Apparatus for millimetre-wave spectroscopy of Rydberg positronium

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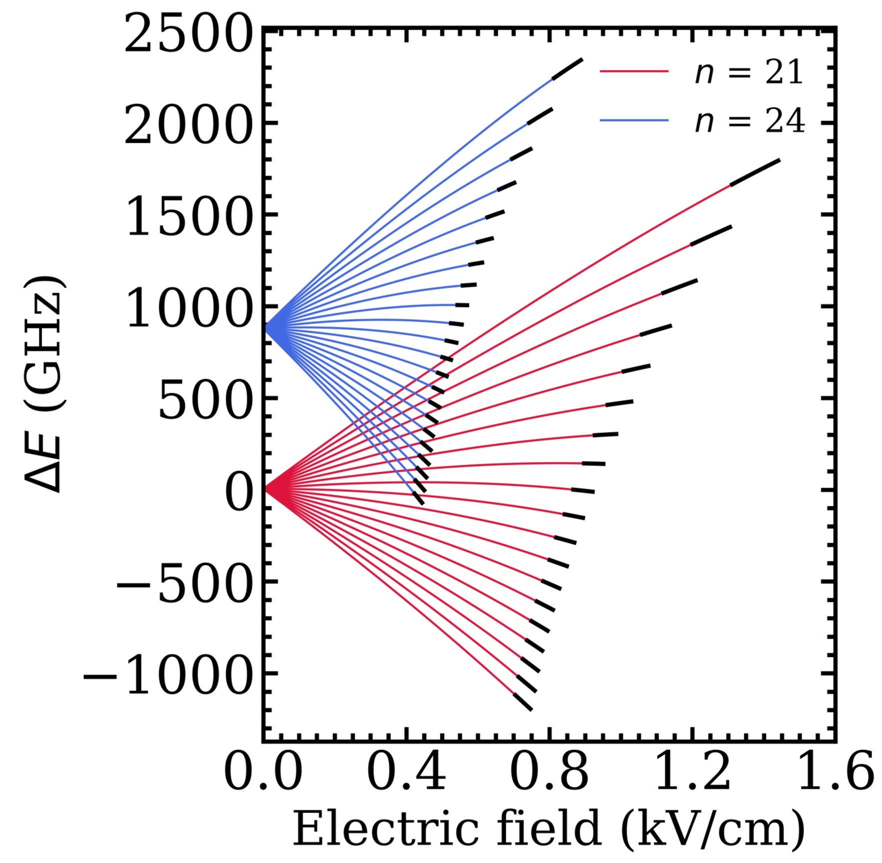
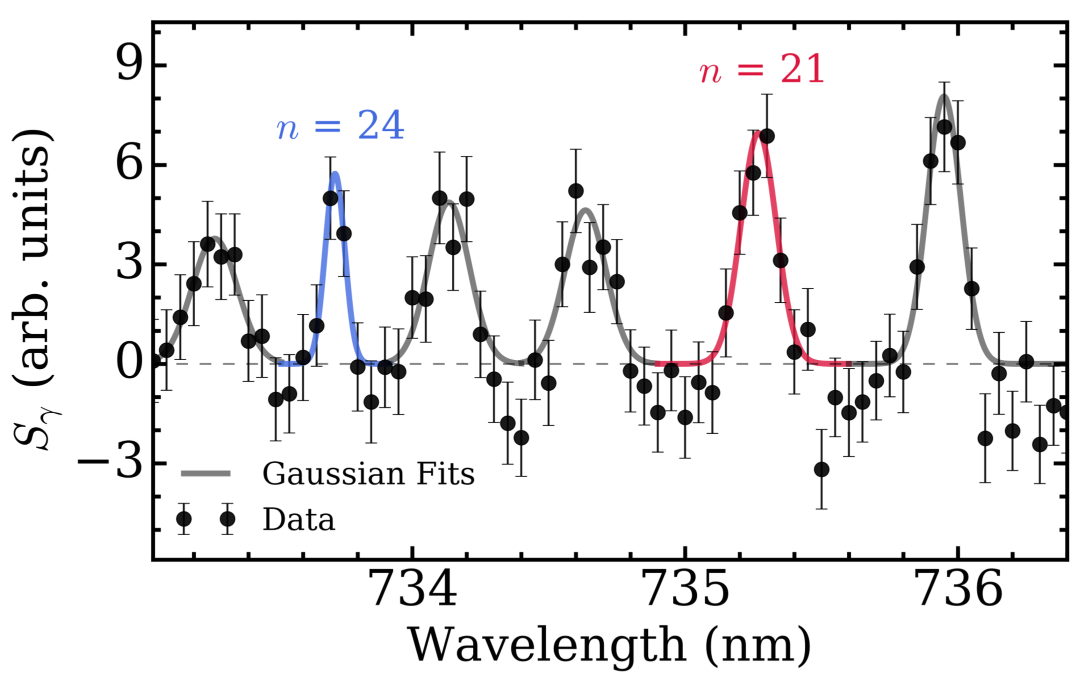
Introduction

