New Experimental Value for the Orthopositronium Decay Rate

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The vacuum decay rate of orthopositronium formed in a gas is determined, after extrapolation to zero gas density, to be $7.056 \pm 0.007\ \mu\text{sec}^{-1}$. The discovery of two systematic effects in a previous powder experiment is discussed. A new measurement of the decay rate in SiO_2 powders yields results in agreement with the new gas value. The experimental values are still in disagreement with the most recent theoretical calculation, $7.0386 \pm 0.000\,16\ \mu\text{sec}^{-1}$.

In two previous Letters[1,2] we have reported on precision measurements of the orthopositronium (o-Ps) decay rate, λ. Our results were in strong disagreement with the existing quantum electrodynamic calculation[3] computed to order α, $\lambda = \lambda_0 \times [1 + (1.86 \pm 0.45)\alpha/\pi] = 7.242 \pm 0.008\ \mu\text{sec}^{-1}$, $\lambda_0 = (2/9\pi)\alpha^6(mc^2/\hbar)(\pi^2 - 9)$, as well as with two previous experimental results,[4,5] 7.262 ± 0.015 and $7.275 \pm 0.015\ \mu\text{sec}^{-1}$, in which o-Ps was formed in gases. We had obtained a value of $7.09 \pm 0.02\ \mu\text{sec}^{-1}$ by direct measurement in vacuum and a value of $7.104 \pm 0.006\ \mu\text{sec}^{-1}$ by extrapolating measured decay rates in SiO_2 powders to zero powder density. These results prompted Caswell, Lepage, and Sapirstein[6] to reexamine the calculation of the radiative corrections. Their work has produced a new theoretical value of the o-Ps decay rate of $\lambda = \lambda_0[1 - (10.348 \pm 0.070)\alpha/\pi] = 7.0379 \pm 0.0012\ \mu\text{sec}^{-1}$. The calculation has recently been extended[7] to include a term $-\frac{1}{3}\alpha^2 \ln\alpha^{-1}$ with the final result being $7.0386 \pm 0.000\,16\ \mu\text{sec}^{-1}$. In addition, preliminary work (not including systematic checks) by our own[8] and another group[9] using o-Ps formation in gases has shown that the previous gas measurements must now be regarded as having given unaccountably high values.

The situation at this time, therefore, shows a clear discrepancy between theory[6] and the powder experiment[1] as well as a possible discrepancy between theory and the vacuum experiment.[2] In this Letter we report two new results which substantially change the above situation.

1. We have measured the decay rate of o-Ps formed in gases. The decay rate extrapolated to zero gas density is interpreted to be the vacuum decay rate. Our new result, including all necessary systematic tests, is $7.056 \pm 0.007\ \mu\text{sec}^{-1}$.

2. Two systematic effects have been discovered in the previous SiO_2 powder experiment. We have reinvestigated this experiment using the same setup as was previously described.[1] We now find that the decay rate extrapolated to zero powder density is in agreement with our new gas value! This brings all of the existing experimental values into agreement. As will be discussed later, we do not yet feel that the agreement with theory is satisfactory.

The new gas experiment used the same ^{68}Ge positron source and scintillator cap, electronic timing method [time-to-amplitude converter and multichannel analyzer (TAC-MCA)], prompt rejection, and initially the same NaI(Tl) γ-ray detectors as were used in the SiO_2 powder experiment.[1] Pilot B plastic detectors later replaced the NaI scintillators. A cylindrical gas chamber having a stepped internal diameter of about 18 cm was used as shown in Fig. 1. The steps provided for the stable positioning of pairs of flat end plates at separations of 10, 5, 2.5, or 1.25 cm, thus allowing for four different chamber volumes. Gas pressure was measured with a Wallace and Tiernan precision gauge with a specified accuracy of better than ±7 Torr. This gauge was calibrated against a Barocel type 511-12 electronic manometer.

The gases used were Freon-12, chosen because of its high stopping power for positrons, and isobutane, which has a cross section for positron

annihilation 30 times higher than Freon has and hence quenches the free-positron lifetime component. Isobutane permitted our o-Ps data to be analyzed as a single exponential decay, plus a background of random coincidences, even at 200 Torr. The signal-to-noise ratio (A/B), as defined in Refs. 1 and 2, ranged from 16 at 200 Torr to 75 at 1600 Torr. The data were analyzed in the manner described in Ref. 1 and yielded plots of λ versus gas density as shown in Fig. 2. The intercepts at zero gas density were obtained by least-squares fitting. In Table I we summarize the results of nine such extrapolations, each of which corresponds to a systematic check.

