New precise measurement of the hyperfine splitting of positronium

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Outline

• Positronium Hyperfine Splitting (Ps-HFS)
• Material effect and Ps thermalization
• Our New Experiment
• Analysis and Results
• Prospects & conclusion
Positronium (Ps)

- Bound state of an electron (e⁻) and a positron (e⁺)
- Precision test of bound-state Quantum ElectroDynamics (QED).

\[
\vec{S} = 1 \text{ (Triplet)}
\]

Ortho-positronium (o-Ps)
- Spin=1  The same quantum number as photon
- o-Ps → 3γ (, 5γ, ...)

\[
\vec{S} = 0 \text{ (Singlet)}
\]

Para-positronium (p-Ps)
- Spin=0  pseudo-scalar
- p-Ps → 2γ (, 4γ, ...)

Lifetime 142 ns

Continuous spectrum

Lifetime 125 ps

Monochromatic 511 keV
Positronium Hyperfine Splitting (Ps-HFS)

Energy difference between two spin eigenstates of the ground state Ps

\[ \vec{\mu} = \frac{e}{2m} \vec{\sigma} \] spin-spin interaction

Quantum oscillation effect is also large (40%)
Discrepancy Between Previous Experiments and Theory

Previous experimental results are consistently lower than theory.

Previous experimental average

Theory (2014)

PRD 89 (2014) 111301(R)
PRA 90 (2014) 042502

Previous experimental average

203.388 65(67) GHz
(3.3 ppm)

O(\alpha^3 \ln \alpha^{-1})
+ some of O(\alpha^3)
QED theory

203.391 90(25) GHz
(1.2 ppm)

16 ppm (4.5 \sigma) significant discrepancy
Possible reasons for the discrepancy

- Common systematic uncertainties in the previous experiments
  1. Non-uniformity of the magnetic field.
  2. Underestimation of material effects. Unthermalized o-Ps can have a significant effect especially at low material density. *cf. o-Ps lifetime puzzle (1990’s)*

We introduced new methods to reduce these systematic errors.

- Need new development on calculation of bound-state QED or New physics beyond the Standard Model.
Estimation of Material Effect in previous experiments

- Need material (in this case gas molecules) so that positron can get electron and form Ps → Ps feels electric field of material

Strength of the Stark Effect
\[ \propto \sim \text{Collision rate with surrounding molecules} \]
\[ \propto (\text{Density of surrounding molecules}) \times (\text{Ps velocity } v)^{3/5} \]

→ If the Ps velocity is constant (under assumption that Ps is well thermalized), the material effect is proportional to gas density.

→ The Previous experiments

Phys. Rev. A
1984 30 1331
Ritter, Egan, Hughes et al.

**FIG. 7.** Measured values of \( \Delta \gamma \) vs \( N_2 \) gas density (amagat). The closed circles are from the present work. The straight line is the best fit described in Eq. (14).
Evolution of Ps velocity

Strength of the Stark Effect
\( \propto \sim \text{Collision rate with surrounding molecules} \)
\( \propto (\text{Density of molecules}) \times (\text{Ps velocity } v(t))^{3/5} \)

Ps loses its kinetic energy and gets room temperature
= Thermalization

It takes longer time to thermalize in lower density
→ Linear extrapolation could be a large O(10ppm) systematic uncertainty

→ We measured Ps thermalization independently.
Used obtained result for analysis of Ps-HFS measurement.

< Simulation of time evolution of Ps velocity in N\(_2\) gas >
Experimental Technique

Indirect Measurement using Zeeman Effect

In a static magnetic field, the $p$-Ps state mixes with the $m_z=0$ state of $o$-Ps (Zeeman effect).

$\rightarrow$ $2\gamma$-ray annihilation (511 keV monochromatic signal) rate increases. This increase is our experimental signal.

Approximately,

$$\Delta_{mix} \approx \frac{1}{2} \Delta_{HFS} \left( \sqrt{1 + 4x^2} - 1 \right),$$

$$x = \frac{g'\mu_B B}{\hbar \Delta_{HFS}}.$$ 

This is not precise enough, so we solve time evolution of density matrix.

$\mu$...
Waveguide

Large bore superconducting magnet

Cavity and detectors at the center of the magnet.

Almost all of the materials inside the magnet bore is non-magnetic
Our new Experiment

- High power RF (500W CW)
- High performance $\gamma$-ray detectors
- RF cavity (Filled with pure i-C$_4$H$_{10}$)
- $\beta$-tagging system $\rightarrow$ Solve systematic error from non-thermalized Ps.
- Large bore superconducting magnet + compensation coils $\rightarrow$ Solve systematic error from non-uniformity of magnetic field.
- 1.5 ppm uniformity and 1 ppm stability
- $^{22}$Na (1 MBq)
**β-tagging system**

- Tag $e^+$ from the $^{22}\text{Na}$ by thin (0.1 mm) plastic scintillator.
  $\rightarrow t=0$

- DAQ Trigger is made by coincidence of $e^+$ tag signal and $\gamma$-ray detection.

