Recent progress towards positronium Bose-Einstein condensation

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https://tabletop.icepp.s.u-tokyo.ac.jp/Tabletop_experiments/English_Home.html

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Contents

• Motivation for Ps-BEC: Good candidate for the first antimatter laser.
• Our new idea to realize Ps-BEC
• 1S-2P Ps excitation experiment by shining 243 nm UV laser
Our Target: Positronium Bose-Einstein Condensation (Ps-BEC)

- Ps must be dense and cold
- High critical temperature because of Ps light mass (14K at $10^{18} \text{ cm}^{-3}$)
- One of the best candidates for the first antimatter BEC
- BEC is “Atomic laser”. We would like to make the first antimatter laser and perform new experiments using the coherency of Ps-BEC.

Current Records

* : D. Cassidy et al. physica status solidi 4, 3419 (2007)
Applications of Ps-BEC

1. **Antimatter gravity:**
   Build Ps-BEC atomic interferometer to see gravitational effect on antimatter.
   
   - Gravity shifts phase of Ps in different paths
   - Intensity of Ps could blink by changing the path length

2. **511 keV γ-ray laser**
   
   - o-Ps BEC to p-Ps by 203 GHz RF
   - p-Ps BEC collectively decays into coherent 511 keV gamma-rays

   **Diagram:**
   - 1S
   - o-Ps → 511 keV
   - p-Ps → 511 keV
   - 203 GHz RF
   - Vacuum


Phys. stat. sol. 4, 3419 (2007)
Two challenges to realize Ps-BEC

Main problem
Ps lifetime is only 142 ns

Two challenges
1. Instant creation of dense Ps
   $> 10^{17}$ cm$^{-3}$ in $< 50$ ns
2. Rapid cooling of Ps
   $< 10$ K in $\sim 300$ ns

Our new idea:
3 technologies to realize Ps-BEC
Our new idea to realize Ps-BEC

1. Positron focusing system

Nanosecond positron bunch
$10^8$ e$^+$, 5 keV, polarized

Focus into $\phi=6$ µm

1. Many-stage Brightness Enhancement System
Create dense positron bunch
Our new idea to realize Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler

Nanosecond positron bunch
10^8 e^+, 5 keV, polarized

Focus into φ=6 μm

1. Many-stage Brightness Enhancement System
Create dense positron bunch

2. e^+ → Ps converter/condenser/cooler
   Silica (SiO_2)

Cool down to 4K by cryogenic refrigerator

Nano pores Φ= 50-100 nm

Magnified View

n= ~10^{17} cm^{-3}
Our new idea to realize Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling

Nanosecond positron bunch
$10^8 e^+, 5$ keV, polarized

1. Many-stage Brightness Enhancement System
   Create dense positron bunch

Combine thermalization and laser cooling
   to cool Ps down to 10 K in 300 ns

2. $e^+ \rightarrow$ Ps
   converter/condenser/cooler
   Silica ($\text{SiO}_2$)

243nm UV laser

Focus into $\phi=6 \ \mu$m

Cool down to 4K by cryogenic refrigerator

Combination of Thermalization and Laser cooling is efficient enough to realize Ps-BEC

1. Thermalization
   • Efficient at > 200 K
   Initial Ps energy is 0.8 eV = 6000 K.
   Cooling Ps down to 100 K

2. Laser cooling
   • Efficient at < 200 K
   Cooling Ps down to < 10 K is possible

✓ Combining these two methods is essentially important

With laser cooling

Only by thermalization (based on our thermalization measurement)

MC simulated temperature evolution

$T_c$ of $n_0=4 \times 10^{18} \text{ cm}^{-3}$

BEC transition at 10 K!
Key technology of laser cooling of Ps: Exciting Ps to 2P state

→ Shining UV laser to Ps inside the silica pores

Interactions of 2P-state Ps surrounded by materials are not well known.

Previous reports using nanoporous silica
• Frequency shift and narrow resonance:
• Immediate annihilation of 2P-Ps and broad resonance:
  B. S. Cooper et al. PRB 97, 205302 (2018).

➢ These phenomena make laser cooling of Ps difficult.
  We have tested it using our silica aerogel sample (pore size = 50 nm).
Exciting Ps to 2P state by shining 243 nm, 3 ns pulsed UV laser.

