Positronium: Old Dog, New Tricks

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1951: First production of positronium by Martin Deutsch

100 ns lifetime of triplet Ps

From M. Deutsch
Phys. Rev. 82, 455 (1951)
Ps production further improved using beams (1972) which can interact with surfaces more efficiently: almost any target will create some Ps in vacuum.

The metastable electron-positron bound state can exist in different configurations depending on the relative spin states of the positron and the electron. These are known as para-positronium (p-Ps), with total spin $S = 0$ and ortho positronium (o-Ps) with $S = 1$. These spin states have very different lifetimes:

\[
|S, m\rangle = |0, 0\rangle = \frac{1}{\sqrt{2}} \left( |\uparrow \downarrow\rangle - |\downarrow \uparrow\rangle \right)
\]

$\tau_{\text{p-Ps}} = 125$ ps

\[
|S, m\rangle = |1, 0\rangle = \frac{1}{\sqrt{2}} \left( |\uparrow \downarrow\rangle + |\downarrow \uparrow\rangle \right)
\]

$\tau_{\text{o-Ps}} = 142$ ns

\[
|S, m\rangle = |1, 1\rangle = |\uparrow \uparrow\rangle
\]

\[
|S, m\rangle = |1, -1\rangle = |\downarrow \downarrow\rangle
\]

Any process that converts o-Ps to p-Ps is easy to see in lifetime spectra.
Energy levels of hydrogen and positronium

\[ E_n(H) = -\frac{\mu e^4}{2\hbar n^2} = -\frac{1}{n^2} \times 13.6\text{eV} \]

\[ \mu_H = \frac{m_e M}{m_e + M} \approx m_e \]

\[ \mu_{Ps} = \frac{m_e^2}{2m_e} = \frac{m_e}{2} \]

\[ E_n(Ps) = -\frac{1}{n^2} \times 6.8\text{eV} \]

Gross energy levels are half that of H. The large positron magnetic moment makes the “hyperfine” splitting much larger than is the case for H.
Ps energy levels: excited state Zeeman mixing leads to fast annihilation.

S. M. Curry, Phys Rev A 7 447 (1973)
1982: first laser excitation of Ps: 1S-2S Chu and Mills

\[ \frac{3}{16} R_\infty - \frac{3}{14} \Delta \nu_{\text{hfs}} + \cdots \]

2 photon resonant 3 photon ionization of triplet Ps
Measurement of the Positronium $1^{3}S_{1} - 2^{3}S_{1}$ Interval by Doppler-Free Two-Photon Spectroscopy

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and

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(Received 27 February 1984)

Positrons obtained from a d.c beam and magnetic bottle trap:
$\sim 20$/pulse 20 ns
Positrons obtained from an electron Linac (pair production) 
$\sim 10^5$/pulse (15 ns)  
But only one count per pulse!
Measurement of the Positronium $^{1}S_{1}$-$^{2}S_{1}$ Interval by Continuous-Wave Two-Photon Excitation

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(Received 1 October 1992)

Positrons obtained from a microtron
\~$10^{4}$/pulse 25 ns

\[ \nu \left( ^{1}S_{1}-^{2}S_{1} \right) = 1233607216.4 \pm 3.2 \text{ MHz} \]
Ps has been available in the lab for 60+ years: Why so few optical experiments?

- Dc beams $\sim 10^6$-$10^7$ e$^+/sec$ (MAX) $\rightarrow$ Ps production: around 1MHz
- Hard to get enough laser power at this rep rate (and you would need to know when each Ps atom is made)
- Either have to (1) make a high power CW laser (i.e., with a build up cavity) or (2) bunch the positron beam and use a pulsed laser at lower rep rate
- Previous experiments used a LINAC (or microtron) to get a pulsed beam: not very practical for a university laboratory
- Build up cavities can be hard to set up and operate for long periods of time (as is typical in a positronium experiment), and Ps source has to be in the cavity
- *Surko traps now make pulsed beam production feasible for a typical university lab, and thus facilitate laser spectroscopy of Ps, & single shot lifetime measurements provide an easy detection method*

$\rightarrow$ *There are now many more opportunities for Ps experimentation*
Principal of operation of the Surko buffer gas trap:

Positrons lose energy by collisions with $N_2$ gas and become trapped in potential well.

Collected positrons can be ejected and bunched to $\sim 1$ ns wide: d.c beam is converted into a pulsed beam.

High voltage parabolic buncher provides sub-nsec pulse widths with $10^7$ positrons/pulse.


