where.[6]

Rainbow scattering in general must also be associated with a collision between two saddle points in the complex angular momentum plane, and it should therefore be expected that the CFU method also leads to improved results[13] in more general cases.

*Work supported in part by the National Science Foundation.

[1]H. C. Van de Hulst, *Light Scattering by Small Particles* (Wiley, New York, 1957).

[2]K. W. Ford and J. A. Wheeler, Ann. Phys. (New York) 7, 259 (1959).

[3]U. Buck, Rev. Mod. Phys. 46, 369 (1974); W. A. Friedman, K. W. McVoy, and G. W. T. Shuy, Phys. Rev. Lett. 33, 308 (1974); D. A. Goldberg and S. M. Smith, Phys. Rev. Lett. 33, 715 (1974).

[4]G. Mie, Ann. Phys. (Leipzig) 25, 377 (1908).

[5]H. M. Nussenzveig, J. Math. Phys. 10, 82, 125 (1969).

[6]V. Khare and H. M. Nussenzveig, to be published.

[7]G. B. Airy, Trans. Cambridge Phil. Soc. 6, 379 (1838).

[8]In the particle picture (molecular, nuclear cases), each real saddle point is associated with a classical path, rather than a geometrical ray.

[9]C. Chester, B. Friedman, and F. Ursell, Proc. Cambridge Phil. Soc. 53, 599 (1957).

[10]Although great care has been taken to choose computed points at sufficiently small intervals, rapidly varying portions of the curves may be subject to slight interpolation errors; however, the conclusions derived from comparison among the curves would not be affected.

[11]Actually, it is the sum f_1+f_2 that represents the corresponding contribution to the efficiency factor (see Ref. 1).

[12]In Figs. 1 to 3 and in Fig. 5, these deviations are more noticeable in polarization 2, because of its lower intensity.

[13]After submission of this work, we came across the paper by M. V. Berry, Proc. Phys. Soc., London 89, 479 (1966), where the CFU method was applied to rainbow scattering by a Lennard-Jones potential, showing substantial improvement in one numerical example.

Search for Orthopositronium Decay into Four Photons as a Test of Charge-Conjugation Invariance*

Kenneth Marko and Arthur Rich
Physics Department, University of Michigan, Ann Arbor, Michigan 48104
(Received 15 July 1974)

We report the preliminary results of an experiment designed to search for the C-nonconserving decay of ground-state orthopositronium (1^3S_1) into four photons. In terms of the branching ratio $F_T^{4\gamma}=R_T^{4\gamma}(^3S_1\to 4\gamma)/R_{3\gamma}(^3S_1\to 3\gamma)$, where $R_T^{4\gamma}(^3S_1\to 4\gamma)$ is the C-nonconserving four-photon decay rate and $R_{3\gamma}(^3S_1\to 3\gamma)$ is the C-conserving three-photon decay rate of free orthopositronium in our sample, we find $F_T^{4\gamma}<8\times10^{-6}$ (68% confidence).

We report the preliminary results of a search for the C-nonconserving decay of orthopositronium (o-Ps) 1^3S_1 into four γ rays. This annihilation mode is forbidden by C invariance only.[1] Our experimental results will be discussed in terms of an upper limit on the branching ratio $F_T^{4\gamma}=R_T^{4\gamma}/R_{3\gamma}$ of the C-nonconserving 4γ decay to the C-conserving 3γ decay of o-Ps.

The branching ratio may be related to a C-nonconserving interaction Hamiltonian

$$H_i=(\lambda/m_e^8)e^4\partial_\alpha\rho_\beta F_{\alpha\delta}F_{\delta\beta}F_{\mu\nu}F_{\mu\nu} \tag{1}$$

developed by Mani and Rich.[2] This is the simplest C-nonconserving Hamiltonian that could allow the decay $^3S_1\to4\gamma$. Here λ is the coupling constant on which we set new limits. The other symbols have their usual meaning.

Evaluating the decay rate from the above interaction we find

$$R_T^{4\gamma}=1/\tau_T^{4\gamma}=88\lambda^2\ \mathrm{sec}^{-1}, \tag{2}$$

where $R_T^{4\gamma}$ is the C-nonconserving decay rate into four λ's. The branching ratio is

$$F_T^{4\gamma}=R_T^{4\gamma}/R_{3\gamma}=1.2\times10^{-5}\lambda^2, \tag{3}$$

where we have used $R_{3\gamma}=7.25\times10^6$.[3]

Previous experiments on C nonconservation in Ps have searched for the C-nonconserving 3γ decay of the 1^1S_0 states (parapositronium). The most recent of these[4] compared the threefold coincidence count rate from Ps decay into different angular configurations. The count rates are primarily due to the decay $^3S_1\to3\gamma$, with the process $^1S_0\to3\gamma$ causing a small perturbation in the counting rate. The result obtained for the branching ratio b, the ratio of the decay rates of ${}^1S_0 \to 3\gamma$ to ${}^1S_0 \to 2\gamma$, is $b = (-11.3 \pm 6.2)\times 10^{-6}$. The authors note that b must be greater than zero and infer that $b \le 2.8\times 10^{-6}$ (68% confidence).

