Positronium precision spectroscopy:
Measuring the 1S-2S and excited state hyperfine transitions

this work is supported by the SNF grant 166286 - PI: Paolo Crivelli
ETH slow positron beamlines

- Continuous beam (since 2012)
- Pulsed beam (since 2015)
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see talk by Carlos Vigo Hernandez tomorrow, 16:50
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+Bonus: e+ moderation, back-scattering, Ps formation
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Motivation – Part 1

- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED
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- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED
- 1S-2S transition
  - 0.5 ppb precision
  - check bound state QED up to order $\alpha^7m$

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**1S-2S HFS**

**Theory:**

$\nu^{\text{theory}} = 1233607222.2(6) \text{ MHz}$


**Experiments:**

$\nu^a = 1233607216.4(3.2) \text{ MHz}$

M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)

$\nu^b = 1233607218.9(10.7) \text{ MHz}$


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see next talk by Gregory Adkins
Additional Motivation: CPT violation


see talks on behalf of ALPHA and ASACUSA
Ps 1S-2S: laser system

Requirements:
- High power (up to 1 kW) at 486 nm → detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser ≈ 100 MHz
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Requirements:
- High power (up to 1 kW) at 486 nm \(\rightarrow\) detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser \(\approx\) 100 MHz

- 972nm diode laser
- 3W Tapered Amplifier
- SHG cavity with LBO crystal
- Light at 486nm 1W, 200kHz
- Mirror 1 mounted in double piezo-actuator
- Mirror 2
- High finesse resonator for power build up 500 mW \(\rightarrow\) 1 kW

Incoming laser beam
- e+ beam
- oPs
- Ps target
- Vacuum \(10^{-9}\) mBar
Ps 1S-2S: preliminary results (2014)

First successful scans
(about 3 hours data taking,
~ $10^6$ positronium atoms/point)

S/N ratio should be improved.

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First successful scans
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Need for a bunched beam $\rightarrow$ use buffer gas trap

$\rightarrow$ noise from accidentals reduced by 2 orders of magnitude

$\rightarrow$ In addition to lifetime method possibility to use pulsed lasers for systematic studies and increased signal rate

Ps 1S-2S: Updated detection techniques

- Direct photo-ionization in the exciting laser
Ps 1S-2S: Updated detection techniques

- Direct photo-ionization in the exciting laser
- 2S photo-ionization in separate laser
Ps 1S-2S: Updated detection techniques

- Direct photo-ionization in the exciting laser
- 2S $\rightarrow$ Rydberg (e.g. 20P) and field ionization on MCP
  - allows for correction of second order doppler shift (main systematic!)
Ps 1S-2S: Pulsed laser scheme

- Frequency stabilised diode laser (Toptica)
  - 486 nm CW

- Wavelength-meter (High Finesse)
- Computer PID control

- Frequency tripled pulsed Nd:YAG laser – seeded (Spectra Physics)
  - 355 nm pulsed

- Pulsed Dye Amplifier (Radiant Dyes)
  - energy stabilised 486 nm pulsed

- Optical fiber

- PBS
Ps 1S-2S: Pulsed laser scheme

ratio ionized e+ over backscattered e+ (x10, x10) [%]

laser detuning [MHz]
Ps 1S-2S: Studies of systematics

- AC stark shift
  - correct via extrapolation
Ps 1S-2S: Studies of systematics

- Residual first order doppler shift
Ps 1S-2S: Studies of systematics

- Residual first order doppler shift

\[ \Delta v \propto v_{Ps} \cdot \delta \]
Ps 1S-2S: Studies of systematics

- Residual first order doppler shift

\[ \text{ratio } \text{Ps}\ e^+ \text{ over backscattered } e^+ \% \]