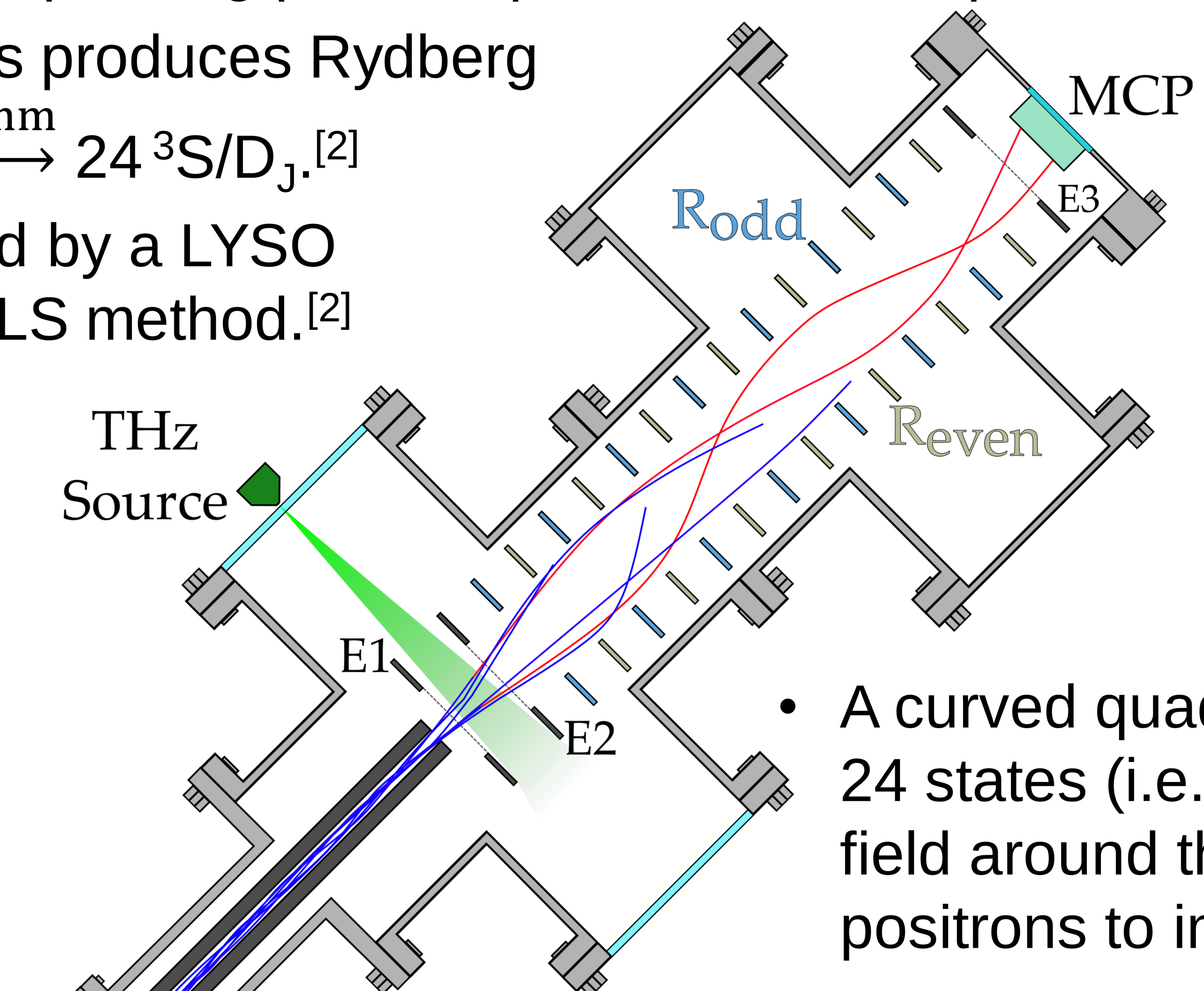
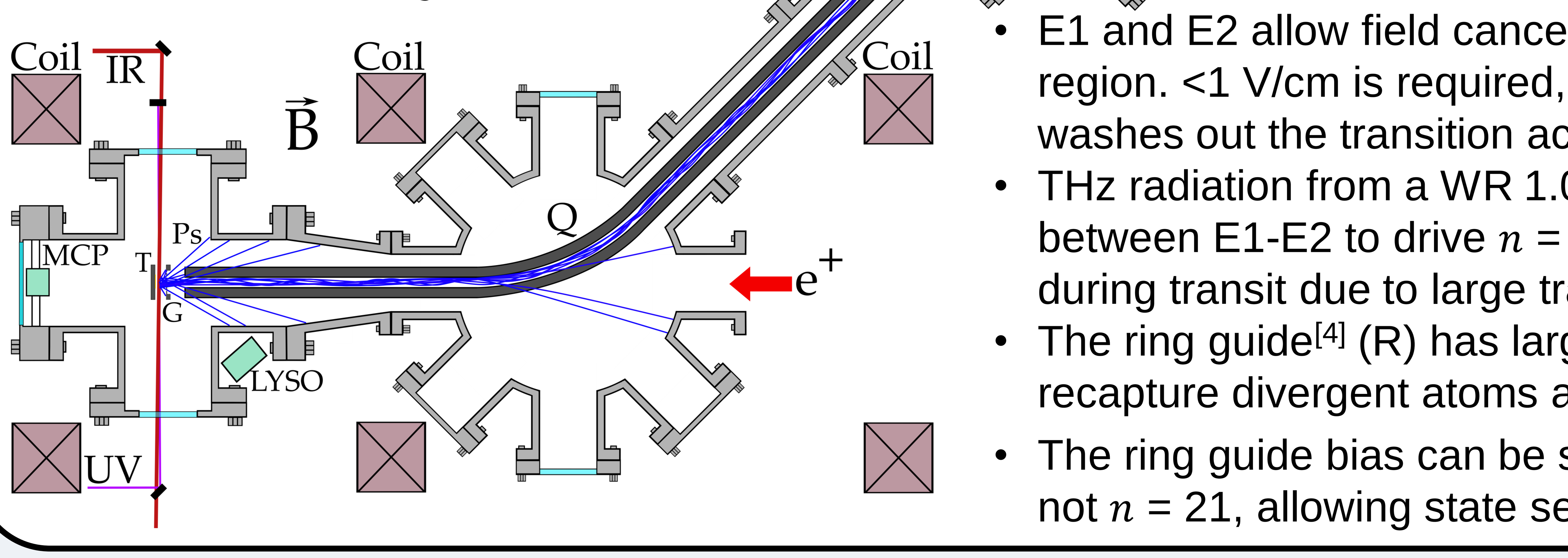
- Positronium (Ps) is the bound state of an electron and a positron, being an atom containing only leptons.
- It can be used for measurements of fundamental constants, such as the Rydberg constant, without hadronic effects from the nucleus.[1]
- Ground state Ps is very short lived at τ_{mean} = 142 ns, causing broad line widths.
- Rydberg states have lifetimes of >10 μs offering narrow linewidths, and have large dipole moments allowing electrostatically controlled long lived beams.
- We will target mm-wave (THz) transitions, such as n = 24 → 21 at 874 GHz, to measure the Rydberg constant.
- This will offer a natural linewidth of ~5 kHz and allow state sensitive detection through field ionization.
- THz transitions are useful for evaluating systematics, but higher precision measurements will be optical.

