One-dimensional chirp cooling of positronium

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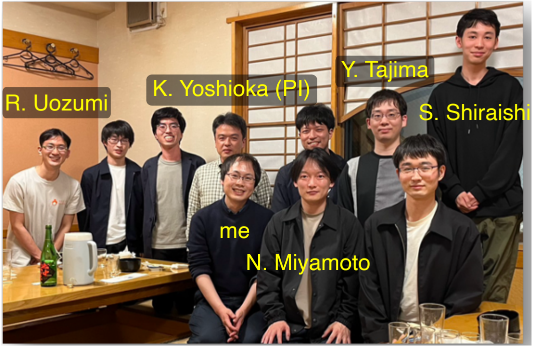
PSAS'2024–International Conference on Precision Physics of Simple Atomic Systems

Groups

Yoshioka group, UTokyo
–AMO and laser



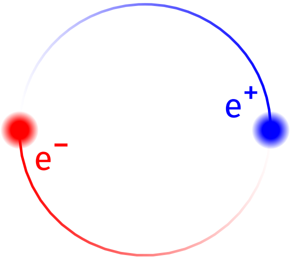
Yoshioka group's photo

Asai group and ICEPP, UTokyo
–particle physics and positronium science

SPF, IMSS, KEK
–positron diffraction and accelerator-based slow positron beam

AIST
–positron microbeam, e^+/Ps chemistry, and multiple slow positron beams

Simplest atom in QED: positronium

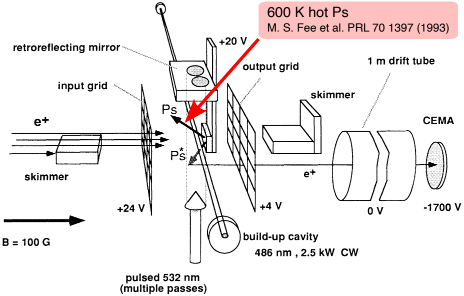


Constitution of positronium (Ps)

- Only light leptons
- Weak and QCD effects are small

Precise prediction by m_e (w/ CPT), α, and QED
Textbook system for testing QED and beyond the Standard Model

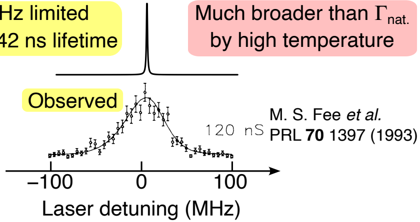
Why cold Ps?



Setup of 1^3S_1–2^3S_1 spectroscopy

Transit-time broadening ⟷ 40 MHz $(T/600\ \mathrm{K})^{0.5}$

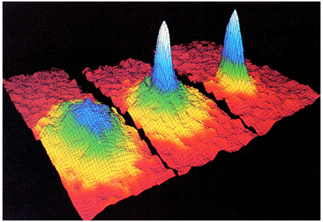
2nd-order Dopper ⟷ 30 MHz $(T/600\ \mathrm{K})$



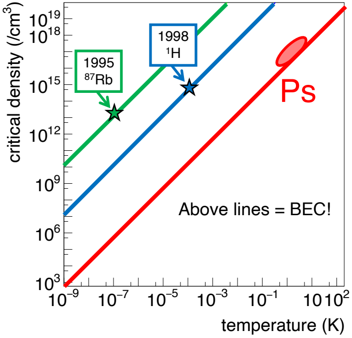
Observed resonance vs some widths

Precision and accuracy in spectroscopy

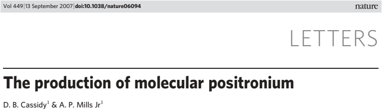
Why cold Ps?



