Experimental Tests of QED in Positronium: Recent Advances

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Abstract. The current experimental situation regarding tests of fundamental physics using positronium is reviewed. Five measurements are discussed and compared with theoretical predictions: the singlet and triplet annihilation decay rates, the ground state and the $n = 2$ energy intervals, and the Doppler-free two-photon excitation of the 1S to 2S transition. Previous results, recent progress (where appropriate), and the outlook for future improvements in these measurements are discussed.

1 Introduction

We will review here experimental tests of quantum electrodynamics (QED) and relativistic bound-state formalism in the positron-electron (e^+, e^-) system, positronium (Ps). Ps is an attractive atom for such tests because it is purely leptonic (*i.e.* without the complicating effects of nuclear structure as in normal atoms), and because the e^- and e^+ are antiparticles, and thus the unique effects of annihilation (decay into photons) on the real and imaginary (related to decay) energy levels of Ps can be tested to high precision. In addition, positronium constitutes an equal-mass, two-body system in which recoil effects are very important.

The major experiments that will be discussed are listed in Table 1. All experimental results reported since the first (*Hydrogen I*) conference for each level interval or decay rate are listed. Since there is no controversy in the theoretical results, only the most recent values of these are listed. Complete references can be found in [1,2,3] (o-Ps decay), [3,4] p-Ps decay, and [5,6] (energy level intervals).

Note that for each interval or decay rate in Table 1 that the most recent experiment was done in the early 1990's and that the most recent theory has been completed in the past three years. At the beginning of the decade the precision of experimental values was better than that of the corresponding theoretical values across the board. At the end of the decade, due to several theoretical advances this trend has been completely reversed. As a result, this review, which is intended to update the experimental advances since the *Hydrogen I* conference, must report on results that have been in the literature for a considerable time. Thus, we will particularly address possible future improvements to each experiment.

Table 1. Comparison of theoretical and experiment results. Where two errors are listed in the experiment column, the first is the statistical and the second is the systemmatic. The error in the difference column is the quadrature sum of the experimental and theoretical error

Decay Rate	**Experiment** $[\mu s^{-1}]$	**Theory** $[\mu s^{-1}]$	**Difference** $[\mu s^{-1}]$
$\lambda(1^1S_0)$	7 990.9(17) [7]	7 989.620(13) [3,4]	−1.4(17)
$\lambda(1^3S_1)$	7.051 4(14) [8]	7.039 968(10) [2,3]	−0.011 5(14)
	7.048 2(16) [9]		−0.008 3(16)
	7.039 8(29) [10]		+0.000 1(29)
Interval	**Experiment** **[MHz]**	**Theory** **[MHz]**	**Difference** **[MHz]**
$1^3S_1 - 1^1S_0$	203 387.5(16) [11]	203 392.0(5) [5]	+4.5(17)
	203 389.10(74) [12]		+2.9(9)
$2^3S_1 - 1^3S_1$	1 233 607 218.9(107) [13]	1 233 607 221.0(10) [5]	+2.1(107)
	1 233 607 216.4(32) [14]		+4.6(34)
$2^3S_1 - 2^3P_2$	8 631(28)(60) [15]	8 626.87(13) [5]	−4.1(70)
	8 619.6(27)(9) [16]		+7.3(28)
	8 624.38(54)(140) [17]		+2.5(15)
$2^3S_1 - 2^3P_1$	13 001.3(39)(9) [16]	13 012.58(13) [5]	+11.3(40)
	13 012.42(67)(154) [17]		+0.2(17)
$2^3S_1 - 2^3P_0$	18 504.1(100)(17) [16]	18 498.42(13) [5]	−5.7(101)
	18 499.65(120)(400) [17]		−1.2(42)
$2^3S_1 - 2^1P_1$	11 181(13) [18]	11 185.54(13) [5]	+5(13)
	11 180(5)(4) [19]		+6(6)
$2^3S_1 - 2^1S_0$	Not yet measured	25 424.69(6) [5]	...
$3^3P_2 - 3^3D_2$	Not yet measured	0.75 [20]	...

2 Decay Rates

2.1 Para-Positronium Decay Rate $\lambda(1^1S_0)$

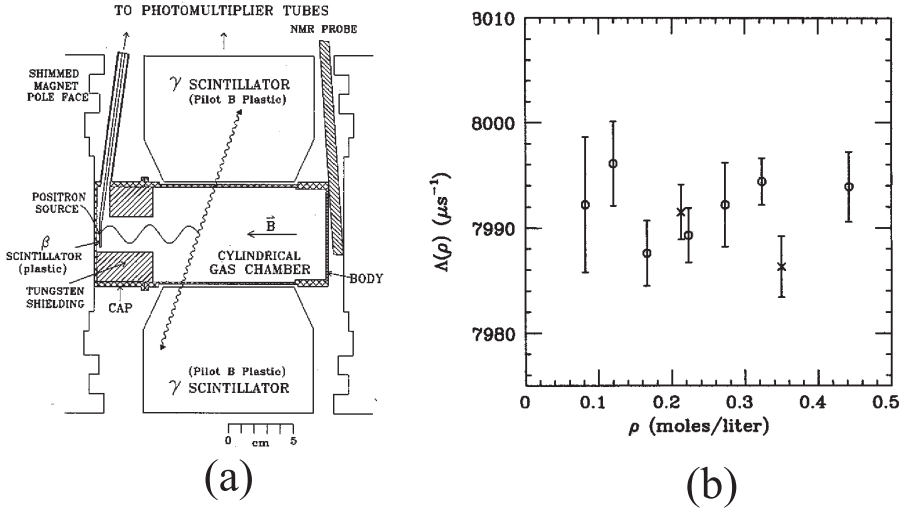

Fig. 1. Experimental apparatus (a) and results (b) for the λ_S measurement (from ref. [7]). The circles in (b) were taken at a magnetic field of 4.25 kG and the crosses at 3.75 kG

Parapositronium (p-Ps) is the spin 0 state of Ps, which decays with rate λ_S into an even number of photons due to charge conjugation invariance. The decay into four photons is significantly suppressed [21] and can be ignored at the current experimental level. The two photon decay rate, λ_2, is calculated using perturbation theory and has been recently calculated [4] through order $(\frac{\alpha}{\pi})^2$ to be[1] 7989.50 $\pm$0.02 μs^{-1}.

