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Study on Bose-Einstein condensation of positronium

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Abstract. A new method to realize Bose-Einstein condensation (BEC) of positronium (Ps) is proposed and a Monte-Carlo simulation was performed to evaluate the cooling efficiency of Ps atoms. Ps-BEC was found to be possible by a method including laser cooling of Ps. Laser specifications for Ps cooling are challenging and development is ongoing. A new temperature measurement method for cold Ps and development of an intense, pulsed, slowpositron microbeam are also necessary. They are under study as outlined in this contribution.

1. Introduction

Positronium (Ps), a bound state of an electron and a positron, is the best candidate to form Bose-Einstein condensation (BEC) with anti-matter for the first time because of the following two advantages: (1) the number of atoms which can be created is much larger for Ps by accumulating slow positrons than any other bosons with anti-matter, (2) its mass is so light that the critical temperature of BEC transition is quite high. Many applications with Ps-BEC are expected, such as the realization of a 511 keV gamma-ray laser via coherent decays of Ps-BEC[1, 2] and a precision measurement of gravity on a positron using an atomic interferometer[3].

Two key technologies are essential to realize Ps-BEC: (1) creation of a dense ensemble of Ps atoms, (2) cooling them down to low enough temperature in a few hundreds of nanoseconds because the lifetime of long-lived ortho-positronium is as short as 142 ns. The state-of-the-art techniques achieved 150 K for the temperature [4] and $10^{15} \,\mathrm{cm}^{-3}$ for the density [3]. The target phase-space density to realize Ps-BEC is 10^{18} cm⁻³ at 14 K. In order to create such dense and cold Ps atoms, we will develop a new slow-positron microbeam and a Ps cooling system which combines a cold cavity and laser cooling.

2. Cooling of positronium

A new experimental method to realize Ps-BEC was recently proposed[5]. In this method, 10^7 spin-polarized slow positrons are focused into a 100 cube nm silica cavity, resulting in around 4000 spin-polarized Ps atoms being created and trapped inside the cavity. The Ps atoms will then be cooled down to 10 K via the following two processes:

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Figure 1. (Left) Temperature evolution of Ps. (Right) Ps velocity distributions. Black: without the laser at t = 380 ns. Red and blue: with the laser at t = 380 ns, and t = 450 ns, respectively. Each arrow in the left panel shows the point at which the velocity distribution with the same color is drawn.



Figure 2. (Left) Time profile of the laser. (Right) Frequency profile of the laser.

- (i) Exchange of kinetic energy between the cold (1 K) silica and Ps (a thermalization process). This process is efficient for Ps from its creation (around 6000 K) down to 300 K.
- (ii) Laser cooling (Doppler cooling) using the 1s 2p transitions. This process is efficient from 300 K down to 10 K.

The cooling efficiency of Ps in this scheme was evaluated by a Monte-Carlo simulation, which was explained in detail elsewhere[5]. The simulation included (1) the thermalization process, (2) Ps-Ps two-body scatterings, (3) interactions between Ps and the laser photons. Figure 1 shows calculated temperature evolutions and selected Ps velocity distributions with and without laser cooling. As the temperature evolution graph shows, cooling with the laser is efficient enough to cool Ps down below the critical temperature with a phase transition to the BEC phase at t = 380 ns. Ps-BEC can be observed by a sharp peak in the velocity distribution as shown in the right panel of figure 1. Around 30% of the remaining Ps atoms are estimated to be in the BEC phase at t = 450 ns.

3. Development of the cooling laser

The wavelength of the cooling laser for Ps is 243 nm (1.23 PHz) ultraviolet light for the 1s - 2p transition. The laser needs some challenging specifications. The first requirement is a special time profile, which is shown in the left panel of figure 2. The laser must operate in pulsed mode in order to achieve enough power to saturate the transitions. The pulse must be long enough to continuously cool Ps down for more than 300 ns. The second requirement is a special frequency profile as shown in the right panel of figure 2. The Doppler effect for a Ps atom is quite large (e.g. 240 GHz at 300 K) due to its light mass. In order to cool Ps with various



Figure 3. A schematic diagram of the laser system for Ps cooling, and an external cavity diode laser for seeding. Details are in [5].



Figure 4. Frequency drift of the ECDL. The frequency should be stabilized within around 1 GHz for the later frequency shift and the sideband generation.

velocities, the frequency distribution must be as wide as 140 GHz. The third requirement is the frequency shift which is also demonstrated in the right panel of figure 2. The center frequency should be shifted in accordance with the temperature of Ps because more Ps need photons whose frequencies are close to the 1s-2p resonance for Ps at rest. The shift should be 60 GHz in 300 ns. This frequency shift during the pulse is a new challenge for optics.

In order to realize the desired laser specifications, a new laser system was designed[5]. Figure 3 show a schematic diagram of the system. A Ti:sapphire seed injection laser generates 729 nm pulsed light of 300 ns. The frequency is tripled via harmonic generations (SHG and THG). Fine tuning of the frequency is performed for a continuous-wave (CW) laser, which is seeded into the Ti:sapphire afterwards. These controls will be done by electro-optic modulators (EOMs).

Development of the Ps cooling laser is ongoing. The CW laser for seeding is now ready as shown in figure 3. An external cavity diode laser (ECDL) was constructed for this seeding light. Performance of the ECDL was examined to confirm that it was powerful and stable (see figure 4) enough for the later stages. The injection seeding into Ti:sapphire is the next step.

4. Temperature measurement method for cold Ps

A method to measure the temperature of Ps as cold as 10 K is necessary for Ps-BEC experiment. We are planning to perform Doppler spectroscopy using the 1s - 3s transition (410 nm visible wavelength) because the laser system can be easily constructed. Figure 5 shows required laser specifications for 10 K Ps and an expected resonance curve with 10^7 Ps atoms by a Monte-Carlo simulation. A sufficiently high precision can be obtained during a several-day run with a modern intense slow-positron beamline. Development of this laser is currently under study. Spectroscopy for Ps in cold silica is planned to confirm the ability of the method and also to



Figure 5. (Left) Required laser specifications for the 1s - 3s Doppler spectroscopy. (Right) An expected resonance curve for 10^7 Ps in total at t = 300 ns, 10 K. A gamma ray detector is assumed to be LaBr₃(Ce) scintillator (20 ns fall time and 5% FWHM energy resolution at 511 keV) with 5% detection efficiency for 2 gamma 511 keV decay.



Figure 6. A proposed 3-stage brightness enhancement system to achieve 10^7 slow positrons with a 100 nm beam waist. The desired beam compression is 1/20 at each stage.

perform a precise measurement of thermalization process between Ps and silica.

5. Overview of the slow-positron microbeam

Development of a slow-positron microbeam with a 100 nm beam waist is essential to obtain a high enough density of Ps to realize Ps-BEC. A brightness enhancement technique[6] will be implemented and improved for this purpose. Considering a reduction of beam diameter is by a factor of around 20 at each stage of brightness enhancement, with 2×10^9 bunched slow positrons, and transmission type remoderators with 20% efficiency each, 10^7 positrons in 100 nm is possible using a 3-stage brightness enhancement system as shown in figure 6. Design of the buncher and the beam optics are currently under study.

6. Roadmap for Ps-BEC

The first step is the temperature measurement by Doppler spectroscopy in two years. After establishing the temperature measurement method, laser cooling of Ps will be performed in four years. The slow positron system will be developed at the same time and combined for Ps-BEC.

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