

The sub-THz direct spectroscopy of positronium hyperfine splitting

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Abstract. The positronium hyperfine splitting is a good target to study Quantum Electrodynamics in the bound state. There is a large discrepancy between precision measurements and a theoretical calculation. We are planning to directly measure the positronium hyperfine structure for the first time. A gyrotron oscillator is used as a novel radiation source in terahertz region. A Fabry-Pérot resonator is also developed to increase photon density. We have already observed the direct transition at 202.9 GHz. The direct measurement of $\mathcal{O}(100 \text{ ppm})$ will be performed within about a year.

1. Introduction

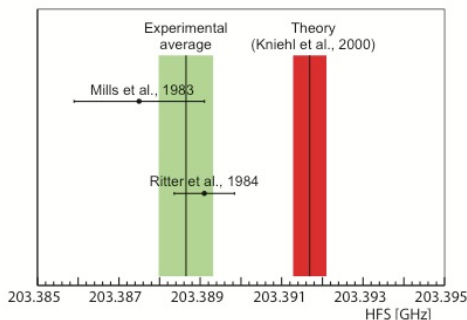


Figure 1. Discrepancy of Ps-HFS.

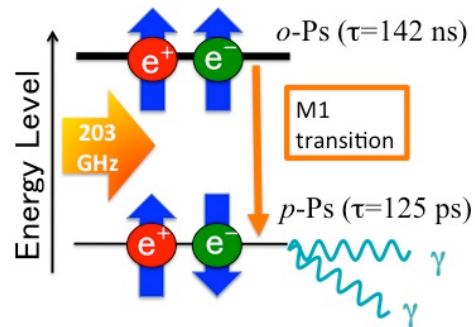


Figure 2. Schematic of the direct transition between Ps-HFS levels.

The hyperfine splitting of ground-state positronium (Ps-HFS) is a notable physics quantity to study Quantum Electrodynamics (QED) in the bound state. Some measurements of Ps-HFS were performed in 1980s. Precise calculations have been developed recently. The average of previous two experiments is 203.388 65(67) GHz (3.3 ppm) [1][2], whereas the theoretical value

of $\mathcal{O}(\alpha^3 (\ln \alpha)^{-1})$ is 203.391 69(41) GHz (2.0 ppm) [3]. Figure 1 shows this large discrepancy of 3.9σ (15 ppm) between measurements and the QED calculation. In order to validate the QED theory, common systematic uncertainties in all previous experiments have to be checked.

All the foregoing studies measured the Zeeman interval under a static magnetic field of about 1 T. The positronium hyperfine splitting is indirectly calculated by the Zeeman splitting of about 3 GHz. Therefore, we point out inhomogeneity of the static magnetic field might be one of the underestimated systematic errors. A direct measurement of Ps-HFS without any magnetic fields can be free from this suspicion.

Figure 2 schematically shows how to measure Ps-HFS directly. An electromagnetic wave of about 203 GHz stimulates the transition from *o*-Ps to *p*-Ps. Since *p*-Ps promptly (125 ps) decays into two γ rays, this transition can be probed by an increase of two γ -ray annihilation ratio which draws a Lorentzian curve with changing frequency. The natural rate (the spontaneous emission rate) of this direct transition is extremely small ($3.37 \cdot 10^{-8} \text{ s}^{-1}$) because this is a magnetic dipole transition (M1 transition). High power terahertz radiation of $\mathcal{O}(10 \text{ kW})$ is essential in this experiment.

2. Terahertz Optics

High power 203 GHz radiation is achieved by developing two novel terahertz devices: *gyrotron oscillator* and *Fabry-Pérot resonator*.

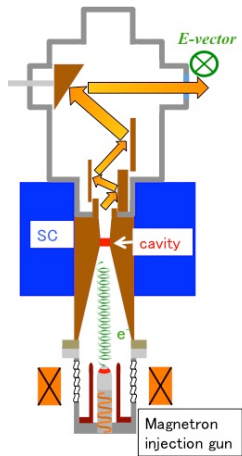


Figure 3. Schematic view of a gyrotron oscillator.