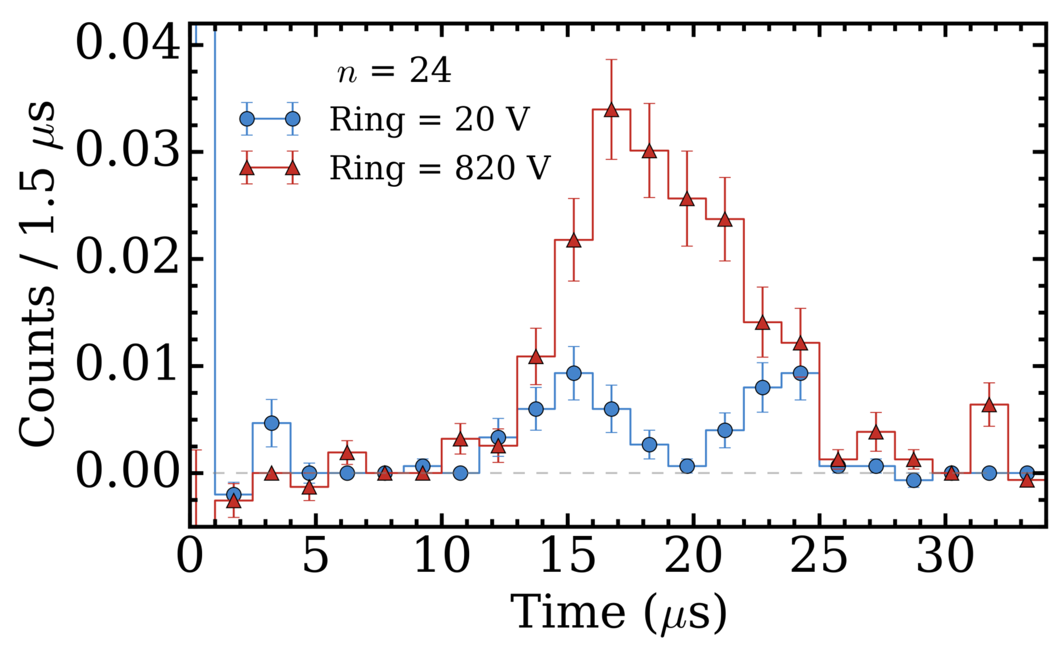


Apparatus

- Ps is made in the ground state by implanting positron pulses into mesoporous SiO_2 film (T).[2]
- A 2-step 2-colour excitation process produces Rydberg states, $1\,^3S_1 \xrightarrow{UV=243nm} 2\,^3P_J \xrightarrow{IR=733.7nm} 24\,^3S/D_J$.[2]
- Positronium production is monitored by a LYSO scintillation detector and the SSPALS method.[2]



