tional Symposium on Electron and Photon Interactions at High Energies, Stanford Linear Accelerator Center, September, 1967 (Clearing House of Federal Scientific and Technical Information, Washington, D.C., 1968).

[5]Experimental result on $\gamma p \rightarrow \pi^+ n$ gives the E_γ dependence of the cross section as $\sim 1/E_\gamma^2$ for E_γ above 2 GeV. See B. Richter, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968).

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TIME REVERSAL AND THE K^0 MESON DECAYS. II.

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Current data on the decay $K^0 \rightarrow 2\pi$ are used to extend the results of an earlier analysis testing these reactions for T invariance irrespective of CPT symmetry. The extended analysis together with recent work on pion production data allow us to establish that T is not conserved in these decays.

In a recent paper[1] (I), we showed that time-reversal symmetry is most likely broken in the decays of the K^0 meson into two pions. Of course, this result had been inferred via the fundamental CPT theorem ever since the discovery in 1964 that CP symmetry is not conserved in these reactions.[2] However, the CPT theorem itself is being tested most rigorously at the level of accuracy in principle attainable in the sensitive K^0 interference experiments, although present data do not suffice to decide this issue. Therefore, despite a strong theoretical prejudice that CPT will be found to remain valid, statements concerning T invariance or its breaking which can be made at this time based upon existent data are presumably useful—especially since T invariance has been validated when tested directly elsewhere, as in the null results for the electric dipole moment of the neutron and electron and the absence of a transverse muon spin polarization in $K_{\mu 3}$ decays.[3]

Improved data have provided a twofold impetus for the present work:

(1) In I it was only assumed that the phase θ_{+-} of the Wu-Yang[4] parameter η_{+-} was known to lie roughly in the first quadrant in determining the region of T nonconservation. Despite persistent difficulties in determining the regeneration phase in matter, θ_{+-} is presently known to a considerably higher degree of accuracy. Moreover, a vacuum regeneration result has since been obtained by Böhm et al.,[5] permitting greater confidence in our knowledge of θ_{+-}. Using these improved data, the region of T nonconservation in Fig. 2 of I can be expanded appreciably at the expense of the ruled areas indicating ambiguity in that figure. The new results are shown in Fig. 1 of the present paper where the boundaries of the regions of T nonconservation are given for various compilations of the data on the parameter θ_{+-}. Included are the Vienna-Conference average[6] $\langle \theta_{+-} \rangle = 59° \pm 6°$ and the recent CERN-Conference quotation $\langle \theta_{+-} \rangle = 43° \pm 8°$.[7] It is seen that the boundaries of these regions have become relatively insensitive to these changes. An appreciable contribution to the width of the crescent-shaped domain in Fig. 1 where T nonconservation cannot be established comes from imprecision in the phase of $\bar{\epsilon}$ due to possible 3π and leptonic CP-nonconserving contributions to the mass matrix as discussed in I.

(2) A possible ambiguity in the value of the s-wave pion-pion phase-shift difference $\delta_0 - \delta_2$ (isospin indexed) appears to have been cleared up. The preferred solution for δ_0 of Marateck et al.[8] shows that the value of this phase shift lies well within the first quadrant at 500 MeV. (At the kaon rest mass, δ_2 is known to be small and negative, whence the value of the difference $\delta_0 - \delta_2$ is dominated by δ_0.) Previously a fourth- (or second-) quadrant solution for $\delta_0 - \delta_2$ could not be ruled out. Therefore, in I a definite conclusion of T nonconservation could not be stated. As noted in an appendix, the prior possibility of a third-quadrant solution is of no relevance. [We remark that even the solutions for this parameter in Fig. 3(a) of Ref. 8 that are discarded in Fig. 3(b) of that paper lie in the first quadrant, but much closer to 90° than the preferred solution.]

