Excited states of positronium in electric fields

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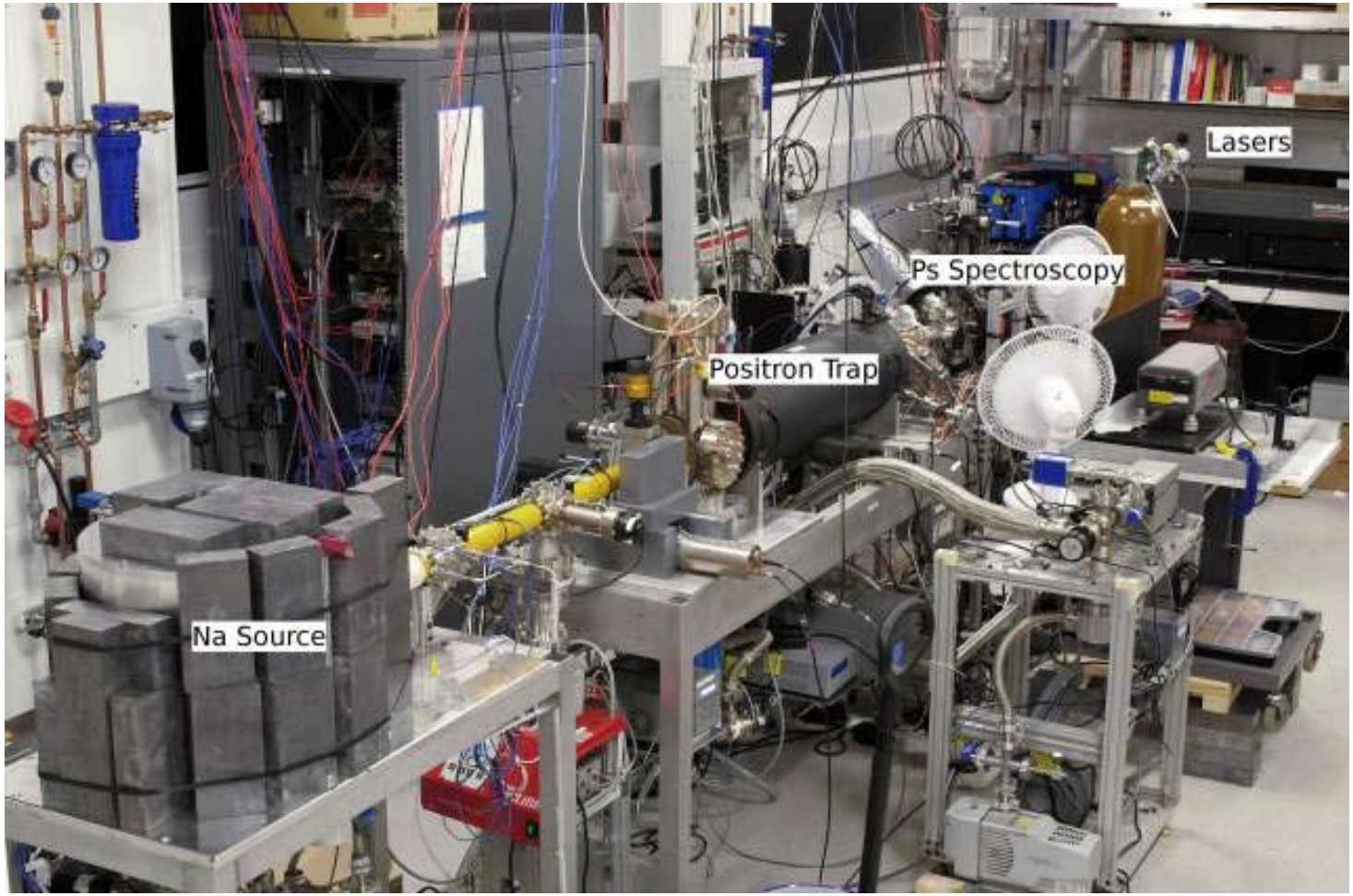

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Collaborators (past and present)

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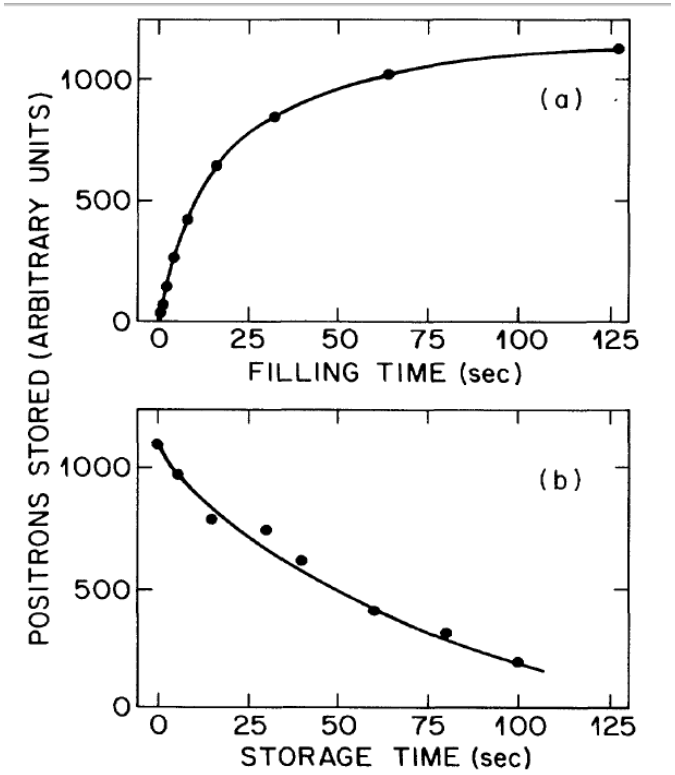
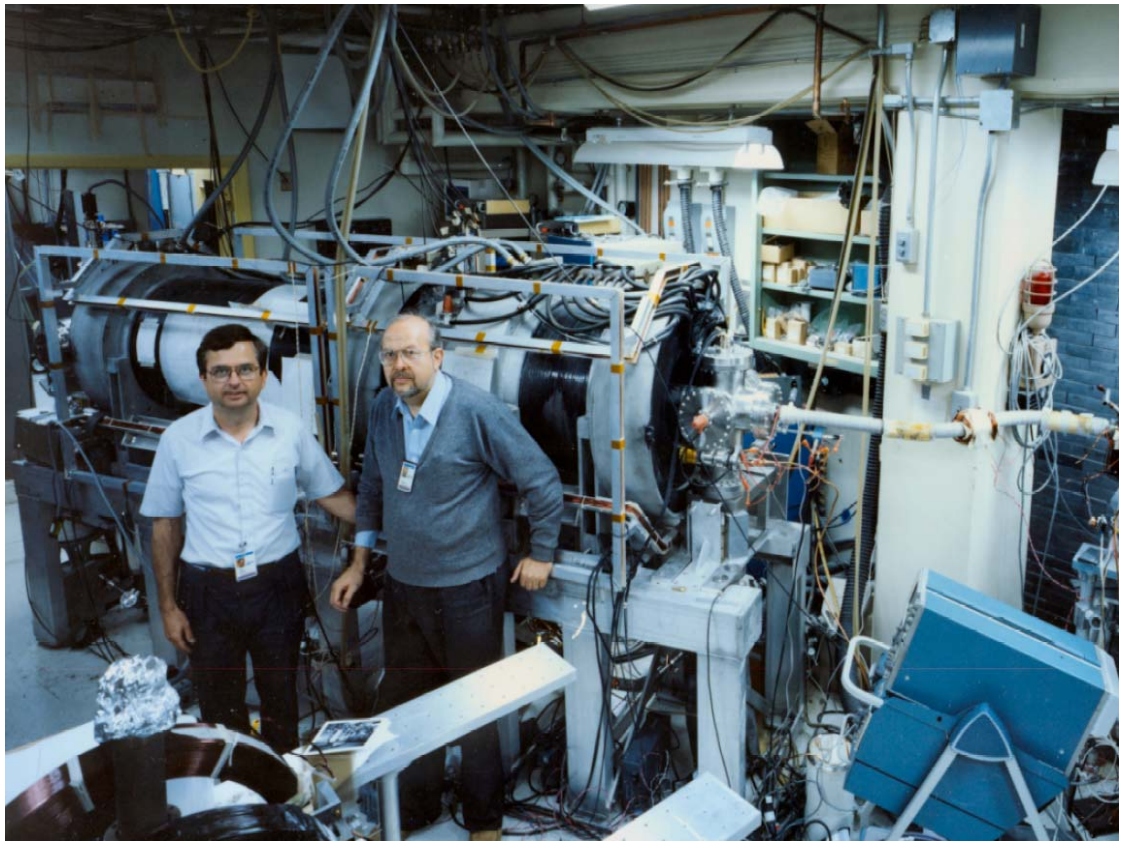
Positronium: easy to make, available in many labs, but relatively few experiments involving excited states produced by laser excitation: WHY??

There are some difficulties when it comes to experimentation with Ps atoms:

- There are never enough of them (efficiency)
- They don't live very long (lifetime)
- They tend to go all over the place (divergence)
- They are low mass and hence generally fast (Doppler)

1989: Surko Leventhal & Passner demonstrate positron accumulation. Now it is possible to obtain high intensity pulsed beams without large facility based devices. This changed opened the door to new experiments (see plenary on Monday)



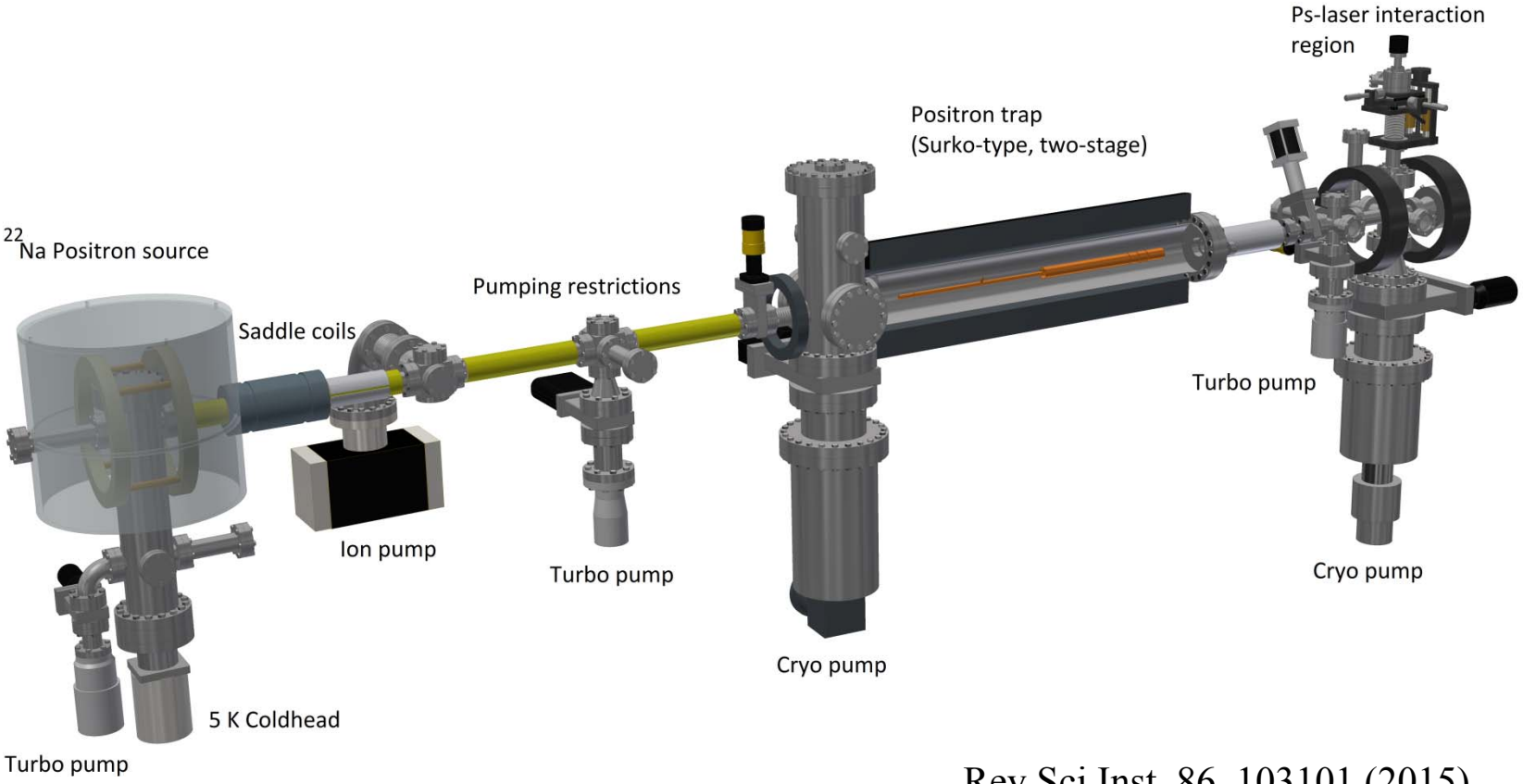


Cliff Surko and Al Passner with the first buffer gas positron trap at Bell Labs (in Allen Mills' lab)

