Measurement of the Vacuum Decay Rate of Orthopositronium*

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Orthopositronium (o-Ps), formed on the cone of a channel electron multiplier by 400-eV positrons, is shown to diffuse quickly into an MgO-coated evacuated chamber with energies up to 0.8 ± 0.2 eV. The decay rate of o-Ps is measured to be $7.09 \pm 0.02\ \mu\text{sec}^{-1}$, where the error is due principally to systematic effects. This result is interpreted to be the first direct measurement of the vacuum decay rate of the o-Ps. It is in disagreement with the theoretical value of $7.242 \pm 0.008\ \mu\ \text{sec}^{-1}$ and previous experiments in gases as well.

In a previous Letter[1] Gidley, Marko, and Rich (GMR) reported the decay rate of orthopositronium (o-Ps) in powders of SiO_2 to be a linear function of the free volume density. The result of extrapolating the decay rate to zero density was $7.104 \pm 0.006\ \mu\text{sec}^{-1}$. This result is $(1.9 \pm 0.1)\%$ below the theoretical value[2] of $7.242 \pm 0.008\ \mu\text{sec}^{-1}$ and more than 2% below the results of two experiments in gases,[3,4] $7.262 \pm 0.015\ \mu\text{sec}^{-1}$ and $7.275 \pm 0.015\ \mu\text{sec}^{-1}$. GMR noted that their result could plausibly be interpreted as the vacuum decay rate. Ford, Sander, and Witten,[5] after a detailed consideration of the possible interactions of Ps with the surface of SiO_2, found no reason to doubt that the extrapolated value is the free-space decay rate. We report here the results of a completely different experiment in which o-Ps is demonstrated to be decaying in vacuum. The decay rate is found to be in agreement with the reported value of GMR.

Our method for measuring the vacuum decay rate is based on the observation[6] that o-Ps is efficiently formed at or near the surface of a solid by slow positrons ($E < 1$ keV) and then diffuses into the surrounding vacuum. In order to measure the time interval between the formation of Ps and its decay into γ rays we have developed a novel technique for detecting the time at which the Ps is formed. The MgO-coated cone of a channel electron multiplier (CEM) is used as the Ps formation surface and the CEM detects the secondary electrons expelled by the incident positron. The Ps so formed is then confined in an MgO-coated evacuated chamber and the annihilation γ rays are detected by three NaI detectors.

The apparatus consists of (1) a slow-positron generator and an electrostatic focusing system,[7] (2) an interaction region, and (3) a detector-timing system. A 46-mCi ^{58}Co β^+-source and an Au-MgO moderator[8] are used to produce slow positrons, which are subsequently accelerated and focused into a beam. Two cylindrical mirror energy analyzers, a 1-m flight path, and 10 cm of lead shield the detectors from high-energy positrons and γ rays from the source.

The interaction region is shown in Fig. 1. A beam ($500\ \text{sec}^{-1}$) of 400-eV positrons is focused through a 6-mm-diam entrance hole onto the MgO-coated cone of a CEM where Ps is formed with about 15% efficiency. The Ps diffuses into

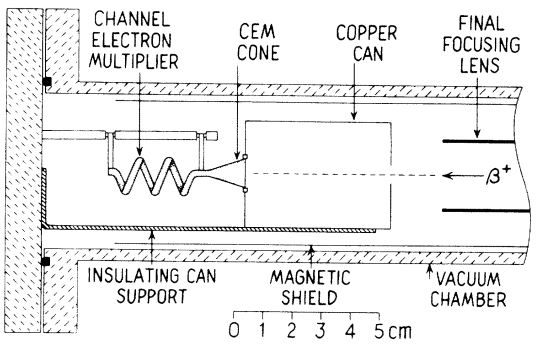

FIG. 1. Evacuated interaction region.

an evacuated (10^{-6} Torr) MgO-coated copper can which confines the Ps to a region of uniform γ detection efficiency. A thin (less than 0.1 mm) layer of MgO is fumed onto all of the interior surfaces of the confinement can and the CEM cone in order to minimize pickoff. The cone is held at -400 V and the can at -50 V to insure that positrons which are backscattered from the cone are returned within a few nanoseconds. This prevents the data from being affected by the decay of low-energy, long-lived, backscattered positrons.

