Positronium Decay Rates

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1. Introduction

In this paper we briefly review all positronium (Ps) decay rate measurements (including those of the excited states and the Ps negative ion) that have been completed to date. The results are compared with theoretical values. The Ps system represents the most rigorous confrontation with theoretical decay rate calculations for any QED system.

2. Measurement of the 1^3S_1 decay rate of Ps In a recent publication [1], a new 200 ppm measurement of the vacuum decay rate, λ_T of triplet Ps formed in a gas was presented. The result, $\lambda_T = 7.0516 \pm 0.0013 \mu s^{-1}$, represents a factor of four improvement over previous measurements and is in substantial agreement with existing experimental results, the most recent of which are (see bibliography in reference 1) $7.056 \pm 0.007 \mu s^{-1}$, $7.045 \pm 0.006 \mu s^{-1}$, $7.051 \pm 0.005 \mu s^{-1}$, and $7.050 \pm 0.013 \mu s^{-1}$. These latter values are all 1-2.5 standard deviations above the present theoretical value and the new measurement exceeds theory by 10 experimental standard deviations.

The theoretical value of λ_T may be expressed as the sum of decay rates into three gammas (λ_3), five gammas (λ_5), *etc.*: $\lambda_T = \lambda_3 + \lambda_5 + \ldots$. The contribution of λ_5 has been calculated [2], [3] to be $\lambda_5 \sim 10^{-6} \lambda_3$, and is thus negligible. The leading term is:

$$\lambda_3 = \frac{\alpha^6 mc^2}{\hbar} \frac{2(\pi^2 - 9)}{9\pi} \left[1 + A_3\left(\frac{\alpha}{\pi}\right) - \frac{1}{3}\alpha^2 \ln \alpha^{-1} + B_3\left(\frac{\alpha}{\pi}\right)^2 + \ldots \right]. \tag{1}$$

The two most recent calculations give $A_3 = -10.266 \pm 0.011$ [4] and $A_3 = -10.282 \pm 0.003$ [5]. The coefficient B_3 is still uncalculated, and one obtains through order $\alpha^2 \ln \alpha$, $\lambda_3 = 7.03830 \pm 0.00005 \mu s^{-1}$ [$1 \times (\alpha/\pi)^2$ adds only 0.00005 μs^{-1} to λ_3]. If one assumes that the disagreement between the theoretical and experimental values of λ_T is due

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to the $(\alpha/\pi)^2$ term, then $B_3 = 340 \pm 33$ is required to bring theory and experiment into agreement. We note here that it may be more appropriate [6] to write the second order term as a coefficient times α^2 rather than $(\alpha/\pi)^2$, so that the (still rather large) coefficient of 34 would explain the difference. Exotic, non-QED decay modes of o-Ps have been considered [7], [8] to account for the discrepancy but recent axion searches place severe restrictions on such decays [9].

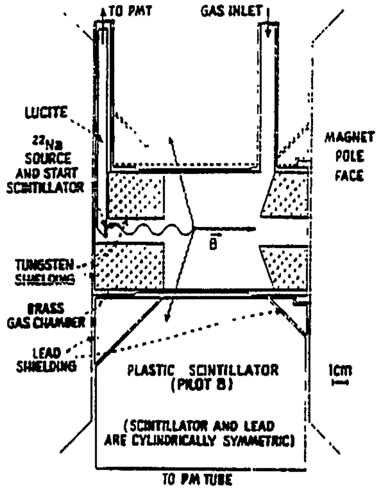

Fig. 1. The gas-filled Ps formation chamber and detector arrangement.

