Two-photon positronium spectroscopy

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Antimatter Experiment: gravity, Interferometry, Spectroscopy
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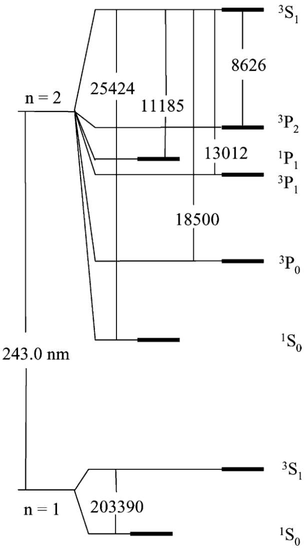
Goal

We want to measure two transitions in Ps:

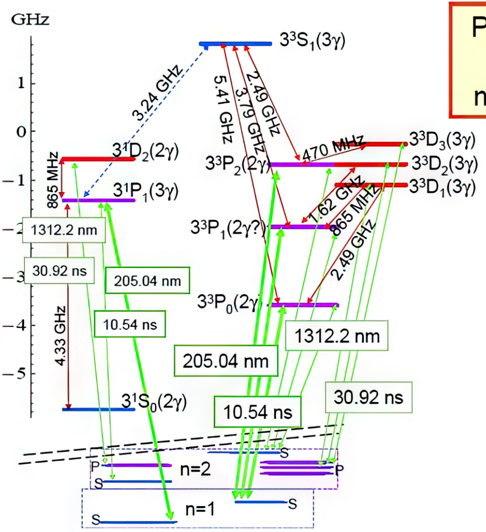
- 243 nm $1^3S_1 \rightarrow 2^3S_1$ - state-of-the-art value 1233607216.4(3.2) MHz.
- 205 nm $1^3S_1 \rightarrow 3^3S_1$ - never measured before

Energy levels $n = 1 \to n = 2$



Level	$\tau_{\text{ann.}}$ (ns)	Ref.	$\tau_{\text{fl.}}$ (ns)	Ref.
$1\,^1S_0$	0.125	[186]	N/A	N/A
$1\,^3S_1$	142	[20]	$\gtrsim 10^{16}$	[187]
$2\,^1S_0$	1	[186]	$\simeq$243 100 000	[188]
$2\,^3P_0$	100 000	[184]	3.19	[148]
$2\,^3P_1$	$\simeq\infty$	[184]	3.19	[148]
$2\,^1P_1$	3 330 000	[185]	3.19	[148]
$2\,^3P_2$	384 000	[184]	3.19	[148]
$2\,^3S_1$	1 136	[20]	$\simeq$243 100 000	[188]

Energy levels $n = 1 \rightarrow n = 3$



Ps trans. ⇔ n=3:
optical in nm,
microwave in Hz

Energy levels to order α^4

electr. dipole trans.
strong

wake

trans. with B

Technique - two-photon spectroscopy

Ps can be cooled to 170(20) K. The temperature translates to Doppler-broadening (for $1^3S_1 \rightarrow 2^3S_1$) of

$$\Delta_{FWHM} = \sqrt{\frac{8kT\ln(2)}{2m_ec^2}}f_0 \approx 350\ GHz. \tag{1}$$

The Doppler-free spectroscopy techniques can be used to mitigate the broadening, e.g., two-photon spectroscopy.

Features:

- 1st-order Doppler broadening is eliminated,
- transition probability is lower than in direct spectroscopy,
- laser wavelength is twice longer than in direct spectroscopy.

Spectroscopy of $1^3S_1 \rightarrow 3^3S_1$

What is the $1^3S_1 \rightarrow 3^3S_1$ transition probability?

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High Resolution Spectroscopy of the Hydrogen Atom: Determination of the 1*S* Lamb Shift

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We have measured the 1*S* Lamb shift by comparing the frequencies of the $1S_{1/2}$-$3S_{1/2}$ and $2S_{1/2}$-$6S_{1/2}$ or $2S_{1/2}$-$6D_{5/2}$ two-photon transitions. Our result is 8172.798 (46) MHz. It is the most precise yet reported and is consistent with the larger existing proton radius measurement of $r_p = 0.862(12)$ fm.

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For some fifty years, quantum electrodynamics (QED) calculations have steadily improved for bound atomic systems and now give the energy levels of the hydrogen atom to an impressive accuracy, of order 10^{-11} [1]. The hydrogen level energy is conventionally expressed as the sum of three terms: The energy given by the Dirac equation for a particle with the reduced mass, the first relativistic correction due to the recoil of the proton, and the Lamb shift. The first two terms are exactly known, apart from the uncertainties in the physical constants involved (the Rydberg constant R_∞, the fine structure constant, and the electron-to-proton mass ratio). The Lamb shift contains all the other corrections, i.e., the QED corrections, the other relativistic corrections due to the proton recoil, and the effect of the proton charge distribution. Precise measurements of the Lamb shift are required to test QED calculations or, if we suppose these calculations exact, to determine the proton charge radius. This last point is important, because there are two inconsistent measurements of the proton radius, $r_p =$ 0.805(11) and 0.862(12) fm [2,3]. Further, precise values of the Lamb shifts are essential to deduce R_∞ from recent optical measurements of hydrogen frequencies [4,5].

