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Comments on the Unitarity Bound in $K_L^0 \to \mu^+\mu^-$†

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Two alternatives to reconcile the present disagreement between experiment and the "simple" unitarity bound in $K_L^0 \to \mu^+\mu^-$ are considered. These alternatives presume that *CP* violation does not play the dominant role (via Reϵ) in the resolution of this puzzle. They are (1) the introduction of new muonic interactions, and (2) the existence of a new pseudoscalar meson. The first alternative can already be eliminated by present experimental evidence. The second alternative must satisfy a number of restrictions.

I. INTRODUCTION

Recently, the result of an experimental search for the decay

$$K_L^0 \to \mu^+\mu^- \tag{1}$$

was reported by Clark *et al.*[1] They observed no clear evidence for reaction (1), and set an upper bound to this branching ratio. It is

$$R_L^{\text{exp}}(\mu^+\mu^-) \leq 1.8\times 10^{-9} \text{ (90\% confidence limit)}. \tag{2}$$

This upper bound is significantly *below* the "simple" unitarity lower bound[2,3] calculated from assuming (a) unitarity and *CPT* invariance, (b) *CP* invariance, and (c) dominance of the unitarity sum for reaction (1) by the two-photon state.[4] (See Fig. 1.) Taking the branching ratio for[5]

$$K_L^0 \to \gamma\gamma \tag{3}$$

to be

$$R_L^{\text{exp}}(\gamma\gamma) \simeq 5\times 10^{-4}, \tag{4}$$

the "simple" unitarity bound[2,3] gives

$$R_L^{\text{cal}}(\mu^+\mu^-) \geq 6\times 10^{-9}. \tag{5}$$

Dimensional estimates on the validity of (c) have shown that other intermediate states can contribute no more than 10% in the unitarity sum.[3] A detailed estimate of the $\pi\pi\gamma$ contribution[6] and a model estimate of the $\pi\pi\pi$ contribution[7] both support this conclusion.

The role of (b) in deriving the inequality (5) has also been examined. Two cases have been studied:

(i) Neglecting Reϵ,[8] the real part of the *CP*-violating parameter in the neutral kaon system, it was shown that a lower bound still holds.[9-11] This lower bound may be 18% lower than (5) if the decay

$$K_L^0 \to (\gamma\gamma)_{CP=+1}, \tag{6}$$

which violates *CP*, dominates reaction (3). Conversely, the experimental limit given by (2) was used by Farrar and Treiman[9] to set an upper bound[12] on the presence of reaction (6).

(ii) Retaining Reϵ but assuming (c), a triangle inequality was derived by Christ and Lee[7] relating the decay rate for

$$K_S^0 \to \mu^+\mu^- \tag{7}$$

to the decay rates for reactions (1) and (3). In this case, the branching ratio for reaction (7) is constrained [using (2)] to be within

$$10^{-5} \geq R_S^{\text{CL}}(\mu^+\mu^-) \geq 5\times 10^{-7}. \tag{8}$$

This range is roughly 6 orders of magnitude above the corresponding "simple" unitarity bound for the reaction. It also requires the presence of significant *CP* violation either in reaction (7) or in reaction (3).[13]

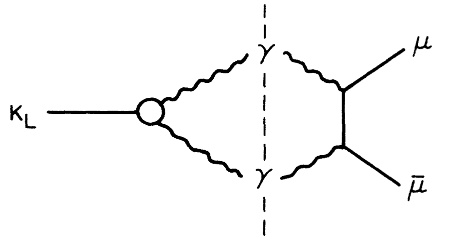

FIG. 1. Contribution of the two-photon state to the absorptive part of $K_L^0 \to \mu^+\mu^-$ is shown.

A candidate for lowering the "simple" unitarity bound therefore exists,[7] and it can be tested via the inequalities in (8). The present status of this branching ratio is[14]

$$R_S^{\exp}(\mu^+\mu^-) \leq 7\times 10^{-6} \tag{9}$$

and it may be possible to improve this by about an order of magnitude within a year.[15]

Although this is certainly an interesting possibility for resolving the present difficulty, it may still be worthwhile to look for other alternatives. For this purpose, we assume in this note that Reϵ does not play a role in the resolution of this puzzle. Thus we equate the absorptive and imaginary parts of the amplitude(s) for reaction (1).[8] It seems apparent in this case that if the relevant existing experimental results hold, the contribution, in the standard way, of intermediate states in the unitarity equation cannot generate terms of sufficient magnitude to effect the necessary cancellation of the two-photon contribution. Thus novel solutions would be needed. Whatever the alternative, we must assume that in order to reconcile (2) and (5) the dispersive part of the amplitude(s) for reaction (1) is small and that the absorptive part(s) will be largely canceled by the particular mechanism which is introduced.

