Development of a Deep-ultraviolet Chirped Pulse Laser for Doppler Cooling of Positronium

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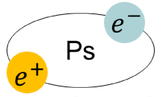
Introduction

Positronium (Ps)

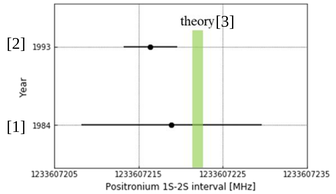
- Exotic atom
  - an electron and its anti-particle, a positron
- Hydrogen-like and pure-leptonic system



Ps mass $= 2m_e$

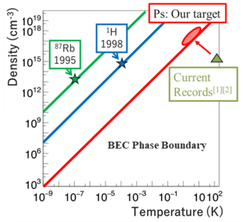
Benefits from cold Ps atoms

(1) Precision spectroscopy



Cold Ps would reduce
- second-order Doppler shift
- transit time broadening

(2) Bose-Einstein Condensation



Critical temperature : ~ 10 K at 10^{18} cm^{-3}

How to cool Ps

Main problem : Ortho-Ps annihilates into γ-rays with a lifetime of 142 ns.
Rapid cooling method is necessary.

➢ Conventional cooling method (thermalization with solids) was able to cool down Ps gas to 150 K[4], which is limited by the decrease of the cooling efficiency in the low temperature region.

➢ Doppler cooling is a potentially powerful method that could ideally cool Ps gas at room temperature to the recoil limit of 0.6 K within one microsecond.

- RMS velocity at 300 K: 8.3×10^4 m/s
- Recoil velocity: 1.5×10^3 m/s
- Natural linewidth of the 1S-2P transition: 50 MHz
- Spontaneous emission lifetime of the 1S-2P transition: 3.2 ns

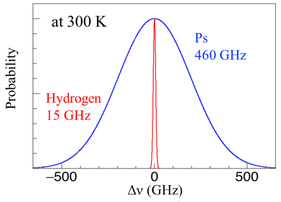
Requirements for Ps laser cooling

① Deep-ultraviolet light
Ps Lyman-α wavelength is 243 nm

② Long pulse duration and sufficient pulse intensity
Cooling Ps atoms down to the recoil limit

③ Broadband and Frequency-chirped laser
Covering large Doppler broadening and staying in resonance with Ps atoms

Doppler-broadened spectrum

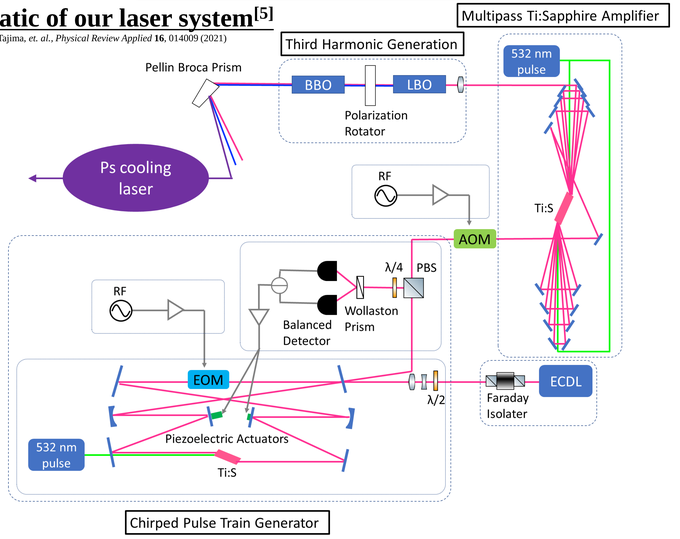


[1] S. Chu *et al.*, *Physics Review Letters*, **52**, 1689 (1984).
[2] M. S. Fee *et al.*, *Physics Review Letters*, **70**, 1397 (1993).
[3] S. G. Karshenboim, *International Journal of Modern Physics A*, **19**, 3879 (2004).
[4] S. Mariazzi *et al. Physics Review Letters*, **104**, 243401 (2010).

