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MEASUREMENT OF THE ORTHOPOSITRONIUM LIFETIME

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ABSTRACT

Thermalization of positronium is discussed in connection with the precision measurement of the orthopositronium decay rate. A new method to correct for the pickoff annihilation is proposed and a preliminary result is presented. A brief review of the searches for unknown decay channels is also given.

1. INTRODUCTION

Positronium(Ps) is a purely leptonic particle-antiparticle system. This is an ideal system for a clean test of quantum electrodynamics (QED) through measurements of its energy levels and lifetime [1].

The theoretical expression for the lifetime of orthopositronium(o-Ps) τ_{QED} is given by [2]

$$\tau_{QED}^{-1} = \frac{\alpha^6 mc^2}{\hbar}\frac{(2\pi^2-18)}{9\pi} \times \left[1 - 10.282(3)\left(\frac{\alpha}{\pi}\right) - \frac{1}{3}\alpha^2 \ln\alpha^{-1} + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3}{2\pi}\alpha^3(\ln\alpha^{-1})^2\cdots\right]. \quad (1)$$

The correction to the order $O(\alpha^2)$ has not been fully calculated. Recently Labelle *et al.*[3] made an estimate of some of the contributions to this order and obtained $\tau_{QED} = 142.038$ ns.

The vacuum lifetime of o-Ps has been repeatedly measured by using gases[4, 5, 6, 7], oxide powders[4], and slow positron beams[8, 9]. With only a few exceptions[7, 8], the experimental results give significantly shorter lifetime than the theory. For example, the most recent experimental value by Nico *et al.*[9], $\tau = 141.880 \pm 0.032$, is shorter than the theoretical value of Lebelle *et al.* [3] by 1100 ppm or 5 standard deviations.

The discrepancy might be explained when the second order radiative correction is fully calculated and turn out to be exceptionally large. Another possibility is that it is indicating the existence of an unknown exotic decay mode. The third possibility is that there might still remain systematic experimental errors.

2. SEARCH FOR EXOTIC DECAY MODES

Recent attempts to search for exotic decay modes are as follows:

(1) o-Ps $\longrightarrow \gamma\, X^0$: This is a possibility that o-Ps decays into a γ ray and a long-lived neutral boson which interacts with electrons very weekly. Examples are the axion and the dilaton. The experiment consists in a search for an emission of a single photon with a well defined energy

in a time delayed region where all the unbound positrons and parapositronium (p-Ps) atoms have annihilated. The contribution from this decay modes has been confirmed to be below 1ppm(90% C.L.)[10].

(2) o-Ps $\longrightarrow \gamma\Phi^0$: This is a search for a decay into a photon and a boson Φ^0 which couples strongly with photons. Since such a particle decays promptly into 2γ, the method (1) cannot be used to detect this process. However, the first γ must have a well defined energy, and thus a peak buried in the continuous 3γ spectrum is searched for. It has been confirmed that this contributes less than 300ppm(90% C.L.) in the Φ^0 mass region below 900 keV/c^2[11]. But no restriction has been placed in the heavier mass region.

(3) o-Ps $\longrightarrow$ invisible: This is a search for a decay into very weekly interacting particles, such as millicharged fermions. The experiment consists in a search for an event in which no γ ray is detected after a positron emission from the source. The restriction obtained on this mode of decay is 3ppm (90% C.L.)[12].

(4) o-Ps $\longrightarrow \gamma\gamma\gamma^*$: This is a search for a decay into 2γ plus an unknown vector boson γ^* having the same quantum numbers as the photon. The method (2) cannot be used because the photons here have a continuous spectrum. The experiment thus consists of a search for a singlet coupling positron-electron pair annihilation into $\gamma\,\gamma^*$ and a conversion of the information obtained into the probability of this process. It has been confirmed that this mode contributes less than 10ppm(90% C.L.)[13].

