## Experimental progress towards measuring antimatter gravity using positronium

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## Does antigravity exist?



Image credit: Rolf Landua / CERN

In theory: controversial.

In direct experiments:  $-65 < \frac{M_g}{M} < 110$  by antihydrogen experiment.

The ALPHA Collaboration and A. E. Charman, Nat Commun 4, 1785 (2013).

#### Experimentally, it is still unknown.

### Positronium Simple and easy to produce

#### Positronium (Ps)

- An exotic hydrogen-like atom consisting of an electron and a <u>positron</u>
- Unstable: 142 ns lifetime (S=1)

#### ✓ <u>Neutral</u>

Essential for gravity measurement



#### ✓ <u>Simple</u>

Purely leptonic to be free from theoretically difficult QCD

<sup>22</sup>Ne





Na-22 positron M. Charlton et al., source NIM A **985**, 164657 (2021).

## Free fall, interferometry, spectroscopy to measure gravity effect

Free fall, interferometry

T. J. Phillips, Hyperfine Interactions 109, 257 (1997).

D. B. Cassidy and S. D. Hogan, Int. J. Mod. Phys. Conf. Ser. 30, 1460259 (2014).



#### Spectroscopy



Fig. 1. Derivation of the gravitational red shift.

S. G. Karshenboim, Astron. Lett. 35, 663 (2009).

Different distance from the Sun:  $\frac{\Delta U(r_{\text{max}}) - \Delta U(r_{\text{min}})}{c^2} \simeq 3.2 \times 10^{-10}$ 

### Cold positronium is necessary

 $m_{Ps} \sim 2m_e$ : The lightest atom => large velocity



The high temperature is the largest source of the uncertainty and bias For interferometer, coherence will be increased

# A new method is required for cooling



Cooling via the thermalization is too slow...

## Principle of Laser Cooling

Laser cooling: Particle is cooled by absorbing photons' momentum



- We use 1S 2P transition for Ps to absorb photon
- Laser wavelength is detuned slightly longer than resonance

## Principle of Laser Cooling



- 1. Only counter-propagating photons are absorbed by Doppler effect
- 2. Decelerate by photon's momentum
- Spontaneously de-excite in 3.2 ns with isotropic direction photon Recoil cooling limit ~ 0.3 K

## Laser cooling of positronium requires broadband and chirped laser



We have developed a laser with long duration and broadband with chirp 2022/07/05

#### Development of laser system K. Yamada et al., λ/4 PBS Counter Phys. Rev. Applied 16, Timing 0.0 µs RF 014009 (2021). llaston m **ECDL** λ/2 Faradav Isolater Time (µs) 100 Frequency (GHz) **Chirped Pulse Train Generator**

Broadband, chirp and long duration optimized for Ps ~ 600 ns are confirmed

# ~ 50% of Ps at 300 K could be cooled to 1 K in 300 ns



Naïve expectation by the current laser's performance

# Experiment to demonstrate laser cooling



Of emitted Ps without cooling

**Experiment at KEK-SPF** 

We have established a method to evaluate Ps velocity distribution

## Summary

- Ps is a unique system suitable for testing antimatter gravity
- Cooling of Ps is a breakthrough
- We cool Ps by laser cooling



Built an optimized laser with broadband, chirp and long duration



Perform demonstration experiment at KEK-SPF

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