Another possibility is to use higher 2*S*-*nS*/*D* transitions. In this paper we present a measurement of the 1*S* Lamb shift deduced from the comparison of the 1*S*-3*S* and 2*S*-6*S*/*D* frequencies, which are also in the ratio 4:1. The 2*S*-6*S* and 2*S*-6*D* transitions are narrower (300 kHz and 1.3 MHz, respectively) and stronger than the 2*S*-4*S* and 2*S*-4*D*. To exploit this advantage, uncertainty due to light shifts, greater for the two-photon transitions due to stray electric fields is also larger (by a factor of 17), but the effect in this case is negligible. The 1*S*-3*S* transition is much weaker than the 1*S*-2*S* (by a factor of 140 with a cw laser of 50 kHz bandwidth), and much broader, but this line is not the limiting factor. With this method, we have measured the Lamb shift with an uncertainty of 5.6 parts in 10^6.

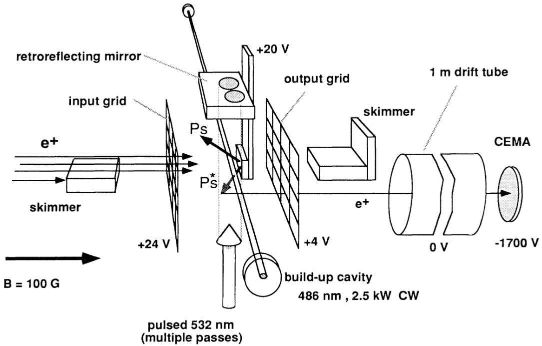
Figure 1 shows the general scheme of our experiment. A home-made titanium-sapphire laser at 820 nm is used to excite the two-photon transitions, either the 2*S*-6*S*/*D* or, after two frequency doubling steps, the 1*S*-3*S*. The laser frequency is actively stabilized by locking to a cavity using an FM sideband method, and the jitter is reduced to the level of 5 kHz. The long term stability is guaranteed

From the theory:

- Transition probability ratio for $1S - 2S$ and $1S - 3S$ is similar in H and other two-body atoms.
- For hydrogen, the ratio is 140.

State-of-the-art spectroscopy of $1^3S_1 \to 2^3S_1$

- Light source: Coherent 699-21 CW right dye laser 486 nm 500 mW,
- Power enhance: build-up cavity $\mathscr{F} = 10^5$ (real build-up $7.6 \cdot 10^3$),
- Peak intracavity power 2.5 kW, peak intensity 1.7 $\mathrm{MW/cm^2}$.



Fee, M.S. et al. (1993). *Measurement of the positronium* $1^3S_1 \to 2^3S_1$ *interval by continuous-wave two-photon excitation*. PRL 70(10), 1397-1400.

How much power do we need for 1S - 3S?

Estimation based on the measurement of $1^3S_1 \rightarrow 2^3S_1$

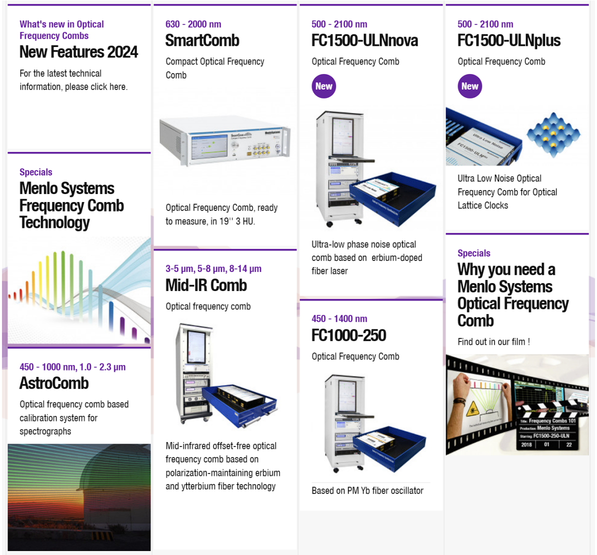
- From old meas.: $6 \cdot 10^3$ Ps was created, and a small portion was excited with at least 600 W of light.
- For a higher number of Ps (10^6 Ps), the power can be lower to have the same S/N ratio.
  - For $1^3S_1 \rightarrow 2^3S_1$

$$600\ W \cdot \frac{6 \cdot 10^3}{10^6} = 3.6\ W \tag{2}$$

  - For $1^3S_1 \rightarrow 3^3S_1$

$$140 \cdot 3.6\ W \approx 500\ W \tag{3}$$

Optical frequency comb: available range



What's new in Optical Frequency Combs

New Features 2024

For the latest technical information, please click here.

