Precise Measurement of the HFS of Positronium using the Zeeman Effect I: Experimental Set-up and RF System

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Abstract. Positronium is a QCD-free system and the measurement of its hyperfine splitting provides a strict test of quantum electrodynamics (QED). Recent research revealed a discrepancy of 3.9σ (15 ppm) between the theoretical prediction and previous experimental results [3, 4, 5]. The experimental values are consistent with each other (3.3 ppm) and are all systematically lower than the theoretical prediction (Figure 1). This could be a result of new physics, a miscalculation of the QED correction, or common systematic uncertainties that

1. Introduction
Positronium (Ps), the bound state of an electron and a positron, is a QCD-free system suitable for strict testing of quantum electrodynamics (QED). The ground state of Ps has two spin states (spin 0 and spin 1), and its so-called “hyperfine splitting” (Ps-HFS) is the energy difference between these states. Ps-HFS is sensitive to new physics beyond the standard model via vacuum oscillation of the S = 1 state of Ps (ortho-positronium, o-Ps). If an unknown light particle (such as an axion or a millicharged particle) exists, it contributes to the energy level, causing a discrepancy from the QED prediction.

Recently, a new calculation of the $\mathcal{O}(\alpha^3)$ correction to Ps-HFS has been developed [1, 2]. It revealed a 3.9σ (15 ppm) discrepancy between the theoretical prediction and previous experimental results [3, 4, 5]. The experimental values are consistent with each other (3.3 ppm) and are all systematically lower than the theoretical prediction (Figure 1). This could be a result of new physics, a miscalculation of the QED correction, or common systematic uncertainties that
Figure 1. Discrepancy between theoretical prediction and experimental values for Ps-HFS have not been considered. We investigate some of the possible sources of systematic error using an improved experimental set-up.

2. Measuring procedure
In all previous precision measurements, the Ps-HFS transition was not directly measured, due to technical difficulties with producing the required 203 GHz frequency. Instead, an indirect approach was used. The energy levels of Ps in a static magnetic field are split by the Zeeman effect. The energy splitting of Ps (between perturbed o-Ps and unperturbed o-Ps) is about 3 GHz in the presence of a magnetic field of 0.9 T. This energy difference ($\Delta E$) is a function of Ps-HFS ($\Delta \nu$) and the magnetic flux density ($B$). Ps-HFS ($\Delta \nu$) can then be derived from $\Delta E$ and $B$.

$$\Delta E = \frac{\Delta \nu}{2} \left( \sqrt{1 + x^2} - 1 \right)$$  \hspace{1cm} (1)

$$x \sim 0.2B[T]$$  \hspace{1cm} (2)

Figure 2 shows the experimental set-up of the prototype run (July–September 2009). The purpose of this run was to clarify the possible problems and systematic errors in the experiment in preparation for the first run.

Ps is generated by directing positrons from a $^{22}$Na positron source (700 kBq) into an RF cavity filled with nitrogen gas. The cavity also stores high-power 3 GHz microwaves. The cavity is surrounded by $\gamma$-ray detectors [six LaBr$_3$(Ce) scintillators] that have good energy resolution (3% at 511 keV). This good resolution means that $2\gamma$ decay can be tagged using energy information from a single crystal which yields a higher signal rate than the traditional geometrical back-to-back tagging using the coincidence of two scintillators. The cavity and the $\gamma$-ray detectors are located inside a large superconducting magnet, which applies a uniform magnetic field to the cavity. Microwaves are supplied from an external amplifier.

When the Zeeman energy shift $\Delta E$, which changes with $B$, is resonant with the RF frequency, the transition from $m_z = \pm 1$ to $m_z = 0$ increases, and the $m_z = 0$ state quickly decays into $2\gamma$. Ps-HFS can be identified by the central value of the resonance peak obtained by scanning the magnetic field.

The performance of the transition RF, the uniformity of the magnetic field, and the estimation of material effects are the main sources to systematic uncertainty in this experiment.
The Ps is spread over a large region of the cavity, and the nonuniformity of the static magnetic field over this region was the main source of the uncertainty in past results. By using a large-bore (800 mm) superconducting magnet, this run achieved a uniformity of 10.4 ppm (RMS), which contributes 22 ppm to the systematic uncertainty in Ps-HFS. In future runs we will compensate for this nonuniformity with additional coils (currently under development).

The Ps is produced in the nitrogen gas. Its initial kinetic energy is on the order of 1 eV. It collides with the gas molecules frequently, losing kinetic energy gradually until it reaches 30 meV (thermalization). The electric field of the gas molecules shifts the energy state of the Ps (the Stark effect). In previous experiments, this material effect was estimated by extrapolation to the vacuum from the measured Ps-HFS values at various pressures (about -33 ppm/atm). This procedure assumes that the Ps is well thermalized, and that its mean velocity is the same in the gas at various pressures. In earlier decay rate measurements, we revealed that this thermalization is slow (on the order of the lifetime of o-Ps), and that the assumption of good thermalization is not satisfied, which results in large systematic errors [6]. Nonthermal Ps would also affect the Ps-HFS measurement.