(1) Excite Ps to 2P state by shining 243 nm UV laser.

(2) If nothing special happens...
- Ps is de-excited to 1S state with lifetime of 3.2 ns (Lyman-alpha).

(2’) If lifetime of 2P-Ps inside pores is short as reported...
- Annihilation rate to gamma-rays is increased.
Experimental setup at KEK slow positron facility (KEK-SPF) in Tsukuba, Japan

KEK-SPF B1 beamline

Energy | 5 keV
Highest Intensity | $10^5$ e$^+$ / pulse
Repetition | 50 Hz
Time width | 16 ns
Size | $\Phi \sim 10$ mm

Positrons are focused to 4 mm so that it matches the laser size.

Vacuum chamber
We used silica aerogel as silica cavity. Capped the surface of the aerogel by amorphous silica thin film using plasma CVD.

Silica aerogel 0.1 g cm$^{-3}$
50 nm pores
0.5 mm thick

CVD thickness 75 nm

- Consistent with the lifetime expected in 50 nm pores.
- High Ps formation fraction (50% of stopped positrons)

- We obtain $\sigma$-Ps in the pores as expected.

Timing spectrum of bulk-PALS measurement using $^{22}$Na with $t=1$ mm silica aerogel

$$\tau = 129.9 \pm 1.1 \text{ ns}$$
$$I = 13\%$$
UV laser was produced using optical parametric oscillator (OPO) pumped by Nd:YAG laser.

### Laser specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy</td>
<td>300 µJ</td>
</tr>
<tr>
<td>Linewidth (243 nm)</td>
<td>0.06 nm</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Pulse width</td>
<td>3 ns</td>
</tr>
<tr>
<td>Repetition</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

OPO is borrowed from Yoshimura group in Okayama University. We appreciate it.
Slow component of o-Ps annihilations is observed in silica-aerogel timing spectrum without shining UV laser.

PMT signals made by annihilation gamma-rays detected by LaBr$_3$(Ce) scintillator (absolute signal height)
2P-Ps annihilates into gamma-rays immediately in silica aerogel.

Annihilation gamma-ray signal is increased at the timing of shining UV laser.

WITH laser (A)

Without laser (B)

UV laser shining

Long component is decreased because of annihilations of Ps which are excited to 2P state.

PMT signals made by annihilation gamma-rays detected by LaBr$_3$(Ce) scintillator (absolute signal height)
2P-Ps annihilates into gamma-rays immediately in silica aerogel.

Only UV laser of 300 µJ pulse caused Ps annihilations to gamma-rays. Lifetime of 2P-Ps is short in silica aerogel.
Broad resonance (1 nm)
Lifetime or something else?

Scanned the increase of gamma-ray annihilations by changing the wavelength of the UV laser.

- Equivalent lifetime is 30 fs (< mean free time in the silica pores \( \sim O(100 \text{ fs}) \))
- Other reason? ex) Stark effect (Prof. Saito)
Next step: Laser cooling of Ps in vacuum

As a proof-of-concept of our method to cool Ps efficiently enough for realizing Ps-BEC.

For the problem of short lifetime of 2P-Ps in silica aerogel pores, we will investigate some hypotheses.

- There is chemically unstable structure on the surface of the silica aerogel.
- Positrons of Ps are absorbed in silica particles because the binding energy of 2P-Ps is small.
- We will try nano-size cavities other than silica aerogel.
Summary

1. Three technologies to develop for Ps-BEC

2. 2P-Ps annihilates into gamma-rays immediately in silica aerogel pores.

3. Next step: Laser cooling of Ps in vacuum

https://tabletop.icepp.s.u-tokyo.ac.jp/Tabletop_experiments/English_Home.html
Backup
Positronium (Ps) is a good probe for fundamental physics

Bound state of an electron (e\(^-\)) and a positron (e\(^+\))

- Exotic atom with antiparticle
  - Good to explore the mystery of antimatter
- Pure leptonic system
  - Experiments and theoretical calculations can be compared in high precision without uncertainties of hadronic interactions.
Why the 2P-Ps lifetime so short?