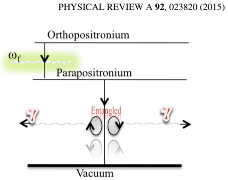
Bose–Einstein condensation Nobel Prize in 2001



BEC phase diagram



Dense Ps created

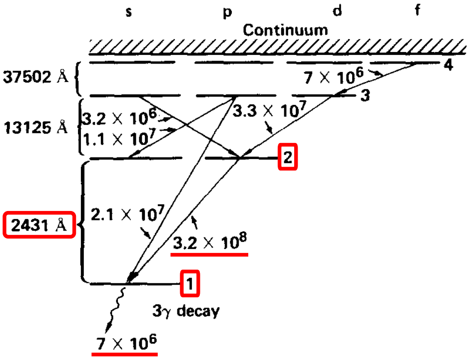


Gamma-ray laser

First BEC with antimatters and gamma-ray laser

Proposal of Ps laser cooling

E. P. Liang and C. D. Dermer, Opt. Commun. **65**, 419 (1988)



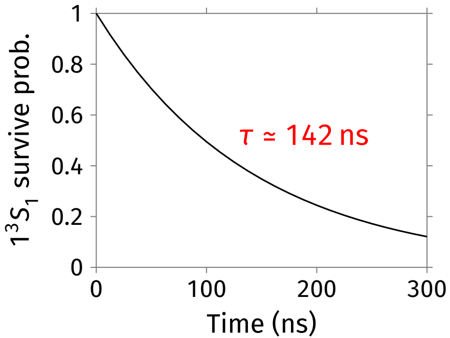
ortho–Ps level diagram

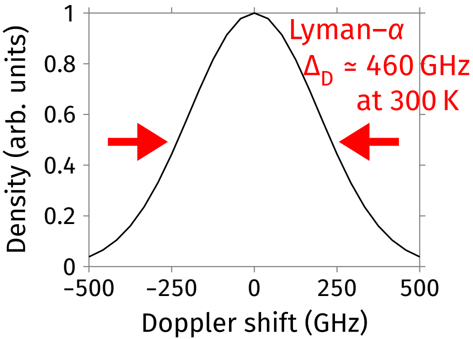
Cooling efficiency estimation

oPs Transitions	λ(Å)	$A(s^{-1})$	T_{min}(mK)	Δt_1(s)
1s–2p	2431	3.17×10^{8}	21.2	1.73×10^{-7}

