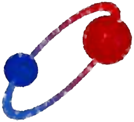
Rydberg-Stark States of Positronium



Adam Deller

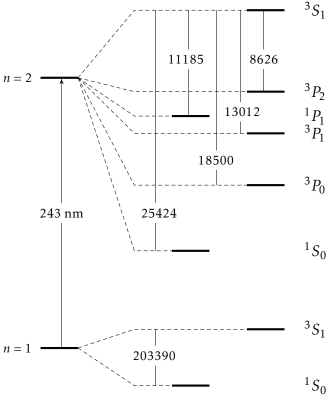
AMOPP, Department of Physics and Astronomy
University College London

WAG2015, August 2015

Positronium

The $n = 1$ ground-state is separable into a short lived (0.125 ns) $s = 0$ singlet, and long lived (140 ns) $s = 1$ triplet states,

$$\begin{aligned} |0,0\rangle &= \frac{1}{\sqrt{2}}\left(|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle\right), \\ |1,0\rangle &= \frac{1}{\sqrt{2}}\left(|\uparrow,\downarrow\rangle + |\downarrow,\uparrow\rangle\right), \\ |1,1\rangle &= |\uparrow,\uparrow\rangle, \\ |1,-1\rangle &= |\downarrow,\downarrow\rangle. \end{aligned}$$



[1] R. Ley (2002) *Appl. Surf. Sci.*, **194**:301

Gravity Measurements with Positronium?

Rydberg Ps Drift Tube

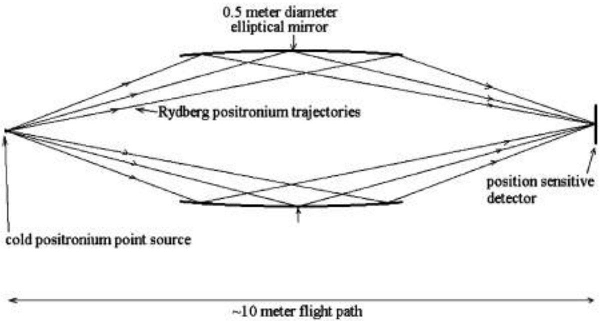


Fig. 1. Experiment to measure the gravitational free fall of $n = 25$ Rydberg positronium.

[2] A.P. Mills Jr. and M. Leventhal (2002) *Nucl. Instr. and Meth. in Phys. Res. B*, **192**:102

Interrogating Ps with lasers

Interrogating Ps with lasers

Interrogating Ps with lasers

a brief history (pre 2008)

1982 Excitation of the Positronium $1^3S \rightarrow 2^3S$ Two-Photon Transition

Steven Chu and Allen P. Mills, Jr. Phys. Rev. Lett.**48**, 1333

1990 Optical saturation of the $1^3S \rightarrow 2^3P$ transition in positronium

K. P. Ziock, C. D. Dermer, R. H. Howell, F. Magnotta, K.M. Jones, J. Phys. B **23**, 329

First observation of resonant excitation of high—n states in positronium

K. P. Ziock, R. H. Howell, F. Magnotta, R. A. Failor, and K. M. Jones, Phys. Rev. Lett. **64**, 2366

1993 Measurement of the positronium $1^3S \rightarrow 2^3S$ interval by continuous-wave two-photon excitation

M. S. Fee, S. Chu, A. P. Mills, Jr., R. J. Chichester, D. M. Zuckerman, E. D. Shaw, and K. Danzmann, Phys. Rev. A**48**, 192

Experiment Programme

- Positron Accumulation
  - Low-energy positron beam
  - Buffer-gas positron trap
  - Radial compression and time focusing

Experiment Programme

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- Positronium Spectroscopy
  - Cool positronium production
  - REMPI spectroscopy via 1s2p (UV + Green)
  - Rydberg Ps (UV + IR)
  - Positronium Stark-states
  - Manipulation of Rydberg-Stark states of Ps

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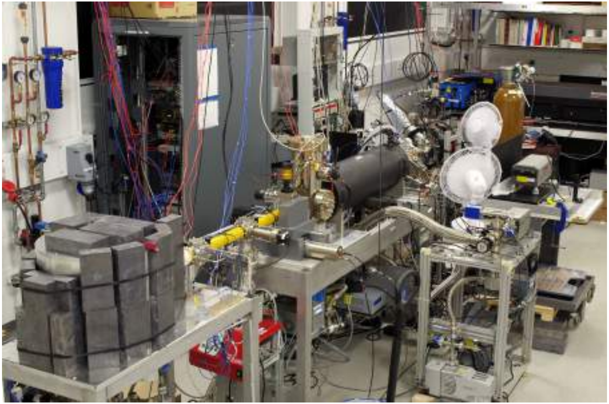
- Colder positronium production
- (Anti)gravity measurements with positronium

