# Fundamental Physics with Cold Positronium

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# Fundamental Physics with Cold Positronium

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**Abstract.** The use of positron plasmas to produce intense positron pulses has made it possible to create relatively large instantaneous positronium densities. This in turn provides an opportunity to perform improved precision spectroscopy measurements on positronium that will be limited by systematic rather than statistical effects which will improve present QED positronium tests by orders of magnitude. Further increases in the positronium density will lead to the production of a positronium Bose-Einstein condensate, further increasing the accuracy of such measurements and making it possible to study the phase diagram of a matter-antimatter condensate for the first time.

**Keywords:** Positron; Positron accumulator; Positronium; $Ps_2$; Bose-Einstein condensate; QED.
**PACS:** 36.10.Dr, 34.80.Nz, 82.33.Ln 12.20.Fv.

## INTRODUCTION

The ability to accumulate and store positrons in Surko-Penning-Malmberg traps [1] has proved to be of great utility in a number of experimental endeavours, most notably the production of Antihydrogen [2] and measurements of positron scattering from atoms and molecules at very low energies [3]. Similar methods have also made it possible to perform experiments with systems containing more than one positronium (Ps) atom [4].

Studies of Ps-Ps interactions are complicated by two main difficulties. First, Ps has a relatively short lifetime (142 ns or less in the ground state) and so one cannot simply store up Ps atoms. Secondly, positrons are rather scarce and so it is necessary either to create them in some sort of high energy process (e.g., using an electron linac or a nuclear reactor [5]) or capture the output from a radioactive isotope (which must itself be created in a reactor or accelerator). Large scale facilities that may be used to generate Intense positron beams are generally extremely expensive, and as a result the most common way to produce positron beams in the laboratory is to use a beta emitting radioisotope, the standard being $^{22}$Na. However, current technology limits the useful activities of such sources to ~ 100 mCi or less, from which slow positron beams of less than $10^7$ $s^{-1}$ may be generated. This is obviously too low to study interactions between Ps atoms directly. Since Ps cannot be stored the solution is to collect positrons and then use them all at once to create bursts of Ps atoms, and for this the positron plasmas generated by Surko type traps are well suited.

Up to $10^8$ positrons can be stored in our arrangement, and other systems have stored more than $10^9$ particles [6]. By rapidly dumping positron plasmas held in a trap we have been able to produce intense, sub-ns, positron bursts with instantaneous currents of more than 10 mA [7]. By implanting these positron bursts into suitable targets, Ps

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atoms may be created that have a reasonable chance of interacting with each other, and in this way we have begun to study Ps-Ps interactions.

So far we have observed the formation of molecular positronium ($Ps_2$) on the internal surfaces of porous silica [8] and on a clean metal surface [9] as well as spin exchange quenching (SEQ) between oppositely polarized ortho-positronium atoms [10]. The main objective of our research, however, is to produce an ensemble of *spin polarised* positronium atoms in a cavity at a density where they might undergo a phase transition and form a Bose-Einstein condensate (BEC) at an experimentally realistic temperature [11].

In this regard SEQ and $Ps_2$ formation are undesirable, insofar as they represent a loss mechanism that will reduce the final Ps density. Conversely, these processes lead to a critical experimental signal that would be absent if a fully spin polarized beam were used, and at the Ps densities we have been able to achieve so far provide the only evidence we have for Ps-Ps interactions.

Since the incident positron beam used is derived from the beta decay of the isotope $^{22}Na$ it is naturally partially spin polarized [12], and steps may be taken to increase the net beam polarization at the cost of intensity. The SEQ and/or $Ps_2$ formation mechanisms may serve as diagnostics in experiments carried out at higher densities in which they are not the main focus. It is therefore necessary to understand the details of these processes, not only because of their intrinsic scientific interest but also because they present a useful tool for the development of procedures to produce a high density spin aligned positronium ensemble, and thence a Ps BEC [13].

In general Bose-Einstein condensation is of interest because it is a macroscopic manifestation of a fundamentally quantum mechanical effect. The essence of the phenomenon is that, below a certain critical temperature $T_c$, a macroscopic fraction of a collection of identical particles obeying Bose-Einstein statistics (bosons) will "condense" into the single lowest energy state, which will only occur if the density of particles is higher than a certain threshold for a given temperature. The creation of atomic BEC's has been accompanied by an explosion in other technological uses of atom traps, including the atomic fountain clock [14], sensitive gravimeters based on atom interferometry [15], quantum computation schemes [16], and unbreakable quantum cryptography methods [17].

It should be pointed out that, while it is intriguing that the low mass of positronium means that BEC formation may occur at or near room temperature (for achievable densities), it is the novel effects associated with the collective properties of a matter-antimatter system that make the positronium BEC worthy of study. Indeed, the scarcity of antimatter in general, and the concurrent difficulties associated with producing large numbers of positronium atoms far outweigh any advantages conferred by the higher transition temperature, as evidenced by the spectacular success of alkali atom and hydrogen BEC research [18, 19]. However, there are a number of unique aspects to the positronium BEC that are of sufficient interest to justify the efforts needed to create this system:

- First, it is important to note that the total spin 2 ortho-positronium-ortho-positronium scattering length is positive ($a_2$ = 0.83 Å) [20, 21]. The small positive scattering length makes a collection of spin-polarized o-Ps atoms (all in the m=1

triplet state) a nearly non-interacting ideal gas that may undergo Bose–Einstein condensation [22].

