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Measurement of the C-forbidden $2\ ^3S_1 \rightarrow 2\ ^1P_1$ transition in positronium

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Positronium (Ps)

- The bound state of an electron and a positron.
- Hydrogenic atom.
- Fine structure unlike hydrogen (annihilation, spin-orbit coupling, spin-spin interactions).
- Purely leptonic, ideal system for testing bound state QED theory.
- Has eigenstates of C (charge conjugation) and CP (charge conjugation and parity) - ideal for testing fundamental symmetries.

Ps n = 2 transition measurements

- Measurements of Ps energy levels are much less precise than theory.
- $2\ {}^{3}S_{1} \rightarrow 2\ {}^{2S+1}\mathrm{P}_{J}$ (J = 0, 1, 2) intervals:
    - Uncertainty in theory = 80 kHz[1].
    - Until recently, experimental uncertainties > 1 MHz.
- Difficulties:
    - Hard to produce in large numbers.
    - Very fast (doppler broadening, transit time broadening).
    - Unstable against annihilation.

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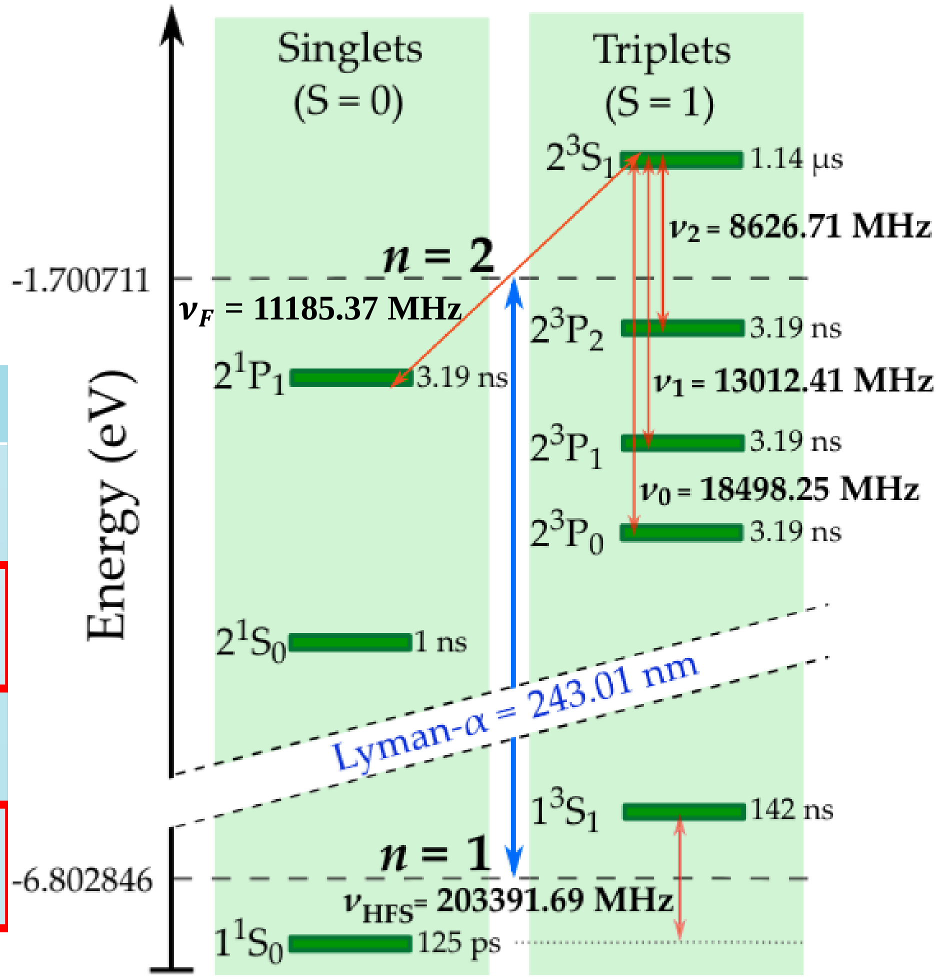
[1] A. Czarnecki et al, Phys. Rev. A 59, 4316 (1999).

State of Ps n = 2 tests

- Measure two intervals: $2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_1$ (ν_1) and $2\,^3\mathrm{S}_1 \rightarrow 2\,^1\mathrm{P}_1$ (ν_F).
- Performed in a range of magnetic fields.

