Positronium spectroscopy of the positronium n=2 fine structure

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UCL Ps Spectroscopy

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Outline

- Positronium
- Previous experiments
- UCL positron beamline
- Measurement
- Experiments:
- Experiment 1: waveguide with large chamber + FEM simulations
- Experiment 2: Horn antenna
- Experiment 3: Waveguide with small chamber
- Conclusions

Positronium (Ps)

- Ps: positron bound to electron via Coulomb force
- Ps: purely leptonic, should be described by QED
- Reduced mass: Ps = $m_e/2$ (H = $0.9995m_e$)
- Bohr energy levels are roughly half that of hydrogen
- The fine structure is different to hydrogen (spin-spin, annihilation)
- Should be able to calculate energy levels and decay rates to high precision
- n = 2 fine structure intervals have a theoretical uncertainty of 80 kHz

Previous Experiments:

Transition	Experiment (MHz)	Ref.	Theory (MHz)	Ref.
$2^3S_1 \rightarrow 2^3P_2$	$8624.38 \pm 0.54_{stat} \pm 1.40_{sys}$	Hagena *et al.*, 1993	8626.71 ± 0.08	Czarnecki *et al.*, 1999
$2^3S_1 \rightarrow 2^3P_1$	$13012.41 \pm 0.67_{stat} \pm 1.54_{sys}$	Hagena *et al.*, 1993	13012.41 ± 0.08	Czarnecki *et al.*, 1999
$2^3S_1 \rightarrow 2^3P_0$	$18499.65 \pm 1.20_{stat} \pm 4.00_{sys}$	Hagena *et al.*, 1993	18498.25 ± 0.08	Czarnecki *et al.*, 1999

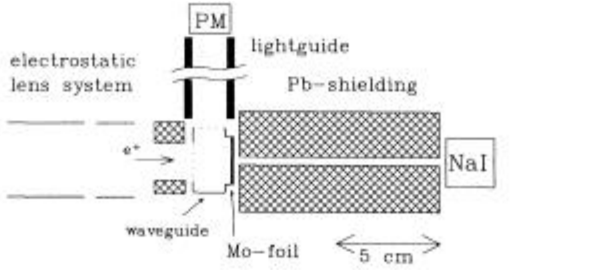
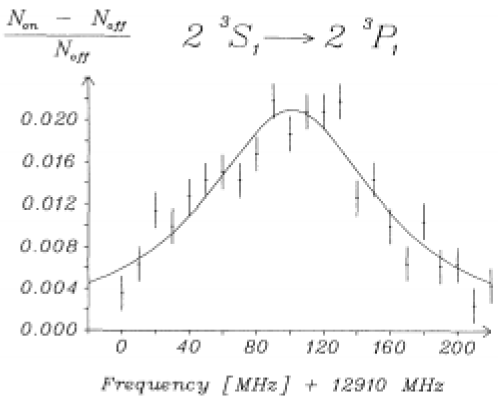
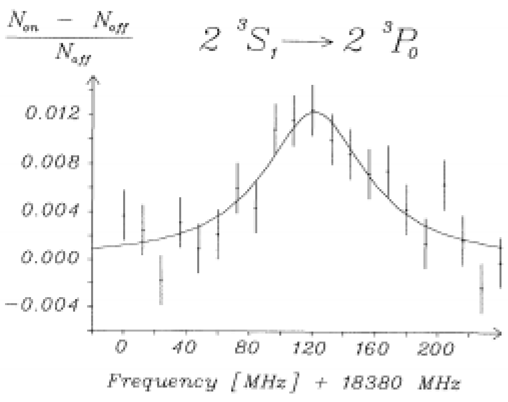
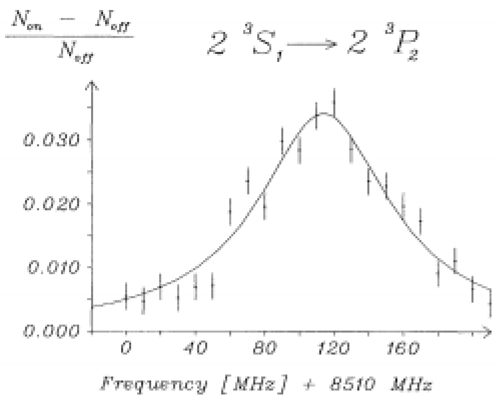


FIG. 1. Interaction region of Ps* atoms ($n=2$) and microwave radiation.

- Previous measurements are from 1993
- Previous measurements have uncertainties ranging from 1.4 MHz to 4 MHz.
- This is much larger than the theoretical uncertainty



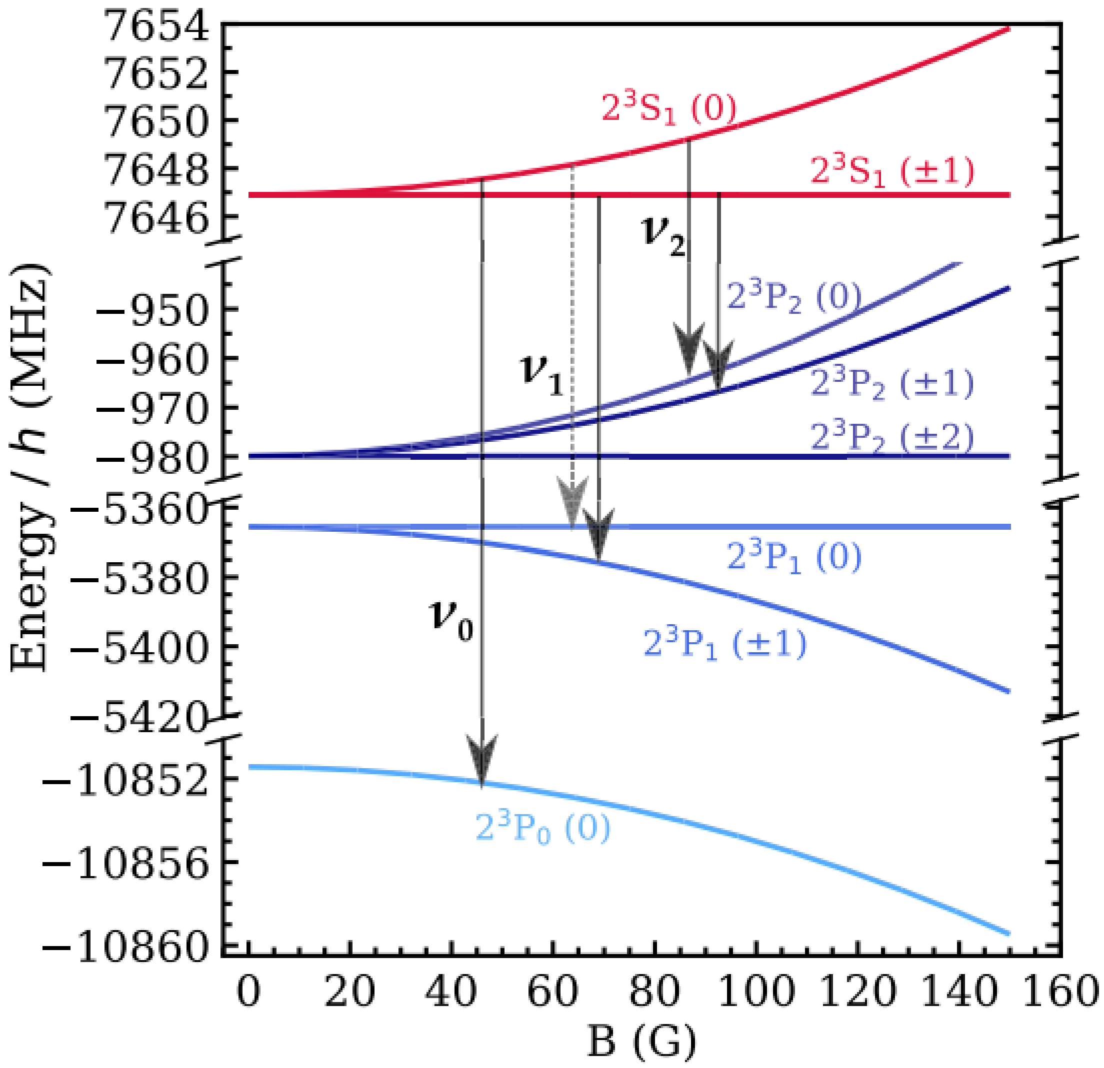




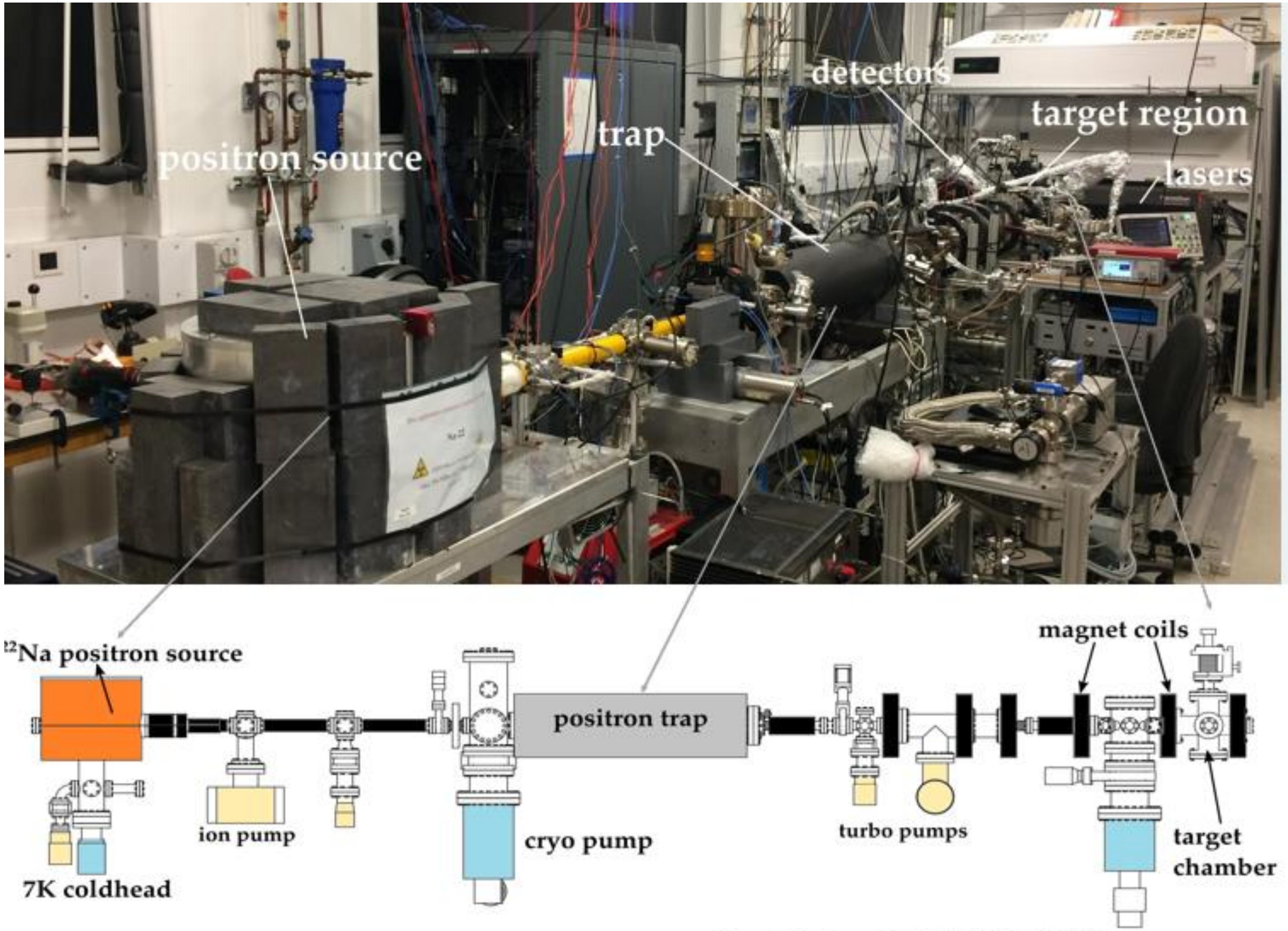
Hagena et. Al. *Phys. Rev. Lett.* **71** 2887 (1993)

n = 2 triple Ps levels

- Due to polarization of microwave guide radiation, excite $\Delta m_j=0$ transitions
- Need to make measurement in a magnetic field in order for positron confinement, we measure a zeeman shifted lineshape