The present investigation uses an entirely different approach. As a result of our selection of detector configuration we have no C-allowed 4γ decays that can strike our four counters! Instead of looking for a small change in a large background count rate, we have imposed a set of strict conditions on our signal to reduce the noise background from all processes which could conspire to produce a 4γ coincidence. We are therefore able to measure the count rate from ${}^3S_1 \to 4\gamma$ directly.

The experimental method is as follows: We form o-Ps by using positrons from a Na^{22} source embedded in a spherical sample of MgO powder. The powder consists of particles of average radius 100 Å with a bulk density of about 0.1 g/cm^3. The behavior of Ps in these powders has been shown, via hyperfine and lifetime measurements,[5,6] to be that of essentially free o-Ps. Positrons incident on the powder form Ps with a probability of about 30%. The o-Ps atoms live long enough to diffuse out of the grains and into the interstitial spaces where, under the proper conditions of sample preparation, they live their full free-annihilation lifetime.

The decay of o-Ps is examined by using a set of ten scintillation counters which are divided into two systems. The anticoincidence timing (ACT) system consists of six plastic scintillators and serves primarily to detect the 1.27-MeV γ ray that is emitted simultaneously with the emission of a positron in Na^{22} decay. The detection of this γ ray signals the possible formation of Ps and initiates a search by the detector system (DS) for four γ's in delayed coincidence with the 1.27-MeV γ. The DS comprises four identical counters of 4-in.×4-in. NaI(Tl) crystals mounted on RCA 4522 photomultiplier tubes located at the corners of a tetrahedron (Fig. 1). The tetrahedral geometry is used because it is a decay configuration which is forbidden for the C-allowed ${}^1S_0 \to 4\gamma$ decays,[2] but favored for the ${}^3S_1 \to 4\gamma$ mode. For sufficiently small solid angles for each counter, as in the present experiment, three counters cannot intercept a single plane through the powder source. In addition, no two counters are collinear. These latter two features are important in noise suppression from 3γ and 2γ annihilation processes, respectively.

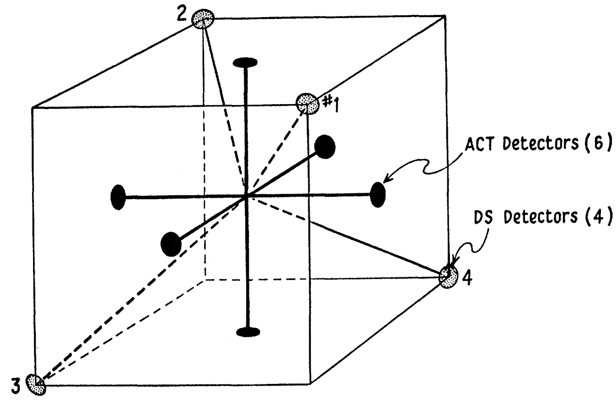

FIG. 1. Schematic representation of geometry for the scintillation counters in the charge-conjugation experiment.

The delayed-coincidence search is carried out in a period (hereafter called the search interval) of 20 to 120 nsec after ACT is triggered. During the search interval, the ACT system performs a second function and operates in anticoincidence with the DS to suppress noise from other processes that could produce four simultaneous counts in the DS. The signals from the ten counters are processed by a system of pulse shaping and logic circuitry to see if a set of energy and timing requirements are met. Signals satisfying all requirements are considered candidates for events. The observed event rate and the event rate expected from noise considerations are compared and together used to establish an upper limit to $F_T^{4\gamma}$ and to λ.