(5) o-Ps $\longrightarrow 2\gamma$: This is a process normally forbidden by the conservation of the angular momentum and the charge conjugation invariance. However, since the cross section for the 2γ annihilation is 1,100 times larger than the 3γ annihilation, only 1 ppm breakdown of the conservation laws will explain the observed discrepancy. The search for this process suffers from the pickoff annihilation in which the positron in o-Ps annihilates with an electron of the medium into 2γ. However, the spectrum for the pickoff annihilation is broad due to the momentum of the electrons of the medium, while the γ rays from the 2γ annihilation of the thermalized or nearly thermalized Ps is narrow. Thus the branching ratio can be determined by observing the mixing of the narrow component in the 0.511 MeV photopeak spectrum. The contribution from this decay mode has been observed to be less than 350ppm(90% C.L.)[14, 15].

(6) o-Ps $\longrightarrow 4\gamma$: This process is also forbidden. The possibility has been restricted to below 8ppm(68% C.L.)[16].

All these modes of decays are restricted to a low limit except for the mode (2) in an unexplored restricted region. Thus the possibility of an exotic decay to explain the discrepancy is now very low.

3. DECAY TIME SPECTRUM OF ORTHOPOSITRONIUM

The analysis of the annihilation rate of o-Ps inevitably includes correction for the pickoff annihilation on the experimental chamber wall, and in the Ps formation media such as gases and oxide powders, because Ps cannot be created in a really empty space. If the chamber has a positron inlet hole as in an experiment using a slow positron beam[8, 9], then one must also take account of the escape of the o-Ps through it.

In a closed cavity experiment using gases or oxide particles the observed annihilation rate is the sum of the intrinsic rate and the pickoff rate;

$$\lambda_{obs} = \lambda_3 + \lambda_{pickoff}. \tag{2}$$

Since the pickoff rate is proportional to the rate of collision of o-Ps with material, it is proportional to the average velocity of the o-Ps atom v_{Ps} as well as the density ρ of the gas or oxide powder. A complication comes from that v_{Ps} degrades gradually from the initial value

of around 4.2×10^5m/s ($\sim$ 1 eV) to the thermal value of 8.1×10^4 m/s ($\sim \frac{3}{2}k_BT$). The pickoff annihilation rate thus depends on time;

$$\lambda_{pickoff}(t) \propto v_{Ps}(t)\rho. \tag{3}$$

The population of o-Ps is expected to decrease in accordance with

$$\frac{dN(t)}{dt} = -(\lambda_3 + \lambda_{pickoff}(t))\, N(t), \tag{4}$$

the solution of which is

$$N(t) = N_0 \exp\left(-\lambda_3 \int_0^t (1 + \frac{\lambda_{pickoff}(t')}{\lambda_3})\, dt'\right). \tag{5}$$

Furthermore, the observed spectrum is not simply proportional to $N(t)$ but to

$$I(t) = \varepsilon_{2\gamma}\, \lambda_{pickoff}(t)\, N(t) + \varepsilon_{3\gamma}\, \lambda_3\, N(t), \tag{6}$$

where $\varepsilon_{2\gamma}$ and $\varepsilon_{3\gamma}$ are the detection efficiencies of the γ rays from the 2γ and 3γ annihilation events, respectively. They include the energy dependent efficiencies of the detectors and the electrical energy window settings. Note that the 2γ part is non-exponential not only from the exponential factors but also from the prefactor.

The importance of the thermalization in the measurement of o-Ps lifetime was first pointed out by Chang *et al.*[17]. In recent measurements by Westbrook[6] with gas molecules, the effect of the thermalization was carefully taken into account. They examined the effect of the thermalization of Ps by stepping out the start time of the fitting region of the spectrum, and observed gradual lowering of the fitted decay rate as the starting time was stepped out. They used the decay rate determined by the value of the fit starting at 180ns (except for the lowest pressure Ne and neopentan runs) where they found that the fitted decay rate stabilized.