- \( \approx +500 \mu \text{rad} \)
Ps 1S-2S: Status and outlook

- **Status**
  - pulsed beam operational
  - enhancement cavity installed and locked
  - new detection schemes tested with pulsed dye amplifier and additional dye laser
  - systematic studies with pulsed laser underway
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- **Outlook**
  - next step: switch to CW excitation
  - precision of 0.5 ppb feasible
    - stringent test of current QED calculations
    - constrain SME coefficients (measure sidereal shifts)
  - further improvements require cold positronium (e.g. via Rydberg deceleration)
Ps is purely leptonic system
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Precision test bench for
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Motivation – Part 2

- Ps is purely leptonic system
- (almost) free from
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED
- Hyperfine structure
  - Very precise measurements in 1970s and 1980s
  - Almost 4 sigma discrepancy with most recent QED result

Ps HFS: Indirect measurements

- In a static magnetic field:
  - antiparallel spin states pick up $\Delta E$
  - magnetic quenching
Ps HFS: Indirect measurements

- In a static magnetic field:
  - antiparallel spin states pick up $\Delta E$
  - magnetic quenching

- one calculates $\Delta_{HFS}$ from:
  - $\Delta_{mix} \approx 0.5 \cdot \Delta_{HFS} \left( \sqrt{1 + q^2} - 1 \right)$
  - where: $q \propto \frac{B}{\Delta_{HFS}}$
Ps HFS: Indirect measurements

- In a static magnetic field:
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- one calculates $\Delta_{HFS}$ from:
  - $\Delta_{mix} \approx 0.5 \cdot \Delta_{HFS} \left( \sqrt{1 + q^2} - 1 \right)$
  - where: $q \propto \frac{B}{\Delta_{HFS}}$
- Disadvantages
  - needs very high B-Fields ($\sim 1 \, T$)
  - inhomogeneities in the fields contribute directly to systematic errors

\[ \text{Ps HFS: Indirect measurements} \]
Ps HFS: Measurements in dense gases

- In dense gases
  - gas acts as $e^+$ target
  - $e^+$ can ionize a gas atom
  - $e^+$ picks up the $e^-$ and forms Ps
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Ps HFS: Measurements in dense gases

- In dense gases
  - gas acts as $e^+$ target
  - $e^+$ can ionize a gas atom
  - $e^+$ picks up the $e^-$ and forms Ps
- Advantage: no need for a beam
- Disadvantages:
  - E field of gas atoms $\rightarrow$ Stark effect
  - Needs extrapolation to vacuum
  - High MW powers can strongly interfere with Ps production in gases

Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter
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- Direct transition
  - doesn’t need strong B field
  - no homogeneity concerns

\[ \begin{align*}
1^3S_1 & \quad \text{Microwave} \quad 203 \text{ GHz} \\
1^1S_0 & \quad 3\gamma \ (\tau = 142 \text{ ns}) \quad 2\gamma \ (\tau = 124 \text{ ps})
\end{align*} \]
Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter
- Direct transition
  - doesn’t need strong B field
  - no homogeneity concerns
- use 486nm laser
- Microwave sources
  - 100’s mW (w/o Amp.)
  - 100’s W (with Amp.)
Ps HFS: Schematic overview of the experiment

SiO2 target

e+

Ps
Ps HFS: Schematic overview of the experiment

SiO2 target

486nm laser

e+
P5
Ps
Ps*
Ps HFS: Schematic overview of the experiment

SiO2 target

486nm laser

collimator

e⁺

Ps

Ps*
Ps HFS: Schematic overview of the experiment

- SiO2 target
- 486nm laser
- collimator
- confocal resonator
- waveguide feed
- e+
- Ps
- Ps*
- decay to 2γ 511keV each
Ps HFS: Schematic overview of the experiment

