New Precision Measurement of Hyperfine Splitting of Positronium

Akira Ishida1,a
1Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
aishida@icepp.s.u-tokyo.ac.jp

Keywords: quantum electrodynamics, positronium, hyperfine splitting

Abstract. Positronium is an ideal system for precision tests of bound-state quantum electrodynamics (QED). One of the most precisely tested quantities of positronium is the ground-state hyperfine splitting (HFS). Recent progress on theoretical calculation revealed that there was a 16.0 ± 3.5 ppm (4.5 σ) discrepancy between the old experimental value and the theoretical calculation. We performed a new measurement which took into account the positronium thermalization effect for the first time. The result was HFS = 203.3942 ± 0.0016 (stat., 8.0 ppm) ± 0.0013 (syst., 6.4 ppm) GHz, which was consistent with the QED calculation within 1.1 σ, whereas it disfavored the old experimental values by 2.6 σ. It also showed that the positronium thermalization effect on HFS was as large as 10 ± 2 ppm, which was consistent with the discrepancy level within 1.5 σ, which could be the reason of the discrepancy. We are planning to perform a new experiment which uses a slow positron beam and perform HFS measurement in vacuum, instead of using gas as all of the other precision measurements. It will be completely free from material effect on HFS, including the thermalization effect. In this proceeding, summary of our previous work and details of the future new experiment are discussed.

Introduction

Positronium (Ps), the bound state of an electron and a positron, is a purely leptonic system which is very good for precision tests of bound-state quantum electrodynamics (QED). It is free from hadronic or finite-size uncertainties which are generally seen in other atomic systems like hydrogen or muonium. It is also a pure matter-antimatter system, which means that it is sensitive to new physics beyond the standard model of particle physics via the quantum oscillation of virtual annihilation (Ps → γ* → Ps). The energy difference of the ground states between the spin-triplet state (1S0, orthopositronium) and the spin-singlet state (1S0, parapositronium) is the ground-state hyperfine splitting (HFS, ΔHFS). It is one of the most precisely tested properties of Ps [1].

Ps HFS was firstly measured in 1952 [2]. The most precision measurements were performed in 1970s and 1980s by two independent groups [3, 4, 5]. They are consistent with each other, and the average of the two experiments is

\[ \Delta_{\text{HFS}}^{\text{exp-old}} = 203.38865(67) \text{ GHz} \]  \hspace{1cm} (1)

In 2014, we performed a new precision measurement which took into account the Ps thermalization effect for the first time:

\[ \Delta_{\text{HFS}}^{\text{exp-Tokyo}} = 203.3942 \pm 0.0016 \text{ (stat., 8.0 ppm)} \pm 0.0013 \text{ (syst., 6.4 ppm)} \text{ GHz} \]  \hspace{1cm} (2)

Theoretically, Ps HFS can be calculated accurately only by bound-state QED. The expression which is expanded in α is summarized in, e.g., References [8, 9, 10]. Efforts to obtain the coefficient for O(α3) non logarithmic term are ongoing since 2014 [8, 9, 10, 11, 12, 13], mainly motivated by our new experimental result and experimental efforts to obtain improved precision. The most recent value is:

\[ \Delta_{\text{HFS}}^{\text{th}} = 203.39189(25) \text{ GHz} \]  \hspace{1cm} (3)
Fig. 1 summarizes the current situation of Ps HFS measurements and the theoretical calculation. The old experimental average $\Delta_{\text{exp, old}}^{\text{old}}$ is significantly discrepant from the bound-state QED theory $\Delta_{\text{HFS}}^{\text{th}}$ by $16.0 \pm 3.5$ ppm (4.5 $\sigma$), which is sometimes referred as ‘Ps-HFS puzzle’. On the other hand, our new experimental result $\Delta_{\text{exp, Tokyo}}^{\text{HFS}}$ has a good agreement with the theory $\Delta_{\text{HFS}}^{\text{th}}$ within 1.1 $\sigma$, whereas it is different from the old experimental values by 2.6 $\sigma$.