- A positronium atom laser could be created from a positronium BEC that escapes into the vacuum via stimulated tunnelling from a physical cavity through one (or more) narrow channels in the cavity wall. Since the Ps atoms would tunnel without gain or loss of energy, a highly mono-energetic beam would be produced in vacuum (the energy being that of the positronium in the many particle ground state of the cavity).
- A positronium atom laser beam excited (Doppler-free) to a high Rydberg state could be used in a Mach-Zender type interferometer to measure the positronium gravitational redshift, and by inference reveal the gravitational interaction of antimatter [23].
- Since positronium atoms annihilate, it is possible for significant rates of stimulated annihilation to occur in a sufficiently dense positronium BEC in which all the atoms are flipped into the singlet state, providing the basis for an annihilation gamma ray laser [24,25] and a measurement of the Compton wavelength with an uncertainty comparable to its part in $10^{11}$ linewidth.

Antimatter gravity and gamma ray laser studies are, to say the least, technically demanding experiments, and their realization will almost certainly require some advances in positron generation and accumulation technology. However, underpinning this exciting work are the experiments currently underway, and in particular the most significant advances will be predicated upon the existence of a Ps BEC. The demonstration of such therefore represents a crucial milestone on this experimental path.

As a purely leptonic, matter-antimatter system, positronium is very well suited for the study of quantum electrodynamic (QED) effects in bound systems [26,27,28] via spectroscopy of it's energy levels and measurements of its decay rate [29]. Indeed, theoretical calculations of positronium energy levels and annihilation rates are actually at a higher level of precision than experimental measurements [30]. The main reason for this is that the difficulties associated with producing useful antimatter particles mean that experimental measurements of Ps are generally limited by statistical rather than systematic effects.

Hydrogen and muonium are also systems that offer the possibility of stringent QED tests [31], but each have their own attendant difficulties. In the case of hydrogen, the proton structure limits the applicability of pure QED, and uncertainty in the muon-electron mass ratio means that precision muonium measurements cannot currently be used to test QED to high precision.

Precision measurements of positronium would be made even more accurate using a Ps BEC since the second order Doppler shift would be greatly reduced. For example, the present theoretical value for the 1S-2S interval in positronium is accurate to 0.5 ppb (parts per billion) [32], while the best measurement to date is accurate to 2.6 ppb [33]. Even without a BEC it should be possible to measure this interval to within ~ 50 KHz, or about 0.05 ppb. However, a positronium atom laser would make an ideal source for this measurement, with a possible precision of order < 0.001 ppb. Positronium is believed to be fully described at this level of precision in terms of pure QED theory, and a positronium 1S-2S measurement of this accuracy could be directly related to the fundamental constants, allowing an improved interpretation of more

precise standards such as the hydrogen 1S-2S interval. The experimental values of the positronium ground state hyperfine splitting (hfs) (that is, the difference in the ground state energies of the singlet and triplet states) are even less well known, and presently do not agree with the theoretical value (although the discrepancy is only 4 standard deviations and so does not necessarily imply any new physics). The best measurement so far is accurate to 3.6 ppm [34], with another measurement at 7.9 ppm [35] while the most recent theoretical value is known to 0.8 ppm [36]. For some time the experimental values were known to a higher accuracy than the theoretical values, but this is no longer the case; thus, it is timely to re-visit these measurements. Because QED is so fundamental and because it is exactly applicable to these measurements a persistent discrepancy could indicate new physics, which would have profound implications for the standard model.

## EXPERIMENTAL TECHNIQUES

The production of positron plasmas from a radioactive source and a buffer gas trap has been discussed at length in the literature [1, 7] and we shall offer only a brief outline here as our arrangement is not very different from the standard Surko trap. A slow mono-energetic positron beam of around $5 \times 10^6$ $s^{-1}$ was generated using a ~ 30 mCi $^{22}Na$ source and a neon moderator [37]. This beam was used to supply a positron trap and accumulator that produced plasmas containing around $5 \times 10^7$ positrons in a ~1 mm FWHM spot every minute or so (in a 500 G axial magnetic field). These positron plasmas are long lived, with lifetimes well over 1000 seconds, mostly due to the confinement afforded by a rotating electric field [38, 39] that essentially eliminates cross field transport, a leading loss mechanism [40]. This field is applied using segmented electrodes in the accumulator and as well as aiding confinement also increases the positron density. A schematic of the source, trap and accumulator layout is shown in Fig. 1.

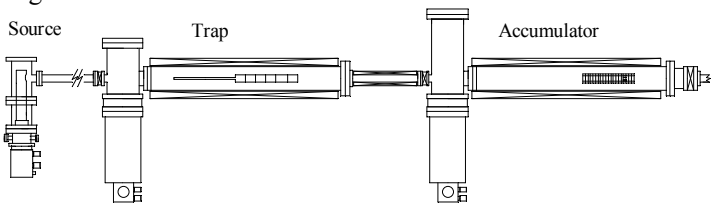


**FIGURE 1.** A schematic layout of the positron source, accumulator and trap. This system is essentially the same as a standard Surko trap except that the final accumulation region is in a separate vacuum system, which allows us to obtain long lifetimes since the pressure is reduced.

The compression of the positron plasmas in time means that we cannot use the usual detection methods, since the intense sub-ns gamma ray pulse will saturate most detectors. To avoid this we use either a $PbF_2$ Cherenkov emitter or a $PbWO_4$ scintillator [41]. Both of these have very low light outputs (<1% of that from NaI) and mitigate the problem of saturation. The positron beam density is controlled via the parameters of the "rotating wall" electric field in the accumulator. This allows us to reduce the density by a factor of ~ 5 without changing the magnetic fields, which

means that parameters that depend on the field, such as beam transport, detector efficiency and the Zeeman mixing of the positronium m = 0 substates, do not change when the beam density is varied.