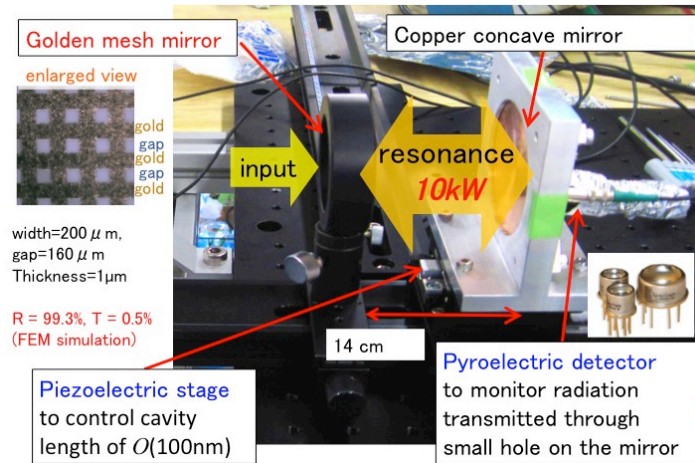


Figure 4. Photograph of the Fabry-Pérot cavity.

2.1. Gyrotron oscillator

A gyrotron oscillator developed in the field of nuclear fusion is the most powerful radiation source in terahertz region. It consists of a magnetron injection gun (MIG), a cavity in a superconducting magnet and an internal mode-converter as shown in Fig. 3. Electrons emitted from MIG move in a cyclotron motion under a strong magnetic field. The interaction between electrons and the cavity self-consistently bunches the cyclotron motion of many electrons to extract a coherent electromagnetic wave upward from the cavity. The internal mode-converter shapes raw radiation into a linearly polarized gaussian beam [4]. Output power of our gyrotron is about 300 W stably when acceleration voltage and current are 18 kV and 500 mA, respectively. Oscillation frequency is more or less monochromatic ($\Delta f = 1 \text{ MHz}$).

2.2. Fabry-Pérot resonator

Gyrotron output of 300 W is insufficient to drive the Ps-HFS transition. A Fabry-Pérot resonator is used to increase photon density. Figure 4 shows a photograph of the Fabry-Pérot resonator. A golden mesh mirror is developed to efficiently introduce a gaussian beam into the resonator. An opposite side is a concave Copper mirror on which a pyroelectric detector monitors transmitted radiation through a very small hole. Cavity length is controlled by a piezoelectric stage with accuracy of $\mathcal{O}(100\text{ nm})$. The equivalent power in this resonator is measured over 10 kW, which can sufficiently stimulate the direct transition of positronium.

3. Positronium assembly and γ -ray detectors

The Fabry-Pérot resonator is in a chamber filled with nitrogen gas. We produce positronium there with a positron source ^{22}Na as shown in Fig. 5. A thin plastic scintillator exists next to the source so as to tag time of the positron emission, which is used for delayed coincidence to reduce a prompt annihilation background. Four $\text{LaBr}_3(\text{Ce})$ crystal scintillators surrounds the resonator. Transiting p -Ps decays into two back-to-back γ rays of 511 keV, while o -Ps decays into three γ rays. Since these crystal scintillators have high energy resolution (FWHM 4% @511 keV), the signal of the direct transition can be efficiently separated from the o -Ps background.

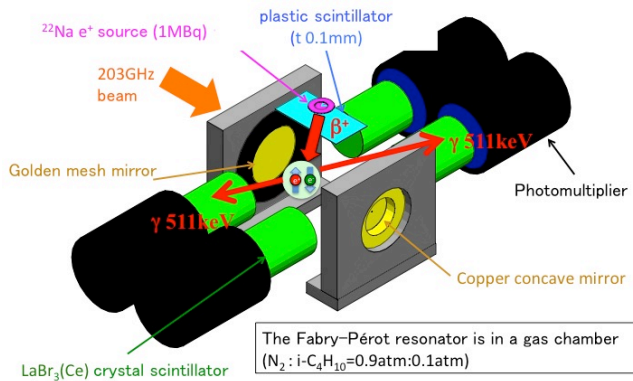


Figure 5. Arrangement of the positronium assembly and γ -ray detectors.