Transition	Measured (MHz)	$\Delta_{\text{meas.}}$ (ppm)	Theory (MHz)	$\Delta_{\text{theo.}}$ (ppm)
$2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_0$ (ν_0)	18 499.65(5.2)	230[1]	18498.25(8)	4.8[2]
$2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_1$ (ν_1)	13012.42(1.68)	129[1]	13012.41	6.1[2]
$2\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_2$ (ν_2)	8627.94(95)	110[3]	8626.71	9.3[2]
$2\,^3\mathrm{S}_1 \rightarrow 2\,^1\mathrm{P}_1$ (ν_F)	11180.0(9.0)	600[4]	11185.37(8)	7.2[2]



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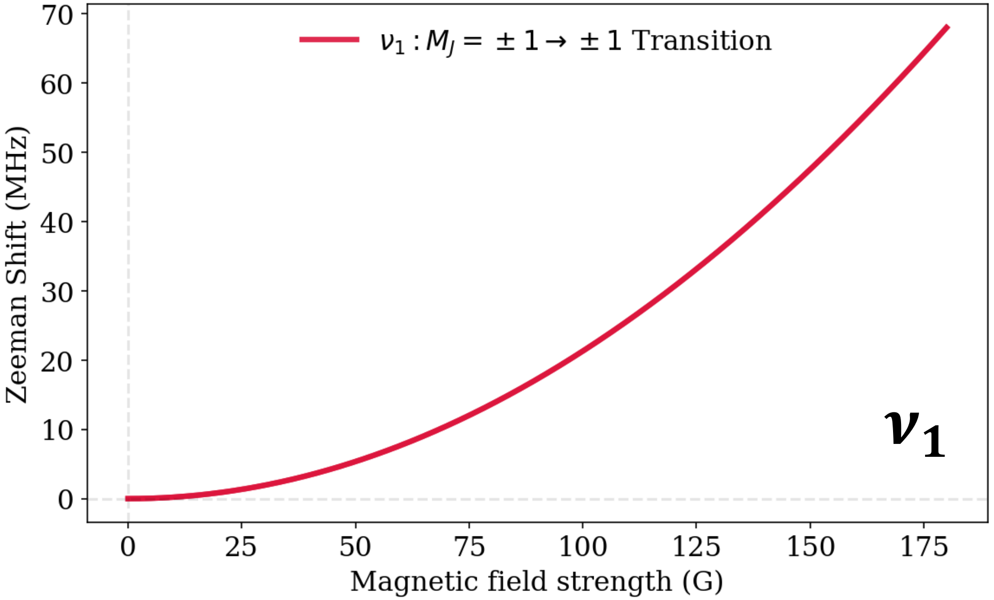
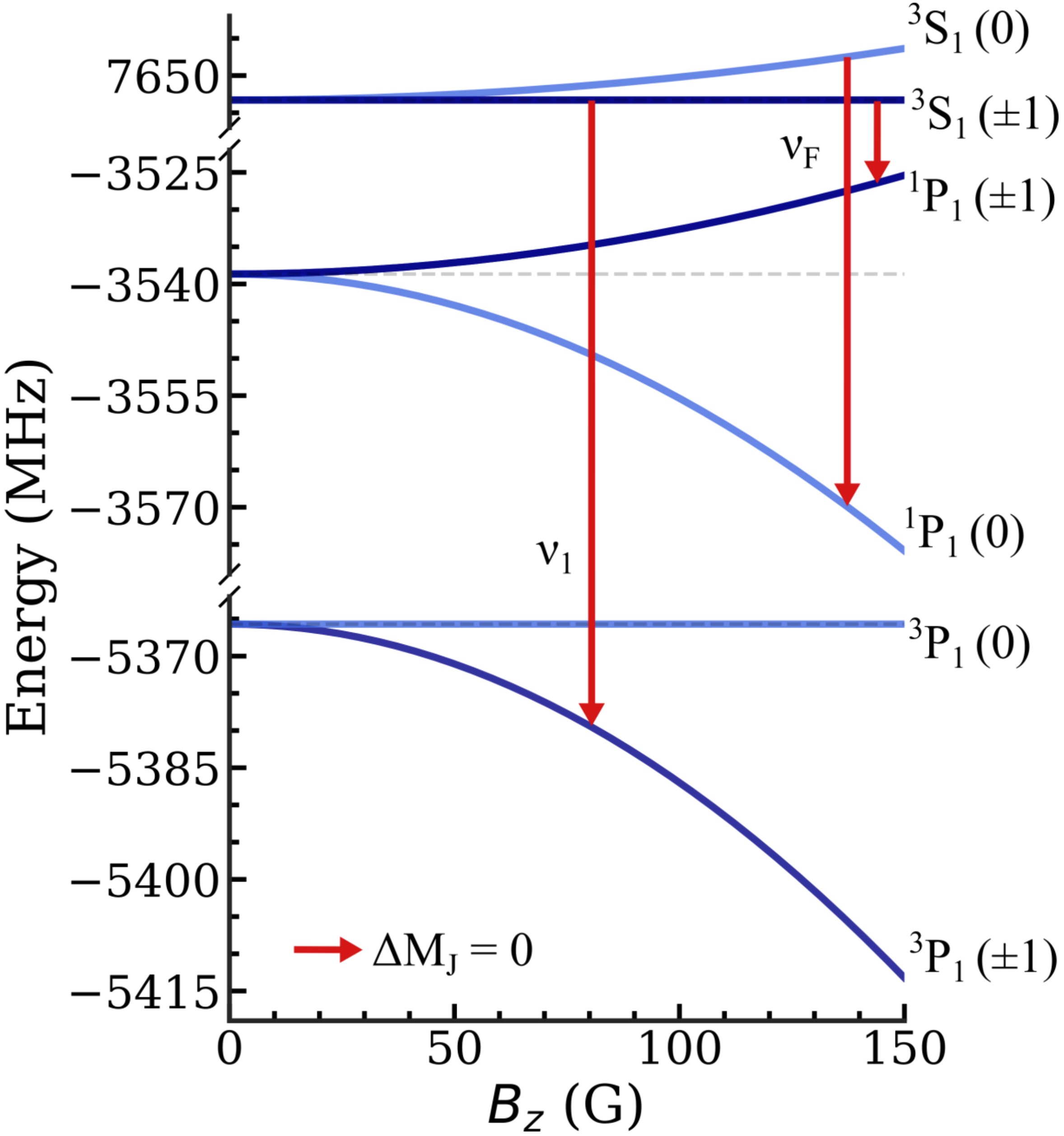
[1] D. Hagena, et al, Phys. Rev. Lett., 71:2887–2890 (1993).
[2] A. Czarnecki et al, Phys. Rev. A 59, 4316 (1999).
[3] R. E. Sheldon et al, Phys. Rev. Lett. 131, 043001 (2023).
[4] R. Ley et al, Hyperfine Interactions, 89(1):327–341 (1994).

