Measurement of five-photon decay in orthopositronium

Toshihiro Matsumoto, Masami Chiba, Ryosuke Hamatsu, Tachishige Hirose,
Jinfeng Yang, and Jie Yu*
Department of Physics, Tokyo Metropolitan University, 1-1 Minami Ohsawa, Hachioji-shi, Tokyo 192-03, Japan

(Received 26 January 1996)

We have measured five-photon decay of orthopositronium (o-Ps) and obtained the branching ratio of o-Ps$\rightarrow 5\gamma$ to o-Ps$\rightarrow 3\gamma$ as $[2.2^{+2.6}_{-1.6}(\text{stat.})\pm 0.5(\text{syst.})]\times 10^{-6}$, being consistent with the lowest-order QED calculation. Hence the five-photon decay process does not account for the discrepancy between the experimentally obtained decay rate for o-Ps and the theoretically calculated decay rate for o-Ps$\rightarrow 3\gamma$. [S1050-2947(96)02809-0]

PACS number(s): 36.10.Dr, 12.20.Fv, 13.10.+q

I. INTRODUCTION

The three-photon decay rate ($\lambda_{3\gamma}$) of orthopositronium (o-Ps) is calculated including higher order corrections [1,2] as

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

where α stands for the fine-structure constant and B represents the coefficient of the order $(m\alpha^8)$ in the decay rate, which has not yet been calculated completely. Recently, it was reported [3] that the decay rate of o-Ps ($\lambda_{o\text{-Ps}}$) obtained experimentally is larger than the calculated value based on quantum electrodynamics (QED) by 0.14%(6.2σ). In order to remedy this conflict within the framework of QED, B should be as large as about $\sim$250 [2]. This discrepancy may also be attributed to the emergence of exotic particles (e.g., axion), which increases the o-Ps decay rate. Actually many experiments have been carried out to search for these particles up to now, but, to our knowledge, none of these experiments has been successful in observing such particles.

Charge conjugation invariance requires that the o-Ps decay rate becomes

$$\lambda_{o\text{-Ps}}=\lambda_{3\gamma}+\lambda_{5\gamma}+\lambda_{7\gamma}+\cdots, \quad (2)$$

where $\lambda_{5\gamma}$ and $\lambda_{7\gamma}$ are the decay rates of o-Ps$\rightarrow 5\gamma$ and 7γ, respectively. If $\lambda_{5\gamma}$ is negligibly small ($\lambda_{5\gamma}/\lambda_{3\gamma}\sim 10^{-6}$ [4,5]) as QED predicts, the o-Ps decay rate experimentally obtained can be compared with the QED prediction for o-Ps$\rightarrow 3\gamma$ as was done in Ref. [3]. In order to clarify the problem in the o-Ps decay rate mentioned above, we performed an experimental study on the o-Ps$\rightarrow 5\gamma$ process whose decay rate is $O\sim m\alpha^8$ in the lowest order. In addition, we improved the theoretical value of the decay rate 10 times compared with previous calculations [4,5].

*Present address: The Institute of Japanese Union of Scientists and Engineers, Shibuya-ku, Tokyo, Japan.