A serious effect seen in Table I is the systematically higher annihilation rate given by the NaI as compared to the plastic scintillator. This difference is due to the tail from the extreme wing of the prompt resolution curve which spuriously added counts to the channels at earlier times in the spectrum. Because of the uncertainty in the time distribution of these poorly resolved prompt events (extending out to 300 nsec), we consider the NaI data to be unreliable at the level of 0.010 μsec^{-1} and hence we have eliminated them from our quoted value. This effect was not observed in the earlier powder experiment because it was necessary to step the start channel of the fitting program out well beyond the prompt peak (see Ref. 1). Systematic checks of the Pilot B scintillators, including five runs with the chamber evacuated to test the flatness of the background, conclusively demonstrate the series 4–9 (Table I) are free of any prompt resolution effect.

Series 7–9 provide strong additional checks on the system linearity, the electronic rejection scheme, and our knowledge of the actual spectrum shape. In addition, careful consideration has been given to the effect of wall collisions on the o-Ps decay rate. The linearity of λ versus density does not guarantee the absence of a small wall effect at the level of 0.01–0.02 μsec^{-1}. Thus we have attempted to amplify any wall effect by reducing the chamber end-plate separation from 10 to 1.25 cm. This should increase the effect of wall collisions on the decay rate by a factor of 10. No effect was observed at the level of ± 0.009 μsec^{-1} in isobutane at 750 Torr. As an even stronger test we restored the 10-cm plate separation and filled the chamber volume with an aluminum honeycomb having a hexagonal cell size of 0.5 cm. This enhances the wall effect by a factor of 20–30 while maintaining the same chamber-detector geometry. Again no effect was observed and we conclude that the data presented in Table I are free of any wall effect down to the level of 0.001 μsec^{-1}.

Our value for λ, obtained from a weighted average of the Pilot B data and after a -0.002-μsec^{-1} correction for pressure calibration, is 7.056 ± 0.007 μsec^{-1}. The contributions to the error in λ are shown in Table II. Although we have averaged six values from Table I we have not reduced the error by $\sqrt{6}$ since each series represents a systematic test. We have taken a statistical error of ± 0.006 μsec^{-1} to be representative of the Pilot B data. An alternative approach would be to combine the errors as usual in a weighted average assuming that none of the systematic errors which we searched for were present at the level of accuracy considered. This approach yields a statistical error of ± 0.003

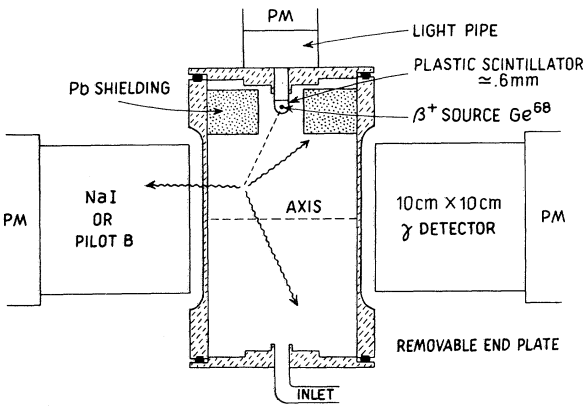

FIG. 1. Expandable gas chamber and detector arrangement.

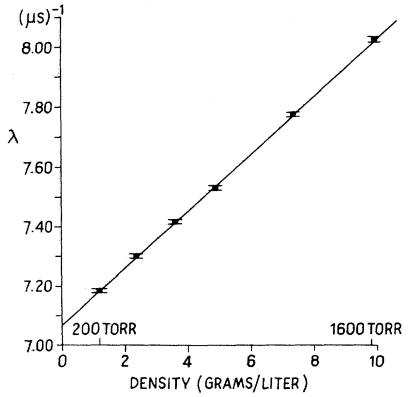

FIG. 2. Plot of decay rate versus density for a gas mixture of 80% Freon-12 and 20% isobutane. These data represent one of the nine extrapolations reported.

TABLE I. Summary of the results of nine different extrapolations to zero gas density using the 10-cm gas-chamber plate separation.

