Toward a Realization of Bose-Einstein Condensation of Positronium

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The University of Tokyo

AIST

Advanced Photon Science Alliance

55th Course: International school of subnuclear physics, EMFCSC
2017.06.14-23 in Erice, Italy
Positronium: 
Probes on Fundamental Physics

- The bound state of an electron and positron
- Unstable atom decaying into gamma rays

◆ Sensitive probe on fundamental physics
- With anti-particle
  - Suit for exploring the mystery of anti-matter
- Pure leptonic system
  - Experiments and theory calculations (QED) can be compared in high precision ($10^{-6}$), sensitive for small effects from Beyond Standard Model
My target: Positronium Bose-Einstein condensation

Bose-Einstein condensation (BEC)
- Almost all of atoms in a cloud occupy a single quantum state
- Atoms must be dense and cold

Important feature
- BEC is “Atom laser”: Macroscopic matter-wave
- Amplifier of microscopic effects into macroscopic level
- Example: Matter-wave interference

Spatial image of dense rubidium-87 around $T_c$ (critical temperature) of BEC

Nobel prize 2001

Science 275, 637 (1997)
Why BEC of “Positronium”

Because Ps has anti-matter!

Hot topic in particle physics and cosmology

Anti-matter should not be same as matter to explain why matters left in the universe

Many experiments are searching on matter anti-matter symmetry

From Alan Stonebraker

No BEC with anti-matter so far!

BEC with anti-matter can be good tool to search on anti-matter mystery by using BEC coherency

T2K experiment in neutrino mixing

The antiproton decelerator at CERN

Produce atoms with antiproton such as $\bar{H}$
What we can do with Ps-BEC

1. **Measure anti-matter gravity by atom-interferometer**
   - Deceleration by gravity shift phases of Ps in different paths
   - Test weak-equivalent principle on anti-matter

2. **511 keV gamma-ray laser**
   - $o$-Ps BEC to $p$-Ps by 203 GHz RF
   - $p$-Ps BEC collectively decays into coherent 511 keV gamma-rays
   - New photon source in sub-MeV energy region
   - Macroscopic entanglement

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**Phys. stat. sol. 4, 3419 (2007)**
Challenges to realize Ps-BEC

Conditions to realize Ps-BEC
- High density
- Low temperature
- For Ps, 14 K at $10^{18}$ cm$^{-3}$
- Critical temperature ($T_C$) is very high due to Ps light mass
- Ps annihilation life time is only 142 ns

Necessary techniques
1. Instance creation of dense Ps in around 10 ns
2. Fast cooling of Ps to 10 K in around 100 ns

1. **Create dense positrons and convert into Ps at once**

   - $\approx 10^8$ positrons in nanoseconds bunch
   - keV energy

   - Inject into a silica (SiO$_2$) material with $\approx 100$ nm beam waist by focusing

   - Silica is well-known Ps converter
   - $\approx 50\%$ prob.

   - $10^9$ positron accumulation was achieved elsewhere.

   - We will construct new focusing system to achieve 100 nm beam waist
2. **Cooling by thermalization process**

   **1st step**
   By collisions with cold silica cavity wall
   = Thermalization process

Cold Silica < 10 K
First observation of thermalization process in cryogenic environment

Ps has only \(\sim 100\) ns! Can they be thermalized in such a short time?