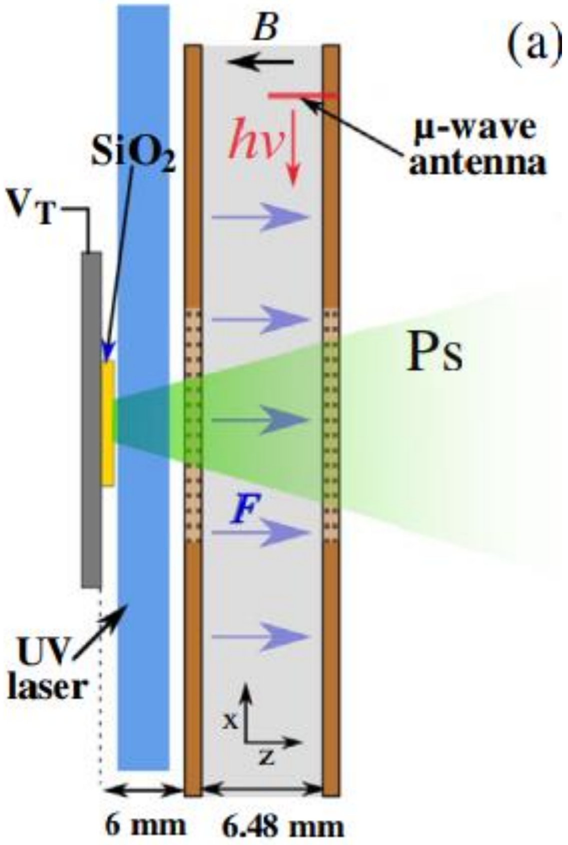


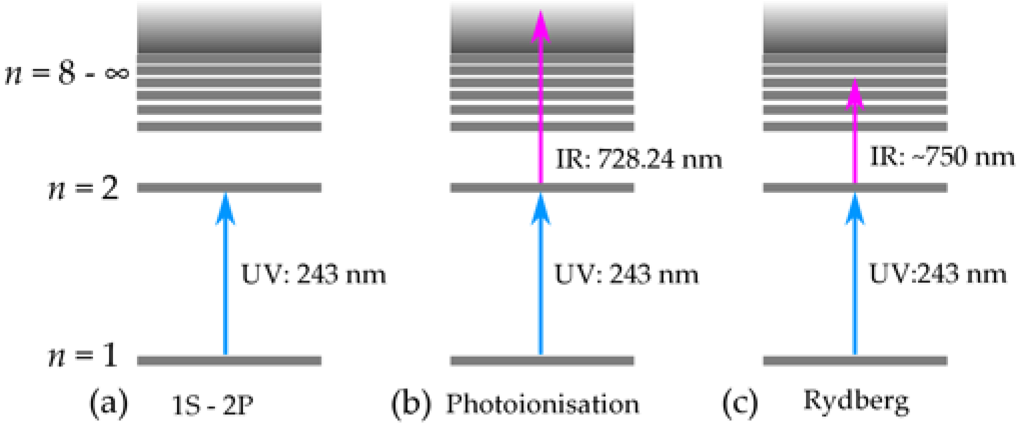
UCL Positron Beamline

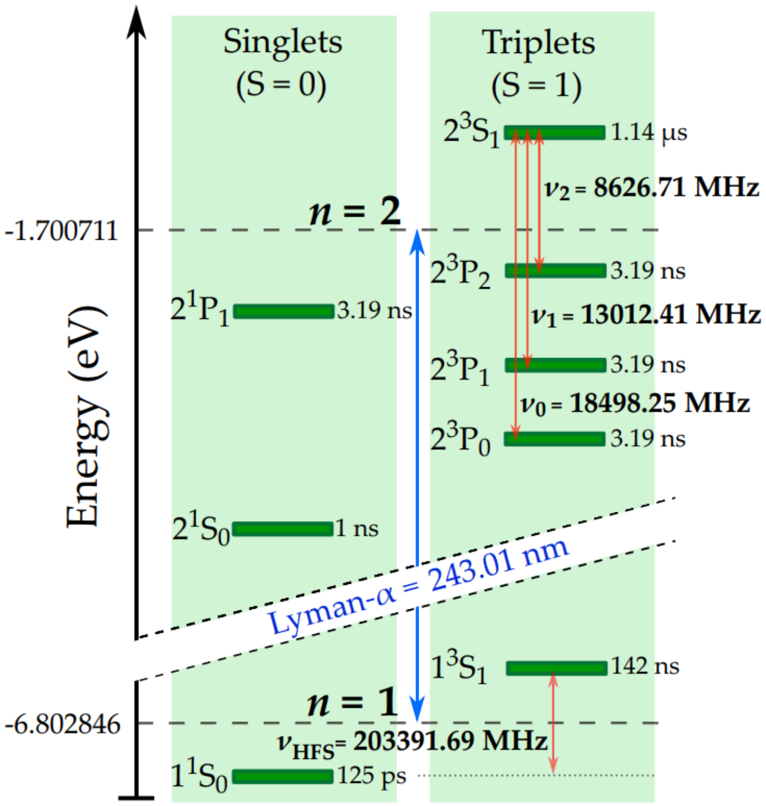


Rev. Sci. Inst. **86** 103101 (2015)

Positronium excitation



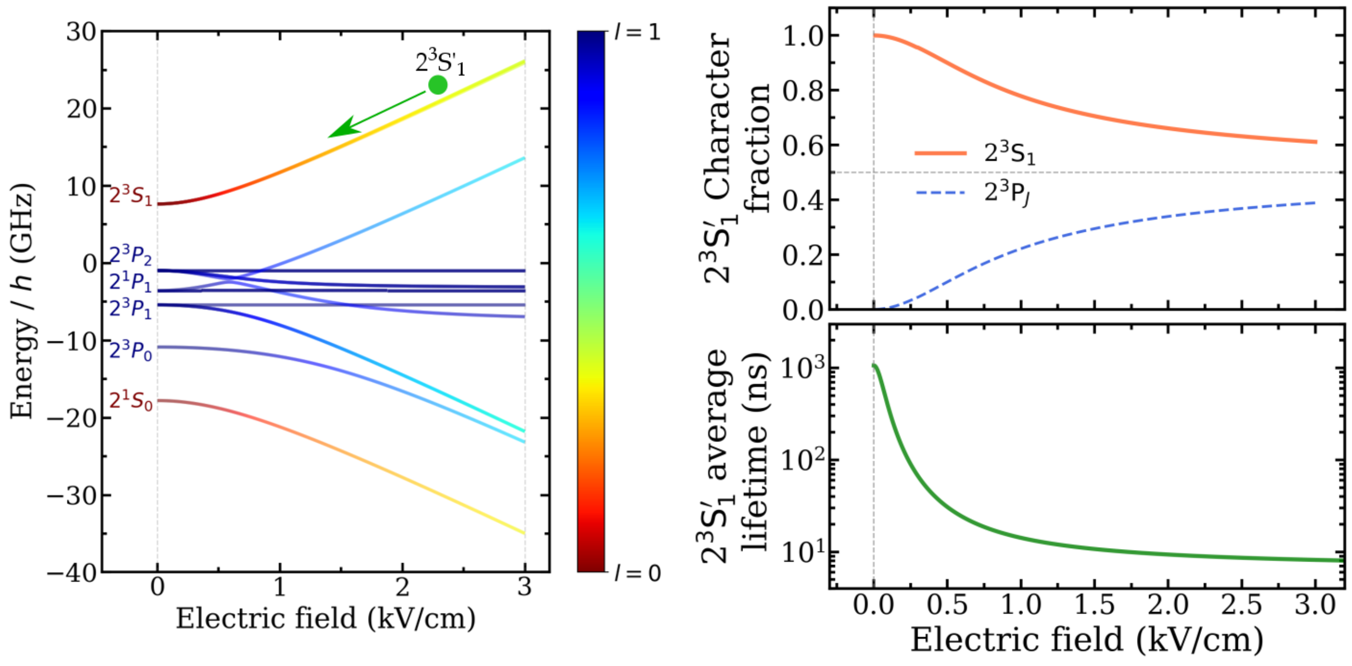




Gurung et. Al. *Phys. Rev. Lett.* ***125*** 073002 (2020)

2^3S_1 Production

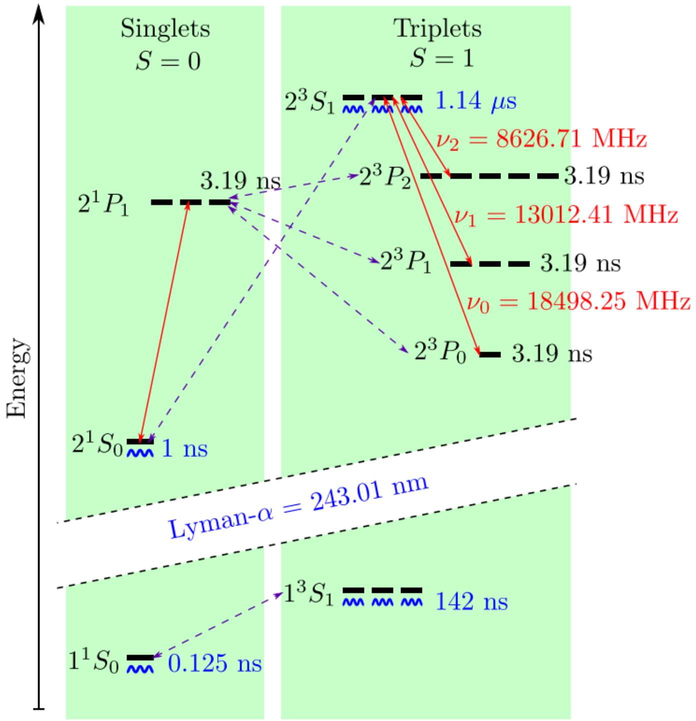
- Ps atoms irradiated with UV dye laser (243 nm)
- Laser excitation performed in electric field to Stark mix states with S and P character (2^3P_J+2^3S_1)
- Turning off the electric field causes states to adiabatically evolve into long lived 2^3S_1
- These Ps atoms then fly through the microwave guide

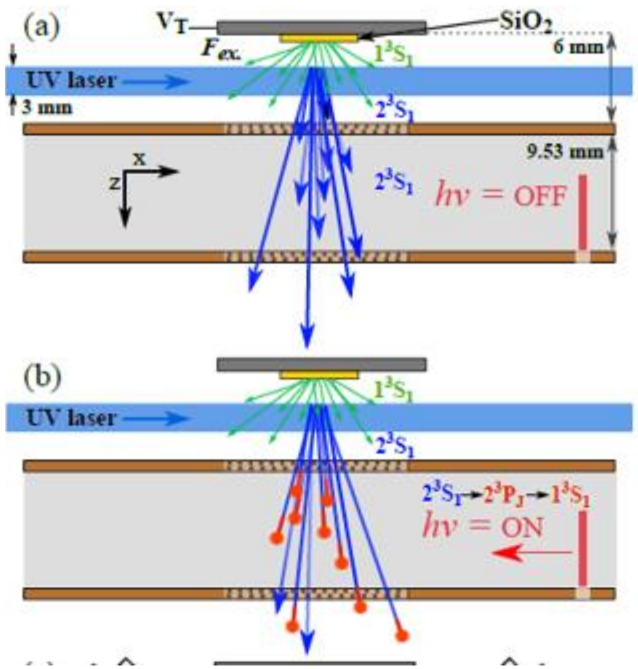


Microwave region

- Rectangular waveguides used, 3 configurations:

Waveguide	Dimensions (mm)	Range (GHz)	Cutoff (GHz)
WR-51(ν_0)	12.95 × 6.48 × 160	15–22	11.58
WR-75 (ν_1)	19.05 × 9.53 × 160	10–15	7.87
WR-112 (ν_2)	28.5 × 12.6 × 160	7–10	5.26

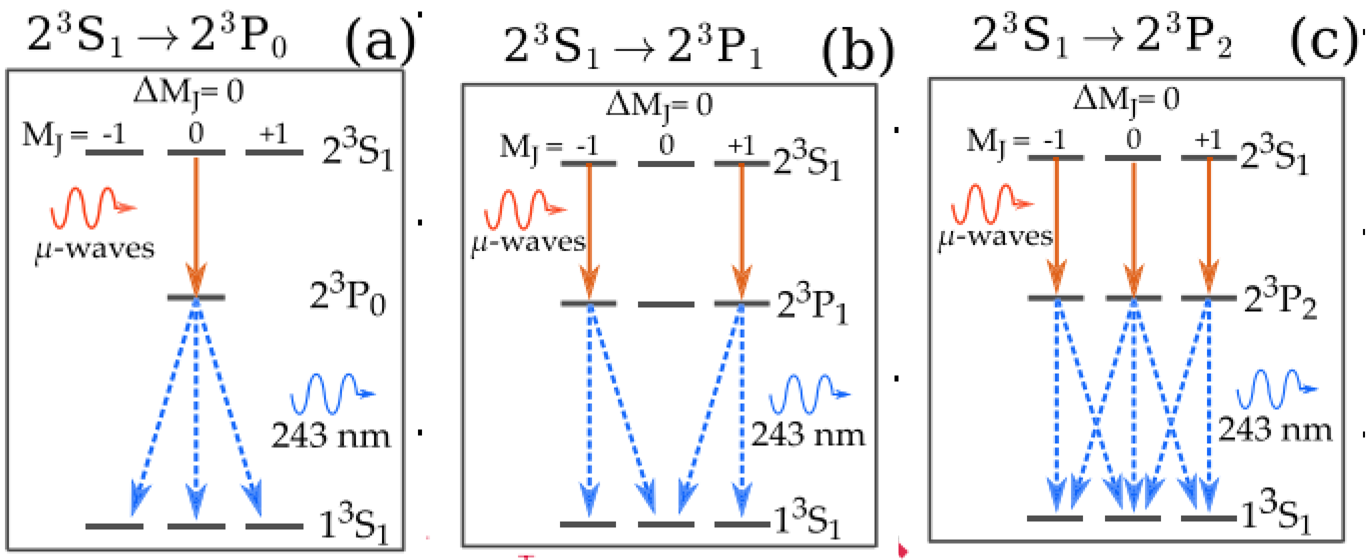




- Drive the 23S1 -> 23PJ (ν_J) transitions
- Ps admitted through high transmission (95%) tungsten mesh
- Microwave in TE_{10} mode
- Kept constant power at all frequencies