UCL Positronium Lab

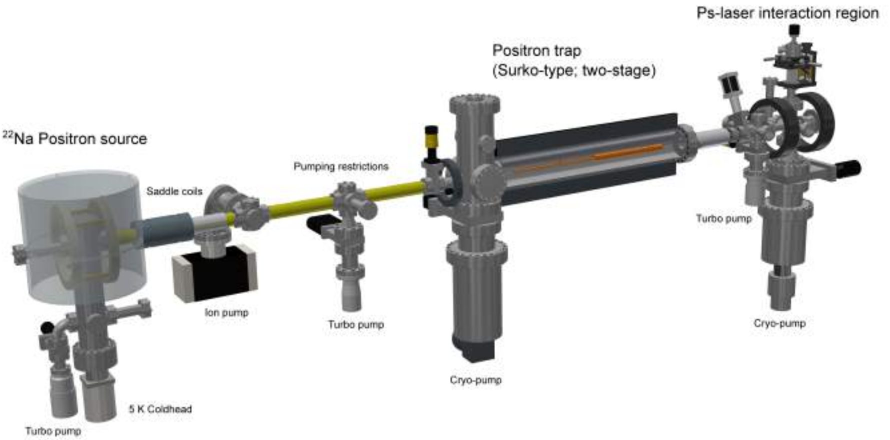
January 2014

UCL Positronium Lab

October 2014

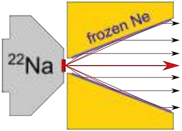


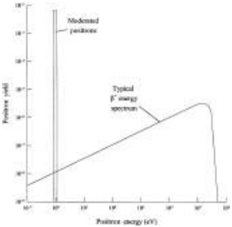
UCL Positronium Lab

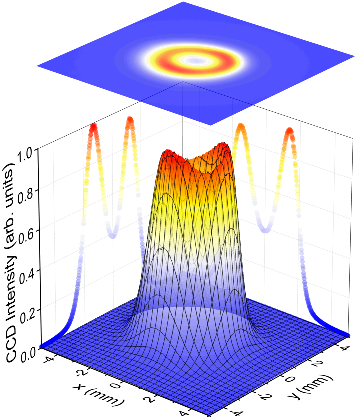


Positron Accumulation

Solid Neon Moderator



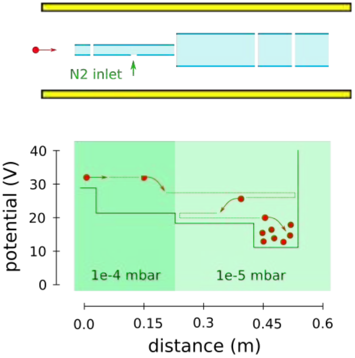


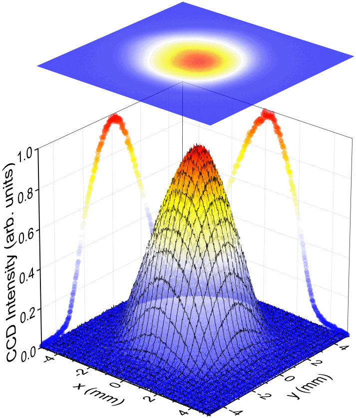


[3] E.M. Gullikson and A.P. Mills, Jr. (1986) *Phys. Rev. Lett.*, **57**:376

Positron Accumulation

Buffer-gas Positron Trap

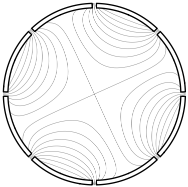


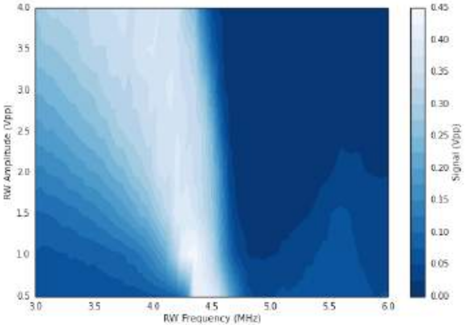


[4] C.M. Surko *et al.* (1988) *Hyperfine Interact.*, **44**:185

Positron Accumulation

Rotating quadrupole electric field radially compresses the cloud and improves accumulation by reducing diffusion to the walls, however, cooling gas (CF_4) is needed to counter heating.



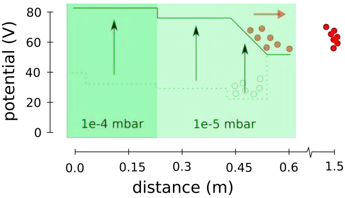


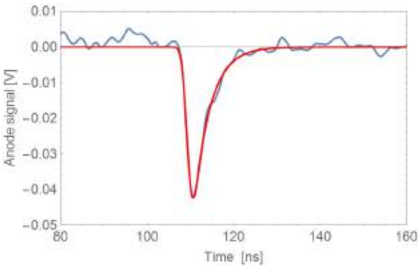
[5] A. Deller *et al.* (2014) *New J. Phys.*, **16**:073028

Positron Accumulation

Pulses applied to the electrodes ejects the positron cloud from the trap.

A fast PbF_2 Cerkenov radiator + PMT is used to measure time-width of the annihilation gamma-ray pulse generated when the positrons impact a solid target near the focus.