- We newly measured thermalization process in cryogenic silica aerogel

GM 4K cryocooler

Silica aerogel holder

Tunable in 20 ~ 300 K

Scintillators to detect Ps creation and decay gamma rays
Plastic for e\(^+\) from \(^{22}\)Na
LaBr\(_3\) for annihilation gammas
Principle to measure Ps temperature

- Measure rate of collisions between Ps and silica particle

**Pick-off 2γ annihilation**
- A positron in Ps and an electron in silica by collisions
- 511 keV mono energy

**3γ self annihilation**
- Both a positron and an electron are in Ps
- 0 ~ 511 keV continuous energy spectrum

Pick-off annihilation rate \( \lambda_2 \propto n \sigma v \)

- \( n \): Density of electrons in silica particle
- \( \sigma \): Cross section of Pick-off annihilation

\[ \lambda_2 \]

By measuring \( \lambda_2 \) vs Ps life, temperature evolution of Ps can be measured

2017/06/06
Result of the measurement

Temperature evolutions of Ps are modeled by elastic collision model
\[
\frac{dE}{dt} = -\frac{2}{LM} \nu \left( E - \frac{3}{2} k_B T \right),
\]
\[
\nu = \sqrt{\frac{2E}{m_{PS}}},
\]
\[
\lambda_2(t) = \frac{C}{L} \times \nu
\]

Important parameter is \( M \):
Effective mass of silica for elastic collision with Ps

Measured \( M = 170 \pm 10 \text{ a.m.u} \)

- Smaller than previous experiments in high T or with gases
- Faster cooling!
Method to realize Ps-BEC

2. **Cooling by laser**

   **2nd step**
   Irradiate 243 nm UV laser to cool Ps down to 10 K

   Silica is transparent in UV

   243 nm UV laser
Method to realize Ps-BEC

2. Cooling by laser

2nd step
Irradiate 243 nm UV laser to cool Ps down to 10 K

Silica is transparent in UV 243 nm UV laser

By detailed MC simulation

<table>
<thead>
<tr>
<th>Time (ns)</th>
<th>Without Laser</th>
<th>With Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^3</td>
<td>10^2</td>
</tr>
<tr>
<td>200</td>
<td>10^2</td>
<td>10^2</td>
</tr>
<tr>
<td>400</td>
<td>10^1</td>
<td>10^1</td>
</tr>
<tr>
<td>600</td>
<td>10^0</td>
<td>10^0</td>
</tr>
</tbody>
</table>

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Ps
Method to realize Ps-BEC

2. Cooling by laser

2nd step
Irradiate 243 nm UV laser to cool Ps
to down to 10 K

Silica is transparent in UV 243 nm UV laser

Below $T_c$
- Ps-BEC possible

With Laser

Ps

By detailed MC simulation

Temperature (K)

Time (ns)

With Laser

Temperature (K)

Time (ns)

Below $T_c$
- Ps-BEC possible

By detailed MC simulation

Temperature (K)

Time (ns)

Ps

24

Silica is transparent in UV 243 nm UV laser

Below $T_c$
- Ps-BEC possible

With Laser

Temperature (K)

Time (ns)
Special home-made laser system

- No laser cooling with anti-matter so far!
- Schematic diagram of the new system optimized for Ps

![Schematic diagram of the new system optimized for Ps](image)

- Ti:Sapphire
- EOM2: Sideband Generator
- EOM1: Wavelength Shifter
- SHG: 729 nm
- THG: 365 nm, 243 nm
- Q-switched Pump Laser
- CW Laser: 729 nm
- 10 mJ
- 10 mW
- 40 µJ

2017/06/09
Laser development is going well

- Schematic diagram of the system

- 729 nm CW
- 729 nm Pulse
- 729 nm (red) light
- 10 mJ
- Nd:YAG pulse
- Optical cavity
- Ti:Sapphire
- ECDL-Box
- To controller
- 729 nm pulse
- 365nm
- Blue
- LBO crystal
- 729 nm pulse
- EOM2 Sideband
- 243 nm
- THG
- 4 mm
- 365 nm
- Laser Diode
- InGaAsP
- gratings
- EOM1 Wavelength Shifter
- SHG
- THG
- EOM2 Sideband Generator

- Ti:Sapphire

- 10 µJ
- 10 mW
- Q-switched
- Pump Laser
Laser development is going well

- Schematic diagram of the system

**Plans**
1. Laser cooling in 1 - 2 years!
2. Positron focusing in 3 - 4 years!!
3. Ps-BEC in 5 years!!!
Summary

- Ps-BEC is a good candidate of the first BEC with anti-matter, which has a rich potentials on both fundamental and application physics.