A measurement of λ_S using magnetic singlet-triplet state mixing on positronium formed in gases was completed in 1994 [7]. A direct measurement of λ_S is impractical due to the extremely short lifetime ($\lambda_S^{-1} \sim 0.125$ns). However, by applying a magnetic field to the spin 1 state of Ps, orthopositronium (o-Ps), the m = 0 singlet and triplet states are mixed, which increases the more measurable o-Ps decay rate, λ_T ($\lambda_T^{-1} \sim 140$ns). The decay rate of field perturbed m = 0 o-Ps, λ'_T, is given by:

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

where b is a parameter that is nominally linearly dependent on the magnetic field [7]. It is therefore possible to determine λ_S by precisely measuring λ'_T and

[1] The $\alpha^3 \ln^2 \alpha$ and $\alpha^3 \ln \alpha$ terms are also taken into account.

λ_T and knowing the average magnetic field experienced by the Ps. The magnetic field is adjusted to give $\lambda'_T \approx 5\lambda_T$.

The apparatus used in measuring λ_S is shown in Figure 1a. A gas chamber is inserted into a 12" NMR magnet capable of several kG fields. A start signal for a time digitizer is obtained when positrons from a ^{68}Ge source pass through a thin plastic scintillator connected to a photomultiplier tube. The stop signal comes from the detection of annihilation γ rays from o-Ps formed and decaying in the gas. The resulting time spectrum is fitted to determine λ'_T and λ_T at a particular gas density. Eqn. 1 is used to determine λ_S. The measurement is repeated for several gas densities to investigate systematic effects due to the gas. The results are shown in Figure 1b for two different values of the applied magnetic field. The data are in excellent agreement over the entire density range of the experiment. The average value obtained is $\lambda_S = 7990.9 \pm 1.7 \mu s^{-1}$ and is in excellent agreement with theory.

Future of $\lambda(1^1S_0)$

It is interesting to note in Figure 1b that the deduced value of λ_S (labeled $\Lambda(\rho)$ in the figure) is quite insensitive to the buffer gas density, ρ. This indicates that this experiment is likely to be less sensitive to the possible thermalization effects to be discussed in regard to the o-Ps decay rate. This would then permit future improvements in precision for λ_S. However, the 125 ppm statistical error in λ_S [7] is overshadowed by a systematic error of 150 ppm in the determination and stability of the differential linearity of the lifetime spectrum. The effect arises because of the enormous number of events required in fitting a two-component (λ'_T and λ_T) spectrum to high precision. To improve precision beyond the 200 ppm present level will require further systematic calibration of the time digitizer and improvement in the magnetic field homogeneity. We are not aware of any efforts that are trying to improve on the 1994 measurement.

2.2 Ortho-Positronium Decay Rate $\lambda(1^3S_1)$

Introduction

The triplet state of Ps, orthopositronium, decays with rate λ_T into an odd number of photons since an even number is forbidden by charge conjugation. Momentum conservation forbids decay into a single photon thus the minimum allowable number of photons is three. The decay of o-Ps into five photons [21] can be ignored at the level of current experiments. The three photon decay rate, λ_3, is calculated using perturbation theory. The long-awaited order α^2 radiative corrections have been calculated very recently [2] and the decay rate is determined to be[2] 7.039934 $\pm$0.00001 μs^{-1}.

This paper will concern itself with the three most precise measurements of λ_T, two of which were performed at the University of Michigan [8] [9] and one

[2] The $\alpha^3 \ln^2 \alpha$ and $\alpha^3 \ln \alpha$ terms are also taken into account.

at the University of Tokyo [10]. These experiments are representative of the measurements of λ_T in that they use a gas [8], a powder [10] or a vacuum-surface interface [9] to form o-Ps (hereafter refereed to as the gas, powder, and vacuum experiment, respectively). Once o-Ps is formed it will interact with the surrounding environment, which may increase the decay rate, λ, in the case of collisional quenching (decays into 2γ instead of 3γ), or decrease λ, in the case of electric fields (Stark Shift). In all cases it is necessary to remove these effects to determine the *vacuum* decay rate λ_T. This is done by a variety of techniques, which will be discussed in more detail below.

Gas λ_T measurement

The 1989 gas decay rate measurement [8] used an apparatus very similar to the one shown in Figure 1a. Positrons from a radioactive β decay source were stopped in a buffer gas and formed o-Ps. The magnetic field forces the positrons to move in an axial helical path, which increases the signal rate. A start signal for a time-to-digital converter (TDC) was provided by detection of the emitted β particle while the stop signal came from the detection of an annihilation γ ray. The resulting time histogram was fitted to extract a decay rate, λ, which accounts for the additional annihilation of the positron with the molecular electrons in the buffer gas. It is given by:

$$\lambda = \lambda_q(n, v) + \lambda_T. \tag{2}$$

Here $\lambda_q(n, v)$ is the Ps velocity (v) dependent collisional quenching rate of o-Ps with gas molecules having a number density of n. To remove the effect of $\lambda_q(n, v)$, λ is measured at several gas densities and then extrapolated to zero density. Four different gases, isobutane, neopentane, neon, and nitrogen were used to check for systematic effects due to the particular gas. The value of λ_T determined in 1989 [8] was $7.0514 \pm 0.0014\,\mu s^{-1}$, which represents an 8.2σ disagreement with theory. A major limitation of this gas experiment is the asymptotically decreasing value of λ as a function of the start time of the fit. It is now understood to be due to the unexpectedly long time for o-Ps to slow down and thermalize in gases [22]. The full impact of this problem will be discussed in a later section.