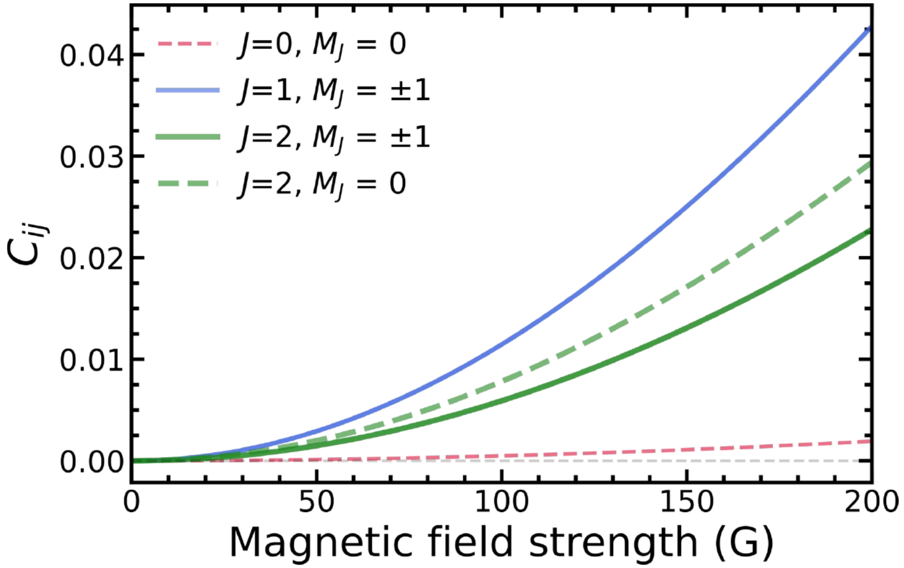
Microwave transitions

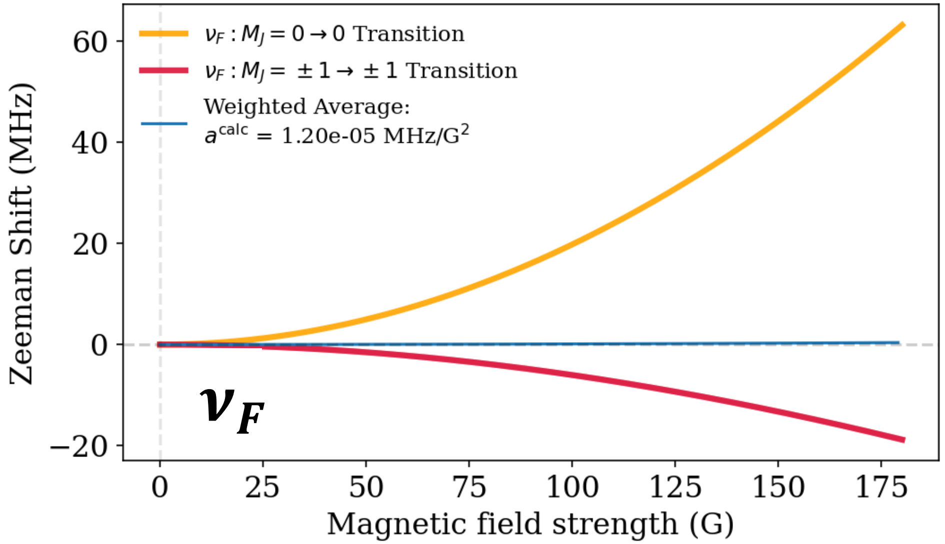
- $\Delta M_J = 0$ transitions are driven.
- ν_F:
    - $2\,^3\mathrm{S}_1(0) \rightarrow 2\,^1\mathrm{P'}_1(0)$
    - $2\,^3\mathrm{S}_1(\pm1) \rightarrow 2\,^1\mathrm{P'}_1(\pm1)$
- ν_1:
    - $2\,^3\mathrm{S}_1(\pm1) \rightarrow 2\,^3\mathrm{P}_1(\pm1)$





