Positronium 1S-2S transition frequency measurement

Paolo Crivelli

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PSI2013 workshop, 12th of September, 2013

My work is supported by the Ambizione grant of the SNSF PZ00P2_132059 and ETH under the research grant ETH-47-12-1
Positronium (Ps)

Two ground states:

Parapositronium (p-Ps) singlet spin state $^1S_0$

$$|0, 0\rangle = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2} \quad s = 0 \quad \text{(singlet)}$$

Orthopositronium (o-Ps) triplet spin state $^3S_1$

$$|1, 1\rangle = \uparrow\uparrow$$
$$|1, 0\rangle = (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2}$$
$$|1, -1\rangle = \downarrow\downarrow \quad s = 1 \quad \text{(triplet)}$$
Positronium (Ps)

Two ground states:

Parapositronium (p-Ps) singlet spin state $^1S_0$

Orthopositronium (o-Ps) triplet spin state $^3S_1$

$\Gamma^{-1} = \tau \approx 125 \text{ ps (in vacuum)}$

Pirenne and Wheeler in 1946

\[
\Gamma^{(0)}_{2\gamma}(n^1S_0) = \sigma_{2\gamma}^1 v |\psi_n(0)|^2 = \frac{1}{2} \frac{m_e c^2}{\hbar} \frac{\alpha^5}{n^3}
\]
Positronium (Ps)

Two ground states:

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$\Gamma^{-1} = \tau \approx 125 \text{ ps (in vacuum)}$

$0 \leq |k_i| \leq 511 \text{ keV}$

$\Gamma_{2\gamma}(n^1S_0) = \sigma_{2\gamma}v|\psi_n(0)|^2 = \frac{1}{2} \frac{m_e c^2}{\hbar} \frac{\alpha^5}{n^3}$

Pirenne and Wheeler in 1946

$\Gamma_{3\gamma}(n^3S_1) = \frac{2}{9\pi} (\pi^2 - 9) \frac{m_e c^2}{\hbar} \frac{\alpha^6}{n^3}$

Ore and Powell in 1949

$\Gamma^{-1} = \tau \approx 142 \text{ ns (in vacuum)}$
Positronium 1S-2S transition

Ps Energy levels

\[
\begin{array}{ccc}
4 & \text{3S} & \text{3P} & \text{3D} \\
3 & 2^3S_{1.1 \mu s} & 2P_{3.2 \text{ ns}} \\
1 & ^3S_{142 \text{ ns}} \\
\end{array}
\]

2 photons transition
\[\lambda = 486 \text{ nm}\]
Natural linewidth 1.2 MHz
Positronium 1S-2S transition

Ps Energy levels

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2 photons transition

λ=486 nm

Natural linewidth 1.2 MHz

\begin{align*}
\nu^\text{theory} &= 1233607222.2(6) \text{ MHz} \\
\nu^a &= 1233607216.4(3.2) \text{ MHz} \\
\nu^b &= 1233607218.9(10.7) \text{ MHz}
\end{align*}


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

Positronium 1S-2S transition

Ps Energy levels

- n = 4
  - 3S
  - 3P
  - 3D
- n = 3
  - $2^3S_1$ 1.1 µs
  - 2P 3.2 ns
- n = 2
  - $3^S_1$ 142 ns

2 photons transition
$\lambda = 486$ nm
Natural linewidth 1.2 MHz

Theory

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


Experiment

$v^a = 1233607216.4(3.2)$ MHz

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

$v^b = 1233607218.9(10.7)$ MHz


Measurement of 1S-2S of Ps at a level about $5 \times 10^{-10}$ => check QED calculations at the order $\alpha^7m$ and provide best determination of $m_{e^+}/m_{e^-}$.
## Hydrogen like vs Ps

Various contributions to the energy levels

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Leptonic atoms free of nuclear size effects!
Attempts with charged anti-particles were not conclusive -> use neutral objects. 
Recent measurement at CERN with trapped anti-H (ALPHA):
\( \overline{m}_G / m_G = (+100, -65) \) at 5% confidence level
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\[ \frac{m_G}{m_G} = (+100, -65) \text{ at 5\% confidence level} \]

Two approaches to direct measure effect of gravity on anti-matter:
1) Gravity fall of anti-matter (anti-hydrogen at CERN): Aegis, GBar
2) Use the gravitational redshift

