Sub-THz Spectroscopy of the Ground State Hyperfine Splitting of Positronium

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Outline

• Introduction (Ps, Ps-HFS)
• Experimental Setup
  ✓ Quasi-optical system
  ✓ Ps assembly & transition measurement detectors
• Analysis & Current Status
• Summary
Ps is the bound state of e\(^-\) and e\(^+\) (e\(^+\) is the antiparticle of e\(^-\))

- The lightest hydrogen-like atom
- Unstable, particle-antiparticle system
- Simple, good target to study bound state QED (Quantum ElectroDynamics)
Positronium \((o\text{-}Ps, \, p\text{-}Ps)\)

- **Para-positronium** \((p\text{-}Ps)\)
  \[ S = 0 \text{ Spin singlet} \]
  Short lifetime (0.125 nsec)
  \(p\text{-}Ps \rightarrow 2\gamma \, (, \, 4\gamma, \,...)\)
  511 keV (= electron mass) \(\gamma\) rays

- **Ortho-positronium** \((o\text{-}Ps)\)
  \[ S = 1 \text{ Spin triplet} \]
  Long lifetime (142 nsec)
  \(o\text{-}Ps \rightarrow 3\gamma \, (, \, 5\gamma, \,...)\)
  Continuous energy spectrum
Hyperfine Structure of the Ground State of Positronium (Ps-HFS)

- Energy difference between o-Ps and p-Ps, about 203 GHz.
- A large (3.9 σ, 15 ppm) discrepancy between the measured and the theoretical value.
- All of the previous measurements are indirect measurements using static magnetic field.

→ We plan to “directly” measure Ps-HFS using high power sub-THz (203 GHz) radiation.

Exp.
- 203.388 65(67) GHz (3.3 ppm)
- O(α³) QED calc.
- 203.391 69(41) GHz (2.0 ppm)
First Direct Measurement of Ps-HFS with New Sub-THz Technique

- Drive stimulated emission from o-Ps to p-Ps using 203 GHz radiation.
- Since p-Ps decays into 2\(\gamma\) promptly (125 ps), 2\(\gamma\) annihilation increases when Ps are exposed to 203 GHz radiation.
- The natural transition rate is \(10^{14}\) times smaller than decay rate of o-Ps. High power (> 10kW) sub-THz radiation is necessary.
- Frequency has to be changed from 201 to 206 GHz in order to measure transition curve.
Experimental Setup

- **Fabry-Pérot resonator**
- Accumulate sub-THz radiation
- **22Na β⁺ source & β⁺ detector**
- **Ps** are formed in gas
- **γ-ray detectors**
- **Fabry-Pérot resonator**
  - Accumulate sub-THz radiation

**Gyrotron**
**FU CW G1**

**Mode Converter**

**SC magnet**
**MIG**

**window**

**M1**
**M2**
Gyrotron “FU CW GI”

- Gaussian beam power ~ **350 W** (5Hz, duty 30%)
- Replacing gyrotron cavities of different sizes to change frequency without breaking vacuum of the MIG.
• Sharpness $\Gamma = 1.7\mu$m (Finesse = 430), and coupling $C = 62$
  $\rightarrow$ Gain of the resonator is 85! (incident power ~ 350W)
Ps Assembly and $\gamma$-ray detectors

Signal = 2$\gamma$ decay of $\sigma$-Ps (monochromatic 511keV • back-to-back)

- $^{22}$Na $e^+$ source (1MBq)
- Au mesh mirror
- Cu concave mirror
- Plastic scintillator (t 0.1mm)
- $\text{LaBr}_3(Ce)$ crystal scintillators
- Neopentane 1 atm
- Photomultipliers

Form $\text{Ps}$ by stopping $e^+$ in gas

203GHz Gaussian Beam

2$\gamma$ = $\gamma$ decay of $\sigma$-Ps (monochromatic 511keV • back-to-back)
Ps-HFS transition@203.6GHz, 52kW

• A measurement at a frequency point takes about 3 weeks (2 weeks for preparation, 1 weeks for data acquisition)

• When Ps are exposed to 203 GHz radiation, $^o$-Ps$\rightarrow$3$\gamma$ (tail at the left of 511keV peak) decrease and $^o$-Ps($\rightarrow$p-Ps)$\rightarrow$2$\gamma$ (511keV peak) increase. The 511keV peak during beam OFF is due to $^o$-Ps+e$^-$→2$\gamma$+e$^-$ (pick off annihilation).
• We have already measured transitions at 201.8 GHz, 203.6 GHz. The data points are consistent with the theoretical curve.
• We are going to measure at three more frequencies to estimate Ps-HFS within this year.
Summary

• We plan to directly measure Ps-HFS (203.4 GHz) for the first time by developing new sub-THz technique.

• High power (>10 kW) and frequency tunability from 201 GHz to 206 GHz are necessary, so we use a demountable type gyrotron “FU CW GI” and a high finesse Fabry-Perot resonator with a gold mesh mirror.

• We have already measure transitions at two frequencies. In order to measure Ps-HFS, we will perform three more measurements at different frequencies within this year.