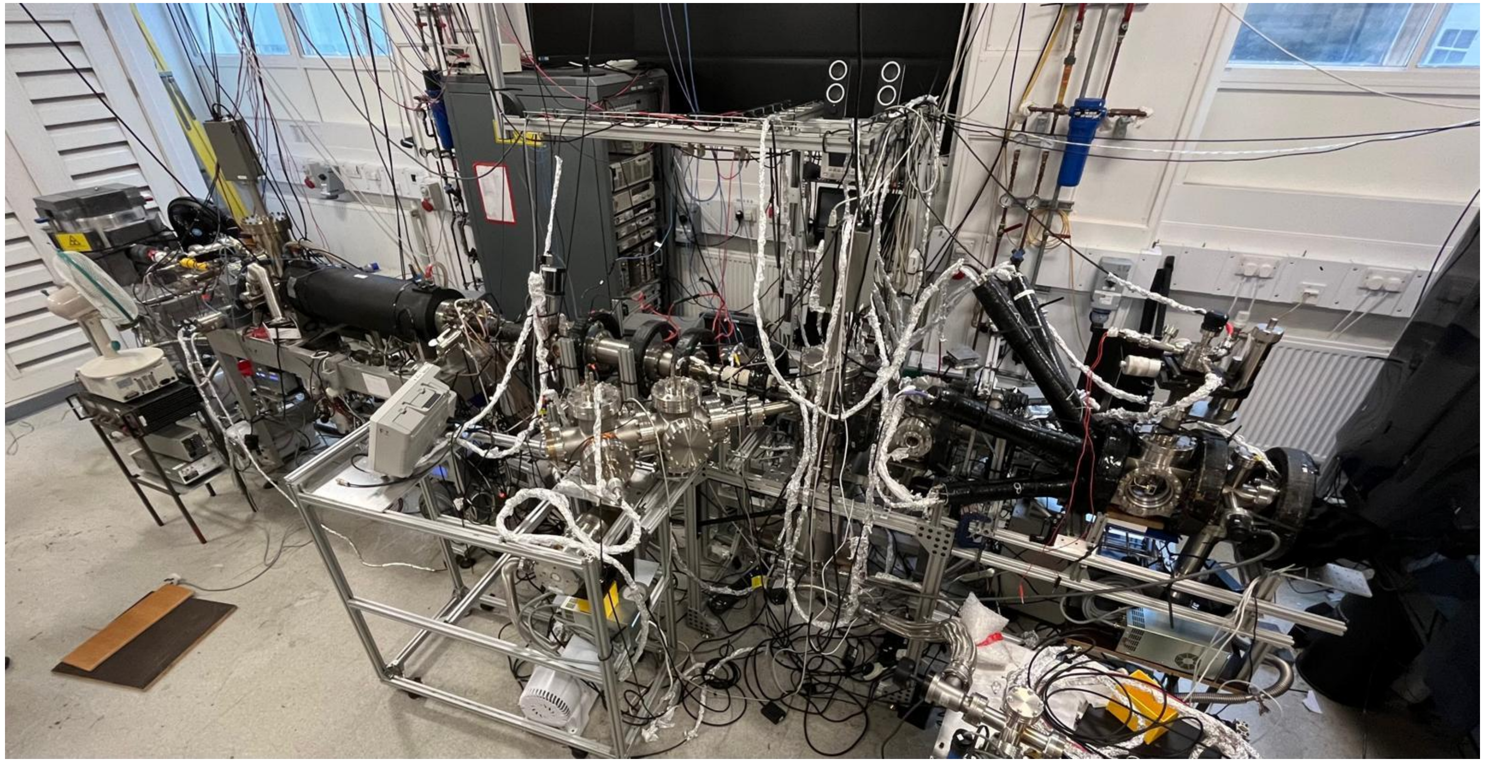
Microwave transitions





- Magnetic fields mix states of equal ℓ and equal M_J, but $\Delta S = \pm 1$.
- $2\,{}^3\mathrm{S}_1 \rightarrow 2\,{}^1\mathrm{P}_1$ occurs due to Zeeman mixing of $2\,{}^1\mathrm{P}_1$ with $2\,{}^3\mathrm{P}_J$ (J=0,1,2) states.
- Zeeman mixing coefficients, C_{ij}, are determined by diagonalization of the Zeeman Hamiltonian.
- Average Zeeman shift using $\mathrm{C}_{ij} * I_{mj} * N$ as the weights for the transitions, where I_{mj} are the angular components of the transition strength and N is the number of possible transitions for each M_J.
- Fit $\nu_R = aB^2 + \nu_j$, where a is a constant, B is the magnetic field and ν_j is the zero-field excitation frequency.