II. EXPERIMENTAL APPARATUS

To observe five-photon decay in o-Ps, we used a multi-γ-ray spectrometer (MGS), with which our group had carried out the experiment of the $e^+e^-\rightarrow 4\gamma$ process and the search for exotic decay modes [6,7]. Since details of the MGS were already reported in Refs. [6,7], we only describe here features related with the present measurement. The MGS consists of 32 NaI(Tl) scintillation counters, each being located on a center of each surface of an icosidodecahedron. Figure 1(a) shows the cross section of MGS containing eight modules, each of which comprises an NaI(Tl) scintillator (diameter of 3 in. and length of 4 in.) with a lead collimator and a photomultiplier tube (PMT:Hamamatsu R1911). The front face of the NaI(Tl) crystal is located at a distance of 261.6 $\pm$0.6 mm from the center of the MGS covering a solid angle of (0.521$\pm$0.005)% of 4π sr. In order to reject backgrounds efficiently, we designed lead collimators that could prevent photons due to Compton scattering in the NaI(Tl) scintillator from entering another NaI(Tl) scintillator except for backward scattering. A photon scattered in a NaI(Tl) scintillator must penetrate at least 30 mm of the lead collimator to enter another crystal. As a result, we can suppress at the rate of 10^{-6} for Compton-scattering photons of 300 keV, which corresponds to the maximum energy of scattered photons if incident photons have energy of 511 keV. In the MGS, there are 16 collinear couples of NaI(Tl) scintillators facing each other and 15 planes including the origin of the MGS with the eight NaI(Tl) scintillators. The typical energy resolution is measured as $\sigma_E/E=(40.2/\sqrt{E}+1.89)\%$ (E in keV). Signals from 32 PMT's are independently fed to discriminators, scalers, analog-to-digital converters, and time-to-digital converters in the standard NIM and CAMAC systems. Data are collected with a personal computer (NEC PC-H98) and then transferred to a VAX 3000 for further analysis.

Figure 1(b) shows a central part of the MGS called a ''target region'' including a positron source, plastic scintillators, silica aerogels, and hard-vinylchloride cases. The positron source ^{68}Ge (73 kBq on average during the experimental period) with a diameter of 4 mm, a thickness of 0.5 mm, and a density of 1.39 g/cm^3 is placed between two plastic scintillators (NE102A) with dimensions $0.5\times 10\times 15$ mm^3. The isotope of ^{68}Ge decays into ^{68}Ga only through electron capture with a half-life of 288 days and then ^{68}Ga decays

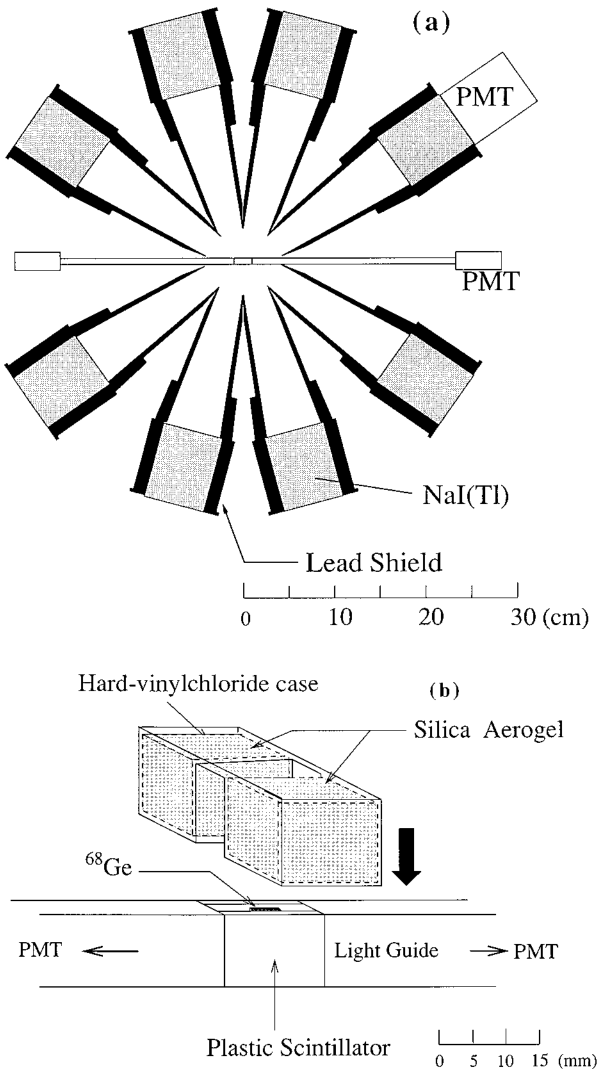

FIG. 1. (a) Cross section of the multi-γ-ray spectrometer. (b) Bird's-eye view around the target region. The radioisotope (^{68}Ge) is located between the plastic scintillators, which are saddled with the two pieces of silica aerogels.