- Time difference of these signals is $\text{Ps}$ life time of each event.

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**Diagram Notes:**
- RF Cavity
- RI Source ($^{22}\text{Na}$ 1 MBq)
- Plastic Scintillator
- PMT
- Pb shield
- $\gamma$

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**Image Notes:**
- Plastic scintillator
- Lid of cavity
- $22\text{Na}$ at the center
- 75 mm
Timing spectra (RF-OFF)

Suppress Prompt and Accidental backgrounds by a Timing window of 50 ns – 440 ns

→ 20 times higher S/N
Unthermalized o-Ps events are also suppressed.

@ 0.881 amagat
Lifetime is clearly shortened by RF due to the Zeeman transition.
Energy spectra

511 keV ± 1σ

High S/N

Accidental spectrum is subtracted using 1000—1430 ns timing window.

\( 2\gamma \) decay rate increases because of the Zeeman transition. Calculate \((RF-ON - RF-OFF) / RF-OFF\) of count rates in the 511 keV ± 1σ energy window.
Resonance line

- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns is divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of $\Delta_{\text{HFS}}$ and pick-off rate ($\propto n v^{3/5}$) is taken into account.

$\Delta_{\text{HFS}} = 203.394 \pm (16) \text{ GHz} \ (8.0 \text{ ppm}) \quad \chi^2/\text{ndf} = 633.3 / 592 \ (p = 0.12)$
Quality check: gas-density dependence of Ps-HFS

Completely separate analysis which determine $\Delta_{\text{HFS}}$ value at each gas density has been performed to provide additional insight into the complete experimental data set and confirm their quality, although this method cannot take into account the time evolution of Ps-HFS.

![Graph showing the relationship between gas density and HFS difference with no strange behaviour.](image)
## Systematic errors (Main ones)

<table>
<thead>
<tr>
<th>Source</th>
<th>ppm in $\Delta_{\text{HFS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>o-Ps pick-off rate</td>
<td>3.5</td>
</tr>
<tr>
<td>Gas density measurement</td>
<td>1.0</td>
</tr>
<tr>
<td>Spatial distribution of density and temperature of gas in the RF cavity</td>
<td>2.5</td>
</tr>
<tr>
<td>Thermalization of Ps</td>
<td>1.9</td>
</tr>
<tr>
<td>Non-uniformity</td>
<td>3.0</td>
</tr>
<tr>
<td>Offset and reproducibility</td>
<td>1.0</td>
</tr>
<tr>
<td>NMR measurement</td>
<td>1.0</td>
</tr>
<tr>
<td>RF power</td>
<td>1.2</td>
</tr>
<tr>
<td>$Q_L$ value of RF cavity</td>
<td>1.2</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.0</td>
</tr>
<tr>
<td>Choice of timing window</td>
<td>1.8</td>
</tr>
<tr>
<td>Quadrature sum</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Combined with 8.0 ppm stat. err., $\Delta_{\text{HFS}} = 203.394 \pm 2(21)$ GHz (10 ppm).
Estimation of non-thermalized o-Ps effect

• In order to evaluate the non-thermalized o-Ps effect on Ps-HFS, fitting without taking into account the time evolution of $\Delta_{\text{HFS}}$ and pick-off rate was performed. (well-thermalized assumption)

• Other procedures were the same (used 50 – 440 ns timing window)

• Result was:

  $203.392 \pm 16 \text{ GHz} \ (\chi^2/\text{ndf}=721.1/592, \ p=2 \times 10^{-4})$

  (cf. with time evolution $203.394 \pm 16 \text{ GHz}, \ (\chi^2/\text{ndf}=633.3/592, \ p=0.12))$

• This value is lower than the fit with time evolution by as large as $10 \pm 2 \text{ ppm}$. This is comparable to the discrepancy of previous experimental results and theory (16 ppm).

• This effect might be larger if no timing window is applied, since Ps-HFS is dramatically changing in the timing window of 0—50 ns because of the rapid change of Ps velocity.