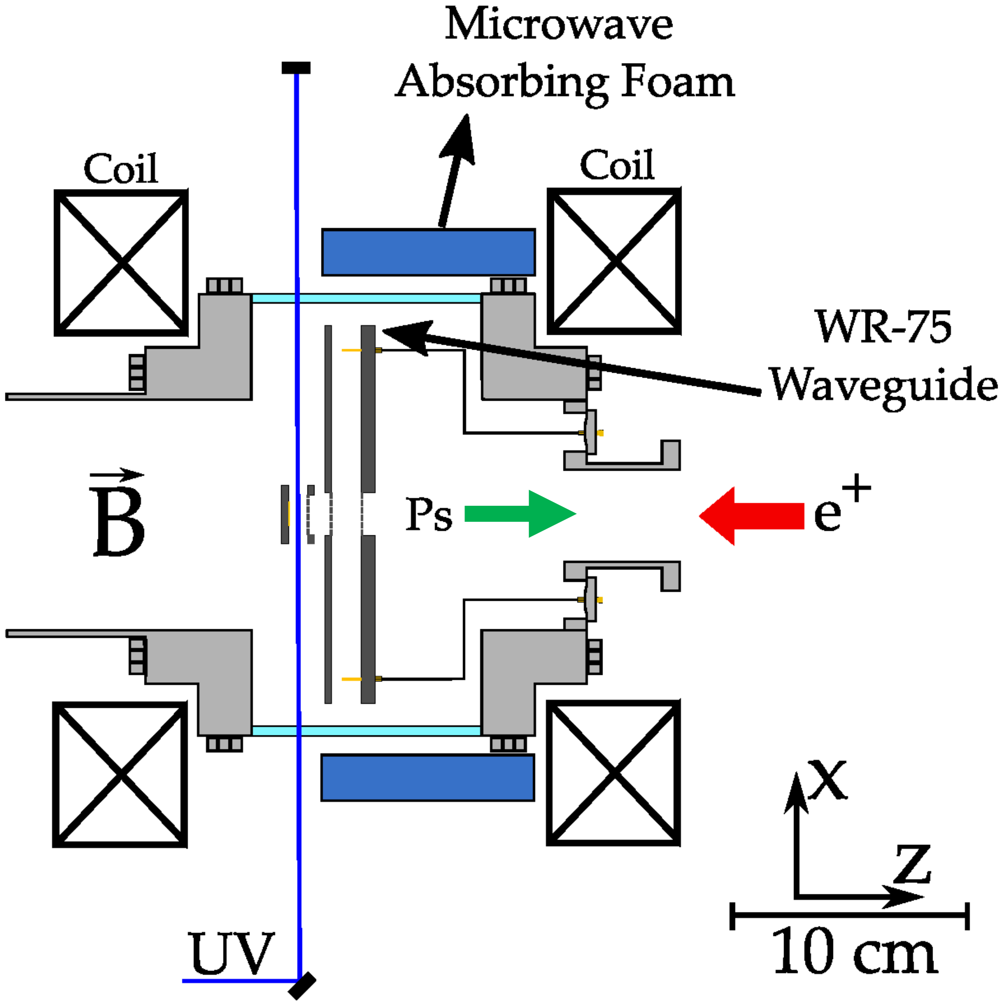
Beamline



See **B. S. Cooper et al, Rev. Sci. Instrum. 86, 103101 (2015)** for details on beamline

- β^+ from ^{22}Na source, moderated with solid neon.
- Two stage Surko-type buffer gas trap ($\mathrm{N_2}$ and $\mathrm{SF_6}$) , operating at 1 Hz, rotating wall and buncher.
- e^+ pulses of < 4 ns / 3 mm and transported magnetically to target chamber.

Ps production and excitation



- $1\,^3S_1$ produced by implantation of e^+ into an SiO_2 target.
- Single-photon $1\,^3S_1 \rightarrow 2\,^3S_1$ excitation using 243 nm UV radiation (retro-reflected).
- Performed in an electric field to allow transition to occur.
- WR-75 rectangular waveguide.
- TE_{10} mode was propagated.
- Reversible microwave direction to cancel doppler shifts.
- Radiation polarised parallel to the quantisation axis, defined by the applied magnetic field, drives $\Delta M_J = 0$ transitions.

