New Precision Measurement of the Decay Rate of Singlet Positronium

A. H. Al-Ramadhan and D. W. Gidley
Physics Department, University of Michigan, Ann Arbor, Michigan 48109
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The singlet decay rate has been measured using magnetic singlet-triplet state mixing for positronium formed in a N_2-isobutane gas mixture. We find $\lambda_S = 7990.9 \pm 1.7\ \mu s^{-1}$. At 215 ppm this result is 6.5 times more accurate than the previous measurement [D. W. Gidley, A. Rich, E. Sweetman, and D. West, Phys. Rev. Lett. **49**, 525 (1982)] and is the first measurement sensitive enough to test the relative order $\alpha^2 \ln \alpha$ term in the singlet decay rate calculation.

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Positronium (Ps), the purely leptonic atom of the electron and positron, is an attractive system to test relativistic bound state quantum electrodynamics (QED) calculations, especially the ground state triplet and singlet annihilation decay rates, λ_T and λ_S. There are two measurements of λ_T, each at the 200 ppm level, that are 9σ (1900 ppm) [1] and 6σ (1400 ppm) [2] above the theoretical value [3,4]. This discrepancy has attracted both experimental and theoretical attention to consider exotic decay modes of orthopositronium (o-Ps) into axions [5], noninteracting particles [6] (e.g., millicharged particles [7]), momentum violating modes [8], and even mirror universes [9]. There is only one precision measurement of λ_S [10], but, at 1400 ppm, it is not precise enough to determine whether a comparable discrepancy exists. This is unfortunate because the theoretical calculation is more straightforward than it is for λ_T, and indeed when the second order radiative corrections are calculated they may resolve the λ_T difference. These calculations are underway [11–13] and there is some indication [11,12,14,15] that these corrections could be large for λ_T. We would expect the simpler second order corrections to λ_S to be calculated first, thus permitting a rigorous test of QED at the best experimental precision attainable. In this Letter we report a new measurement of λ_S with 215 ppm precision, a factor of 6.5 improvement over the previous result and comparable to the best measurements of λ_T.

The singlet decay rate may be expressed as

$$\lambda_S = \lambda_2 + \lambda_4 + \lambda_6 + \cdots, \tag{1}$$

where the subscript is the number of photons in the final state. The singlet can decay only to an even number of photons due to the charge conjugation symmetry. All but the two photon term are negligible at the present level of accuracy, e.g., $\lambda_4 \simeq 1.3 \times 10^{-6} \lambda_2$ [16]. Thus,

$$\lambda_S \simeq \lambda_2 = \lambda_{02}\left[1 + A\left(\frac{\alpha}{\pi}\right) + B\alpha^2 \ln \alpha^{-1} + C\left(\frac{\alpha}{\pi}\right)^2 + \cdots\right], \tag{2}$$

where $\lambda_{02} = \frac{1}{2}\frac{mc^2}{\hbar}\alpha^5 = 8032.5\ \mu s^{-1}$ [17]. The first order radiative correction coefficient is $A = -(5 - \frac{\pi^2}{4}) = -2.533$ [18,19]. It produces a -5880 ppm correction. The coefficient B has been recently calculated to be 2 [20] in disagreement with an earlier value of $\frac{2}{3}$ [3]. Thus λ_S=7989.5 μs^{-1} or λ_S=7986.7 μs^{-1}, respectively, a difference of 350 ppm. The coefficient C due to the second order radiative corrections is not calculated yet and could contribute $\pm 0.4\ \mu s^{-1}$ (50 ppm) if $C = 10$. It is this term in the o-Ps calculation that needs to be around 240 ± 40 to resolve the difference between theory and experiment.

The lifetime of singlet Ps ($\lambda_S^{-1} \sim 0.125$ ns) is too short for a direct precision measurement. However, by applying a magnetic field the $m = 0$ states of $n = 1$ Ps mix and the ($m = 0$) triplet state, o-Ps′, is quenched by this mixing. To better than 8 ppm accuracy the o-Ps′ decay rate is [21]

$$\lambda'_T = (1 - b^2)\lambda_T + b^2 \lambda_S, \tag{3}$$

where $b^2 = \frac{y^2}{1+y^2}$, $y = \frac{x}{1+(1+x^2)^{1/2}}$, and $x = \frac{2g'\mu_0 B}{E_T - E_S}$. Here $g' = g(1 - \frac{5}{24}\alpha^2)$, and $E_T - E_S$ is the Ps hyperfine energy splitting at zero field. Typically $\lambda'_T \sim 30\ \mu s^{-1}$ at $B = 4$ kG. Therefore, λ_S is determined from Eq. (3) by precisely measuring λ'_T and λ_T and knowing the average magnetic field experienced by Ps.