Since, however, the vacuum lifetime of o-Ps determined in these gas experiments[6] differ significantly from the theoretical value, and since those of monoenergetic positron beam experiments[8, 9] differ from each other, it is nevertheless worthwhile to look into the thermalization of Ps in more detail and try more direct correction for the time dependent pickoff annihilation rate.

4. THERMALIZATION OF POSITRONIUM

The thermalization of o-Ps through the collisions with silica particles and gas molecules has been studied using Ps produced in silica aerogel[17, 18, 19, 20]. Silica aerogel is an aggregate of ultrafine amorphous silica particles having three-dimensional network structure.

The thermalization of o-Ps due to collisions with the silica particles can be observed by the angular correlation of annihilation radiation (ACAR) from silica aerogel in vacuum, and the effect of the collisions with gas molecules by the ACAR in gas atmosphere.

Figure 1 shows the data in silica aerogel in vacuum[19]. The data taken with no magnetic field ($B = 0$) is composed of two components: self-annihilation of p-Ps and the non-Ps annihilation. A small fraction of pickoff annihilation of o-Ps also contributes. When a static magnetic field is applied, one of the o-Ps substates mixes with the p-Ps state and annihilates into 2γ, allowing us to observe its momentum by the ACAR. The additional narrow peak appearing in the presence of a magnetic field represents the component resulting from the 2γ self-annihilation of the perturbed o-Ps. The values of τ_o in the figures are the mean lifetime of the perturbed

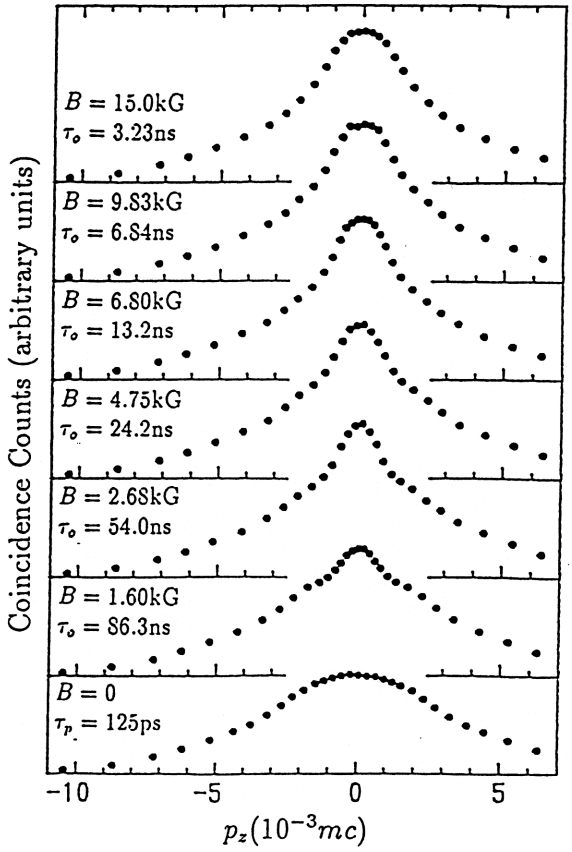

Figure 1: ACAR data for silica aerogel in vacuum.