Powder λ_T measurement

An experiment performed at the University of Tokyo [10] uses time-resolved γ-ray spectroscopy to subtract the nominally 1% effect of Ps collisional quenching on the measured decay rate of Ps formed in low-density powders of SiO_2. Using this technique one acquires a time spectrum and an energy spectrum of o-Ps formed and annihilating in a silica powder (pictured in Figure 2a). A timing start signal is derived from a positron emitted from a ^{22}Na β^+ source, which is sandwiched between two pieces of scintillator connected to a photomultiplier tube. The source is inserted into a vacuum container filled with low-density SiO_2 powder in which the β^+ are quickly stopped and form o-Ps. Annihilation γ rays

from o-Ps are detected using CsI detectors, which generates a stop signal for the timing system. In parallel, a high resolution energy spectrum is obtained using the germanium detector. An energy spectrum for a time window of 160-710 ns is shown in Figure 2c. The solid line is a simulated spectrum of pure o-Ps 3γ decay. The excess counts peaked around 511 keV are the 2γ annihilations due to o-Ps quenching with electrons in the powder. The resulting $\frac{2\gamma}{3\gamma}$ ratio, and thus the collisional quenching rate, is found for various time windows and is shown in Figure 2b. Using the measured $\frac{2\gamma}{3\gamma}$ ratio, the corresponding measurement of λ from the timing spectrum is corrected to determine λ_T directly without performing any extrapolation over powder density. The authors claim it is a measurement of λ_T that is free of the ambiguities of Ps thermalization and the extrapolations encountered in the gas or vacuum experiments. The Tokyo result is $\lambda_T = 7.0398 \pm 0.0029\ \mu s^{-1}$, which is in good agreement with theory and is roughly 2.5σ below each of the gas [8] and vacuum [9] measurements.

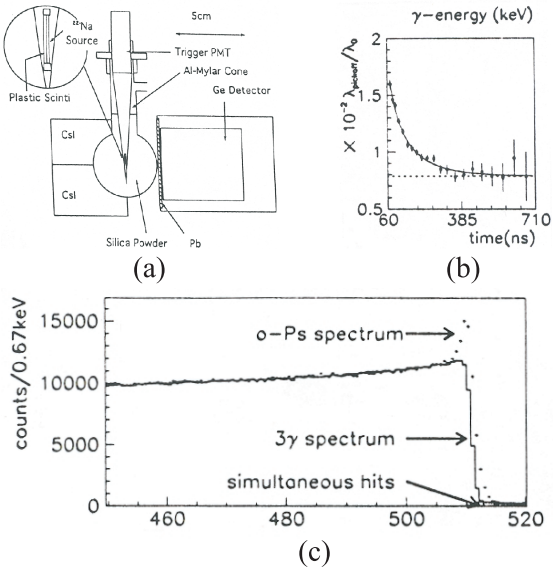

Fig. 2. Tokyo powder apparatus and results (from ref. [10])

This elegant experiment has one major systematic effect that has not been addressed and thus renders it to be a determination of a *lower limit* on λ_T. This 2γ spectroscopic technique completely neglects effects that decrease the decay rate (and therefore have nothing to do with quenching into 2γ's). The Stark effect is the most obvious concern [24]. Electric fields from Van der Waals interactions with grain surfaces as well as fields produced from charging of the insulating powder grains by the ionizing beta-decay positrons polarizes the Ps, hence reducing the electron-positron wavefunction overlap and thus decreasing

the decay rate. Put another way, electric fields mix in excited states of Ps that have much smaller annihilation rates than that of λ_T. Stark-induced decreases in the ground-state Ps splitting (which depend on the wavefunction overlap in precisely the same way as the decay rate) as large as 750 ppm have been measured in *compressed* SiO_2 powders [23]. An extrapolation in powder density might be required to account for this effect, but the density dependence is not clear in the case of powder grain charging. A Stark-induced decrease in λ at the several hundred ppm level cannot be ruled out [24]. Hence this 2γ technique requires further systematic tests and some improvement in statistical precision in order to resolve the discrepancy with theory.

Vacuum λ_T experiment

The vacuum experiment of 1990 [9] is systematically very different from the gas and powder measurements in that it uses a beam of monoenergetic positrons to form positronium in an evacuated cavity, which significantly reduces the interaction of o-Ps with the surrounding media. The apparatus is shown in Figure 3. Positrons from a ^{22}Na source are injected into a tungsten ribbon (tungsten has a negative work function for positrons), which moderates the positrons to a few eV. The ejected slow positrons are focused onto a nickel remoderator. Secondary electrons emitted from the nickel are detected in an channel electron multiplier array and used as a start signal for the TDC. This signal is also used to open an electrostatic gate farther down the beam. The use of gating significantly reduces the random background and provides for an excellent signal-to-noise ratio. The beam of remoderated positrons is focused through a 3 mm diameter aperture at 700 eV into an MgO-lined, evacuated cavity of about 100 cm^3 volume. Ps is formed on the inside surface of the cavity, which confines the Ps expelled into the vacuum. The annihilation γ ray is detected using scintillation detectors and utilized as a stop for the TDC. Several different cavities and apertures are used to investigate any systematic effects due to the confinement region. The resulting extrapolation is very small as depicted in Figure 4. The measured value for λ_T is $7.0482 \pm 0.0016\ \mu s^{-1}$ and it disagrees with theory by 5.2σ.

The major problem encountered in this vacuum experiment was that the fitted decay rate did not become constant until all data before t$\cong$ 450 ns were excluded. The result was that the final error is dominated by the 210 ppm statistical error from fitting beyond 450 ns. It was found [25] that this problem is due to collisionally-dissociating fast Ps formed by positron backscattering from the fumed MgO surface. To check whether this fast Ps could systematically increase the decay rate beyond 450 ns, a technique similar to that used in the Tokyo powder measurement was used in 1991 [26] to look directly for 2γ quenching events. The results are shown in Figure 5. The solid line is a theoretical 3γ continuum spectrum. The channels on either side of 511 keV are circled. The data are visually consistent with a pure o-Ps continuum with no 2γ peak at 511 keV (compare to Figure 2c). A 233 ppm limit is set on the branching ratio to a pair of 511 kev γ rays and a 200 ppm limit is set on the branching ratio to a pair