Two-stage Surko-type buffer gas trap:
10^5 positrons/pulse
1 Hz
Pulse width 3 ns FWHM
Spot size 4 mm FWHM
Very well suited to Ps excitation with standard pulsed lasers

1s-2p excitation requires abut 5 nJ/cm^2 in a 5 ns pulse *per natural linewidth:*

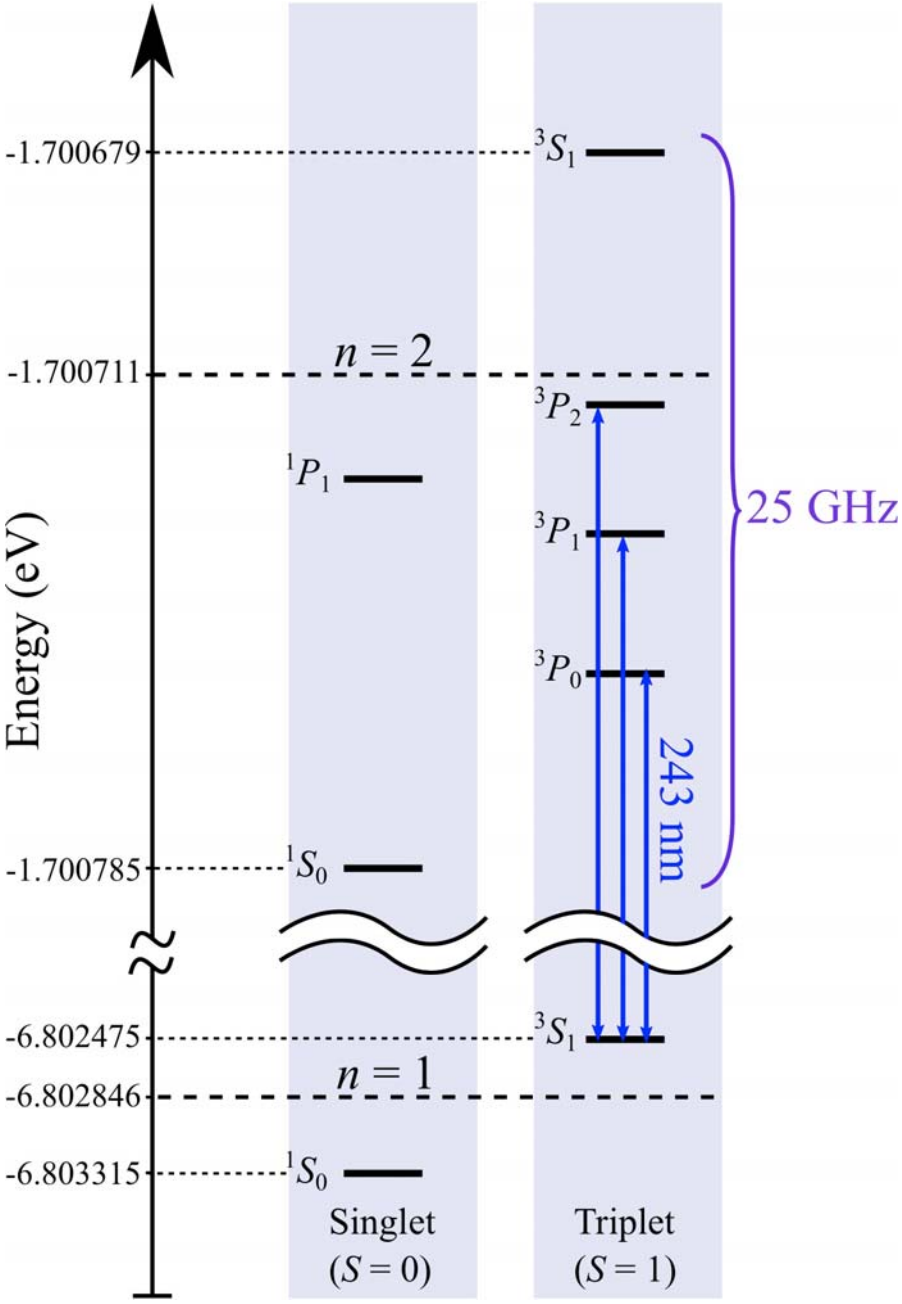
This would be great, except that we have a huge amount of Doppler broadening so we actually need to cover 500 GHz instead of 50 MHz, and thus we need 10,000 times more laser intensity



Rev Sci Inst. 86, 103101 (2015).

Transition	e^+ source	Laser	Comments	year	Ref.
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	RI/gas	L	No signal observed	1954	[94]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	RI/gas	L	Signal not statistically significant	1974	[95]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{S}_1$	MB	P	First unambiguous Ps excitation signal	1982	[96]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	MB	P	Precision measurement (12 ppb)	1984	[97]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	L	P	Ps Lyman-α	1990	[98]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	L	P	First Rydberg Ps	1990	[99]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{S}_1$	M	P	Photoionization by 532 nm laser	1991	[100]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{S}_1$	M	CW	Precision measurement (2.6 ppb)	1993	[101, 102]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Doppler spectroscopy of Ps	2010	[103, 104]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	PsX formation on semiconductors	2011	[105–107]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Ps cavity shift and narrowing	2011	[108]
$\mathrm{Ps}^- \rightarrow \mathrm{Ps} + \mathrm{e}^-$	L	P	Photodetatchment of Ps^- ions	2011	[109]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Excited Ps in Paschen back regime	2011	[110]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	Efficient Rydberg Ps production	2012	[111]
$\mathrm{Ps}_2 \rightarrow \mathrm{Ps} + \mathrm{e}^- + \mathrm{e}^+$	ST	P	Molecular Ps spectroscopy	2012	[112]
$\mathrm{Ps}^- \rightarrow \mathrm{Ps} + \mathrm{e}^-$	L	P	Energy tunable Ps beam	2011	[113]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}' \rightarrow 1\,^1\mathrm{S}_0$	ST	P	First optical Ps hyperfine measurement	2012	[114]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	Doppler corrected Balmer spectroscopy	2014	[115]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{S}_1$	RI	CW	Annihilation of $2\,^3\mathrm{S}_1$ states	2015	[116]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	High-precision Rydberg TOF	2015	[117]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	Selective production of Ps stark-states	2015	[118]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Laser enhanced Ps TOF	2015	[119]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Ps Lyman-α	2015	[120]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}_J$	ST	P	Ps cooling in transmission targets	2015	[121]
$1\,^3\mathrm{S}_1 \rightarrow 2\,^3\mathrm{P}' \rightarrow 1\,^1\mathrm{S}_0$	ST	P	Stark and Zeeman mixing of $n = 2$ Ps	2015	[122, 123]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow 30\,^3\mathrm{S}/30\,^3\mathrm{D}$	ST	P	Ps Stark-states	2016	[124]
$\mathrm{Ps}^- \rightarrow \mathrm{Ps} + \mathrm{e}^-$	L	P	Ps^- ion shape resonance	2016	[125]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	Measurement of fluorescence lifetimes	2016	[126]
$1\,^3\mathrm{S} \rightarrow 3\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	$n = 3$/Rydberg excitation	2016	[127]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow 10\,^3\mathrm{S}/10\,^3\mathrm{D}$	ST	P	Electrostatic guiding of Ps	2016	[128]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow 30\,^3\mathrm{S}/30\,^3\mathrm{D}$	ST	P	Angle resolved Ps spectroscopy	2016	[129]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow n\,^3\mathrm{S}/n\,^3\mathrm{D}$	ST	P	Rydberg Ps MCP detector	2016	[130]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{S}'_1 \rightarrow 2\,^3\mathrm{S}_1$	ST	P	1-photon production of $2\,^3\mathrm{S}_1$ atoms	2017	[131]
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow 14\,^3\mathrm{S}/14\,^3\mathrm{D}$	ST	P	Electrostatic velocity selection of Ps	2017	
$1\,^3\mathrm{S} \rightarrow 2\,^3\mathrm{P} \rightarrow 32\,^3\mathrm{S}/32\,^3\mathrm{D}$	ST	P	Electrostatic Ps beam focusing	2017	

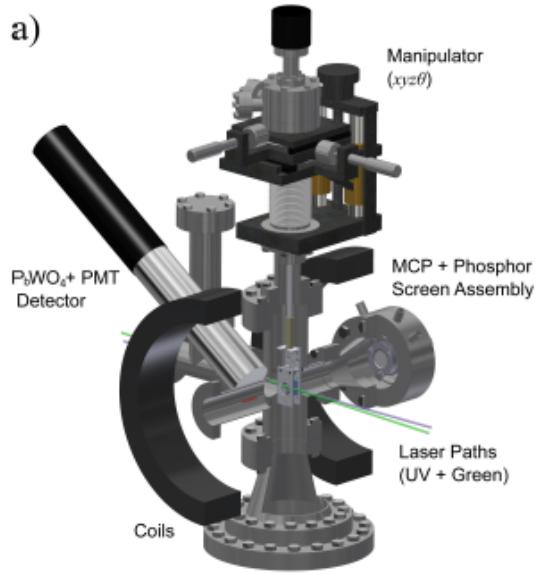
Table 1. Time line of optical excitation experiments involving positronium atoms, ions an molecules. This list is not abridged and includes all instances of Ps excitation with laser light to date. We have not indicated the J values for some transitions to Rydberg levels are they are fully Stark mixed. The positron sources used are Radioactive isotopes and gas moderation and Ps production (RI/gas), mono-energetic beams based on radioactive isotopes (RI), magnetic bottle (MB) traps, linac (L) or microtron (M) accelerator based beams, or source-based Surko traps (ST). The light sources used are lamps (L), or pulsed (P) or continuous wave (CW) lasers.