This experiment represents a major improvement in the technique presented in Ref. [10]. The apparatus consists of a 3 inch diameter gas chamber located between the poles of a 12 inch Varian NMR electromagnet (see Fig. 1). Positrons from a 5 μCi ^{68}Ge-^{68}Ga source pass through a 0.020 inch plastic scintillator which is coupled by a Lucite light pipe to an Amperex XP2020 photomultiplier tube (PMT). The γ rays from the subsequent decay of Ps or free e^+-e^- annihilation are detected in a 12 inch diameter annular ring of Pilot B plastic scintillator coupled by 30 inch long light pipes to four Hamamatsu R1250 PMT's. The spectrum is a histogram of the time intervals between these two signals. To improve the statistical accuracy, which was the major source of uncertainty in the previous experiment, we increased the positron-stopping power of the gas by using N_2 at high pressure (2–10 atm) with a small admixture of isobutane [1]. To accomodate the higher data rates (150 kHz start, 25 kHz stop) we have replaced the 5 kHz time digitizer [10] with a fast (1 MHz) CAMAC digitizer (LeCroy model

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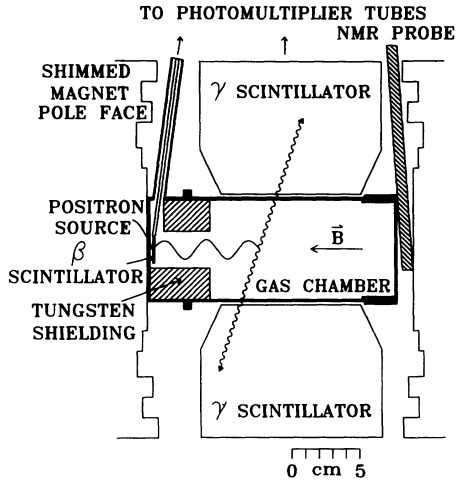

FIG. 1. The gas chamber and detector arrangement.

4204). As a result the data rate in the lifetime spectrum is now typically 10 times higher than that in the 1982 experiment. To reduce the uncertainty in the magnetic field determination an NMR probe was inserted as shown in Fig. 1 to permit continuous monitoring of the field.

The gases used are premixed, certified standards of N_2 with a small percentage of isobutane. The partial pressure ratios of isobutane used are 4%, 8%, 12%, and 16%. The gas in the chamber is changed every four days and a typical run requires one month. The spectra are acquired at two different values of the magnetic field, 4.25 kG and 3.75 kG, and at total gas pressures of 1500–8000 Torr.

At a given gas pressure the lifetime spectrum (after a straightforward correction for the stop rate [22]) is fitted using a five parameter maximum likelihood program with the functional form

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

The starting channel of the fit is stepped out in 5 ns (one channel) intervals from $t = 15$ to 110 ns. For $t \geq 30$ ns the χ^2 of the fit typically equals the number of degrees of freedom and the fitted decay rates at $t = 30$ ns are taken to be the measured values of $\lambda_T(\rho)$ and $\lambda_T'(\rho)$ at that gas density. We calculate a quantity Λ defined as

$$\Lambda(\rho) = \frac{\lambda_T'(\rho) - \lambda_T(\rho)}{b^2} + \lambda_T(0), \quad (5)$$

where ρ is the density of the gas and $\lambda_T(0) = \lambda_T$ the vacuum triplet decay rate $\lambda_T = 7.0482(16)\ \mu s^{-1}$ obtained from Ref. [2]. From Eq. (3) $\Lambda(\rho = 0) = \lambda_S$ [actually $\Lambda(0)$ is 10 ppm smaller than λ_S [21]]. Thus we could determine λ_S by extrapolation to zero density. However, we know from Ref. [1] that $\lambda_T(\rho)$ is linear in ρ over a large range of gas pressure. Thus, we can assume that

$$\lambda_T(\rho) = \lambda_T + m\rho \quad (6)$$

and

$$\lambda_T'(\rho) = \lambda_T' + m'\rho, \quad (7)$$

where m and m' are the gas quenching rates for o-Ps and o-Ps′. We will show that to high accuracy $m = m'$, and thus the determination of Λ at each gas density represents a measurement of λ_S. We have therefore biased our data acquisition to higher gas densities for better statistical accuracy in λ_S and we have varied the isobutane admixture as a systematic test. As a result we are not able to concomitantly make a precision determination of λ_T using Eq. (6), which requires more data at low gas density and with a constant mixing ratio [23]. Instead we use the fitted values of $\lambda_T(\rho)$ [which have error bars 10 times smaller than $\lambda_T'(\rho)$] as a sensitive indicator of any gas-related systematic effects, e.g., contamination and collisional effects.

