pressed in more compact form as

$$-(1/2mm')\epsilon_{\mu\nu\lambda\sigma}p_\lambda q_\sigma \bar{\Xi}^0(p')\Omega_\nu^-(p),$$

where $p=p'+p$ and $q=p'-p$. The current is clearly conserved.

[9]We thank Professor A. Salam for this observation.

[10]Since we are assuming exact SU(3) symmetry, actually there is no contribution from the second term in each bracket. We write these terms for completeness.

[11]K. Kawarabayashi, Phys. Rev. Letters 14, 86, 169(E) (1965); K. Kawarabayashi and R. White, International Centre for Theoretical Physics Report No. IC/65/5 (to be published); S. P. Rosen and P. Pakvasa, Phys. Rev. Letters 18, 773 (1964); M. Suzuki, Phys. Letters 14, 64 (1965); G. Altarelli, F. Bucella, and R. Gatto, Phys. Letters 14, 70 (1965); P. Babu, Phys. Rev. Letters 14, 166 (1965); R. Ferrari, M. Konuma, and E. Remiddi, to be published.

[12]A similar cancellation occurs in the course of the calculation of spin-2^+ meson decay into two pions (R. Delbourgo, private communication). This might suggest a new selection rule in $\tilde{U}(12)$ symmetry.

[13]This procedure is equivalent to regarding the gradient operator ∇ as a vector in the group SU(2) and constructing the interactions such that they transform as the $(\underline{8},\underline{1})$ member of $\underline{35}$.

EXPERIMENTAL TEST OF CHARGE-CONJUGATION INVARIANCE*

D. Cline and R. M. Dowd
Department of Physics, University of Wisconsin, Madison, Wisconsin
(Received 1 March 1965)

The decay mode

$$\pi^0 \to \gamma+\gamma+\gamma \qquad (1)$$

has been sought in order to test the validity of C (charge-conjugation) invariance for electromagnetic and strong interactions. It is well known that decay mode (1) is allowed by all selection rules except C invariance.[1] Since the decay involves an additional photon in the final state, compared to ordinary π^0 decay, the rate for decay mode (1) should be depressed by at least (1/137) relative to the normal mode even if C invariance is badly violated. The only previous search known to us for decay mode (1)[2] obtained an upper limit of 1.2% relative to the normal mode and was, therefore, insensitive to possible violation of C invariance. The motivation for the present experiment came from the fact that no experimental test of C invariance with good statistics had been performed, although the results of some experiments do give indication that C invariance is valid in strong and electromagnetic interactions.[3]

The π^0 mesons for this experiment were produced with a unique energy in the reaction

$$K^+ \to \pi^+ + \pi^0 \qquad (2)$$

($K_{\pi 2}$); the K^+ mesons from the Berkeley Bevatron were stopped in the Lawrence Radiation Laboratory heavy-liquid bubble chamber, filled with C_3F_8. The radiation length of C_3F_8 is ~28 cm. Reaction (2) is particularly suited to the detection of decay mode (1), because the direction of the three gamma rays and the direction of the π^+ are sufficient to overdetermine, by one constraint, the decay kinematics. Since only angle measurements are involved, this constraint is quite tight.

The detection procedure for decay mode (1) via $K_{\pi 2}$ decay consisted of searching for all stopped K^+ decays with a single positive secondary that had three electron-positron pairs pointing at the decay vertex.[4] The secondary was not required to stop in the chamber, but the following conditions were imposed on candidates in order to eliminate most of the "non-$K_{\pi 2}$" background:

(1) The maximum length of the secondary and/or the ionization was required to be inconsistent with τ' decay. This includes events where the secondary scatters or makes a star.

(2) No events were accepted where the secondary was definitely a positron. If a secondary stopped in the chamber, the track ending and/or length was required to be inconsistent with the $K_{\mu 3}$ decay.