RSI 77, 073106 (2006)
Spatial compression:
Positron plasma storage depends critically on rotating wall compression
Zero frequency modes limit compression but can be partially mitigated by correction coils

Strong drive RW compression invented by Danielson & Surko PRL 94 035001 (2005)
We use “single shot” lifetime spectroscopy to determine how much Ps is created ($f_d$), and the effects of laser irradiation ($S$), where

$$f_d = \frac{\int_{50 \text{ns}}^{300 \text{ns}} V(t) \, dt}{\int_{-50 \text{ns}}^{300} V(t) \, dt},$$

Direct positron annihilation and singlet Ps contribute to the prompt peak

$$S = \frac{f_d (\text{off}) - f_d (\text{on})}{f_d (\text{off})}$$

2P states will develop a singlet component in a magnetic field, changing the lifetime and thus reducing $f_d$

These spectra are obtained simply by connecting a fast gamma ray detector to a fast oscilloscope

A low background can be achieved by collecting the trapped positrons after a long delay. Or one could use a channeltron to detect the positrons directly (can be tricky in a high magnetic field)

We don’t generally use this method because the lifetime spectrum signal is very easy, but some version of it may be necessary for looking at low numbers of Rydberg atoms
Despite thermal “activation” in yield curve, Ps energy doesn’t depend on target temperature.
Si and Ge (probably other semi conductors as well) produce monoenergetic Ps via an exciton-like surface state. Laser irradiation promotes this process and produces more Ps so the target will survive and stay clean and produce Ps at any sample temperature.

It is possible that this Ps formation mechanism can be used to produce monoenergetic and/or cold Ps if the surfaces are prepared in the right way.

Initial work suggests that Photoemission of Ps is just as efficient at low temperatures, and it should be possible to efficiently produce Ps at any sample temperature.

PRL 107 033401 (2011)
Spectroscopy of Ps: correlate changes in the Ps annihilation rate with the laser wavelength $\lambda$


Ground state mixing of $m = 0$ singlets and triplets leads to reduced Ps fraction.

Quenching is suppressed for very high fields so making laser cooling feasible.

Lamb dip and hyperfine crossover resonance with one and two UV beams (relies on quenching)
All optical measurement of hyperfine interval could help resolve the current $\sim 4 \sigma$ discrepancy between experiment and theory.

Note that the Ps recoil has to be taken into account at this level of precision. With a narrower laser we will resolve different 2P levels

$$\lambda_L = 243.0218 \pm 0.0005 \text{ nm}$$

$$\lambda_C = 243.0035 \pm 0.0005 \text{ nm}$$

$$E_{\text{hfs}} = 198.4 \pm 5 \text{ GHz}$$

lots of improvements needed!

Confined Ps: formation in porous (silica) films

- Mean free path depends on pore size ~ 2-10 nm typical
- Film thickness ~ 50-500 nm
- Positron implantation
- Positron diffusion (< 1 ns)
- Positronium formed in bulk material
- Positronium bulk diffusion (< 1 ns)
- Positronium emitted into voids
- Positronium escapes into vacuum or annihilates in void (τ ~ 10-100 ns)

Lasers probe vacuum Ps

Lasers probe Ps inside the pores and/or in vacuum

λ ~ 243 nm

λ = 532 nm

Mean free path depends on pore size ~ 2-10 nm typical
Ps cooling in a porous film

The longer it takes for Ps to escape the cooler it will be as there will be more collisions with the walls (and a lower yield).

For small enough pores it may not be possible to reach the ambient temperature as the confinement energy in the pores sets the lower limit.
Cavity shift and narrowing of Ps 1S-2P transition

The effect of the cavity on the line center of the transition is to shift it to shorter wavelength.

Difference between (b) and (c) is a time delay of 10 ns. The increasing yield of vacuum Ps indicated the emission time of Ps from the porous film.

High density pulses: Ps-Ps interactions

\[ \Gamma \sim 1/50 \text{ ns}, \text{(typical for our } \sim 5 \text{ nm porous films)} \]

\[ \sigma \sim 1 \times 10^{-15} \text{ cm}^2, \text{ calculated [Mitroy et al. Phys. Rev. A 65 022704 (2002)]} \]

\[ \nu \sim 1 \times 10^7 \text{ cm}^2\text{s}^{-1} \text{ (thermal Ps)} \]

so Ps-Ps scattering is can be seen for a Ps density of around \( 10^{15} \text{ cm}^{-3} \)

If you stop the beam in \( \sim 100 \text{ nm} \) then you need an areal density of \( \sim 10^{10} \text{ cm}^{-2} \).

Two processes that will reduce \( f_d \)

- **Spin exchange quenching (SEQ)**
  \[ \text{o-Ps}_{(m=1)} + \text{o-Ps}_{(m = -1)} \rightarrow 2 \text{ p-Ps} + 2E_h \]
  \[ \text{o-Ps}_{(m=1)} + \text{o-Ps}_{(m = -1)} \rightarrow 2 \text{o-Ps}_{(m=0)} + 2E_h \]

- **Positronium molecule (Ps}_2\text{) formation**
  \[ X + \text{o-Ps}_{(m = 1)} + \text{o-Ps}_{(m = -1)} \rightarrow X + \text{Ps}_2 + E_b \]
Strong drive plasma compression allows for precise control of Ps density.