In the experimental technique used in our new measurement [1] Ps is formed in a gas in a magnetic field of 6.8 kG (Fig. 1). The field confines positrons to the axis of the chamber and reduces the $1^3\mathrm{S}_1(m=0)$ lifetime to 13 ns. The $1^3\mathrm{S}_1(m=\pm 1)$ states are unperturbed and continue to decay in the field with a rate, λ, which depends on the particular gas and its density. The decay rate is determined by fitting of the annihilation lifetime spectrum and λ_T is then determined by extrapolating λ to zero gas density. The results of this extrapolation are: isobutane $7.0524 \pm 0.0013\ \mu\mathrm{s}^{-1}$, neopentane $7.0551 \pm 0.0026\ \mu\mathrm{s}^{-1}$, nitrogen $7.0487 \pm 0.0018\ \mu\mathrm{s}^{-1}$, and neon $7.0501 \pm 0.0023\ \mu\mathrm{s}^{-1}$ with the weighted average value being $7.0514 \pm 0.0013\ \mu\mathrm{s}^{-1}$. The uncertainty is obtained from the isobutane result with the other gases treated as systematic tests.

The measurement of λ_T has included extensive systematic tests [1]. These include: i) measurement of λ_T to at least $\pm 0.0026\ \mu\mathrm{s}^{-1}$ (350 ppm) in four different gases, ii) use of two independent digital timing systems with, and without, electronic noise rejection, iii) use of different positron source strengths to search for effects related to the signal-to-noise ratio. A detailed discussion of possible systematic errors related to physical effects in the gases has been published [10]. The most important of such effects include: 1) any non-linearities in λ vs. gas density, 2) formation of long-lived excited states of Ps, and, 3) incomplete thermalization of Ps that could result in time dependent collisional quenching ("pickoff") of Ps. With these systematics in mind we have recently performed an extrapolation of λ vs. gas density using only high density (pressure greater than one atmosphere) N_2 and Ne gases where Ps thermalization and excited state quenching should be rapid. Using only our data with $P > 1$ atmosphere and published [11] high pressure data for N_2 (7-36 atmospheres) and Ne (7-39 atmospheres) we extrapolate to zero density to find $\lambda_T = 7.0491 \pm 0.0021\ \mu s^{-1}$ and $7.0483 \pm 0.0029\ \mu s^{-1}$ respectively. The close agreement of these values with the values measured entirely below two atmospheres is a strong systematic check on the gas related effects mentioned above.

All of the systematic tests [1, 10] to date support the results of reference [1]. The 1900 ppm difference with theory remains unresolved at this time. A new and systematically very different experiment designed to reach ~ 100 ppm accuracy [12] using a slow positron beam with Ps formation in an evacuated cavity is now underway. Results are expected within one year.

3.Measurement of the 1^1S_0 Ps Decay Rate There is only one precision measurement of the singlet ground state (parapositronium) decay rate [13] with sufficient accuracy to test the first order radiative connections to λ_S. The singlet decay rate may be expressed as $\lambda_S = \lambda_2 + \lambda_4 + \lambda_6 \ldots$. Since $\lambda_4(\sim 1.5 \times 10^{-6}\lambda_2)$ is small, [3, 14] we need only concentrate on λ_2 in the present discussion. The expression [4] for λ_2 is:

$$\lambda_2 = \frac{mc^2}{2\hbar}\alpha^5\left[1 + A_2(\frac{\alpha}{\pi}) + \frac{2}{3}\alpha^2\ln\alpha^{-1} + B_2(\frac{\alpha}{\pi})^2\ldots\right] \tag{2}$$

where $A_2 = -(5 - \pi^2/4) = -2.532$ and B_2 is, as yet, uncalculated. Through order $\alpha^2\ln\alpha^{-1}$ the decay rate is $\lambda_2 = 7.9866\ \text{ns}^{-1}$ [$1 \times (\alpha/\pi)^2$ would add $0.0004\ \text{ns}^{-1}$].