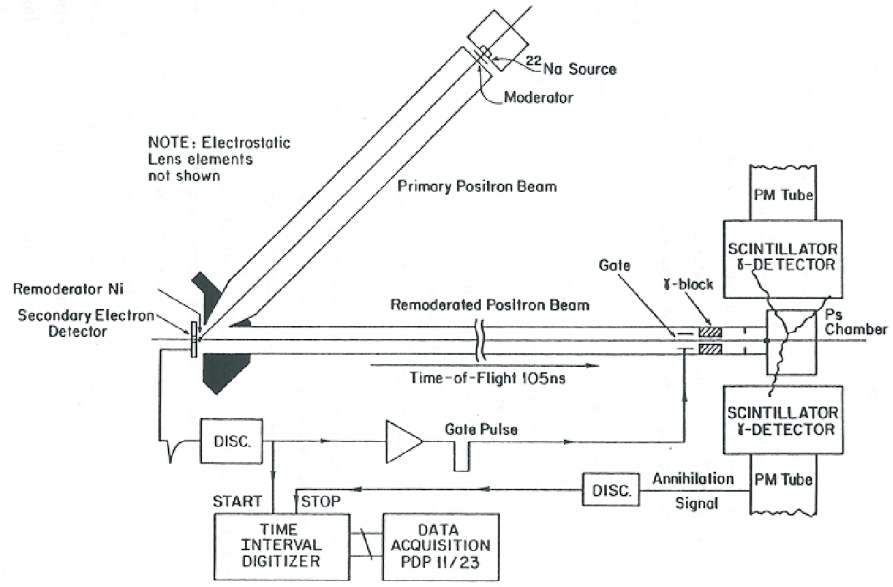

Fig. 3. The apparatus used in the vacuum λ_T experiment (from ref. [9])

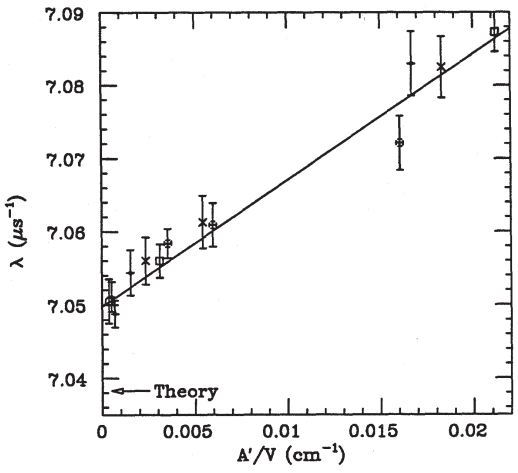

Fig. 4. Extrapolation of the decay rate to determine the effect of the entrance aperture (from ref. [9]). The arrow labeled "theory" should now be moved to 7.04 [2]

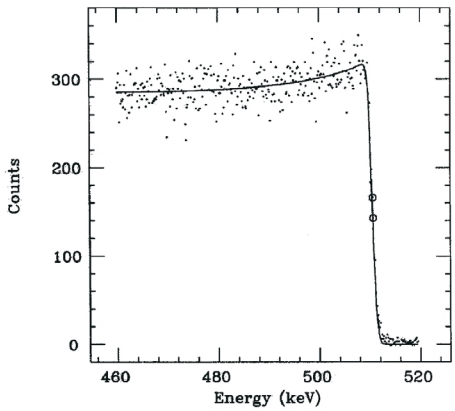

Fig. 5. Gamma-ray spectrum for vacuum orthopositronium measurement (from ref. [26])

of unequal energy γ rays that sum to 1022 keV. Hence, the 2γ quenching mode cannot be responsible for the discrepancy between theory and experiment.

Exotic decay modes

Motivated by the observed decay rate discrepancy between QED theory and experiment for λ_T, numerous searches have been performed for forbidden, small or exotic decay modes. An exotic decay branch, besides o-Ps $\rightarrow 3\gamma$, with roughly 10^{-3} branching ratio could be causing the higher decay rate and is given by $\lambda_{obs} = \lambda_{3\gamma} + \lambda_{exotic}$. Many candidate decay branches have been proposed in the literature and numerous experiments have unsuccessfully searched for exotic decays. The proposed decay branches naturally divide into two categories: 1) decays to the wrong number of photons, o-Ps $\rightarrow 5\gamma; 4\gamma; 2\gamma; 1\gamma; 0\gamma$ and 2) decays involving a hypothesized, neutral exotic particle with a small mass (<1 MeV), o-Ps $\rightarrow \gamma + A^o; 2\gamma + X^o$ where A^o is an axion-like particle and X^o is a charge conjugation (C) odd boson (the charge conjugation operator interchanges particles and anti-particles, the Ps eigenvalue is odd or even: o-Ps is C-odd, p-Ps is C-even and 1γ is C-odd). All of the "wrong number of photons" decays have established upper limits well below the size of the λ_T discrepancy. However, the most marginal are the modes where o-Ps $\rightarrow 2\gamma$ (see for example [26]). A similar situation holds for the exotic neutral particle searches. There is no evidence supporting the existence of such particles. For an overview of the individual experiments the reader is referred to the 1997 review [27].

The primary conclusion is that there is no evidence for the existence of any exotic decay branch from o-Ps, which, in turn, could be causing the o-Ps decay rate discrepancy. The statistical significance of the negative results is, in most cases, overwhelming. On the other hand, o-Ps exotic decays cannot be conclusively ruled out as the cause of the decay rate discrepancy. Certain mass

regions for the axion-like A^o particle are still unconstrained. To dispense with these mass regions, new experimental ideas and innovations are required. For the X^o particle (C-odd boson) that couples directly to 3γ, there exist no limits, regardless of the $X^o \rightarrow 3\gamma$ lifetime, strong enough to exclude the o-Ps decay rate discrepancy. However, the experimental prospects are promising for pushing X^o limits into meaningful regions. Significant progress has been achieved in eliminating the numerous possibilities. However, as long as the o-Ps decay rate remains controversial, it appears that the exotic decay hypothesis will remain tenable.

Re-examination of the gas λ_T measurement

In the 1989 gas measurement of λ_T [8] it was believed that Ps was thermalized under all conditions of the decay rate measurement thereby insuring that the collisional quenching rate is constant when the decay rate is fitted. The thermalization process manifests itself in this experiment as a decay rate that asymptotically decreases as the start time of the fit is increased. If incompletely thermalized o-Ps annihilates at a higher rate, then the lowest gas density data would be the most susceptible to any systematic effect and the density extrapolation would determine a systematically high value of λ_T. Indirect arguments and observations concerning Ps thermalization in gases were extensively discussed [8]. Recently, a direct measurement of o-Ps thermalization [22] using the same apparatus as the 1989 gas decay rate experiment has been completed. A high resolution Ge detector is used to measure the Doppler broadening of the 511 keV γ rays from magnetically induced 2γ triplet Ps decays. Thus a time-dependent average Ps kinetic energy can be determined down to a lower limit of about 0.3 eV set by the stability and energy resolution of the Ge detector. The measured thermalization times are significantly longer than previously believed for all of the gases used in the experiment and result in a smaller momentum transfer cross sections than calculated (see ref. [22] for comparisons).