There are three systematic effects that are the direct result of using a gas as the positronium formation target. First, positrons that have collisionally fallen below the N_2 Ps formation threshold energy can live long enough to disrupt the fitting at $t = 30$ ns. To quench these slow positrons isobutane is mixed with the gas and a partial pressure of at least 100 Torr is required [1]. A second pressure-dependent effect has to do with the thermalization time of Ps. At the lowest gas pressure used (1500 Torr) we observed a small but significant decrease in the fitted value of λ_T as the start channel of the fit was stepped out to $t = 60$ ns (at which point the Ps collision rate is presumably constant). At 3000 Torr the fitting is stable for $t \geq 30$ ns. We account for both of these effects, slow positrons and Ps thermalization, by suitable selection of the total pressure, isobutane fraction, and the start channel of the fitting program. At or above 3000 Torr both effects are negligible for $t \geq 30$ ns. The third gas-related systematic has to do with the density dependence of $\Lambda(\rho)$ and hence the equality of m' and m. This will be considered later.

With the improved data rates of this experiment there is a significant probability that two or more Ps atoms are formed after a start signal is initiated. To properly account for double-Ps events it is necessary to add three small rate-dependent terms to Eq. (4) such that

$$N(t) = A' \exp(-\lambda_T' t) + A \exp(-\lambda_T t) + B + C_{00} \exp(-2\lambda_T' t) + C_{10} \exp[-(\lambda_T + \lambda_T')t] + C_{11} \exp(-2\lambda_T t), \quad (8)$$

where $C_{ij} = -TR_iR_j\left(\frac{\lambda_i+\lambda_j}{\lambda_j}\right)$, and i or j is 0 for o-Ps′ or 1 for o-Ps. T is the time of the measurement. R_i and λ_i are the detected data rate and decay rate of the corresponding state. The three components correspond to two coincident Ps atoms that are in any combination of the two states. They are too small in intensity to be fitted for di-

rectly. Instead we simulate the spectrum in Eq. (8) and fit Eq. (4) to it to determine the effect on λ_T' and λ_T. The resulting correction to $\Lambda(\rho)$ ranges from +50 ppm to +120 ppm with an average effect of +75 ppm on λ_S. We conservatively estimate the error in this correction to be about 40%, or ±30 ppm in λ_S.

The magnetic field is not uniform throughout the gas chamber, but varies by ±500 ppm along the axis and by ±1900 ppm at 1 inch from the axis. The weighted average field experienced by Ps can, however, be determined much more precisely. For each value of the magnetic field, the magnetic field profile along the axis, $\pm\frac{1}{2}$ inch and ±1 inch off axis were measured along with the value of the field at the NMR probe position. Since λ_T' depends quadratically on the magnetic field, we determine a weighted rms field value using the measured profiles and a weighting function that is the product of a pressure-dependent, exponential, positron-stopping profile and a measured gamma-ray detection efficiency profile. The rms field is not very sensitive to either of these profiles. We estimate that the uncertainty in λ_S attributable to this averaging process is ±60 ppm, which is mostly due to the field inhomogeneity at 1 inch off the axis.