We now discuss the set of conditions that a signal must meet in order to qualify as a possible event. They are as follows: (1) Four γ's must strike the four DS counters within the fourfold fast-coincidence resolving time of 16 nsec. (2) The energy of each of the γ's must lie within the range 90–360 keV (the ΔE window). This energy range is determined by decay kinematics. (3) The sum of the energies of the four γ's must equal the Ps rest-mass energy to within approximately the energy resolution of the DS. (4) The fourfold delayed coincidence in the DS must occur within 20 to 120 nsec after the ACT system has been triggered. The delay after triggering is introduced to suppress noise from processes involving the prompt annihilation of positrons. (5) No anticoincidence pulse must be generated by the ACT system during the entire search interval. This requirement is made to suppress noise from multiple decays within the fast-coincidence resolving

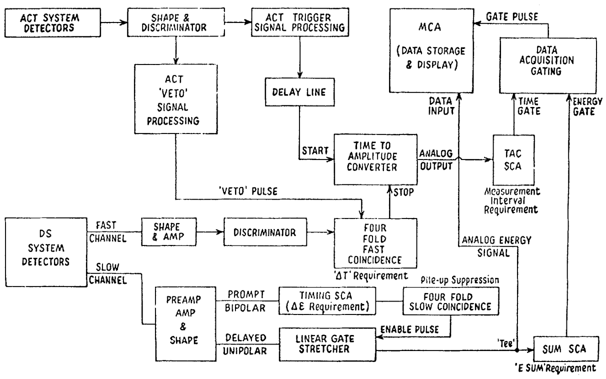

FIG. 2. Block diagram of electronics used for signal analysis and data storage.

time. (6) The fourfold coincidence in the DS must occur at a time when none of the DS counters has been struck by a γ ray for a period of 2.5 μsec. This requirement eliminates distortion of data due to pulse pileup.

A signal that meets these requirements is a condidate for an event. A block diagram of the electronics used to process the detector signals is shown in Fig. 2. A more detailed description of the instrument will be published elsewhere.

With the use of the six criteria above to specify an event, the count rate from ${}^3S_1 \to 4\gamma$ into our detector configuration is

$$R_{\mathrm{DS}}{}^{4\gamma} = R_S F_{{}^3S_1} F_T F_{DG} F_{\Delta E} F_{SI} F_G F_T{}^{4\gamma}. \qquad (4)$$

Here R_S is the Na^{22} decay rate into positrons (1.1×10^6 decays/sec). $F_{{}^3S_1}$ is the fraction of positrons that form o-Ps; we find $F_{{}^3S_1} = 0.16 \pm 0.02$. F_T is the fraction of 1270-keV γ's that trigger ACT ($F_T = 0.5$). F_{DG} is the fraction of 4γ decays that would strike the four DS counters if the decay matrix element were independent of decay kinematics. If $\Delta\Omega$ is the solid angle subtended by each DS detector at the source ($\Delta\Omega/4\pi \cong 0.024$) then $F_{DG} = 4.4(\Delta\Omega/4\pi)^3$.[2] Evaluated in this manner, F_{DG} should give a conservative estimate of the decay rate into the tetrahedral configuration, since the assumption of a constant matrix element weights all configurations equally, including those prohibited by conservation of spin and orbital angular momentum. $F_{\Delta E}$ is the fraction of 4γ decays in which all the γ's are detected and deposit their energy in the four DS scintillators. This fraction is determined experimentally for our crystals by using a set of calibrated γ-ray sources. We find $F_{\Delta E} = 0.39$, in good agreement with a calculated value of 0.42 obtained from standard NaI efficiency tables. F_{SI} is the fraction of o-Ps atoms that decay during the search interval. We have measured the lifetime of o-Ps to be 136.8 ± 2.0 nsec in our sample, so that $F_{SI} = 0.45$. We note that the observation of the free-annihilation lifetime implies an upper limit of about $1{:}10^3$ annihilations via direct annihilation or singlet decay. "Quenching" processes which would increase the o-Ps decay rate could provide a channel for 4γ decay from an admixture of the singlet-state wave function. This decay mode is not a problem, however, since the "quenching" rate is very small and, in addition, the 4γ decay rate is about 10^{-7} of the 2γ rate in any quenching process.[2] F_G is various other factors, viz., dead-time corrections in the ACT system and the DS, energy and time resolution, etc., which reduce the count rate by a factor of 0.18. Again, this factor is determined empirically and agrees with its calculated value.

The count rate from the C-nonconserving decay in our apparatus is

$$R_{DS}{}^{4\gamma} = 1.6\times 10^{-1} F_T{}^{4\gamma} \text{ count/sec}$$

$$\text{or } 0.14 \text{ count/day at } F_T{}^{4\gamma} = 10^{-5}.$$

We note that this is a factor of 80 lower than the event rate predicted in Ref. 2. This loss in event rate was due in large part to limitations in the apparatus we were able to construct with the resources available. In future work, we should be able to attain a factor-of-20 increase in the present event rate.

