<u>Toward a Realization of</u> Bose-Einstein Condensation of Positronium

<u>Kenji Shu¹</u>,

X. Fan¹, T. Murayoshi¹, A. Ishida¹, T. Namba¹, S. Asai¹, K. Yoshioka²,

M. Kuwata-Gonokami¹, N. Oshima³, B. E. O'Rourke³, R. Suzuki³

¹Dept. of Physics, Graduate School of Science, and International Center for Elementary Particle Physics (ICEPP), <u>The University of Tokyo</u>, ²Photon Science Center (PSC), Graduate School of Engineering,

The University of Tokyo,

³National Institute of Advanced Industrial Science and Technology (AIST)



2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics 2017.06.06 in Krakow, POLAND

Positronium: Probe on Fundamental Physics



Sensitive probe on fundamental physics

- Exotic atom with anti-particle
 - Suit for exploring the mystery of anti-matter
- <u>Pure leptonic system</u>
 - Experiments and theory calculations can be compared in high precision (*ppm* level)

Our works:









Next target : **Positronium Bose-Einstein condensation**

Bose-Einstein condensation (BEC)

- Almost all of atoms in a cloud occupy <u>a single quantum state</u>
- Atoms must be dense and cold



Spatial image of dense rubidium-87 around T_c (critical temperature) of BEC 2017/06/06

Important feature

- BEC is <u>"Atom laser"</u>
- Quiet and coherent: Microscopic quantum effect in macroscopic such as matter-wave interference
- Breakthrough to <u>study</u> microscopic world

Before release trapped by double-well expand to overlap

After release



Why BEC of "Positronium"

Because Ps has <u>anti-matter</u>! First BEC with anti-matter.

Hot topics in particle physics and cosmology

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



From Alan Stonebraker

 Many experiments are searching on matter anti-matter symmetry





T2K experiment in neutrino mixing

BEC with anti-matter can be good tool to search on this hot topic by using coherency The antiproton decelerator at CERN Produce atoms with antiproton such as H

What we can do with Ps-BEC

Measure anti-matter gravity 1. by atom-interferometer



<u>511 keV gamma-ray laser</u> 2.



- Deceleration by gravity shift phase of Ps in different paths
- Path length 20 cm to see gravity effects with weak-equivalent principle Phys. stat. sol. 4, 3419 (2007)

Phys. Rev. A 92, 023820 (2015)

- o-Ps BEC to p-Ps by 203 GHz RF
- *p*-Ps BEC collectively decays into coherent 511 keV gamma-rays
- Probe with x10 shorter wavelength than current x-rays
- Macroscopic entanglement

Challenges to realize Ps-BEC

Conditions to realize Ps-BEC

- High density
- Low temperature
- For Ps, 14 K at 10¹⁸ 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 (around 10 ns) creation of dense Ps
- 2. Fast cooling of Ps to 10 K in around 100 ns



Method to realize Ps-BEC

New method: K. Shu et al. J. Phys. B 49, 104001 (2016)

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



construct new focusing system to achieve 100 nm beam waist

Positron focusing

Currently, a few μ m waist is achieved to probe fine structures of a surface

Principle of positron focusing (brightness enhancement):



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

emittance can be acquired!

Plan to use this method for many stages, but <u>repulsive force</u> between positrons themselves can be problem because it is dense Now studying and designing beam optics \succ

Method to realize Ps-BEC

2. <u>Cooling by thermalization process</u>

<u>1st step</u>

By collisions with cold silica cavity wall

= Thermalization process



First observation of thermalization process in cryogenic environment

We newly measured thermalization process in cryogenic silica aerogel (=porous material made by SiO_2) to confirm how they are cooled





Scintillators and PMTs to detect Ps creation and decay Plastic for e⁺ from ²²Na LaBr₃ for annihilation gammas

Method to measure thermalization process Use Pick-off annihilation

Measure rate of collisions between Ps and silica particle



Result of the measurement



Thermalization curves of Ps in various silica temperature

 Thermalization into cryogenic temperature was clearly observed Temperature evolutions of Ps are modeled by elastic collision model

$$\frac{dE}{dt} = -\frac{2}{LM} v (E - \frac{3}{2}k_BT),$$

$$v = \sqrt{\frac{2E}{m_{Ps}}},$$

$$\lambda_2(t) = \frac{C}{L} \times v$$
Important parameter is M:

Effective mass of silica for elastic collision with Ps

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

 Smaller (thermalize faster) than other experiments in high T or with gases

Method to realize Ps-BEC

2. <u>Cooling by laser</u>



Ż

Method to mealize Ps-BEC

2. Cooling by laser



Ż

Method to mealize Ps-BEC

2. Cooling by laser



Principle of Laser Cooling

Laser cooling: Cool atoms by absorptions of photons' momentum



- 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

 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. <u>Wide linewidth</u>
 - Doppler effect is large due to Ps light mass, so laser linewidth must cover wide Doppler width



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



Requirements for Cooling Laser How special?

	Ps cooling laser	Common laser
Time duration	300 ns	CW or Pulse with 10ns or 100 fs
Linewidth	80 pm	< 2 pm or > 10 nm
Wavelength shift	40 pm in 300 ns	No example in my knowledge

- 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 thestate-of-the-arts optics technologies

Special home-made laser system

Schematic diagram of the system



Special home-made laser system

1. Wavelength control : shift and broadening in 729 nm CW by EOMs





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



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



Pulse shape detected by photo diode detector

- ✓ 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

Special home-made laser system

Wavelength conversion using non-linear optics

✓ Complete!



SHG 729 nm \rightarrow 365 nm is also done



on paper

Plan to complete other parts around one year, then conduct laser cooling experiment with modest Ps density

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. Thermaliztion 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!