- New method has been proposed using dense positrons and cooling by the thermalization process and laser cooling. Thermalization process in cryogenic temperature has been measured for the first time, and it is efficient enough to realize BEC with laser cooling.

- Cooling laser for Ps requires very special optics, so new system is currently under development. Prototype long pulse mode is confirmed to be possible.

- Developments on creating dense, focused positrons is also under study in parallel.

- We will do laser cooling first and then go to BEC!
Backup
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 \textit{ortho}, then stimulated into \textit{para} by 203 GHz photon

511 keV photon density vs BEC density from Ref. 1.5 cm $\times$ $\phi$ 10 $\mu$m 長い Ps-BEC

Anti-matter Gravity Measurement

Difference of the paths will rotate relative phase between split 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)
Focusing positrons

- Positron beam can be guided & focused by magnetic fields

From N. Oshima et al. J. Appl. Phys. 103, 094916(2008)

\[ \uparrow \downarrow \text{Positron Probe Microanalyzer system at AIST} \]
- Multi-stage enhancements of intensity:
  1. Focusing by large gradient of mag-field
  2. Transmit moderator to reduce emittance

- This system has achieved 25µm (FWHM)
- Improvements are under studying for:
  1. Magnetic lenses
  2. Moderators
Currently, a few $\mu$m waist is achieved to probe fine structures of a surface

Principle of positron focusing (brightness enhancement):

- Focusing lens by magnetic field
- bunched $e^+$ beam
- Focusing in steep angle to re-moderator
- Thin metal (W, Ni) moderator
  - keV energy
  - $\sim 100 \text{ nm}$
  - re-emitted in eV energy
    - $\approx$ positron negative work function
- Thermalize and diffuse to rear surface
- Narrow beam with low emittance can be acquired!


Plan to use this method for many stages, but **repulsive force** between positrons themselves can be problem because it is dense

- Now studying and designing beam optics
光透明シリカキャビティの開発

次のステップはレーザー冷却
光に透明なPs生成・閉じ込めキャビティが必要
➢ 100 nm 微細加工可能な機能性シリカガラスが候補

必要要求
1. 高いポジトロニウム生成率

100 nmオーダーの穴加工できる

機能性シリカガラスの性質

作ったガラス

透過スペクトル

通常の合成シリカガラス
今回の微細加工可能ガラス

常温では光透過率OK
極低温でも実測する

* 22Na由来の陽電子（数百 keV）を入射したときの崩壊寿命

ガラスの中まで陽電子が入る

ガラス中のo-Ps寿命1.6 ns
強度は~5割

通常のシリカガラスと同程度の高いo-Ps生成率（5割以上）を確認
現在、産総研にて、低速陽電子（数keV）を入射して、ガラス表面から飛び出すPs生成の確認実験を実施中
エリプソメーターによる透過率測定

試料なしの時とありの時とで、
波長ごとに受光面に入れる光量の比を測定
→透過率スペクトル
エリプソメーターによる透過率測定

・測定結果の一例: ほぼレイリー散乱でFit可能

現時点でのアロゲルでの光の吸収は確認されていない

\[
\chi^2 / \text{ndf} = 0.04197 / 506
\]

\[
p0 = 0.03884 \pm 0.0005878
\]

\[
p1 = 1.609e+10 \pm 4.216e+07
\]

エアロゲルの透過率スペクトル: レイリー散乱でほぼ説明がつく
低温での Ps 生成率とレーザー


FIG. 1. Schematic diagram of the sample chamber for positron lifetime and Doppler broadening measurements under UV irradiation.