The positron plasmas are ejected from the accumulator by a parabolic potential, rapidly applied across the extent of the trapped plasma, which produces a pulse about 30 ns wide (FWHM). A secondary high voltage buncher downstream further compresses this to a sub-ns pulse (typically, 0.8 ± 0.1 ns). A pulsed magnet coil around the target region produces a field of around 1.5 T which compresses the beam spot to ~ 300 microns or less. (NB: these numbers tend to vary depending on the particular experimental requirements, but the maximum final positron beam areal density is always close to $4 \pm 1 \times 10^{10}$ $cm^{-2}$, which may be due to limitations in the RF signal we can apply to the plasma in the accumulator). The firing sequence for the magnet and bunchers is shown in Fig 2.

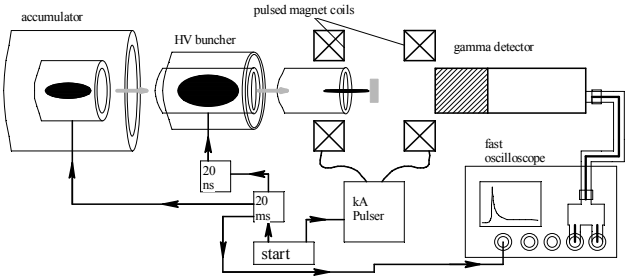


**FIGURE 2.** The firing sequence for data acquisition using SSPALS. As soon as the positron accumulation phase is complete and all required plasma manipulations have been performed a start signal begins the sequence. Because of its inductance it takes around 20 ms for the magnet to come on, and the HV buncher must be delayed by around 20 ns to account for the transit time of the positron plasma from the accumulator.

The technique of single shot positron annihilation lifetime spectroscopy (SSPALS [42]) involves recording the voltage output from a photomultiplier tube (PMT) directly using a fast oscilloscope following the implantation of an intense positron pulse into a target. The timing resolution of this method is presently ~ 3 ns, mostly due to the response of the PMT. This is more than an order of magnitude worse than may be obtained using conventional lifetime spectroscopy methods [43], but obviously such methods cannot practically be used for measuring what are effectively transitory phenomena. Moreover, the entire system response (including characteristics of the PMT as well as amplifier noise, cable reflections etc) is folded into lifetime spectra obtained in this way, which further complicates later analysis. Despite these limitations, however, changes in the lifetime spectra as a function of the beam density due to Ps-Ps interactions are clearly evident, as is detailed below.

It is not practical to increase the positron beam density by using a stronger magnetic field, and so the next beam upgrade will involve the addition of a remoderation stage [44] before the target. This process involves focusing the beam into a small spot on a remoderator foil (in this case a ~ 100 nm thick Ni foil will be used). The transverse energy given to the beam by the focusing is dissipated, and the phase space of the re-emitted beam is significantly reduced (since the thermalisation

process is non-conservative). Even though the total efficiency of the remoderation process is low (around 10-20%) the beam density is greatly increased by this process. In order to do this is it is necessary to extract the beam from the magnetic field, after which electrostatic lenses are used to transport and focus the positrons. We expect that this will increase the beam density by at least two orders of magnitude.

## POSITRONIUM-POSITRONIUM INTERACTIONS

When positrons are implanted into certain porous materials (such as silica) positronium may form in the bulk material and diffuse into the internal voids [45]. Ps atoms that diffuse into the voids cannot generally re-enter the bulk material, and so they tend to diffuse through the voids. If these voids are interconnected, and if the incident positron beam density is high enough, it is possible for such Ps atoms to interact with each other, which is the basis for some of our experiments using silica films with both randomly distributed and aligned pores (of around 3-5 nm diameter). In the experiments we have conducted so far we estimate that each Ps atoms visits around $10^4$ pores during its lifetime, but that the density corresponds to around 1 Ps atom per $10^5$ pores. That is, there is about a 10% chance of Ps atoms interacting with each other. Nevertheless, even this small interaction rate leads to perturbations in the lifetime spectra that are readily apparent, and it has been possible to study Ps-Ps interactions in this way.

Ps atoms in nano-meter sized cavities behave in essentially the same way as they do in vacuum, except that their lifetime may be determined primarily by "pick off" annihilation following interactions with the cavity walls [46] (if the cavity walls contain paramagnetic centers (i.e., unpaired electrons) then this process can drastically reduce the lifetime [47]). In our previous work we observed lifetimes between 20-50 ns, which is long enough for Ps-Ps interactions to occur. When this happens the Ps decay rate may be increased due to various different processes, namely, SEQ and $Ps_2$ formation. We may describe these processes in the following way:

1. $o-Ps_{m=1}+o-Ps_{m=-1}\rightarrow p-Ps+p-Ps+2E_H$
2. $o-Ps_{m=1}+o-Ps_{m=-1}\rightarrow o-Ps_{m=0}+o-Ps_{m=0}+2E'_H$
3. $X+o-Ps_{m=1}+o-Ps_{m=-1}\rightarrow X+Ps_2+E_b$

Here o-$Ps_m$ refers to the long lived ortho-positronium in the magnetic substate m, p-PS to the short lived para-positronium, $E_H$ is the relevant hyperfine energy difference between the states, X refers to a third body (surface) necessary for $Ps_2$ formation to conserve energy and momentum and $E_b$ is the $Ps_2$ binding energy (~ 0.44 eV [48]). In process (1) two triplet atoms are converted to singlets and thus decay rapidly, which increases the decay rate. Similarly, in (2) m = 0 triplets result from the collision, and because of the strong magnetic field these atoms are quenched and decay quickly, also increasing the decay rate. Finally, when molecules are formed (3) the resulting lifetime is 0.25 ns [49], and mean decay rate observed is again increased. Because these are all small changes in the total lifetime spectrum it is not possible to resolve them with our present arrangement, and in effect they all look the same with respect to

the timing data. That is to say, using timing data alone we cannot tell the difference between these processes [4].