into the ground state of ^{68}Zn with a branching fraction of 89% through β^+ decay and into the excited state with a fraction of 1.3% followed by transition γ rays of 1077 keV. Positrons emitted from the source first enter into the plastic scintillators with which we count the number of positron and start time-to-digital conversion. Light produced in the plastic scintillators is guided by two acrylic light guides with dimensions $4\times10\times320$ mm^3 to two PMT's (Hamamatsu R647), which provides trigger signals. For efficient creation of o-Ps, we use two pieces of silica aerogels ($19\times10.6\times19$ mm^3, with the density of 0.3 g/cm^3) produced by Gadelius Co. Ltd., which are enclosed with hard-vinychloride cases, and set them outside the plastic scintillators. The dimension of the hard-vinylchloride case is $10\times20\times20$ mm^3 with a thickness of 0.2 mm for the inner side and 0.5 mm for the outer side. The positron passing through the plastic scintillator forms o-Ps in the silica aerogel. Sometimes o-Ps collides with electrons in surrounding materials or unpaired electrons of oxygens in air and then annihilates into two-photon (pick-off) annihilation, which shorten the lifetime of o-Ps compared with that of 142 ns in vacuum. For suppression of the pick-off annihilation with unpaired electrons of oxygens, we let N_2 gas flow continuously (50 ml/min) through the hard-vinylchloride cases.

To improve the time resolution of the NaI(Tl) scintillators, we obtained the detection time with respect to the energy deposit. Then we utilized two-photon annihilation events in which one photon scattered in the target region and lost its energy. The detection time is affected by its energy deposit (E) since lower pulse-height signals from the PMT are slow to reach the threshold level in the discriminator. After the time walk correction, we determined the energy dependence of the time resolution as $\sigma_t(\mathrm{ns})=33.97/(\sqrt{E}-6.534)-10.16/(E-38.03)$ (E in keV) giving rise to $\sigma_t=2$–3 ns in the energy range $E=250$–511 keV as described in Ref. [7].

III. SIMULATION

We estimate an acceptance in the MGS using a detector simulator combined with an event generator. In order to generate $e^+e^-\rightarrow3\gamma$, 4γ, and 5γ events, we perform the lowest-order QED calculation using a series of programs, GRACE [9] and BASES/SPRING. [10]. Thus the branching ratio of $e^+e^-\rightarrow5\gamma$ to $e^+e^-\rightarrow3\gamma$ is obtained as

$$R=\frac{\lambda_{5\gamma}}{\lambda_{3\gamma}}=(0.9591\pm0.0008)\times10^{-6}, \tag{3}$$

which is improved 10 times compared with the previous calculations, i.e., $R\simeq1.0\times10^{-6}$ [4] or $\simeq0.96\times10^{-6}$ [5]. The error of our calculation is mainly due to integration processes in BASES.

Interaction of positrons with materials in the target region is investigated by a target simulator based on EGS4 [8] with the kinetic-energy cutoff of 30 keV in NaI(Tl) and 5 keV in the target region for electrons, positrons, and photons. In this simulation, we take account of the energy spectrum of positrons emitted from the ^{68}Ga source and the complete geometry of the target region. Thus, we obtain that 79.3% of all positrons emitted from the ^{68}Ga source enter the plastic scintillator and 31.9% (R_s) of the entering positrons stop in the silica aerogel.

The detector simulator consists of the EGS4 code including the geometry and materials of the lead collimators and the NaI(Tl) scintillators with aluminum windows. Using this detector simulator combined with the GRACE and BASES/SPRING [Monte Carlo (MC) simulation], we evaluate the geometrical acceptance G with three and five hits as $G_{3\gamma}=(2.77\pm0.04)\times10^{-3}$ and $G_{5\gamma}=(5.0\pm0.4)\times10^{-5}$, respectively. These geometrical acceptances are derived from rejecting events with collinear hits in NaI(Tl) scintillators.