Specials

Menlo Systems Frequency Comb Technology

450 - 1000 nm, 1.0 - 2.3 µm

AstroComb

Optical frequency comb based calibration system for spectrographs

630 - 2000 nm

SmartComb

Compact Optical Frequency Comb

Optical Frequency Comb, ready to measure, in 19'' 3 HU.

3-5 µm, 5-8 µm, 8-14 µm

Mid-IR Comb

Optical frequency comb

Mid-infrared offset-free optical frequency comb based on polarization-maintaining erbium and ytterbium fiber technology

500 - 2100 nm

FC1500-ULNnova

Optical Frequency Comb

New

Ultra-low phase noise optical comb based on erbium-doped fiber laser

450 - 1400 nm

FC1000-250

Optical Frequency Comb

Based on PM Yb fiber oscillator

500 - 2100 nm

FC1500-ULNplus

Optical Frequency Comb

New

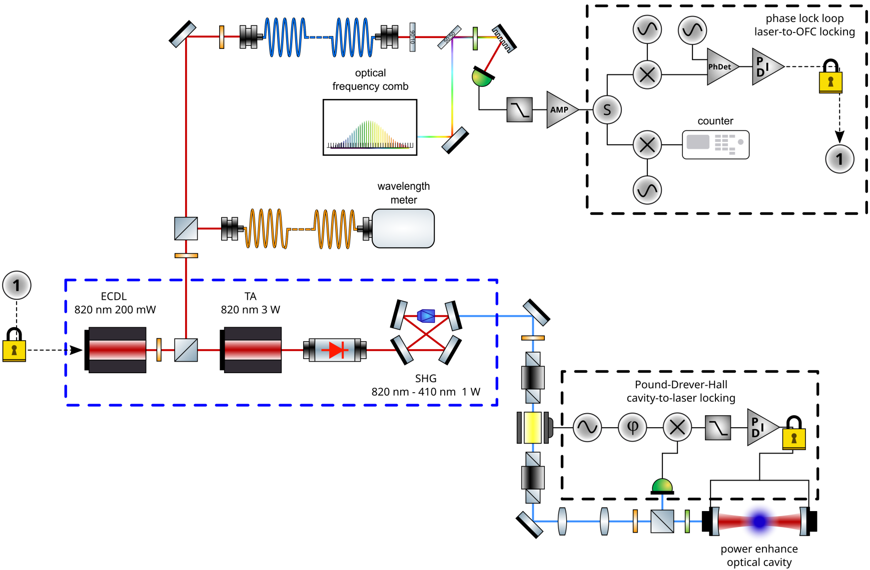
Ultra Low Noise Optical Frequency Comb for Optical Lattice Clocks

Specials

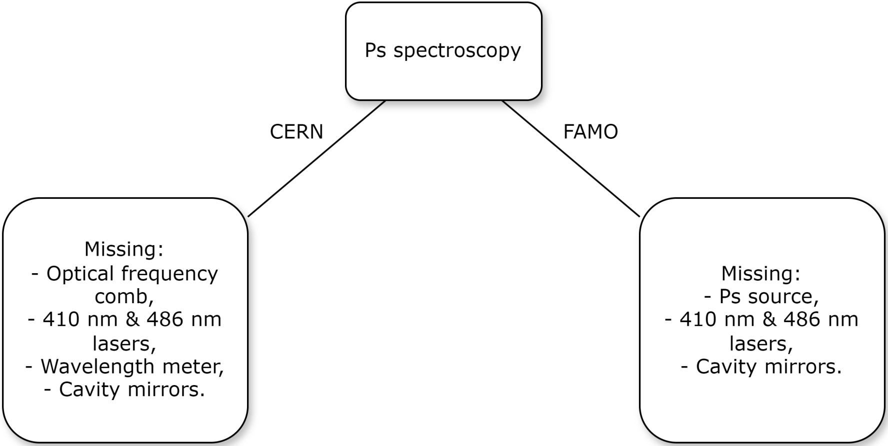
Why you need a Menlo Systems Optical Frequency Comb

Find out in our film !

Spectroscopy of $1^3S_1 \rightarrow 3^3S_1$ – our proposal



Possible ways



Ps spectroscopy

CERN

FAMO

Missing:
- Optical frequency comb,
- 410 nm & 486 nm lasers,
- Wavelength meter,
- Cavity mirrors.

Missing:
- Ps source,
- 410 nm & 486 nm lasers,
- Cavity mirrors.