Precise measurement of HFS of positronium using Zeeman effect

A Ishida¹, G Akimoto¹, Y Sasaki¹, A Miyazaki¹, K Kato¹, T Suehara¹, T Namba¹, S Asai¹, T Kobayashi¹, H Saito², M Yoshida³, K Tanaka³, A Yamamoto³, Y Urushizaki⁴, I Ogawa⁴, T Idehara⁴ and S Sabchevski⁵

¹ Department of Physics and ICEPP, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
² Institute of Physics, the University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo, 153-8902, Japan
³ High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan
⁴ Research Center for Development of Far Infrared Region, University of Fukui, 3-9-1 Bunkyo, 910-8507 Fukui, Japan
⁵ Institute of Electronics of the Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria

E-mail: ishida@icepp.s.u-tokyo.ac.jp

Abstract. The ground state hyperfine splitting of positronium, \( \Delta_{\text{HFS}} \), is sensitive to high order corrections of QED. A new calculation up to \( O(\alpha^3) \) has revealed a 3.9 \( \sigma \) discrepancy between the QED prediction and the experimental results. This discrepancy might either be due to systematic problems in the previous experiments or to contributions beyond the Standard Model. We propose an experiment to measure \( \Delta_{\text{HFS}} \) employing new methods designed to remedy the systematic errors which may have affected the previous experiments. Our experiment will provide an independent check of the discrepancy. The measurement is in progress and a result of \( \Delta_{\text{HFS}} = 203.385 \pm 0.011 \) GHz (58 ppm) has been obtained from the prototype run. A measurement with a precision of \( O(\text{ppm}) \) is expected within a few years.

1. Introduction

Positronium (Ps), a bound state of an electron and a positron, is a purely leptonic system which allows for very sensitive tests of QED. The precise measurement of the hyperfine splitting between orthopositronium (o-Ps, \( 1^3S_1 \)) and parapositronium (p-Ps, \( 1^1S_0 \) ) (Ps-HFS) provides a good test of bound state QED. Ps-HFS is expected to be relatively large (for example compared to hydrogen HFS) due to a relatively large spin-spin interaction, and also due to the contribution from vacuum oscillation (o-Ps \( \rightarrow \gamma^* \rightarrow \) o-Ps). The contribution from vacuum oscillation is sensitive to new physics beyond the Standard Model.

Figure 1 shows the measured and theoretical values of Ps-HFS. The combined value from the results of the previous 2 experiments is \( \Delta_{\text{HFS,exp}} = 203.388 \) GHz (3.3 ppm) \([1, 2]\). Recent developments in nonrelativistic QED (NRQED) have added \( O(\alpha^3) \) corrections to the theoretical prediction which now stands at \( \Delta_{\text{HFS,th}} = 203.391 \) GHz (2.0 ppm) \([3]\). The discrepancy of 3.04(79) MHz (15 ppm, 3.9 \( \sigma \)) between \( \Delta_{\text{HFS,exp}} \) and \( \Delta_{\text{HFS,th}} \) might either be due to the common
systematic uncertainties in the previous experiments or to new physics beyond the Standard Model.

There are two possible common systematic uncertainties in the previous experiments. One is the unthermalized o-Ps contribution which results in an underestimation of the material effect. This effect has already been shown to be significant [4]. The other is the uncertainty in the magnetic field uniformity which was cited as the most significant systematic error by previous experimenters.

2. Experimental setup

The energy levels of the ground state of Ps are shown as a function of static magnetic field in Figure 2. Due to technical difficulties in directly stimulating $\Delta_{\text{HFS}}$, we make an indirect measurement by stimulating the transition $\Delta_{\text{mix}}$. This is the same approach as previous experiments. The relationship between $\Delta_{\text{HFS}}$ and $\Delta_{\text{mix}}$ is given by the Breit-Rabi equation

$$\Delta_{\text{mix}} = \frac{1}{2} \Delta_{\text{HFS}} \left( \sqrt{1 + x^2} - 1 \right),$$

in which $x = 2g'\mu_B H/h\Delta_{\text{HFS}}$. $g' = g \left( 1 - \frac{5}{24}\alpha^2 \right)$ is the $g$ factor for a positron (electron) in Ps [5], $\mu_B$ is the Bohr magneton, $H$ is the static magnetic field, and $h$ is the Plank constant.

