# Polarisation effects in spectroscopy of the positronium n = 2 fine structure intervals

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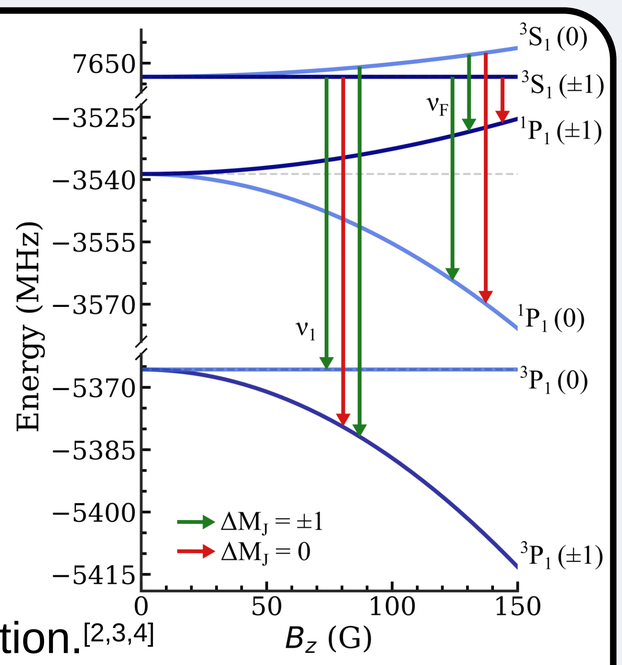
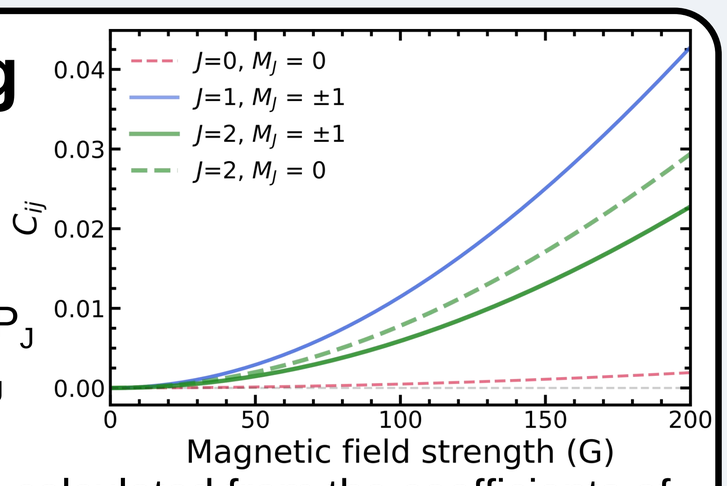
## Introduction

- The n = 2 Positronium (Ps, the bound state of an electron and positron) fine structure intervals have been measured several times to test bound-state quantum electrodynamics.[1]
- All previous measurements were performed using waveguides of fixed polarisation.[2,3,4]
- Horn antennas offer a way to change the polarisation of the microwave radiation.
- We drove $2\,^3S_1 \rightarrow 2\,^{2S+1}P_1$ ($S$ = 0, 1) transitions, known as $\nu_F$ and $\nu_1$, using a horn antenna to evaluate the effect of polarisation in free-space Ps microwave spectroscopy.



