# Four and Five Photon Decays of Positronium: Tests of QED and C

P.A. Vetter and S.J. Freedman
*U.C. Berkeley Physics Department and Lawrence Berkeley National Laboratory*

We have measured the annihilation of positronium to four and five photons using Gammasphere[1]. These measurements test Quantum Electrodynamics calculations at $\alpha^7$ and $\alpha^8$, and test charge conjugation invariance. Positronium is produced in two states, $^1S_0$ para-positronium (p-Ps) and $^3S_1$ ortho-positronium (o-Ps), which have eigenvalues of the charge conjugation operator (C) +1 and $-1$. Since the C eigenvalue of the photon is $-1$, there is a C-invariance selection rule for the number of decay photons from each state: p-Ps annihilates to an even number, while o-Ps annihilates to an odd number of photons. The probability for p-Ps to decay to four photons has a calculated branching ratio $R_4 = 1.4388(21) \times 10^{-6}$[2], and the branching ratio for o-Ps to five photons is calculated to be $R_5 = 0.9591 \times 10^{-6}$[3]. The branching ratio $R_4 \equiv \Gamma(\text{p-Ps}\rightarrow 4\gamma)/\Gamma(\text{p-Ps}\rightarrow 2\gamma)$ where $\Gamma(4\gamma) = \Gamma_{\text{LO}}(4\gamma)\left[1 - 14.5(6)\alpha/\pi + O\left(\alpha^2\right)\right]$, with the lowest order rate $\Gamma_{\text{LO}}(4\gamma) = 0.0138957(4)m\alpha^7$. The branching ratio for five photon decay is $R_5 \equiv \Gamma(\text{o-Ps}\rightarrow 5\gamma)/\Gamma(\text{o-Ps}\rightarrow 3\gamma)$, with $\Gamma(5\gamma) = \Gamma_{\text{LO}}(3\gamma)\left[0.0189(11)\alpha^2\right]$, and the three-photon decay rate $\Gamma_{\text{LO}}(3\gamma) = 2/(9\pi)\left(\pi^2 - 9\right)m\alpha^6$. This yields $\Gamma(5\gamma) \propto \alpha^8$ at tree-level.

Positronium was produced in Gammasphere using a 10 $\mu$Ci $^{68}$Ge source encapsulated in a thin plastic scintillator, and surrounded by silicon dioxide aerogel. Data acquisition was triggered by a positron pulse in the scintillator and two or more "clean" hits in Gammasphere modules. Of the $1.18 \times 10^{10}$ events written to tape, $3.73 \times 10^9$ passed cuts as positronium anninilation. Cuts were made on energy and momentum sums, and time coincidence between module hits. Geometric cuts on colinearity and coplanarity discriminated against backgrounds.

The detection efficiency of Gammasphere for 2, 3, 4, and 5-photon decays was found from GEANT-based Monte-Carlo simulations. Simulations accounted for the allowed kinematic distribution of photon momenta in each mode. The simulation included the distribution of annihilation vertices inside the 6 cm diameter Ps source, dead and missing detector elements in Gammasphere, and detector energy resolution. We studied contributions from background four and five-photon events using event mixing on raw data from two and three-photon events. The main backgrounds arise from accidental coincidences between different decay events in which some of the photons were Compton scattered. We expected 0.35 background five-photon events and 2.75 four-photon events.

From the time distribution of the annihilation events in Figure 1, the populations of o-Ps and p-Ps can be separated. p-Ps decays with a mean lifetime of $\approx 120$ ps, (promptly with the positron trigger) while o-Ps had a mean lifetime of $\approx 112$ ns. Measured branching ratios are summarized in Table I. Our results agree with QED predictions for allowed four and five-photon decays. A previous measurement of the (o-Ps $\rightarrow 5\gamma$) decay [4] observed a single event, with an expected background of 0.4 events. The decay modes (o-Ps $\rightarrow 4\gamma$) and (p-Ps $\rightarrow 5\gamma$) would violate charge conjugation symmetry, and our limits for the non-existence of such decays represent a modest improvement over previous measurements.

TABLE I: Errors are statistical, systematic.

| Decay Mode | $1\sigma$ errors | 90% C.L. Limit |
|---|---|---|
| p-Ps$\rightarrow 4\gamma$ | $1.14 \pm 0.33 \pm 0.21 \times 10^{-6}$ | $< 1.92 \times 10^{-6}$ |
| o-Ps$\rightarrow 5\gamma$ | $1.67 \pm 0.99 \pm 0.37 \times 10^{-6}$ | $< 6.4 \times 10^{-6}$ |
| o-Ps$\rightarrow 4\gamma$ | $2.0 \pm 1.0 \pm 7.7 \times 10^{-7}$ | $< 3.7 \times 10^{-6}$ |
| p-Ps$\rightarrow 5\gamma$ | $0.3 \pm 0.3 \pm 1.3 \times 10^{-7}$ | $< 2.7 \times 10^{-7}$ |

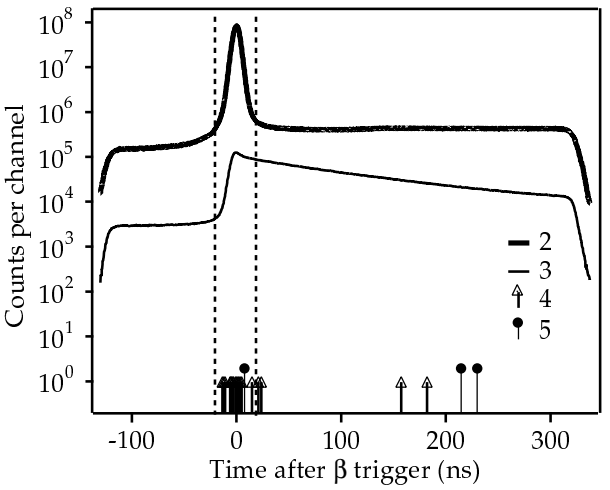


FIG. 1: Ps annihilation events as a function of time after the $\beta$ decay ($t = 0$). Dashed lines are at $\pm 20$ ns. Five-photon counts have been offset for visibility.

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