FIG. 3. Positron-lifetime spectra before and after UV irradiation for (a) silica aerogel heat treated at 200 °C, (b) Degussa Alumina C, (c) silica aerogel heat treated at 800 °C, and (d) Cab-O-Sil.
Components for the measurement

- Positron comes from $^{22}\text{Na}$ RI
- Detected by a thin plastic scintillator
- Acquire $t = 0$ (Ps creation timing)

- Get electron from silica and form Ps in pore
- Ps collides many times with the silica with various temp.
- Annihilate into $\gamma$ rays by Pick-off / self annihilation

- Detect $\gamma$ rays by $\text{LaBr}_3(\text{Ce})$ scintillator
- Count Pick-off annihilation events vs Ps life

22Na radio isotope

The thin plastic scintillator

Silica aerogel: porous material made by silica
Density: $0.11 \text{ g/cm}^3 \rightarrow \text{Mean free path 60 nm}$
Deducing Pick-off annihilation rate

Use difference between energy spectra of Pick-off 2γ/Self 3γ

**Pick-off 2γ**: 511 keV peak

**Self 3γ**: Continuous

Define energy regions to enhance each annihilation event

Self annihilation rate \( \lambda_3 \) is constant

\[ N_{in\ 3\gamma} = \varepsilon_3 \lambda_3 \int dt\ N_{Ps} + 2\gamma \text{ Contamination} \]

\[ N_{in\ 2\gamma} = \int dt\ \varepsilon_2 \lambda_2(t)N_{Ps} + 3\gamma \text{ Contamination} \]

\[ \langle \lambda_2(t) \rangle = \frac{\varepsilon_3 N_{in\ 2\gamma}}{\lambda_3} = \frac{\varepsilon_2 N_{in\ 3\gamma}}{\varepsilon_3 \lambda_3} \]

⇒ After rejecting contamination

Detection efficiencies are by Geant4

Recorded energy spectrum
(Ps life 30 - 300 ns)
Accidental events are subtracted by energy spectrum in 1200 - 1500 ns

2017/06/06
Energy spectrum of annihilation gammas

From Pick-off collisional decay gammas: 511 keV

Decay from self-three gamma-rays annihilation

Normalize region to show number of remained Ps because decay rate $\lambda_3$ is constant as 7.04 $\mu$m$^{-1}$

Energy (keV)

Counts (arb.)

300 K
210 K
130 K
20 K
Silica Effective Mass (a.m.u)

Energy (eV)

This experiment
Nagashima(1995) ACAR
Saito(2013) 2γ/3γ
Chang(1987) DBS
Nagashima(1998) ACAR
Assuming range of M
Center value of M

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Doppler Spectroscopy

243 nm & 532 nm pulsed laser

$E(eV)$

Vacuum

532 nm

2p

243 nm

1s

Expected resonance curve for 10 K Ps with $10^7$ Ps in total, at $t=300$ ns

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/ndf</td>
<td>3.105 / 4</td>
</tr>
<tr>
<td>Constant</td>
<td>$0.118 \pm 0.007273$</td>
</tr>
<tr>
<td>Mean</td>
<td>$0.3335 \pm 1.669$</td>
</tr>
<tr>
<td>Ps Temperature (K)</td>
<td>$11.82 \pm 1.648$</td>
</tr>
</tbody>
</table>
$t = 380 \text{ ns}$
$t = 380 \text{ ns}$
$t = 450 \text{ ns}$

$7 \text{ K (広)} + 30\% \text{ BEC (鋭)}$
Principle of Laser Cooling

Laser cooling: Cool atoms by absorptions of photons’ momentum

Ps Internal states

- $2p$ ($\tau = 3.2\text{ns}$)
- $1s$

$E = 5.1\text{eV}$

$= 243\text{nm UV}$

To let Ps absorb photon, use $1s - 2p$ transition

Incident laser wavelength is detuned slightly longer than resonance
Principle of Laser Cooling