• It strongly suggests that the reason of the discrepancy in $\Delta_{\text{HFS}}$ is the effect of non-thermalized Ps.
Our new result taking into account the Ps thermalization is:

\[ \Delta_{\text{HFS}} = 203.3942 \pm 0.0016 \text{ (stat., 8.0 ppm)} \]
\[ \pm 0.0013 \text{ (sys., 6.4 ppm) GHz} \]

Favors QED calculation
(Consistent with theory within 1.1\(\sigma\), disfavors previous experiments by 2.6\(\sigma\) )
Future prospects
Measurement in vacuum using slow positron beam
(hopefully better than 1 ppm result within 4—5 years)

• High statistics (scan in vacuum instead of extrapolation)
• Completely free from material effect
• Short measurement period reduces systematic errors
Conclusion

There is a large 4.5 $\sigma$ discrepancy of Ps-HFS between the previous experimental values and theoretical calculation. We performed a new precise measurement which obtains time information.

- It reduced possible systematic uncertainties in the previous experiments (Non-thermalized Ps effect and Non-uniformity of magnetic field).
- Ps thermalization function was measured to treat material effect correctly. Time evolution of $\Delta_{\text{HFS}}$ and pick-off rate due to Ps thermalization was taken into account.
- **Non-thermalized Ps effect turned out to be as large as 10 ± 2 ppm.** The result taking into account the Ps thermalization effect correctly was $\Delta_{\text{HFS}} = 203.394 2 \pm 0.001 6$ (stat., 8 ppm) $\pm 0.001 3$ (syst., 6.4 ppm) GHz, which is consistent with QED calculation within $1.1\sigma$, whereas it disfavors the previous measurements by $2.6\sigma$.
- **Our new result shows that the Ps thermalization effect is crucial for the measurement.**
Backup
How to measure the Ps velocity $v(t)$?

- Use *pick-off* of o-Ps

- $\text{pick-off}(t) = \text{pick-off cross section} \times \text{density of material} \times \text{o-Ps amount} (t) \times v(t)^{0.6}$

$v(t)^{0.6}$

**pick-off (2\(\gamma\) decay)**

$\propto$

**o-Ps (3\(\gamma\) decay)**

Surrounding Material

$\leq 511\text{keV } 2\gamma\text{ decay}$

Immediately annihilate
Measurement of Ps Thermalization
Experimental Setup (Overall)

• Timing; START by Plastic Scintillator & STOP by Ge detector
• Stop e\(^+\) in the gas and form Ps
• Source is inside the vacuum chamber.
• Change thermalization condition by changing the gas pressures.

\[ \beta^+ \text{ source (}^{22}\text{Na, 30kBq)} \]
\[ \text{Tag } \beta^+ \text{ with plastic scintillator} \]
\[ \gamma\text{-ray} \]

\[ \text{Ps formation} \]
\[ \text{i-C}_4\text{H}_{10} \text{ gas (gas only or gas+aerogel)} \]

Yuichi Sasaki
Estimate amounts of o-Ps and pick-off

1. Make energy spectrum at each timing window.
2. o-Ps is normalized at continuous region (480—500 keV).
3. 511 ± 3 keV is taken as pick-off.
4. Efficiencies of o-Ps, pickoff, and pileup are estimated by MC simulation.

Isobutane only / Isobutane + aerogel measurement. Change gas pressure, measure 2g/3g at various gas pressures.
Analysis of thermalization measurement

• Use timing window of 40—800 ns in order to avoid prompt peak. Use the following equation for fitting.

Parameter to fit: $\sigma_m$: Momentum-transfer cross section

$$
\frac{d}{dt} E_{av}(t) = -\sqrt{2m_{Ps}}E_{av}(t) \left( E_{av}(t) - \frac{3}{2} k_B T \right) \left( \frac{8}{3} \sqrt{\frac{2}{3\pi}} \frac{2\sigma_m n}{M} + \alpha \left( \frac{E_{av}(t)}{k_B T} \right)^\beta \right)
$$


• Thermalization of Ps before 40 ns, where kinetic energy of Ps is high, has been already measured by Doppler Broadening Spectroscopy (DBS) method to be $\sigma_m = 146 \pm 11 \text{ Å}^2$, $E_0 = 3.1^{+1.0}_{-0.7}$ eV (initial kinetic energy)


• Isobutane has a rovibrational level at 0.17 eV. Value of $\sigma_m$ can be different above (DBS) and below (pick-off) this level. $\rightarrow$ Fit with fixed initial condition of DBS result, but change $\sigma_m$ at 0.17 eV.
Velocity dependence of pickoff rate in isobutane gas

\[ \propto v^{0.6} \ (= E^{0.3}) \]

Simultaneous fit of all gas densities

\[ \sigma_m = 50.7^{+8.8}_{-7.9} \ \text{Å}^2 \]

Consistent results from gas-only measurement and with aerogel measurement.

mean \( \sigma_m = 47.2 \pm 3.9 \ \text{Å}^2 \)

systematic error 5.4 Å

\[ \rightarrow \sigma_m = 47.2 \pm 6.7 \ \text{Å}^2 \]