The measured thermalization rates for the gases used in the 1989 λ_T experiment clearly indicate that at the lowest pressures, the Ps is well above room temperature at the beginning of the measurement window. To determine the systematic effect of epithermal Ps on the λ_T measurement it then becomes crucial to know how the collisional quenching rate, $\lambda_q(n, v)$, depends on Ps velocity/temperature. We can write $\lambda_q(n, v)$ as:

$$\lambda_q(n, v) = n\sigma_q(v)v, \tag{3}$$

where $\sigma_q(v)$ is the annihilation quenching cross section for Ps with velocity v colliding with essentially stationary gas molecules. Recent direct measurements [28] of $\lambda_q(n, v)$ from room temperature to 300°C have seen a clear increase in all of the gases ranging from 160 to 800 ppm/°C. Thus a correction to the 1989 gas result is required.

We have used an elastic scattering thermalization model [29] to generate a spectrum using the temperature dependence of λ_q from the above quenching

experiment as input. The rate of Ps thermalization is varied and fitted and the values of the measured decay rates from the 1989 experiment are adjusted until they match the simulation. From this the "true" asymptotic value for the decay rate is found. Our *preliminary* [30] corrections are shown in Figure 6. The decay rate for each gas needs to be corrected downward with a somewhat smaller shift necessary for N_2 and Ne. The new average value for the decay rate is approximately 2.5σ lower than previously thought. It moves just below the vacuum value, albeit in slightly better agreement now with that value. It still disagrees significantly with the powder measurement and theory. These corrections for the two hydrocarbon gases are preliminary as we are still exploring alternative fitting procedures based on molecular, inelastic thermalization models. In addition, the precision attained for N_2 and Ne corrections relies on the use of high pressure data supplied by the University College London group (see discussion in ref. [8]) and this raises concern over possible non-linear behavior of λ in gas density. Given such ambiguities it becomes preferable at some point to consider the future of systematically improved λ_T measurements rather than attempting corrections to a decade old measurement. This is the focus of the next section.

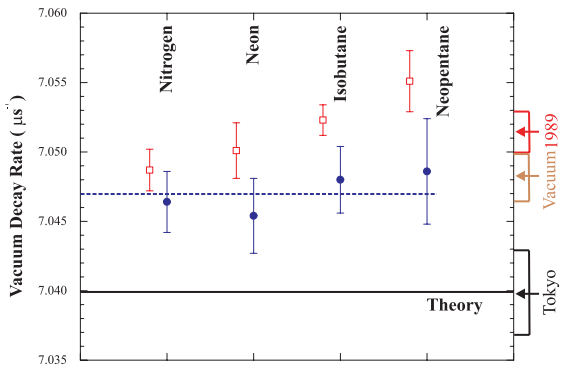

Fig. 6. Corrections to the λ_T values for each of the gases used in the 1989 gas measurement

Future of λ_T measurements

The ubiquitous problem encountered in all positronium decay rate measurements to date is isolating the positronium from the formation medium in order to determine the "vacuum" decay rate. In both gas and powder experiments the interactions (Ps quenching and Ps polarization) with these media need to be accounted for. This can involve extrapolations of λ to zero density in the formation medium, as in the Michigan experiment, and/or spectroscopic corrections for 2γ decays as in the Tokyo experiment. At Michigan we decided a decade ago to abandon powder media in future precision experiments because we could

not guarantee the uniformity of density throughout the sample and hence we could not systematically trust the linearity of the typically 1-2% extrapolation to zero density. The Tokyo 2γ technique eliminates this level of extrapolation for quenching, but collisional Stark shift reductions in λ at the few hundred ppm might require density extrapolations for improved measurements. Moreover, if powder charging by the radioactive source is present such extrapolation in density may not be appropriate and powders may again have to be abandoned at the 100 ppm level in λ_T.

For gas λ_T experiments it now appears (see previous section) that the slow thermalization of Ps presents severe limitations on improving the precision of λ_T. To thermalize Ps quickly one must use higher gas pressures and this directly increases the magnitude of the extrapolation and concerns over three-body collisions/nonlinearities in density begin to manifest themselves. Furthermore, the presence of low energy positrons (positrons below the Ps formation threshold) often necessitates the use of quench gas mixtures and determining the pressure-to-density conversion over a large range in mixture pressure becomes problematic. Thus gas measurements are less attractive unless a special gas can be found that combines rapid Ps thermalization at low enough densities to minimize quenching. Such a gas has not yet been found.

Formation of Ps on the vacuum-surface interface of an evacuated cavity largely eliminates the interaction of the formation medium with the Ps. However, Ps formation at a surface typically produces Ps with an eV of kinetic energy and it then becomes necessary to confine the Ps to a region of uniform γ-ray detection efficiency. The two main systematics are then related to the loss of Ps through the cavity entrance aperture [9] and the formation of fast (10 eV) Ps from backscattered positrons off the target surface [25]. Recent development of a new hybrid surface looks very promising as a source of copious *thermalized* Ps. It incorporates a thin, one micron layer of *porous* silica deposited on a Si wafer and is an offshoot of the microelectronic industry's search for low dielectric insulating films for next generation, small scale devices. We have been extensively investigating Ps lifetimes in such candidate films as a new means of measuring pore size and pore interconnectivity [31]). We find that o-Ps is copiously formed at the 30-50% level in these silica films with porosities in the range around 70%. More importantly for decay rate experiments, the Ps is free to diffuse through and out of the thin film with nearly 100% escaping into the vacuum. When Ps does so, it escapes after sufficient collisions so as to be nearly completely thermalized. The degree to which the Ps is thermalized depends on the positron beam implantation energy since deep (high energy) Ps implantation requires more collisions to diffuse back to the silica surface. Hence, the average escape energy of Ps can be crudely tuned with the beam implantation energy. The porosity and pore size in the silica film can also be controlled to provide extensive systematic checks on the measured decay rate. A new decay rate measurement using such porous thin films is presently underway at Michigan. Yet another method to eliminate Ps interactions with materials is to make a beam of Ps and observe the time dependence of gamma emission from a swarm of Ps

atoms. A major difficulty in such an experiment is to insure the uniformity of gamma detection efficiency both in space and time. Such an experiment is being undertaken at the University of Mainz [32]).