The difference in the lifetime annihilation spectra caused by Ps-Ps interactions is a non-linear perturbation that may be described by the following differential equation for the density $n$ as a function of time $t$:

$$\frac{dn}{dt} = -\gamma n(1+\beta n) \tag{1}$$

Here $\gamma$ is the decay rate, which we assume here is determined only by the pick off annihilation (in reality there may be several components, including one due to the self annihilation, but these may be neglected here) and $\beta$ represents the non-linear part due to Ps-Ps interactions. If $\beta$ is equal to zero we have the usual exponential decay (with one component) and this parameter is therefore a measure of the extent to which Ps-Ps interactions occur. Re-write equaton (1) as

$$-dt = \frac{dn}{(\gamma n)(1+\beta n)} = dn\left(\frac{1}{\gamma n} - \frac{\beta}{\gamma(1+\beta n)}\right). \tag{2}$$

Integrating we obtain,

$$-\gamma t + C = \ln(n) - \ln(1+\beta n) \tag{3}$$

$$\frac{n}{1+\beta n} = C_0 \exp(-\gamma t)\,. \tag{4}$$

If the number of atoms at time t = 0 is $n_0$ we have $C_0 = \frac{n_0}{1+\beta n_0}$. Then,

$$n = \frac{n_0}{(1+\beta n_0)\exp(\gamma t) - \beta n_0.} \tag{5}$$

(which of course yields the usual decay rate when β = 0). Figure (3) shows simulated lifetime spectra for various values of β, assuming an arbitrary linear decay rate of 0.02 $ns^{-1}$. It is clear that as β increases the initial decay rate also increases, as we would expect. Real lifetime spectra are obviously more complicated than this, but the additional components such as the prompt annihilation peak, detector noise, PMT response, other lifetime components etc are constant, so that by taking a difference spectrum between a high density and a low density beam (for which we would expect some approximation to β > 0 and β = 0 respectively) all of these will be subtracted out.

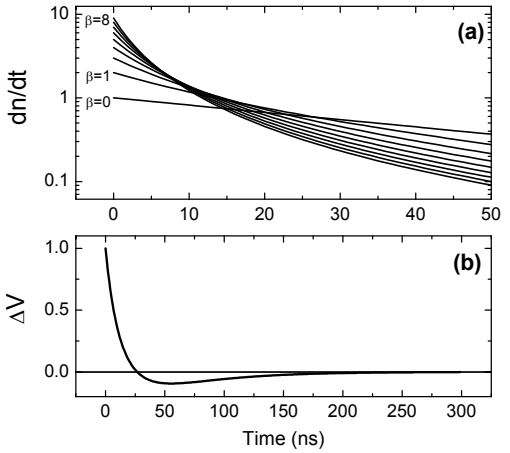


**FIGURE 3.** (a) A representation of idealized lifetime spectra (area normalized) for different values of the parameter β. (b) Difference spectra obtained by subtracting the interacting case (β =1) from a spectrum in which β =0. If features that do not depend on the beam density are entirely subtracted out then the resulting difference spectra obtained using real data should have a form similar to that shown in (b).

We fit the difference spectra to a function of the form:

$$\Delta V \propto dn(t,\beta)/dt - dn(t,0)/dt = A\gamma\left(\exp(-\gamma t) - \frac{(1+\beta)\exp(\gamma t)}{[(1+\beta)\exp(\gamma t) - \beta]^2}\right) \qquad (6)$$

where A is an arbitrary scaling parameter. Fits of this type of function to our data indicate that there is indeed a non-linear, density dependent component to the lifetime spectra and hence also provide further evidence that we are observing Ps-Ps interactions.

In order to distinguish between SEQ and $Ps_2$ mechanisms, additional data beyond lifetime spectra are required. Such data may be obtained by considering the properties of the sample in which the Ps is formed. In particular, since the formation of $Ps_2$ requires a third body it is, at least at the present densities obtained, constrained to take place on a surface. Thus, the rate for this process (if it occurs at all) may depend on the population of surface states. It is well known that surface Ps may be thermally desorbed [50] so that, under the right circumstances, the $Ps_2$ formation rate is a function of sample temperature. No such dependence would be expected with SEQ since this process likely occurs primarily between non-thermal Ps atoms, and in any case would only depend weakly on the temperature. However, SEQ can be affected by the structural properties of the sample since the outgoing states must be able to accommodate the hyperfine triplet-singlet energy difference.