II. HYPOTHETICAL MUONIC INTERACTIONS

If new muonic interactions exist, the absorptive part of the amplitude(s) for reaction (1) may contain additional terms which would directly invalidate the "simple" unitarity bound. Nonmuonic reactions remain largely unaffected, thus no absorptive part would be introduced into the amplitude(s) for reaction (3). Such interactions are attractive in that muons and electrons would be *(ad hoc)* different.[16] However, with the great precision to which muon quantum electrodynamics (QED) has been checked,[17] and with the absence of anomalies in hadronic production of muon pairs,[18] these interactions may not (and indeed, do not) survive such tests.

We consider hypothetical muonic interactions for the three possible intermediate states in the unitarity sum for reaction (1).[19] The contribution of the assumed interactions to the absorptive part of the amplitude for reaction (1) is given in Fig. 2, along with the form of these interactions.

Figure 2(a) shows a modification of muon QED. In order for the needed cancellation to occur, the strength of the assumed interaction will be

$$|g_a| M_K^{\,3} \simeq 0.7e^2 \,. \tag{10}$$

A coupling of this order of magnitude is completely ruled out by experiments on photoproduction of wide-angle muon pairs[20] and by the measured values[21] of the muon anomalous magnetic moment, $\frac{1}{2}(g_\mu - 2)$.[22]

The hypothetical three-pion–muon-pair interaction is shown in Fig. 2(b). It is a direct coupling of muons to hadrons. Here we find that

$$|g_b| M_K^{\,2} \simeq 0.5 \,. \tag{11}$$

With such an interaction strength, there would be copious production of muon pairs in hadronic reactions. These have not been observed.[18] Furthermore, such an interaction would also contribute significantly[23] to $\frac{1}{2}(g_\mu - 2)$.

The hypothetical interaction for the $2\pi\gamma$ intermediate state is also taken to exist between pions and muons, and it is given in Fig. 2(c). The required coupling strength is again large, i.e.,

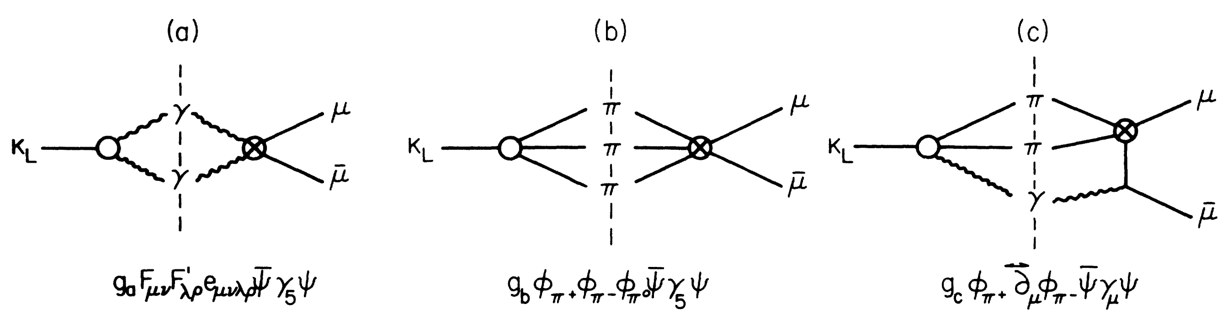

FIG. 2. Anomalous muonic interactions are assumed (crossed circles) for the possible intermediate states, i.e., (a) two-photon, (b) three-pion, and (c) two-pion-plus-photon, in order to generate additional terms in the absorptive part of $K_L^0 \to \mu^+\mu^-$ to cancel the contribution from Fig. 1. The explicit forms of the interactions are also given.