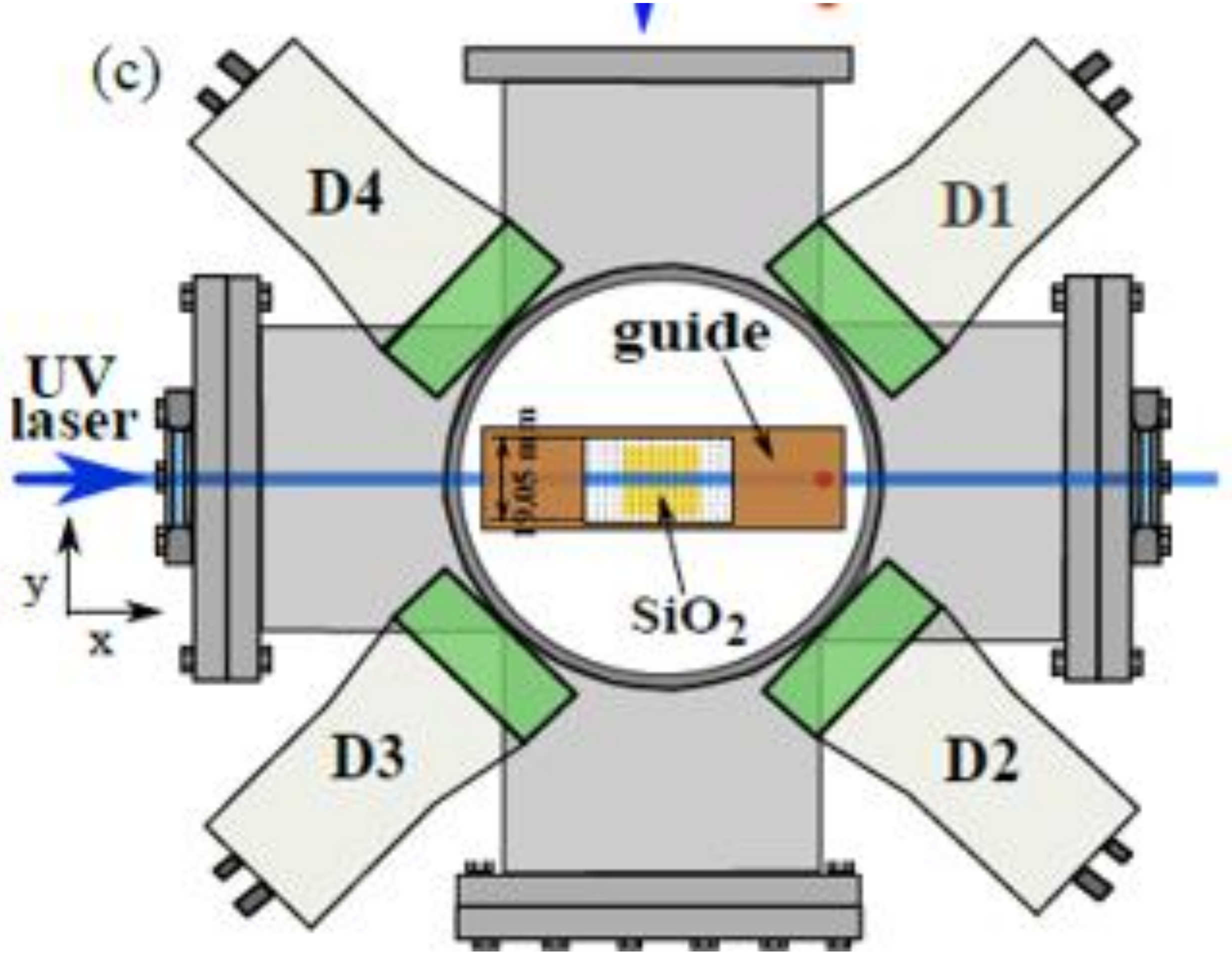
Ps Transitions and detection

- μ-waves drive transition to the 2^3P_J states
- This state has a mean radiative lifetime of 3.2 ns
- Spontaneous radiative decay may proceed via ΔMJ = 0, and ΔMJ = +/- 1
- These atoms will decay to the 1^3S_1 ground state
- Then self-annihilation will occur with a mean lifetime of 142 ns



Ps Detection

- Annihilation gamma rays detected by LYSO detectors placed around chamber
- Generates a lifetime spectra
- LYSO: 40 ns response time and high quantum efficiency
- Connected to a high speed oscilloscope



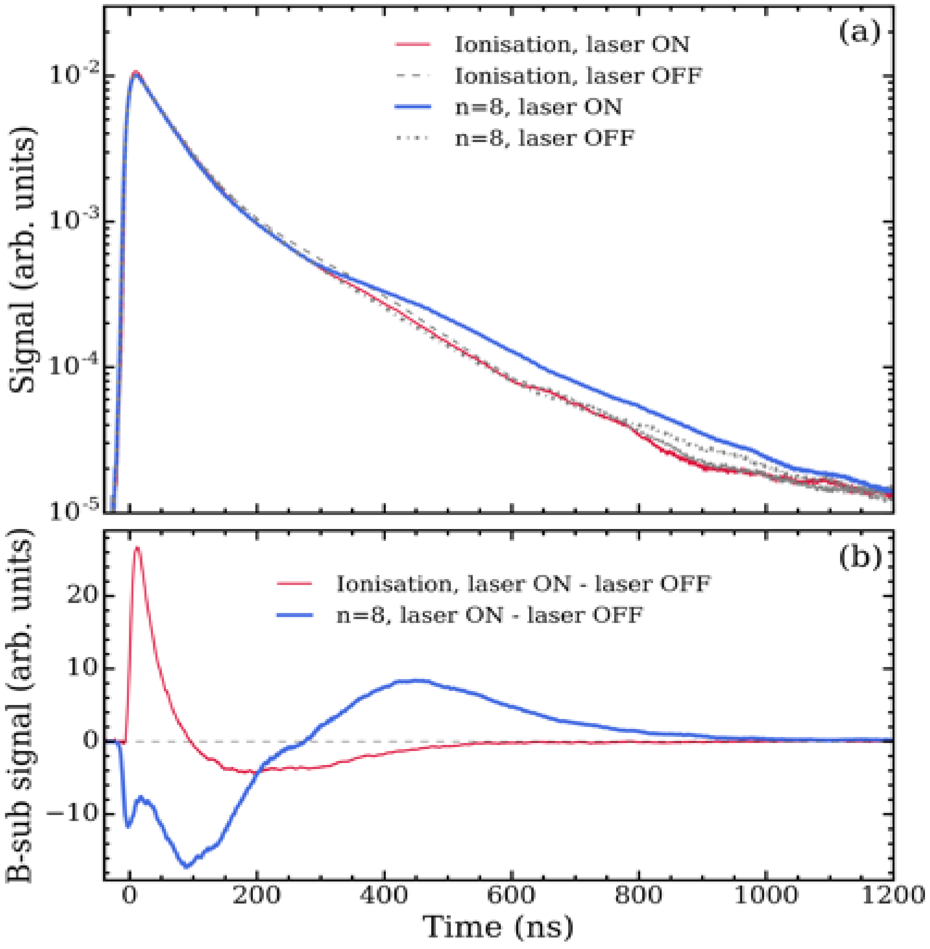
Single Shot Positronium Annihilation Spectroscopy (SSPALS)

- Delayed fraction (f_d): given by the changes in the spectra (events happening later in time)

$$f_d = \int_B^C V(t) \Big/ \int_A^C V(t),$$

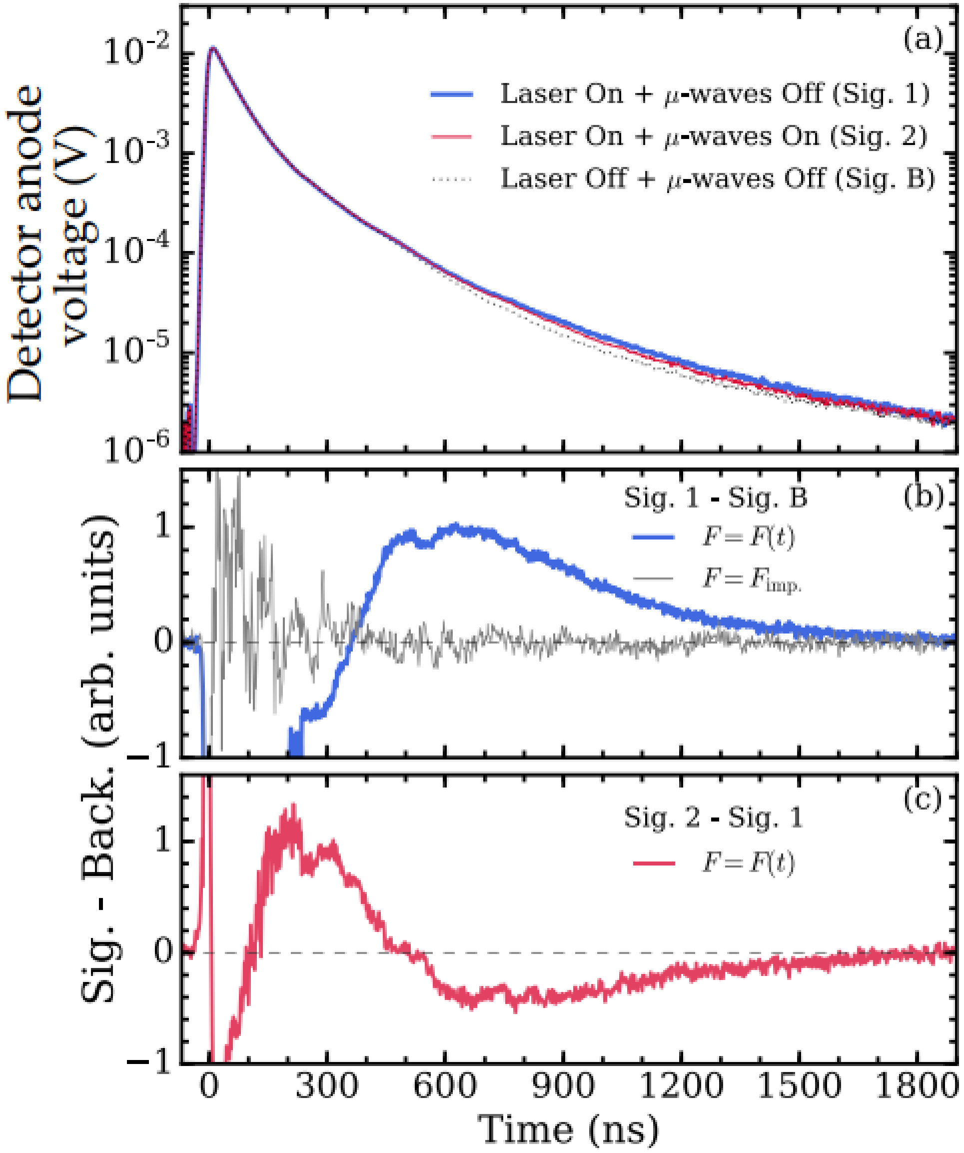
$$S = (f_d(off) - f_d(on)) / f_d(off)$$

- Different lifetime spectra for different processes

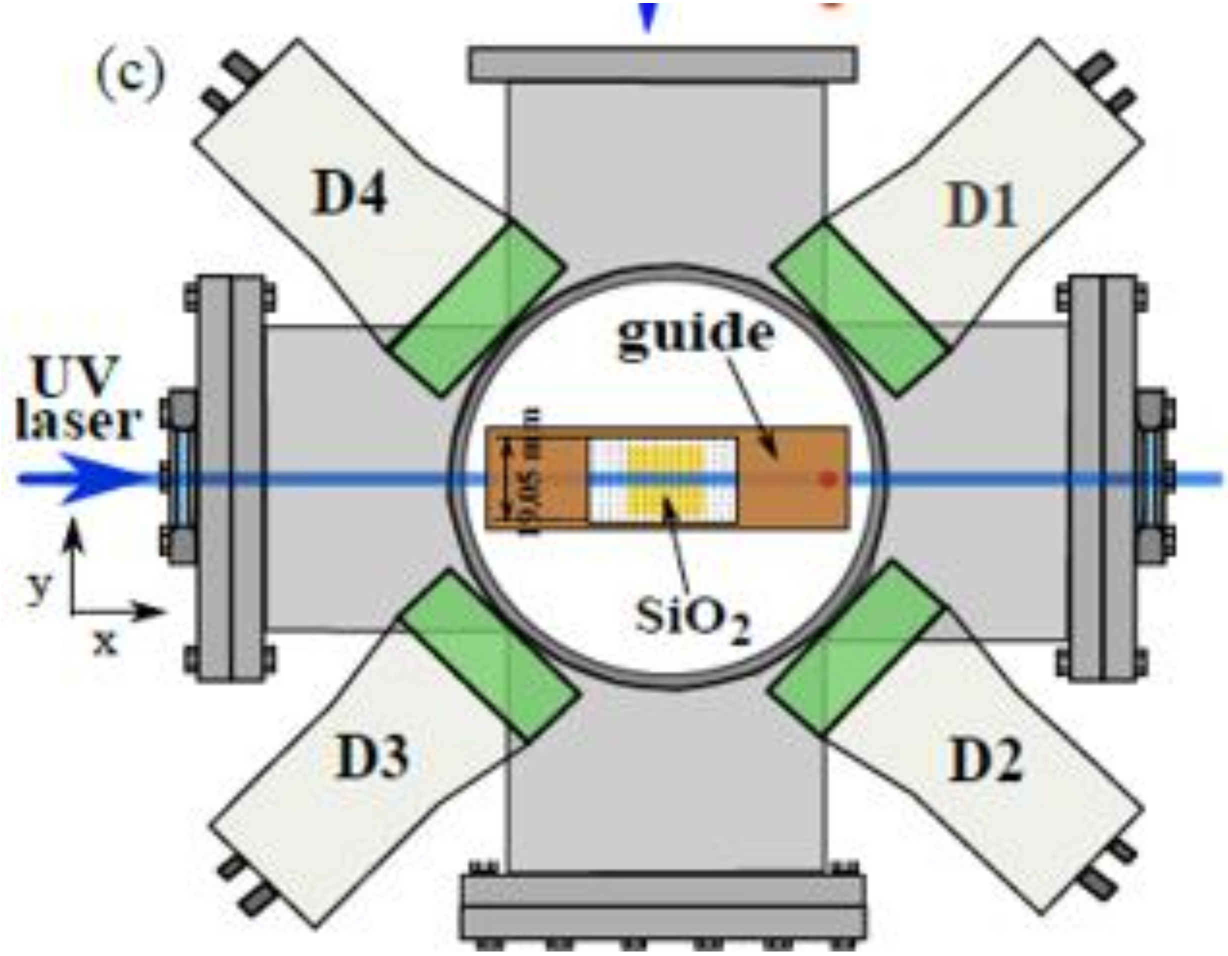


Microwave Signal

- Laser on + μ-waves off: Background signal in which the 2^3S_1 atoms proceed through chamber until self-annihilation (τ = 1.1 μs) or collision with chamber wall, signal is late compared to ground state
- Laser on + μ-waves on: 2^3S_1 -> 2^3P_2, these then transition to ground state (τ = 3.2 ns) -> 1^3S_1 (τ = 142 ns)