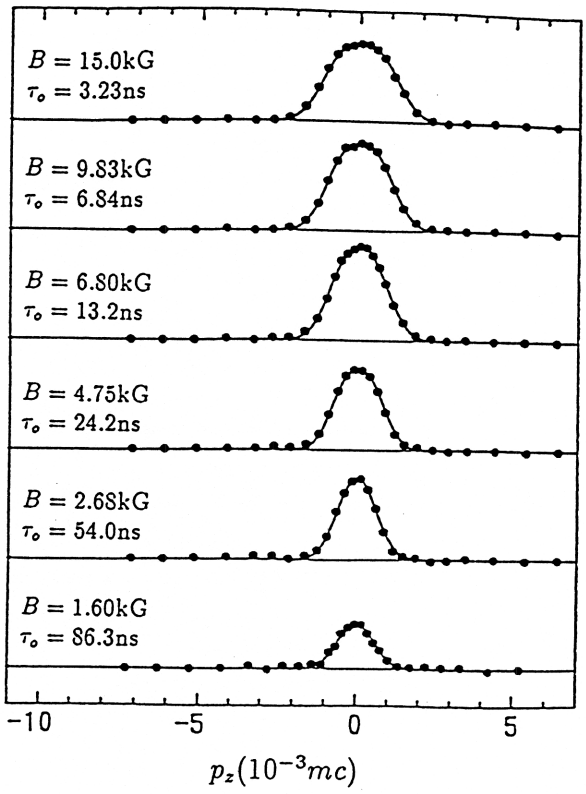

Figure 2: Perturbed o-Ps component obtained from figure 1.

o-Ps calculated with including the effect of the pickoff annihilation on the silica grains. Figure 2 shows the perturbed o-Ps component, which has been isolated by subtracting the $B = 0$ data from the average of the ACAR data for $+B$ and $-B$[19].

Similar data are taken in gas atmosphere, which show the thermalization of the perturbed o-Ps due to collisions with the gas molecules in addition to those with the silica grain surface.

If the fractional energy loss of the Ps per collision is proportional to E^{α}, then the average energy $E(t)$ of the Ps changes in accordance with the following differential equation,

$$\frac{d}{dt}E(t) = -C\sqrt{2m_{Ps}E(t)}(E(t) - \frac{3}{2}k_BT)(\frac{E(t)}{k_BT})^{\alpha}, \tag{7}$$

where C is a constant and m_{Ps} denotes the mass of Ps. Analysis of the ACAR data suggests that $\alpha = 2.3 \pm 0.7$ in the energy range 0.1eV$\leq E(t) \leq$0.3eV[19]. In the case of thermalization in gases where the elastic scattering dominates, we expect that $\alpha \sim 0$ and the averaged fractional energy loss per collision is given by $(2m_{Ps}/M)(\sigma_m/\sigma)$, where M is the mass of the molecule and σ_m and σ are the momentum-transfer cross section and the total elastic scattering cross section, respectively. Then the equation (7) can be solved analytically to give

$$E(t) = (\frac{1 + Ae^{-bt}}{1 - Ae^{-bt}})^2 \frac{3}{2}k_BT, \tag{8}$$

where $b = (2\sigma_m n/M)\sqrt{3m_{Ps}k_BT}$; n is the number density of the gas molecules and the constant A is determined by the initial Ps energy. The averaged positronium velocity at time t is then

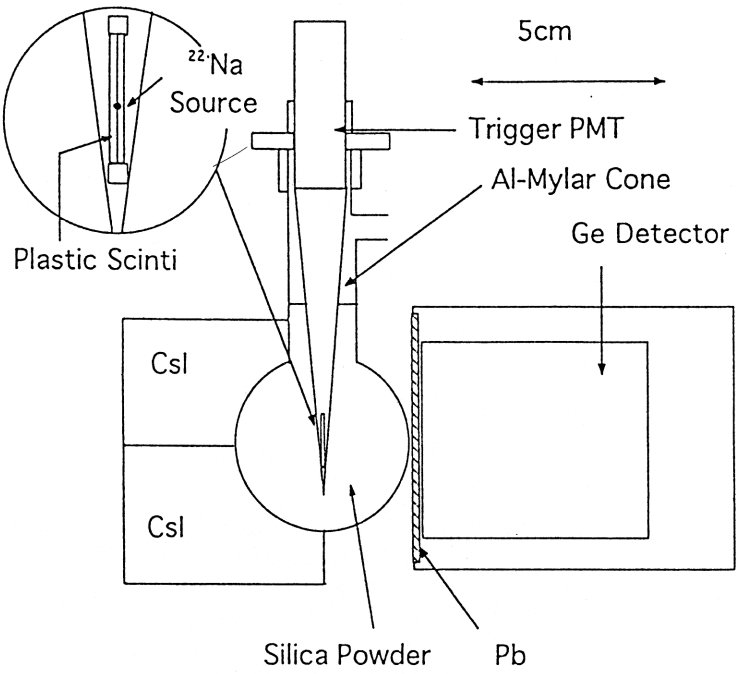

Figure 3: Experimental setup.