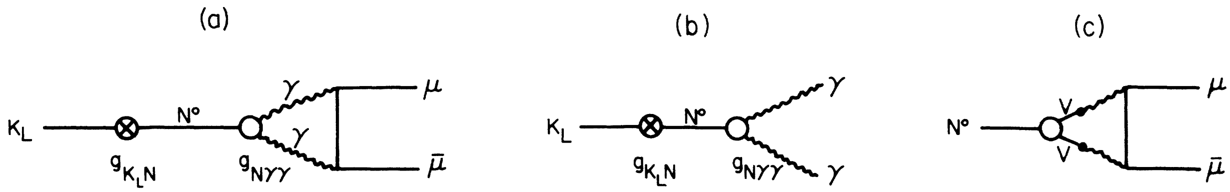

FIG. 3. Existence of a new particle, N^0, and its contributions to (a) $K_L^0 \to \mu^+\mu^-$ and (b) $K_L^0 \to \gamma\gamma$ are shown. (c) The decay $N^0 \to \mu^+\mu^-$ with the vector-dominance model of Quigg and Jackson (Ref. 2) is also shown.

$$|g_c|M_K^2 \simeq 1\,, \tag{12}$$

and it is ruled out in a manner similar to the above.

The strength of the hypothetical couplings can be estimated from simple arguments. For the first case, power counting in e is sufficient. For the other cases, a stronger coupling is needed to overcome the effects of three-body phase space. Since the required coupling strengths for new muonic interactions are large, these can already be ruled out by present data. The introduction of new muonic interactions therefore does not seem to resolve the disagreement between (2) and (5).

III. NEW PARTICLE AT K^0 MASS

If a new particle (N^0) with $J^{PC} = 0^{-+}$ exists with its mass near that of the neutral kaon[24] and is coupled to two photons, then the absorptive part of the amplitude for reaction (1) would have contributions from the intermediate N^0 state in addition to that from the usual two-photon state. The presence of N^0 would also necessarily contribute to reaction (3).

If N^0 is to contribute significantly to the absorptive part of the amplitude for reaction (1), the decay mechanism shown in Fig. 3(a) must be important. Its amplitude is given by

$$L_N \equiv \frac{g_{K_L N}}{2M_K(\Delta_N - i\frac{1}{2}\Gamma_N)} A_{N^0 \to \mu\bar{\mu}}\,. \tag{13}$$

Reaction (3), proceeding via the N^0 pole (it dominates the π^0 and η^0 pole contributions), is shown in Fig. 3(b). Its amplitude is given by

$$L_{\gamma\gamma} \equiv \frac{g_{K_L N}}{2M_K(\Delta_N - i\frac{1}{2}\Gamma_N)} g_{N^0\gamma\gamma}\,, \tag{14}$$

where $\Delta_N \equiv M_N - M_K$ and Γ_N is the N^0 width. We separate $A_{N^0\to\mu\bar{\mu}}$ into real and imaginary parts, i.e.,

$$A_{N^0\to\mu\bar{\mu}} \equiv R + iI\,. \tag{15}$$

Since the absorptive part of the amplitude for reaction (1) is equal to $\mathrm{Im}L_N$, it can be picked out from Eq. (13),

$$\mathrm{Im}L_N \equiv \frac{g_{K_L N}}{2M_K(\Delta_N^2 + \frac{1}{4}I_N^2)}(\Delta_N I + \tfrac{1}{2}\Gamma_N R)\,, \tag{16}$$

and $\mathrm{Re}L_N$ is assumed to have been canceled (by second-order weak or neutral-current interactions, etc.).

For $A_{N^0\to\mu\bar{\mu}}$, we take the vector-dominance model of Quigg and Jackson[2] which is shown in Fig. 3(c). With usual vector-meson masses, i.e., $M_V \sim 1$ GeV/c^2, the real (R) and imaginary (I) parts of $A_{N^0\to\mu\bar{\mu}}$ are approximately equal.[2] For a cancellation to be effective in $\mathrm{Im}L_N$, it then becomes necessary that

$$|\Delta_N| \sim \Gamma_N\,. \tag{17}$$

As seen from Eq. (14), $L_{\gamma\gamma}$ will have a significant imaginary part. Furthermore, Γ_N is expected to be small in any model ($\lesssim$100 keV, a discussion will follow); thus N^0 will have essentially the same mass as the K_L^0.