Line shape measurements

- Time resolved gamma-ray spectroscopy using scintillation detectors allows differentiation of long- and short-lived states.
- Measure population transfer from the long-lived $2\,^3\mathrm{S}_1$ state to the short-lived $2\,^{2S+1}\mathrm{P}_J$ state (S_γ) as a function of frequency.

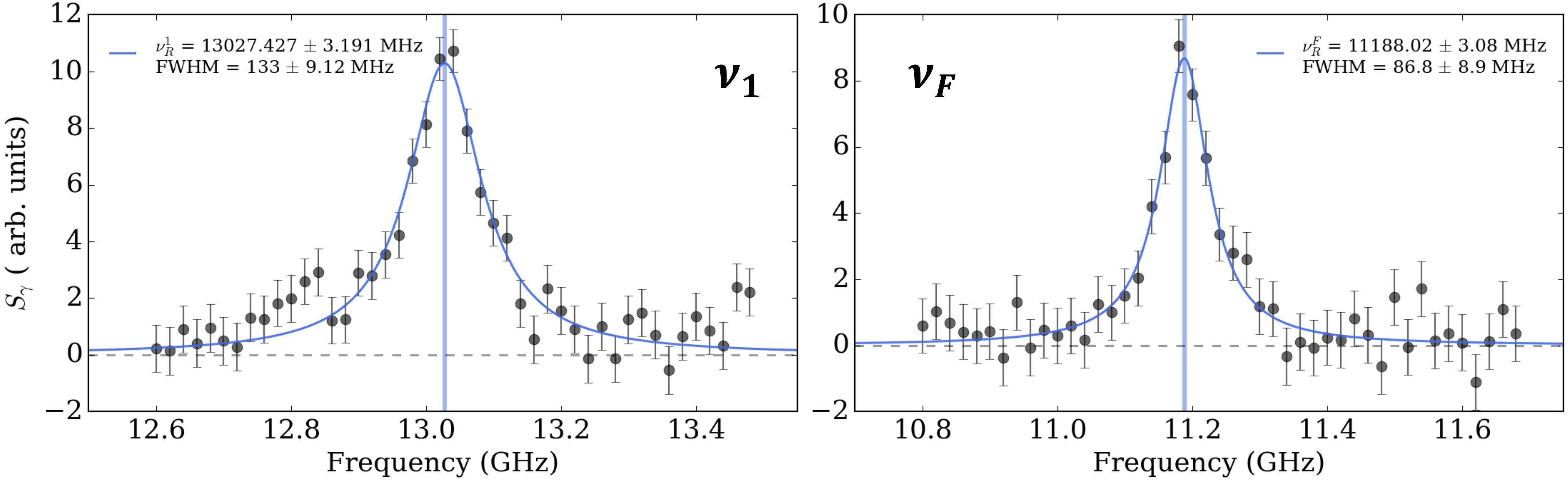
$$2\,^3\mathrm{S}_1 \xrightarrow{\substack{\text{stimulated}\\ \text{emission}}} 2\,^3\mathrm{P}_1 \xrightarrow{\substack{\text{fluorescence}\\ \tau_{\text{mean}}=3.2\text{ ns}}} 1\,^3\mathrm{S}_1 \xrightarrow{\substack{\text{self annihilation}\\ \tau_{\text{mean}}=142\text{ ns}}} 3\gamma$$

$$2\,^3\mathrm{S}_1 \xrightarrow{\substack{\text{stimulated}\\ \text{emission}}} 2\,^1\mathrm{P}_1' \xrightarrow{\substack{\text{fluorescence}\\ \tau_{\text{mean}}=3.2\text{ ns}}} 1\,^1\mathrm{S}_0 \xrightarrow{\substack{\text{self annihilation}\\ \tau_{\text{mean}}=125\text{ ps}}} 2\gamma$$