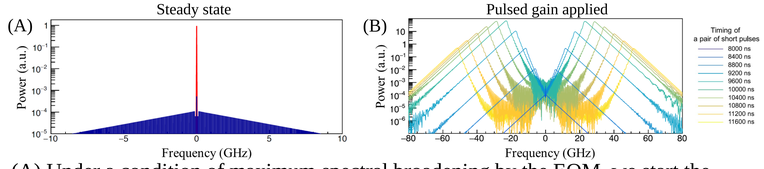
Experimental Setup

Schematic of our laser system[5]

[5] K. Yamada, Y. Tajima, *et. al.*, *Physical Review Applied* **16**, 014009 (2021)



- A pulsed Ti:S laser was injection seeded by a cw, single-mode laser at 729 nm.

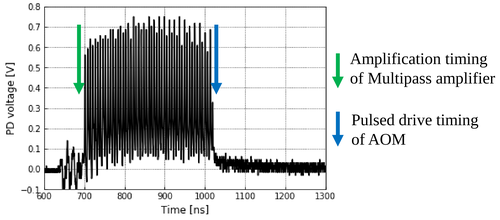


- (A) Under a condition of maximum spectral broadening by the EOM, we start the excitation of the Ti:S crystal in the cavity.
- (B) A rapid frequency chirp appears in the positive and negative directions through a combination of the pulsed gain and the phase modulation. Specifically, the FSR of the laser cavity (78.7 MHz) gives the number of times a pulse passes through the EOM per second, and its peak optical frequency shifts in each phase modulation event.
- The injection-locked pulsed laser with an electro-optic modulator emits submicrosecond-long pulses that consist of a train of short pulses, and has a rapid frequency chirp in positive and negative directions.
  We refer to this unique laser as a **chirped pulse train generator (CPTG).**

Results & Discussion

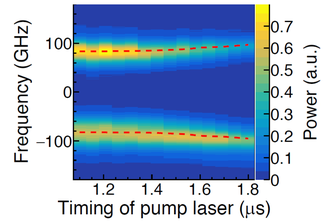
Characteristics of cooling laser

- In the time domain



- The waveform of the output pulse becomes a pulse train due to the discrete frequency modes generated by the EOM.
- We achieved the long pulse duration suited for cooling Ps.
- Average pulse energy was about 500 μJ ,which is sufficient to saturate the 1S-2P transition.

- In the frequency domain

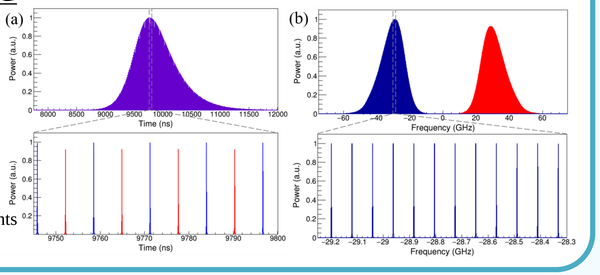


- Time-resolved measurement of the spectrum was performed by changing the multipath amplification timing.
- Fast chirp rate of ±42 GHz/μs in both the positive and negative directions.

Numerical simulation of CPTG

Characteristics of CPTG is numerically calculated[4].
(a) Power waveform of the output pulse of the CPTG
(b) Spectrum of the optical pulse shown in (a)

Red and blue colors of the pulse pairs in (a) indicate higher and lower frequency components shown in (b).



Conclusion & Prospect

Conclusion

- We have successfully developed the prototypical cooling laser for Ps by a combination of the pulsed gain and the phase modulation at the CPTG.

Prospect

- A demonstration of the laser cooling of Ps is ongoing.
- Applying to chirped cooling of atomic and molecular gases.
- Precision spectroscopy of Ps for testing bound-state quantum electrodynamics.
- Achieving the first BEC in a system containing antimatter.

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To know more: K. Yamada, Y. Tajima, *et. al.*, *Physical Review Applied* **16**, 014009 (2021)