In a static magnetic field, the p-Ps state mixes with the $m_z = 0$ substate of o-Ps hence the $|+\rangle$ state annihilates into 2 $\gamma$-rays with a lifetime of about 8 ns (with our experimental conditions). The $m_z = \pm 1$ substates of o-Ps annihilate into 3 $\gamma$-rays with a lifetime of about 140 ns. When a microwave field with a frequency of $\Delta_{\text{mix}}$ is applied, transitions between the $|+\rangle$ state and $m_z = \pm 1$ substates of o-Ps are induced so that the 2 $\gamma$-ray annihilation rate increases. This increase is our experimental signal.

The prototype run of the measurement has been performed. A schematic diagram of the experimental setup of the prototype run is shown in Figure 3. Following are the main improvements in our experiment which we expect will significantly reduce systematic errors present in previous experiments.

2.1. Large bore superconducting magnet (Figure 4)

A large bore superconducting magnet is used to produce the magnetic field ($\sim 0.866$ T) which induces the Zeeman splitting. The bore diameter of the magnet is 800 mm, and its length is 2 m. The large bore diameter means that there is good uniformity in the magnetic field in the region where Ps is formed (11 ppm without utilization of any compensation).
2.2. \(\beta\)-tagging system and timing information

The positron source is \(19 \mu\text{Ci (700 kBq)}\) of \(^{22}\text{Na}\). A plastic scintillator 10 mm in diameter and 0.2 mm thick is used to tag positrons emitted from the \(^{22}\text{Na}\). The scintillation light is detected by photomultipliers and provides a start signal which corresponds to the time of Ps formation. The positron then enters the microwave cavity, forming Ps in the \(\text{N}_2\) gas contained therein.

Ps decays into photons that are detected with LaBr\(_3\) (Ce) scintillators. Accumulating measurements of the times of positron emission and \(\gamma\)-detection results in decay curves of Ps as shown in Figure 5. The timing information is used to improve the accuracy of the measurement of \(\Delta_{\text{HFS}}\) as follows:

(i) Imposing a time cut means that we can select well thermalized Ps, reducing the unthermalized \(\alpha\)-Ps contribution. It should also be possible to precisely measure the
contributions of unthermalized o-Ps, and of material effects (we plan to make such measurements in future runs).

(ii) A time cut also allows us to avoid the prompt peak (contributions of simple annihilation and of fast p-Ps decay), which greatly increases the S/N of the measurement.

2.3. High performance γ-ray detectors
Six γ-ray detectors are located around the microwave cavity to detect the 511 keV annihilation γ-rays. LaBr₃(Ce) scintillators, 1.5 inches in diameter and 2 inches long are used. LaBr₃(Ce) scintillators have good energy resolution (4% FWHM at 511 keV) and timing resolution (0.2 ns FWHM at 511 keV), and have a short decay constant (25.6 ns). The good energy resolution and the high counting rate of LaBr₃ results in very good overall performance for measuring 2γ decays. In particular the good energy resolution allows us to efficiently separate 2γ events from 3γ events, negating the need to use a back-to-back geometry to select 2γ events, thus greatly increasing the acceptance of our setup.

This γ-ray detector system greatly reduces the statistical error in the measurement.

2.4. RF system
Microwaves are produced by a local oscillator signal generator and amplified to 500 W with a GaN amplifier (R&K A2856BW200-5057-R).

The microwave cavity is made with oxygen-free copper; the inside of the cavity is a cylinder 128 mm in diameter and 100 mm long. The side wall of the cavity is only 2 mm thick in order to allow the γ-rays to efficiently escape. The cavity is operated in the TM₁₁₀ mode. The resonant frequency is 2.9 GHz and \( Q_L = 14700 \pm 50 \). The cavity is filled with gas (90% N₂ and 10% iso-C₄H₁₀) with a gas-handling system. iso-C₄H₁₀ is used as the quenching gas to remove background 2γ γ-ray annihilations.