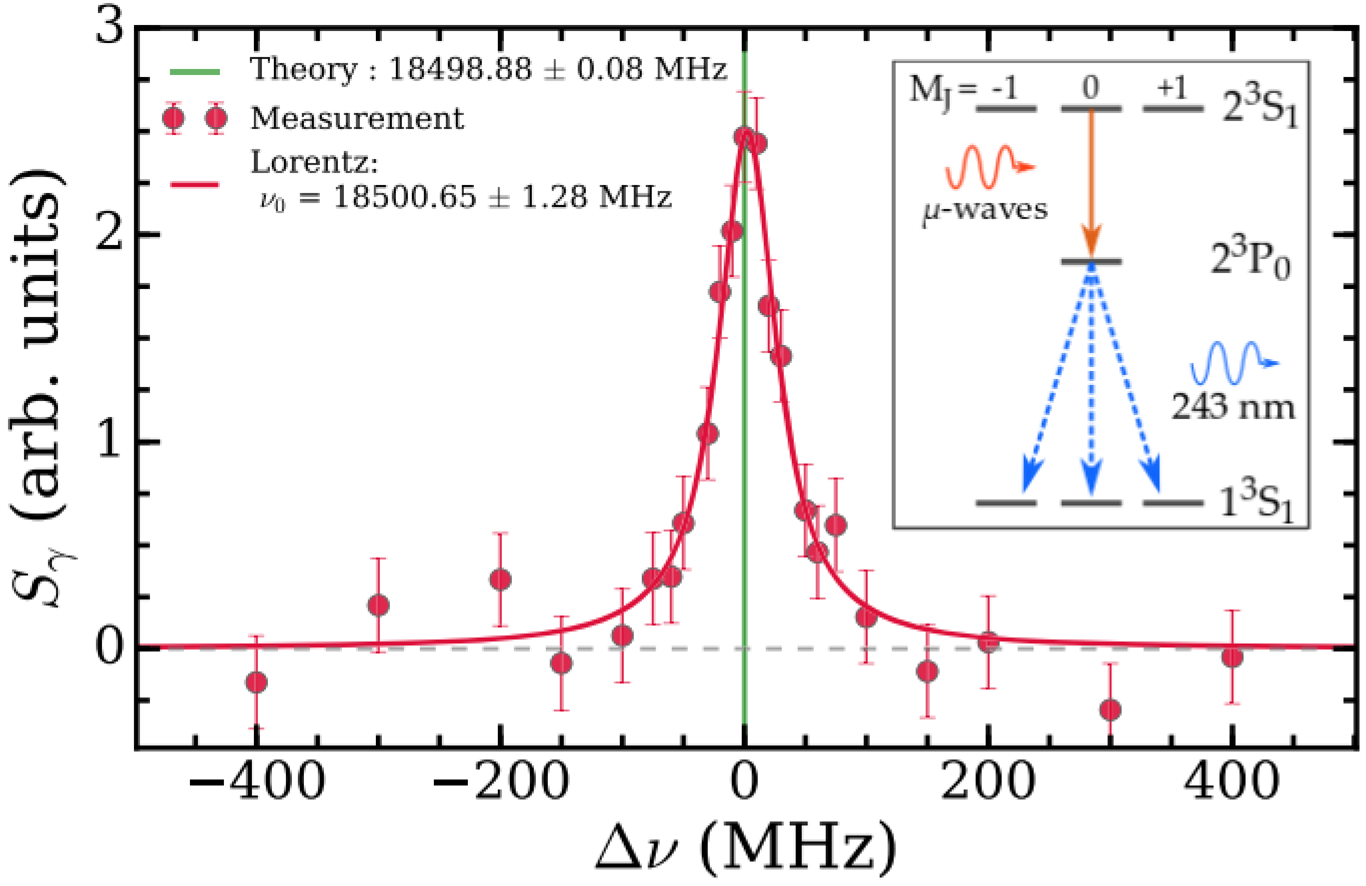


Experiment 1: waveguide in large chamber



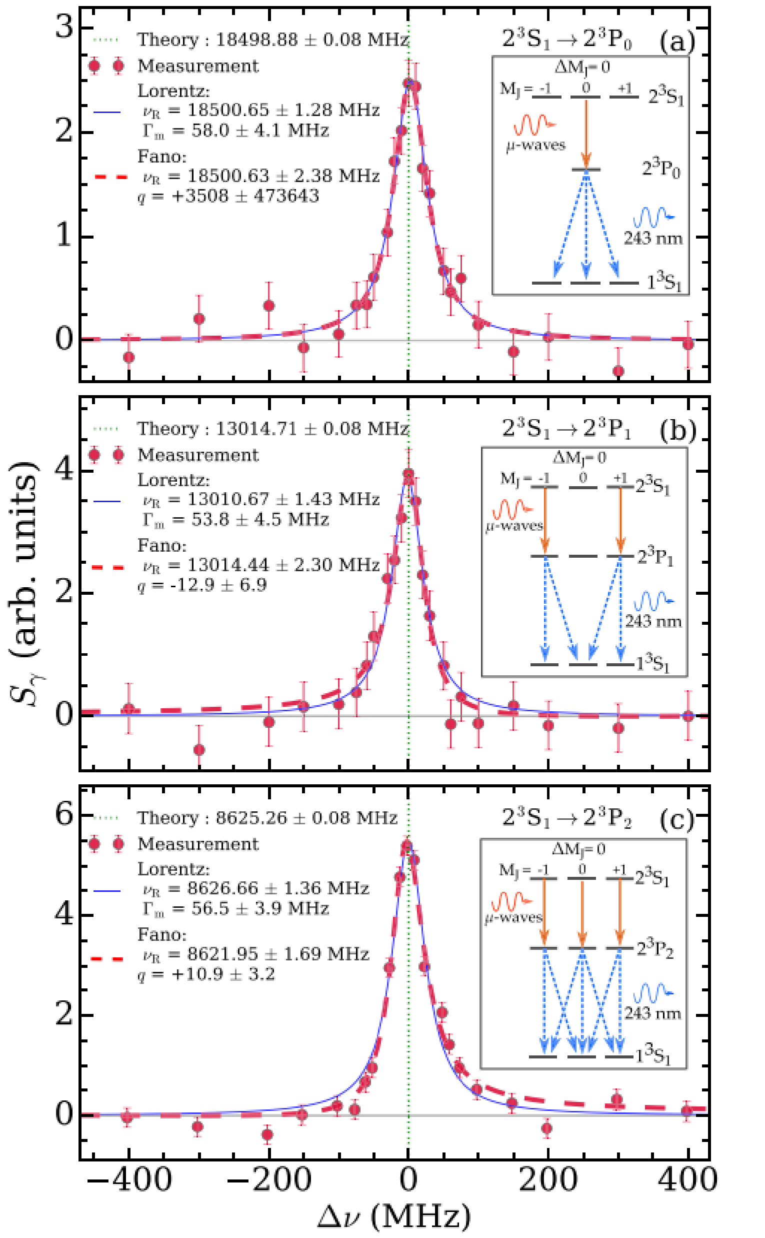
Microwave Signal - Lineshape

- By scanning across the μ-wave frequency, ν, can produce a lineshape
- Fit a Lorentzian
- At 32 G: ν_0= 18500.65 +/- 1.28 MHz
- Theory at 32 G: 18498.88 +/- 0.08 MHz
- Linewidth: ~60 MHz



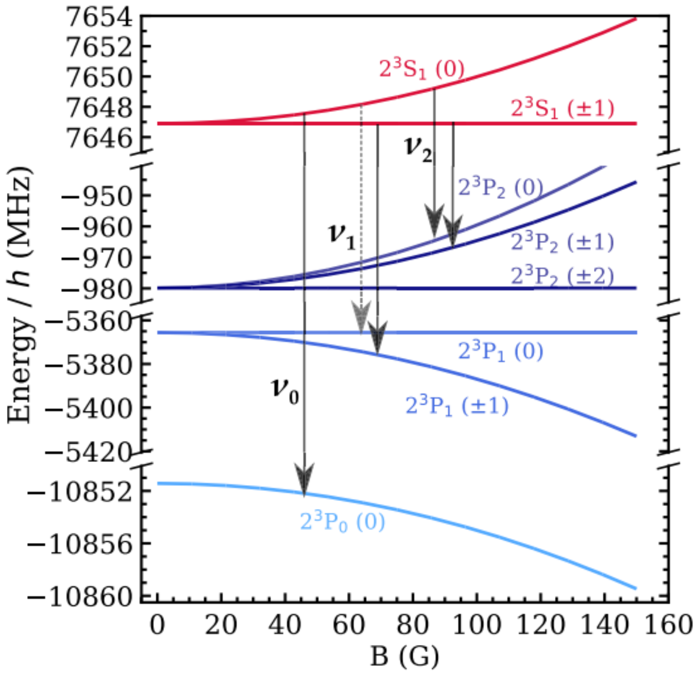
Lineshapes

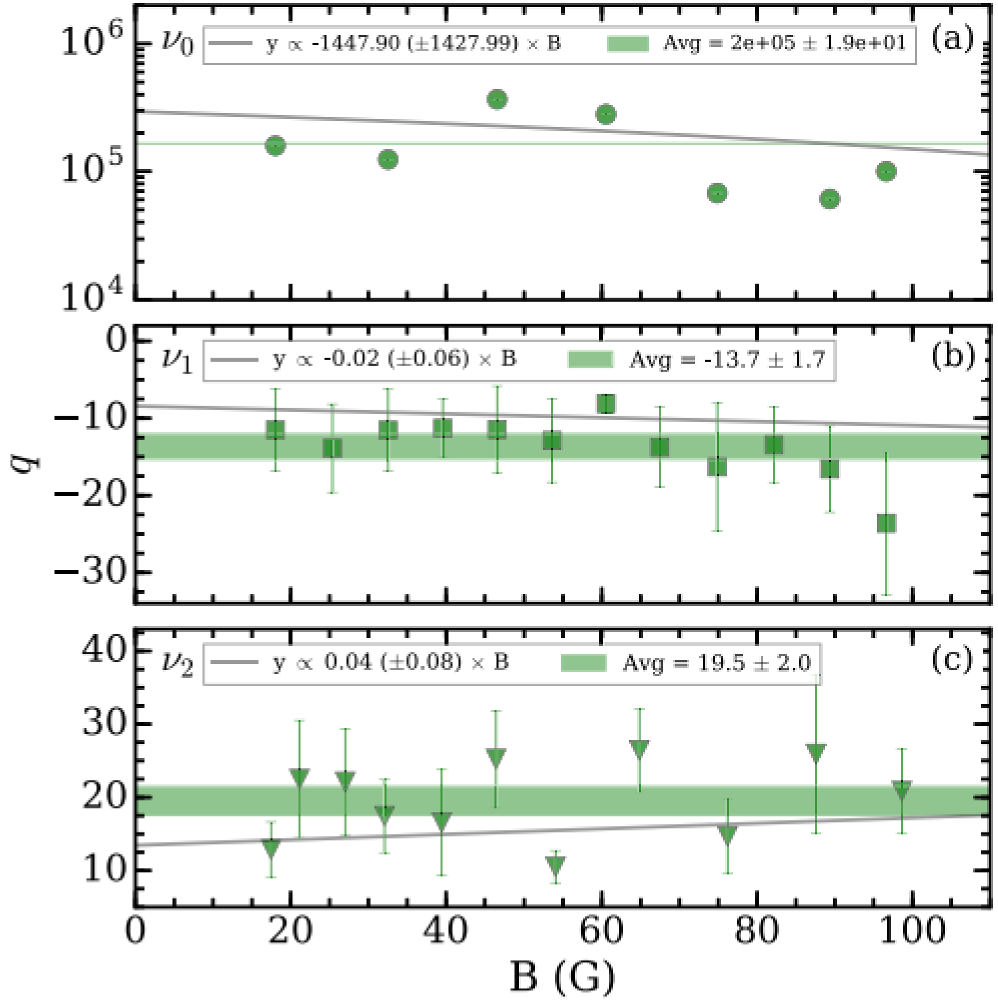
- See asymmetry in ν_1 and ν_2 lineshapes
- Fit Fano function
- This gives different directions of asymmetry
- Cannot really extract meaningful centroid value
- ν_0 is not asymmetric (large q value for Fano fit)