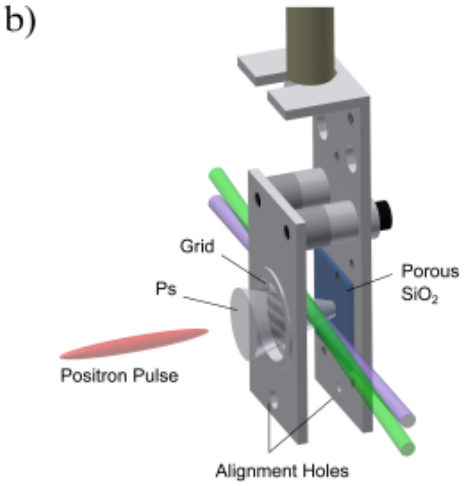


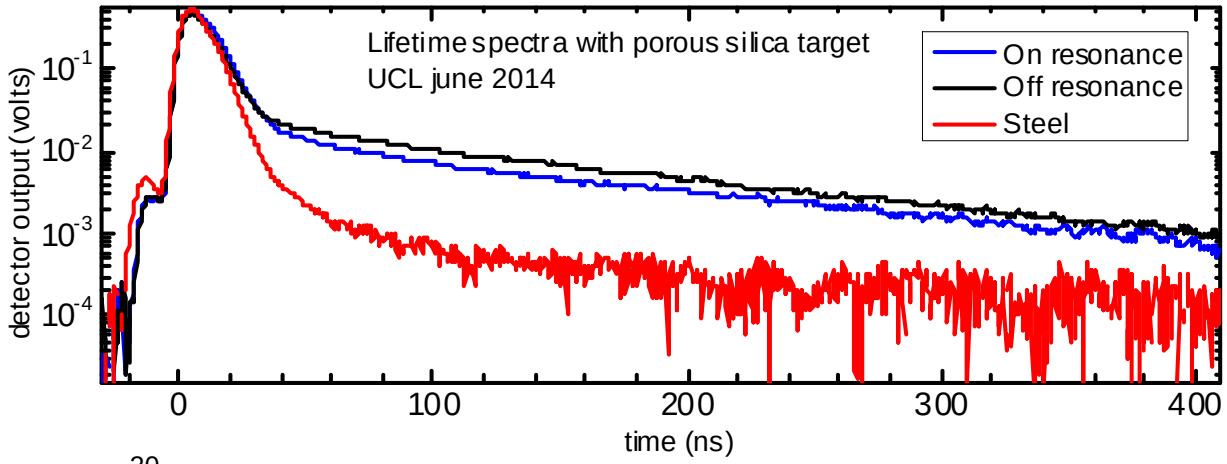
Excitation to n = 2 requires UV light (~ 243 nm) that can be produced quite easily. However, it also requires a large bandwidth because of the Doppler broadening. This means that in general one does not excite specific (n = 2) states, since the laser bandwidth covers the entire 2P manifold

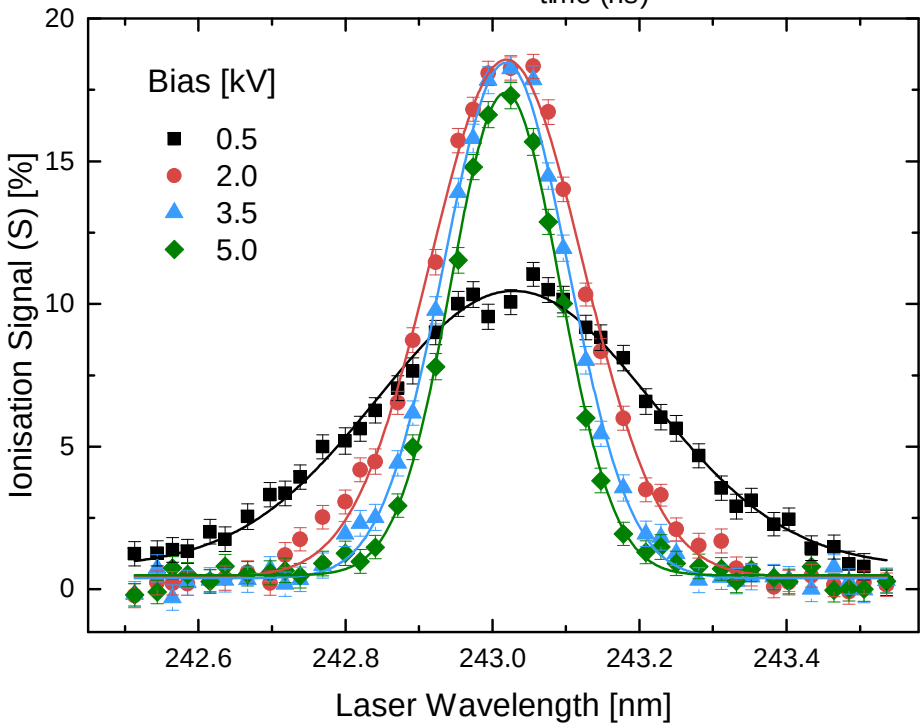
Need to use Doppler free methods (e.g., saturated absorption spectroscopy) and a narrower laser bandwidth to see individual states: another example of why we **really** need colder Ps.

Laser induced changes in the amount of Positronium present may be observed via annihilation radiation using single-shot lifetime spectra:

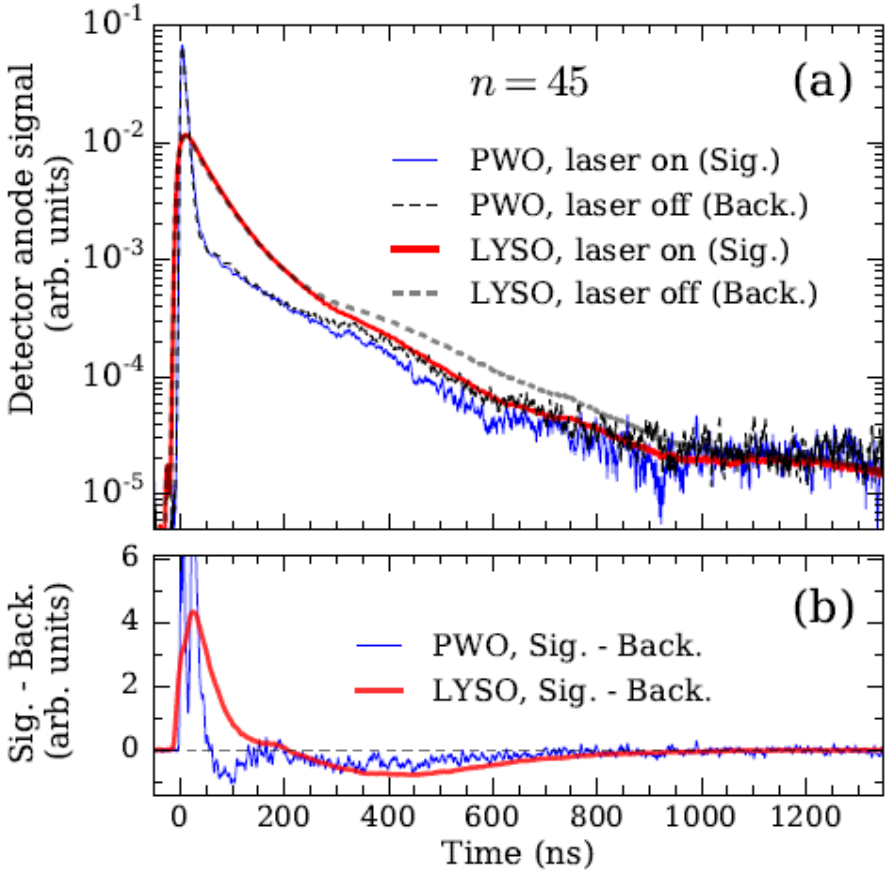


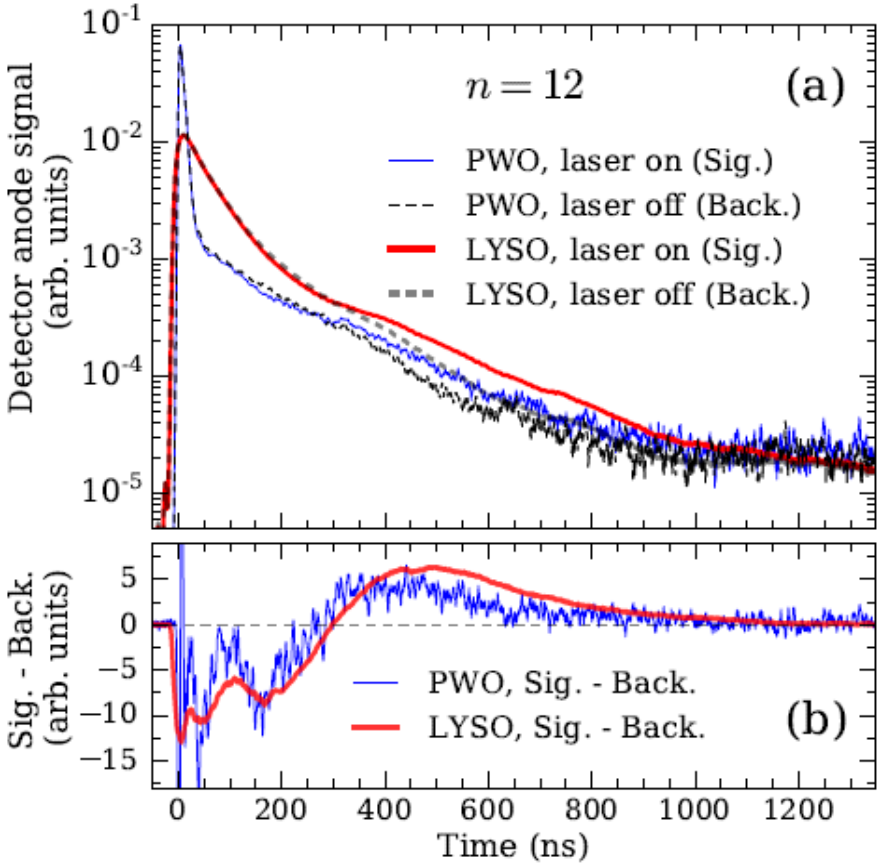






Lutetium yttrium oxyorthosilicate (LYSO) based detectors are much better for single shot lifetime measurements than PWO