given by

$$v_{Ps}(t) = \sqrt{2m_{Ps}E(t)}. \tag{9}$$

Equation (8) indicates that, for example, in 0.2 amagat of a gas for which $\sigma_m \sim 10 \times 10^{-16}$ cm^2 and $M \sim 20$ amu, the degradation of the average Ps energy to 10% above the thermal energy takes about 500ns. When the fractional energy loss depends on energy as E^α ($\alpha > 0$) as has been found for silica aerogel in vacuum, then the thermalization can be even slower.

5. EXPERIMENT

We measured the lifetime spectrum and the energy spectrum for o-Ps in a low density(ρ=0.03 g/cm^3) silica powder simultaneously in order to apply a novel method of correction of the pickoff annihilation contribution to the o-Ps lifetime spectrum.

The experimental setup is shown in figure 3. A 0.04 μ Ci of ^{22}Na source is sandwiched between plastic scintillator foils of diameter 12 mm and thickness 100 μm and placed in the pointed end of a cone of 25 μm thick aluminated mylar sheet. The scintillation light produced when a positron passes through the scintillator is collected by the cone and detected by a photomultiplier to give the start signal. The positron goes into the silica powder and form Ps.

The annihilation γ-rays are detected by CsI scintillators and a high purity coaxial Ge detector. The CsI scintillators provide stop signals for the time spectrum and the Ge detector provides the energy spectrum. Three different types of time-to-digital converters (TDC) coupled to each CsI scintillation counter are used in parallel in order to check insensitivity of the data to the stop signal processing. The data taken by a CAMAC system are recorded with the information on lifetime and energy of all the detectors. This makes it possible to make the energy selection or time selection off line.

Figure 4 shows the time spectrum with the energy window 370-440 keV where the first term in equation (6) is negligibly small. Figure 5 shows the energy spectrum in the time range 138.5ns $\sim$ 158.3 ns after the prompt peak. Figure 5(a) is the raw data including accidental

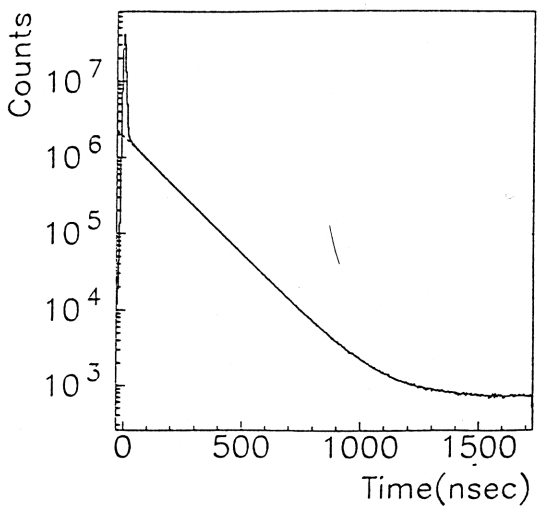

Figure 4: Time spectrum of a CsI detector with the energy window 370-440keV.