Asymmetry

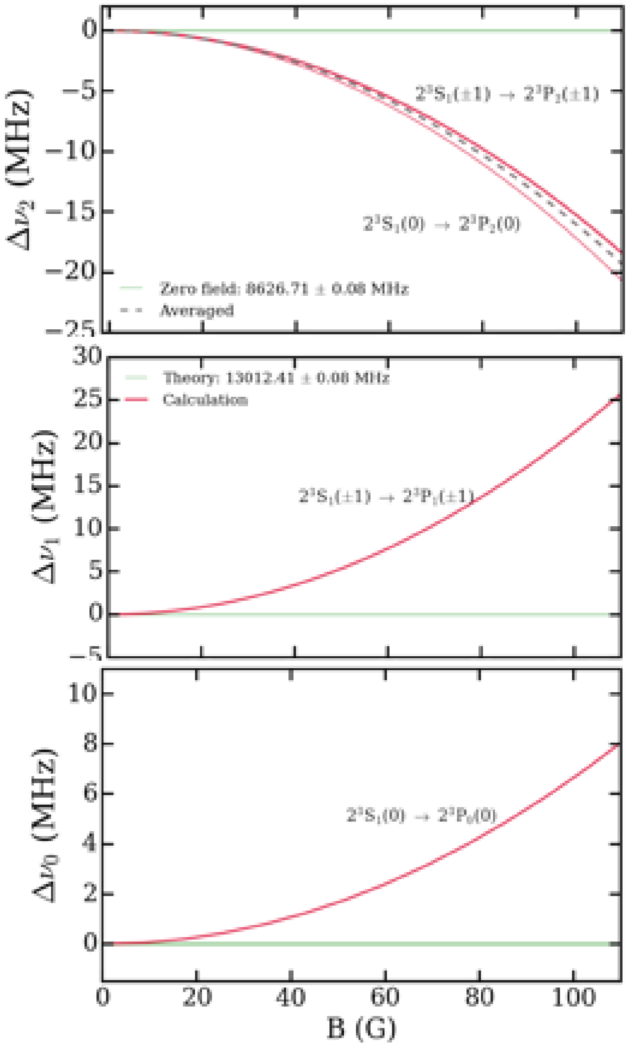
- Could this be due to driving multiple transitions?
- Asymmetry was consistent for different values of magnetic field

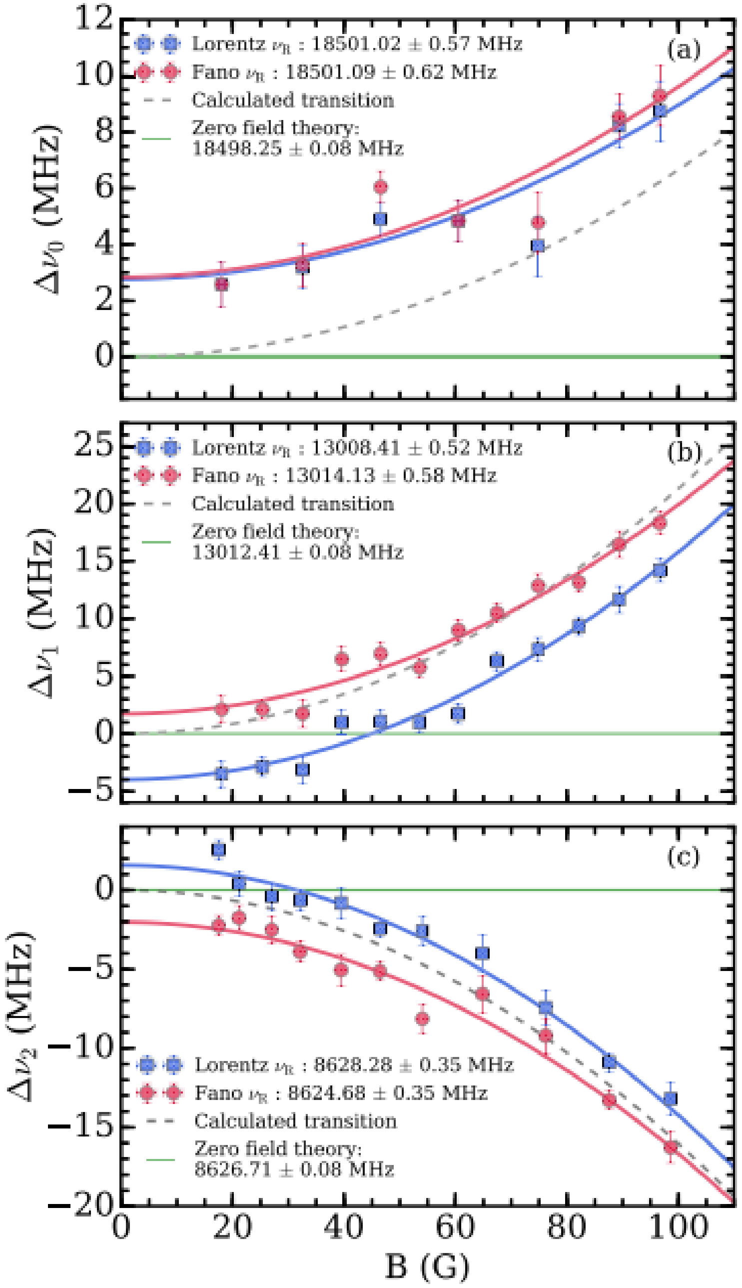




Positronium (Ps)

- The Zeeman effect is quadratic
- Fit a quadratic to the centroid values at each magnetic field (aB^2+c)
- Extrapolate to zero field in order to get zero field transition value
- Compare Fano fit to Lorentz fit: both are shifted from theory



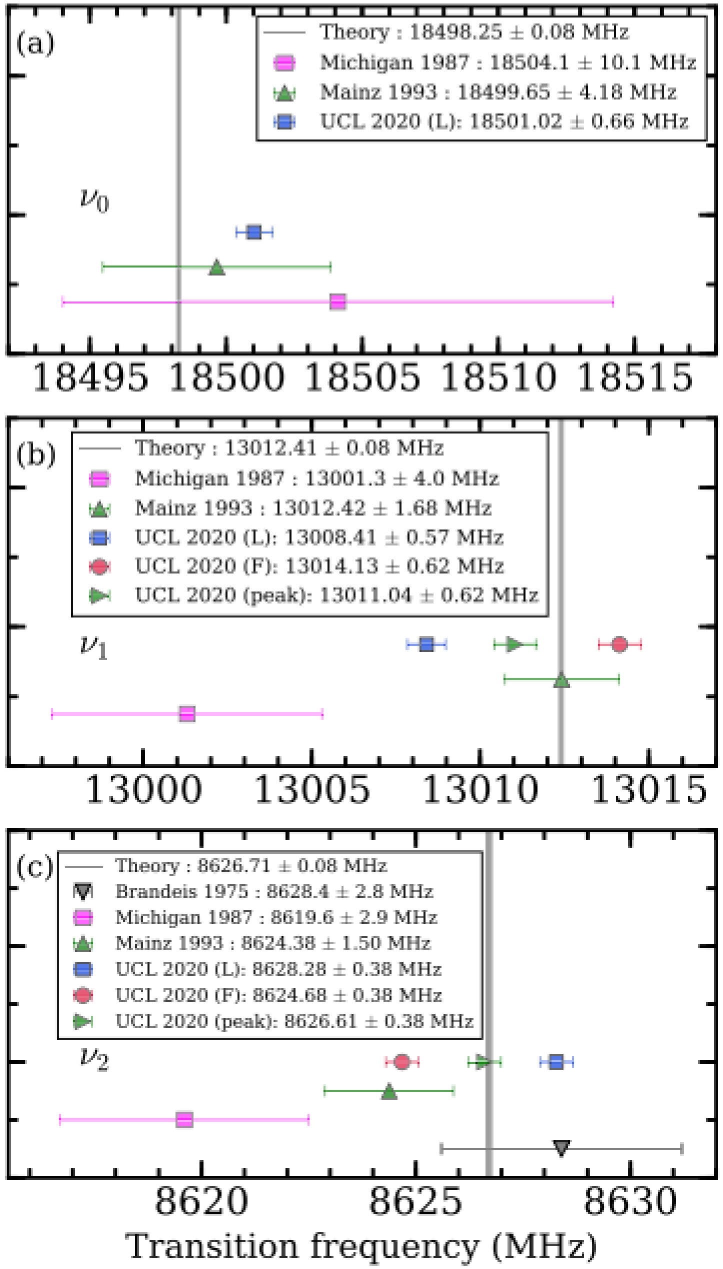


Systematic Error

- Use of 50 meV atoms vs (1993) 2 eV beam can eliminate the following systematics:
  Zeeman and motional Stark effects eliminated by extrapolation
- Lower microwave power used < + 10 kHzac Stark shift
- Stray electric fields cause Stark shifts, also < +10 kHz
- Largest source of systematic error: possible laser and waveguide misalignment which causes a Doppler shift. Estimate for a misalignment of +/- 2^o causes +/- 100, 150, and 215 kHz for $\nu_{2,}$ ν_1 and ν_0

Final Result

- Systematics, quantum interference effects not enough to account for difference
- Significant improvement in precision on previous measurements (1993)

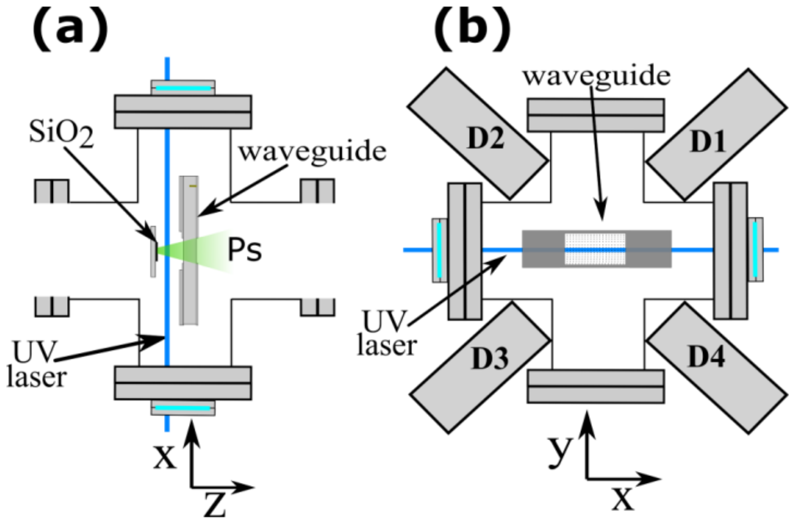


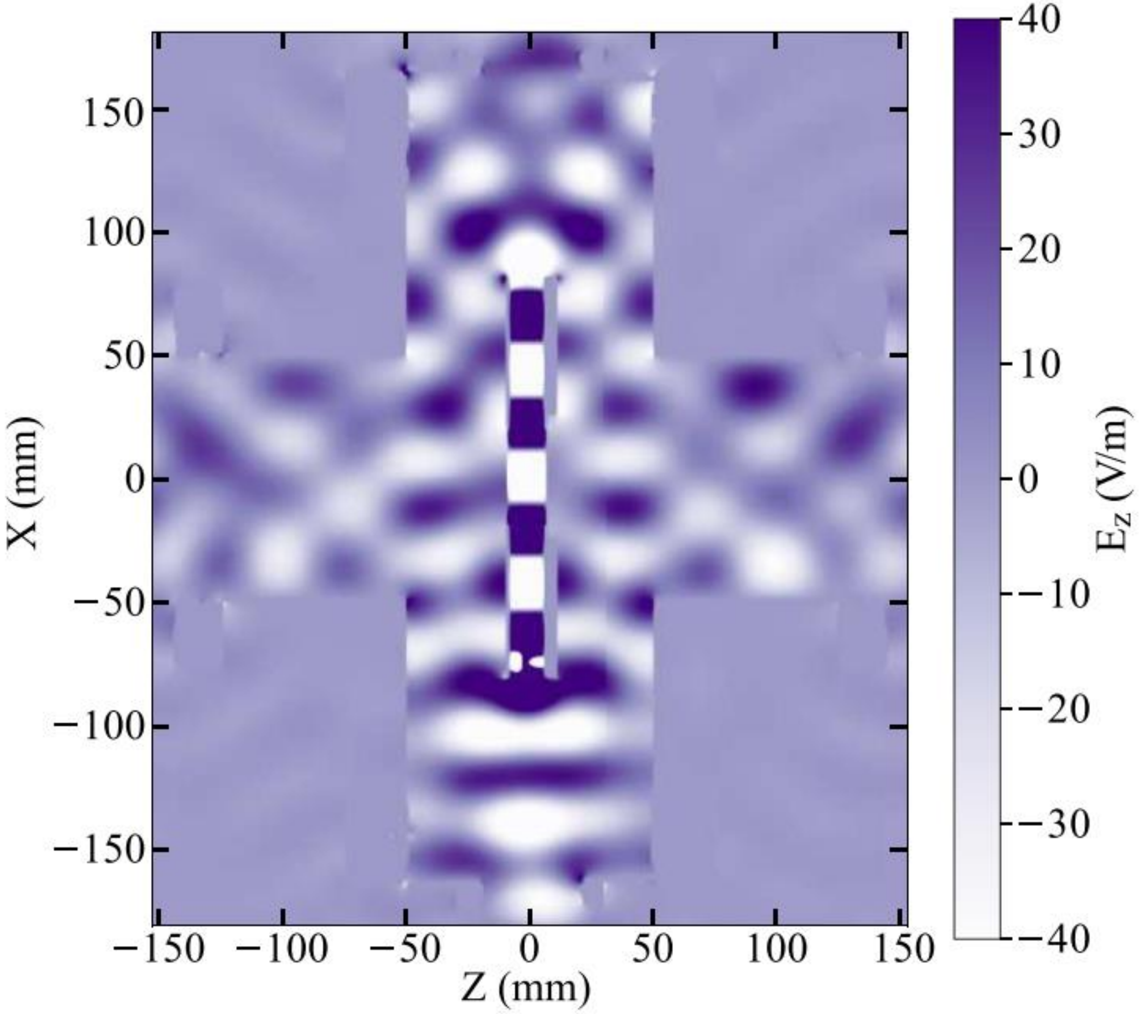
Conclusions, first iteration of Microwave experiment