Fit function:

$$V(t) = \frac{1}{2} A exp \frac{\sigma^2 - 2t\tau + 2x_0\tau}{2\tau^2} erfc\left(\frac{-t\tau + x_0\tau + \sigma^2}{\sqrt{2}\sigma\tau} \right)$$

$\sigma \approx 4$ ns (positron pulse width)

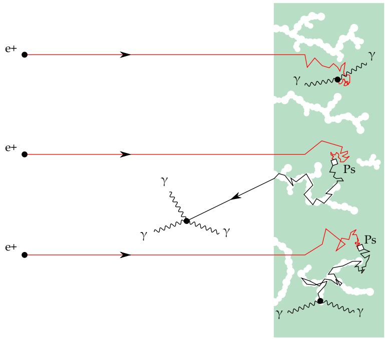
Positronium Production

Compressed and bunched positrons transported to target chamber.

Positrons attracted to target by electric potential and embedded into porous silica.

The positrons form Ps in the bulk, then diffuse through the pores to vacuum.

Conversion efficiency of ~ 30 %.



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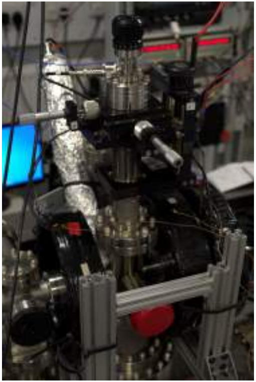
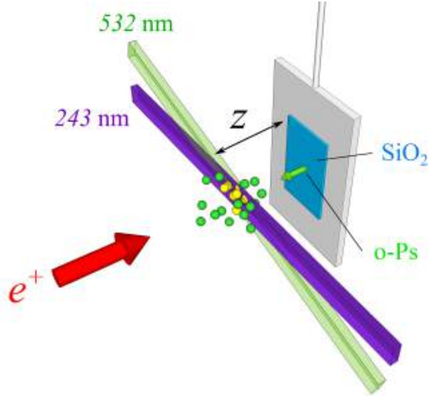
[6] L. Liszkay, *et al.* (2008) *Appl. Phys. Lett.*, **92**(6):063114.

Positronium Spectroscopy

Target Mount

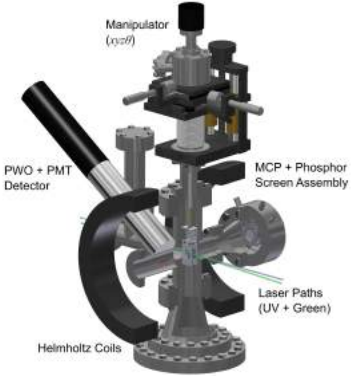


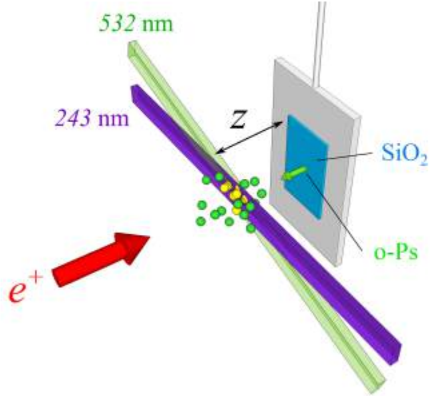
Target mount and ($PbWO_4$ + PMT) gamma ray detector.



Positronium Spectroscopy

Target Mount

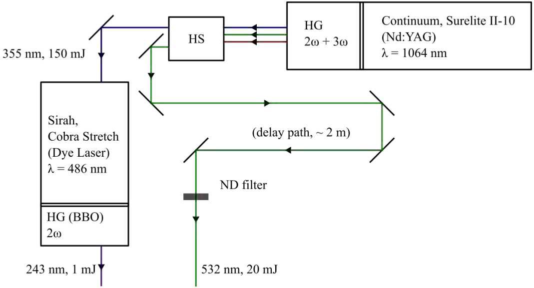




Target mount and ($PbWO_4$ + PMT) gamma ray detector.

Positronium Spectroscopy

Broadband UV Laser



243 nm (UV):

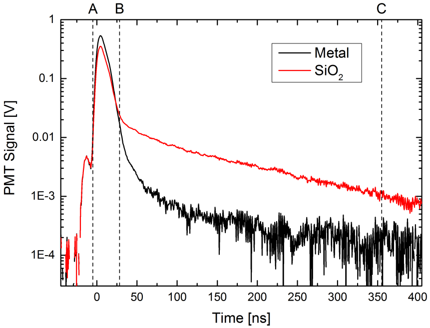
- 0.1 - 4.0 mJ
- $\Delta t = 6$ ns
- $\Delta\nu \sim 85$ GHz

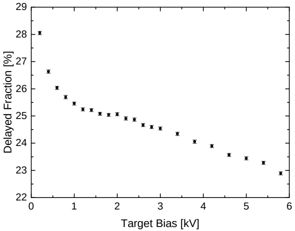
532 nm (Green):

- 10 - 40 mJ
- $\Delta t = 6$ ns
- $\Delta\nu \sim 20$ GHz

Positronium Lifetime Spectroscopy

Single-Shot Positron Annihilation Lifetime Spectroscopy



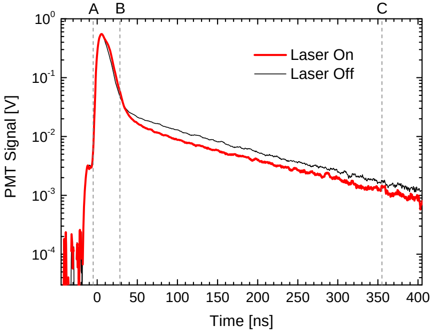


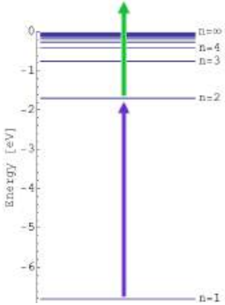
$$f = \int_B^C V(t)\ dt \Big/ \int_A^C V(t)\ dt\ .$$