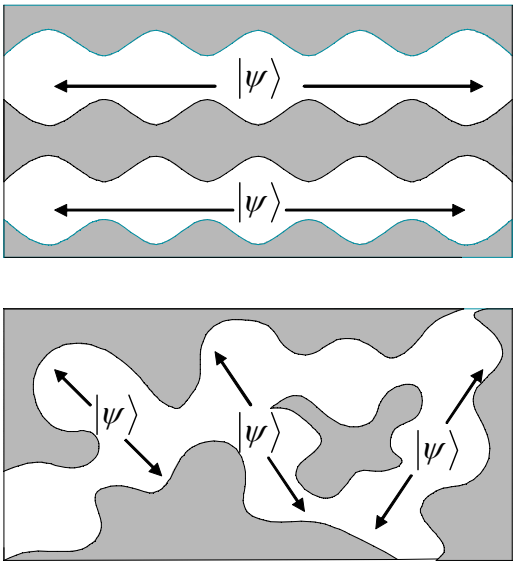


**FIGURE 4.** Two separate targets with interconnected pores were used. The top panel shows a target in which the pores are aligned into 1-dimensional channels, which means that there is a continuum of accessible eigenstates for Ps atoms contained therein. The bottom panel is a representation of a sample in which the pores are interconnected but randomly orientated; here, at low energies, only discrete eigenstates are accessible.

Figure 4 depicts samples of porous silica films with different pore structures. The top panel shows pores aligned along one dimension, while in the bottom panel the pores are randomly aligned. If the pores are aligned then there will be a continuum of eigenstates accessible to Ps atoms, and thus SEQ will be allowed. For randomly aligned pores this is not the case, and at low energies the accessible eigenstates will be discreet and SEQ will be suppressed. Since the Ps atoms have to diffuse to find each other it is unlikely that SEQ will take place between energetic (that is, non-thermalised) particles, for which this suppression may not occur. At higher densities, however, this will not necessarily be the case.

Although SEQ appears to be suppressed in the randomly aligned sample, we did observe that the amount of long lived Ps present increased with temperature, while the quenching effect Q (which depends on the value of β) decreased. This is shown in figure 5. We interpret these data as being due to the thermal desorption of surface state Ps. When the Ps is desorbed it lives longer in the voids, but is unable to form $Ps_2$ and, due to the nature of the pore structure, the desorbed Ps is unable to then take part in SEQ interactions. No temperature dependence of the Ps yield or the quenching effect was observed with the aligned sample, indicating that there was no surface state present and therefore no $Ps_2$ formation therein.

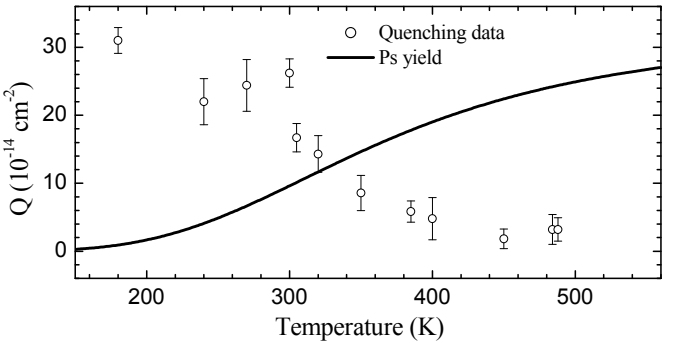


**FIGURE 5.** The quenching data and Ps yield as a function of temperature. The Ps yield is scaled to match Q which itself depends on the parameter β (see ref [8] for details). The fact that the quenching goes down while the Ps yield goes up with temperature suggests that the quenching process depends directly on the population of the surface state, which indicates the formation of $Ps_2$ via positronic surface states.

Figure 6 shows lifetime and difference spectra for the two samples described above. As is evident from these data, we have been able to confirm that various Ps-Ps interactions have been observed in more or less the expected manner. While it is interesting to study both the spin exchange quenching process [10] and the formation of $Ps_2$ [8], the primary objective of our research is to collect an ensemble of spin aligned Ps atoms in a large cavity and form a Bose-Einstein condensate [24]. Even without forming a condensate, however, a dense collection of cold Ps atoms may still be used to perform precision spectroscopy measurements.

In the samples used so far the Ps most likely cools to near room temperatures in ~10-20 ns via collisions with the cavity walls. However, for the larger voids needed to produce a high density Ps cloud the thermalisation rate of Ps is expected to be rather low. Saito and Hyodo have estimated that in a cavity $0.1 \times 0.1 \times 1$ μm$^3$ (as envisioned for the production of a Ps BEC [11]) the time to cool to the ambient temperature is significantly longer than the lifetime [51]. This suggestion is supported by a number of experiments in which Ps atoms in cold samples (< 50K) do not reach thermal equilibrium, so that below a certain temperature (that depends on the pore size) the decay rate no longer depends on the sample temperature [52, 53].

While the exact thermalisation rate will depend on a number of parameters other than the size of the cavity (such as the internal surface chemistry [54] or the presence of a cooling gas [55]) it seems clear that collisional cooling will be insufficient to produce a Ps BEC unless we are able to achieve densities of around $10^{19}$ cm$^{-3}$ or much smaller cavities are used. We estimate that with the present experimental arrangement the maximum Ps density obtained is ~ $10^{15}$ cm$^{-3}$. In order to increase this we intend to remoderate the beam [44,56] which we expect to increase the density by at least two and possibly as much as three orders of magnitude. However, this methodology is not expected to produce densities higher than this, and so laser cooling of the Ps will be employed.