3. Analysis and current status
The prototype run was performed from 29 June 2009 to 18 September 2009 using the large bore magnet with no compensation (compensation magnets to reduce the uniformity to \( O(ppm) \) are planned but are not yet installed). In the overall period, the trigger rate was about 3.5 kHz and the DAQ rate was about 0.7 kHz. The data acquisition was performed using CAMAC. The 2γ γ-ray annihilation rate has been measured at various magnetic field strengths with a fixed RF frequency.

3.1. Data analysis
Figure 5 shows examples of measured timing spectra. The peak coming from prompt annihilation and p-Ps decay is followed by the decay curve of o-Ps and then the constant accidental spectrum. A timing window of 30–200 ns is applied to select o-Ps events. Figure 6 shows the 2γ transition spectrum, which is obtained as follows:

(i) The accidental contribution is subtracted using the timing window \( t = 700–900 \text{ ns} \).
(ii) The ordinary o-Ps decay spectrum is also subtracted. This spectrum is obtained by running without RF power, and is normalized to the 2γ transition spectrum in the region 380–460 keV.

The 2γ transition spectrum is measured at different magnetic field strengths. The resonance lines obtained are shown in Figure 7.

Fitting the measured points with the Breit-Wigner function results in center values of the magnetic field of \( B_0 = 0.865 5665(71) \text{ T} \) (8.2 ppm) at 1.5 atm and \( B_0 = 0.865 662(10) \text{ T} \) (12 ppm) at 1.0 atm.

Systematic errors of the prototype run are summarized in Table 1.
Figure 5. Decay curves of Ps. The solid line is on-resonance (0.8659 T) RF ON, and the dotted line is RF OFF. An energy window of 492–530 keV is applied.

Figure 6. Energy spectra at different magnetic field strengths. The solid line is on-resonance (0.8659 T) RF ON and the dashed line is off-resonance (0.8614 T) RF ON. A timing window of 30–200 ns is applied, and the accidental spectra from 700–900 ns and RF OFF have been subtracted.

Figure 7. Resonance lines. Error bars are smaller than the marker size.

Table 1. Systematic errors of the prototype run.

| Element                                      | Errors in $\Delta_{\text{HFS}}$ (ppm) |
|----------------------------------------------|---------------------------------------|
| Non-uniformity of the magnetic field         | 22                                    |
| Analysis method$^1$                          | < 40                                  |
| Line-shape correction$^1$                    | < 20                                  |
| Gas pressure dependence                      | 8                                     |
| Thermalization of Ps$^2$                     | < 20                                  |
| RF frequency                                 | 6                                     |
| Q-value of the cavity                        | 10                                    |
| Magnetic field correction                    | 4                                     |
| Stability of the magnetic field              | 2                                     |
| NMR measurement                              | 2                                     |
| Quadrature sum                               | 56                                    |

$^1$ Further analysis will reduce these uncertainties.

$^2$ Direct measurement of Ps thermalization function will reduce this uncertainty.
The preliminary value of $\Delta_{HFS}$ calculated from equation (1) is

$$\Delta_{HFS} = 203.385 \pm 0.003\text{(stat.)} \pm 0.011\text{(sys.)} \text{GHz (58 ppm)} ,$$

which is consistent with both of the previous experimental values and with the theoretical value.

3.2. Next steps
The following improvements are planned for future measurements:

(i) Compensation magnets will be installed and $O$(ppm) magnetic field uniformity is expected to be achieved.

(ii) Measurements at various pressures of gas will be performed to estimate the material effect (the Stark effect). The accumulation of these measurements will result in an $O$(ppm) statistical error within a few years.

(iii) The timing information allows for a measurement of Ps thermalization as a function of time [4]. We can thus precisely measure the material effect including the thermalization effect.

4. Conclusion
A new experiment to measure the Ps-HFS which reduces possible common uncertainties in previous experiments has been constructed and the prototype run has been finished. A preliminary value of $\Delta_{HFS} = 203.385\pm0.003\text{(stat.)}\pm0.011\text{(sys.)} \text{GHz (58 ppm)}$ has been obtained, which is consistent with both of the previous experimental values and with the theoretical calculation. Development of compensation magnets is underway with a view to obtaining $O$(ppm) magnetic field homogeneity for the final run. The final run will start in about a year. A new result with an accuracy of $O$(ppm) will be obtained within a few years which will be an independent check of the discrepancy between the present experimental values and the QED prediction.

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