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Assuming antigravity:

\[ \nu(r) = \nu_0 \times \begin{cases} 
1 + \frac{U(r) - U(\infty)}{c^2} & \text{for } H \\
1 & \text{for } Ps \\
1 - \frac{U(r) - U(\infty)}{c^2} & \text{for } H^1
\end{cases} \]
Effect of gravity of antimatter -2

- Assuming antigravity:

\[ \nu(r) = \nu_0 \times \begin{cases} \left( 1 + \frac{U(r) - U(\infty)}{c^2} \right) & \text{for } H \\ \frac{1}{\left( 1 - \frac{U(r) - U(\infty)}{c^2} \right)} & \text{for } \bar{H} \end{cases} \]

- $\Delta U$ for different altitudes in the gravitational field of the earth is too weak for $P_s$

\[ dh = 5000m \implies \frac{\Delta v}{v} = 5.2 \times 10^{-13} \]
Assuming antigravity:

\[ F \downarrow \text{apple} \quad \text{apple} \quad \text{apple} \uparrow F \]

\[ \nu(r) = \nu_0 \times \begin{cases} 
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\end{cases} \]

\[ \Delta U \text{ for different altitudes in the gravitational field of the earth is too weak for Ps} \]

\[ dh = 5000 \text{m} \quad \Rightarrow \quad \frac{\Delta \nu}{\nu} = 5.2 \times 10^{-13} \]

\[ \Delta U(r_{\text{max}}) - \Delta U(r_{\text{min}}) \approx 3.2 \times 10^{-10} \]

Measurement of 1S-2S Ps, Mu or HBar at a level about $1 \times 10^{-10}$ => sensitivity to check the shift of antigravity.
New measurement ongoing @ ETH

P. Crivelli (ETHZ), D. Cooke (ETHZ), S. Friedreich (ETHZ), A. Rubbia (ETHZ), A. Antognini (ETHZ), K. Kirch (ETHZ/PSI), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette)

Project supported by the SNSF Ambizione grant (PZ00P2_132059) and by ETH (Research Grant ETH-47 12-1)
ETHZ slow positron beam

Production of positronium in vacuum requires slow positrons
The positron source

70 MBq $^{22}\text{Na}$ e+ source & Neon moderator chamber
Positron transportation

150000 \( e^+ / s \)

\( E_{\text{kin}} = 200 \) eV

Separation of Slow and fast \( e^+ \)

Magnetic coils for positron transportation (quasi-uniform longitudinal field of 70 Gauss)
Positron-Positronium conversion target

150000 $e^+/s$

Acceleration 1-20 keV

Positronium formation region
Positron implantation

Porous Silica thin film ~1000nm 3-4 nm pore size

Vacuum

Positron implanted with keV energies
Rapidly thermalizes in the bulk (~ps)

A fraction undergo direct annihilation

Makhovian profile

\[ P(x, E) = \frac{m x^{m-1}}{x_0^m} e^{-(x/x_0)^m} , \]

\[ x_0 = \frac{x_m}{\Gamma((1/m) + 1)} , \]

\[ x_m = \frac{40}{\rho} E^{1.6} , \]
Positronium formation in SiO$_2$ by capturing 1 ionized electron (spur electrons) (1/4 pPs, 3/4 oPs)

\[ W_{Ps} = \mu_{Ps} + E_B - 6.8 \text{ eV} = -1 \text{ eV} \]

Diffusion to the pore surface and emission in the pores

Thermalization via collisions and diffusion in the interconnected pore network

A fraction of them is emitted into vacuum.
Ps detection

Gamma detectors

Target

e$^+$ from the beam

Gamma detectors
Ps detection

Target

Secondary e⁻ → START time for detectors
Ps detection

Target

Gamma detectors

Ps

Gamma detectors
Positron annihilation lifetime spectra - PALS

\[ f(t) = Ae^{-t/\tau} + B \]

- Constant: \( A = 4730.7 \)
- Lifetime: \( \tau = (142.8326 \pm 0.5108) \text{ ns} \)
- Background: \( B = 270.2 \)

Graph showing the decay of positron annihilation events over time.