The proximity of the N^0 and K_L^0 masses would imply a significant mixing of the two states unless the coupling between these states is very weak. To examine the strength of this interaction, we consider reaction (3) which has been taken to be dominated by the N^0 pole [Fig. 3(b)]. Previous estimates of this decay assumed π^0 and η^0 pole dominance (giving a purely dispersive amplitude), and yielded roughly the observed result. We use the η^0-pole model for comparison. Thus, using (17),

$$\left|\frac{g_{K_L N}}{g_{K_L \eta}}\right| \simeq \left(\frac{\Gamma_{\eta\to\gamma\gamma}}{\Gamma_{N\to\gamma\gamma}}\right)^{1/2} \frac{\Gamma_{N\to\mathrm{all}}}{|M_\eta - M_K|} \lesssim 10^{-3}\,, \tag{18}$$

for $\Gamma_N \lesssim 100$ keV and $\Gamma_{\eta\to\gamma\gamma}/\Gamma_{N\to\gamma\gamma} \approx 1$. The K_L^0-to-N^0 coupling needed is significantly weaker than the usual weak interaction.

The N^0 has, of course, not been observed either in strong or electromagnetic production reactions. The absence of such observations can be used to put limits on $\Gamma_{N\to\mathrm{all}}$ and $\Gamma_{N\to\gamma\gamma}$.

If the G parity of N^0 is -1 (isospin $I_N = 1$), the strong three-pion decay of N^0 would be allowed, though suppressed by a small three-body phase space. Thus,

$$\Gamma_{N\to\mathrm{all}} \approx \Gamma_{N\to 3\pi} \simeq 2(g_N^{\mathrm{strong}})^2\ \mathrm{keV}\,. \tag{19}$$

We estimate g_N^{strong} from strong production of 3 pions from nucleons. Roughly, we expect the production ratio of N^0 to η to be $\sim(g_N^{\text{strong}}/g_\eta^{\text{strong}})^2$. Judging from the absence of a three-pion-invariant-mass peak at M_K,[25] we estimate

$$(g_N^{\text{strong}}/g_\eta^{\text{strong}})^2 \lesssim 0.1 \tag{20}$$

so that

$$(g_N^{\text{strong}})^2/4\pi \lesssim 0.1\times 3 \tag{21}$$

and

$$\Gamma_{N\to\text{all}} \simeq \Gamma_{N\to 3\pi} \lesssim 10 \text{ keV} \quad (G_N=-1)\,. \tag{22}$$

We consider the Primakoff effect[26] in estimating an upper limit to $\Gamma_{N\to\gamma\gamma}$. Integrating over the invariant mass of the two photons in $\gamma p \to \gamma\gamma p$, the production rate via N^0 is $R_N \propto \Gamma_{N\to\gamma\gamma}{}^2/\Gamma_{N\to\text{all}}$. This is to be compared with the analogous η production rate $R_\eta \propto \Gamma_{\eta\to\gamma\gamma}{}^2/\Gamma_{\eta\to\text{all}}$ (where $\Gamma_{\eta\to\gamma\gamma} \sim \frac{1}{3}\Gamma_{\eta\to\text{all}} \sim 1$ keV). From the absence of a 2γ peak near M_K,[27] we estimate that $R_N/R_\eta \lesssim 0.1$ and

$$\left(\frac{\Gamma_{N\to\gamma\gamma}}{\Gamma_{\eta\to\gamma\gamma}}\right)^2 \lesssim 0.1\,\frac{\Gamma_{N\to\text{all}}}{\Gamma_{\eta\to\text{all}}}\,. \tag{23}$$

If $G_N=-1$, we use (22) to get

$$\Gamma_{N\to\gamma\gamma} \lesssim \Gamma_{\eta\to\gamma\gamma} \quad (G_N=-1) \tag{24}$$

whereas if $G_N=+1$ (isospin $I_N=0,2$), we expect

$$\Gamma_{N\to\gamma\gamma}/\Gamma_{N\to\text{all}} \sim \Gamma_{\eta\to\gamma\gamma}/\Gamma_{\eta\to\text{all}}$$

and

$$\Gamma_{N\to\gamma\gamma} \lesssim 0.1\Gamma_{\eta\to\gamma\gamma} \quad (G_N=+1)\,. \tag{25}$$

Note that (22), (24), and (25) can be used in (18) for a better estimate of $|g_{K_L N}/g_{K_L\eta}|$.