[7]D. Cassidy, *et al.* (2006) *Appl. Phys. Lett.*, **88**(19):194105

Positronium Spectroscopy

REMPI



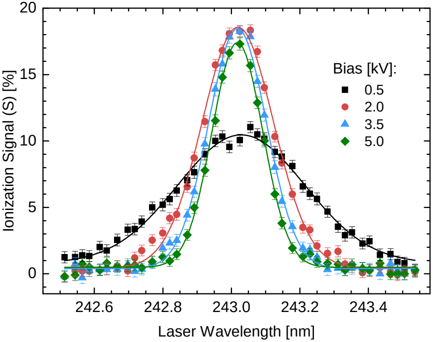


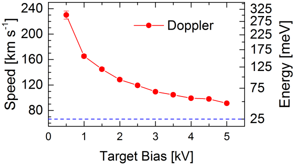
$$S = \frac{f_b - f}{f_b}.$$

[8] D. Cassidy, *et al.* (2006) *Appl. Phys. Lett.*, **88**(19):194105

Positronium Spectroscopy

1s2p Doppler Linewidth





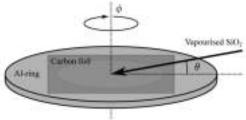
$$\langle v_x^2 \rangle = (c\sigma/\lambda_0)^2$$

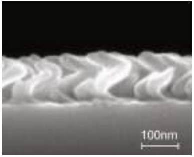
Energy of the emitted Ps decreases with increasing e^+ implantation energy - minimum around 40 meV.

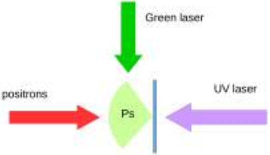
[9]D. B. Cassidy, *et al. Phys. Rev. A* (2014) **81**:012715

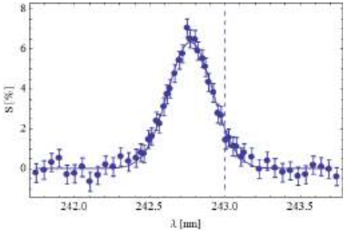
Positronium Spectroscopy

Aarhus transmission films - Doppler shift







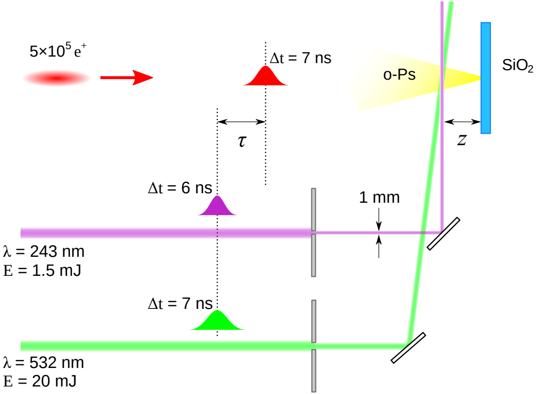


$\langle v_z \rangle \approx 164$ km/s (150 meV)