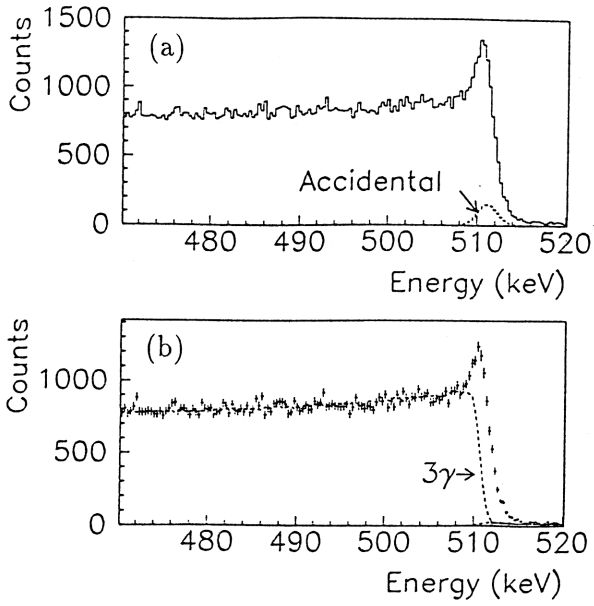

Figure 5: Energy spectra in the time range from 138.5ns to 158.3ns after the prompt peak. (a): Raw data including accidental background (shown by the dashed line). (b): Spectrum after subtraction of the accidental background.

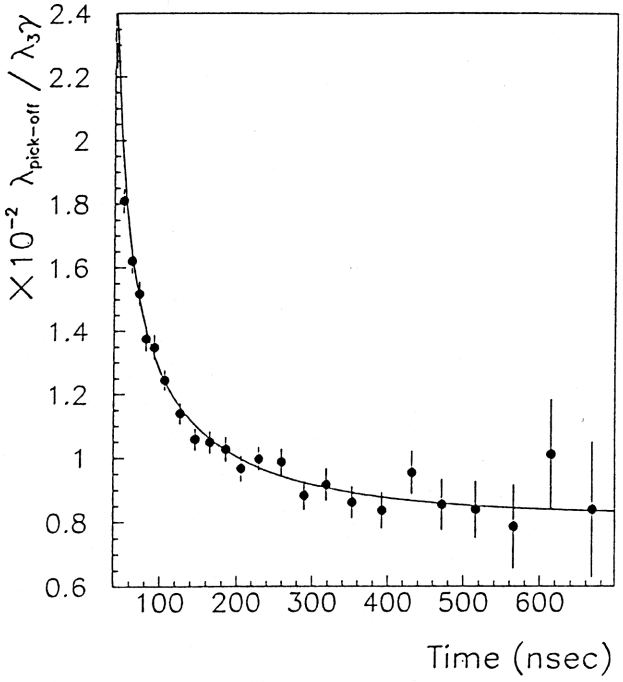

Figure 6: Pickoff annihilation rate as a function of time.

background spectrum which mainly consists of the 2γ peak from the prompt annihilation and whose shape and intensity can be known by the spectrum in far later time region. Figure 5(b) shows the spectrum after the subtraction of the accidental spectrum.

In order to determine the ratio $\lambda_{pickoff}(t)/\lambda_3$, we performed Monte Carlo simulation of the energy spectrum, in which the geometries of the setup and the various materials are reproduced in detail. The 3γ's are generated with including order α correction [21]. The 3γ part of the spectrum is shown in figure 5(b) by a dashed line.

The ratio $\lambda_{pickoff}(t)/\lambda_3$ determined to reproduce the energy spectrum data in each selected time region is plotted in figure 6. The pickoff rate decreases with time as the Ps thermalizes and the collision with the grain surface becomes less frequent.

We fitted the data with equation (3) by assuming that v_{Ps} is given by equation (7). We incorporated the routine to numerically solve equation (7) in the fitting procedure with letting α be a fitting parameter. Best fit was obtained with $\alpha = 0.8 \pm 0.4$ as shown by the solid line. The value is smaller than that suggested by the ACAR experiment[19].

Then the numerical values for $\lambda_{pickoff}(t)/\lambda_3$ shown by the solid line is tabulated and equation (1) was fitted directly to the lifetime data.

Our tentative result for the o-Ps lifetime obtained in this way without resorting to the linear extrapolation is

$$\tau = \lambda_3^{-1} = 142.15 \pm 0.03 \pm 0.05 \text{ ns}, \tag{10}$$

where the first error is from the statistics of the time spectrum and the time calibration and the second is from the statistics of the energy spectrum and the systematics. The errors from the Monte Carlo simulation and the numerical analysis are not completely included yet.

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