Based upon the results shown in Fig. 1 and the

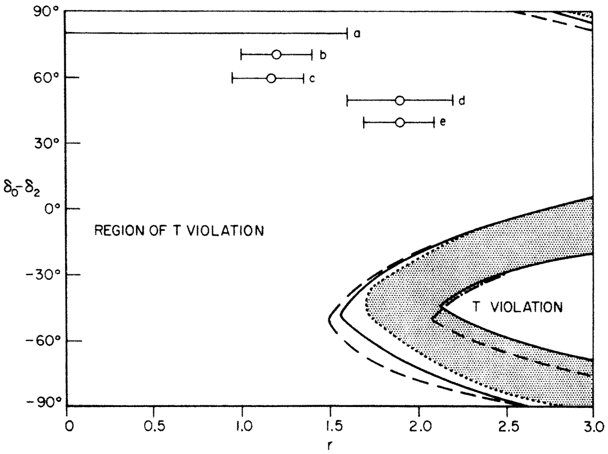

FIG. 1. Extended region of T nonconservation. $r \equiv |\eta_{00}|/|\eta_{+-}|$. Values of r based upon recent measurements of $|\eta_{00}|$ are shown by the points a–e for $|\eta_{+-}| = (1.90 \pm 0.06)\times 10^{-3}$ [V. L. Fitch, Comments Nucl. Particle Phys. 2, 63 (1968)]. The points a–e are given respectively, by the following workers: a, D. F. Bartlett et al., Phys. Rev. Letters 21, 558 (1968); b, M. Banner, J. W. Cronin, J. K. Liu, and J. L. Pilcher, Phys. Rev. Letters 21, 1107 (1968); c, I. A. Budagov et al., Phys. Letters 28B, 215 (1968); d, J. M. Gaillard et al., Rutherford Laboratory Report No. RPP/H135, 1968 (to be published); e, R. J. Cence et al., in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished). The solid curves were derived using the pre–Vienna-Conference average value $\langle\theta_{+-}\rangle = 49° \pm 8°$ [N. Barash-Schmidt et al., University of California Lawrence Radiation Laboratory Report No. UCRL 8030, 1968 (unpublished); A. Barbaro-Galtieri, private communication]. The broken curves were obtained using the value $\langle\theta_{+-}\rangle = 59° \pm 6°$ current at the Vienna Conference (Cronin, Ref. 6). The shaded regions, where T nonconservation cannot be established, were determined using the recent CERN-Conference average, $\langle\theta_{+-}\rangle = 43° \pm 8°$ (Steinberger, Ref. 7). Within the regions labeled "T violation," the T-invariant triangular relations discussed in I fail to be obeyed by at least 2.5 standard deviations in the variable θ_{+-} for all compilations listed, i.e., for $23° < \theta_{+-} < 74°$. Individually, the various curves represent 2.5 σ boundaries for each compilation cited.

work of Marateck et al., we conclude that present data suffice to establish that time-reversal symmetry is broken in the decays of the K^0 meson into two pions. Our result is consistent with but otherwise independent of the validity of the CPT theorem, which these same experiments ultimately will test.[9]

Appendix (Technical remarks).—(1) Our analysis breaks down when $\delta_0-\delta_2 = \pm 90°$ since it was assumed in I that the quantity $|A_2/A_0|$, discussed there, is small compared with unity. Since $A_2/A_0 \propto \sec(\delta_0-\delta_2)$, the approximation is poor in the vicinity of ±90°. This proviso is wholly irrelevant for the preferred solution for $\delta_0-\delta_2$ given by Marateck et al. (It is pertinent, but probably unimportant for the solutions they discard.) (2) The 180° phase ambiguity in $\delta_0-\delta_2$ discussed by Marateck et al. is irrelevant from our point of view since Fig. 1 (or Fig. 2 of I) remains invariant under transformation $(\delta_0-\delta_2) \to (\delta_0-\delta_2+180°)$. [See Eq. (6) of I.]

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Note added in proof.—Since submission of this paper, I have learned that T invariance has been questioned in the reactions $p, n \rightleftharpoons d, \gamma$ by a Princeton group [C. E. Friedberg et al., Bull. Am. Phys. Soc. 14, 76 (1969) and D. H. Bartlett, private communication] and by a Universities of California at Los Angeles and Berkeley–Michigan Collaboration.[10]

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[4]T. T. Wu and C. N. Yang, Phys. Rev. Letters 13, 380 (1964).