[10]S. L. Andersen, *et al. Eur. Phys. J. D* (2014) **68**: 124

Positronium Spectroscopy

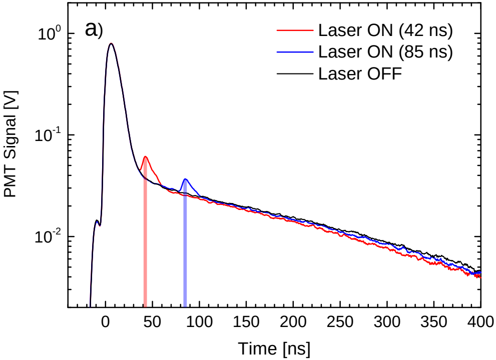
Time-of-Flight

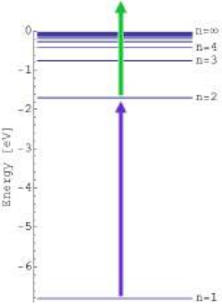


[11] A. Deller, *et al. New. J. Phys.* (2015) **17**: 043059

Positronium Spectroscopy

Time-of-Flight

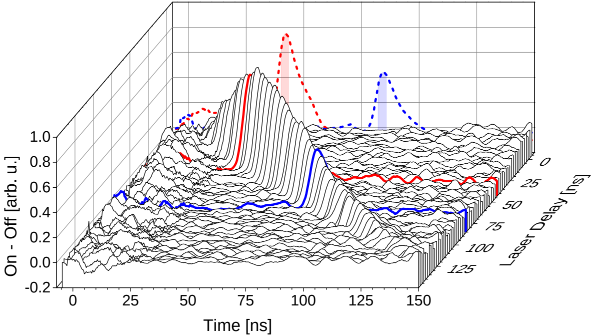


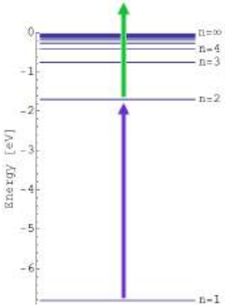


[12] A. Deller, *et al. New. J. Phys.* (2015) **17**: 043059

Positronium Spectroscopy

Time-of-Flight

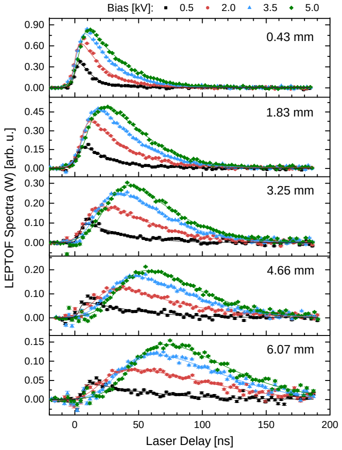


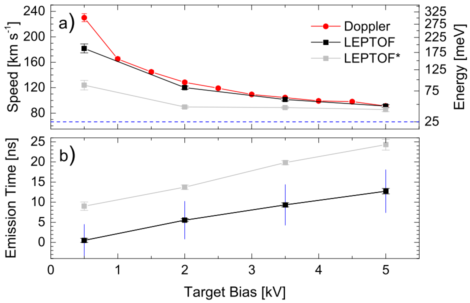


[13] A. Deller, *et al. New. J. Phys.* (2015) **17**: 043059

Positronium Spectroscopy

Time-of-Flight



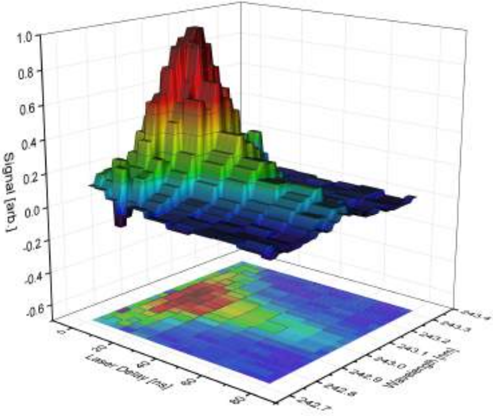


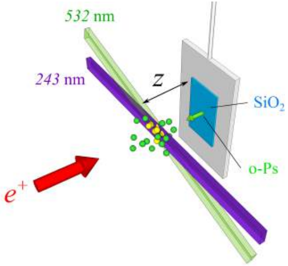
(*) without calculated correction

[14] A. Deller, *et al. New. J. Phys.* (2015) **17**: 043059

Positronium Spectroscopy

Time-of-Flight + Doppler



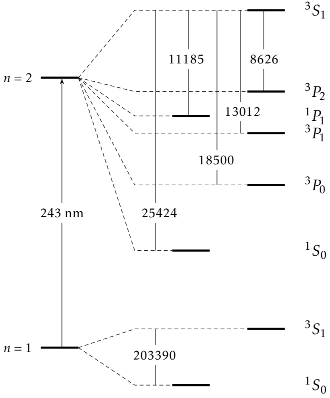


Positronium Spectroscopy

Magnetic Quenching

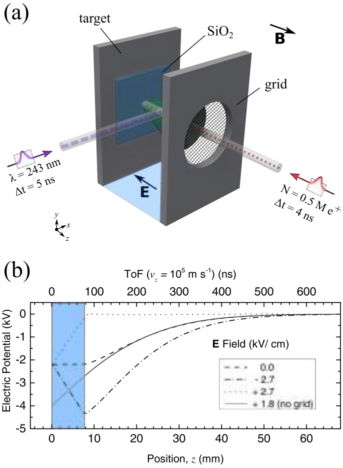
Exciting the Lyman-α transition in a magnetic field mixes the singlet and triplet spin states, which generally reduces the overall lifetime; ergo, a significant difference in SSPALS spectra can be observed using only the UV laser.

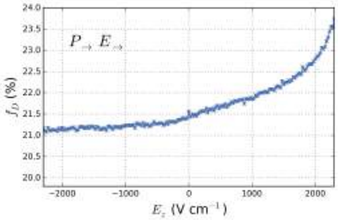
The mixing depends strongly on the magnetic field strength, the states populated within the 2P manifold (UV polarization), and also the electric field.