In summary, the restrictions imposed upon the N^0 are

(i) $|M_K - M_N| \sim \Gamma_{N\to\text{all}} \lesssim 10$ keV $(G_N=-1)$

$$\lesssim 0.1 \text{ keV} \quad (G_N=+1)\,, \tag{26}$$

(ii) very weak coupling of K_L^0 to N^0 as compared to η^0,

$$|g_{K_L N}/g_{K_L\eta}| \approx 2\times10^{-4} \quad (G_N=-1)$$
$$\approx 2\times10^{-5} \quad (G_N=+1)\,, \tag{27}$$

(iii) strong and electromagnetic interactions of N^0 compared to that of η^0 are

(a) $|g_N^{\text{strong}}/g_\eta^{\text{strong}}|^2 \lesssim 0.1\,,$ (28)

(b) $\Gamma_{N\to\gamma\gamma}/\Gamma_{\eta\to\gamma\gamma} \lesssim 1 \quad (G_N=-1)$

$$\lesssim 0.1 \quad (G_N=+1)\,. \tag{29}$$

To the present authors, the nature of these restrictions makes such an alternative rather unattractive as the solution to the $K_L^0 \to \mu\mu$ puzzle.

IV. CONCLUSIONS

We have considered several alternatives[28] in an attempt to reconcile the experimental upper bound, (2), and the calculated "simple" unitarity (lower) bound, (5), for reaction (1). These alternatives presume that Reϵ can be neglected so that the imaginary part of reaction (1) amplitudes are equal to the corresponding absorptive parts. The introduction of new muonic interactions has been shown not to be compatible with QED, and the introduction of a new particle, though not ruled out by experiment as such, appears unattractive due to the nature of the restrictions which are imposed. Nature, however, is not bound by our (ever-changing) esthetics.

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[1]A. R. Clark, T. Elioff, R. C. Field, H. J. Frisch, R. P. Johnson, L. T. Kerth, and W. A. Wenzel, Phys. Rev. Letters 26, 1667 (1971).

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[3]B. R. Martin, E. de Rafael, and J. Smith, Phys. Rev. D 2, 179 (1970); 4, 272 (E) (1971).

[4]With this assumption, the amplitude for reaction (3) is fixed to be largely dispersive. Any intermediate state contributing to the absorptive part of this amplitude will necessarily contribute to the absorptive part of the amplitude for reaction (1).

[5]J. Enstrom *et al.*, Phys. Rev. D 4, 2629 (1971); J. Cronin *et al.*, Phys. Rev. Letters 18, 25 (1967); M. Banner *et al.*, *ibid.* 21, 1107 (1968); R. Arnold *et al.*, Phys. Letters 28B, 56 (1968); L. Criegee *et al.*, Phys. Rev. Letters 17, 150 (1966).

[6]M. K. Gaillard, Phys. Letters 35B, 431 (1971).

[7]N. Christ and T. D. Lee, Phys. Rev. D 4, 209 (1971); see also Ref. 11.

[8]If Reϵ is neglected, the absorptive and imaginary parts of the amplitude for reaction (1) would be equal.

Using the notation of Ref. 10, and defining

$$L_{CP} \equiv \mathcal{A}(K_L^0 \to \mu^+\mu^-,\ CP = 1) = N^{-1}(pF_2 + qG_2),$$

$$L_{\text{non}-CP} \equiv \mathcal{A}(K_L^0 \to \mu^+\mu^-,\ CP = +1) = N^{-1}(pF_1 + qG_1),$$

$$S_{CP} \equiv \mathcal{A}(K_S^0 \to \mu^+\mu^-,\ CP = +1) = N^{-1}(pF_1 - qG_1),$$

$$S_{\text{non}-CP} \equiv \mathcal{A}(K_S^0 \to \mu^+\mu^-,\ CP = -1) = N^{-1}(pF_2 - qG_2),$$

$$N = (|p|^2 + |q|^2)^{1/2}, \quad \epsilon \equiv (p - q)/(p + q),$$

where p and q are the standard parameters which give the admixture of K^0 and $\bar{K}^0$ states in K_S^0 and K_L^0. [See J. Steinberger, in *Proceedings of the Topical Conference on Weak Interactions, CERN, 1969* (CERN, Geneva, 1969), p. 291.] The Christ-Lee equations for the difference between the absorptive and imaginary parts are

$$\text{Abs}(L_{CP}) - \text{Im}(L_{CP}) = i(\text{Re}\epsilon)S_{\text{non}-CP},$$

$$\text{Abs}(L_{\text{non}-CP}) - \text{Im}(L_{\text{non}-CP}) = i(\text{Re}\epsilon)S_{CP},$$

where terms of order ϵ^2 have been neglected.

[9] G. R. Farrar and S. B. Treiman, Phys. Rev. D 4, 257 (1971).

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[11] B. R. Martin, E. de Rafael, J. Smith, and Z. E. S. Uy, Phys. Rev. D 4, 913 (1971).