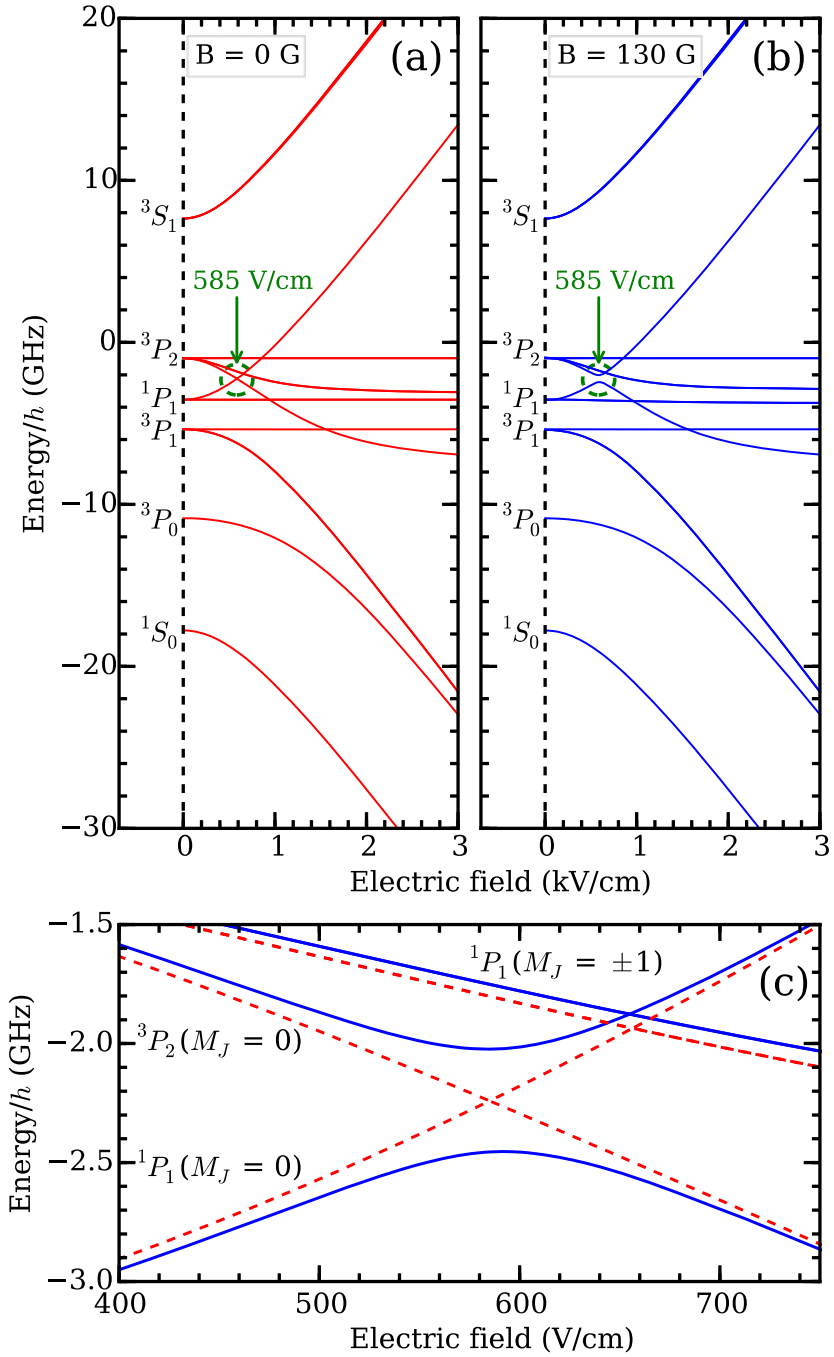




n = 45 Ps is field ionized immediately after production

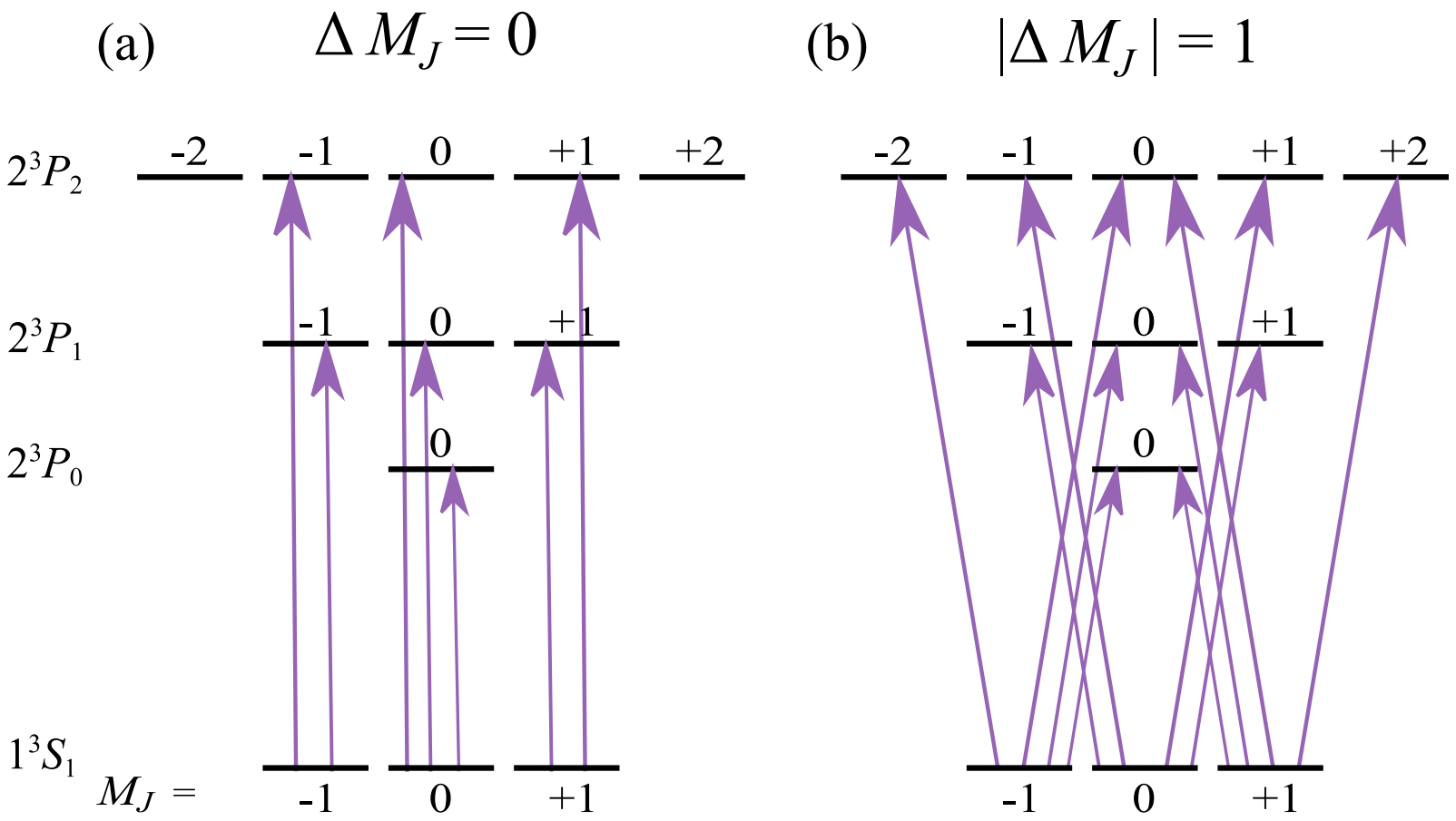
n = 12 Ps hits the chamber wall around 500 ns after production

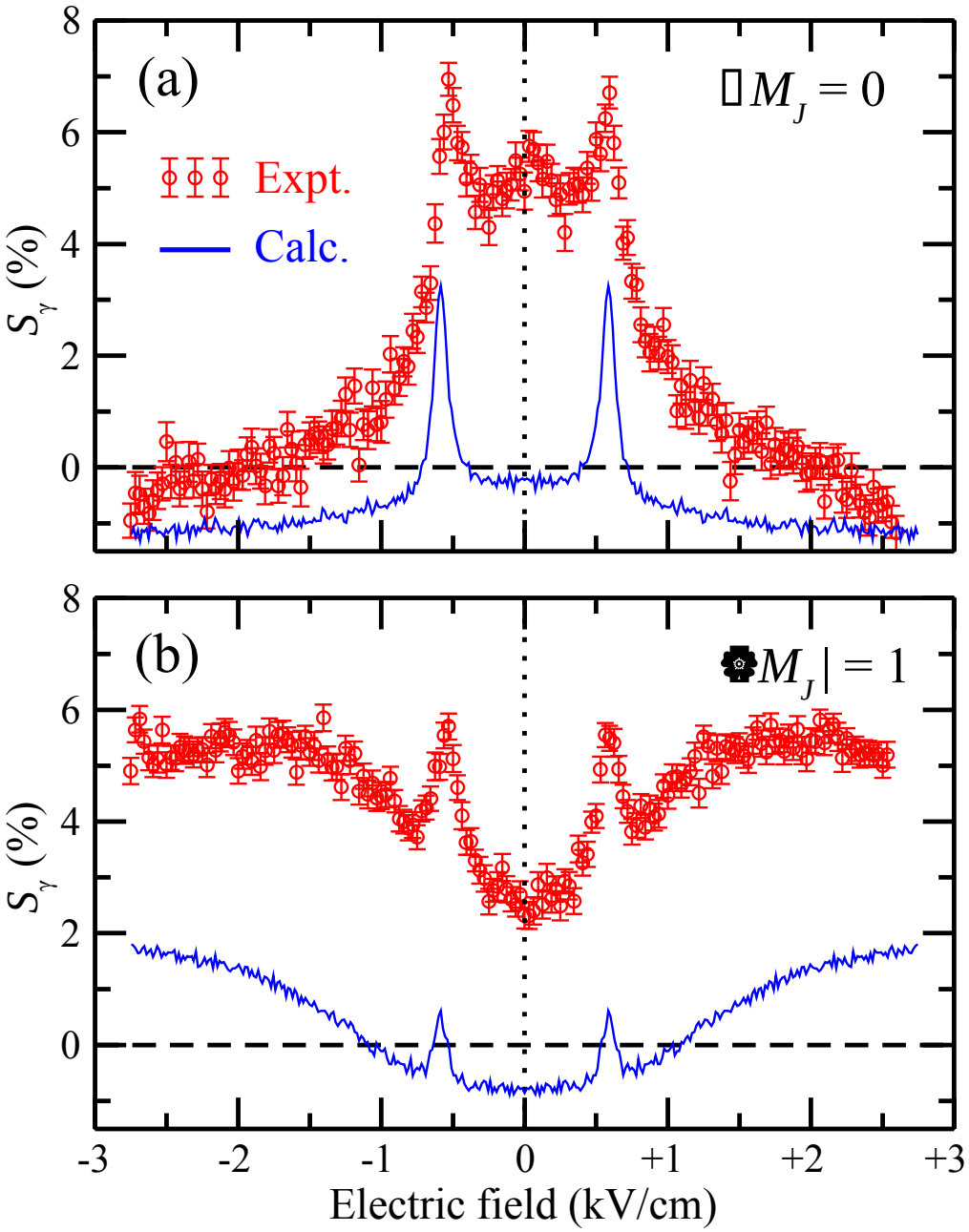
Nuclear Instruments and Methods A, **828** 163 (2016)



Zeeman mixing between singlet and triplet states can give rise to large changes in lifetime. This effect can be enhanced significantly by **Stark mixing**, so that with suitable laser polarization MQ can occur even in a relatively weak magnetic field (Stark-Enhanced Magnetic quenching)

Laser polarization matters as it affects which states are populated



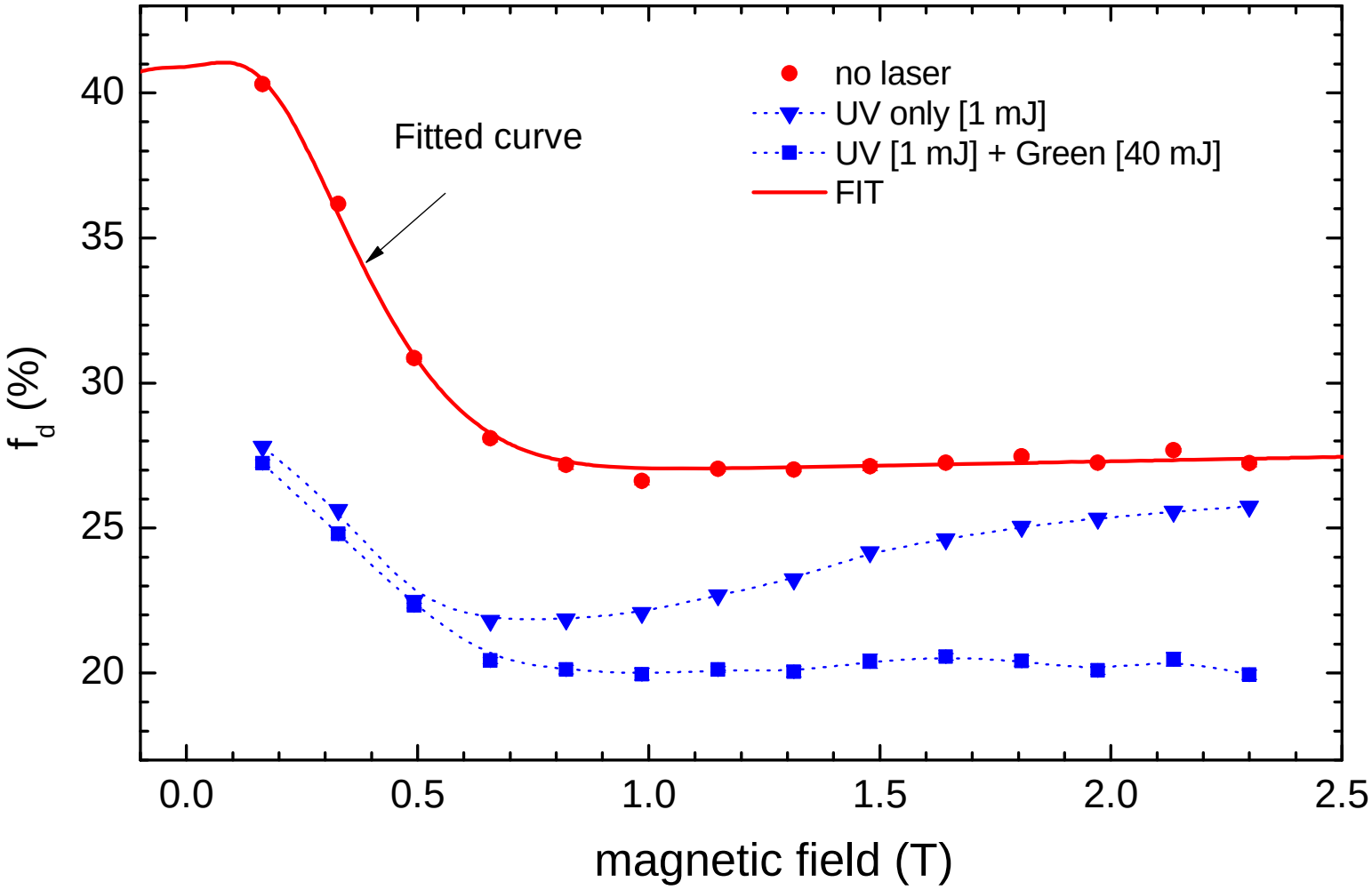


Stark enhanced magnetic quenching:

