Experiment for the First Direct Measurement of the Hyperfine Splitting of Positronium

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Abstract. Positronium is an ideal system for the research of the bound state QED. The hyperfine splitting of positronium (Ps-HFS: about 203 GHz) is a good tool to test QED and also sensitive to new physics beyond the Standard Model via a quantum oscillation between an ortho-Ps and a virtual photon. Previous experimental results show 3.9σ (15 ppm) discrepancy from the QED calculation. All previous experiments used an indirect method with static magnetic field to cause Zeeman splitting (a few GHz) between triplet states of ortho-Ps, from which the HFS value was derived. One possible systematic error source of the indirect method is non-uniformity of the static magnetic field. We are developing a new direct Ps-HFS measurement system without static magnetic field. In this measurement we use a gyrotron, a novel sub-THz light source, with a high-finesse Fabry-Pérot cavity to obtain enough radiation power at 203 GHz. The present status of the optimization studies and current design of the experiment are described.

1. Introduction
Positronium (Ps), the electron-positron bound state, is a purely leptonic system. The energy difference between ortho-positronium (o-Ps, $^3S_1$ state) and para-positronium (p-Ps, $^1S_0$ state), hyperfine splitting of positronium (Ps-HFS), is a good target to verify bound state QED precisely. The Ps-HFS value is approximately 203 GHz (0.84 meV), which is significantly larger than hydrogen HFS (1.4 GHz). One reason for the large Ps-HFS is the quantum oscillation: o-Ps → $\gamma^*$ → o-Ps (o-Ps has the same quantum number as a photon). Since some hypothetical particles (such as a millicharged particle) can participate in the quantum oscillation, resulting in a shift of Ps-HFS value, its precise measurement provides a probe for new physics beyond the Standard Model.
Measurements of the Ps-HFS have been performed in 70’s and 80’s with the combined precision of 3.3 ppm[1, 2]. The results were consistent with 1st and 2nd order calculation of the QED available at that time. However, the 3rd order corrections have been calculated recently, with the new prediction of 203.39169(41) GHz[3]. This differs from the measured value of 203.38865(67) GHz by 3.9, 15ppm. This discrepancy may come from new physics or the common systematic errors in the previous measurements.

In all previous measurements, the Ps-HFS transition was not directly measured, since 203 GHz was too high frequency to produce and control. They measured Zeeman splitting of o-Ps instead. A static magnetic field makes Zeeman mixing between \( m_z = 0 \) state of o-Ps and p-Ps, the resultant energy level of \( m_z = 0 \) state becomes higher than \( m_z = \pm 1 \) (Zeeman splitting). This Zeeman splitting, which is approximately proportional to the HFS energy level, is a few GHz frequency if \( \sim 1 \) Tesla magnetic field is applied. They applied uniform magnetic field in RF cavities where positronium was produced, causing Zeeman transition and resultant o-Ps to p-Ps transition. However, uncertainty (especially non-uniformity) of the static magnetic field can be a large source of systematic error of HFS.

In contrast to the indirect method, we plan to directly measure the HFS transition, which does not need a static magnetic field, and is thus free from the systematic error from the field. To cause the direct transition, a powerful 203 GHz radiation field is necessary. We are developing sub-THz to THz light source called a gyrotron, and also a high-finesse Fabry-Pérot cavity to accumulate sub-THz photons for the direct HFS measurement.

2. Gyrotron

![Schematic of gyrotrons.](image1.png)

![Picture of the gyrotron for the HFS experiment.](image2.png)

The gyrotron[4] is a novel high power source for sub-THz to THz frequency region. The structure of gyrotrons is shown in Fig. 1. The electrons are produced and accelerated at the DC electron gun, concentrated and rotated as cyclotron motion in the superconducting magnet. The cyclotron frequency \( f_c \) is given as

\[
f_c = \frac{eB}{2\pi m_0 \gamma},
\]

where \( B \) is the magnetic field strength, \( m_0 \) is the electron rest mass and \( \gamma \) is the relativistic factor of the electron. A cavity is placed at the maximum magnetic field, whose resonant frequency

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is tuned just to the cyclotron frequency to enhance the monochromatic light. The electrons stimulate resonance of the cavity and produce coherent photons at the cavity. The photons are guided to the output port through the window, while electrons are dumped at the collector.

We developed a gyrotron operating at $f_c = 203$ GHz with $B = 7.425$ Tesla, $\gamma \sim 1.02$, shown in Fig. 2. The obtained power is 609 W at output of Gyrotron, which is reduced to 440 W during transmission through the waveguide system to the positronium cavity. The frequency width is determined by $B$ uniformity and $\gamma$ spread by thermal distribution of electrons, and is expected to be less than MHz, which is narrow enough to make resonance at the Fabry-Pérot cavity. Measured result with a similar gyrotron shows the frequency width is less than 10 kHz[5]. The frequency can be tuned by changing the $\gamma$ factor with different acceleration of electrons, but the tuning range is limited by the resonant width of the cavity to several hundreds of megahertz. The power of the gyrotron will be monitored using pyroelectric detectors to account for corrections to the transition probability.