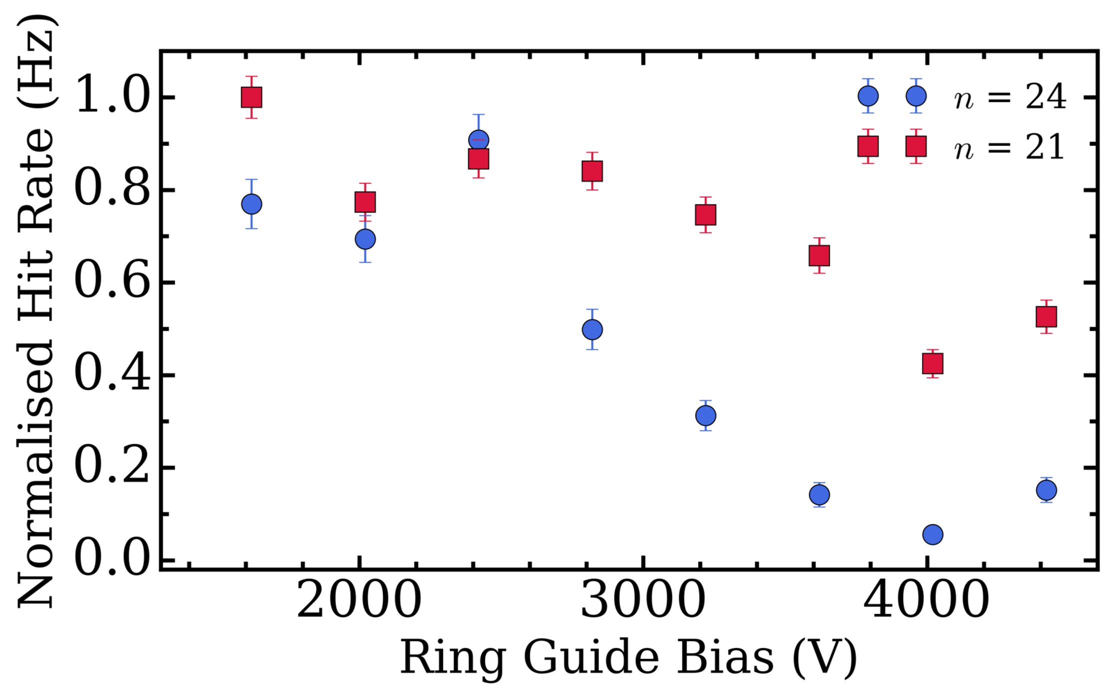





- A curved quadrupole guide (Q) extracts LFS n = 24 states (i.e. k > 0) from the static magnetic field around the positron beam while allowing positrons to impact the SiO_2 film unimpeded.[3]
- E1 and E2 allow field cancellation in the THz application region. <1 V/cm is required, above which Stark broadening washes out the transition according to tests in Rydberg He.
- THz radiation from a WR 1.0 horn antenna can be applied between E1-E2 to drive n = 24 → 21, but atoms diverge during transit due to large transverse velocity of ~30 km/s.
- The ring guide[4] (R) has large spatial acceptance to recapture divergent atoms after application of the THz field.
- The ring guide bias can be selected to field ionise n = 24 but not n = 21, allowing state sensitive detection on an MCP.

Status

- n = 21 and n = 24 guiding observed where the average velocity of the guided atoms is ~70 km/s from ToF measurements.
- Ring guide works as a Stark filter, achieving an optimized signal difference of 71% between n = 21 and n = 24.
- Can improve guiding efficiency with closer ring spacing and boost detection efficiency by adding a dedicated field ionization region in front of the MCP.
- High velocities will cause 35 MHz of Doppler broadening and 2 MHz of transit-time broadening. Need colder Ps source, which is not available, or better detection efficiency to enable selection of colder Ps from the existing distribution while compensating for the associated lower the count rate.



[1] S. G. Karshenboim, *Phys. Reports,* **422,** 1-63, (2005)
[2] B. S. Cooper, *Rev. Sci. Intrum.,* **86,** 103101, (2015)
[3] A. M. Alonso, *PRA,* **95,** 053409, (2017)
[4] M. H. Rayment, *PRA,* **100,** 013410, (2019)

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