Hypotheses

1. Interaction between 2P-Ps and paramagnetic radicals formed by UV laser shining is strong.
   - Checked experimentally.

2. There is chemically unstable structure on the surface of the silica aerogel.

3. Positrons of Ps are absorbed in silica particles because the binding energy of 2P-Ps is small.
Are paramagnetic radicals formed by shining UV laser the reason?

Ps formation fraction

Both formation fraction and lifetime of Ps are decreased by 40%.

$\sigma$-Ps lifetime

Both formation fraction and lifetime of $1S$-Ps are decreased by 40%.

Correlation between Ps lifetime and formation fraction

Paramagnetic radicals are thought to be formed at hydrophobic methyl group on surface of the silica aerogel.
Annihilation rate of 2P-Ps does not depend on the amount of paramagnetic radicals.

Annihilation of 2P-Ps is not caused by paramagnetic radicals formed by UV laser.

Annihilation of 2P-Ps was observed also in the sample annealed in dry air in order to remove surface methyl group.
Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter
3. Ps cooling laser

Positron bunch $10^8 e^+, 5$ keV, polarized

Focus into $\phi=6 \mu m$

243nm UV laser

1. Many-stage Brightness Enhancement System

2. $e^+ \rightarrow$ Ps converter
   Produce, condense and cool Ps
Positron Focusing
1. Positron system

Brightness Enhancement System
Focus positrons and create dense positron bunch
Controll the positrons by magnetic field

Magnified View
keV energy
Remoderator
Ni \sim 100 \text{ nm}
Re-accelerate negative HV mesh

Emitted in eV energy

Narrow and low-emittance positron beam can be created
Many-Stage Brightness Enhancement System

1. Positron focusing system

- Repeat the Brightness Enhancement multiple times and gradually focus the positrons.
- Currently focusing into 30 µm* is possible by this method so we consider improving this technique
- Now studying and designing beam optics

*N. Oshima et al. Materials Science Forum 607, 238(2008)

### Calculation

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ps Density* (cm(^{-3}))</td>
<td>2.5 x 10(^{12})</td>
<td>4.9 x 10(^{13})</td>
<td>6.8 x 10(^{14})</td>
<td>6.8 x 10(^{16})</td>
</tr>
<tr>
<td>Diameter</td>
<td>5 mm</td>
<td>500 µm</td>
<td>60 µm</td>
<td>6 µm</td>
</tr>
<tr>
<td>e(^+) Number</td>
<td>1 x 10(^{8})</td>
<td>2 x 10(^{7})</td>
<td>4 x 10(^{6})</td>
<td>4 x 10(^{6})</td>
</tr>
</tbody>
</table>

Positronium density 6.8\(\times\)10\(^{16}\) cm\(^{-3}\) is achievable

*Positronium Production rate 10% is assumed
Three technologies to develop for Ps-BEC

1. Positron system
2. Ps converter
3. Ps cooling Laser

Positron bunch
$10^8$ $e^+$, 5 keV, polarized

Focus into $\phi=6$ µm

243nm UV laser

1. Many-Stage Brightness Enhancement System

2. $e^+ \rightarrow$ Ps converter
   Produce, condense and cool Ps
Two Challenges for Ps Laser Cooling

1. Rapid cooling
   - Short Ps lifetime: 142 ns
   - Largest energy gap: 1S-2P (243 nm)
   - 6.4 ns × 50 ~ 300 ns
   → Cool down Ps with single long pulse

2. Broadband laser
   - Ps light mass: 2m_e
   - Doppler broadening is 30 times larger than Hydrogen
     → Broadband (150 GHz) laser is necessary to cool down all the Ps

243 nm broadband CW laser with enough power is difficult
→ 243 nm sub-micro-second pulsed broadband laser
Commercially unavailable → Build cooling laser system ourselves
Production of sub-micro-second pulsed broadband laser