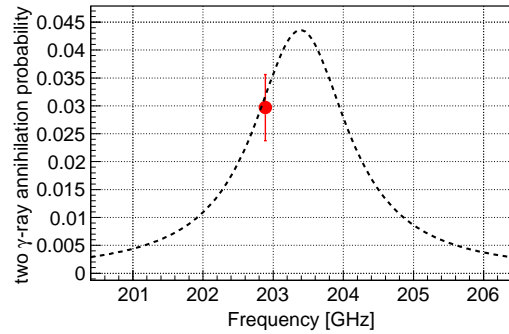


Figure 6. The direct transition at 202.9 GHz. The solid point shows the measured transition; the dotted line does a theoretical prediction.

4. Current Result and Improvements

The direct transition at 202.9 GHz was performed [5][6]. Figure 6 shows the observed transition compared with a theoretical calculation. The direct transition is obtained with significance of 5.4σ . The measured natural transition rate $A^{exp} = 3.1_{-1.2}^{+1.6} \cdot 10^{-8} \text{ s}^{-1}$ is consistent with theoretical value $A^{theo} = 3.37 \cdot 10^{-8} \text{ s}^{-1}$. The error of this experimental rate is mainly due to the accuracy of absolute power calibration of terahertz radiation.

In order to measure the Ps-HFS directly, the frequency must be swept around 203.4 GHz. Unfortunately, frequency of the gyrotron oscillator is fixed. A gyrotron cavity is a waveguide-like cavity (open cavity) in which electrons from the magnetron injection gun moves in a cyclotron motion. The oscillation frequency can be changed within the Q-value of the cavity, while it is too narrow (100 MHz) to draw the whole resonance curve of the Ps-HFS (FWHM 1.3 GHz). We decided to create some gyrotron cavities with different diameters to change oscillation

frequency. We will replace the gyrotron cavity when we measure different frequency points. All the necessary cavities have been already prepared.

The Fabry-Pérot cavity has a problem. The golden mesh mirror is melted away under accumulated power of 20 kW. Since it was evaporated on a quartz substrate whose thermal conductivity is very small ($5 \text{ WK}^{-1}\text{m}^{-1}$), the mesh pattern cannot be cooled by water. High-resistance silicon ($150 \text{ WK}^{-1}\text{m}^{-1}$) was selected as a new substrate. Figure 7 shows a carefully designed mesh mirror with water cooling. Figure 8 shows an obtained resonance of the new Fabry-Pérot resonator. The resonance occurs when cavity length matches half-integer multiple of wavelength (1.47 mm). This figure shows one of these resonances. Equivalent power in the resonator becomes over 20 kW. Water cooling works very well.

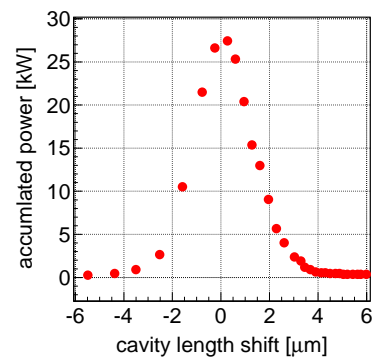
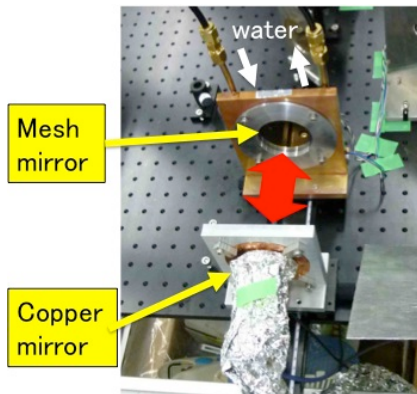


Figure 7. Photograph of silicon mesh with water cooling. **Figure 8.** Measured resonance of the new Fabry-Pérot resonator.

5. Conclusion

The measured value of Ps-HFS significantly differs from a theoretical calculation. The direct measurement of Ps-HFS has a potential to study this problem in the future. We firstly observed the direct transition from *o*-Ps to *p*-Ps using a gyrotron oscillator and a Fabry-Pérot resonator. All the requirements have been already fulfilled to operate the direct measurement of Ps-HFS. Positronium hyperfine splitting will be measured with accuracy of $\mathcal{O}(100 \text{ ppm})$ in about one year for the first time. In order to improve the accuracy to ppm level, we need following three improvements. First, a 0.1% level power detector of a terahertz wave should be developed. Next, a positron beam should be used to increase statistic. Finally, the experiment should be performed in vacuum, so that the thermalization effect of positronium would be eliminated.

References

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