3 Energy Level Intervals

3.1 Ground State Interval

The calculation of the order $\alpha^4 Ry$ corrections to the ground state interval ($1^3S_1 - 1^1S_0$) has been recently completed [5] yielding $\Delta\nu = 203,392.0$ MHz with an estimated theoretical uncertainty of 0.5 MHz based on expectations of the size of the uncalculated order $\alpha^5 Ry$ terms. We treat the 0.5 MHz estimate as a 1σ error bar to obtain the roughly 3σ differences from the longstanding experiments $\Delta\nu$ (Yale '84) $= 203,389.10 \pm 0.74$ MHz [12] and $\Delta\nu$ (Brandeis '75) $= 203,387.5 \pm 1.6$ MHz [11]. It has been 16 years since the last $\Delta\nu$ measurement was published and we know of no program to remeasure $\Delta\nu$. Again, we note that theory has leapt ahead of experiment.

Future of ground state interval

A new $\Delta\nu$ value could be a timely contribution to the field of precision measurements as this is the most rigorous test of QED using the positronium bound state. There is additional motivation to reconsider such a measurement since the same kind of Ps thermalization effects causing problems in the gas decay rate experiments may cause shifts in these $\Delta\nu$ experiments, which were also performed in gases. Similar to decay rate experiments these measurements require an extrapolation in the collisional pressure shift to zero density. In fact we can estimate that Ps was, on average, typically 10 times thermal energy at the lower N_2 pressures used in the Yale experiment. Unfortunately, no estimate of a $\Delta\nu$ correction can be made since we do not know how the pressure shift depends on energy/temperature. Some correction is probably warranted (and it is entirely possible that it could be large enough to account for the difference with theory) but there is no reliable way of calibrating such a correction without effectively redoing the experiment. Our group is presently evaluating a new method based on lifetime techniques to measure $\Delta\nu$. Time-resolved spectroscopy can assure that Ps is thermalized and can also improve the signal-to-noise ratio by almost an order of magnitude over the previous experiments. Such improvements in technique are virtually required for any new ground state splitting experiments as the Yale and Brandeis experiments seemed to have pushed the present technique to its ultimate limits.

3.2 Rydberg Interval

The interval $2^3S_1 - 1^3S_1$ has been measured by the method of two-photon, Doppler-free excitation in two experiments [13][14]. We will detail the latter experiment, which employs continuous-wave excitation.

Fast positrons are created by bremsstrahlung pair-production in an electron microtron accelerator. These are moderated and bunched into 25 ns packets at 30 Hz, each comprised of 2×10^4 slow positrons. The positrons are guided by a 150-G magnetic field and implanted at 1-2 keV kinetic energy onto an Al(111) crystal heated to 576 ± 5 K as shown in Figure 7a. About 30% of the incident positrons come off the surface as thermal positronium with a velocity distribution that is a beam Maxwellian.

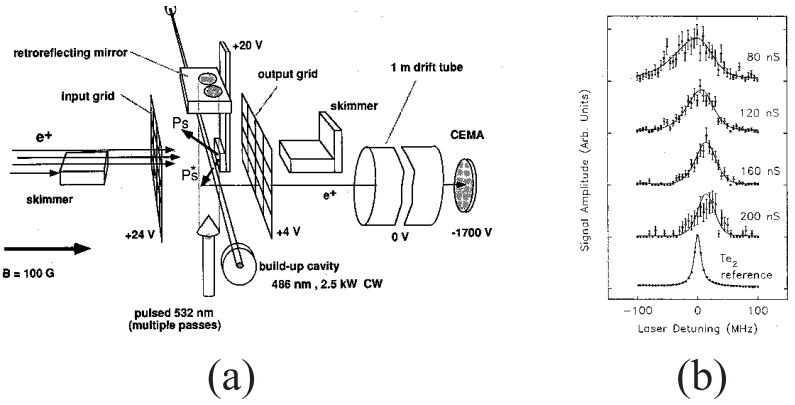

Fig. 7. Apparatus and results for cw $2^3S_1 - 1^3S_1$ interval measurement (from ref. [14])

A small fraction of the orthopositronium atoms produced pass through the cw-excitation beam, where they are promoted to the 2^3S_1 level and then through a multi-pass doubled-YAG beam at 532 nm, where they are photo-ionized. The photo-ionized positron is electro-statically accelerated and magnetically-guided into a channel-electron multiplier array (CEMA) where it is detected. The time-of-flight between the incident positron pulse and the photo-ionization pulse determines the range of positronium velocities detected.

The major improvement over the previous measurement [13] is the use of cw rather than pulsed excitation for the two-photon transition. This eliminates frequency chirping effects that caused the major systematic uncertainty in [13]. Sufficient intensity (maximum 1.7 MW/cm^2) was achieved by injecting 486 nm light from a single-frequency ring dye laser into a high finesse build-up cavity. The detected transition rates are scanned across the resonant frequency for four different velocity groups and referenced to the Te_2 (e) absorption line as shown in Figure 7b. These results are fitted by theoretical line-shapes that include second-order Doppler and ac-Stark shifts. Any motional Stark shifts are eliminated by extrapolation to zero velocity. The final result for the $2^3S_1 - 1^3S_1$ interval is 1233 607 216.4 $\pm$ 3.2 MHz, which is in reasonable agreement with the recent theory result of 1233 607 221.0 $\pm$ 1.0 MHz.

Future of Rydberg interval

Systematic improvements in the measurement of the $2^3S_1 - 1^3S_1$ interval could be made using cold positronium. The authors of [14] state "Laser cooled Ps would permit a measurement of the $1S-2S$ transition to reach a precision significantly better than the 1.3 MHz natural linewidth".