$$\boxed{2\,^3\mathrm{S}_1:\ \tau_{mean} = 1136\text{ ns}}$$

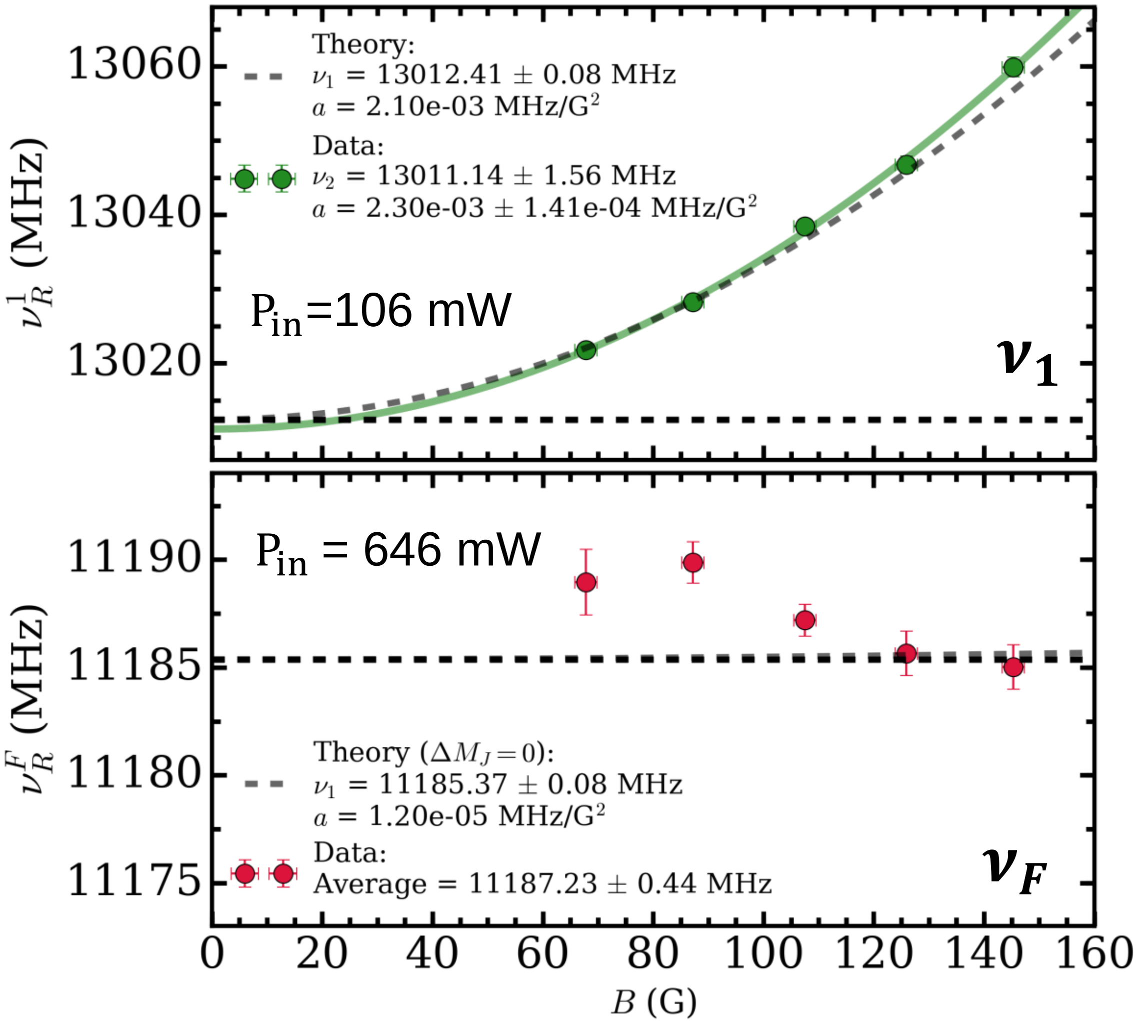
Line shape measurements

- Time resolved gamma-ray spectroscopy using scintillation detectors allows differentiation of long- and short-lived states.
- Measure population transfer from the long-lived $2\,^3S_1$ state to the short-lived $2\,^{2S+1}\mathrm{P}_J$ state (S_γ) as a function of frequency.



- Fit Lorentzian functions to extract centroids, ν_R^1 and ν_R^F.