The peaks at 585 V/cm correspond to the magnetic mixing at the (field-free) avoided crossings, where the singlet and triplet character of the Stark and Zeeman mixed eigenstate is maximal

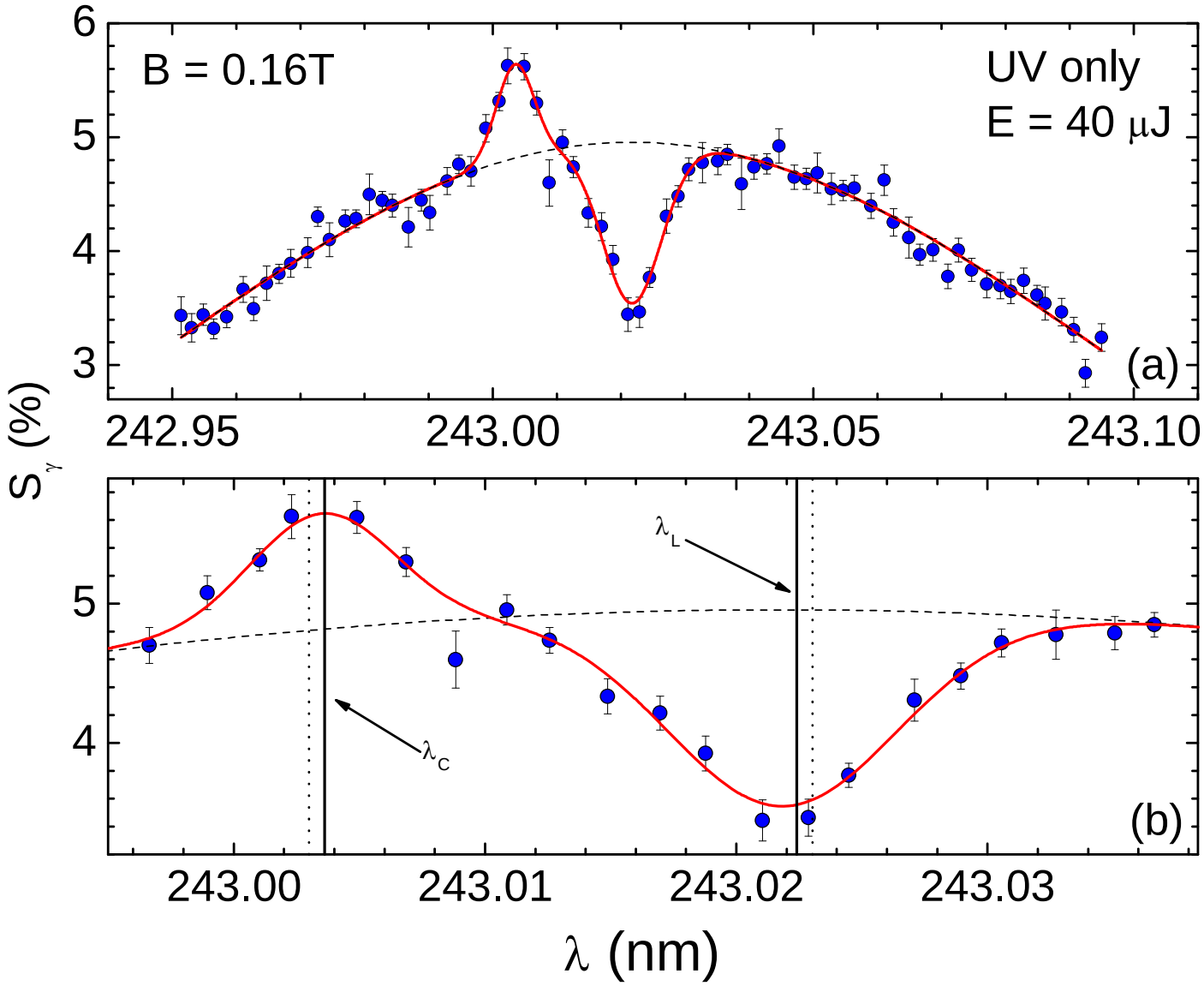
Ps in the Paschen-Back regime

Ps energy levels scale with $1/n^3$ so it is roughly 8 times easier to mix singlets and triplets after excitation to n = 2



This means it would be in principle be possible to laser cool Ps in a strong magnetic field

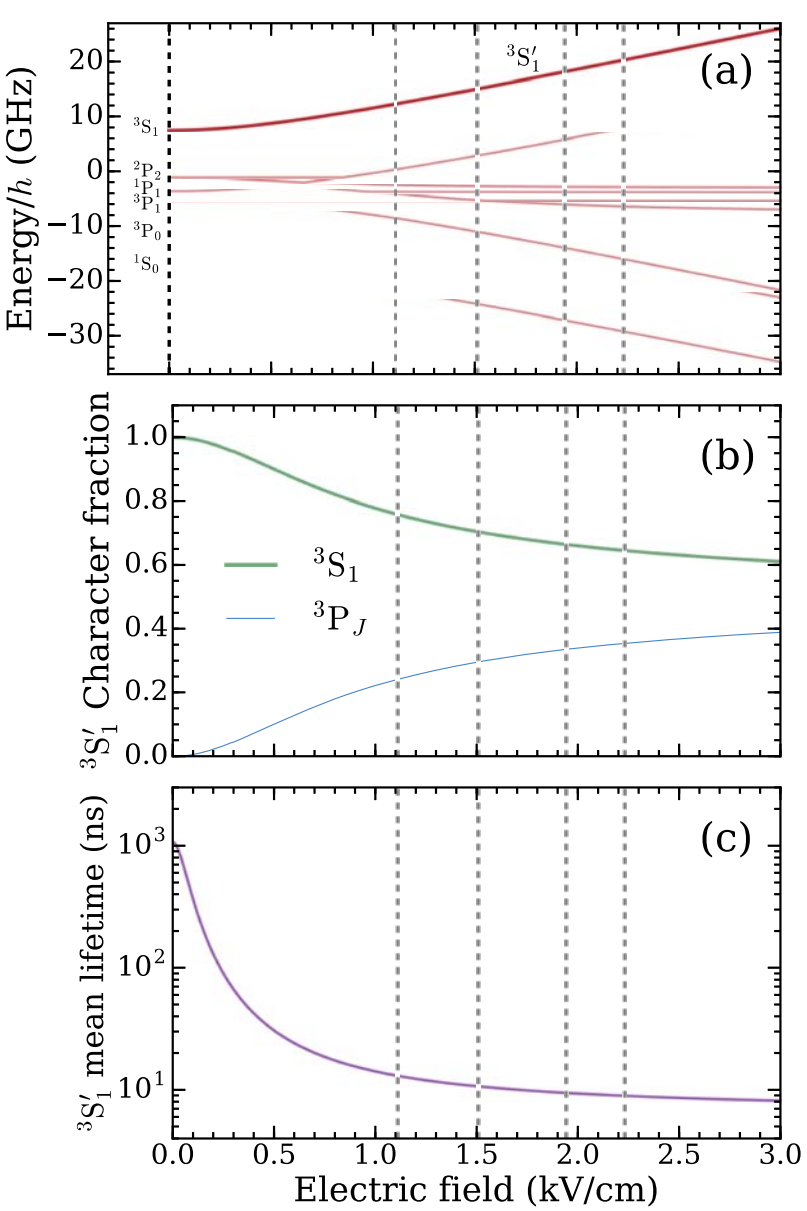
Saturated absorption spectroscopy: measurement of Hyperfine interval

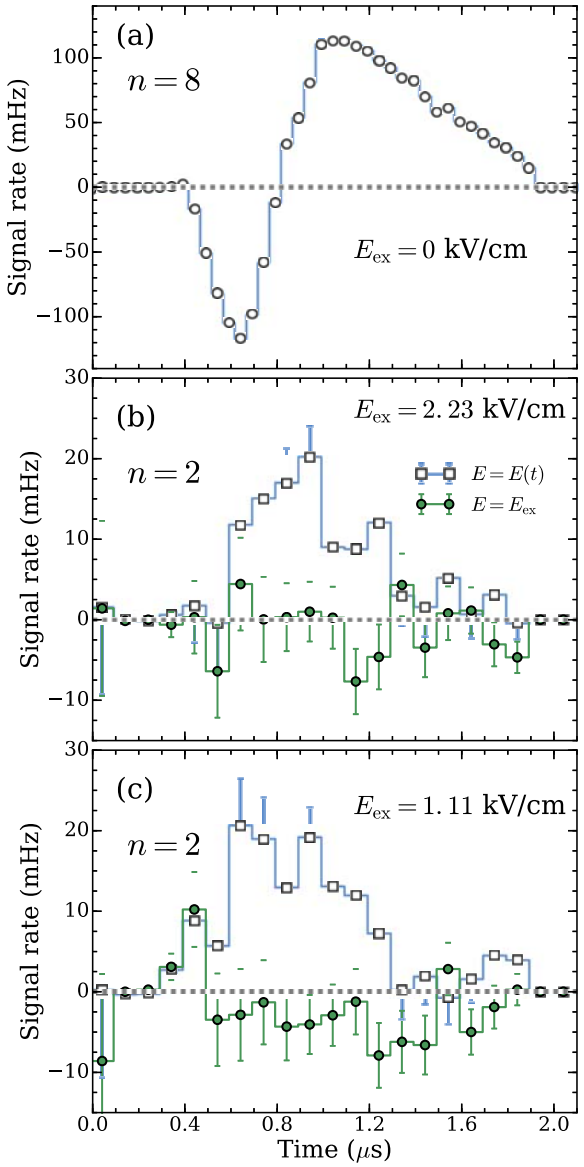


Crossover peak can only be seen as a result of magnetic quenching

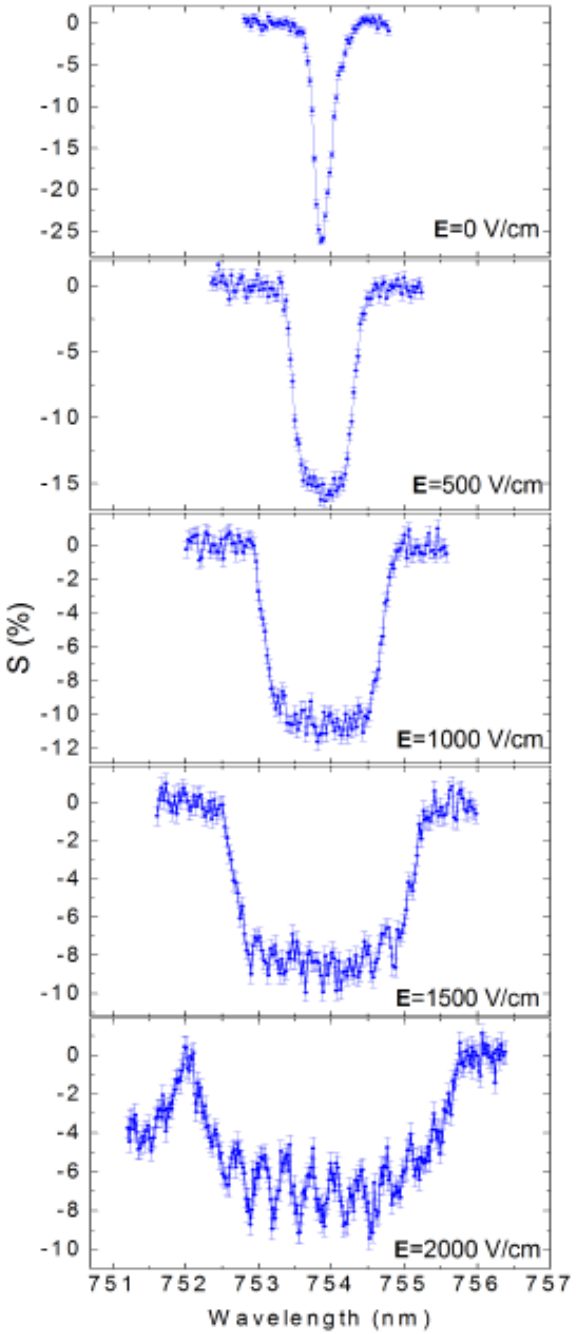
Not a very good measurement, partly because of laser width and low number of Ps with the correct speed