1. Only counter-propagating photons are absorbed by Doppler effect
2. Decelerate by photon’s momentum
3. Spontaneously de-excite in 3.2 ns with random direction photon (no effect on Ps temperature)
Requirements for Cooling Laser

No laser cooling of Ps (anti-matter systems)
For Ps, several special features are necessary

1. **Long time duration pulse**
   - Cooling of Ps takes around 300 ns (~Ps life)
Requirements for Cooling Laser

2. **Wide linewidth**
   - Doppler effect is large due to Ps light mass, so laser linewidth must cover wide Doppler width

![Diagram](chart.png)

At 300 K

- Wide

Resonant

- Also Wide

Cooling laser should cover this wide 80 pm linewidth
Requirements for Cooling Laser

3. **Fast shift of wavelength**
   - Resonant wavelength shifts as Ps atoms get cold
   - Fast shift (40 pm in 300 ns) of pulse laser has never been achieved

![Graph showing laser wavelength and Ps velocity](image)

At 50 K

Largely shift by cooling

At 300 K

Resonant wavelength of laser should be also shifted according to cooling 40 pm in 300 ns
Requirements for Cooling Laser
How special?

<table>
<thead>
<tr>
<th></th>
<th>Ps cooling laser</th>
<th>Common laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time duration</td>
<td>300 ns</td>
<td>CW or Pulse with 10ns or 100 fs</td>
</tr>
<tr>
<td>Linewidth</td>
<td>80 pm</td>
<td>&lt; 2 pm or &gt; 10 nm</td>
</tr>
<tr>
<td>Wavelength shift</td>
<td>40 pm in 300 ns</td>
<td>No example in my knowledge</td>
</tr>
</tbody>
</table>

- Even though laser optics are deeply developed, many features which Ps requires are special because laser cooling of Ps is a new challenge.

- New design has been considered by combining sophisticated the-state-of-the-arts optics technologies.
1. **Wavelength control**: shift and broadening in 729 nm CW by EOMs

EOMs can generate wavelength modulated light by applying RF for CW red light.

---

**Diagram Description**

- **EOM1**: Wavelength Shifter
- **EOM2**: Sideband Generator
- **Laser Diode**: Output
- **Gratings**: 729 nm light
- **ECDL-Box**: 729 nm (red) light
- **CW Laser 729 nm**: 10 mW
- **40 µJ**: 243 nm
- **EOMs** can generate wavelength modulated light by applying RF for CW red light.

---

**Notes**

- **EOMs**:
  - SHG
  - THG

- **Pump Laser**: 10 mW

- **Gratings**: 729 nm

- **Laser Diode**: opnext HL7301MG (InGaAsP)

- **ECDL-Box** to controller
Special home-made laser system

729 nm CW light oscillates in pulse mode using Ti:S gain

532 nm pulse to excite Ti:Sapphire

10 mJ

10 mW

SHG

365 nm

THG

729 nm

40 μJ

243 nm

10 mJ

Laser intensity

Time

EOM2
Sideband Generator

EOM1
Wavelength Shifter

Nd:YAG pulse Pump Laser

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Development: Prototype long pulse

Developed a bit short cavity with high reflectivity mirrors.

Expected pulse time duration: 200 ns
Development:
Prototype long pulse

Developed a bit short cavity with high reflectivity mirrors
Expected pulse time duration: 200 ns

- Nd:YAG pulse
- Absorb 532 nm YAG
- Amplify 729 nm red

2017/06/06
Development: Prototype long pulse

Developed a bit short cavity with high reflectivity mirrors
Expected pulse time duration: 200 ns
Confirmed 200 ns long pulse at 729 nm

- Long pulse consisted with prototype design is achieved!
- Make larger cavity (L~4 m) to store light for longer time to achieve 300 ns time duration

Pulse shape detected by photo diode detector
Special home-made laser system

Wavelength conversion using non-linear optics

✓ Complete!