The timing of positron emission, which is negligibly close to the timing of Ps formation, is tagged with a thin (100 $\mu$m) plastic scintillator. Using an appropriate timing window cut, we can reduce the amount of the nonthermal Ps and select the well-thermalized Ps. The contribution of the nonthermal Ps as a function of time and pressure can also be measured. (We will measure it precisely in future runs.)

We focus on the RF system used in this experiment and its performance in the following section.

3. The RF system and its performance

The RF system is designed to meet the following requirements.

(i) Unlike the case for transitions of ordinary atoms such as hydrogen, a high-power RF source is necessary in order to obtain a sufficient transition signal. This is because the lifetime of o-Ps is short (142 nsec), which means that relatively little of the produced Ps can transit before decaying. The transition probability is proportional to the RF power, and about 29% of the o-Ps transits at an RF field strength of 2 mT.

(ii) The transition probability of o-Ps depends on the integrated power of the applied RF. We must control this integrated power with an accuracy of less than 0.1%.
(iii) Ps-HFS is derived from $\Delta E$ (the frequency of the RF source) and the strength of the applied magnetic field. The frequency of RF should be stable [less than $\mathcal{O}(1 \text{ppm})$].

Figure 3 shows the RF system used in the prototype run, which consists of two parts. The bold black line (upper part of Figure 3) is the system supplying the cavity with high-power RF. The area bounded by the faint red line (lower part of Figure 3) is the monitoring and feedback system, which stabilizes the RF power and frequency.

3.1. Requirement 1: RF power

The stored energy in the cavity is proportional to the product of the Q-value and the applied power. The cavity is cylindrical, and the resonance mode used is $TM_{110}$. This mode concentrates the RF power in the axial region of the cavity. The B field lines are parallel to the cavity axis. A positron emitted by the $^{22}$Na isotope source at the bottom of the cavity spirals around the magnetic field lines and thus forms Ps in the axial region.

For this experiment we used a resonance frequency of 2856MHz (S-band). The RF source used in this experiment consists of a signal generator and a gallium nitride amplifier. The maximum output power of the amplifier is about 600 W. The transmission path from the amplifier to the cavity consists of a waveguide which suppresses losses to about 10%. In this measurement, 409 W of high-power RF is applied to the cavity.

The resonance performance of the cavity is described by its Q-value. The resonance curve is Lorentzian, and the Q-value is defined by the resonant frequency over the full width at half maximum (FWHM), which is equal to the stored energy over the power loss per angular frequency. We monitored the Q-values daily during the prototype run. The measured Q-values were greater than 14,000 (the resonance curve is shown in Figure 5).

This RF system achieved a sufficient number of Ps transitions to measure Ps-HFS.

3.2. Requirement 2: Stability of the RF power

We monitored cavity reflection, RF power, and resonant frequency drift to get feedback about the power and frequency of the RF system. Figure 4 shows the power fluctuations in the amplifier gain. The green line is the power input to the amplifier, and the red line is the power output from the amplifier. Each line is independently scaled for comparison of the fluctuations.

(The amplifier gain is about $+50 \text{dB}$, so the absolute value of the output power is about $10^5$ times larger than the input power.) The ratio of output power to input power fluctuated by a
3.3. Requirement 3: Stability of RF frequency

The stability of the RF frequency is affected by drifting in the cavity’s resonance frequency which arises from thermal expansion/contraction of the cavity. This drift is of order 6 ppm (Figure 6). Though the RF power is stable and the cavity temperature is moderated by a water chiller, the resulting stability is still inadequate. This instability is a result of drifting in the surrounding air temperature. (≈ 10°C). (Figure 7). Our goal is to stabilize the temperature around the cavity and reduce the resonant frequency drift to 1 ppm.

4. Conclusion and outlook

This experiment measures Ps-HFS using the Zeeman effect. Its RF system requires stable, high-power output at a stable frequency. The prototype run clarified the problems with the set-up and achieved promising progress toward the first run, as detailed below.

(i) High power: The RF system successfully supplies the cavity with high-power RF. (409 W of power was supplied, and the Q-values of the RF cavity were greater than 14,000.)
(ii) Stable power: The output power of the amplifier was also stable, fluctuating by less than 0.1%.

(iii) Stable frequency: We will update the RF system to improve the stability of the resonant frequency.

In spring of 2010, we will start the first run, aiming at a precision on the order of 1 ppm.

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