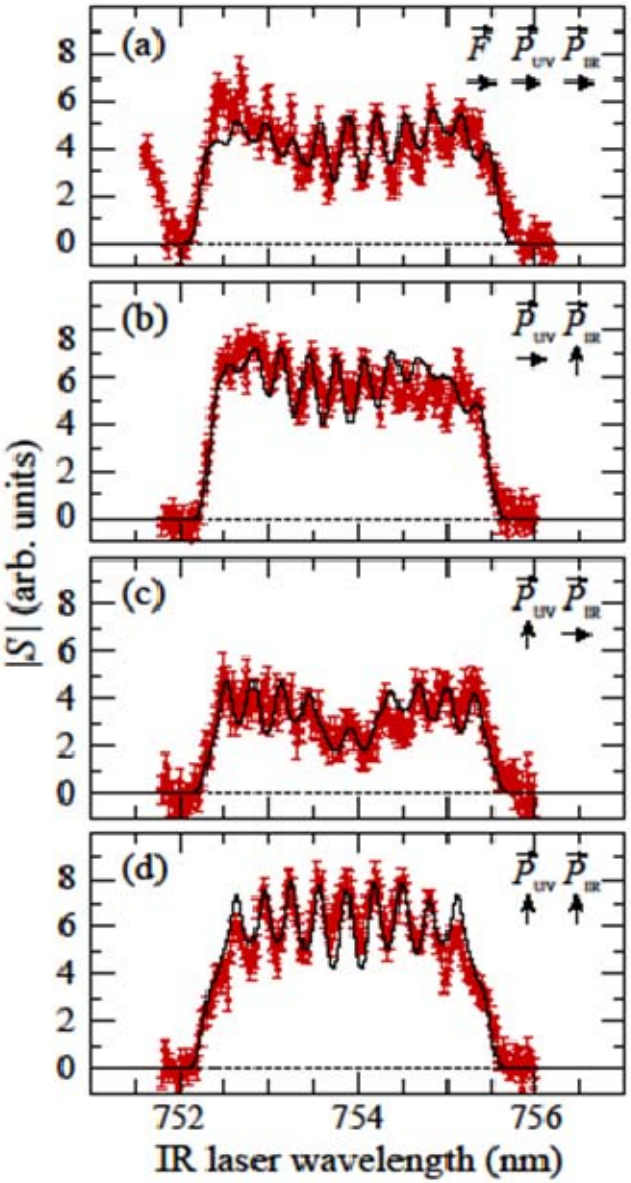
2S production by single-photon excitation





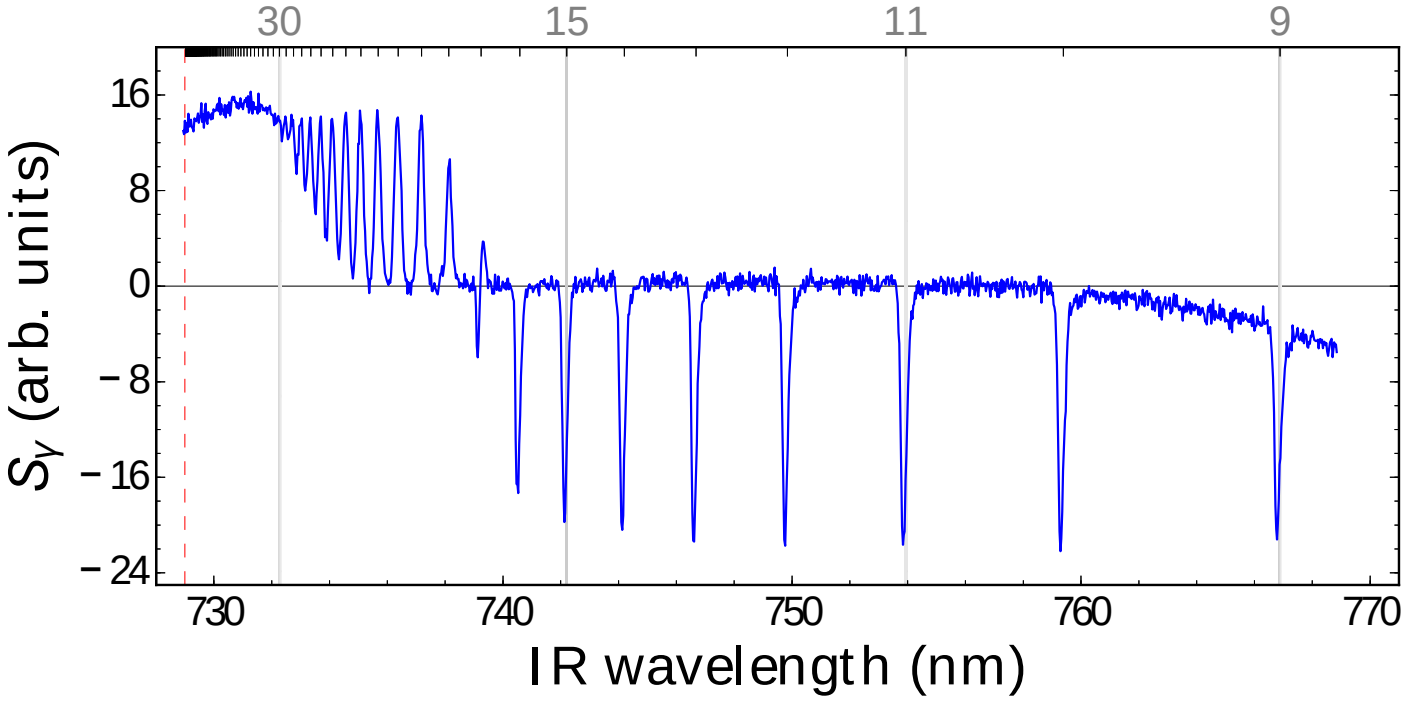
Stark states (n = 11)





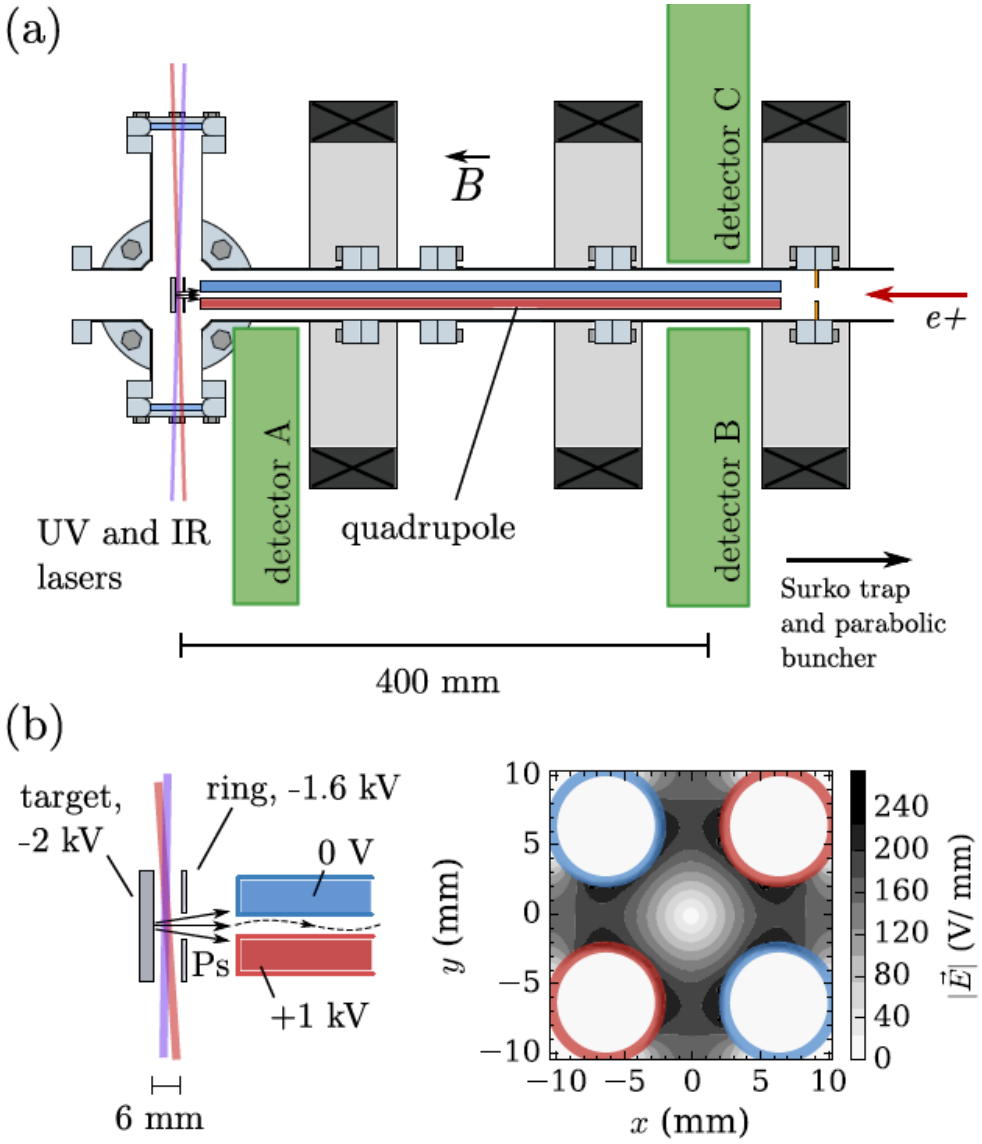
Increasing the electric field in the excitation region splits the line (Stark effect). Limited spectral resolution means large fields are needed to see different Stark states. The asymmetry comes mostly from the Stark effect on the intermediate n = 2 states

We can make any states we want, but we cannot resolve them above n = 30 or so because of the large bandwidth of our laser and Doppler broadening effects