The most serious source of noise in the experiment occurs when two γ's from o-Ps strike two DS counters, and a 1270-keV γ from an uncorrelated Na^{22} decay and one of the 511-keV γ's from the same Na^{22} decay's positron undergoing prompt 2γ annihilation strike the remaining two DS counters. The background rate from this process, referred to as $R_{3\gamma,\mathrm{prompt}}$ is estimated to be

$$R_{3\gamma,\mathrm{prompt}} = 1.9\times 10^{-6} \text{ count/sec}$$

$$\text{or } 0.16 \text{ count/day}.$$

This noise source constitutes more than 90% of the background. Numerous other sources of noise which make up the remaining 10% of the noise rate were discussed in Ref. 2. A full discussion of all noise processes will be presented in a subsequent publication.

The actual data collection for this experiment covered a period of 24 days, although calibrations and various systematic tests consumed about four months. During the data collection period four candidates for events were found, a number consistent with the expected noise rate. From this data we find (68% confidence)

$$F_T^{4\gamma} < 8 \times 10^{-6}, \quad \lambda < 0.8.$$

The above 68% confidence interval is determined with the assumption that the event distribution is governed by Poisson statistics. Because of the low event rate, the distribution has not been established experimentally, although we have established that Gaussian statistics apply to various coincidence rates that occur lower in the logic chain.

We also note that these limits are obtained by assuming that the matrix element is independent of the decay kinematics. With reference to Mani and Rich's Hamiltonian, for which the tetrahedral configuration is a favored final state, the limits established are about a factor of 5 lower for $F_T^{4\gamma}$ and 2.7 times lower for λ.

Since the event rate is in agreement with well-established noise estimates, no systematic tests designed to change the basic event rate (see Ref. 2 for a discussion of such tests) were considered necessary. Such tests would have been instituted were there a statistically significant discrepancy between the predicted and observed event rates. In any case, several tests with the instrument for delayed-coincidence processes which could produce count rates ranging from 10 counts/sec to about 30 counts/day (with altered signal criteria to bring the count rates up to practical levels) were performed. In particular, the threefold count rate from two o-Ps γ's (from the process ${}^3S_1 \to 3\gamma$) in delayed coincidence with the ACT trigger was measured and agreed with prediction. This result substantiates the validity of our estimate of the count rate from $R_{3\gamma,\mathrm{prompt}}$ which includes this process. A lower count rate (30 counts/day) from the process in which two prompt β^+ annihilations take place within the fast-coincidence resolving time resulting in four hits on the DS was measured and also agreed with prediction.

In future work, we anticipate modifications which could permit us to set limits of better than $1:10^6$ on $F_T^{4\gamma}$. On the theoretical side, it has recently been suggested[7] that λ cannot be expected to be as large as unity as a consequence of the high-energy behavior of Mani and Rich's interaction. A value of λ as large as is required to produce an observable $F_T^{4\gamma}$ could lead to serious discrepancies between theory and experiment in high-energy e^--e^+ interactions. A change in the high-energy behavior of H_i would be necessary to preserve consistency between any observed C nonconservation and extrant high-energy observations. We hope to see further investigation of this point.

We are pleased to acknowledge helpful discussions and correspondence with Professor N. Christ, Professor G. Kane, Professor H. Mani, and Professor L. Radicati. We thank Dr. R. Paulin and Professor W. Brandt for providing us with our powder samples as well as for useful discussions. Mr. D. Hartman, Mr. S. Geman, Mr. T. Sherred, and Mr. G. Greenberg all helped in the construction and operation of the experiment. We are indebted to Mr. R. Welch at Ortec Inc. and Mr. T. Grabowski at RCA for providing information and equipment to evaluate new techniques for signal processing.

*Preliminary work on this experiment was supported by the Research Corporation, the Institute of Science and Technology, the Office of Research Administration, and the Phoenix Project of the University of Michigan. The project is now supported by the National Science Foundation under Grants No. GP24924 and No. GP41654.

[1]L. Michel, Nuovo Cimento 10, 319 (1953).

[2]H. S. Mani and A. Rich, Phys. Rev. D 4, 122 (1971).

[3]A. Ore and J. L. Powell, Phys. Rev. 75, 1696 (1949).

[4]A. P. Mills and S. Berko, Phys. Rev. Lett. 18, 420 (1967).

[5]D. J. Judd, Y. K. Lee, L. Madansky, E. R. Carlson, V. W. Hughes, and B. Zundell, Phys. Rev. Lett. 30, 202 (1973).

[6]R. Paulin and G. Ambrosino, J. Phys. (Paris) 29, 263 (1968).

[7]N. Christ, private communication.