[5]A. Böhm et al., Phys. Letters 27B, 321 (1968) report $\theta_{+-} = 46° \pm 15°$. The preliminary value $\theta_{+-} = 68° \pm 8°$ for Cu regeneration quoted by V. Bisi et al., in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished) is to be revised downward. Their result, $\theta_{+-} - \theta_f = 98° \pm 6°$ remains unchanged; C. Rubbia, private communication. However, the value of θ_f quoted by S. Bennett, D. Nygren, H. Saal, J. Sunderland, and J. Steinberger, Phys. Letters 27B, 239 (1968) has been revised. Presently $\theta_f = -42° \pm 5°$; S. Bennett, private communication. Thus, the result of Bisi et al. becomes $\theta_{+-} = 56° \pm 8°$.

[6]J. W. Cronin, in Proceedings of the Fourteenth In-

ternational Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), and private communication.

[7]J. Steinberger, in Proceedings of the CERN International Conference on Weak Interactions, Geneva, Switzerland, 1969, as reported to me by Vincent Peterson, private communication.

[8]S. Marateck et al., Phys. Rev. Letters 21, 1613 (1968). At 500 MeV, $\delta_0-\delta_2=+30°\pm10°$; W. Selove, private communication.

[9]CPT symmetry has, of course, been confirmed when tested elsewhere, as in the charged-pion-lifetime result, $\tau_+/\tau_-=1.000\,64\pm0.000\,69$ of S. Ayres et al., Phys. Rev. Letters 21, 261 (1968).

[10]M. Longo and J. Helland, private communication.

PHOTON ABSORPTION IN NUCLEI AND VECTOR-MESON DOMINANCE

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We show that in some applications of vector-meson dominance to photon reactions in nuclei the mass of the ρ meson cannot be neglected at photon energies of current interest. Thus, in calculation of the photon absorption cross section in the optical-model approximation, the effect of the ρ mass m_ρ is important for photon energies $\omega \lesssim m_\rho^2(R/\sigma N)^{1/2}$, where R and N are the radius and density of the nucleus, and σ is the total ρ-nucleon cross section.

It has been pointed out by Bell[1] and by Stodolsky[2] that vector-meson dominance implies hadronlike behavior for photons in interactions with nuclei. If nuclear reactions initiated by photons and ρ mesons are proportional, photons should appear to be strongly absorbed in photonuclear processes at high energies. For example, the total photoabsorption cross section should vary approximately as $A^{2/3}$ instead of as A, where A is the number of nucleons. If the ρ mass is neglected, the linear A dependence of this cross section does not occur because of destructive interference between the photon and ρ-meson waves in the nucleus. However, at photon energies ω such that the coherence length ω/m_ρ^2 between the photon and ρ-meson waves is comparable with or less than the radius R of the nucleus we expect that the ρ mass is important.[3] We will show that the volume contribution to the cross section is then not canceled by ρ-γ interference.

To illustrate the importance of the ρ-γ mass difference we calculate the scattering of photons using the optical model for the nucleus in the eikonal approximation. At impact parameter b, the photon wave ψ_γ and the ρ-meson wave ψ_ρ satisfy the following equations in the nucleus:

$$\partial\psi_\gamma/\partial z = ik_\gamma n_{\gamma\gamma}\psi_\gamma + ik_\gamma n_{\gamma\rho}\psi_\rho, \tag{1}$$

$$\partial\psi_\rho/\partial z = ik_\rho n_{\rho\gamma}\psi_\gamma + ik_\rho n_{\rho\rho}\psi_\rho, \tag{2}$$

where $n_{ij}=\delta_{ij}+2\pi N f_{ij}/k_i^2$ is the complex index of refraction in the nucleus in terms of the forward γ- and ρ-nucleon scattering amplitudes f_{ij}. For an incident photon of momentum k_γ on a nucleus of radius R the boundary conditions are

$$\psi_\gamma = \exp[-ik_\gamma(R^2-b^2)^{1/2}], \tag{3}$$

$$\psi_\rho = 0 \tag{4}$$

at $z=-(R^2-b^2)^{1/2}$.