In the experiment, Ps is formed in isobutane gas in a uniform magnetic field of about 4 kG (the experimental arrangement is almost identical to that shown for λ_T in

Fig. 1). The magnetic field mixes the m= 0 triplet and singlet states and, as a result, the m= 0 triplet decay rate is increased to

$$\lambda'_T = \frac{1}{1+y^2}\lambda_T + \frac{y^2}{1+y^2}\lambda_S \quad ,$$

$$\text{where} \qquad y = \frac{x}{1+\sqrt{1+x^2}}, \text{ and } x = \frac{2g'\mu_B B}{h\Delta\nu} \approx \frac{B(kG)}{36.287} \quad . \tag{3}$$

Thus the annihilation lifetime spectrum has two exponential components: the unperturbed decay from the m= ±1 states; and the "quenched" decay from the m= 0 state (at 4 kG the lifetime is about 30 nsec). Measurement of these decay rates, λ_T and λ'_T, at gas pressures ranging from 200 – 1400 torr allows one, after extrapolation to zero gas density, to solve (3) for λ_S. Measurements were made at three different magnetic fields and the average result is $\lambda_S = 7.994 \pm 0.011$ nsec^{-1}, in agreement with the λ_2 calculation at the 1400 ppm level.

Considering the 1900 ppm difference between the measured value of λ_T and λ_3, it would be interesting to measure λ_S at comparable precision ($\sim$ 200 ppm). The current $\lambda_S - \lambda_2$ difference is (1100 ± 1400) ppm and cannot distinguish such an effect. A measurement at the 200 ppm level would be of immediate interest since the computationally simpler B_2 will probably be calculated before B_3. We will shortly begin construction of a λ_S experiment that is designed to reach the 200 ppm level of precision.

4. Measurement of the Ps$^-$ Decay Rate The Ps negative ion, consisting of two electrons and one positron, is a relatively simple system for testing many-electron calculational schemes [15]. There is recently additional interest in measuring the ground state decay rate of Ps$^-$, Γ, [16] to see if the 1900 ppm discrepancy surrounding λ_T enters into Γ by way of λ_S. Approximately 98% of Γ is given simply by the spin average, $\Gamma \approx 0.25\lambda_S + 0.75\lambda_T$. Thus, if there is a sizable discrepancy in λ_S (see previous discussion) it would show up at the same level in Γ.

The best theoretical value [17, 18] of Γ is 2.0861 ns^{-1}. This two photon, Hylleras-type calculation also includes order-α corrections for 3-photon annihilation and 2-photon radiative corrections [17].

The Ps$^-$ ion was first observed by Mills [19], who has reported the only measurement of Γ to date [20]. In this experiment, Ps$^-$ is formed on a thin carbon film and accelerated by applying a constant potential, V, to two grids separated by a distance, d. Measurements of the number of ions reaching the second grid as a function of d (and hence the proper time since Ps^- emission) yields $\Gamma = 2.09 \pm 0.09\ ns^{-1}$. A remeasurement [16] of Γ using an improved variation of this time-of-flight technique is presently underway with the goal of achieving 1000 ppm accuracy.

5. Measurement of the Radiative Decay Rate of Ps in the 2^3P_J (J = 0, 1, 2) States

The radiative decay rate γ of 2^3P_J Ps was measured as a byproduct of an experiment [21] to determine the frequency intervals ν_J between the 2^3S_1 and 2^3P_J states (J=0,1,2). The 2^3P_J states decay to the 1^3S_1 state by emission of a Lyman-α photon at 243 nm. To lowest order in α, the expected decay rate

$$\gamma = 1/\tau = \frac{5\pi}{64}\alpha^3\frac{Ry}{h} = 313.8\mu s^{-1} \tag{4}$$

is half that for the corresponding transition in hydrogen.

In this experiment Ps in the 2^3S_1 state is irradiated with microwaves of varying frequency and a resonant increase in 2^3P_J states is observed as the result of stimulated emission. The signature for the 2^3P_J state is its emission of a Lyman-α photon leaving the Ps in the 1^3S_1 state which subsequently annihilates to three gammas with a lifetime $\lambda_T^{-1} = 142$ ns.

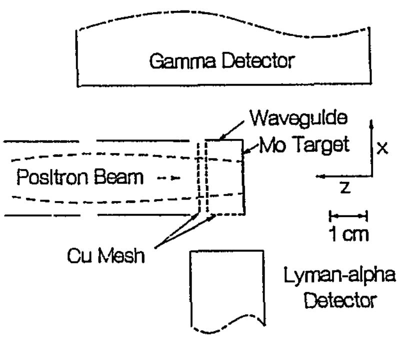

Fig. 2 Experimental Apparatus. (See text for a detailed description.)