**Ps thermalization effect and our new precision measurement**

Gas molecules were used in all the measurements in order to form Ps from positrons. The gas molecules surrounding Ps make electric fields which shift the Ps energy levels by the Stark effect. Before our measurement, Ps HFS were measured at many gas densities and they were extrapolated linearly to vacuum in order to correct the effect. However, it was shown that the effect should depend as (gas density)$^{3/5}$ in general atomic collisions with the Lennard-Jones potential [14]. Ps has O(eV) kinetic energy right after its formation, and it loses its kinetic energy by colliding with surrounding gas molecules. This Ps thermalization process takes time as long as its lifetime (142 ns) at low gas densities used in the measurements (O(0.1 amagat)). The timescale of the Ps thermalization depends on the gas density, which means the simple extrapolation used in the old measurements were insufficient and time-dependent Ps velocity change must be taken into account.

Our new measurement (2) took into account this Ps thermalization effect for the first time. It showed that the effect was as large as $10 \pm 2$ ppm, which was consistent within 1.5 $\sigma$ with the discrepancy level of $16.0 \pm 3.5$ ppm. It suggested that the reason of the Ps HFS puzzle was the Ps thermalization effect. The details of the experiment can be found in References [6, 7].

**Future plan**

A new experiment to obtain $\approx 1$ ppm or better precision is necessary to give the final answer to the Ps HFS puzzle. The indirect measurement using the Zeeman effect still seems to be the most suitable way, since the other methods [15, 16, 17] has not yet obtained even better than 200 ppm precision. In this case, one of the most promising way is to form Ps in vacuum and measure Ps HFS in vacuum using a slow positron beam, since there are at least the following five benefits:

- It is completely free from Ps thermalization effect because Ps velocity does not change. Ideally, Ps does not collide with any materials in transition volume.
• It does not rely on extrapolation of the Ps HFS pressure shift because it directly measures Ps HFS in vacuum.

• It can accumulate high statistics easily because it is not necessary to measure the Zeeman transitions at many different gas densities, i.e. only one measurement in vacuum is enough. In gas experiment, it was very inefficient to accumulate statistics because the positron stopping efficiency became quite small at low gas density, although the Zeeman transition measurements at low gas densities were the most important for the pressure-shift extrapolation.

• High power microwaves can be applied without discharging, which increases transition rate. In gas experiment, only limited power of microwaves could be applied at low gas density because of discharge, which also made the measurements very inefficient at low gas densities.

• Higher statistics can make the measurement shorter, which decreases the other systematic uncertainties from instability of the experimental setup, in particular the microwave system.

The concept of the future experimental setup is shown in Fig. 2. The goal is to measure Ps HFS with \( \approx 1 \) ppm precision by a few weeks, using a \( \approx 100 \) Hz pulsed positron beam. There are two candidates of available beam lines for this experiment: KEK [18] and CEA Saclay [19]. The largest systematic uncertainty in the future experiment will be the inhomogeneity of the static magnetic field. It is necessary to improve the homogeneity to \( O(0.1 \text{ ppm}) \). It is also necessary to measure the map of the magnetic field in-situ during the experiment. We are planning to perform a new experiment of this type and obtain a new result within 4–5 years.

Summary

There is a 16 ppm (4.5 \( \sigma \)) significant discrepancy in Ps HFS between the old experimental values and the bound-state QED calculation, which is called Ps-HFS puzzle. Recently we performed a new precise microwave spectroscopy using the Zeeman effect. It used new techniques to reduce possible systematic uncertainties in the old experiments: Ps thermalization effect and inhomogeneity of magnetic field. The new result was consistent with theory, whereas it disfavored the old experimental average by 2.6 \( \sigma \). It also revealed that the Ps thermalization effect was as large as 10 \( \pm 2 \) ppm, which suggested that the effect was the reason of Ps-HFS puzzle. We are planning to perform a new experiment which performs HFS measurement in vacuum using a slow positron beam. There are many benefits in this measurement, especially it is completely free from Ps collision effects including the Ps thermalization effect. A new result will be obtained hopefully within 4–5 years.

Acknowledgments

Our new measurement was performed by a collaboration with T. Namba, S. Asai (Department of Physics and ICEPP, The University of Tokyo), T. Kobayashi (ICEPP, The University of Tokyo. Currently at KEK), H. Saito (Department of General Systems Studies, The University of Tokyo), and M. Yoshida, K. Tanaka, and A. Yamamoto (KEK). Warm thanks are due to facilities and the entire members of the Cryogenics Science Center at KEK without whose excellent support this experiment could not have been successfully performed. It was supported by JSPS KAKENHI Grant No. 23340059.
References

[1] S.G. Karshenboim, Precision physics of simple atoms: QED tests, nuclear structure and fundamental constants, Phys. Rep. 422 (2005) 1-63.