UCL data
1 Hz rep rate
3 ns, 10^5 e^+
Multi-event detection

Guiding Rydberg Ps with an electrostatic quadrupole field

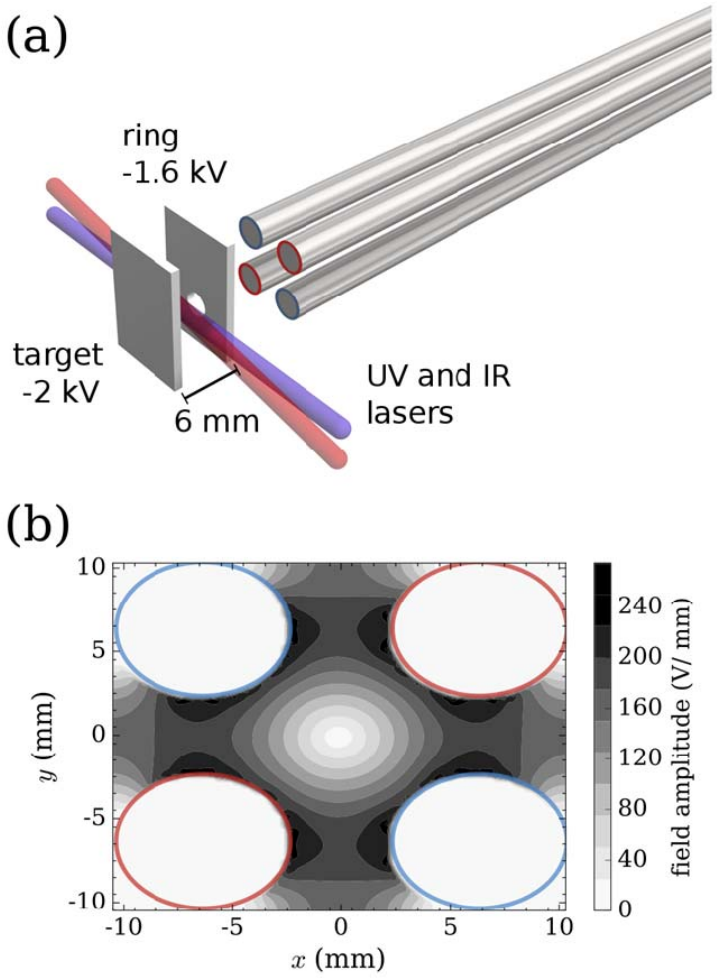


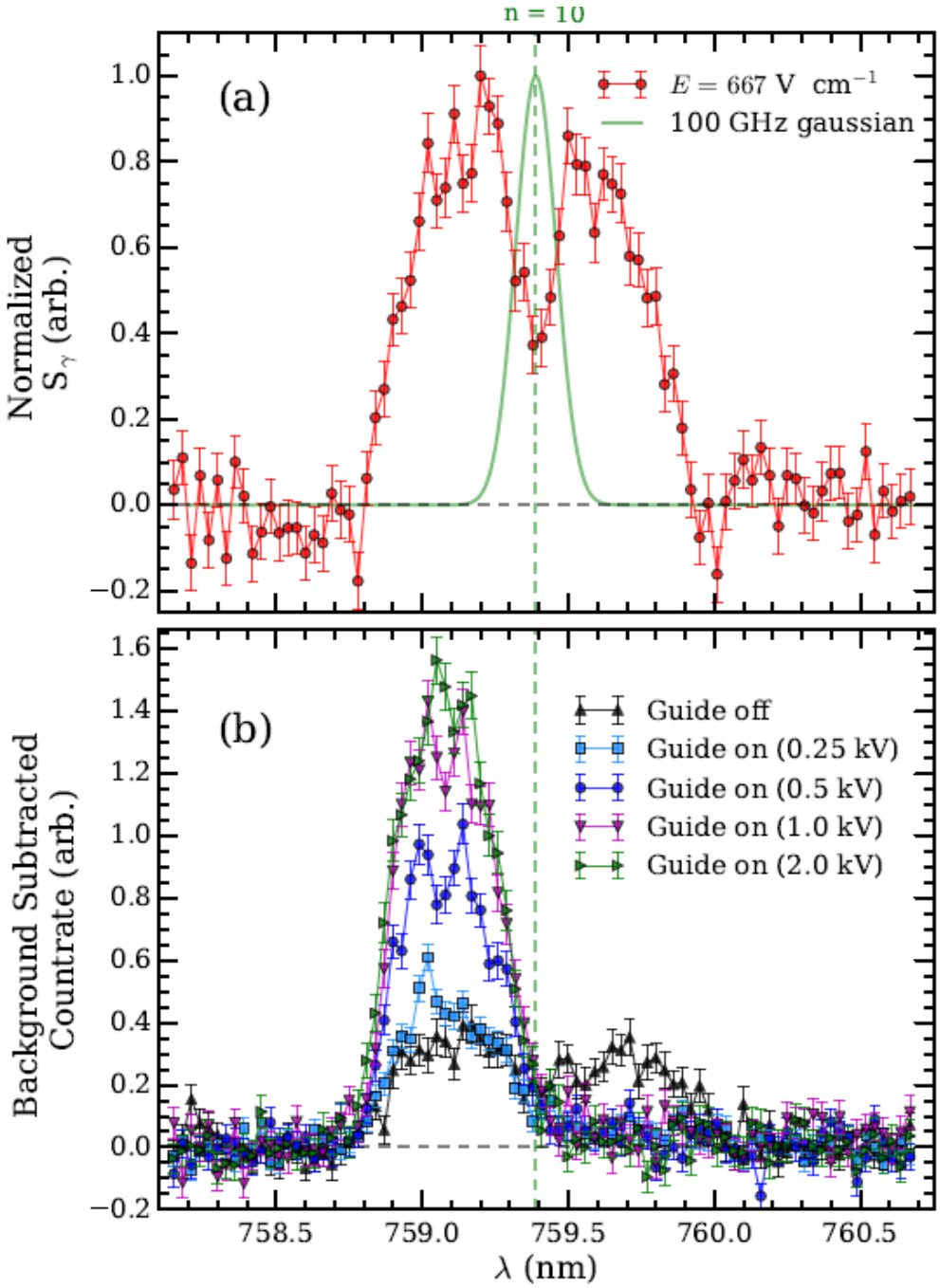
The quadrupole guide is at ground potential when the positron pulse passes through. The it is turned on (in 10 ns) after the Ps is excited

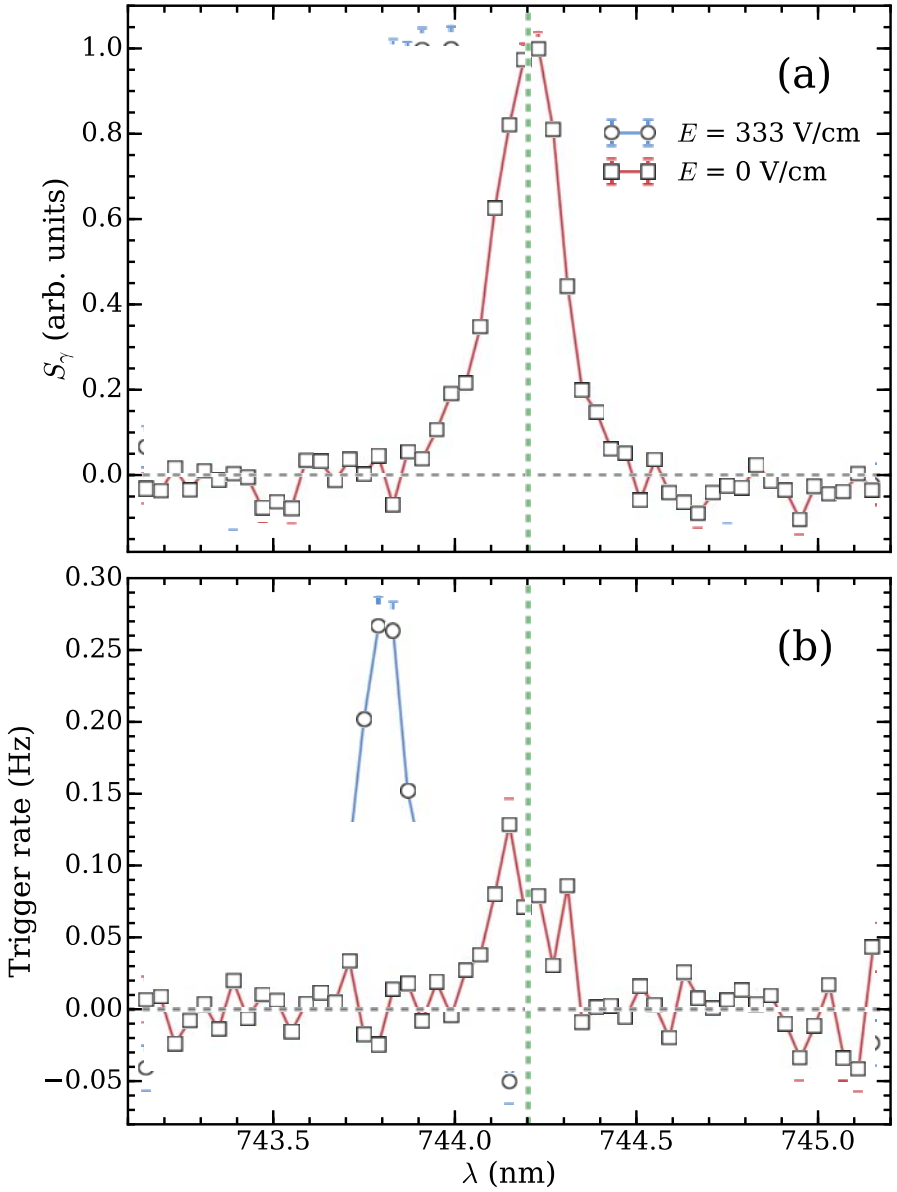
Detector A measures single-shot lifetime data