The γ detector-timing system has been described in detail by GMR.[1] Three 4-in.×4-in. NaI detectors are mounted at 120° to each other in a plane perpendicular to the axis of the interaction region and centered on the confinement can. The time interval (≤ 2 μsec) between the CEM start signal and a predetermined number (1 or 2) of the o-Ps annihilation γ rays is measured with a time-to-amplitude converter, multichannel analyzer system. The system time resolution is approximately 7 nsec. The overall time calibration error including the linearity of the system is 0.05%. GMR checked the system by measuring the lifetime of the 14-keV nuclear excited state of ^{57}Fe and found the result to be in excellent agreement with previous experiments.

Two typical time spectra are shown in Fig. 2. The data are fitted by a three-parameter maximum-likelihood program[9] with

$$N(t) = A\exp(-\lambda t) + B,$$

where λ is the decay rate of o-Ps and B is the intensity of the uncorrelated background. This spectrum shape is an excellent approximation[1] to the expected spectrum because of the low count rates (less than 1000 counts/sec) used in this experiment. The χ^2 of the fit was equal to the number of degrees of freedom for $t > 120$ nsec.

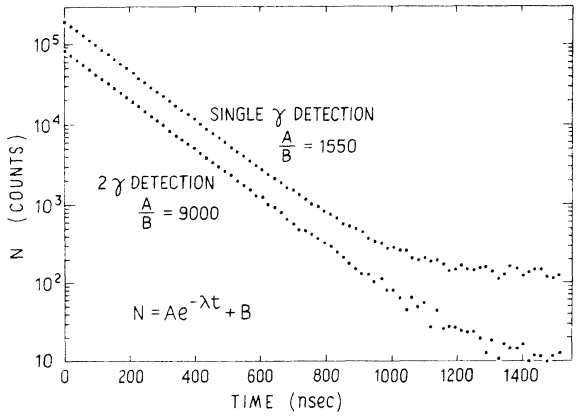

FIG. 2. Two time spectra beginning 70 nsec after the prompt peak. The 2γ data were acquired with the requirement that at least two annihilation γ rays be detected while the single-γ detection required only one or more γ rays.

The decay rates λ (as a function of can diameter, can length, and number of annihilation γ's required) are given below within 1 standard deviation:

$$\lambda(3.8\text{ cm},\ 5\text{ cm},\ 1) = 7.094 \pm 0.006\ \mu\text{sec}^{-1},$$

$$\lambda(3.8\text{ cm},\ 2.5\text{ cm},\ 1) = 7.093 \pm 0.007\ \mu\text{sec}^{-1},$$

$$\lambda(3.8\text{ cm},\ 2.5\text{ cm},\ 2) = 7.100 \pm 0.008\ \mu\text{sec}^{-1}.$$

We observed a systematic oscillation in the fitted decay rate of 0.015 μsec^{-1} about the quoted value as the start channel of the fitting program was successively stepped out in 50-nsec intervals from 70 to 670 nsec after the prompt-annihilation peak. While the origin of this effect is not completely understood at present, we estimate that it can contribute a systematic error of at most ± 0.015 μsec^{-1}.

The effect on the decay rate of nonuniform spatial detection efficiency was investigated and found to be negligible. The loss of o-Ps through the entrance hole of the confinement can into a region of lower detection efficiency was checked with the 5-cm-long can by using successively larger entrance holes. We estimate that the observed decay rate is increased 0.01 μsec^{-1} by the 6-mm hole. Thus, we find the vacuum decay rate of o-Ps to be 7.09 ± 0.02 μsec^{-1}, where 75% of the error is due to systematic effects.

