Development of a chirped pulse laser for cooling positronium

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The benefits from a cooled gas of Ps below 10 K

Precision spectroscopy of Ps (Measurement of 1S-2S transition frequency)



[2] M. S. Fee et al., Physics Review Letters, 52, 1069 (1964) [2] M. S. Fee et al., Physics Review Letters, 70, 1397 (1993)

Realization of the first BEC of antimatter



[3] S. Mariazzi et al. Physics Review Letters, 104, 243401 (2010)

[4] D. Cassidy et al. physica status solidi, 4, 3419 (2007)

<Our Goal>

Realization of

the first Bose-Einstein Condensation of antimatter using positronium(Ps)

<Main Challenges>

1. Instant production of dense Ps

2. Rapid cooling of Ps

Cooling Ps atoms to around 10 K in a few hundred nano-seconds (Critical temperature is 14 K at 10^{18} /cm^3)



Challenges of laser cooling for rapid cooling of Ps below 100 K



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Recoil velocity : $\frac{\hbar\omega}{mc}$ (ex. Rb : 5.9×10^{-3} m/s, Ps : 1.5×10^{3} m/s)

The requirements for laser cooling of Ps

Finish cooling before annihilation



Cooling Ps from 300 K to 10 K requires about 50 excitation cycles.



Long pulse duration about 300 ns (at 243 nm)



The Doppler broadening of Ps is large because of its small mass

- Broadband laser (FWHM: 150 GHz)
- Frequency-chirped laser (200 GHz/µs)

Previous research on cooling laser of Ps

Cooling laser proposed in the previous research^[3]



[3] T. Kumita, et al. Nuclear Instruments and Methods in Physics Research Section B, 192, 171 (2002).

Requirements for laser cooling of Ps

- The wavelength of the cooling laser is adjustable for exciting 1S-2P transition
- Bandwidth is about 150 GHz
- · Frequency chirp is necessary for effective cooling
- Pulse duration is about 300 ns

The characteristics of the laser system

- The wavelength of the output laser pulse is around 243 nm but not sufficiently reproducible
- The bandwidth of this laser is about 86 GHz
- Frequency chirp is not achieved
- Pulse duration is 280 ns









Schematic diagram of cooling laser



Chirped Pulse Train Generator



Schematic diagram of cooling laser Multipass Ti:Sapphire Amplifier K. Yamada, Y. Tajima, et. al., Physical Review Applied 16, 014009 (2021) Third Harmonic Generation Pellin Broca Prism LBO **BBO** Polarization Rotator Ps cooling LBO crystal laser Third harmonic generation 729 nm LBO BBO 243 365 nm 243 nm 729 nm 365 nm nm (15 mJ) (5 mJ) (1 mJ) EOM 243 Time [µs] [nm] The pulsed laser has the following features: Piezoelectric A 532 nm A long pulse duration pulse A broadband spectrum and a rapid frequency chirp Ti:S at around 243 nm

Chirped Pulse Train Generator

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Demonstration of properties of cooling laser

Power waveform at 243 nm 0.8 0.7 0.6 Power (a.u.) 0.5 0.4 0.3 PD v 0.2 0.1 0.0 -0.100 800 900 1000 1100 1200 1300 Time [ns]

Time-integrated spectrum



Observing frequency chirp

Changing the timing of the pump laser for the multipass amplifier



- Center frequency : 1S-2P transition frequency 120 GHz
- Pulse width : > 300 ns
- Bandwidth : 200 GHz

- Pulse energy : 1 mJ
- Chirp rate : ± 42 GHz/μs

Overview of the cooling laser $(2.0 \text{ m} \times 1.1 \text{ m})$



Laser transport



Laser cooling experiment at KEK



High Energy Accelerator Research Organization (KEK)





Laser system for prototypical laser cooling



Summary

- Ps-BEC is the best candidate for the first antimatter BEC
- Laser cooling of Ps using the 1S-2P transition is a promising method for rapid cooling of Ps well below 100 K

Requirements for laser cooling of Ps

- 1. A broadband spectrum and a frequency chirp to overcome the large Doppler broadening
- 2. A long pulse duration comparable to the lifetime of Ps

Result

- We developed the unique laser for cooling Ps
 - 1. A train of short pulses inside the 300-ns-long contour (approximately 2 times as long as the annihilation lifetime of Ps)
 - 2. Spectral broadening by EO modulation spanning over 200 GHz in total and two characteristic peaks in the spectrum
 - 3. A rapid frequency chirp (\pm 42 GHz/ μ s) in the positive and negative directions

Next steps

- Demonstration of laser cooling of Ps atoms, using the current prototypical laser
- Update the specification of the cooling laser for more efficient cooling of Ps