Series	Gas Pressure ratio Freon: isobutane	Scintillators	Pressure (Torr)	Extrapolated λ (μsec^{-1})	Refs. Notes
1	80:20	NaI(Tl)	200–1000	7.072 ± 0.009	a,b
2	80:20	NaI(Tl)	200–1600	7.070 ± 0.005	b
3	100:0	NaI(Tl)	200–1600	7.072 ± 0.005	b
4	80:20	Pilot *B*	400–1600	7.054 ± 0.007	
5	80:20	Pilot *B*	200–600	7.063 ± 0.008	c,d
6	0:100	Pilot *B*	200–750	7.053 ± 0.007	c,d
7	0:100	Pilot *B*	200–1600	7.058 ± 0.007	c
8	0:100	Pilot *B*	200–1600	7.058 ± 0.006	c,e
9	0:100	Pilot *B*	200–1600	7.061 ± 0.006	c,f

[a] Positron source strength 17% that of later series.

[b] Data eliminated from final value (see text).

[c] Signal-to-noise ratio increased a factor of 2 by shielding detectors from directly viewing source.

[d] Pb liner on inside chamber walls increases positron backscattering and hence improves signal-to-noise ratio by a factor of 2.

[e] TAC spectrum inverted in time by reversing the roles of the positron and γ-ray signals at the TAC. The positron signal is delayed 1.2 μsec.

[f] This series used a more effective pulse rejection criterion than the others and is insensitive to any afterpulsing in the start detector photomultiplier.

μsec^{-1} and a total error of ±0.0045 μsec^{-1}. This is the minimum possible error to be associated with the experiment; however, we quote ±0.007 μsec^{-1} as the most probable experimental error.

Because our new gas result does not agree with our previous powder result, 7.104 ± 0.006 μsec^{-1}, we have reinvestigated the powder experiment. Two serious systematic effects have been discovered. A −0.01 μsec^{-1} correction to the intercept results from systematic errors in the method of determining the powder and powder-pellet densities. It was found that the uncompressed powder compacts under evacuation and heat treatment and that the compressed powder pellet expands by approximately 4% when released from the pellet press.

TABLE II. Contributions to the error in λ, in units of μsec^{-1}.

Counting statistics	± 0.006
Virial coefficient	± 0.0025
Pressure calibration	± 0.002
Temperature of gas	negligible
Gas contamination	negligible
Wall annihilations	± 0.001
PM tube afterpulsing	± 0.001
Total (quadrature sum)	± 0.007

A second correction to the earlier powder results is due to the effect of ion afterpulsing in the positron (start signal) photomultiplier. Ions returning to the cathode of the photomultiplier can generate a second pulse (afterpulse) which occurs about 500 nsec after the initial start pulse. Afterpulsing is associated with approximately 1% of the start pulses. Such afterpulses trigger the prompt rejection system (see Ref. 1), causing it to reject erroneously some true signal events at this time. A correction of −0.01 to −0.03 μsec^{-1} is necessary based on reasonable estimates of the afterpulse intensity. The above two corrections account for the discrepancy between the gas and powder results.

To test further the agreement of our gas and powder experiments we have remeasured *o*-Ps decay rates in three different samples of SiO_2 powder using the same source and powder holder as shown in Ref. 1. Pilot *B* scintillator was used instead of NaI and the new rejection scheme of series 9, Table I, was used to eliminate any effect of afterpulsing. Two data points for each sample (one powder and one pellet) were measured and λ was plotted as a function of ρ^* (see Ref. 1). The results of these two-point extrapolations to $\rho^* = 0$ are (with statistical error only) 7.075 ± 0.008, 7.062 ± 0.012, and 7.055 ± 0.012 μsec^{-1}. Systematic uncertainties related to meas-

uring the density and guaranteeing its uniformity throughout the powder sample lead us to associate a systematic error of $\pm 0.02\ \mu\text{sec}^{-1}$ with the above results. The value of the o-Ps decay rate in the powders is then $7.067 \pm 0.021\ \mu\text{sec}^{-1}$.

We conclude that there is no discrepancy between the results of the gas and powder experiments. In addition, we do not consider the difference between our new result and our previous measurement in vacuum[2] to be significant since this earlier experiment is subject to the additional $-0.01\ \mu\text{sec}^{-1}$ systematic effect associated with the NaI detectors. We do *not*, however, consider our experimental results to be in satisfactory agreement with the theoretical value of 7.0386 $\pm 0.000\,16\ \mu\text{sec}^{-1}$. This statement is based not only on the gas result, $7.056 \pm 0.007\ \mu\text{sec}^{-1}$, but also on the giving of due consideration to the values of λ obtained in the vacuum experiment and in the recent powder experiments.

In view of the possible discrepancy noted above and because of its importance as a test of both quantum electrodynamics and the Bethe-Salpeter equation, we are continuing our experimental program on the o-Ps decay rate. We now feel that a significant decrease in error is possible so that any discrepancy between theory and experiment which our current work may be revealing will be definitely resolved.

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