#### Dense positronium formation for Bose-Einstein condensation Akira Ishida<sup>1,\*</sup>,

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12.5th International Workshop on Positron and Positronium Chemistry (PPC 12.5) 2021.08.31 Internet

#### 2021/08/31

# Contents

- Motivation for Ps-BEC
- Overview of our Ps-BEC project:

  - Positron focusing system
     Ps generator/condenser/cooler
  - 3. Ps laser cooling

 $\rightarrow$  Details will be presented in the following talks by R. Uozumi and Y. Tajima.

This talk

 $\rightarrow$  A related talk will also be presented on

September 3 (Friday) by K. Shu.



### 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<sup>18</sup> cm<sup>-3</sup>)
- 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.



K. Shu et al., J. Phys. B 49, 104001 (2016), A. Ishida et al., JJAP Conf. Proc. 7, 011001 (2018).



K. Shu *et al.,* J. Phys. B **49**, 104001 (2016), A. Ishida *et al.*, JJAP Conf. Proc. **7**, 011001 (2018). 2021/08/31

#### Self-annihilations of Ps-BEC can generate 2 coherent and entangled gamma-rays: Realization of gamma-ray lasers



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Motivation 2. Revealing hidden rich structures in vacuum and space-time

#### Game change in particle physics



Motivation 3. Pioneering new field of science: macroscopic quantum phenomena of antimatter



Motivation 4. Exploration of unknown energy regions in all quantum optics research

# Game change in the fields of optics, atomic physics, and nuclear physics



### Two challenges to realize Ps-BEC <u>Main problem</u>

Ps lifetime is only 142 ns

#### Two challenges

- Instant creation of dense Ps
   > 10<sup>18</sup> cm<sup>-3</sup> in < 50 ns</li>
- Rapid cooling of Ps
   < 10 K in ~300 ns</li>

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

#### Our idea to realize Ps-BEC

1. Positron focusing system





#### 2021/08/31

#### Our idea to realize Ps-BEC



#### 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</li>
 Cooling Ps down to < 10</li>
 K is possible

 Combining these two methods is essentially important



### Details of each component



Our method to achieve dense enough e<sup>+</sup> bunch for Ps-BEC



We have shown that a high-enough density for Ps-BEC could be reached by the model.

We have considered (1) space charge limited current density (Child-Langmuir law), (2) Brillouin flow, and (3) the beam envelope equation including space charge effect. (N. Oshima, ICPA-18)

#### Positron Brightness Enhancement System (BES)



2021/08/31

#### Positron Brightness Enhancement System (BES)



We have performed a test experiment to focus positron beams at KEK-SPF (Slow Positron Facility), Tsukuba, Japan.

- Highest intensity (5x10<sup>7</sup> slow e<sup>+</sup>/s)
- Variable energy (0.1-35 keV)

Samples and detectors are electrically grounded.



#### Positron focusing test experiment at KEK-SPF





#### Beam profiles

- Energy : 5 keV
- Intensity :  $5 \times 10^5 \ e^+/s$
- Pulse repetition : 50 Hz
- Pulse width : 16 ns

We observed the image of MCP / Phosphor screen recorded by a CCD camera. This focusing lens will be used for Ps laser cooling experiment at the same beamline if it has a good enough performance.

#### MCP images at various currents of the lens coil.



The KEK beam has been focused by the prototype lens.

Detailed analysis and comparation with simulations is ongoing to design and develop a dedicated positron focusing system for Ps-BEC.





Silica (SiO<sub>2</sub>) aerogel was thought to be a good candidate. Capped the surface of the aerogel by amorphous silica thin film using plasma CVD.



Test experiment to Excite Ps inside the silica aerogel pores to 2P state by shining 243 nm, 3 ns pulsed UV laser.



Core process of the Ps laser cooling

- (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).

 $\rightarrow$  Good for laser cooling

- (2') If lifetime of 2P-Ps inside
  - pores is short as reported in
  - B. S. Cooper et al. PRB 97, 205302 (2018)....
- Annihilation rate to gammarays is increased.
  - $\rightarrow$  Bad for laser cooling

Test experiment to Excite Ps inside the silica aerogel pores to 2P state by shining 243 nm, 3 ns pulsed UV laser.



R&D of Ps generator/condenser/cooler other than silica aerogel is also ongoing.

Unfortunately, (2') was the case.

Details will be presented on September 3 by K. Shu.

Ps laser cooling inside the silica aerogel pores is very difficult. Next step: Ps

laser cooling in vacuum

(2') If lifetime of 2P-Ps inside

pores is short as reported in

- B. S. Cooper et al. PRB 97, 205302 (2018)....
- Annihilation rate to gammarays is increased.

 $\rightarrow$  Bad for laser cooling

## Details of each component



# We have developed a prototype laser for cooling Ps. Compact system (2.0 m × 1.1 m)



# Details will be presented in the following talks by R. Uozumi and Y. Tajima.

Reference: K. Yamada et al., Phys. Rev. Applied 16, 014009 (2021).



# We are trying a proof-of-principle experiment to laser-cool Ps in vacuum.

- Create Ps by irradiating a Ps-formation target (silica aerogel with open pores) with positron beam.
- Irradiate Ps emitted from the target with 243 nm UV laser.
- Reflect lasers for multiple times by high reflectance mirrors to obtain the interaction area between the laser and Ps.
- Confine Ps with two silica glass plates.



#### Experimental setup of Ps laser cooling at KEK-SPF







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# Summary

We want to realize an <u>antimatter quantum condensate</u> = positronium Bose-Einstein condensate (Ps-BEC). <u>Gamma-ray lasers</u> may be realized using Ps-BEC as a source.

This talk

- 1. Positron focusing system
- 2. Ps generator/condenser/cooler
- 3. Ps laser cooling  $\rightarrow$  following talks

![](_page_34_Figure_5.jpeg)