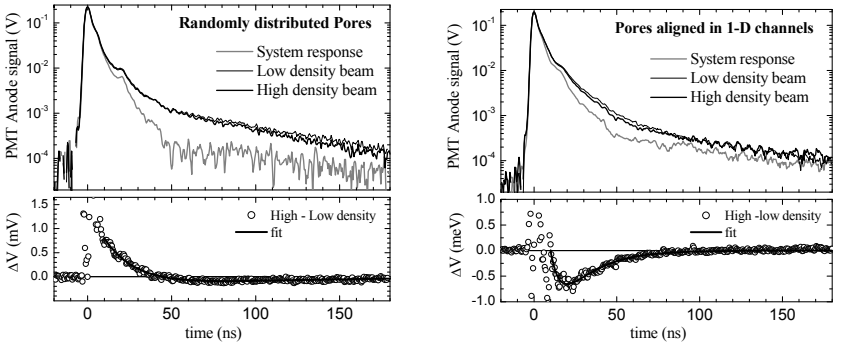


**FIGURE 6.** Lifetime data obtained using the samples with randomly distributed and aligned pores, as shown in the legends. As explained in the text, the former data are attributed to the formation of $Ps_2$ and the latter to SEQ. The lower panels show the difference spectra for both cases (*cf* Fig 3 (b)).

## LASER COOLING OF POSITRONIUM

Increasing the Ps cooling rate using lasers [24] will significantly relax the Ps density requirements for making a BEC and also allow high precision measurements to be made. Laser cooling of positronium has not yet been demonstrated experimentally, although a number of simulations have indicated that it is feasible [57]. We envisage cooling Ps via the 1S-2P transition using 243 nm light. Ps laser cooling is not intrinsically different from ordinary laser cooling. However, because of its relatively low mass, the Ps 1-photon recoil limit (~0.6 K) is much larger than the Doppler limit (~7.5 mK) and represents the minimum temperature one can realistically expect to obtain. (Compare this with Na, which has a recoil limit of 2.4 μK and a Doppler limit of 240 μK, (using the $3p\ ^2P_{3/2}$ - $3s\ ^2S_{1/2}$ transition [58])). Thus, more advanced sub-Doppler cooling techniques (e.g., Sisyphus cooling [59]) cannot be used, although their utility would be limited in any case, due to the short Ps lifetime.

Positronium is emitted into cavities in silica with an energy of ~ 1 eV [60, 61] and, initially, cools rapidly via collisions to ~ 0.2 eV. However, the cooling rate falls off with the temperature, and it may then take many 100's of ns to thermalise [51, 62]. The mean number of absorptions required to laser cool Ps from ~100K to the recoil limit via laser cooling is ~ 30. For a sufficiently powerful laser at > 10 times the saturation intensity (1.3 W/cm$^2$ per 50 MHz bandwidth), nearly half of the Ps atoms will always be in the 2P state (lifetime>>1μs) and hence the mean lifetime will therefore be almost twice that of the ground state (i.e., 284 ns). Thus, cooling from 100K to 0.6 K will be accompanied by the loss of about half the positronium atoms due to self anihilation.

The spontaneous lifetime of 2P Ps is 3.2 ns but at high optical intensities the fastest the atom can be recycled is 6.4 ns. Thus the minimum time for 30 absorptions is ~200 ns. We will use 300 ns duration, 243 nm, 40 GHz linewidth pulses, made by third-harmonic generation of a ~ 500 ns duration 729 nm pulse from a Q-switched and pulse-stretched alexandrite laser, producing at least 20 mJ/pulse at 243 nm. When

focused to a Gaussian diameter of 3 mm, the peak intensity in the 3-d cooling beams will each reach 580 KW/cm$^2$ over a 40 GHz linewidth, which is 580 times the saturation intensity.

The Doppler width is 380 GHz at 100K, and by detuning the cooling laser to -95 GHz (red-shift) from the line center, we will predominantly decelerate atoms. The laser-cooling spectrum will be further shaped by adding a 24 GHz notch using a high finesse Fabry-Perot interferometer in reflection. This will reduce the probability of absorption for atoms within the ±2 photon recoil limit and suppress over-cooling. We will further shape the time-profile of the cooling laser pulse using a Pockel's cell pulse slicer. Ending the cooling pulse with high contrast and timing precision is essential in order to do precision optical spectroscopy of the cooled atoms. If the positronium is not confined to a cavity (as it would be for BEC formation) then during the cooling process, a small diameter swarm of triplet Ps atoms will expand from an initial sub mm radius to about 1.7 mm rms radius due to the accumulative effect of about 30 random momentum kicks. The first order Doppler spread of the cooled Ps will be around ±10$^{-5}$, small enough for extrapolated measurements of the Ps hyperfine interval to a precision of about 100 kHz (0.5 ppm) and of the 1$^{st}$-order Doppler free 1S-2S interval to about 30 KHz (3 part in 10$^{11}$).

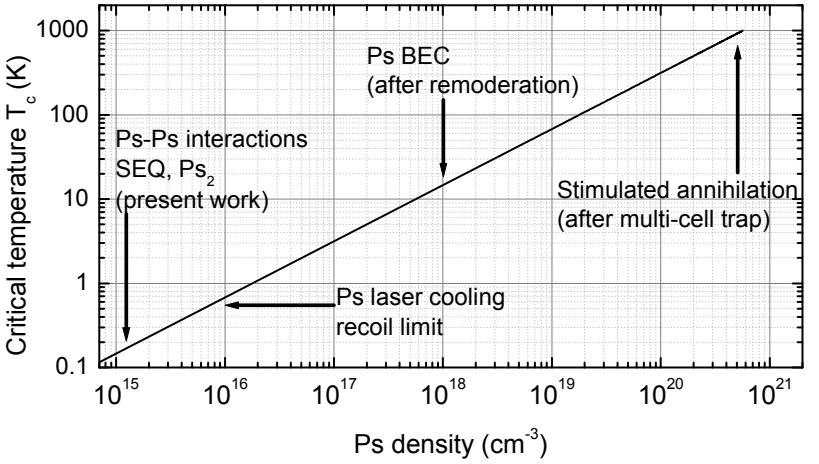


**FIGURE 7.** The critical temperature for a Ps BEC as a function of density with indications of present and future areas of study.

