

New Precision Measurements of the Decay Rates of Singlet and Triplet Positronium

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Both the singlet and triplet decay rates (λ_S, λ_T) of positronium have been measured in a new direct timing experiment based on singlet-triplet state mixing for positronium formed in isobutane gas in a magnetic field. $\lambda_S = 7.994 \pm 0.011 \text{ nsec}^{-1}$ was found, a factor of 10 improvement in accuracy and the first measurement sensitive enough to test the radiative corrections to λ_S . $\lambda_T = 7.051 \pm 0.005 \text{ } \mu\text{sec}^{-1}$ was found, in agreement with previous measurements. The combined λ_T data are not in satisfactory agreement with theory.

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Positronium (Ps), the bound state of the electron and positron, is a purely leptonic system. As such it is free of hadronic and weak-interaction effects to an accuracy well beyond current quantum electrodynamic calculations and experimental precision.¹ This feature of Ps, coupled with the fact that Ps is composed of particles of equal mass moving at velocities of order αc , makes it the most sensitive system available for testing relativistic bound-state formalism in quantum field theory.² The use and importance of Ps to test QED is of course well recognized, but of more recent interest, the field theoretic treatment of Ps is of relevance to the QCD treatment of $q\bar{q}$ bound states such as charmonium and the upsilon particle. Any discrepancies present in the Ps system, particularly if due to the theoretical treatment of the bound state, should be amplified in the QCD calculations since the QCD coupling constant is about 10 times the fine-structure constant (α). A specific calculation ($q\bar{q}$ → four gluons) and its relation to our work will be discussed below.

One of the most fundamental properties of Ps

is its annihilation into two or more photons. Comparison of the measured and calculated values of the Ps triplet and singlet decay rates (λ_T and λ_S) represents the most rigorous check of any decay-rate calculations to date. In this article we present a measurement of λ_S which is 10 times more precise than the previous value. It is the first measurement of λ_S with sufficient accuracy to test the calculated radiative corrections. We have also made a slightly improved measurement of λ_T . Our result is in agreement with three previous measurements of λ_T , all of which are 1 to 2 standard deviations higher than the theoretical value. We discuss the possible 0.2% discrepancy represented by these results later in this article.

The singlet and triplet decay rates may be expressed as

$$\lambda_S = \lambda_2 + \lambda_4 + \lambda_6 + \dots$$

and

$$\lambda_T = \lambda_3 + \lambda_5 + \lambda_7 + \dots,$$

where the subscript indicates the number of photons in the final state. The most recent calculation^{3,4} of λ_3 yields

$$\lambda_3 = \frac{2(\pi^2 - 9)}{9\pi} \frac{\alpha^6 m c^2}{\hbar} \left[1 - \frac{\alpha}{\pi} (10.266 \pm 0.011) - \frac{\alpha^2}{3} \ln \alpha^{-1} \right] = 7.0386 \pm 0.0002 \text{ } \mu\text{sec}^{-1}. \quad (1)$$

The first calculated⁵ radiative corrections to λ_2 , when added to the lowest-order decay rate, yield the result

$$\lambda_2 = \frac{1}{2} \frac{\alpha^5 m c^2}{\hbar} \left[1 - \frac{\alpha}{\pi} \left(5 - \frac{\pi^2}{4} \right) \right] = 7.9852 \text{ nsec}^{-1}. \quad (2)$$

In the last three years, there has been renewed interest in checking λ_2 , in part as a result of the large shifts in both λ_3 and λ_T (see Ref. 1) as well as the presently unsatisfactory agreement between them. The above calculation of λ_2 has been inde-

pendently verified by three groups⁶⁻⁸ and has been extended³ to include a term $\frac{2}{3}\alpha^2 \ln(\alpha^{-1})$ in the square-bracketed expression above. In addition, very recent calculations⁹ of λ_4 have been completed as a consequence of the work on $q\bar{q}$ → four gluons. As expected λ_4 is negligibly small compared to λ_2 ($\lambda_4 \sim 10^{-6}\lambda_2$). Experimental determination of λ_S has lagged far behind theory because singlet Ps decays too rapidly for a precision direct measurement of the decay rate. The only published measurement¹⁰ of λ_S at a precision approaching 1% yielded the value 7.99 ± 0.11