Graph showing the relationship between implantation energy (keV) and vacuum yield (%).
Positron annihilation lifetime spectra - PALS

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Measurement of Ps energy


Time of flight

Doppler spectroscopy
Measurement of Ps energy

Thermal energy 30 meV

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Ps de Broglie wavelength comparable to pore size -> Ps in the pores as to be treated QM

Ground state energy

\[ E_{Ps} = \frac{\hbar^2}{2m d^2} \approx 0.8 \text{eV}(1 \text{nm}/d)^2 \]

Ps as a particle in a box

\[
(H) = kT^2 \left( \frac{1}{Z(a)} \frac{dZ(a)}{dT} + \frac{1}{Z(b)} \frac{dZ(b)}{dT} + \frac{1}{Z(c)} \frac{dZ(c)}{dT} \right)
\]

\[ Z \text{ is the partition function defined as } \]

\[ Z(a) = \sum_{n=1}^{\infty} e^{-\frac{\hbar^2 n^2}{8ma^2}/kT}, \]

Thermal energy 30 meV
Colder Ps from silica films?

In principle it should be easy: use larger pores of 8-10 nm confinement energy \( \sim 50-100\text{K} \) (for muonium we could reach 100 K with 4 nm since de Broglie wavelength much smaller)

A. Antognini et al., PRL 108, 143401 (2010)

Recently: aluminum oxide nano-channels 5-8 nm \( \rightarrow \) 7\% of Ps at 150 K

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Even at room temperature Ps is very fast
~ 7 x 10^4 m/s

-> Second order Doppler shift ~ 30 MHz is expected to be the main systematic in our measurement.

BUT for porous silica one would expect to see at least 3 peaks in the resonance curve
-> correction of the 2nd order Doppler shift
The laser system for Ps 1S-2S

Requirements:

- High power (~kW) at 486 nm to get a detectable signal
- Long term stability (continuous data taking ~days)
- Scanning of the laser ± 100 MHz

Wavemeter
Positron beam and gamma detectors
Laser 486 nm
Laser electronics
Enhancement cavity

Energy = \(-6.8/n^2\) eV

-1.7 eV

-6.8 eV

2\(^{3}\)S \rightarrow 2\(^{1}\)P
1.1 \(\mu\)s, 3.2 ns
2 photons transition

\(\lambda=486\) nm
natural linewidth 1.2 MHz

\[\text{Energy} = -\frac{6.8}{n^2}\text{ eV}\]
The laser (Ps and Mu)

- **486/488 nm TOPTICA LASER**
  - Light at 486/488 nm, 750mW, 200kHz
  - SHG cavity with LBO crystal

- **972 nm diode laser**
  - Mirror 1 (T1, A1) mounted in double piezo-actuator

- **Tapered Amplifier 2.4 W**
  - Mirror 2 (T2, A2)

- **Vacuum 10^{-9} mBar**
  - Ps target
  - Incoming laser beam
  - E+ beam

- **High finesse resonator**
  - For power build up
    - 400 mW → 0.5 kW

- **Space for a 2nd SHG cavity for light generation @ 244 nm for Mu spectroscopy**

**Cavity linewidth few kHz -> laser need to be stabilized to the same level.**
Stabilization - the 972 nm FP

- Long term drift against Te2 (T not yet optimized) < 1 MHz/day

- Short term ~ kHz (efficient incoupling to FP 486 nm)
The enhancement cavity @ 486 nm

- **Laser 486 nm**
- **Cavity Input**
- **EOM**
- **FP 486 nm**

**Static structural directional deformation analysis (ANSYS) along the X axis (units: mm):**

- **1.8918e-6 Max**
- **1.4769e-6**
- **1.062e-6**
- **6.4713e-7**
- **2.3225e-7**
- **-1.8263e-7**
- **-5.9751e-7**
- **-1.0124e-6**
- **-1.4273e-6**
- **-1.8422e-6 Min**

- **Hole for positron beam**
- **Optimized distance 186.7mm for suspending the resonator -> deformation due to gravity does not change mirror separation**

- **Suspension System**

**T1 = 49 ppm, T2 = 7 ppm**
**A1 = 12 ppm, A2=7ppm**
**FSR= 0.55 GHz**
**Linewidth = 7 kHz**
**Finesse ~ 80000**
**Incoupling 40%**

*Ultra-low-loss mirrors from ATFilms (https://www.atflims.com)*
The enhancement cavity @ 486 nm

T1 = 49 ppm, T2 = 7 ppm
A1 = 12 ppm, A2=7ppm
FSR= 0.55 GHz
Linewidth = 7 kHz
Finesse ~ 80000
Incoupling 40%

At 0.4 MW/cm² (0.7 kW circulating power) mirror degradation observed.
Run @ 0.5 kW:
-> Excitation prob ~ 4x10⁻⁴
-> Resonant 3γ PI ~ 4x10⁻⁵

*Ultra-low-loss mirrors from ATFilms (https://www.atflims.com)
The enhancement cavity @ 486 nm

Excitation regions coils (up to 300 G) manufactured and characterized here at PSI with the help of the magnet group (Sanfilippo et al.).
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Problem: after mounting the cavity on beam line could not reproduce the same results, degradation occurred already at 500W ...Suspected input mirror since its transmission changed. Now both mirrors from the same coating run.