Figure (7) shows the Ps BEC critical temperature a function of the Ps density. If the Ps is laser cooled to near the recoil limit then only a modest increase of around one order of magnitude in the present Ps density will be required. Thus, with the expected density after remoderation of ~ 10$^{18}$ cm$^{-3}$, there would be some latitude for variations in the experimental parameters.

## PRECISION OPTICAL SPECTROSCOPY

The positron beam in its present state could be utilized for precision optical spectroscopy measurements, and these would be greatly improved as the beam development continues. For the initial experiments the positron beam would be extracted from the magnetic field, in the same way as described above, but without remoderating. Using the $^{22}$Na source this would mean extracting a 1 mm diameter beam of ~ $5\times10^7$ positrons from a 500 G field. This beam could be brought into a field free region and electrostatically focused to a spot with less than 2 mm diameter onto a cooled silica target.

It is known that positronium emitted from powdered $SiO_2$ has an energy distribution that has a low energy tail, caused by scattering of atoms as they diffuse out into the vacuum [53]. Thus, we may envisage an experiment in which some fraction of the Ps emitted from a silica sample (or some other similar material) will be at temperatures below around 100 K. These atoms would enter a Fabry-Perot cavity tuned for 486 nm in which counter-propagating beams would excite the Doppler-free two-photon 1S-2S transition [63]. Three dimensional laser cooling using the 1S-2P transition as discussed above would be timed to slow the atoms to spend a significant amount of time in the 1S-2S excitation field defined by a 3 mm Gaussian diameter. These excited atoms in the 2S state would then be ionized by a Nd:YAG pulse at 532 nm, and the resulting positrons would be guided to a channel electron multiplier array where they could be detected with high efficiency. If only 1% of the emitted Ps atoms were cold enough (100K) and emitted into the solid angle to be stopped within the 3 mm diameter 1S-2S beam interaction region located 6 mm in front of the $SiO_2$ sample, and as few as 10% of those were cooled to stay within the 1S-2S beam interaction region, we could excite 5% of the population to the 2S state. If we then wait an additional 142 ns after the cooling pulse ended to assure no remnant of the 2P excitation remained and we photoionize 50% of the atoms in the 2S state, then, with $5 \times 10^7$ positrons injected per pulse (and a Ps formation fraction of 0.3) we would expect to detect around 50 positrons per pulse.

Since it takes ~100 seconds to fill the accumulator we could then expect approximately $10^4$ counts in a 12 hour run using the procedure outlined above. This would allow a 20 point spectral measurement of the 1.3 MHz natural linewidth (at 200 KHz intervals) to be made to ~ 3% photon-counting uncertainty in a single day, and a 100 point spectral measurement at 40 KHz intervals with 1% uncertainty per point in ~ 50 days. The 1S-2S interval is presently known to 1 MHz accuracy; a 40 KHz per point measurement with curve-fitting could easily locate the line center to within 10 KHz and provide an improvement of two orders of magnitude in the resolution over the current state of the art, and far exceeding the expected accuracy of the currently calculated value.

Using similar techniques it would also be possible to measure the hyperfine splitting (hfs) of the ground state energy levels of positronium [35] in the following way: A 203 GHz, 300 ns duration pulse with ~2X transform-limited bandwidth (<3 MHz linewidth) and 3 mm diameter could be directed into the laser-cooled atoms and double-passed back through the atoms using a mirror. The required 203 GHz pulse could be generated by difference-frequency generation of two 972 nm laser pulses

frequency separated by 203 GHz in phase-matched ZnTe, with the two 972 nm pulses formed by amplifying the output of two cw diode lasers each locked to comb lines separated by 203 GHz from a frequency-comb generator. The difference frequency would be controlled via the frequency comb generator, and by an additional ±10 MHz using an acousto-optic modulator on one of the beams. The two 972 nm beams would seed a multi-stage parametric amplifier pumped by the residual ~100 mJ, 400 ns, 364.5 nm SH output of the cooling laser system. (Only the 3rd harmonic is used for cooling). The seed beams would propagate collinearly and overlap spatially to experience identical gain dynamics. The two 400 ns duration 972 nm pulses would be amplified to ~5 mJ pulse energy, and after phase-matched difference-frequency generation, we expect ~12% photon conversion or ~ 0.3 μJ of 203 GHz output.. This optical pulse would be directed to the laser-cooled atoms as in the 1S-2S measurement. Over a 3 mm Gaussian diameter, the intensity at 203 GHz would be 17 W/cm$^2$ over 3 MHz linewidth.