nsec⁻¹ and was obtained indirectly from determination of an rf resonant linewidth in connection with a Ps hyperfine-splitting measurement. This measurement was not sufficiently precise to test the calculated 0.6% radiative corrections to λ_2 . In this Letter we report the results of a new experimental technique that has yielded $\lambda_S = 7.994 \pm 0.011$ nsec⁻¹ and $\lambda_T = 7.051 \pm 0.005$ μ sec⁻¹.

In the present experiment, Ps is formed in isobutane gas in a uniform magnetic field, B . The magnetic field mixes the $m = 0$ triplet and singlet states (the $m = \pm 1$ states are unaffected) such that the field-perturbed triplet eigenstate, $\psi_{T'}$, has a vacuum decay rate¹¹

$$\lambda_{T'} = (1 - b^2)\lambda_T + b^2\lambda_S, \quad (3)$$

where $b^2 = y^2 / (1 + y^2)$, $y = x / [1 + (1 + x^2)^{1/2}]$, and

$$x = 2g'\mu_0 B / (E_T - E_S) = B(\text{kG}) / 36.287.$$

Here, $g' \simeq g(1 + \frac{5}{24}\alpha^2)$ and $E_T - E_S$ is the Ps hyperfine energy splitting at zero field. Values of λ_T and $\lambda_{T'}$, measured at various gas pressures from 200 to 1400 Torr, are linearly extrapolated (in density) to zero gas density. This procedure directly yields a new measurement of the triplet decay rate with slightly improved precision over previous measurements. Our major result, however, is that determination of $\lambda_{T'}$, λ_T , and B (i.e., b) allows us, through use of Eq. (3), to obtain λ_S with sufficient accuracy to test the 0.6% radiative corrections rigorously.

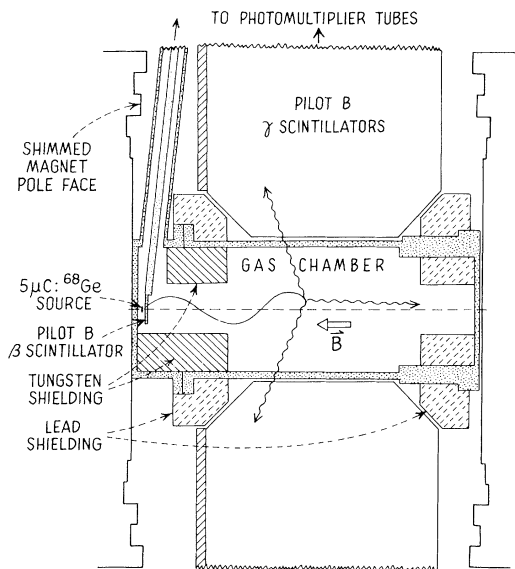


FIG. 1. The gas chamber and detector arrangement.

The apparatus is shown schematically in Fig. 1. The 3-in.-diam (8-cm-diam) gas chamber is located between the poles of a 12-in. (30-cm) Varian NMR electromagnet which has been shimmed to produce a field homogeneous to 400 ppm over an axial distance of 7.5 in. (19 cm).¹² Positrons from a 5- μ Ci ⁶⁸Ge-⁶⁸Ga source pass through a 0.020-in. (0.5 mm) Pilot B plastic scintillator (which is coupled by light pipe to an Amperex XP2020 photomultiplier) and are constrained to the axial region of the chamber by the applied 4-kG magnetic field. Gamma rays from the subsequent decay of Ps or free e^+e^- annihilation are detected in a 12-in.-diam (30-cm-diam) annular ring of Pilot B scintillator coupled to four RCA 4522 photomultipliers by 30-in.-long (76-cm-long) light pipes. The time resolution for each detector is less than 2 nsec. The γ signal ($\approx 5 \times 10^3$ counts/s) and a 1- μ sec cable-delayed β signal (10^5 counts/s) provide the start and stop signals, respectively, to a Hewlett-Packard 5345A digital timer¹³ which has been interfaced to a Nuclear Data 2200 MCA memory. This inverted time spectrum, together with the rejection of prompt events (β - γ coincidence within 20 nsec), is necessary to reduce dead-time pileup at the digital timer.