Laser cooling on Ps should work

Difficulty in Ps laser cooling

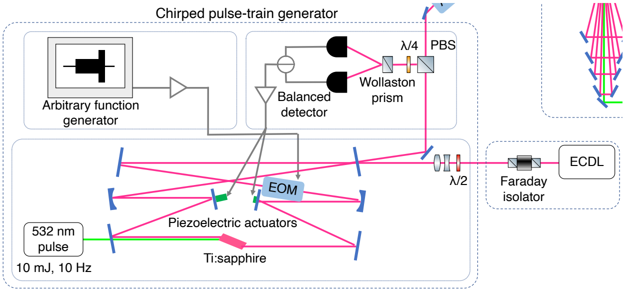


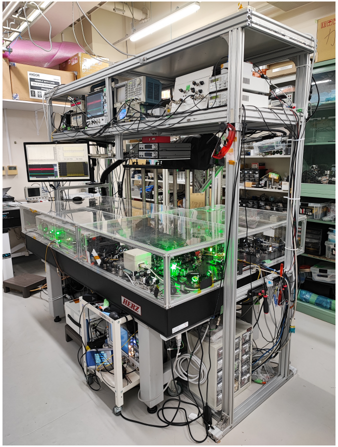


≃ 100 ns cooling → long duration laser

$\times 10^{-3}$ smaller mass than H atom
→ broadband laser

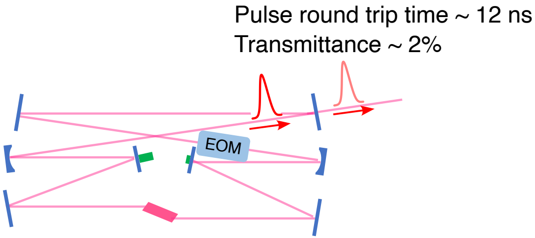
Novel laser for Ps cooling





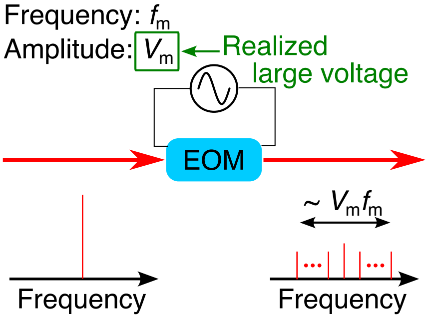
- K. Yamada *et al.*, Phys. Rev. Appl. **16**, 014009 (2021).
- K. Shu *et al.*, Phys. Rev. A **109**, 043520 (2024).

How the laser works



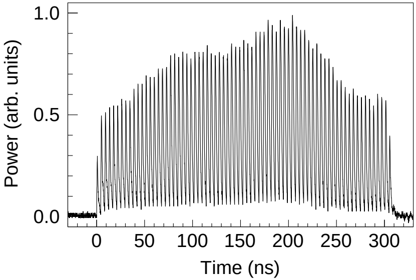
- Long round-trip time
- Small transmittance of the coupler

→ Long duration



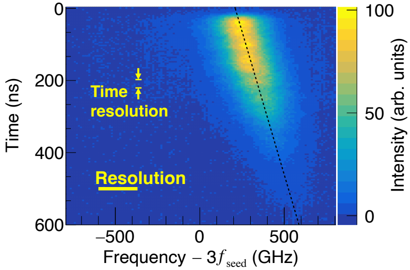
Frequency shifted by each round trip
→ Broadband

Measured emission from the cooling laser



Measured time evolution of power

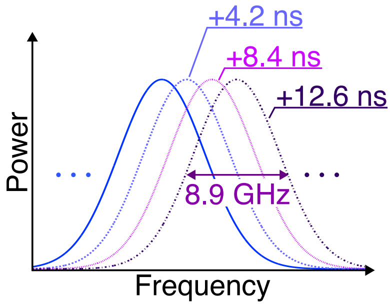
Pulse train continues for 300 ns



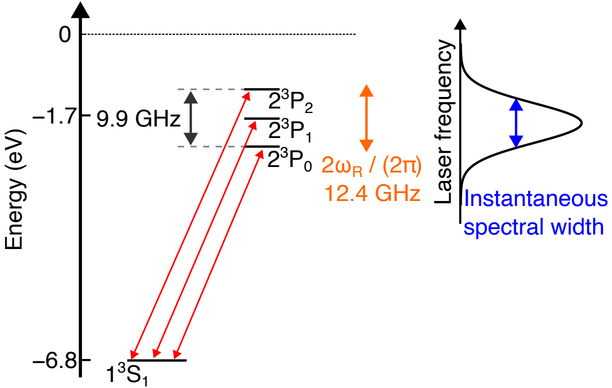
Measured time-resolved spectrum

Sweeps 150 GHz with 0.5 GHz/ns
Optimul rate aligned with Ps deceleration rate: **Chirp cooling**