- Saw asymmetric lineshapes
- Could not extract meaningful centroid values
- Fano and Lorentz fits both gave values shifted from theory
- ν_0 was not asymmetric, (Fano and Lorentz were equivalent), could extract a zero field transition frequency of 18501.02 +/- 0.66 MHz
- This is shifted from the theoretical value of 18498.25 +/- 0.08 MHz
- This gives a difference of 2.77 MHz, which corresponds to 4.2 σ

FEM microwave simulations

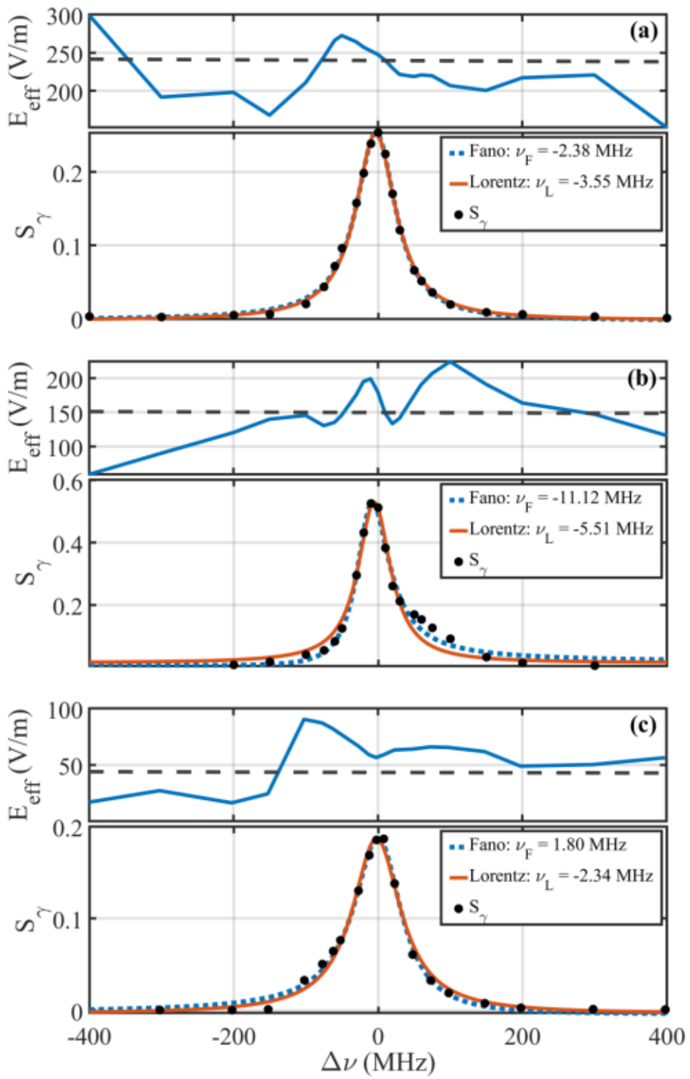
- Used CST studio suite software to simulate the microwave field in chamber



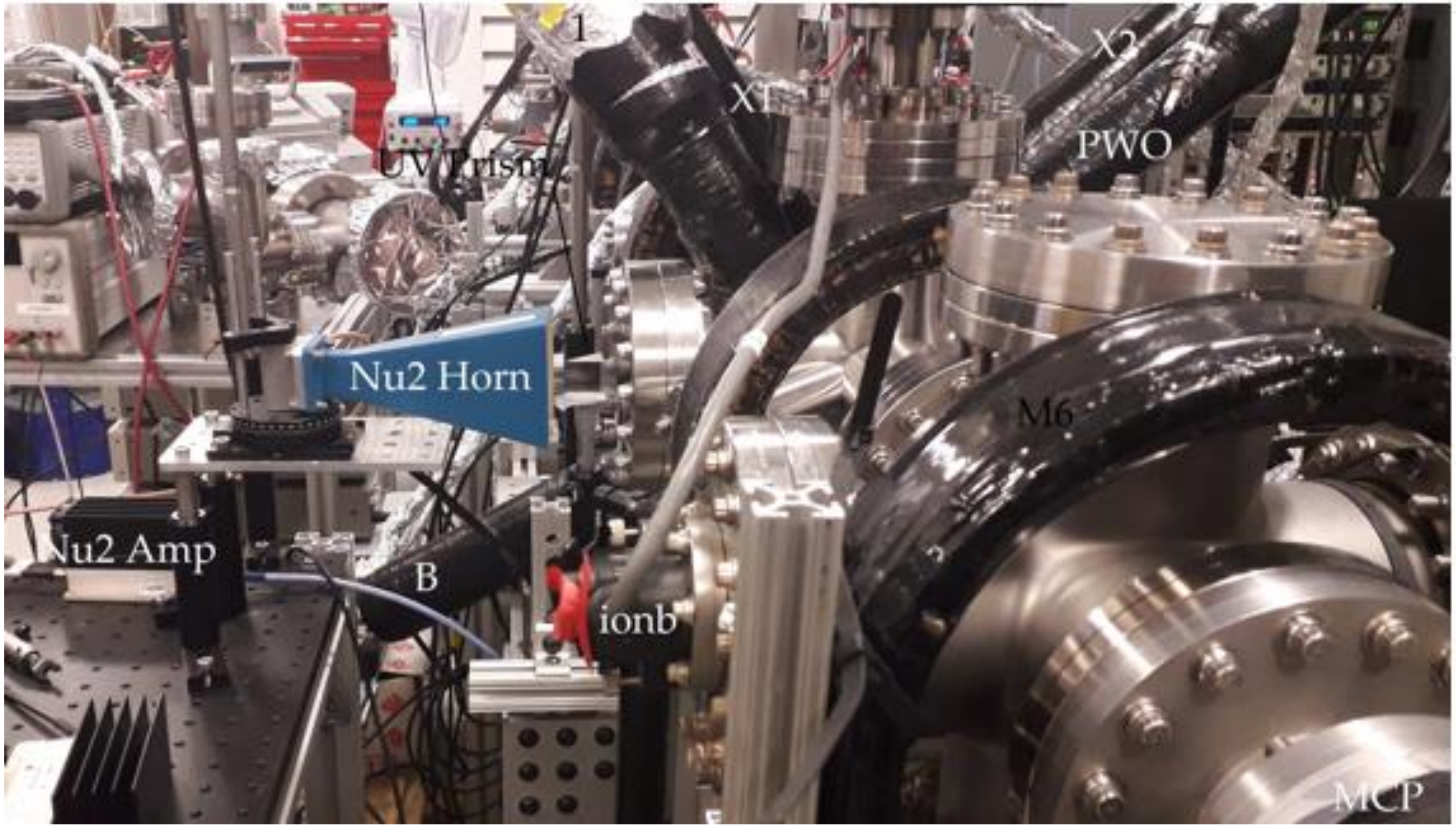


FEM microwave simulations

- The quantum state evolution of the atoms is computed using the master-equation approach
- These lineshapes consider the simulated fields within the waveguides
- Asymmetric behaviour seems to be explained by reflections of the microwave fields within the chamber

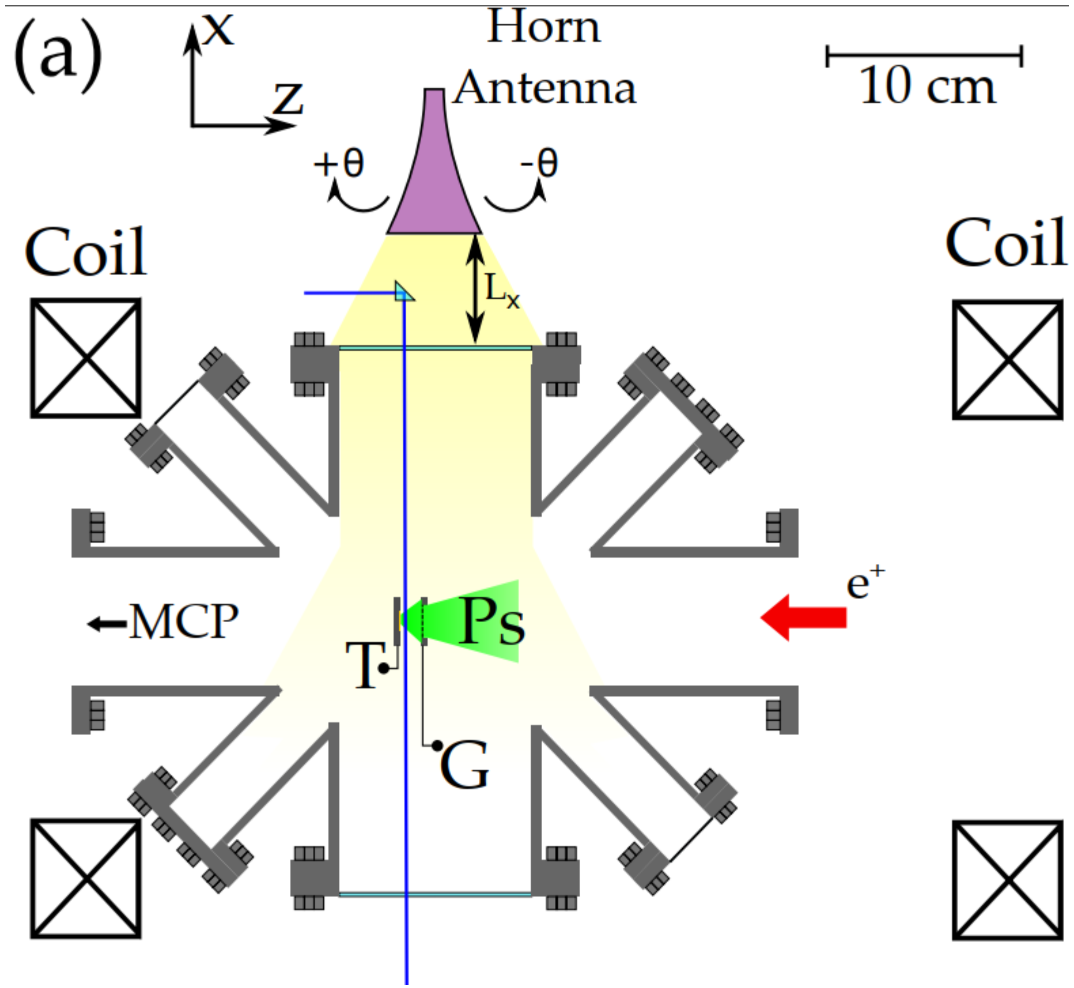


Experiment 2: Horn Antenna



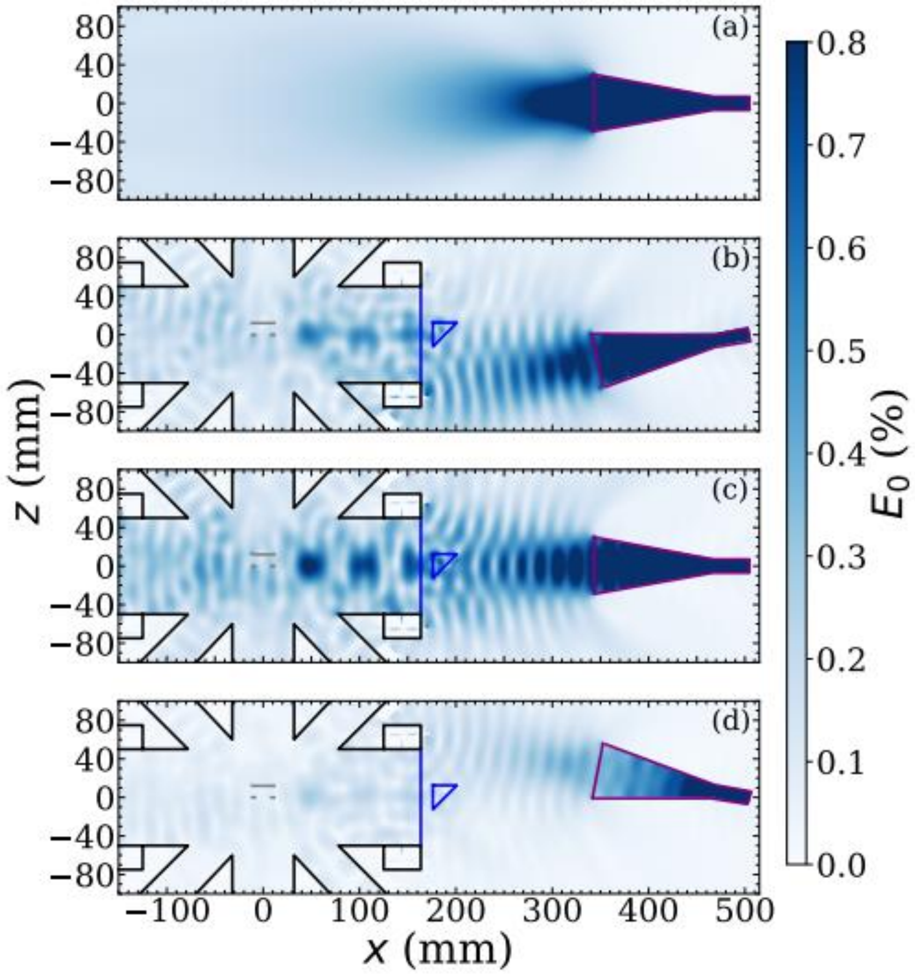
Experiment 2: Horn Antenna

- Horn is external to chamber
- Drives the $2^3S_1 \rightarrow 2^3P_2$ transition
- Microwave radiation should fill chamber – drives transition in free space