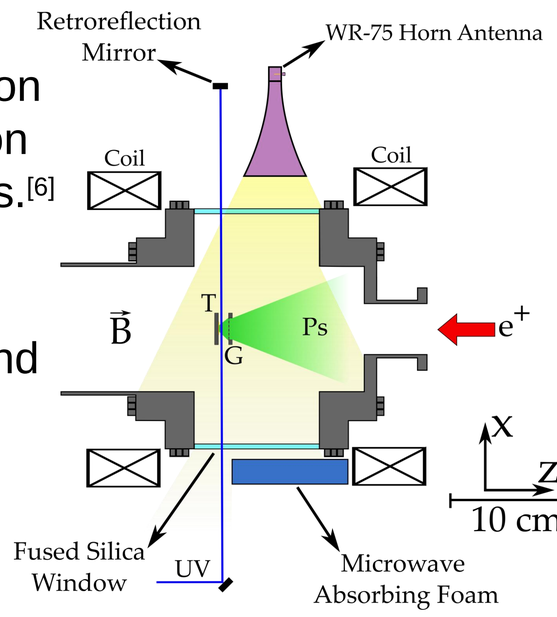

## Zeeman Mixing

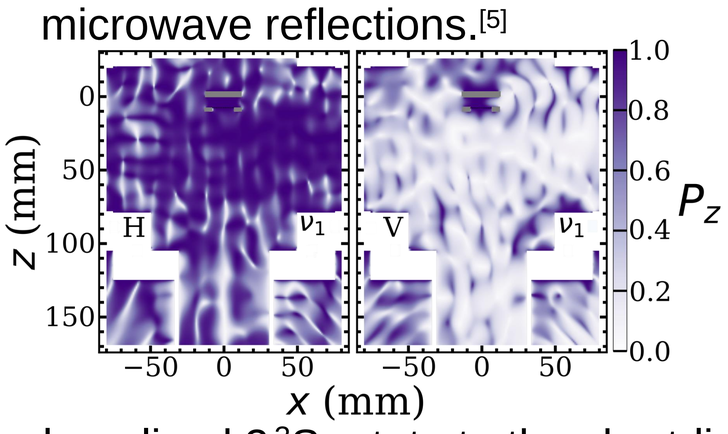
- $\nu_F$ is forbidden in zero field due to charge conjugation symmetry.
- $2\,^1P_1$ levels mix with $2\,^3P_J$ levels with the same $M_J$ in a magnetic field.
- The degree of mixing is calculated from the coefficients of the eigenvectors of the full Hamiltonian matrix $A_{mj}$.




## Experimental Methods

- $1\,^3S_1$ Ps was made by implanting positron pulses into a mesoporous $SiO_2$ film in a field of $\langle B_z \rangle$ = 131 G.[6]
- $2\,^3S_1$ Ps was made by single photon excitation in an electric field: $1\,^3S_1 \xrightarrow{\lambda_{UV} = 243\ \mathrm{nm}} 2\,^3S_1' \xrightarrow{F \approx 2 \rightarrow 0\ \mathrm{kV/cm}} 2\,^3S_1$.[7]
- Time resolved gamma-ray spectroscopy using scintillation detectors allows differentiation of long- and short-lived states.[6]
- A horn antenna emitted radiation parallel to $B_z$ when orientated horizontally (H), and orthogonal to $B_z$ when orientated vertically (V).
- The vacuum chamber was configured to minimise microwave reflections.[5]