Positronium Spectroscopy

Magnetic Quenching





Positronium Spectroscopy

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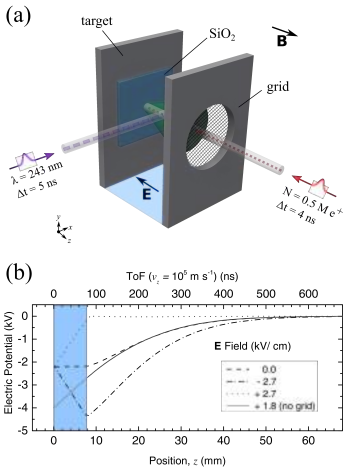
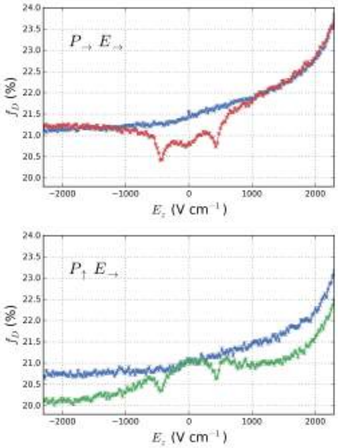
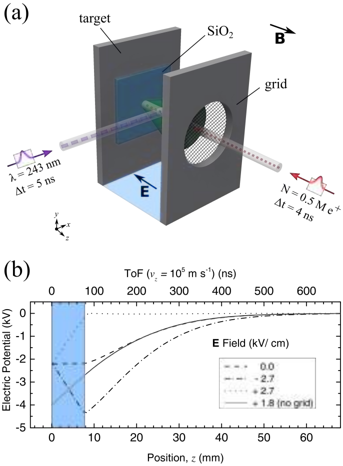
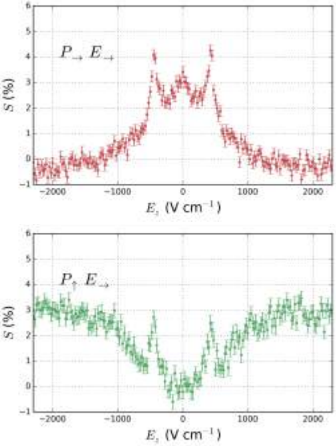




Positronium Spectroscopy

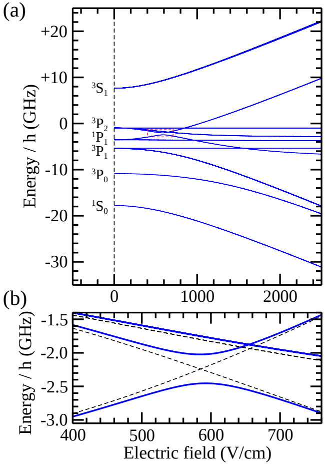
Magnetic Quenching

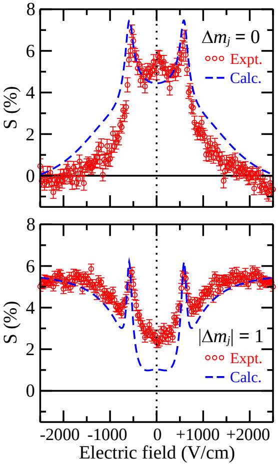




Positronium Spectroscopy

Magnetic Quenching

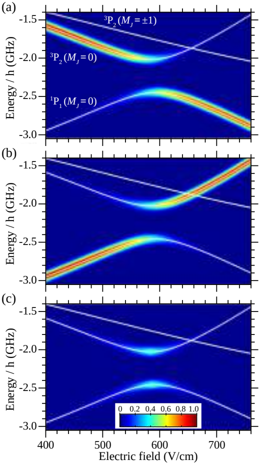


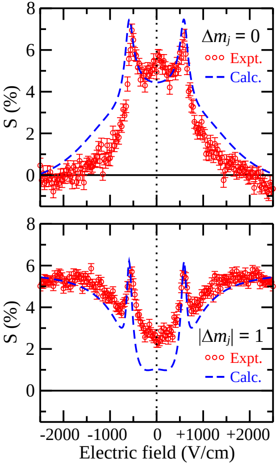


[15] Stephen M. Curry (1973) *Phys. Rev. A*, **7**:447

Positronium Spectroscopy

Magnetic Quenching





[15] Stephen M. Curry (1973) *Phys. Rev. A*, **7**:447

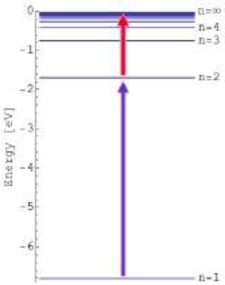
Positronium Spectroscopy

Rydberg Positronium

Positronium can be excited to Rydberg (high-*n*) states using lasers.

"Traditional" excitation scheme (UV + IR): $1S \rightarrow 2P \rightarrow nS/D$.

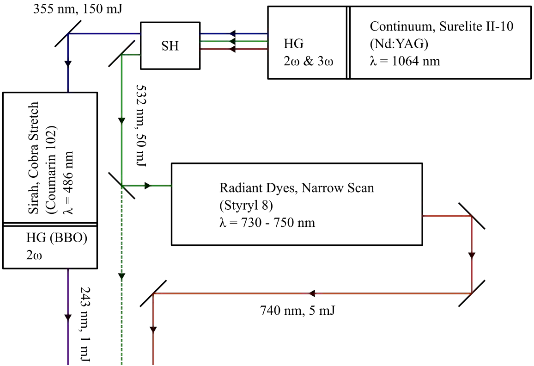
Self-annihilation in Rydberg states is practically negligible. This makes feasible a range of interesting applications, including gravity measurements.