Under this field Ps atoms in the longer-lived triplet state (142 ns lifetime) would be driven to the shorter lived singlet state (0.125 ns lifetime) and we would detect the absorption of 203 GHz via a change in annihilation rate correlated with the presence of the 203 GHz optical pulse. Because the spectral linewidth will be ~ 3 MHz (shaped by the amplification gain dynamics) we would expect to be able to determine the line center to around 1 MHz accuracy in a short time using measured spectral widths of the 972 nm pulses and simple modeling of the difference-frequency spectrum. This will be relatively accurate because the two 972 nm seed pulses will experience exactly the same amplification dynamics and therefore any amplification-dynamic-induced frequency chirps will be similar for the two pulses and cancel to first order in the difference frequency. Further improvement of the hfs interval to 0.1 MHz accuracy may be possible, but would require higher signal to noise measurements as well as shot-to-shot measurement of the temporal shape of the 972 nm pulse with a fast photodiode and high resolution fast digitizing oscilloscope in order to correct the source lineshape on a shot-to-shot basis.

All of the precision measurements could be improved by using positronium in the BEC state in the form of an atom laser emitted from a cavity. This would be done in essentially the same way as described above, except the cooling lasers would act on positronium confined to a cavity, and the 1S-2S excitation and ionization would occur after the BEC had formed and been emitted into the vacuum. Since all the positronium atoms in the Bose-Einstein condensate in a cavity have the same phase, they will form a plane wave traveling away from the surface of the positronium forming target, essentially forming a positronium atom laser [64]. The atoms will be rapidly emitted from the cavity due to stimulated tunneling through the pores in the cavity wall. The de Broglie wavelength, $\lambda_{dB}$, of the emitted positronium atoms will be twice the thickness of the cavity (*i.e.* $\lambda_{dB}=2d$). The diffraction width of the positronium beam will therefore be $\theta \approx 2d/D$. With a cavity diameter $D$= 4 μm and thickness $d$= 100 nm, the beam will have a divergence half angle $\theta \approx 25$ mrad. Because of their very low energy and monochromatic velocity distribution, these atoms would be ideally suited for precision two-photon first-order Doppler free measurements of the triplet 1S-2S interval. The second-order Doppler shift would be only $2\times10^{-11}$ for a cavity 100 nm thick. The slow positronium in vacuum could be excited by the standing wave laser

field in a high finesse Fabry-Perot cavity and the excited atoms would then be photoionized and the free positrons detected with high efficiency by an electron multiplier. The signal at the peak of the 1S-2S resonance would be about $10^4$ counts per pulse, permitting one to achieve a statistical precision of $10^{-3}$ of the linewidth or 1 part in $10^{12}$ in 100 positron shots corresponding to about 30 hours of measurements. (NB: for making a Ps BEC the time needed to fill the accumulator would be ~ 1000 seconds). There would thus be sufficient data to study various cavity induced systematic effects in detail. As discussed previously, the laser metrology should enable better than 1 KHz absolute accuracy (1 part in $10^{12}$) due to use of the optical frequency reference comb generator [65]. The hfs measurements would also be improved by using a Ps atom laser.

## DETECTION OF BOSE-EINSTEIN CONDENSED POSITRONIUM

A collection of spin polarized Ps atoms sufficiently cooled will spontaneously undergo a phase transition and form a BEC, but in many ways the properties of the Bose-Einstein condensed atoms will be similar to those of a non-condensed thermal cloud of atoms slightly above the transition temperature, and the final challenge on the path to produce a Ps BEC is to unambiguously detect its presence.

There will be a negligible difference between the lifetime of a BEC and a cold ensemble of Ps atoms and so annihilation lifetime spectroscopy will be unable to distinguish between them. The most convincing signal of positronium BEC would be a measurement of a sudden narrowing of its parallel momentum distribution to that corresponding to the lowest energy state of the cavity in which it is formed; we intend to observe this via the first order Doppler width of an optical transition. Laser light directed on the Ps in the cavity will have a significant component parallel to the target surface (i.e, along the long axis of the cavity) and thus the Ps Lyman-alpha resonances will be tens of GHz in breadth unless a macroscopic fraction of the atoms are in the cavity ground state. Bose-Einstein condensation will thus be detected from the fact that exactly on the 1S-2P resonance the transmission of the Lyman-alpha light through the cavity will drop significantly if the positronium is in the condensed state.

The Lyman-$\alpha$ probe pulses will be ~ 6 ns in duration and tunable around 235.5 nm, with <30 GHz linewidth. They will be made by sum-frequency generation of the 3$^{rd}$-harmonic of Nd:YAG (355 nm) and the tunable 701 nm output of a Nd:YAG pumped dye laser in phase-matched BBO. Narrower linewidth pulses (<6 GHz) can be achieved for higher resolution spectroscopy by adding an intracavity etalon in the dye laser. Not only will this make it possible to obtain definitive evidence for the presence of a Ps BEC, it would also allow us to experimentally investigate the Ps phase diagram, which would be a significant advance in experimental antimatter chemistry. Measuring the critical temperature as a function of density is of intrinsic scientific interest, and also has much practical value for later work directed towards initiating and studying stimulated annihilation of a Ps BEC.

## CONCLUSIONS AND OUTLOOK

We have started a program of experimentation on many-positron, many-electron systems. So far our work has been limited to observing interactions between pairs of Ps atoms, but the methods used are scalable, and we expect to be able to observe interactions between many thousands of atoms with only minor modifications to the experimental procedure. These techniques, combined with laser cooling of Ps, will make it possible to conduct precision spectroscopic measurements of Ps, and to create a Ps BEC. Using proven technology it seems highly likely that we will be able to create a Ps condensate, and even with the present beam parameters we are confident that, with the right laser systems, we will be able to improve on the best precision 1S-2S measurements by at least an order of magnitude. This area of experimentation is in its infancy, and we have no doubt that there is much exciting work to be done; it is our hope that the modest results we have been able to obtain so far will encourage others to join us in undertaking this work.

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