[2] M. Deutsch, S.C. Brown, Zeeman Effect and Hyperfine Splitting, Phys. Rev. 85 (1952) 1047-1048.

[3] A.P. Mills, Jr., G.H. Bearman, New Measurement of the Positronium Hyperfine Interval, Phys. Rev. Lett. 34 (1975) 246-250.

[4] A.P. Mills, Jr., Line-shape effects in the measurement of the positronium hyperfine interval, Phys. Rev. A 27 (1983) 262-267.

[5] M.W. Ritter, P.O. Egan, V.W. Hughes, K.A. Woodle, Precision determination of the hyperfine-structure interval in the ground state of positronium. V, Phys. Rev. A 30 (1984) 1331-1338.

[6] A. Ishida, T. Namba, S. Asai, T. Kobayashi, H. Saito, M. Yoshida, K. Tanaka, A. Yamamoto, New precision measurement of hyperfine splitting of positronium, Phys. Lett. B 734 (2014) 338-344.

[7] A. Ishida, New Precise Measurement of the Hyperfine Splitting of Positronium, J. Phys. Chem. Ref. Data 44 (2015) 031212.

[8] M. Baker, P. Marquard, A.A. Penin, J. Piclum, M. Steinhauser, Hyperfine Splitting in Positronium to $\mathcal{O}(\alpha^7 m_e)$: One Photon Annihilation Contribution, Phys. Rev. Lett. 112 (2014) 120407.

[9] G.S. Adkins, R.N. Fell, Positronium hyperfine splitting at order $m\alpha^7$: Light-by-light scattering in the two-photon-exchange channel, Phys. Rev. A 89 (2014) 052518.

[10] G.S. Adkins, C. Parsons, M.D. Salinger, R. Wang, R.N. Fell, Positronium energy levels at order $m\alpha^7$: Light-by-light scattering in the two-photon-annihilation channel, Phys. Rev. A 90 (2014) 042502.

[11] M.I. Eides, V.A. Shelyuto, Hard nonlogarithmic corrections of order $m\alpha^7$ to hyperfine splitting in positronium, Phys. Rev. D 89 (2014) 111301(R).

[12] G.S. Adkins, C. Parsons, M.D. Salinger, R. Wang, Positronium energy levels at order $m\alpha^7$: Vacuum polarization corrections in the two-photon-annihilation channel, Phys. Lett. B 747 (2015) 551-555.

[13] M.I. Eides, V.A. Shelyuto, Hard three-loop corrections to hyperfine splitting in positronium and muonium, Phys. Rev. D 92 (2015) 013010.

[14] N. Allard, J. Kielkopf, The effect of neutral nonresonant collisions on atomic spectral lines, Rev. Mod. Phys. 54 (1982) 1103.

[15] A. Miyazaki, T. Yamazaki, T. Suehara, T. Namba, S. Asai, T. Kobayashi, H. Saito, Y. Tatematsu, I. Ogawa, T. Idehara, First millimeter-wave spectroscopy of ground-state positronium, Prog. Theor. Exp. Phys. 2015 (2015) 011C01.

[16] Y. Sasaki, A. Miyazaki, A. Ishida, T. Namba, S. Asai, T. Kobayashi, H. Saito, K. Tanaka, A. Yamamoto, Measurement of positronium hyperfine splitting with quantum oscillation, Phys. Lett. B 697 (2011) 121-126.
[17] D.B. Cassidy, T.H. Hisakado, H.W.K. Tom, A.P. Mills, Jr., Positronium Hyperfine Interval Measured via Saturated Absorption Spectroscopy, Phys. Rev. Lett. 109 (2012) 073401.

[18] K. Wada, T. Hyodo, T. Kosuge, Y. Saito, M. Ikeda, S. Ohsawa, T. Shidara, K. Michishio, T. Tachibana, H. Terabe, R.H. Suzuki, Y. Nagashima, Y. Fukaya, M. Maekawa, I. Mochizuki, A. Kawasuso, New experiment stations at KEK Slow Positron Facility, J. Phys.: Conf. Ser. 443 (2013) 012082.

[19] L. Liszkay, P. Comini, C. Corbel, P. Debu, P. Grandemange, P. Pérez, J.M. Rey, J.M. Reymond, N. Ruiz, Y. Sacquin, B. Vallage, Present status of the low energy linac-based slow positron beam and positronium spectrometer in Saclay, J. Phys.: Conf. Ser. 505 (2014) 012036.