Optimul spectral width of each pulse



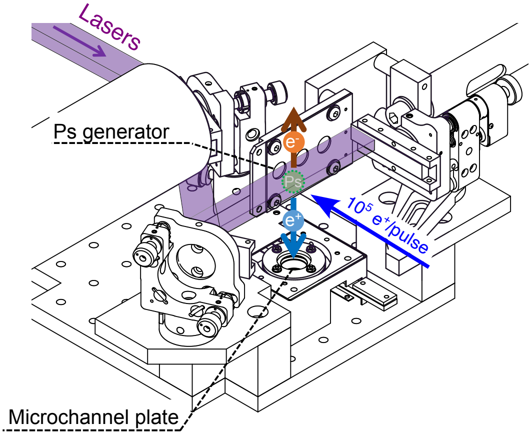
Conceptual output



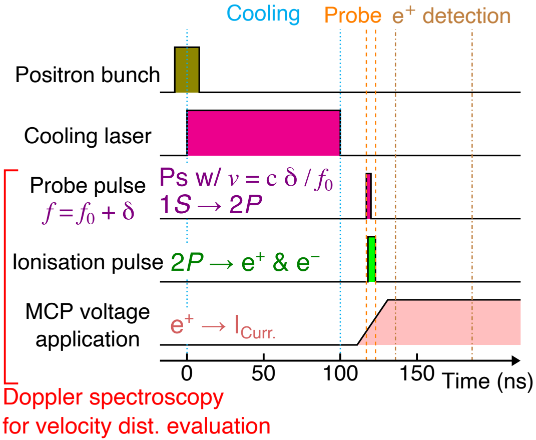
Fine splitting, recoil shift, and spectral width