3. Fabry-Pérot cavity

Photons produced at the gyrotron are transported and accumulated in a cavity shown in Fig.3. Since 203 GHz ($\lambda = 1.475$ mm) photons can be treated optically at the centimeter (or larger) size scale, we plan to use a Fabry-Pérot cavity, consisting of two opposing mirrors to confine photons between them. Unlike RF cavities, the confinement in the Fabry-Pérot cavity is 1-dimensional while the other four sides are open. A metal-mesh mirror is used on the input side of the cavity to pass photons from Gyrotron, and a copper concave mirror is used on the other side.

| mesh material | line width | line separation | reflectance | transmittance | finesse |
|---------------|------------|-----------------|-------------|---------------|--------|
| gold          | 20 $\mu$m  | 50 $\mu$m       | 99.3%       | 0.32%         | 650    |
| gold          | 10 $\mu$m  | 50 $\mu$m       | 98.6%       | 0.75%         | 290    |
| silver        | 50 $\mu$m  | 130 $\mu$m      | 96.9%       | 2.70%         | 180    |

The two most important characteristics of cavities are “finesse ($F$)” and “input coupling”. Finesse can be given as $F = 2\pi/(1 - \rho)$, where $\rho$ is the fraction of power left after one round-trip, characterizing the capability of the cavity to store photons inside. To maximize the $F$, power losses must be minimized, and there are 3 type of loss, diffraction loss, medium loss...
and ohmic loss. With the confinement of photons by the concave mirror and gas medium, diffraction and medium loss are negligible in our cavity. Ohmic loss occurs at the mirrors, which is around 0.15% at the copper mirror and more at the mesh mirror. The ohmic loss at the mesh mirror depends on mesh parameters, and the calculated results are listed in Table 1. Input coupling is the fraction of input power introduced to the cavity mode. It is an important parameter to introduce photons efficiently into the cavity. In our cavity, the input coupling is mainly determined by transmittance of the input mesh mirror, which is also calculated by the simulation.

The finesse and the input coupling were measured using various mesh and concave mirror parameters. Figure 3 and 4 show the test setup, which is consisted of a mesh mirror on the mirror mount and a concave mirror on a piezo stage. Input, transmitted and reflected powers were monitored by three pyroelectric power monitors. By shifting cavity length precisely by the piezo stage, Breit-Wigner resonance shape was observed in the transmit power monitor as shown in Fig.5. Finesse could be obtained from the width of the resonance, and the input coupling was observed with the reflection monitor. With current best combination of the mesh and the concave mirror, \( \mathcal{F} = 650 \) was obtained (see Figure 5). For the input coupling, concrete value could not be obtained because of interference of the reflection power and difficulty to determine absolute power of the reflection/transmission because of non-optimal setup of the power measurements. Input coupling of \( \sim 20\% \) can be estimated with the reflection data.

4. Detection System

Figure 6 shows a schematic view of the whole system in preparation now. Gyrotron power is introduced to the cavity via the mesh mirror, and accumulated between the mesh and the Cu mirror. The \(^{22}\text{Na} \beta^+\)-source is located 30 mm above the cavity. The emitted positrons pass through a \( \beta \)-tag scintillator (t\( \sim \)200\( \mu \)m) to generate start timing. A lead collimator (10 mm length, 15 mm aperture) and a veto scintillator to reach the cavity are introduced to select \( \beta^+ \) stopped in gas. The lead collimator also works as a shield to protect \( \text{LaBr}_3(\text{Ce}) \) scintillators from accidetal photons (mainly 1275 keV and 511 keV photons emitted around the source. The cavity is filled with mixed gas of nitrogen and isobutane to form positronium atoms (20% efficiency). Para-positronium annihilates into two 511 keV photons immediately, while o-Ps remains with \( \tau \sim 142 \) ns and decays into three photons (< 511 keV). Six \( \text{LaBr}_3 \) scintillators surround the cavity to detect photons with high energy resolution of \( \sim 4\% \) (FWHM511keV).
Two photon-decay can be separated from three photon-decay easily using energy information. Two photon-decay will increase when photon frequency from Gyrotoron is close to HFS. We will obtain Breit-Wigner resonance as a function of frequency of photon, and HFS will be obtained directly from the center of Breit-Wigner resonance curve. The LaBr$_3$ scintillators have good timing resolution of $\sim 300$ psec to separate delayed events (signal) from prompt events (positron annihilation) to improve signal ratio significantly.

5. Summary
We are preparing the first experiment probing Ps-HFS with direct method to investigate discrepancy of Ps-HFS value between theory and experiment. We have developed a high power 203 GHz radiation source gyrotron and a Fabry-Pérot cavity with a metal-mesh mirror and a Cu concave mirror. We are now assembling the detection system, and the first data taking is scheduled in about a year.

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