The solution of these equations is elementary. If we keep only lowest order terms in the electromagnetic coupling we obtain for $-(R^2-b^2)^{1/2} \leqslant z \leqslant (R^2-b^2)^{1/2}$

$$\psi_\gamma = \exp[ik_\gamma z], \tag{5}$$

$$\psi_\rho = \frac{k_\rho n_{\rho\gamma}}{k_\gamma - k_\rho n_{\rho\rho}}\left[\exp(ik_\gamma z) - \exp\{ik_\rho n_{\rho\rho}[z+(R^2-b^2)^{1/2}] - ik_\gamma(R^2-b^2)^{1/2}\}\right]. \tag{6}$$

The forward elastic photon scattering $F_{\gamma\gamma}$ is then given by

$$F_{\gamma\gamma} = 2\pi N\int_0^R db\, b\int_{-(R^2-b^2)^{1/2}}^{(R^2-b^2)^{1/2}} dz\,[f_{\gamma\gamma}\psi_\gamma(z,b) + f_{\gamma\rho}\psi_\rho(z,b)]\exp(-ik_\gamma z), \tag{7}$$

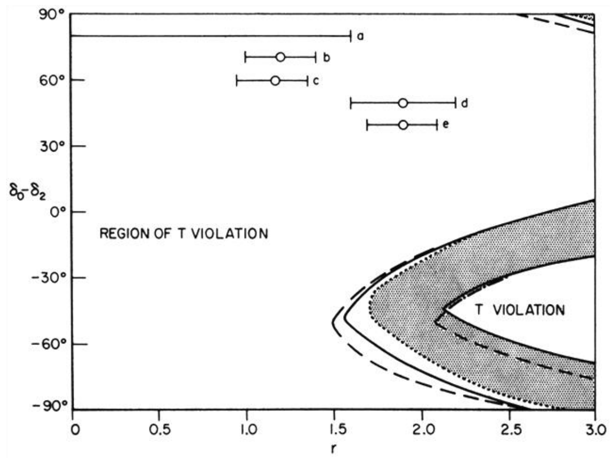

FIG. 1. Extended region of T nonconservation. $r \equiv |\eta_{00}|/|\eta_{+-}|$. Values of r based upon recent measurements of $|\eta_{00}|$ are shown by the points a–e for $|\eta_{+-}| = (1.90 \pm 0.06) \times 10^{-3}$ [V. L. Fitch, Comments Nucl. Particle Phys. 2, 63 (1968)]. The points a–e are given respectively, by the following workers: a, D. F. Bartlett et al., Phys. Rev. Letters 21, 558 (1968); b, M. Banner, J. W. Cronin, J. K. Liu, and J. L. Pilcher, Phys. Rev. Letters 21, 1107 (1968); c, I. A. Budagov et al., Phys. Letters 28B, 215 (1968); d, J. M. Gaillard et al., Rutherford Laboratory Report No. RPP/H135, 1968 (to be published); e, R. J. Cence et al., in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished). The solid curves were derived using the pre–Vienna-Conference average value $\langle\theta_{+-}\rangle = 49° \pm 8°$ [N. Barash-Schmidt et al., University of Califormia Lawrence Radiation Laboratory Report No. UCRL 8030, 1968 (unpublished); A. Barbaro-Galtieri, private communication]. The broken curves were obtained using the value $\langle\theta_{+-}\rangle = 59° \pm 6°$ current at the Vienna Conference (Cronin, Ref. 6). The shaded regions, where T nonconservation cannot be established, were determined using the recent CERN-Conference average, $\langle\theta_{+-}\rangle = 43° \pm 8°$ (Steinberger, Ref. 7). Within the regions labeled "T violation," the T-invariant triangular relations discussed in I fail to be obeyed by at least 2.5 standard deviations in the variable θ_{+-} for all compilations listed, i.e., for $23° < \theta_{+-} < 74°$. Individually, the various curves represent 2.5 σ boundaries for each compilation cited.