論文の内容の要旨

# Direct Measurement of the Hyperfine Structure Interval of Positronium Using High Power Millimeter Wave Technology

## (大強度ミリ波技術を用いたポジトロニウム超微細構造の直接測定)

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Positronium (Ps), the bound state of an electron and a positron, is a purely leptonic system and is a good system with which to precisely study Quantum Electrodynamics (QED). Ps has two spin eigenstates: *ortho*-positronium ($o$-Ps, Spin=1, lifetime=142 ns, three-photon decay) and *para*-positronium ($p$-Ps, Spin=0, lifetime=125 ps, two-photon decay). Positronium hyperfine structure (Ps-HFS) is the energy difference between ground-state $o$-Ps and $p$-Ps. Ps-HFS is about 203 GHz (0.84 meV), and is significantly larger than the hyperfine structure of a hydrogen atom (1.4 GHz).

Precise measurements of Ps-HFS have been performed in 1970's and 80's. Their results are all consistent, and the average of the two most accurate measurements is 203.388 65(67) GHz (3.3 ppm). Higher order corrections of the bound-state QED were calculated in 2000, and the prediction is 203.391 69(41) GHz (2 ppm). A discrepancy of 3.04(79) MHz (15 ppm) is found between the measured value and the QED prediction, which is unlikely to be due to a statistical fluctuation (3.9 standard deviations).

In all previous measurements, the transition between $o$-Ps and $p$-Ps is not observed because 203 GHz is too high a frequency to be handled. This frequency 203 GHz is in the millimeter-wave range of which technology is still under development. Instead, a static magnetic field is applied to cause Zeeman mixing, and Ps-HFS is extracted from the Zeeman shift. There are two possible systematic uncertainties in this method. The first is due to a non-uniformity of the static magnetic field, and the second is due to the non-thermalization of Ps in gas. It is important to re-measure Ps-HFS using a method totally different from previous experiments.

A direct measurement of the Ps-HFS transition without a static magnetic field is free from systematic uncertainties due to magnetic fields. This thesis firstly measures Ps-HFS using a direct transition method with an initial precision of about 0.1%. This new method becomes possible by using a gyrotron as a high-power radiation source and a Fabry-Pérot resonant cavity.

A gyrotron is a millimeter-wave oscillator with the highest power (over 100 W) developed in plasma physics. Frequency stability of a general gyrotron is very monochromatic (FWHM is better than 100 kHz). Since output frequency of a normal gyrotron is lower than 170 GHz, we developed a new gyrotron with 203 GHz output. It was a technical challenge to fabricate such a high frequency (sub-THz) gyrotron. Output frequency is tuned by replacing an internal RF cavity.

A Fabry-Pérot cavity is usually used as an etalon in many frequency regions, and also used as an amplifier in laser physics. Although a basic theory of this cavity is well known, it is non-trivial to put this cavity to practical use in the millimeter-wave range. Some ideas are needed to accumulate high-power radiation ($\sim 20$ kW) and to measure its power with accuracy of 20%.

The direct transition is observed as an increase of two photons of 511 keV from $p$-Ps decay in the Fabry-Pérot cavity. Obtained Ps-HFS is

$$\Delta_{\mathrm{Ps}}^{\mathrm{HFS}} = 203.48 \pm 0.16\,(\mathrm{stat.})^{+0.23}_{-0.25}\,(\mathrm{syst.})\,\mathrm{GHz} \tag{1}$$

Lifetime of $p$-Ps is directly measured

$$\tau_{\mathrm{p-Ps}} = 80 \pm 16\,(\mathrm{stat.})^{+21}_{-17}\,(\mathrm{syst.}). \tag{2}$$

This is also the first direct measurement of $\tau_{\mathrm{p-Ps}}$. These are consistent with the QED calculations.

Some technical improvements are needed to reach a sufficient level of precision to address the observed discrepancy (15 ppm). This thesis points out development of a frequency tunable gyrotron of 100 kW and a method of efficient Ps production in vacuum with a positron beam.