![Diagram of laser system](image)

- **SHG**: 729 nm
- **THG**: 243 nm
- **Q-switched Pump Laser**: 10 mJ
- **CW Laser**: 729 nm
- **EOM1**: Wavelength Shifter
- **EOM2**: Sideband Generator
- **Ti:Sapphire**
SHG 729 nm $\rightarrow$ 365 nm is also done

Just after LBO crystal on paper

- Plan to complete other parts around one year, then conduct laser cooling experiment with modest Ps density
シリカエアロゲルの空孔径

\[ L = \frac{4}{3} \left( \frac{\rho_0}{\rho} - 1 \right) R \]

\( \rho_0 \): シリカ微粒子の密度 (2.2 g/cm³)
\( R \): シリカ微粒子の径 (2.5 nm)

Figure 3. Temperature dependence of the Ps lifetime for cubical pores in the RTE calculation. The mean free path, \( l \), is related to the cube side length by \( l = \frac{2}{3}a \).

Figure 4. Ps lifetime vs temperature for a variety of mean free paths using both 2D and 3D pores in the calculation.

熱化後のPs寿命

カット: $QLa < 540$ keV

エラーの範囲内でフィッティングスタートタイムによらない

Fitting start time (ns)

oPs lifetime (ns)
$E_{Ps}$が高いときの効果

10 ns 弱、0.15 eVへの到達時間が変わる（割合では30%）
Psはエネルギー分布が広いため、0.15 eV以下の平均エネルギーでも熱化関数の形は異なる
電場（$E_//\,\,$）の効果
エネルギーレベル

電場があるとエネルギー ケーブルが変化してしまう、レーザー冷却ができない

このシフトは
離調-周波数幅（2σ）
=240GHz – 140GHz
=100GHz
以下に抑えたい

エネルギーレベルからの要請
→ 電場 $E_// < 10\,\,$kV/cm

$\Delta M=0$

$\Delta M$は遷移の種類（レーザー偏光に依存）
磁場（B）の効果
エネルギーレベル

動的シュタルクを通して
エネルギーレベルを変化

Ps 500Kの速度と仮定
（>500K, レーザー冷却不要）

このシフトも100GHzに抑える

エネルギーレベルからの要請
→ 磁場 B<12T
電磁場中でのクエンチ

以降もPs 500Kの速度と仮定

400nsの冷却期間で、約300回1s←→2p繰り返す

色は許容遷移の種類: ΔM=0
ΔM=+1
ΔM=-1

<table>
<thead>
<tr>
<th>クエンチ確率</th>
<th>生き残り</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002 (2x10⁻³)</td>
<td>55%</td>
</tr>
<tr>
<td>0.001 (1x10⁻³)</td>
<td>74%</td>
</tr>
<tr>
<td>0.0005 (5x10⁻⁴)</td>
<td>86%</td>
</tr>
</tbody>
</table>

1s ←→ 2p 1サイクルあたりのクエンチ確率 at E//=0kV/cm
電場（$E_{//}$）の効果・クエンチ

$E_{//}=2$ kV/cm

$E_{//}=5$ kV/cm

$E_{//}=7$ kV/cm

$E_{//}=10$ kV/cm
電場（E\text{\parallel}）の効果・クエンチ

- クエンチ確率にピークができる
- ピーク位置は、電場の強さとともにシフトする
必要な電場 \( (E_{//}) \) vs 磁場 \( (B) \)

\[ P_{\text{Quench}} < 1 \times 10^{-3} \]
となる領域

\( E_{//}, B \)とともに小だと エネルギーレベルへの 影響の面で好ましい

\( E_{//}, B \)それぞれのエネルギーレベルへの寄与

\( 1 \text{T} \div 1 \text{kV/cm} \)
ピーキングするのは、準位が交差する所
$E_{//}$によって$B=0$でのエネルギーが変化するので。
クエンチピークでの磁場がずれる