A 2.3 T pulsed magnetic field is also used but changing this also changes many other parameters.

Strong drive compression of Surko, Danielson and others has been extremely important for high density Ps experiments,
Ps-Ps scattering induced changes in $f_d$ saturates at high densities when minority spin states are all used up. The resulting Ps gas is almost 100% spin polarised (as required for Ps BEC).

Saturation of quenching data indicates the incident positron beam polarisation.

We find $P \sim 28\%$, proving conclusively that Surko traps do not cause significant depolarisation.

This is very important for BEC production.

Solid line is fit for non-linear decay for two spin populations.
Optical detection of molecular positronium via excited $L = 1$ state

$$Ps_2 + h\nu(250.9 \text{ nm}) \rightarrow Ps_2^*$$

$$(a) \quad \rightarrow Ps + e^+ + e^- \quad (E_{th} = 2.3eV)$$

$$Ps_2^* + h\nu(532 \text{ nm}) \rightarrow Ps^{-(+)} + e^{+(-)} \quad (E_{th} = 1.97eV)$$

$$(b) \quad \rightarrow Ps + Ps^* \quad (E_{th} = 0.6eV)$$

This measurement is difficult because

- Laser damages the target
- Amount of $Ps_2$ formed is low
- Detection is not 100%
- Doppler width large

Cavity shift seems to go the wrong way! Why? We don’t know, could be related to the $Ps_2$ structure (excited state not that much bigger than the ground state, which is not true for Ps)

Population of Rydberg Ps states in 0.16 T magnetic field with an electric field present.

![Graph depicting population of Rydberg Ps states with error bars and Gauss fit.](image-url)
Population of Rydberg Ps states in 0.16 T magnetic field with an electric field present.

Including field ionisation, saturation and Doppler broadening can describe the observed data fairly well.

A 2-photon 1S-nD transition might make it possible to populate selected Rydberg states, as is likely to be required for efficient population of the longer-lived high angular momentum states.
Rydberg atoms have large electric dipole moments and so can be manipulated by field gradients: For example, Electrostatic Rydberg Mirror

The maximum induced electric dipole moment in Ps is $\mu \sim 3n^2 e a_B$
(it is different for different sub states) so can get quite large for Rydberg atoms. The Stark energy shifts mean that field gradients can exert a force on such atoms, making it possible to manipulate them.

Fast (Rydberg) Ps atoms can be slowed down using Stark deceleration:

Experiment (a) and simulation (b) of Stark acceleration and deceleration of $n = 31$ Hydrogen atoms.

If it can be implemented with reasonable efficiency this technique could also be very useful for many different experiments, such as scattering or precision spectroscopy.

Availability of Rydberg Ps opens up the possibility of a gravity measurement. Long lifetimes needed for this:

**How long does it have to be?**
Suppose a 40µm spot, we might need ~20µm displacement to resolve the deflection so $S = \frac{1}{2}gt^2$ (assuming normal gravity) gives 2 ms.

![Graph showing the radiative lifetime as a function of the principal quantum number n, with lines indicating $n^3$ and $n^5$ behaviors.]

The final state we choose will be a compromise between mitigating BBR effects, optimizing the Ps beam focusing and obtaining the longest lifetime consistent with the flight length/Ps energy.

Must also remember that

1) High $n$ states easily ionised by black body radiation (BBR)
2) Circular states are hard to make unless starting from a pure Rydberg level
3) Even BBR induced transitions between $n$, $(n-1)$ or $(n+1)$ may deflect the beam too much
What might a Ps Rydberg gravity experiment look like?*

What n states will be optimal?

How will the circular states be produced?

How cold must the walls be? (BBR)

What Ps converter will work at low temp?

How does this mirror/lens work?

Will the “atom-optics” work on circular states?

Will patch fields deflect the beam?

Can very slow atoms be detected without perturbing their positions?

How long does the flight tube have to be?

Ps has to be very cold

Zero or low B field

need a point e⁺ source

This experiment is on-going; there is a lot to do…

*Any similarity between the diagram shown here and a real experiment is purely coincidental...
Now that we know we can create a spin polarised Ps gas and suppress magnetic quenching of 2P Ps states we can consider making a Ps BEC: We would need to

1) Increase beam/Ps density (multiple traps, improved RW compression, higher magnetic field, better polarisation, engineered target structures)

2) Investigate laser cooling of Ps in cavities

\[ T_c \propto \frac{1}{m(n)^{2/3}} \]
Collaborators

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Funding from US Air Force & NSF,
EPSRC, Leverhulme Trust, UK

Thank you for your attention