IV. ANALYSIS

For the measurement of the production rate of o-Ps in the silica aerogels, we collected events firing three NaI(Tl) scintillators. The data taking is initiated by a coincidence of signals from the trigger counter and three NaI(Tl) scintillators in acollinear positions. We selected $o\text{-Ps}\rightarrow3\gamma$ with the following selection criteria to increase the signal-to-noise ratio: (i) three hits of the NaI(Tl) scintillators should be located in

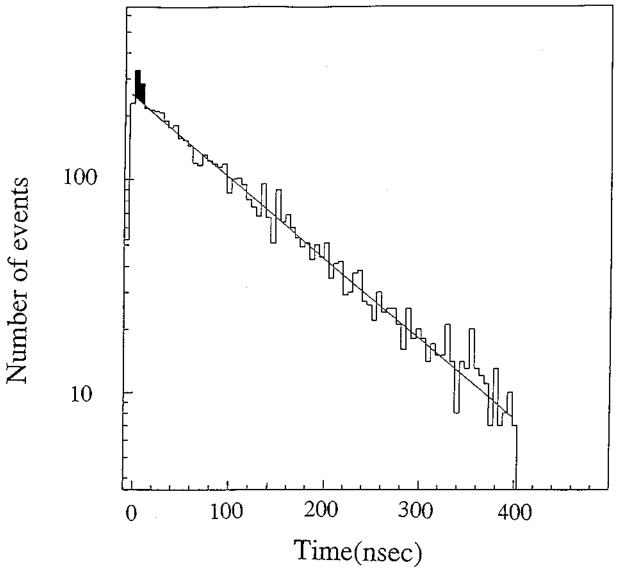

FIG. 2. Time spectrum of three-photon annihilation events. The shaded area near 0 ns shows prompt annihilation of free electron and free positron. The line shows fitted result with the lifetime of 120.6±2.0 ns.

a plane including the origin of the MGS; (ii) mean time $\tau=\Sigma_{i=1}^{3}(t_i/\sigma_t^2)/\Sigma_{i=1}^{3}(1/\sigma_t^2)$ should be within 10 ns$\leqslant\tau\leqslant$360 ns, where t_i is the duration between the trigger counter signal and NaI(Tl) signal of ith photon, and σ_t stands for the time resolution of the ith photon; (iii) total energy sum $E=\Sigma_{i=1}^{3}E_i$ exists in $|E-2m_e|\leqslant$ 60 keV, where m_e is electron mass and E_i is the energy deposit of ith photon; (iv) vector sum of momenta $P=|\Sigma_{i=1}^{3}\vec{P}_i|$ exists in $P\leqslant$100 keV/c, where $\vec{P}_i$ is the momentum vector of ith photon.

We display the distribution of the mean-time spectrum after the selection criteria (i), (iii), and (iv) in Fig. 2. The lifetime of o-Ps in our apparatus is deduced to be 120.6±2.0 ns, which is shortened by the pick-off effect.

In Fig. 2, the shaded area shows that a free positron and a free electron annihilate into three photons promptly without forming o-Ps. In addition, we obtained a number of prompt two-photon annihilations from the number of trigger counter signals and the acceptance derived from the MC simulation. As a result, we deduce the ratio of the three-photon to the prompt two-photon annihilation to be (1.2±0.3)/372, being consistent with QED calculation (1/372) for unpolarized free positron and free electron annihilation at rest.

The o-Ps production ratio ($R_{o\text{-Ps}}$) for one positron stopped in the silica aerogels is deduced as

$$R_{o-\mathrm{Ps}}=\frac{N_{3\gamma}}{N_{e^+}R_sG_{3\gamma}F_{3\gamma}}. \tag{4}$$

Here, $N_{3\gamma}$ represents the number of three-photon events detected experimentally, N_{e^+} represents the number of positrons counted by the trigger counter, R_s represents the ratio of the number of positrons stopped in the silica aerogels with respect to N_{e^+} (0.319), $G_{3\gamma}$ represents the geometrical acceptance for three-photon annihilation $(2.77\pm0.04)\times10^{-3}$, and $F_{3\gamma}$ represents a fraction of three-photon events surviving the selection criteria (i)–(iv) with the MC simulation (0.24). Then the $R_{o\text{-Ps}}$ is obtained as (13.2±0.4)% with the error mainly arising from ambiguity of $G_{3\gamma}$. The energy distribution of a single photon for three-photon decay is well reproduced with the MC simulation, as seen in Fig. 3, where the peaks at around 280 and 430 keV are due to the discrete position of the NaI(Tl) scintillators arranged on the icosidodecahedron.