To interpret the above result as the vacuum decay rate we must demonstrate that the o-Ps leaves the CEM cone and that it decays in the vacuum rather than binding to the MgO wall coating. To do this, a 5-cm-thick lead "telescopic" collimator was constructed for the NaI detectors. A 1-cm slit of each detector face was left unshielded so that the detectors were sensitive only to γ rays from a 2-cm-wide cross-sectional slice of the interaction region.

To demonstrate that the o-Ps is not bound to the CEM cone, the telescope was used to scan the interaction region (see Fig. 3). It is clear that the o-Ps is distributed over the entire length of the can with no more than 10% of the o-Ps annihilations coming from the vicinity of the cone.

In showing that the o-Ps leaves the cone we have made the first direct measurement of the maximum energy of emission of o-Ps from a surface. The telescope was centered 5 cm from the cone (with the confinement can removed) and a

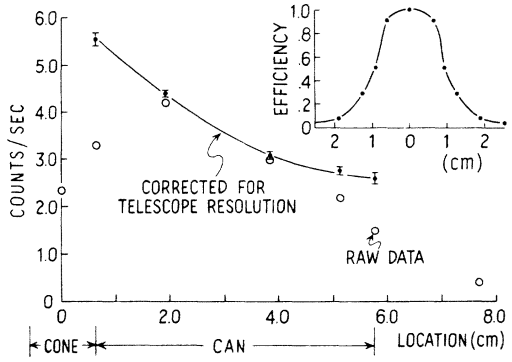

FIG. 3. Plot of the nonprompt count rate (Ps annihilations occurring 35 nsec or more after a CEM start signal) for various locations of the telescope along the axis of the interaction region. The open circles are the observed (background-corrected) count rates while the solid line shows the data corrected for the telescope spatial resolution (see inset).

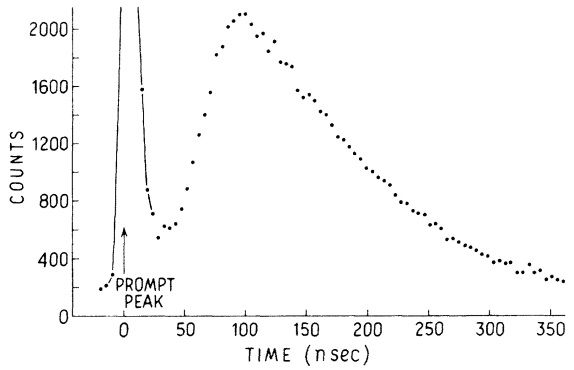

FIG. 4. Time spectrum acquired with the telescope centered on a region 5 cm in front of the CEM cone. The prompt peak is due to the transmitted and scattered prompt-annihilation γ rays; the gap after this peak clearly shows the finite time of flight for the o-Ps to enter the detection region.

time spectrum was recorded (see Fig. 4). The data were corrected for background, o-Ps decay, and the telescope spatial resolution to yield a maximum o-Ps energy of 0.8 ± 0.2 eV. This energy corresponds to an annihilation length of 5 cm and indicates that the Ps makes very few collisions with the confinement can. There are also lower-energy Ps atoms[10] that may have been formed deeper in the MgO layer or may have collided with the cone or walls.