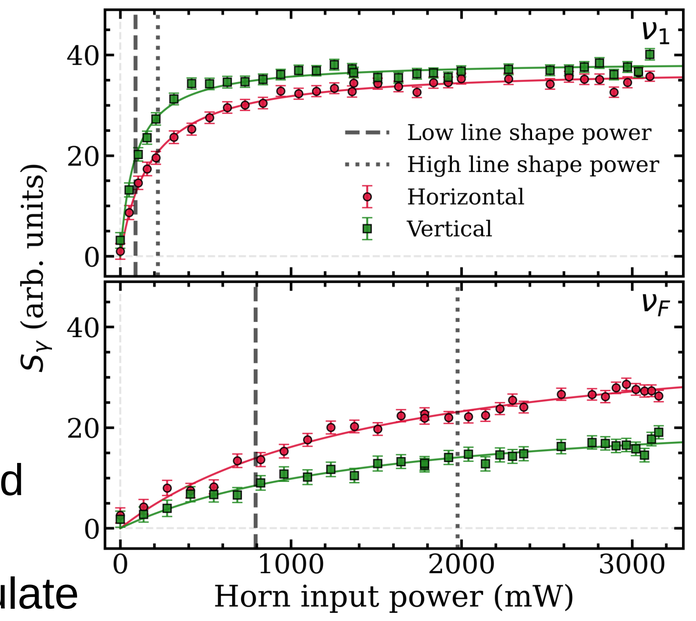


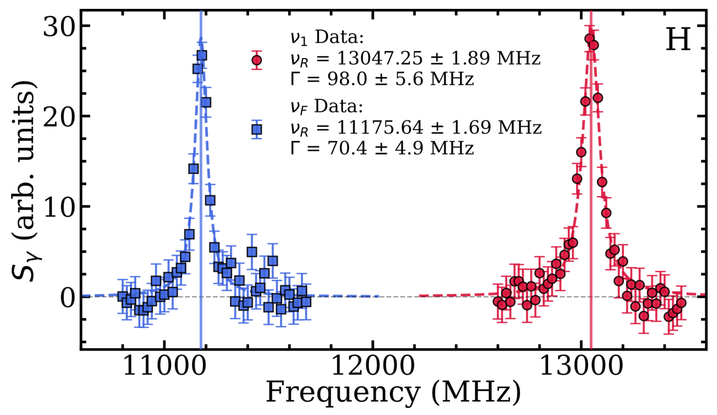

- Simulations indicate the average unpolarised fraction is 30% for both orientations.
- The population transfer from the long-lived $2\,^3S_1$ state to the short-lived $2\,^{2S+1}P_1$ state, $S_\gamma$, was measured as a function of microwave frequency and power.[4]

## Saturation Measurements

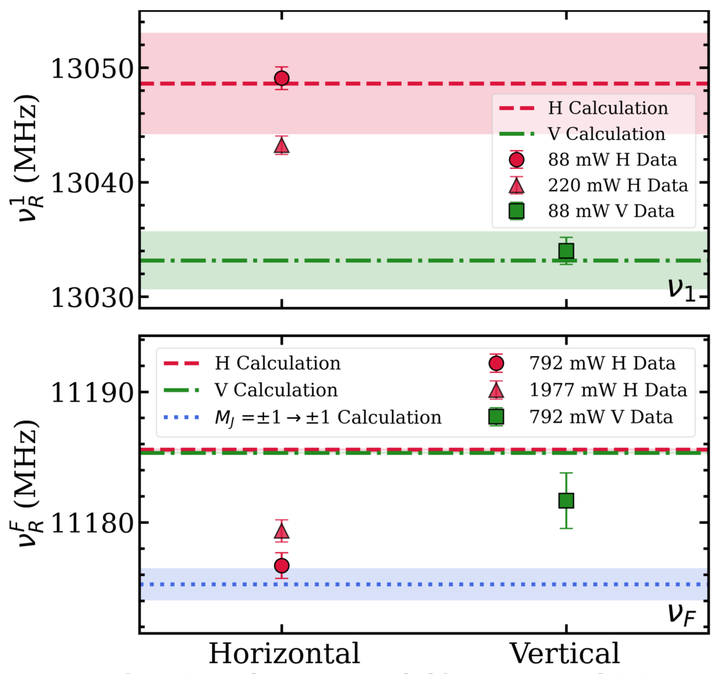
- $\nu_1$ saturation data is consistent with all $2\,^3S_1$ states being depopulated.
- H orientation requires more power to saturate due to $2\,^3S_1$ (0) only being depopulated by low-intensity unpolarised reflections.
- $\nu_F$ does not fully depopulate the $2\,^3S_1$ state in V orientation, indicating depopulation of at least one $2\,^3S_1$ state is highly limited.




## Line Shape Measurements




- Line shapes fitted with Lorentzian functions to extract the resonance frequency. Comparison made to average Zeeman shift for each polarisation.
- At low power $\nu_1$ data are consistent with transitions driven by fully polarised radiation.
- But $\nu_F$ is shifted 4.1σ from theory in the H case. Being consistent with only $2\,^3S_1$ (±1) → $2\,^1P_1$ (±1) being driven.




- High power measurements for H show a shift toward V, indicating low-intensity reflections do become significant.

## Conclusions

- We have verified that horn antennas can be used to perform polarisation resolved Ps spectroscopy in free-space. Although near the saturation regime unpolarised reflections can drive additional transitions.
- The $\nu_F$ saturation and line shape data display unexpected behaviour, likely due to an incomplete model of the Zeeman mixing.
- Ongoing waveguide measurements will further investigate the behaviour of $\nu_F$.

[1] S. G. Karshenboim, *Phys. Reports,* **422,** 1-63 (2005)
[2] S. Hatamian et al., *PRL*, **58**, 1833 (1987)
[3] R. Ley et al., *Hyperfine interactions*, **89**, 327 (1994)
[4] R. E. Sheldon et al., *PRL*, **131**, 043001 (2023)
[5] R. E. Sheldon et al., *PRA,* **107**, 042810 (2023)
[6] B. S. Cooper et al., *Rev. Sci. Intrum.,* **86**, 103101 (2015)
[7] A. M. Alonso et al., *PRA,* **95**, 033408 (2017)

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