Cooling and repump from dark for efficient cooling

1D chirp cooling experiment



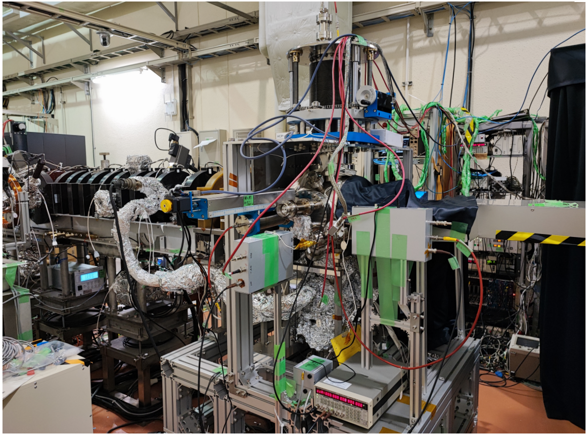
Experimental setup



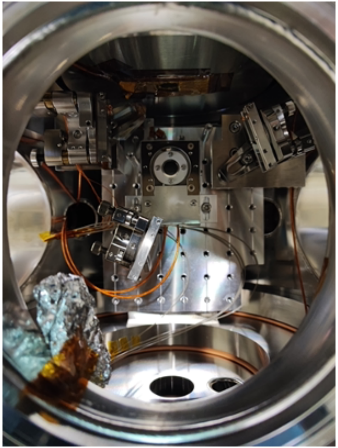
Timing chart

arXiv:2310.08761 under review

Setup photo

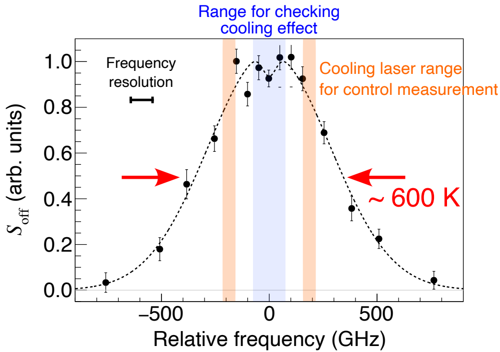


Beamline and chamber

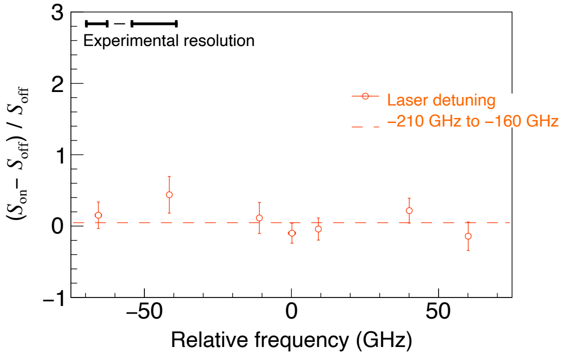


Top view in the chamber

Initial distribution and control measurement

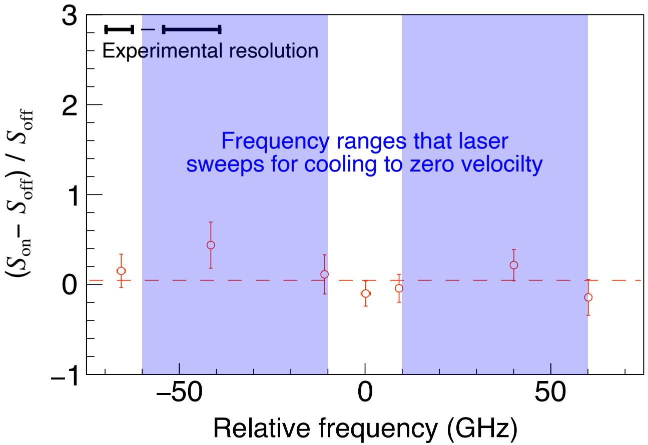


Doppler profile without cooling laser

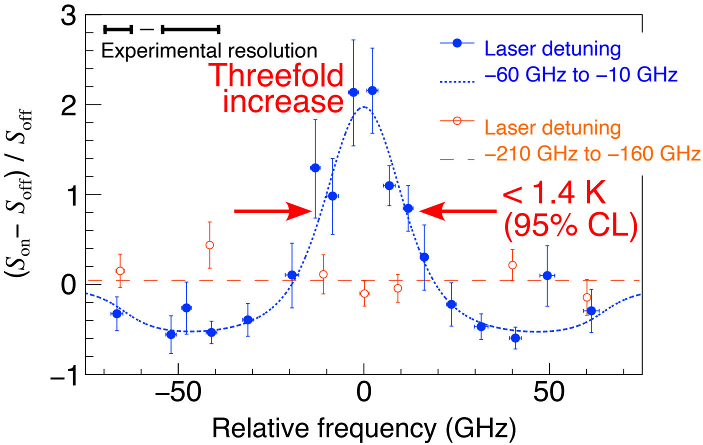


Normalized difference of
Doppler spectrum with cooling laser

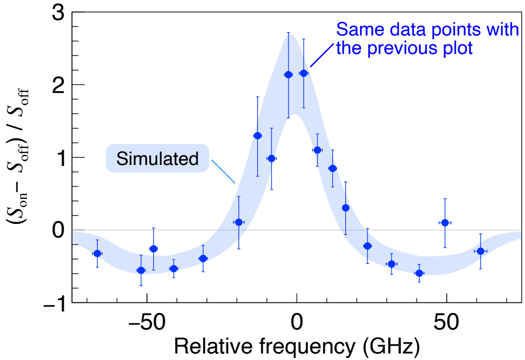
Observed effect of laser cooling



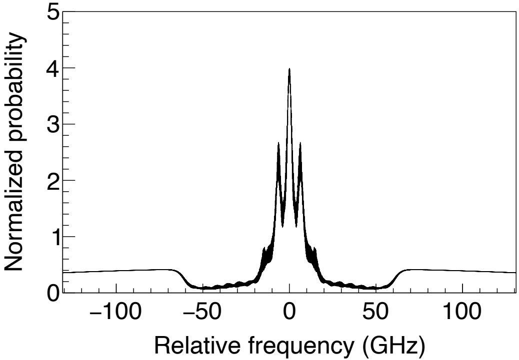
Observed clear evidence of chirp cooling



Comparison with optical Bloch equation simulation



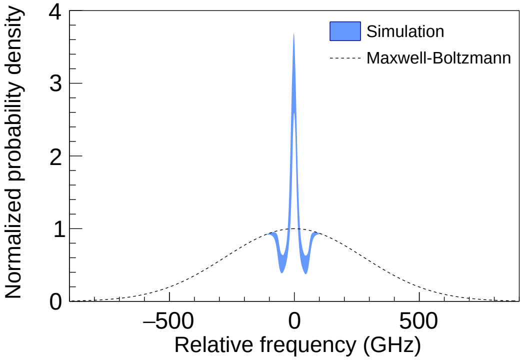
Comparison to a simulated spectrum with experimental conditions considered



Raw simulated Doppler profile

Narrow peaks may originate from coherent population trapping

Improvements?