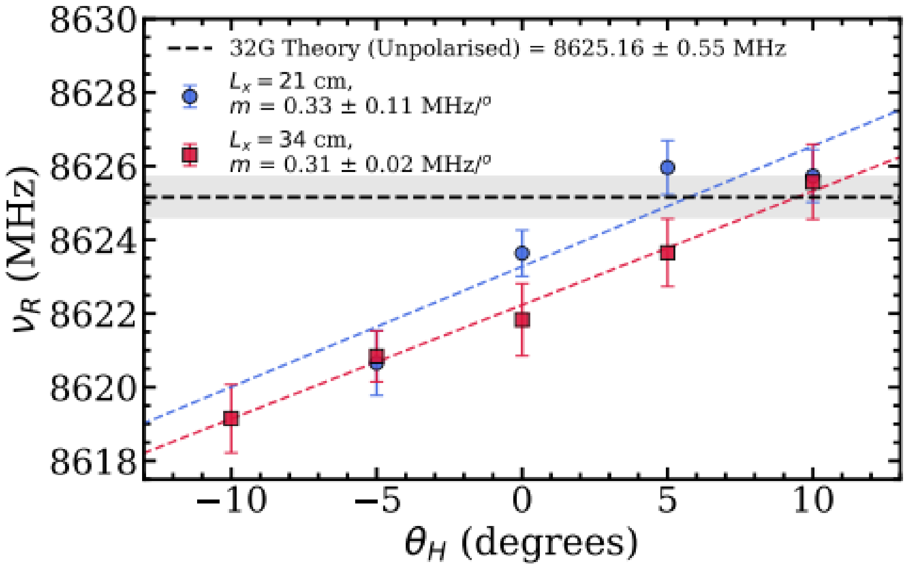
Experiment 2: Horn Antenna

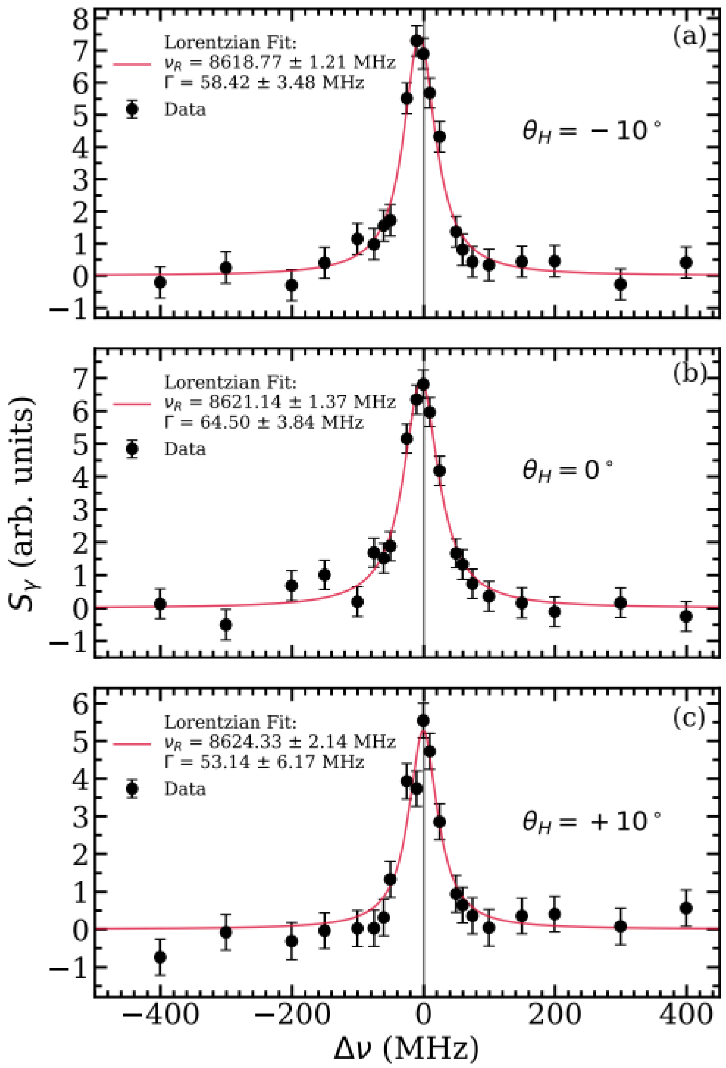
- Microwave field is susceptible to reflections of the field due to chamber



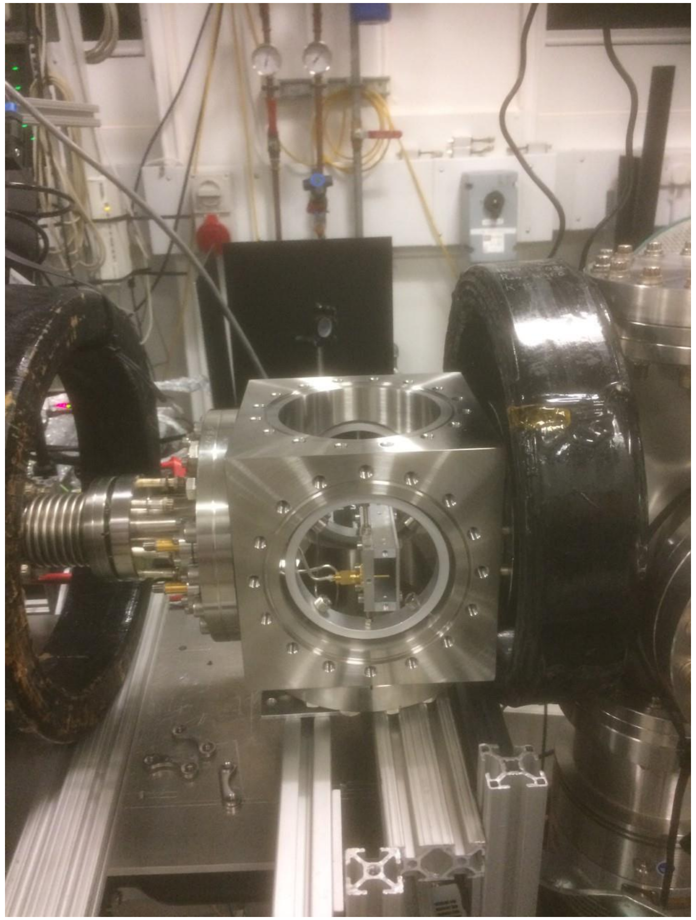
Experiment 2: Horn Antenna

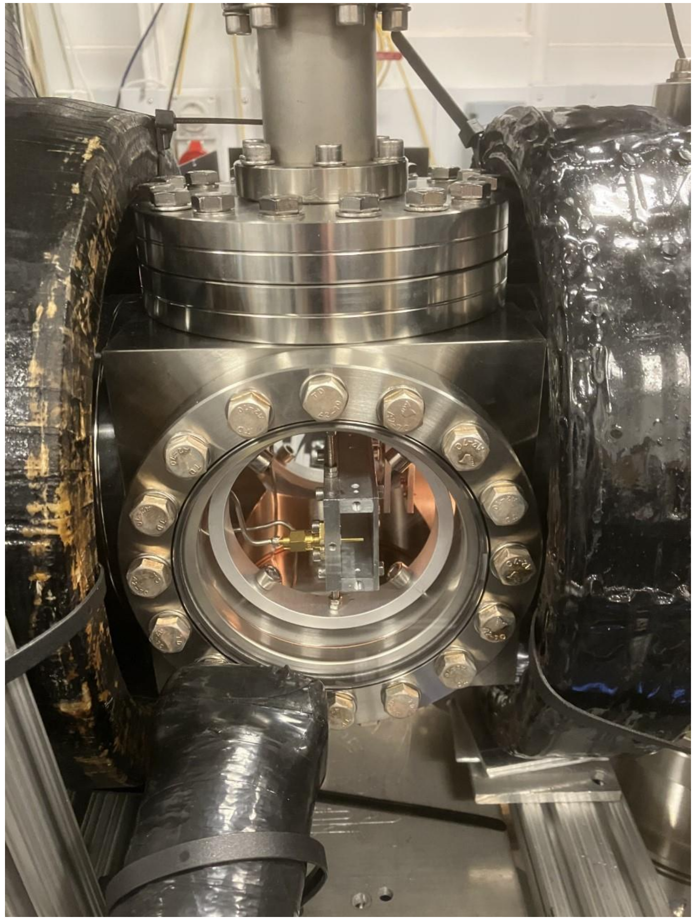
- Took lineshapes for multiple angles
- The centroid depended on angle
- Not suitable for precision measurements





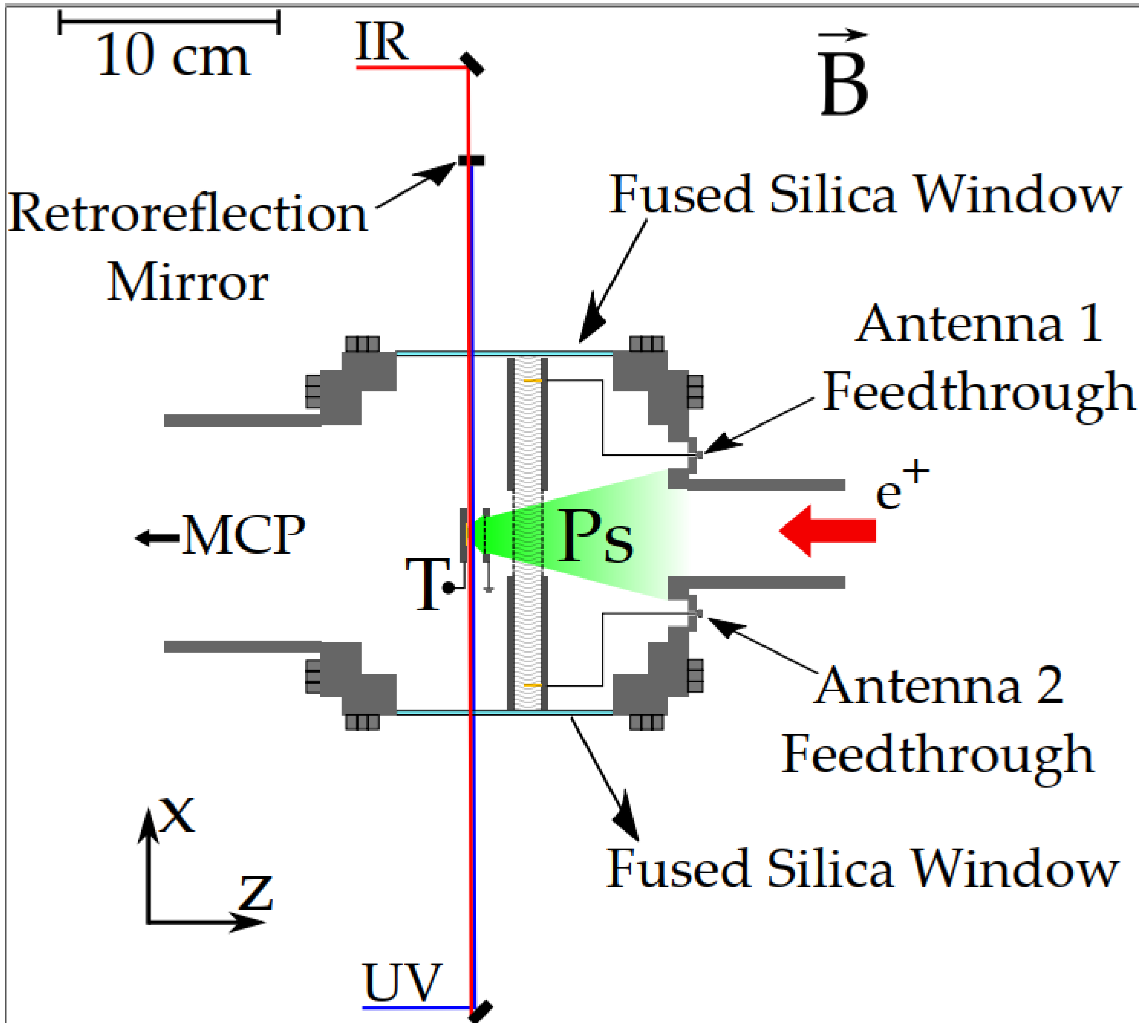
Experiment 3: Waveguide with small chamber