SiO2 target

486nm laser

collimator

confocal resonator

AxPET module (⊥ to beam)

waveguide feed

decay to 2γ 511keV each

AxPET module (⊥ to beam)
Ps HFS: Optimization of 2S surviving fraction

- scan laser parameters
- optimize for 2S fraction
  - PI signal due to 532nm laser
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  - PI signal due to 532nm laser
- include normalization:
  - \( N = \frac{P_{bs}}{\varepsilon_c (1 - P_{bs})} \approx 0.26 \)
Ps HFS: Optimization of 2S surviving fraction

- scan laser parameters
- optimize for 2S fraction
  - PI signal due to 532nm laser
- include normalization:
  - \( N = \frac{P_{bs}}{\varepsilon_c(1-P_{bs})} \approx 0.26 \)
- Surviving 2S fraction:
  - \( P_{2S} \approx 0.5\% \)
- Simulation: % level
Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedance matched coupling hole
  - waveguide signal feed
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- Performance close to design values
  - $Q \approx 26300$ or equivalently $\Gamma_{\text{FWHM}} \approx 1 \text{ MHz}$
  - Coupling efficiency $\approx 70\%$
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- Monitoring and stabilization system
- Performance close to design values
  - $Q \approx 26300$ or equivalently $\Gamma_{\text{FWHM}} \approx 1\, \text{MHz}$
  - Coupling efficiency $\approx 70\%$
- Simulation: HFS transition probability
  - $\approx 0.5\%$ (signal generator)
  - $\approx 15\%$ (additional 10W amplifier)
Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence
    - vertex reconstruction
    - energy cut

\[ m_{Ps} = 1022 \text{ keV} \]

\[ E_{\gamma} = 511 \text{ keV} \]
Ps HFS: Event signature

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- Dominant background (oPs decay)

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\[ \sum E_\gamma = 1022 \text{ keV} \]
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  - misidentification of 3 photon decays as 2 photon decays
    - 2 of the 3 photons almost colinear

\[ m_{Ps} = 1022 \text{ keV} \]
\[ E_{\gamma} \approx 255.5 \text{ keV} \]
\[ E_{\gamma} \approx 511 \text{ keV} \]
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    - one photon very soft
- Granular detector
  - good spatial, temporal, and energy resolution

Ps HFS: Simulation results

- Simulation
  - rate on the order of $10^5 \text{ e}^+/\text{s}$
  - 25% Ps conversion efficiency
- optimization for S/N
  - % level detection efficiency
  - $S/N \approx 10$
- projected sensitivity
  - $\pm 10 \text{ ppm (stat.)}$
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  - $\pm 4 \text{ ppm (syst.)}$

Ps HFS: Current status and outlook

- **Status**
  - 2s excitation optimization working well
  - microwave system successfully tested and up to spec
  - microwave chamber being commissioned
  - new detector DAQ tested and being commissioned
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- **Outlook**
  - precision of a few ppm should be achievable → probe discrepancy with bound state QED
  - more precise measurements feasible
    - LN2 cooling of resonator (increase Q factor significantly)
    - increase MW power (TWT amplifier)
    - improved event analysis (pattern recognition, e.g. neural net)
    - limited by systematic uncertainties
more information: arXiv:1805.05886

**PI:** Paolo Crivelli

**Additional Credits:** G. Wichmann, D. Cooke, A. Antognini, K. Kirch, A. Rubbia
BACKUP SLIDES
CPT – Violation

- CPT can be naturally broken (e.g. in string theory)
- Breaks Lorentz symmetry
- Can be well described at low energy scales as effective field theory: **Standard Model Extension (SME)**
  - built from General Relativity and the Standard Model
  - includes Lorentz- and CPT violating operators
  - up to mass dimension 4 (minimal SME) and above
  - coefficients have to be determined experimentally

Spectroscopy and the minimal SME

- Minimal SME terms can produce striking effects, e.g.
  - Hydrogen sector
    - time dependent shifts in hydrogen spectra (e.g. annual shifts)
    - different hydrogen and anti-hydrogen spectra
  - Positronium sector
    - SM forbidden momentum-polarization correlations in Positronium decay
    - shifts in Positronium spectrum from Lorentz-invariant values
      - 1s-2s transition
      - hyperfine splitting