Each spectrum after being reinverted in time was fitted by using a five-parameter maximum-

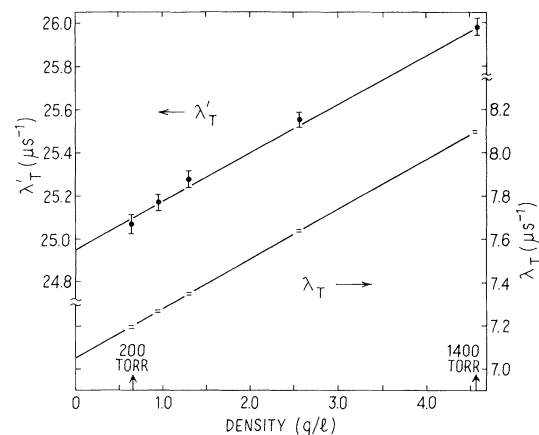


FIG. 2. Triplet decay rates measured at various isobutane gas densities in an applied magnetic field of 3.4432 kG. Fitting by a straight line yielded $\chi^2 = 1.5$ and 0.2 (3 degrees of freedom) for the $\lambda_{T'}$ and λ_T data, respectively. For completeness we note that the fitted slopes of the $\lambda_{T'}$ and λ_T data, averaged for all three magnetic fields, are in agreement as expected; i.e., 0.236 ± 0.007 and 0.229 ± 0.001 μ sec⁻¹/(g/l), respectively.

likelihood program with the functional form

$$N(t) = A \exp(-\lambda_T' t) + B \exp(-\lambda_T t) + C. \quad (4)$$

This expression approximates the actual lifetime spectrum to an accuracy sufficient for this experiment as verified by a detailed investigation of the effects of discriminator dead time, high count rates, random coincidences, and prompt rejection. The fitting program steps out the starting channel of the fit in 8-nsec intervals from $t = 22$ to 110 nsec. For $t \geq 38$ nsec the χ^2 of the fit is observed to be equal to the number of degrees of freedom and the fitted decay rates at $t = 46$ nsec are taken to be the measured values of λ_T' and λ_T at each gas density.

Typically, in 2 days of running, 2×10^8 events were acquired in each lifetime spectrum and four spectra were acquired at each of four or five different gas pressures between 200 and 1400 Torr (see Fig. 2). Pressure was measured with a Baratron 170M-6B capacitive manometer. Both the chamber pressure and temperature were monitored on an hourly basis and the gas density was then calculated with the assumption of a first virial coefficient of $-(600 \pm 80) \text{ cm}^3/\text{mole}$ for isobutane.¹⁴ The results of linear extrapolation to zero density are summarized in Table I for each of the three magnetic fields used.

Our value for λ_S obtained from a weighted average of the three values in Table I is $7.994 \pm 0.011 \text{ nsec}^{-1}$, a factor-of-10 improvement in accuracy over the previous result and in good agreement with the theoretical value. Our value for λ_T is $7.051 \pm 0.005 \text{ } \mu\text{sec}^{-1}$. It is in agreement with previous measurements^{15,16} in gases, 7.056 ± 0.007 and $7.045 \pm 0.006 \text{ } \mu\text{sec}^{-1}$, and a direct measurement¹³ of λ_T in vacuum, $7.050 \pm 0.013 \text{ } \mu\text{sec}^{-1}$. We do not consider the λ_T data as a whole to be in

satisfactory agreement with theory [Eq. (1)].