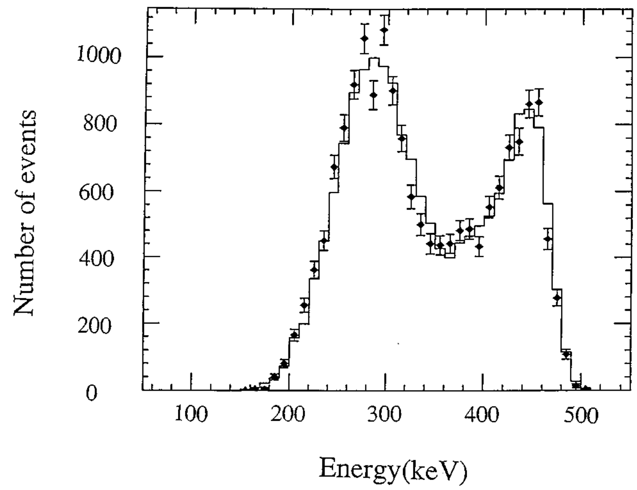

FIG. 3. Single-energy distribution of three-photon annihilation events. Histogram shows the MC simulation. Solid circles show experimental data.

In order to achieve effective suppression of a large amount of two-photon annihilations, we apply trigger conditions for the o-Ps$\rightarrow5\gamma$ process, i.e., the coincidence of the trigger counter signal and any five hits of the NaI(Tl) scintillators located in acollinear positions. We collected 11 251 events for 1.165×10^{12} positrons counted by the trigger counter for the experimental duration of 2.02×10^{7} s. Then the number of formed o-Ps produced in the silica aerogels was deduced to be $N_{o\text{-Ps}}=(4.92\pm0.11)\times10^{10}$.

We choose the following optimum selection criteria for the five-hit events by means of the MC simulation: (a) the energy deposit E_i in NaI(Tl) scintillators, $E_i\geqslant$75 keV for i=1–5; (b) the mean time $\tau=\Sigma_{i=1}^{5}(t_i/\sigma_t^2)/\Sigma_{i=1}^{5}(1/\sigma_t^2)$, 10 ns $\leqslant\tau\leqslant$360 ns; (c) the residual time $\tau_R=\sqrt{1/5\Sigma_{i=1}^{5}(t_i-\tau)^2/\sigma_{ti}^2}$, $\tau_R\leqslant2.0$; (d) the total energy sum $E=\Sigma_{i=1}^{5}E_i$, $|E-2m_e|\leqslant$60 keV; (e) the vector sum of momentum $P=|\Sigma_{i=1}^{5}\vec{P}_i|$, $P\leqslant$100 keV/c. The residual time τ_R represents a measure of simultaneity of the five emitted photons. The selection criteria (a) and (b) are introduced to suppress low-energy bremsstrahlung and prompt singlet annihilations, respectively. The selection criterion (c) is effective to suppress accidental background events that come mainly from the emission of two positrons between the window width 10 and 360 ns. After each selection process (a)–(d), the number of events 11 251 is reduced to 9373, 8473, 920, and 49, respectively. Finally one event (N_{obs}) remains as demonstrated in Fig. 4 where the momentum vectors of each photon projected on the three planes are also given. We apply these selection criteria (a)–(e) to the five-hit events generated by the MC simulation and obtain a selection efficiency $F_{5\gamma}$ of 17%.