Since the o-Ps leaves the MgO-coated cone, there is no reason to expect that the Ps should be bound to the MgO wall layer. To demonstrate that the Ps is unbound, the telescope was centered on the 5-cm-long can. Count rates and time spectra were recorded with and without the MgO-coated entrance plate to the can in place. If the o-Ps were bound to the MgO coating after a single collision then no difference should be observed since the telescope is insensitive to the region of the entrance plate. However, we found a $(20 \pm 1.5)\%$ increase in the o-Ps count rate (corrected for background and normalized to the CEM start rate) and a decrease in the decay (or disappearance) rate from 8.1 ± 0.2 μsec^{-1} to 7.15 ± 0.2 μsec^{-1} when the entrance plate was in place. This must be caused by o-Ps bouncing off the entrance plate and traveling into the detection region. An upper limit for the increase in the count rate of 36% is obtained by assuming a collimated beam of 0.8-eV Ps with specular reflection at the entrance plate. Given these restrictive assumptions, we estimate the result to be consistent with essentially 100% reflection. This result is independent of the focus of the positron beam onto the cone. In addition, if the o-Ps were bound to the MgO coating, the observed decay rate should be characteristic of the powder. The decay rates in two different evacuated powders of fumed MgO have been measured with the method of GMR yielding the lowest value of 7.19 ± 0.01 μsec^{-1}, significantly higher than the present result of 7.09 μsec^{-1}. To check the effect of the confinement surface on the decay rate, the MgO coating was removed from the side walls of the 5-cm can and a 1-cm-thick annulus of polyurethane foam was used to shiled the o-Ps from annihilation on the copper can. The decay rate was 7.11 ± 0.02 μsec^{-1}.

The effect on the fitted decay rate due to possible decays of the 2^3S_1 state with a lifetime greater than 200 nsec and with an intensity low enough to be undetected in the 2γ data is at most 0.02 μsec^{-1} To introduce a 0.02 μsec^{-1} shift with a lifetime less than 200 nsec requires at least a 0.6% ratio of 2^3S_1 to 1^3S_1 (o-Ps) intensities. However, Canter, Mills, and Berko[11] reported a ratio of excited-state production to ground-state production in MgO of only 0.1% for 25-eV positrons. They also note that *no* excited-state formation has been observed with 400-eV positrons.

In summary, we have shown that the o-Ps is free from its formation surface and has an energy less than 1 eV. There is strong evidence to indicate that the Ps is not bound to the thin MgO layer on the confinement can. Our results and previous work allow us to rule out effects of the excited states. Electric field effects, which

could not be completely ruled out in the GMR experiment, are negligible here because we use low-energy positrons and because the o-Ps is essentially free of the surface. All of the results, including the powder data, are consistent with a vacuum decay rate of 7.09 ± 0.02 μsec^{-1}, $(2.1 \pm 0.3)\%$ below the theoretical value.

The advances discussed in GMR and this work lead to many possibilities for future research. In particular, the high signal-to-noise ratio and good statistics of the present work should make possible a 200-ppm measurement of λ when the systematic effects are fully understood. Moreover, our method of detecting the time of the o-Ps formation may allow consideration of a pulsed excitation to the excited states. The Ps-atom and Ps-surface scattering can also be investigated. To help define the limits on the future use of powders in precision measurements, an attempt to observe the Ps ground-state fine-structure splitting in our uncompressed powders is now underway in collaboration with W. Frieze V. W. Hughes, and M. H. Yam.

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Limits on Charmed-Particle Production in Proton-Nucleus Collisions at 400 GeV/c*

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We have searched for the charmed and other new particles by measuring the hadron pair mass spectra in proton-nucleus collisions at 400 GeV/c. Results are presented for π^-K^+, π^+K^-, and $\pi^+\pi^-$ pairs in the mass region from 1.5 to 4.0 GeV/c^2. No evidence for narrow resonances was found. The sensitivity of the search varied from 2×10^{-30} cm^2 at 2 GeV/c^2 to 5×10^{-32} cm^2 at 4 GeV/c^2. Experimental checks were provided by the observation of a clean $J/\psi(3.1)\rightarrow\mu^+\mu^-$ signal.

We report here the first results from a general search for massive narrow resonances produced near 90° in the center-of-mass system of proton-nucleon collisions and decaying to two hadrons. The search was inspired by the hypothesis of a fourth, "charmed," degree of freedom in the hadron spectrum.[1] The introduction of a charmed fermion yields a simple and natural explanation