic energy ≈ 1 eV) to the ground state with a similar or even greater cross section.[14] As a result all P states should deexcite in less than 0.1 ns at the pressures used in our experiments. The other angular momentum states of Ps* are collisionally mixed with P states in a time of order 1 ns.[15] Thus, all Ps* should reach the ground state in a few nanoseconds, a time short enough so that its effect is negligible in our experiment.

Our final result is $\lambda_T = 7.0516 \pm 0.0013\ \mu s^{-1}$. A list of the known systematic effects and their contribution to the error is given in Table II. We know of no systematic effect with the potential to resolve the 10σ discrepancy with the calculations of λ_T which we now observe. We note that the uncalculated coefficient, B, of the order-$(\alpha/\pi)^2$ term would have to be 300 ± 30 in order to resolve the discrepancy. Alternatively, it has been suggested[16,17] that the discrepancy might be due to an exotic decay mode of o-Ps not considered in the QED calculation of λ_T. As a result of recent axion searches,[17] all decay processes with a final state of a single photon and a particle can be ruled out at the 30-ppm level in λ_T. We know of no other candidate decay modes; however, the disappearance (mixing) of Ps into mirror-universe states has been considered.[18] To provide an additional rigorous check of our present measurement we have begun a new experiment (designed to reach an accuracy of $\pm 0.0007\ \mu s^{-1}$) using a slow positron beam with Ps formation in an evacuated cavity (similar to that described in Ref. 9).

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