It is essential to evaluate accurately possible backgrounds since the branching ratio for o-Ps$\rightarrow5\gamma$ is extremely small. Using the MC simulation, we obtain the relative contribution

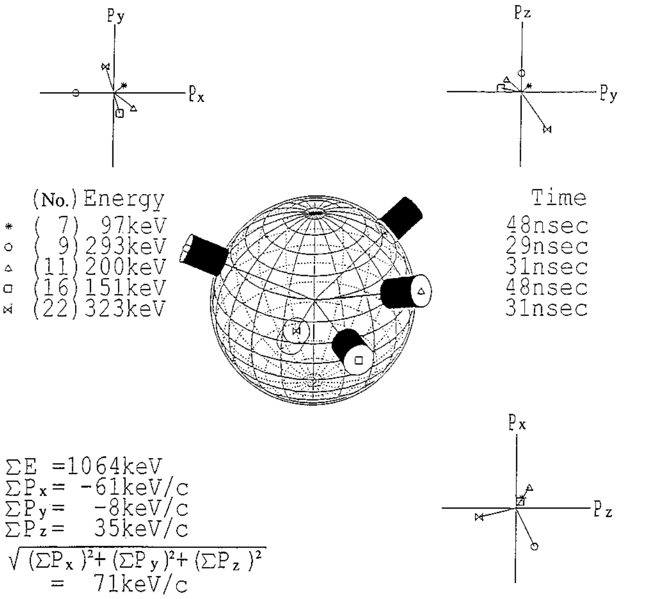

FIG. 4. Display of the o-Ps$\rightarrow 5\gamma$ event survived after the selection criteria (a)–(e). Energy and time of each photon, total energy sum, and vector sum of momentum are presented.

of several background processes that are classified into two categories, namely, one-positron and two-positron backgrounds. The two-positron background represents that two different positrons annihilate within the coincidence-time width (10–360 ns) between the trigger counter and the NaI(Tl) scintillators. On the other hand, the one-positron background is caused by an incident positron, so that 3γ or 4γ annihilation takes place in association with a transition γ ray in ^{68}Zn or bremsstrahlungs produced by positrons in the target region. The number of one-positron backgrounds is suppressed by the selection criteria (a) and (b) to the extent of less than 10^{-4} events. Therefore, we study only two-positron backgrounds after the selections (a)–(e) as given in Table I. The number of backgrounds is normalized to that of the experimental events after the selection criterion (c) since we have checked that the MC simulation and the experimental data are in accord with each other for the distributions of E_i, $\Sigma_{i=1}^{5} E_i$ and $\Sigma_{i=1}^{5} \vec{P}_i$. Finally, we obtain the expected number of backgrounds to be $N_{\rm back}=0.23\pm0.02$ where the error is due to statistical fluctuation in the MC simulation.

TABLE I. Numbers of events for the two-positron background (see text) normalized to 73 kBq ^{68}Ge source. (2γ Compton) stands for one of two photons scattered in the target region; $\gamma(\gamma)$: two-photon annihilations with one missing photon; $\gamma\gamma(\gamma)$: three-photon annihilation with one missing photon; γ_B: bremsstrahlung from initial positron. The notation $\times(+)$ represents accidental coincidence (simultaneous occurrence) between two processes given before and after the notation $\times(+)$.

No.	Type of backgrounds	Background events
1	$\gamma\gamma\gamma\times\gamma\gamma(\gamma)$	0.13
2	$\gamma\gamma\gamma\times[\gamma(\gamma)+\gamma_B]$	0.055
3	$\gamma\gamma\gamma\times(2\gamma$ Compton)	0.034
4	$\gamma\gamma(\gamma)\times(2\gamma$ Compton$+\gamma_B)$	0.007