Measurements of λ_T', λ_T, and hence Λ were made at seven different gas densities at $B = 4.25$ kG and at two densities at $B = 3.75$ kG. $\Lambda(\rho)$ is plotted in Fig. 2 after correction for double-Ps events. Since there is no obvious effect of the two different magnetic fields, we fitted all nine values to a straight line in density. The zero-density intercept is 7990.3 ± 3.1 μs^{-1} and the χ^2 of the fit is an acceptable 9.1 for 7 degrees of freedom. More importantly the fitted slope, 4.0 ± 11 μs^{-1} mole^{-1} liter, is consistent with zero and hence $m' = m$ in Eqs. (6) and (7). If we had no independent information on the equality of m' and m, we would then be limited to the 390 ppm statistical accuracy of the above intercept. The only condition under which we would expect $m' > m$ is if Ps in a magnetic field can collisionally quench by spin exchange with an unpaired molecular electron [24]. In this case o-Ps$'$ is quenched by spin exchange transitions to the three other magnetic substates while the field unperturbed o-Ps states are quenched by only the two transitions to $m = 0$ magnetic substates. Although unexpected in the gases used, we can sensitively search for spin exchange quenching using the high precision obtained in fitting $\lambda_T(\rho)$. We do this by looking for a decrease in $\lambda_T(\rho)$ when the magnetic field is turned off. At $B = 0$ spin exchange quenches the triplet state only if transitions to the singlet state occur. In the field quenching of the $m = \pm 1$ magnetic substates is doubled by spin exchange to the $m = 0$ triplet substate. We searched for such an effect at high gas pressure (7000–9500 Torr) in two different mixtures by collecting field on (or off) data on alternating days over a two week period. The difference in the fitted values of $\lambda_T(\rho)$ (field on-off) showed a marginal effect that would produce a 90±90 ppm increase in Λ at high density (and corresponds to a slope of 1.8±1.8 μs^{-1} mole^{-1} liter in Fig. 2). Therefore, we have taken a simple weighted average of $\Lambda(\rho)$ and made a density-averaged, spin exchange correction of −50±50 ppm (assuming the effect is linear in density). The result, with statistical error only, is λ_S=7990.9±1.0 μs^{-1}.

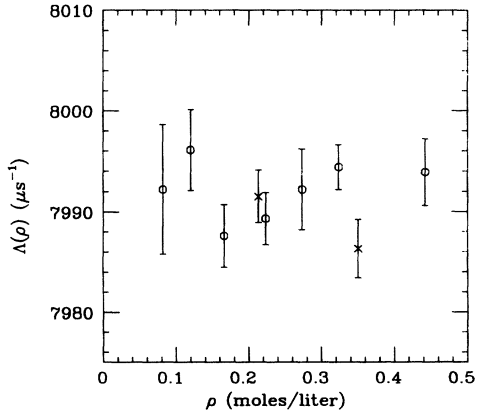

FIG. 2. A plot of the measured $\Lambda(\rho)$, as defined in Eq. (5), in N_2-isobutane gas mixtures after correction for double-Ps events (see text). The × symbol is for data taken at $B = 3.75$ kG and ○ symbol is for data taken at $B = 4.25$ kG. The density range shown corresponds to pressures of approximately 2–10 atm.

The contributions to the overall experimental error are listed in Table I. The averaging of all nine measurements produces a high statistical precision of 125 ppm that cannot be fully realized because of a systematic uncertainty in the differential linearity of the lifetime spectrum. This arises from our inability to precisely determine and guarantee the stability of the 5.0 ns width of each individual channel in the time digitizer. The effect was observed in three high statistics spectra as a χ^2 of about 250–300 for 200 degrees of freedom (with no trend in the residuals). In each case the χ^2 becomes acceptable by reducing the channel-width precision, an effect that corresponds to the quadrature addition of an uncertainty of 150 ppm. Our final result, at 215 ppm precision, is λ_S=7990.9±1.7 μs^{-1}. To compare with theory, Eq. (2), our result can be considered a measurement of the coefficient B (neglect-

TABLE I. Sources of experimental error.

Statistical	±125 ppm
Time calibration	±25 ppm
Differential linearity	±150 ppm
Slow e^+	negligible
Ps thermalization	negligible
Multiple Ps effects	±30 ppm
Spin exchange	±50 ppm
NMR gaussmeter	±10 ppm
B field averaging	±60 ppm
Total error	±215 ppm

ing C). We determine $B = 2.7 \pm 0.8$. If $C < 10$ [14] then there is a maximum error in this result of only ± 0.2. Our measurement is in good agreement with the higher [20] calculated value of $B = 2$.

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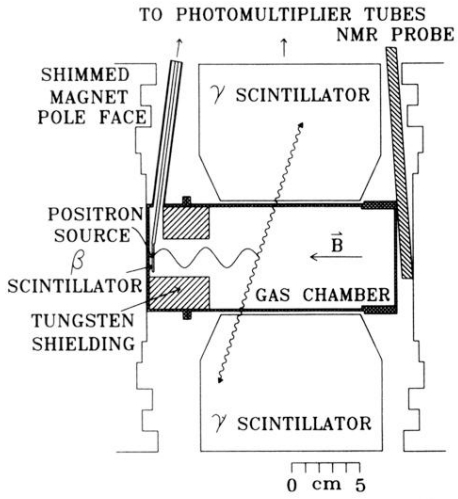

FIG. 1. The gas chamber and detector arrangement.