T1 = T2 = 7 ppm  
A1 = A2 = 7 ppm  
FSR= 0.55 GHz  
Linewidth = 2.5 kHz  
Finesse ~ 225000  
Incoupling 24%

Stable generation of 500 W, no degradation over hours of continuous operation.
1) Detection of Ps 1S-2S – Lifetime method

Detection of annihilation photons. Lifetime of excited S states \( \sim n^3 \)

\[ \frac{\tau_{2S}}{\tau_{1S}} = 8 \]

- 3x10^7 triggers = 10 minutes, \( P_c = 0.5 \text{ kW} \)
- On resonance: 1250 events in 2 hours run

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
<th>1 BGO (2-4(\mu)s)</th>
<th>2 BGO (2-4(\mu)s)</th>
<th>(\Delta T \pm 10 \text{ ns} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2S Ps</td>
<td>4 x 10^3</td>
<td>342</td>
<td>129</td>
<td>127</td>
</tr>
<tr>
<td>1S</td>
<td>9.8 x 10^6</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Accidentals</td>
<td>-</td>
<td>4950</td>
<td>42</td>
<td>4</td>
</tr>
</tbody>
</table>

\( \gamma \) target, gamma detectors, Laser beam, Annihilation.
2) Detection of Ps 1S-2S - PI positrons

Detect photo-ionized positrons (3 photons resonant ionization)
PI prob = 0.1 Exc prob but detection efficiency higher
-> Expected signal rate factor 4 smaller than lifetime method
-> Better control of systematic

Extraction plates 10 V/cm

Laser beam

Ps

Target

Side view

B-field (50-300 G)

Position sensitive MCP

Front view

MCP

Target
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10 V/cm

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Front view

Detection graph:
- Simulated data
- Measured background
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Motional Stark effect \( \sim v^2 t \) (same dependence as 2nd order Doppler
(as done for H at LKB by Biraben et al.)

Study of systematic varying the magnetic field
(well characterized field measured at PSI to better than 1%)
With available source of Ps:
- Porous silica films: 30% @ 40 meV mono-energetic, isotropic emission

1) Uncertainty from statistics 1.8 MHz -> 0.35 MHz.
- Better positron beam (1 mm), higher detection efficiency, no restriction of beam time (careful systematic study), stable Ps formation
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2) Systematic uncertainty 1.9 MHz -> 0.4 MHz.
- Main contribution of 1993 exp. unknown parameters in pulsed photoionization laser -> proposed methods free of this systematic.
- Systematic dominated by 2\textsuperscript{nd} order Dopplershift
Expected accuracy

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Measurement of 1S-2S of Ps at a level about 5x10\textsuperscript{-10} seems feasible
=> check QED
Outlook

- Laser system and positron beam are combined

- In July: problems with enhancement cavity and arcing now solved
  -> stable generation of 500 W and new design for the electrodes in the excitation chamber

- Last week cryocooler to grow Ne moderator started to have problems. The temperature of 7K cannot be kept constant...some maintenance needed (involve handling the radioactive source)...
  Use Ar instead that is providing 30% of Ne efficiency...we will go ahead with that for the moment...
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Efforts to reduce the Ps velocity (~100 K should be achievable with porous films):
  -> new porous films being tested (in collaboration with CEA Saclay) and hierarchical zeolites
  (in collaboration with Prof. J. Perez, ETHZ Chemistry department).
2S hyperfine splitting

GROUND STATE HFS 15 ppm (3.5 \(\sigma\)) discrepancy

See Yamasaki’s talk

Theory


Origin? Experimental problem (linear extrapolation to zero density), theory, new physics?
Goal:
- observe this transition for the first time (a level of 50 ppm seems feasible)
- long term reach accuracy comparable with the one of the ground state, using high granularity detector for background suppression and 10 times stronger positron Source. Colder Ps would be of great help.

Advantages: Different experimental method than measurements in ground state
- no need for extrapolation to zero density since Ps in vacuum
- no need for challenging level control on magnetic field.
- Required power at 25.43 GHz is commercially available.
Thank you for your attention 😊