Ps 1S-2S: original detection scheme

Detection of annihilation photons. Lifetime of excited S states ~ $n^3$

$\tau_{2S}/\tau_{1S} = 8$

- Laser (500W)
- Porous silica
- Aperture 3x3 mm²
- Length 60 mm
- SiN 30 nm window 3x3 mm²

142 ns (1S)
1136 ns (2S)

G4 simulation
Ps HFS: Review - First direct measurement

- Notoriously difficult \((\Delta \nu = 203 \text{ GHz})\)
  - no off-the-shelf sources
  - no off-the-shelf resonators
  - behavior somewhat between microwave and light
- Multiple resonators required
  - need to be changed for every frequency point
- Needs very high MW power
  - very rudimentary power estimation
    - measured the heat absorbed by water

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theory</th>
<th>Direct Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta_{\text{HFS}}^{\text{Ps}} \text{ [GHz]})</td>
<td>203.391 69(16)</td>
<td>203.39^{+0.15} _0.14 \pm 0.11</td>
</tr>
</tbody>
</table>

Positron production

- Positrons produced in $\beta^+$ decay of $^{22}$Na
  - $^{22}$Na $\rightarrow$ $^{22}$Ne$^*$ + $\nu_e$ + $e^+$
    - continuous spectrum: 0 – 543 keV
    - moderate half-life: $\tau_{1/2} = 2.6$ a
  - $^{22}$Ne$^*$ $\rightarrow$ $^{22}$Ne + $\gamma$
    - discrete energy: 1.27 MeV
    - almost immediate process: 3.7 ps delay
    - can be used to tag $\beta^+$ decay of $^{22}$Na

- Need for moderate rate sources
  - CW beam: 300 MBq
  - Pulsed beam: 350 MBq
Positron moderation

- Large energy spread: use moderation
- Solid rare gas moderation
  - 4K cold head
  - tungsten allow shield
  - $^{22}$Na in capsule with
    - 5µm titanium window
  - solid neon film is grown
    - $e^+$ loses energy only inefficiently below band gap ($\approx 20$eV)
    - large fraction of $e^+$ is emitted into vacuum with epithermal energies
Buffer gas trap

Positrons in few eVs bunches (50 ns) At 10 Hz rep rate
Positron bunching and extraction

Positron (7 eV) bunches from the trap 50 ns and 1 mm ($\sigma$) in 120 G

On target (kept at ground): positron bunches of 1 ns with a beam spot of 1 mm extracted to the field free e-m region with 90 % efficiency.

Positronium formation

- Implantation in porous silica thin film
  - approx. 1 µm thick, 3-4 nm pore size
  - $e^+$ energy of a few keV
  - rapid thermalization
- Diffuse and annihilate
- Form Positronium by capturing $e^-$
  - 25% $pPs$ and 75% $oPs$
  - diffusion to surface
  - emission into vacuum
    - $W_{Ps} = \mu_{Ps} + E_B - 6.8$ eV $< 0$ eV

Positronium emission into vacuum

- Very efficient
  - \( \approx 30\% \) of incident \( e^+ \) produce oPs into vacuum
- Almost monoenergetic
  - \( \approx 40 \text{ meV} (\approx 10^5 \text{ m/s}) \)
  - deBroglie wavelength of Ps:
    \[ \lambda_{Ps} = \frac{\hbar}{\sqrt{2 m_{Ps} E_{Ps}}} \approx 0.9 \text{ nm} \frac{1 eV}{E_{Ps}} \]
    - for \( \approx 100 \text{ meV} \) this becomes comparable to pore size!
  - particle in a box
    \[ E_{Ps} = \frac{\hbar^2}{2 m d^2} \approx 0.8 eV \left( \frac{1 \text{ nm}}{d} \right)^2 \]