**High finesse (~200) cavity**
Phase modulation ~200 times

- Coupler 1%

**Sub-micro-second Broadband Laser**
729 nm, 10 Hz

**THG**
Cooling Laser
243 nm, 10 Hz

**Pump laser**
532 nm, 5 ns, 10 Hz
15 mJ/pulse

**Ti: Sapphire**

**Sub-micro-second long pulse**
→ long photon decay time

1. long cavity (3.8 m)
2. High finesse cavity
   loss/cycle = 1%(coupler)+0.6%

**Broadening of pulsed laser**

1. EOM: sideband generation
2. High finesse (~200) cavity
   EOM modulates the laser ~200 times and creates sidebands up to high order.
   → Broaden the laser spectrum effectively
Long and high finesse cavity
A core of the cooling laser system

1. Long cavity (3.8 m) Folded with 8 mirrors (96 × 36 cm²)
2. High finesse (~200)
Ps cooling laser is almost ready

Time profile of 729 nm pulse

- 400 µJ/pulse avg.
- 729 nm pulse
- 10 Hz, 10s
- Time width 500 ns (FWHM)

Spectral profile of 729 nm pulse

- Broadening 17.6±0.6GHz (FWHM) → n = 85

- First high order sidebands generation with pulsed laser
  - ± n = 85 has achieved (FWHM)

- Most difficult and important part of cooling laser is done. Almost ready for laser cooling.

✓ Long pulse: 500 ns
✓ Enough pulse energy: 400 µJ
Overview of the cooling laser system
Compact system (2.0 m × 1.1 m) will be moved to KEK-SPF (Slow e⁺ Facility)

UTokyo, Asano campus
Yoshioka Lab

Construction of Cooling laser system will be finished soon.
Overview of the cooling laser system

Compact system (2.0 m × 1.1 m) will be moved to KEK-SPF (Slow e⁺ Facility)

UTokyo, Asano campus
Yoshioka Lab
Ps thermalization down to 100 K was observed

We confirmed if Ps can be thermalized in its short lifetime (142 ns).

Thermalization curves of Ps in various silica temperature

- Thermalization into cryogenic temperature was clearly observed
- Next, Laser cooling and cool Ps down to 10 K
Ps thermalization slows down at lower Ps kinetic energy

Consistent with older experiments at high temperatures.

Thermalization can cool Ps down to 100 K, but not enough for Ps-BEC. Next cooling: Laser cooling down to 10 K.

\[ \frac{dE}{dt} = -\frac{2}{LM} \sqrt{2m_{Ps}E\left(E - \frac{3}{2}k_B T\right)} \]

\[ p_0 = 10.6 \text{ u} \]
\[ p_1 = 3.3 \text{ u eV} \]
\[ p_2 = 0.73 \text{ u eV}^2 \]

\[ \chi^2 / \text{ndf} = 152/130 \]

Band: 1σ uncertainty
511 keV gamma-ray Laser

Decay from the BEC state (macroscopically occupied) enhances corrective decay

• Directive
• Coherent

BEC shape should be long in one direction (cigar shape) to have long interacting time between Ps and 511 keV photons

Ps-BEC will be formed in ortho, then stimulated into para by 203 GHz photon

511 keV photon density vs BEC density from Ref 1.5 cm x φ 10 μm Ps-BEC
Difference of the paths will rotate relative phase between splitted beams.

It is said that in Ref: 20 cm legs would be enough to see anti-matter gravity’s effect.

Ps must be excited into Rydberg state to be long-lived (~milliseconds).

Interferometer experiment with Ps-BEC from Ref. D. B. Cassidy et al. phys. stat. sol. (c) 4, No. 10 (2007)
t = 380 ns
7 K (broad) + 30% BEC (narrow)
t = 380 ns
7 K (broad) + 30% BEC (narrow)
t = 450 ns
Our works

Hyperfine splitting \((E_{o-Ps} - E_{p-Ps})\)  
*(planning to improve)*

Previous experimental average

QED Theory (2015)

<table>
<thead>
<tr>
<th>Journal</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phys. Rev. Lett. 34, 246</td>
<td>1975</td>
</tr>
</tbody>
</table>

Our New measurement

Our works

CP violation in lepton sector

Search for asymmetry of annihilation gammas’ directions


\[ C_{CP} = 0.0013 \pm 0.0021 \text{(stat.)} \pm 0.0006 \text{(sys.)} \]

First direct transition \(o-Ps \to p-Ps\)

\(o-Ps\) lifetime