Reproduced profile for the observed spectrum, obtained from simulations

Evaluation of the cooling performance

- Temperature of the cooled: ≃1 K
- Cooled ratio: ≃10% of the total

1^3S_1–2^3S_1 spectroscopy with 1 K Ps

- Transit-time broadening: 1.6 MHz
- 2nd-order Doppler shift: 0.05 MHz

Narrow as $\Gamma_{nat.} \simeq$ 1.3 MHz is expected

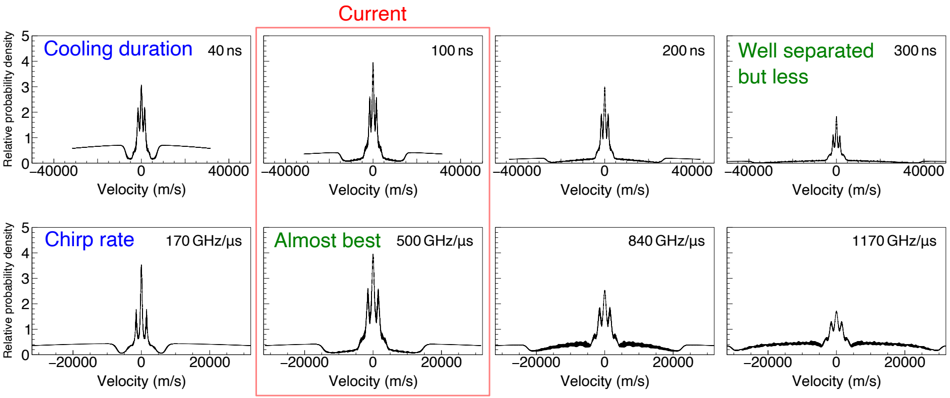
Straightforward ratio improvement (×2)

Current: 40 nm pore at 300 K → 600 K Ps

Better: Cold 5 nm pore → 150 K Ps

S. Mariazzi *et al.*, PRL **104**, 243401 (2010)

Optimization of cooling condition

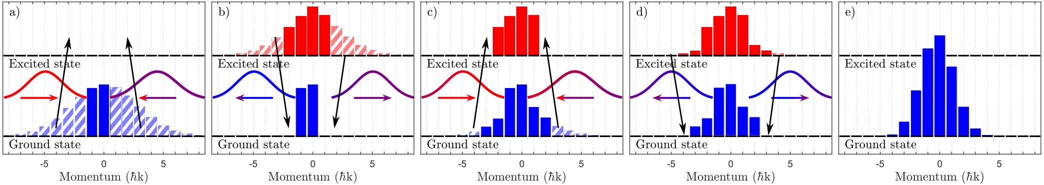


Simulated velocity distribution with different laser parameters

Longer cooling time would be better. Study for suppressing side peaks.

Faster cooling

- Cooling rate is limited by the spontaneous emission rate.
- Use decelerating stimulated emission for de-excitation.
- *c.f.* J. P. Bartolotta *et al.*, Laser Cooling by Sawtooth-Wave Adiabatic Passage, PRA **98**, 023404 (2018).



Cooling process. J. Malamant *et al.*, arXiv:2402.17052.

Velocity distribution can be $\frac{1}{2(=N_{\text{levels}})}$ in 3.2 ns!

25000 m/s at RT vs 1500 m/s deceleration in ≃ 3 ns

Summary and prospect

Summary

- First demonstration of 1D chirp cooling of positronium
- Narrow velocity distribuion corresponding 1 K was obtained

Prospects

- Optimized configuration & 3D cooling
- Precision spectroscopy

Another and simultaneous demonstration with different scheme

c.f. L. T. Glöggler *et al.* (AEḡIS Collaboration), Phys. Rev. Lett. **132**, 083402 (2024)