The branching ratio R of the decay rate for o-Ps$\rightarrow 5\gamma$ to that for o-Ps$\rightarrow 3\gamma$ is derived as

$$R=\frac{\lambda_{5\gamma}}{\lambda_{3\gamma}}=\frac{N_{\rm obs}-N_{\rm back}}{N_{o\text{-Ps}}G_{5\gamma}F_{5\gamma}}, \tag{5}$$

where $N_{o\text{-Ps}}=(4.92\pm0.11)\times10^{10}$, $G_{5\gamma}=(5.0\times0.4)\times10^{-5}$, and $F_{5\gamma}=0.17$. We observe one event of o-Ps$\rightarrow 5\gamma$ ($N_{\rm obs}=1$) and evaluate the number of backgrounds ($N_{\rm back}=0.23\pm0.02$). The errors indicated above are caused by the statistical fluctuation of the MC simulation. Substituting these values, we obtain

$$R=[2.2^{+2.6}_{-1.6}(\text{stat.})\pm0.5(\text{syst.})]\times10^{-6}. \tag{6}$$

The statistical error for 68% C. L. is due to that of $N_{\rm obs}$, which is supposed to obey a Poisson distribution. The systematic error is mainly attributed to the error of $G_{5\gamma}$. The upper limit for the o-Ps$\rightarrow 5\gamma$ process with 90% C.L. is derived under the assumption that the events are observed in a Poisson process that has two components, signal and background, as described in Ref. [11]:

$$R_{\rm upper\ limit}=8\times10^{-6}. \tag{7}$$

V. CONCLUSION

We utilized silica aerogels to produce o-Ps efficiently and detected each photon from three-photon annihilation simultaneously. As a result, we extracted prompt three-photon annihilation of the free positron and free electron from the time spectrum of three-photon decay. The ratio of three-photon to two-photon annihilation was $(1.2\pm0.3)/372$.

We observed one event of o-Ps$\rightarrow 5\gamma$ annihilation. The branching ratio R of the decay rate for o-Ps$\rightarrow 5\gamma$ to that for o-Ps$\rightarrow 3\gamma$ is $[2.2^{+2.6}_{-1.6}(\text{stat.})\pm0.5(\text{syst.})]\times10^{-6}$. We derived a theoretical value of R as $(0.9591\pm0.0008)\times10^{-6}$. Our experimental results for R were consistent with the QED calculation within the errors. On the basis of the MC simulation for our apparatus, we could evaluate possible backgrounds and hence determine in a reliable manner the upper limit 8 ppm (90% C.L.) for the contribution of o-Ps$\rightarrow 5\gamma$ to o-Ps$\rightarrow 3\gamma$. Thus it is concluded that the ratio of the decay rate of o-Ps$\rightarrow 5\gamma$ to the total o-Ps decay rate is 100 times smaller than the discrepancy between the measured decay rate of o-Ps and the decay rate of o-Ps$\rightarrow 3\gamma$ predicted by QED in the 90% C.L. The o-Ps lifetime puzzle remains unsolved.

ACKNOWLEDGMENTS

We would like to thank Dr. S. Nagayama for useful discussions and S. Adachi for his advice to calculate the decay rate of o-Ps$\rightarrow 5\gamma$. This work was partially supported by a Grant in Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan.

[1] W. E. Caswell and G. P. Lepage, Phys. Rev. A **20**, 36 (1979); G. S. Adkins, Ann. Phys. (N.Y.) **146**, 78 (1983).
[2] P. Labelle and G. P. Lepage, Phys. Rev. Lett. **72**, 2006 (1994).
[3] J. S. Nico *et al.*, Phys. Rev. Lett. **65**, 1344 (1990).
[4] G. S. Adkins and F. R. Brown, Phys. Rev. A **28**, 1164 (1983).
[5] G. P. Lepage *et al.*, Phys. Rev. A **28**, 3090 (1983).
[6] S. Adachi *et al.*, Phys. Rev. Lett. **65**, 2634 (1990).
[7] S. Adachi *et al.*, Phys. Rev. A **49**, 3201 (1994).
[8] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, SLAC Report No. 265, 1985 (unpublished).
[9] T. Ishikawa *et al.*, KEK Report No. 92-19, 1993 (unpublished).
[10] S. Kawabata, Comput. Phys. Commun. **41**, 127 (1986).
[11] C. Montanet *et al.*, Particle Data Group, Phys. Rev. D **50**, 1281 (1994).