In all, film containing 210 000 $K_{\pi 2}$ decays was searched for three-gamma events. A total of 74 events satisfying the above conditions was found. These events were measured on a digitized microscope and reconstructed in space. The momentum of the electrons and positrons was obtained from curvature, and the bremsstrahlung energy loss was corrected for using the method of Behr and Mittner.[5] All events were tested for the hypothesis of $K_{\pi 2}$

decay followed by the π^0 decaying via mode (1). Of the 74 events, nine events had an acceptable χ^2 for this hypothesis. These events were looked at carefully on the scanning table, and in every case, one of the three electron-positron pairs also pointed to another decay vertex in the chamber or pointed to an electron or positron in the chamber in such a way as to be consistent with its being a bremsstrahlung photon. We expect that less than 0.01 of all three-gamma decays of the π^0, with the π^0 coming from a $K_{\pi 2}$ decay vertex in the chamber, will have a gamma that also points to another decay vertex in the chamber, or will have a gamma that appears to be a bremsstrahlung from an electron or positron in the chamber.[6] It is therefore more probable, by at least a factor of 10, that these nine events are examples of background.[7] The over-all detection efficiency was computed by generating fake $K_{\pi 2}$ with the π^0 decaying via mode (1). The energy and angular distribution of the photons was generated according to Lorentz-invariant phase space. The conversion efficiency for each photon was computed excluding the chamber volume within 5 cm of the chamber walls. The scanning efficiency was determined from a double scan for τ' decay with three gammas converting in the chamber. Folding in the total detection efficiency, including the scanning efficiency, an effective sample of ~2600 π^0 decays was searched for decay mode (1). The upper limit on the decay mode is

$$\frac{\Gamma(\pi^0 \to 3\gamma)}{\Gamma(\pi^0 \to 2\gamma)} < 3.8 \times 10^{-4}. \quad (3)$$

Assuming a C-nonconservation parameter G, we write for the 3γ rate

$$\Gamma(\pi^0 \to 3\gamma) \sim |G|^2 (1/137)\Gamma(\pi^0 \to 2\gamma). \quad (4)$$

The 90% confidence upper limit on $|G|^2$ is

$$|G|^2 < 0.12. \quad (5)$$

Bernstein and Michel[1] have pointed out that an experiment to detect circular polarization of the gamma rays from ordinary π^0 decay puts a limit on the violation of PT (parity×time reversal) invariance for this system.[8] The limit on C-invariance violation of this experiment combined with the experiment of reference 8 provides a crude but direct test of CPT invariance for the π^0 meson. The upper limit on the CPT-nonconserving parameter is essentially the same as that of the C-nonconserving parameter in (5).

We would like to thank Professor Wilson Powell and his group for helping us obtain the K^+ exposure and for loaning us the film. We would also like to thank Professor W. F. Fry and U. Camerini for useful discussions and Professor R. March for use of his fitting program.

---

*Work supported in part by the Research Committee of the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation, and in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-881.

[1]J. Bernstein and L. Michel, Phys. Rev. 118, 871 (1960).

[2]R. P. Ely and D. H. Frisch, Phys. Rev. Letters 3, 565 (1959).

[3]N.-h. Xuong, G. R. Lynch, and C. K. Hinrichs, Phys. Rev. 124, 575 (1961); A. H. Rosenfeld, D. Carmony, and R. Van de Walle, Phys. Rev. Letters 8, 293 (1962). No direct test of C invariance has been performed for positronium. See, for example, J. Schechter, Phys. Rev. 132, 841 (1963).

[4]Some events were found with two electron-positron pairs and one Compton electron. These events were not used in the analysis because of the difficulty of ascertaining where the Compton electron "points."

[5]L. Behr and P. Mittner, in Proceedings of the International Conference on Instrumentation for High-Energy Physics at CERN, edited by F. M. Farley and M. Meyer (North-Holland Publishing Company, Amsterdam, 1963), p. 446.

[6]This was obtained by counting the number of electron-positron pairs that pointed to a decay vertex in the chamber and also pointed at a τ decay.

[7]Seven of the events were consistent with one gamma being bremsstrahlung from one of the converted gammas from a $K_{\pi 2}$ decay. These events fit the hypothesis for decay mode (1) trivially.

[8]R. L. Garwin, G. Gidal, L. M. Lederman, and M. Weinrich, Phys. Rev. 108, 1589 (1957). The observed circular polarization of the photons from π^0 decay was $(2.0 \pm 9.0)\%$. Using this limit and the fact that a circular polarization would come about because of interference between the PT-invariant amplitude and the PT-noninvariant amplitude, the authors state that the upper limit on $|F|^2$ is 8×10^{-3}, where F is the mixing parameter.