3.3 Intervals in the n = 2 and 3 excited states

Allowed transitions in $n = 2$

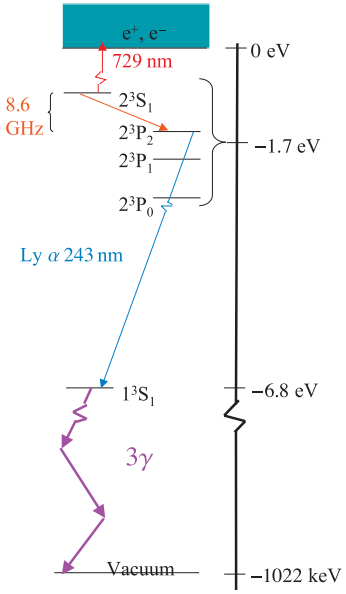

Fig. 8. The $n = 2$ energy level schemes

The techniques used in the three measurements of the $2^3S_1 - 2^3P_J$, $J = 0, 1, 2$ intervals are summarized in Figure 8. In all of these experiments the initial state is the 2^3S_1 state formed from positrons striking a metal target with about 100 eV kinetic energy. The first two measurements [15] [16] detected the transition as a 243 nm Lyman-α photon in delayed coincidence with a detected γ ray from the annihilation of orthopositronium. The most recent and most precise experiment [17], which we detail below, uses only the Lyman-α detection.

The apparatus for this experiment is shown schematically in Figure 9a. The positrons are produced by bremsstrahlung and pair-production at the beam dump of a 36 MeV electron linear accelerator. The positrons are moderated in tungsten vanes and transported to a Molybdenum $n = 2$ formation foil on the

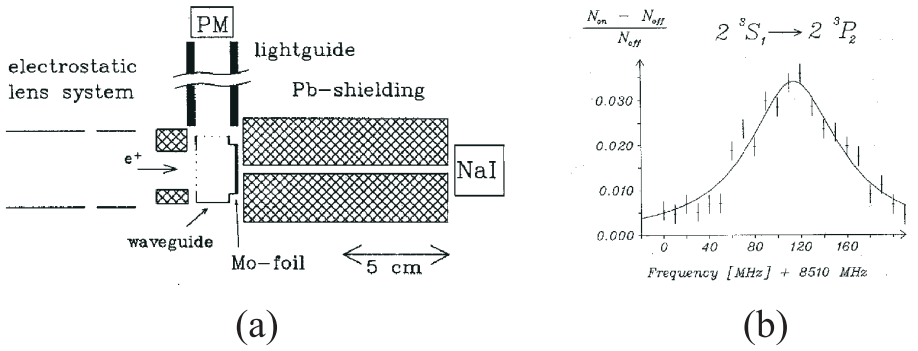

Fig. 9. Apparatus and results for Mainz $n = 2$ fine-structure measurement (from ref. [17])

inner wall of a microwave wave-guide (Figure 9a). About 6×10^4 of the incident positrons form 2^3S_1 positronium. If the microwaves drive one of the transition frequencies $2^3S_1 - 2^3P_J$, $J = 0, 1, 2$ then the P-states radiatively decay in 3.2 ns with the emission of a Lyman-α photon. The photons are collected using a light guide with an evaporated aluminum surface and detected in a solar-blind photo-multiplier. The NaI γ detector and Pb collimator are used to adjust the positron beam position.

The positrons that arrive at the formation foil share the time structure of the electron accelerator, giving 2 μs long pulses of about 10^4 slow positrons at 600 Hz. Since a γ-ray detector would be saturated, the coincidence technique cannot be used, giving an order of magnitude worse signal-to-noise ratio than that in the previous experiments (due to γ scintillations in the Lyman-α photo-multiplier), but the higher data rate more than compensates for this in total time to reach a given precision.

A sample resonance curve for the $2^3S_1 - 2^3P_2$ transition is shown in Figure 9b. These data were fitted with a Lorentzian line shape and the transition frequency extracted. In order to correct for a net Doppler shift due to an asymmetric positronium velocity distribution, measurements were made with the microwaves traveling in both directions through the wave-guide. To insure that the magnitude of the microwave electric field remains constant as the frequency was scanned across the resonance, it was necessary to minimize standing waves and to correct for the dispersion in the wave-guide near cutoff. The results, given in Table 1, are in reasonable agreement with theory for all intervals and in mild disagreement (2.5 σ) with the less precise measurement of [16] only on the $2^3S_1 - 2^3P_1$ transition.

Forbidden transitions in n = 2

The transition $2^3S_1 - 2^1P_1$ is normally forbidden by charge-conjugation invariance, but with the application of a small static magnetic field the Zeeman-

induced transition is allowed. After correction for the Zeeman shift, the level interval was determined in experiments [18] and [19]. The techniques and apparatus are similar to the above allowed transitions with the exception that in [18] the detected γ ray from para-positronium annihilation is not delayed. The results are displayed in Table 1.

Future of excited state spectroscopy

A program is underway at the University of Michigan to measure the $2^3S_1 - 2^3P_J$, $J = 0, 1, 2$ transition frequencies by a method that is statistically and systematically quite different from the previous methods. As shown in Figure 8 the threshold for photo-ionization of $n = 2$ positronium is 729 nm. We have measured the presence of $n = 2$ positronium with better than 50% efficiency by detection of the positron from photo-ionization. This is to be compared to the detection efficiencies of 0.4% and 0.1% for experiments [17] and [16], respectively. This method requires the accumulation of positrons that form $n = 2$ positronium into a pulse of 30 ns duration. We have accomplished this with a Penning-trap positron accumulator described in [33], which produces 250 slow positrons per pulse at 200 Hz with 10 positrons/pulse arriving on the formation surface. The second major departure of this program from the previous measurements is the intended use of the Stark shift induced by an applied electric field to scan the resonance across a fixed micro-wave frequency. This obviates the need to keep the micro-wave electric field constant as a function of frequency. Micro-wave reflections will no longer present any problems – in fact, setting up a pure standing wave will completely eliminate the first-order Doppler shift. We will soon make a preliminary measurement of the transition frequencies using this technique.

A further improvement can be made to this experiment starting with thermal orthopositronium formed on porous SiO_2 films [31] with pulsed Doppler-free, two-photon excitation to the 2^3S_1 state. More of the initial state for the micro-wave transitions would thus be available and time-of-flight velocity systematics can also be done.