[16] K.P. Ziock, *et al.* (1990) *Phys. Rev. Lett.*, **64**:2366
[17] D. Cassidy, *et al.* (2012) *Phys. Rev. Lett.*, **108**:043401
[18] A. C. L. Jones, *et al.* (2014) *Phys. Rev. A*, **90**:012503

Positronium Spectroscopy

UV + IR Laser



243 nm (UV):

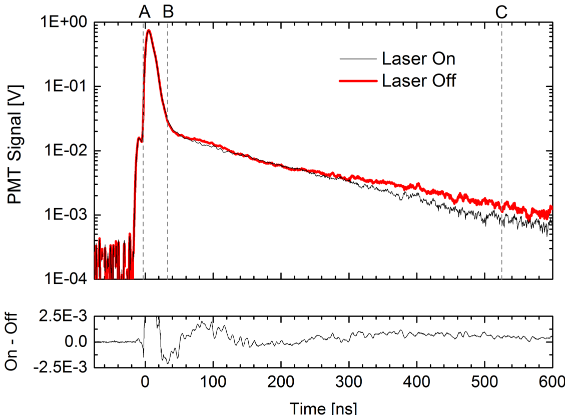
- 0.1 - 4.0 mJ
- $\Delta t = 6$ ns
- $\Delta \nu \sim 85$ GHz

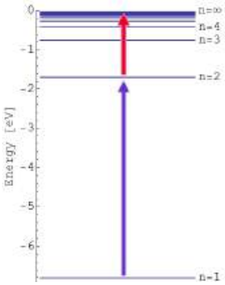
730 - 750 nm (IR):

- 1 - 15 mJ
- $\Delta t = 6$ ns
- $\Delta \nu \sim 5$ GHz

Positronium Spectroscopy

Rydberg Ps ($n = 11$)





$S \approx 0$

[19] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Positronium Spectroscopy

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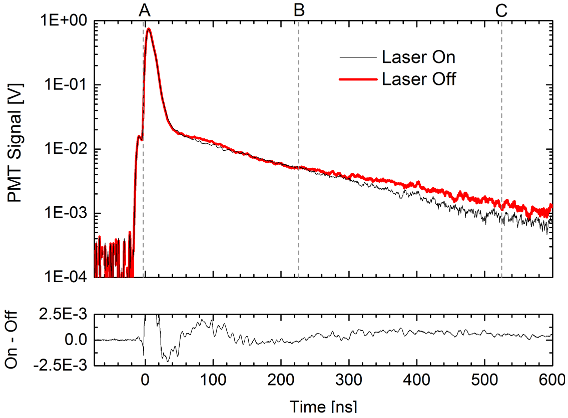
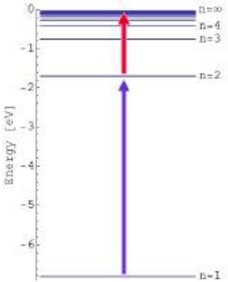


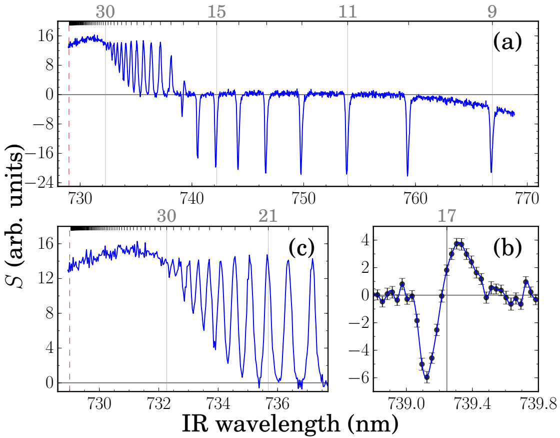


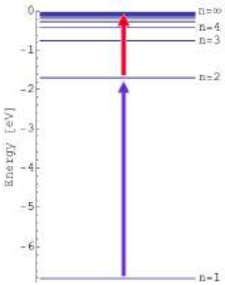
$S \approx -20$

[20] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Positronium Spectroscopy

Rydberg Ps





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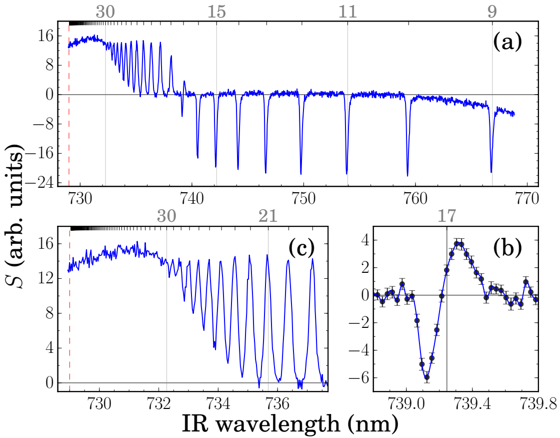
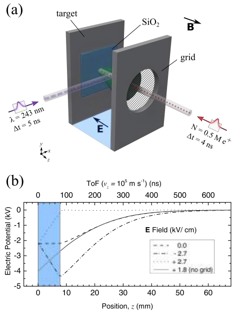
[21] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Positronium Spectroscopy