A schematic representation of the apparatus [21] is shown in Fig. 2. An electrostatically focused beam (10^5 e^+/s at 65 eV) enters a section of waveguide (2.3cm × 1.0cm) and strikes a polycrystalline molybdenum target attached to the opposite inner wall of the waveguide. A fraction (3×10^{-4}) of the incident positrons is emitted from the target as $n = 2$ Ps. Assuming equal distribution in all of the $n = 2$ magnetic substates, 3/16 of them will be in the 2^3S_1 state, and 9/16 will be in the 2^3P_J ($J = 0, 1, 2$) states. Lyman-α photons are detected in a solar-blind photomultiplier with an overall detection efficiency of 1%. One or more of the gamma rays from the subsequent annihilation of the 1^3S_1 states are detected in two Pilot-B plastic scintillators with a combined detection efficiency of 15%.

In the absence of rf in the waveguide, only those 2^3P_J states originally formed contribute to the signal rate $R(0,\nu)$ of a Lyman-α photon with a delayed γ ray. As the rf frequency is scanned the signal rate $R(I,\nu)$ will increase resonantly at the transition frequencies, ν_J. The theoretical expression [21] for the ratio $r \equiv [R(I,\nu) - R(0,\nu)]/R(0,\nu)$ is fitted to data taken in the vicinity of all three transition frequencies and at a variety of rf intensities I. The results are displayed in Table 1. In addition to the results for the ν_J, this fit provides the first measurement of the natural width γ of the 2^3P_J states. The value of γ is taken to be the same for all three 2^3P_J states (in theory the largest difference among the decay rates for different J states due to their energy splittings is 25 ppm) resulting in an averaged value for γ.

Table 1. Results of fit to r. T is the 2^3S_1 transit time across the waveguide and γ is the radiative decay rate of 2^3P_J Ps.

Parameter	Value	σ_{stat}	σ_{syst}	Theory
ν_0	18504.1 MHz	10.0 MHz	1.7 MHz	18496.1 MHz
ν_1	13001.3 MHz	3.9 MHz	0.9 MHz	13010.9 MHz
ν_2	8619.6 MHz	2.7 MHz	0.9 MHz	8625.3 MHz
T	17.3 ns	1.2 ns	4.0 ns	—
γ	284 μs^{-1}	24 μs^{-1}	63 μs^{-1}	313.8 μs^{-1}

The systematic error assigned to γ is due to a simplification in the fitting function used. The fitting function was generated with the assumption that a single time T described the transit of 2^3S_1 Ps across the waveguide, when, in fact, there is an unknown distribution of transit times. Two fits were made with multiple-value distributions (one with two equally likely transit times and the other with a Gaussian distribution of transit times), and the 5 MHz error was accordingly assigned as a conservative estimate of this error.

The result is in good agreement with the theory. The presence of the above systematic error makes the use of this technique to measure γ to better than the 10 μs^{-1}level dependent on detailed knowledge or control of the 2^3S_1 velocity spectrum.

6. Summary

The decay rates of Ps discussed in this paper are summarized in Table 2 below.

Table 2. Positronium Decay Rates (Units - μs^{-1}, Ex=Experiment, Th=Theory)