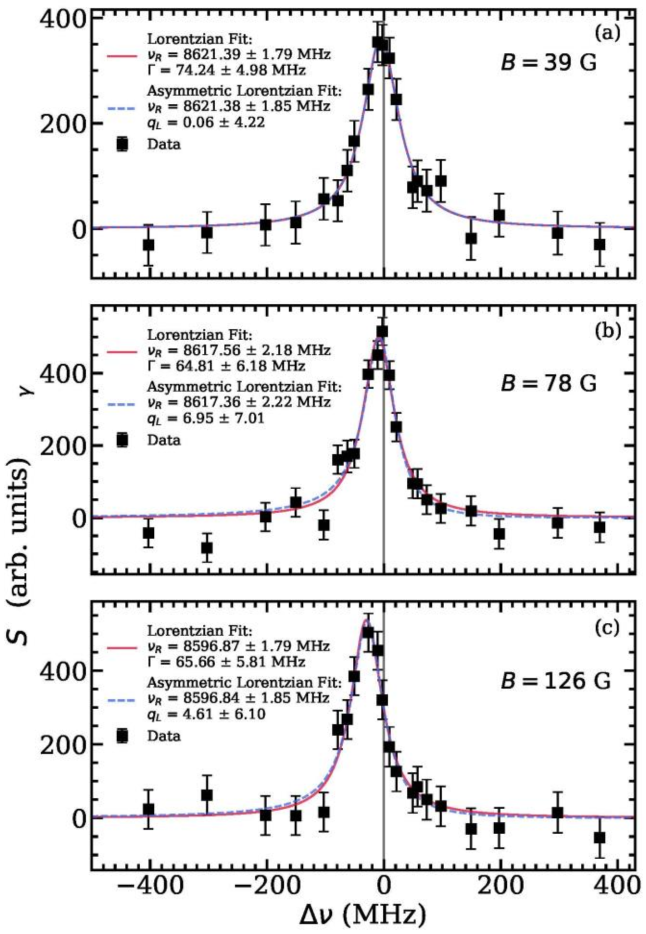
Experiment 3: Waveguide with small chamber

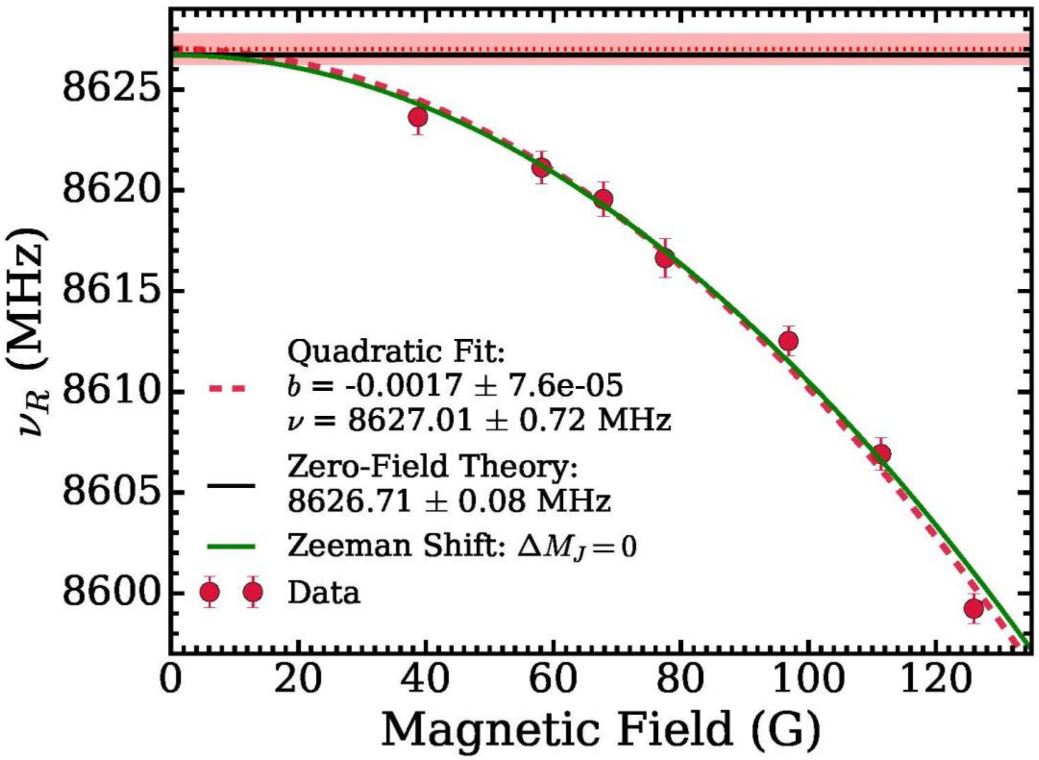
- Two antennas, one at either side
- Can reverse direction of microwaves



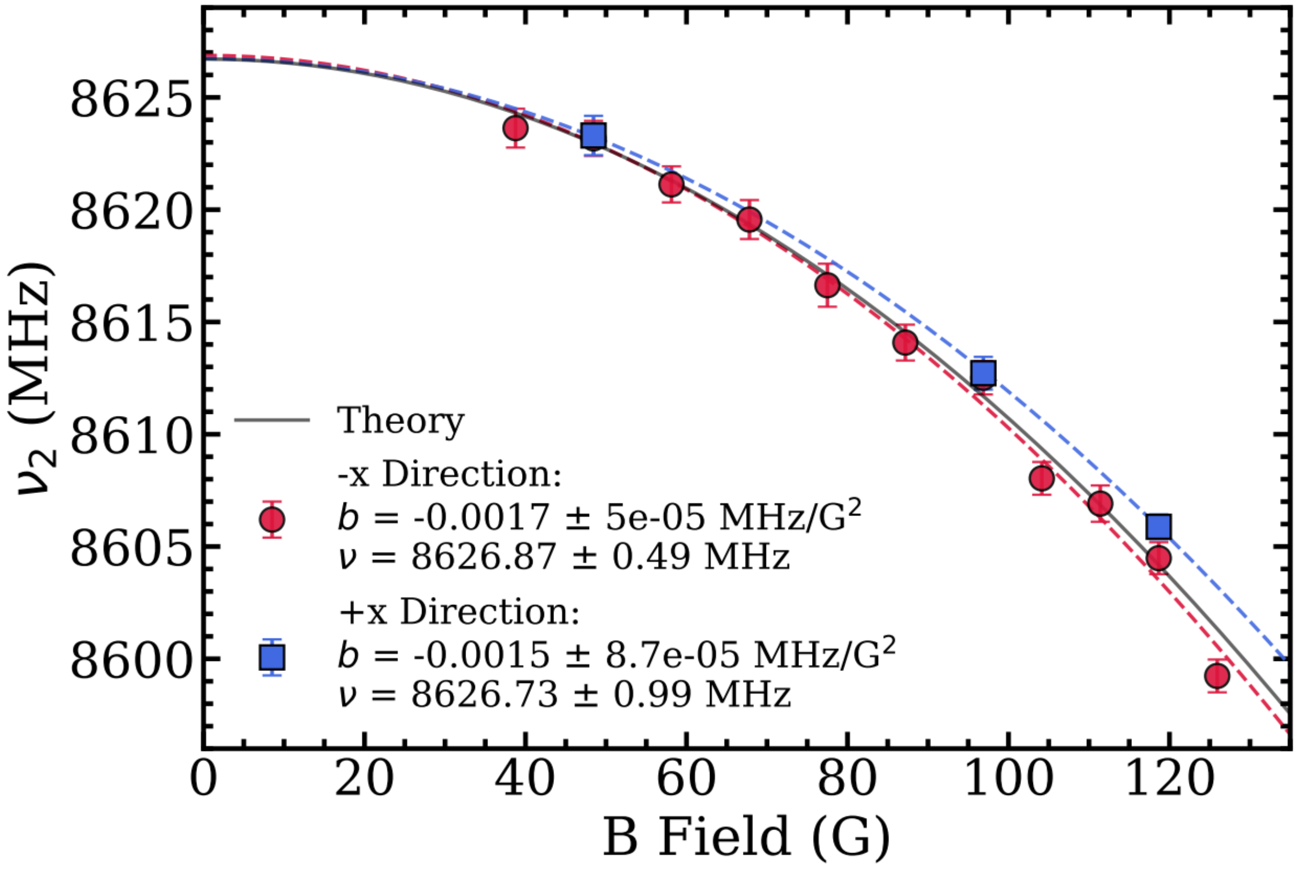
Experiment 3: Waveguide with small chamber

- This new data is not asymmetric
- Currently being taken

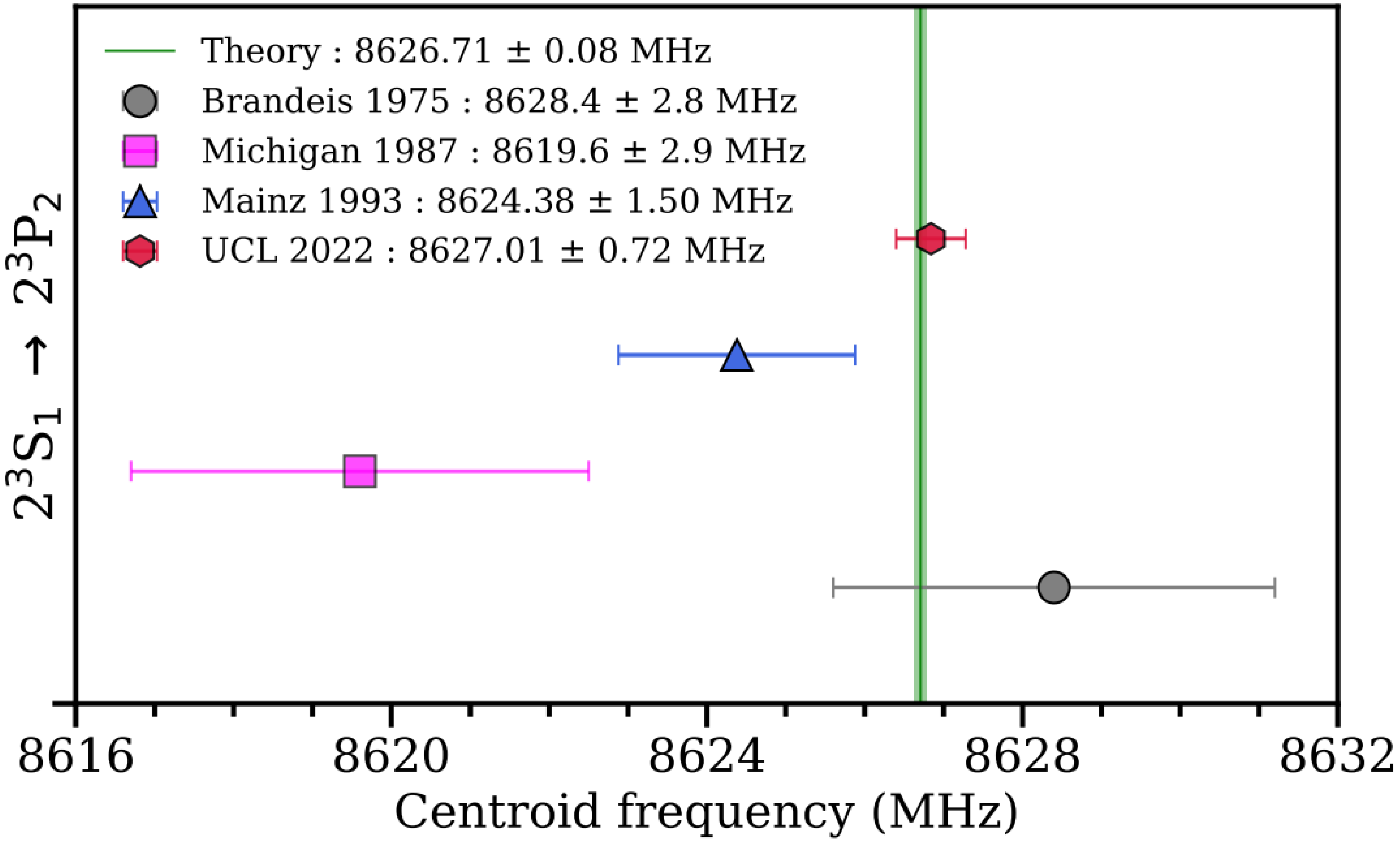




Experiment 3: Waveguide with small chamber



Experiment 3: Waveguide with small chamber



Conclusions – 1st experiment

- Have measured ν_0, ν_1, and ν_2 transitions in a 6 way cross
- ν_1 and ν_2: Asymmetric lineshapes
- ν_0: Significant disagreement with theory
- Simulations suggested that asymmetric lineshapes was due to reflections in the chamber

Conclusions – 2nd experiment

- Measured ν_2 interval using a horn antenna
- Horn antenna was external to vacuum chamber
- Generated microwave radiation in free space
- Produced symmetric lines, but transition frequency was found to be dependent on angle of the antenna relative to chamber

Conclusions – 3rd experiment

- Modified vacuum chamber design to limit microwave relfections in chamber
- Measured ν_2 interval using a waveguide
- No asymmetric lineshapes
- Final value: 8626.84 +/- 0.44 MHz
- Theory: 8626.71 +/- 0.08 MHz

Future experiments

- Eliminate Zeeman shift and measure at zero field – requires positronium beam to be extracted outside of confining field for positron beam
- Use Rydberg helium to characterise waveguides (stray fields)
- Use Ramsey spectroscopy (SOF/FOSOF) methods

Thanks for listening!