Rydberg Ps

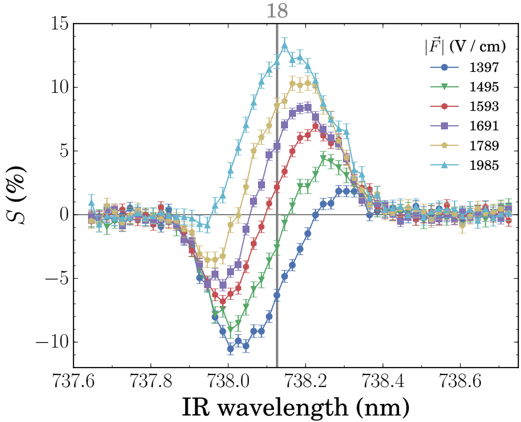


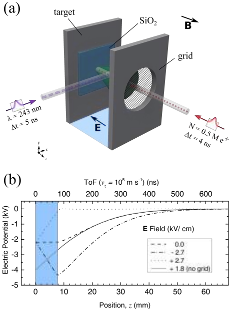


[21] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Positronium Spectroscopy

Rydberg Stark Filter ($n = 18$)

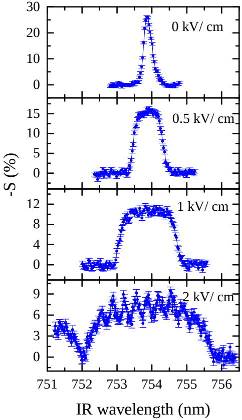


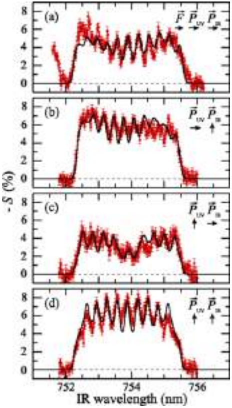


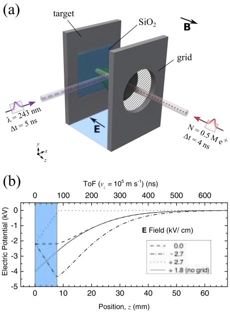
[22] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Positronium Spectroscopy

Rydberg Stark states Ps ($n = 11$)





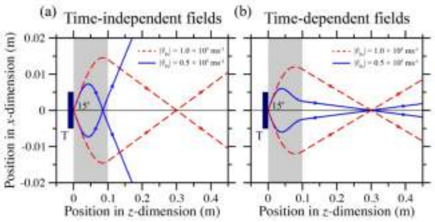


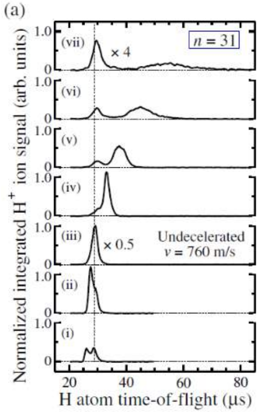
[23] T. Wall, *et al.* (2015) *Phys. Rev. Lett.*, **114**:173001

Stark Deceleration of Ps*

Rydberg Ps beams can be decelerated, deflected or focused with electric field gradients.

Ps: $\mu_{max} = \frac{3}{2} n^2 e(2a_0)$





[24] S. Hogan, and D. Cassidy (2014) *Int. J. Mod. Phys. Conf. Ser.* **30**, 1460259

[25] S. Hogan, *et al.* (2012) *Phys. Rev. Lett.* **108**, 063008

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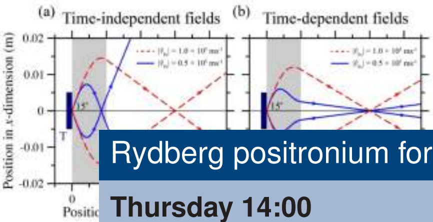

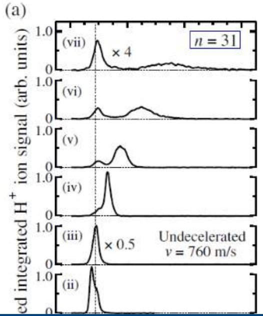

Rydberg positronium for tests of antimatter gravity

Thursday 14:00

S. Hogan

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[26] S. Hogan, and D. Cassidy (2014) *Int. J. Mod. Phys. Conf. Ser.* **30**, 1460259

[27] S. Hogan, *et al.* (2012) *Phys. Rev. Lett.* **108**, 063008

Summary

- Positron Accumulation
  - Low-energy positron beam
  - Buffer-gas positron Trap
  - Radial compression and time focusing

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- Positronium Spectroscopy
  - REMPI spectroscopy (via 1s2p)
  - Time-of-flight and Doppler measurements
  - Stark-enhanced magnetic quenching of the 2p state
  - Rydberg Ps (UV Laser + IR Laser)
  - Positronium Stark-states

Summary

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  - Low-energy positron beam
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  - Radial compression and time focusing
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  - Time-of-flight and Doppler measurements
  - Stark-enhanced magnetic quenching of the 2p state
  - Rydberg Ps (UV Laser + IR Laser)
  - Positronium Stark-states
- Still to do:
  - Manipulation of Rydberg-Stark states of Ps (ask Stephen)
  - Colder positronium production
  - (Anti)gravity measurements with positronium

Acknowledgements

UCL Positronium group (II):

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Technical Support:

Rafid Jawad and John Dumper

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UCL Positronium Group (II)

Thank you for your attention!

http://antimattergravity.com/

a.deller@ucl.ac.uk