The transition frequency $2^3S_1 - 2^1S_0$ has not been measured yet. It could be measured as disappearance of 2^3S_1 via a magnetic dipole transition. Large micro-wave magnetic fields (available e.g. in a resonant cavity) would be necessary for this measurement, but the advantage of a Stark scan could be utilized. We know of no active plans for this measurement.

Various intervals in the $n = 3$ level of Ps are also attractive for investigation. Access to $n = 3$ states could be obtained by Doppler-free, two-photon excitation to the 3^3S or 3^3D levels. Of particular interest is the interval $3^3P_2 - 3^3D_2$ for which the theoretical order α^2Rydberg splitting is identically zero. The order α^3Rydberg radiative corrections [20] bring the interval up to only 0.75 MHz, while the widths of the 3^3P_2 and 3^3D_2 states are 30 MHz and 10 MHz, respectively. The decay rate of the 3^3D_2 state is very sensitive to Stark mixing and a sub-MHz measurement of the interval should be possible. We are pursuing this and other $n = 3$ intervals at Michigan.

4 Summary and Conclusions

The decade of the 90's began with a flurry of experiments testing QED in positronium at ever greater precision. At that time theory was still stuck at relative order α for all decay rate and interval measurements. In the past three years the flurry of papers has been entirely on the theoretical side with all values calculated through relative order α^2. Theory and experiment are in good agreement with the exception of the long-standing discrepancy in the decay rate of orthopositronium and a possible problem in the ground state interval. The ball is now firmly back in the experimentalists' court to improve the measurements wherever possible and to try to resolve the discrepancies.

References

1. G. S. Adkins: *this edition*, pp. 375–386 and references therein
2. G. S. Adkins, R. N. Fell, J. Sapirstein: Phys. Rev. Lett. **84**, 5086 (2000)
3. B. A. Kniehl and A. A. Penin: Phys. Rev. Lett. **85**, 1210 (2000); Err.*ibid.*, 3065
4. A. Czarnecki, K. Melnikov, and A. Yelkhovsky: Phys. Rev. A **62**, 052502 (2000) and references therein
5. K. Pachucki and S. G. Karshenboim: Phys. Rev. Lett. **80**, 2101 (1998) and references therein
6. G. S. Adkins and J. Sapirstein: Phys. Rev. A **61**, 069902 (2000)
7. A.H. Al-Ramadhan and D.W. Gidley: Phys. Rev. Lett. **72**, 1632 (1994)
8. C. I. Westbrook, D. W. Gidley, R. S. Conti, and A. Rich: Phys. Rev. Lett. **58**, 1328 (1987) C. I. Westbrook, D. W. Gidley, R. S. Conti, and A. Rich: Phys. Rev. A **40**, 5489 (1989)
9. J.S. Nico, D. W. Gidley, A. Rich, and P.W. Zitzewitz: Phys. Rev. Lett. **65**, 1344 (1990)
10. S. Asai, S. Orito, N. Shinohara: Phys. Lett. B **357**, 475 (1995)
11. A. P. Mills, Jr., and G. H. Bearman: Phys. Rev. Lett. **34**, 246 (1975) A. P. Mills, Jr.: Phys. Rev. A **27**, 262 (1983)
12. M. W. Ritter, P. O. Egan, V. W. Hughes, and K. A. Woodle: Phys. Rev. A **30**, 1331 (1984)
13. S. Chu, A. P. Mills, Jr., and J. L. Hall: Phys. Rev. Lett. **52**, 1689 (1984) K. Danzmann, M. S. Fee, and S. Chu: Phys. Rev. A **39**, 6072 (1989)
14. M. S. Fee, A. P. Mills, Jr., et al.: Phys. Rev. Lett. **70**, 1397 (1993); M. S. Fee, S. Chu, et al.: Phys. Rev. A **48**, 192 (1993)
15. A. P. Mills, Jr., S. Berko, and K. F. Canter: Phys. Rev. Lett. **34**, 1541 (1975) S. Berko and H. N. Pendleton: Ann. Rev. Nucl. Part. Sci. **30**, 543 (1980)
16. S. Hatamian, R. S. Conti, and A. Rich: Phys. Rev. Lett. **58**, 1833 (1987)
17. E. W. Hagena, R. Ley, et al.: Phys. Rev. Lett. **71**, 2887 (1993)
18. R. S. Conti, S. Hatamian, et al.: Phys. Lett. A **177**, 43 (1993)
19. R. Ley, E. W. Hagena, et al.: Hyperfine Interact. **89**, 327 (1994)
20. I. B. Khriplovich: Private Communication
21. M. Chiba, R. Hamatsu, et al.: Nucl. Instr. Meth. B**143**, 121 (1998)
22. M. Skalsey, J.J. Engbrecht, et al.: Phys. Rev. Lett. **80**, 3727 (1998)
23. M.H. Yam, P.O. Egan, W.E. Frieze, and V.W. Hughes: Phys. Rev. A **18**, 350 (1978)

24. G. W. Ford, L. M. Sander, and T. A. Witten: Phys. Rev. Lett. **36**, 1269 (1976)
25. D.W. Gidley, D.N. McKinsey, and P.W. Zitzewitz: J. Appl. Phys. **78**, 1406 (1995)
26. D.W. Gidley, J.S. Nico, and M. Skalsey: Phys. Rev. Lett. **66**, 1302 (1991)
27. M. Skalsey: Mat. Sci. Forum **255**, 209 (1997)
28. R. S. Vallery, A. E. Leanhardt, M. Skalsey, and D. W. Gidley: J. Phys. B **33**, 1047 (2000)
29. W.C. Sauder: J. Res. Natl. Bur. Stand. **72A**, 91 (1968)
30. D. W. Gidley: April Meeting of the American Physical Society (1998)
31. D. W. Gidley, W. E. Frieze, et al.: Phys. Rev. B **60**, R5157 (1999)
32. G. Werth and R. Ley: Private communication
33. B. Ghaffari, R. S. Conti, and D. W. Gidley: Mat. Sci. Forum **255**, 248 (1997); B. Ghaffari: A Pulsed Positron Beam to Measure the $2^3P_1 \rightarrow 2^3P_J$ Energy Intervals in Positronium: Discovery of Chaotic Transport. Ph. D. Thesis, University of Michigan, Ann Arbor (1997)