[12] New interactions of the type suggested in Sec. II, e.g., for $\pi\pi \to \mu\bar{\mu}$, can, in principle, void this bound. Such interactions, as shown in that section, are already eliminated by available evidence.

[13] This restriction might appear to be somewhat artificial; i.e., if reaction (3) is CP-conserving, then reaction (7) must be CP-violating to achieve the cancellation. Alternatively, reaction (3) can be CP-violating (up to 37%, see Ref. 9), and both contributions have to be canceled by reaction (7). The latter possibility has been discussed in a specific model by S. Barshay, University of Copenhagen report, 1971 (unpublished).

[14] B. D. Hyams *et al.*, Phys. Letters 29B, 521 (1969); R. D. Stutzke *et al.*, Phys. Rev. 177, 2009 (1969).

[15] R. C. Field (private communication).

[16] J. Schwinger, Ann. Phys. (N.Y.) 2, 407 (1957); I. Kobzarev and L. B. Okun, Zh. Eksperim. i Teor. Fiz. 41, 1205 (1962) [Soviet Phys. JETP 14, 859 (1962)]; R. Sugano, Progr. Theoret. Phys. (Kyoto) 28, 508 (1962); T. Kitamura and R. Sugano, *ibid.* 36, 1014 (1966); S. H. Ng and R. Sugano, *ibid.* 43, 1588 (1970).

[17] For a review, see S. J. Brodsky and S. D. Drell, Ann. Rev. Nucl. Sci. 20, 147 (1970).

[18] J. H. Christenson *et al.*, Phys. Rev. Letters 25, 1523 (1970).

[19] We take only CP-conserving interactions. One could introduce CP-violating interactions, but the conclusions would be similar.

[20] J. K. de Pagter *et al.*, Phys. Rev. Letters 17, 767 (1966); S. Hayes *et al.*, *ibid.* 22, 1134 (1969).

[21] J. Bailey *et al.*, Phys. Letters 28B, 287 (1968).

[22] The modification of QED shown in Fig. 2(a) would contribute to $\frac{1}{2}(g_\mu - 2)$ in lowest order, $\alpha(\simeq \frac{1}{137}$, the fine-structure constant).

[23] We use the soft-pion technique to relate the 3π-2μ coupling to the π-2μ coupling. Estimates of $\frac{1}{2}(g_\mu - 2)$ from one-pion emission and absorption then give a result an order of magnitude larger than present experimental errors (see Ref. 20).

[24] For simplicity, we assume CP conservation here. A resonance model has been mentioned in passing by Martin *et al.* (Ref. 11) as a solution to the $K_L^0 \to \mu^+\mu^-$ puzzle.

[25] See, for example, R. A. Grossman *et al.*, Phys. Rev. 178, 2109 (1969).

[26] H. Primakoff, Phys. Rev. 81, 899 (1951).

[27] C. Bemporad *et al.*, Phys. Letters 25B, 380 (1967).

[28] A third alternative would be the existence of a new photon, $\tilde{\gamma}$. Reaction (3) can then proceed via $K_L^0 \to \gamma\gamma$, $K_L^0 \to \gamma\tilde{\gamma}$, and $K_L^0 \to \tilde{\gamma}\tilde{\gamma}$. Two types of experiments have been done to detect the two-photon decays of K_L^0: those observing only one photon and those observing both photons. To detect the photons, they have to be converted to charged particles, which usually are electron-positron pairs. Since both types of experiments are in excellent agreement (see Ref. 5), one concludes that both γ and $\tilde{\gamma}$ must couple identically to electrons. Then from the accuracy of QED for electrons and muons (see Ref. 16), both γ and $\tilde{\gamma}$ must also couple identically to muons. Clearly γ and $\tilde{\gamma}$ must couple identically to the hadron electric charge. However, one might conceive of differences between γ and $\tilde{\gamma}$ for $q^2 \neq 0$ and for anomalous magnetic-moment-type couplings. Thus it is conceivable that the $\gamma\gamma$, $\gamma\tilde{\gamma}$, and $\tilde{\gamma}\tilde{\gamma}$ intermediate states mutually cancel in the absorptive part of reaction (1). With this alternative, a similar anomalous behavior for $\eta \to \mu^+\mu^-$ might exist. However, $\eta \to \mu^+\mu^-$ has been observed by B. D. Hyams *et al.* [Phys. Letters 29B, 128 (1969)] and no anomalous behavior is seen.