Contributions to the error in λ_S and λ_T are shown in Table II. The statistical error for λ_S in Table II is a representative statistical error associated with each value in Table I. We have not reduced the error by $\sqrt{3}$ because acquiring data at different magnetic fields is a systematic test of possible field-dependent effects. For example, the field profile and the positron stopping profile throughout the Ps formation region are different for each value of B , affecting our magnetic field monitoring and field averaging technique. Also, the field-perturbed lifetime varied between 28 and 40 nsec. Consistency in the derived value of λ_S indicates that deviations from Eq. (4) are indeed negligible at the present level of accuracy.

We have treated the statistical error in λ_T in the same manner as described above except that the representative statistical error has been taken to be the rms deviation ($0.004 \text{ } \mu\text{sec}^{-1}$) of the three values of λ_T in Table I because of the slightly overdispersive nature of the data. No field-dependent trends are observed in λ_S or λ_T . Errors associated with pressure, temperature, and magnetic field monitoring are virtually eliminated by the use of a precision capacitive manometer, a precision thermistor thermometer, and a digital NMR gaussmeter. The effects of gas contamination and Ps annihilations at the chamber wall were studied quantitatively in Ref. 14 and are negligible in this experiment.

In summary, we have measured both the singlet and triplet decay rates of Ps in a new kind of direct timing experiment based on singlet-triplet state mixing in a magnetic field. At the 0.14% level λ_S is found to be in agreement with theory. However, as was discussed above, we feel that

TABLE I. Results of extrapolation to zero gas density for λ_T and λ_T' , and the derived value of λ_S using Eq. (3). The statistical error in the last displayed significant figure is shown in parentheses while the error shown for the weighted averages represents the total experimental uncertainty (see Table II).

B (kG)	λ_T (μsec^{-1})	λ_T' (μsec^{-1})	λ_S (nsec $^{-1}$)
3.4432	7.051(3.8)	24.95(3)	8.013(13)
4.1054	7.046(2.4)	32.31(3.5)	7.980(11)
4.3310	7.056(2.6)	35.20(4)	7.994(11)
Wt. avg.	7.051 ± 0.005		7.994 ± 0.011
Theory	7.0386		7.9852

TABLE II. Contributions to the error in λ_S and λ_T in units of μsec^{-1} .

	λ_S	λ_T
Statistics	11	0.004
Pressure measurement	0.5	0.001
Virial coefficient	1.0	0.002
B measurement	1.2	...
Temperature variations	negligible	negligible
Gas contamination	negligible	negligible
Wall annihilation	negligible	negligible
Total (quadrature sum)	11	0.005

the λ_T data as a whole do not agree with the calculated value of λ_3 . To resolve the unsatisfactory agreement between λ_T and λ_3 , we have initiated a new measurement of λ_T , which should reach an accuracy of 200 ppm, using a modified version of the present apparatus.

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Nonlocal Gauge Theories

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From a generalization of the covariant derivative, nonlocal gauge theories are developed. These theories enjoy local gauge invariance and associated Ward identities, a corresponding locally conserved current, and a locally conserved energy-momentum tensor, with the Ward identities implying the masslessness of the gauge field as in local theories. Their ultraviolet behavior allows the presence as well as the absence of the Adler-Bell-Jackiw anomaly, the latter in analogy with lattice theories.

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There exists at present an impressive body of evidence supporting the relevance of the gauge principle to the description of particle interactions. Currently, the greater part of the theoretical effort in extending the standard model to a more fundamental theory is concerned with the problems of mass hierarchy and family repetition.¹ The present work was motivated by the idea that a suitable generalization of gauge field theories which could enrich their structure while retaining the underlying gauge principle may lead to a resolution of these problems. Nonlocal

gauge theories (NLGT) are promising candidates for this generalization insofar as they are effectively equipped with a continuum of mass scales *ab initio* and in a gauge-invariant way. However, regardless of how relevant these considerations turn out to be, we find NLGT's quite interesting and worthy of serious study in their own right.² Specifically, the theories developed here (a) have a unique structure based on local gauge invariance and a locally conserved current, (b) have a locally conserved energy-momentum tensor, (c) naturally reduce to their local counter-