n = 1	
$\lambda_{Ex}(1^1S_0 \rightarrow 2\gamma) \equiv \lambda_S = 7994(11)$	Gidley, Rich, Sweetman, West (1982)
$\lambda_{Th}(1^1S_0 \rightarrow 2\gamma) \equiv \lambda_S = 7986.6(0.1)$	Caswell, Lepage (1979), Adkins (1983)
$\lambda_{Th}(1^1S_0 \rightarrow 4\gamma) \sim 1.5 \times 10^{-6} \lambda_{Th}(1^1S_0 \rightarrow 2\gamma)$	Adkins, Brown (1983)
$\lambda_{Ex}(1^3S_1 \rightarrow 3\gamma) \equiv \lambda_T = 7.0514(13)$	Gidley, Westbrook, Conti, Rich (1987)
$\lambda_{Th}(1^3S_1 \rightarrow 3\gamma) \equiv \lambda_T = 7.03830(5)$	Caswell, Lepage (1979), Adkins (1983)
$\lambda_{Th}(1^3S_1 \rightarrow 5\gamma) = 10^{-6} \lambda_{Th}(1^3S_1 \rightarrow 3\gamma)$	Lepage et al. (1983), Adkins (1983)
n = 2	
$\lambda_{Ex}(2^3P \rightarrow 1^3S_1 + hv) \equiv \gamma = 284(72)$	Hatamian, Conti, Rich (1987)
$\lambda_{Th}(2^3P \rightarrow 1^3S_1 + hv) \equiv \gamma = 313.8$	
Ps^-	
$\lambda_{Ex}(1^1S^e \rightarrow 2\gamma) = 2090(90)$	Mills (1983)
$\lambda_{Th}(1^1S^e \rightarrow 2\gamma) = 2086.1(0.2)$	Bhatia, Drachman (1983), Ho (1983)

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REFERENCES

1. Westbrook, C.I., Gidley, D.W., Conti, R.S., and Rich, A., Phys. Rev. Lett. 58, 1328 (1987).
2. Adkins, G.S., Annals of Physics 146, 78 (1983).
3. Lepage, G.P., Mackenzie, P.B., Streng K.H., and Zerwas, P.M., Phys. Rev. A 28, 3090 (1983).
4. Caswell, W. and Lepage, G.P., Phys. Rev. A 20, 36 (1979).

5. Adkins, G.S. and Brown, F.R., Phys. Rev. A 28, 1164 (1983).
6. Lepage, G.P. and Adkins, G.S., private communication (1987). This modification was suggested since bound state corrections of order α^2 will occur as well as radiative corrections of order $(\alpha/\pi)^2$.
7. Cleymans, J. and Ray, P.S., Nuovo Cimento 37, 569 (1983).
8. Samuel, A.L., submitted for publication (1987).
9. Wahl, W., Proceedings of the Symposium "Production of Low-Energy Positrons with Accelerators and Applications", Giessen, FRG (1986) (to be published in Appl. Phys. A).
10. Gidley, D.W., Westbrook, C.I., Conti, R.S., and Rich, A., in "Atomic Physics with Positrons, NATO ASI Series B, Volume 169", edited by J.W. Humberston and E.A.G. Armour, (Plenum Press, NY, 1988), p 277.
11. Coleman, P.G., Griffith, T.C., Heyland, G.R. and Killeen, T.L., J. Phys. B 8, 1734 (1975).
12. Nico, J.S., Gidley, D.W., Zitzewitz, P.W., and Rich, A., Bull. Am. Phys. Soc. 32, 1051 (1987).
13. Gidley, D.W., Rich, A., Sweetman, E. and West, D., Phys. Rev. Lett. 49, 525 (1982).
14. Muta, T. and Niuya, T., Prog. Theor. Phys. 68, 1735 (1982).
15. Bhatia, A.K. and Drachman, R.J., Phys. Rev. A 35, 4051 (1987).
16. Friedman, P.G., Mills, A.P., Jr. and Zuckerman, D., Bull. Am. Phys. Soc. 33, 953 (1988).
17. Bhatia, A.K. and Drachman, R.J., Phys. Rev. A 28, 2523 (1983).
18. Ho, Y.K., J. Phys. B 16, 1503 (1983).
19. Mills, A.P., Jr., Phys. Rev. Lett. 46, 717 (1981).
20. Mills, A.P., Jr., Phys. Rev. Lett. 50, 671 (1983).
21. Hatamian, S., Conti, R.S., and Rich, A., Phys. Rev. Lett. 58, 1833 (1987).