Zeeman shifts

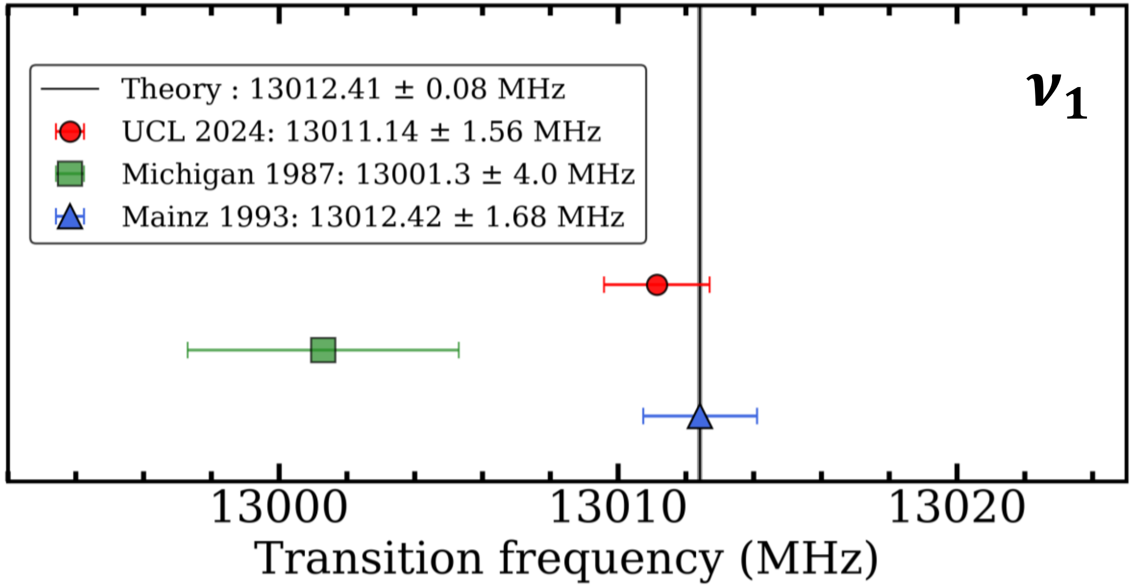


- Measurements taken at multiple magnetic fields to allow extrapolation to zero-field.
- ν_1 is Zeeman-shifted as expected, and a quadratic function is fit for extrapolation to zero-field.

Current hypothesis:

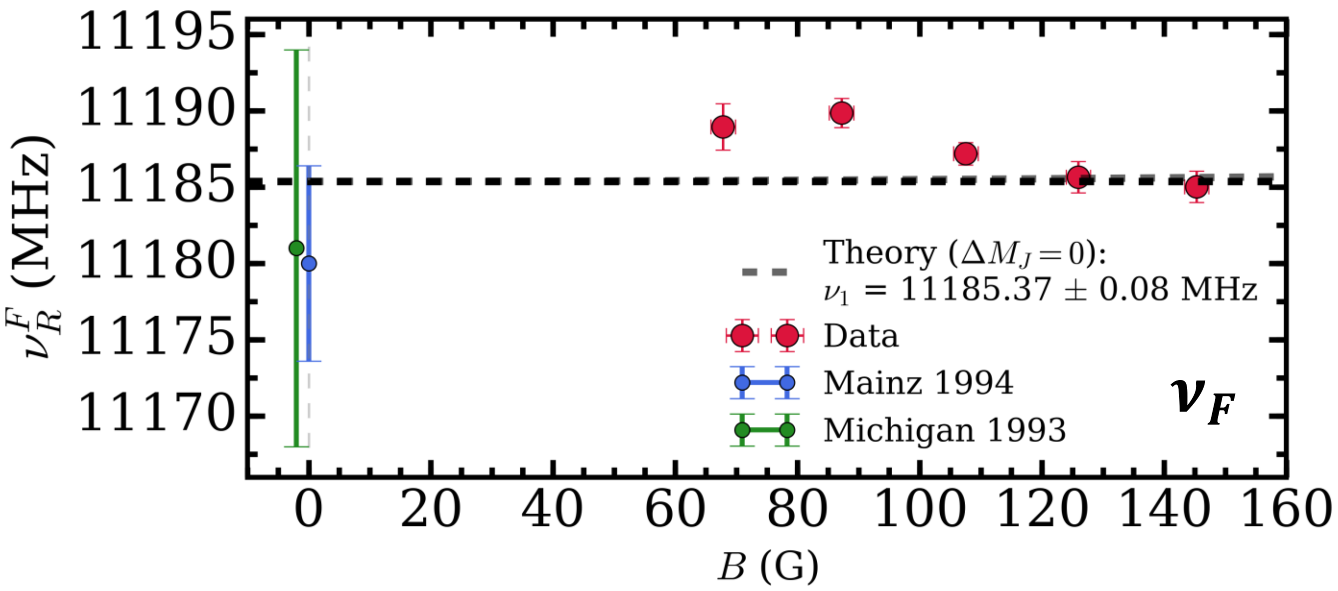
- AC Stark-shifts and quantum interference (QI) effects on the scale of a few MHz for ν_F due to higher power.
- Incomplete Zeeman mixing model and line shape model

Zero-field transition frequencies



- Aiming for an improvement in precision of both ν_R^1 and ν_R^F compared to previous measurements.
- ν_1 is well understood: no significant disagreement of ν_R^1 with theory, and previous issues mostly resolved.

- ν_R^F is more complicated due to Zeeman mixing and possible AC Stark shifts and QI: agrees with theory at high magnetic fields.
- Statistical error **only**.



Systematic errors

- No first order Doppler shifts or recoil due to reversible microwave direction.
- From previous work[1] we estimate second order Doppler shifts to be < 1 kHz, and the effect of stray electric fields to be < 10 kHz.
- Work on the Zeeman mixing model and line shape model is ongoing.
- AC stark shifts and QI effects will be determined by simulations and calculations. Lower power measurements will be run to mitigate these effects, but they could be on the MHz scale for ν_F.

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[1] L. Gurung et al, Phys. Rev. A **103**, 042805 (2021).

Ongoing work

- Continue development of Zeeman mixing and line shape models
- Continue with measurements at a range of powers

Thank you!

Future plans

- Slower Ps
- Production of polarized Ps using microwave or laser selection

@PsSpectroscopy