Detectors B and C measure single events

Stark-state dependent transport



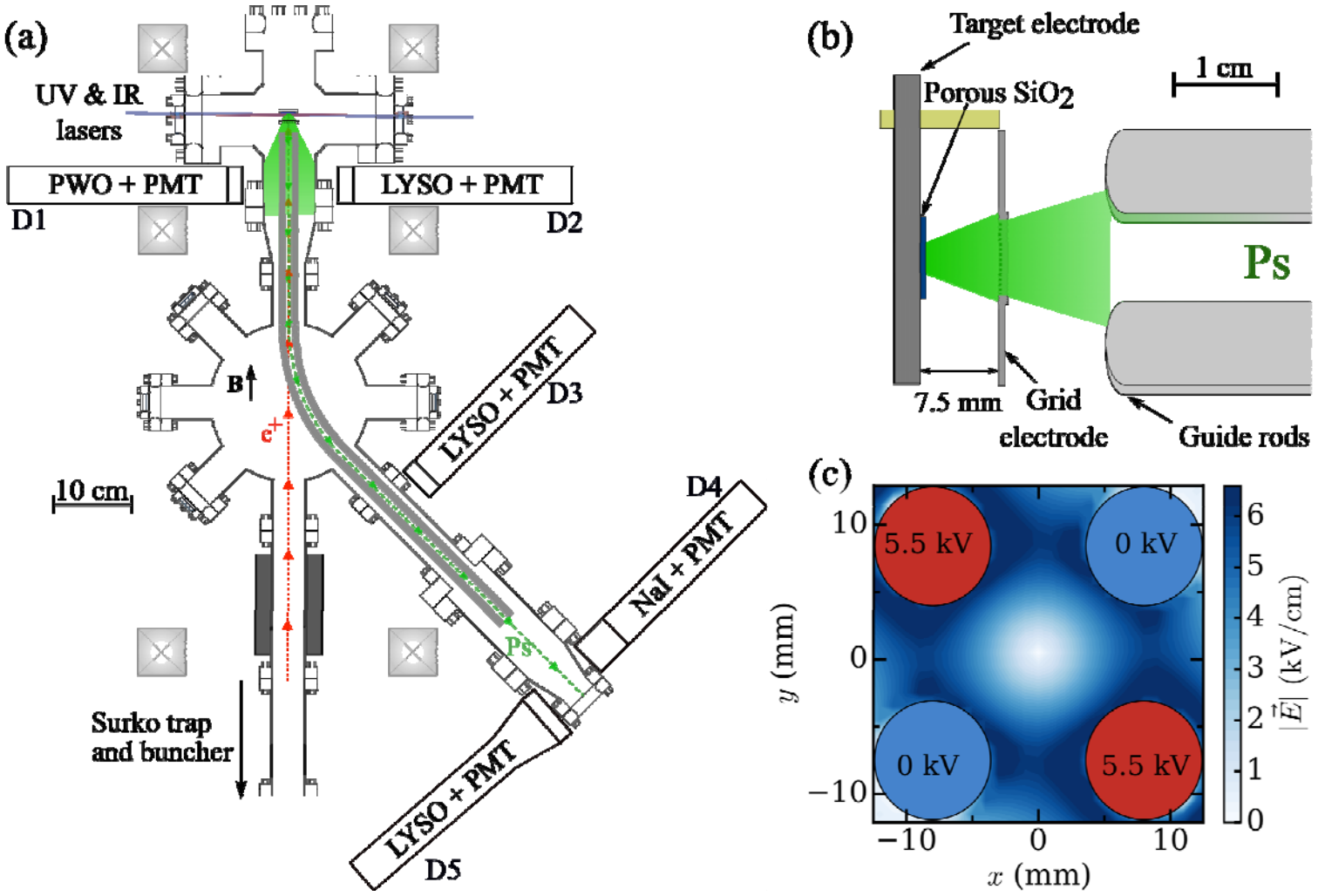




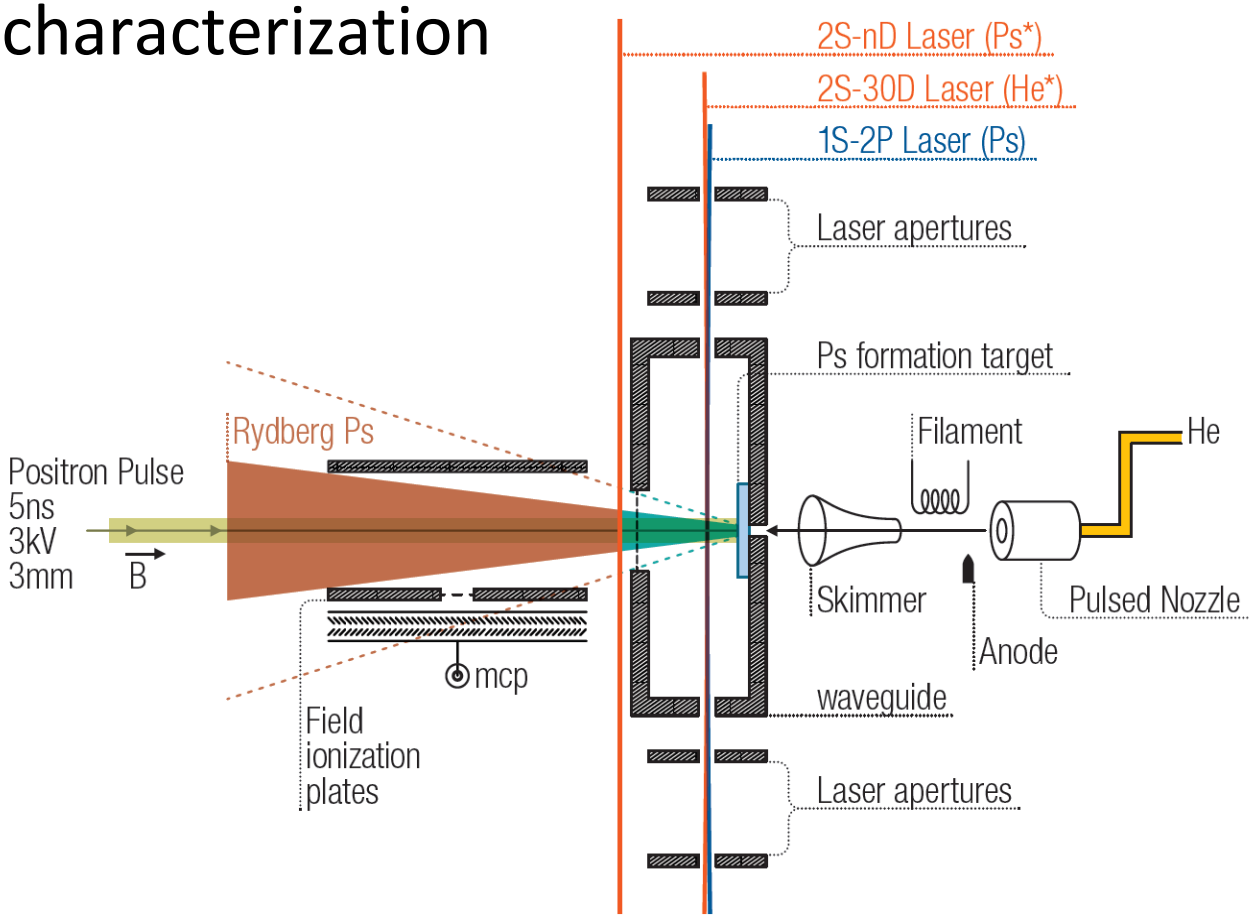
Selecting the low field seeking states by tuning the excitation laser is more efficient (since we don't excite atoms to unguidable high field seeking states

This is not always possible: you have to apply a field to split the line enough so that you can access one part of the Stark manifold. That means the width has to be on the order of the laser bandwidth and/or the Doppler width of the transition. For us this means states above n = 15 or so start to overlap

Curved guide: useful for getting the Ps beam off the positron trap axis, and also acts as a velocity selector



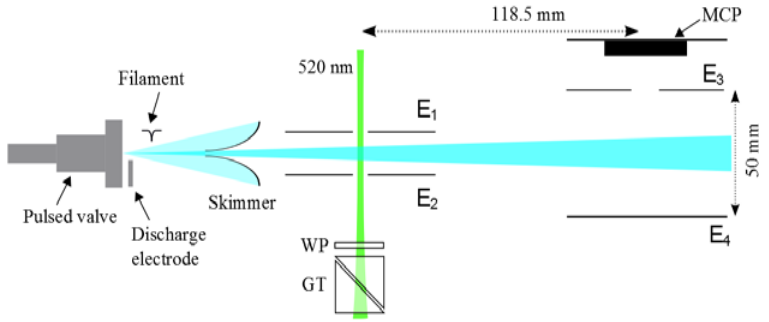
microwave spectroscopy of n = 2 Ps with Rydberg Helium field characterization

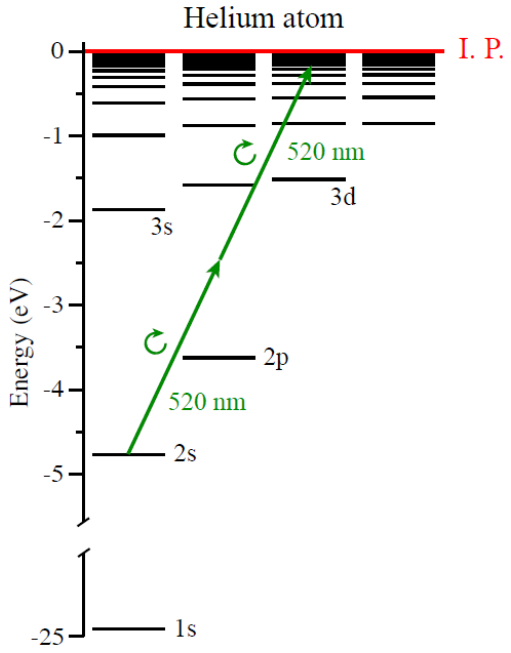


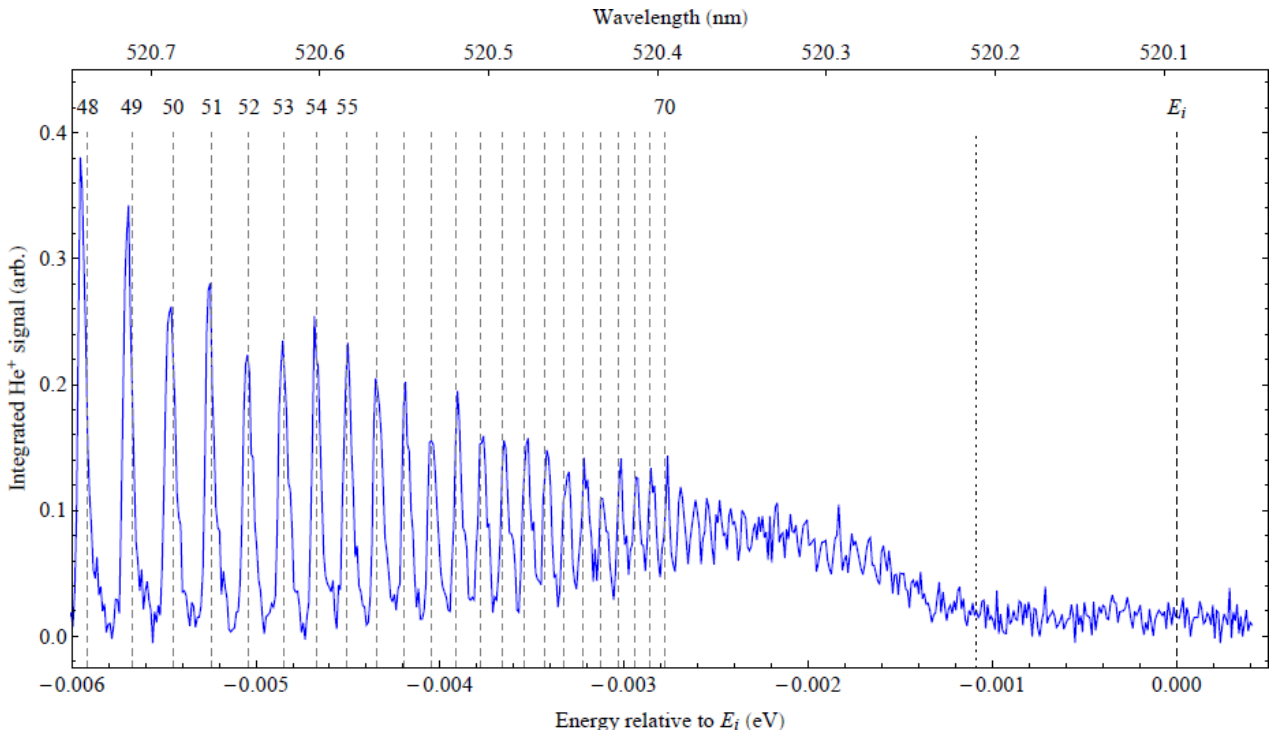
Can use He as a way to map out the magnetic field in the Ps excitation region, and for E field cancellation. We will also perform optical transitions (n = 25 -2) to measure Ps Rydberg constant: ultimate goal is to get to part in 10^{12}

Helium tests: 2-photon excitation scheme:

In order to achieve better state selection and avoid the limited overlap of the laser with the Doppler broadened transitions we will attempt to produce Rydberg Ps via a two-photon transition. Initial test experiments done with metastable Helium:







Circular polarization. No field applied in the excitation region. Approximately 5 GHz wide dye laser, with beam focussed to a spot of size 0.5 mm by 0.1 mm (1/e waist). Pulse energy ~ 10 mJ in 5 ns.

Wall et al. Phys. Rev. A **90**, 053430 (2014)

Directions of future work:

- Find improved sources of cold Ps
- Better resolution of Rydberg states (pulse amplification)
- Microwave spectroscopy of n = 2 levels (fine structure)
- Improve control of Ps motion with electrostatic fields
- Ps control with time varying fields: deceleration/focusing
- Creation of long-lived circular states (with microwaves)
- Microwave spectroscopy of Rydberg levels (Rydberg constant)
- Optical transition (n = 25 to n = 2: Better Rydberg constant)
- Ps free-fall/interferometry gravity measurements…..

Thank you for your attention

antimattergravity.com

What might a Ps Rydberg gravity experiment look like?