Experimental Restrictions on Ne'eman's Fifth Interaction*

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Recently, Ne'eman has proposed a "fifth interaction" between the strangeness current and a neutral vector meson χ, for the purpose of breaking SU(3) symmetry. We show that a χ mass less than $2m_\pi$ would be inconsistent with a variety of experiments, including K-mesonic atoms, the long-range pp potential, K_1 regeneration from a K_2 beam, the Lamb shift, modern refinements of the Cavendish "ice-bucket" experiment, and the absence of $\pi^0 \to \gamma+\chi$ and $\chi \to e^+ + e^-$. The remaining possibility, that m_χ exceeds $2m_\pi$, is discussed briefly.

I. INTRODUCTION

RECENTLY, Ne'eman[1] has proposed an interaction between the strangeness current and a neutral vector meson χ, which would break SU(3) symmetry in much the same way that the interaction between the electric current and the photon breaks the symmetry of isotopic-spin space. To account for the rather large violations of SU(3) symmetry, the χ coupling to the strangeness current must have $g_\chi^2/\hbar c \sim \frac{1}{10}$ to $\frac{3}{10}$, thus providing a "fifth interaction" with strength intermediate between the strong and electromagnetic interactions.[2] Ne'eman stressed that the fifth interaction could explain not only why SU(3) symmetry is badly broken, but also why isospin and strangeness remain good quantum numbers—a question on which the alternative mechanism of spontaneous symmetry violation in a bootstrap calculation has thus far failed to shed any light.

A particle interacting only with the strangeness current would be rather hard to detect in our non-strange world, as Ne'eman pointed out, and at first sight even a massless χ might have escaped previous notice.[3] This suggestion that a light particle with fairly strong coupling might have gone undetected all these years stimulated a search for experiments in which the χ should have showed up if it exists. In the present paper we record the experimental arguments we have thought of,[4] making no pretense that they are exhaustive. For all χ masses in the range $0 \leq m_\chi \lesssim 2m_\pi$, we find experiments which rule out the χ by factors of order 10, and over part of this range limits on vacuum polarization and the rate of K_1^0 regeneration from a K_2^0 beam, for example, rule out the χ by much larger factors. Present experiments do not rule out χ with mass $m_\chi > 2m_\pi$, though the only known candidate at present is the ϕ, as discussed by Ne'eman.

We present our experimental cases and discussion roughly in order of increasing χ mass, progressing from $m_\chi < 10^4$ eV (Sec. II) to $m_\chi < 2m_\pi$ (Sec. IV) to $m_\chi > 2m_\pi$ (Sec. V). The evidence is summarized in Table I. Section III deals with the anomalous K_1 regeneration from a K_2 beam observed by Leipuner *et al.*[5] We find that the fifth interaction could provide an explanation of anomalous regeneration were it not for the accumulated evidence against $m_\chi < 2m_\pi$ presented in Secs. II and IV, which makes the explanation untenable.[5a]

II. EVIDENCE AGAINST $m_\chi < 2m_e$

A. K-Mesonic Atoms

If the χ were massless or very light, a K^- meson trapped in an atom[6] would cascade down to the low atomic levels primarily by χ emission rather than γ emission, because the χ coupling $g^2{}_\chi \sim \frac{1}{10}$ is at least 10 times stronger than electromagnetism.[7] The time required to reach low levels where nuclear capture takes place would be reduced, and 90% or more of the expected x rays would be missing. Similarly, the number of Auger electrons, emitted when the K drops in level and gives off a virtual photon that is absorbed by an orbiting electron, would be reduced by 90% due to the

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[1] Y. Ne'eman, Phys. Rev. **134**, B1355 (1964).

[2] We use units such that $e^2/\hbar c = 1/137$, and $\hbar = c = 1$. In all numerical estimates, we use the conservative figure $g_\chi^2/\hbar c = \frac{1}{10}$.

[3] Ne'eman also suggested that the χ may couple to muons in such a way as to cause the large muon-electron mass difference. In this case, the close agreement of muon properties with quantum electrodynamics can be maintained only if $m_\chi \gtrsim 1$ BeV. The suggestions that χ couples to strangeness currents and to muon currents seem to have no compelling interconnection, however, and we consider the theory in which χ does *not* couple to the muon current, thus opening the possibility that m_χ is small.

[4] On the theoretical side, G. Feinberg [Phys. Rev. **134**, B1295 (1964)] has advanced an argument which concerns the massless χ. As he points out, a spin-1 field W_μ has the equation of motion

$$\partial_\mu(\partial_\nu W_\mu - \partial_\mu W_\nu) + m_0^2 W_\mu = g j_\mu,$$

where m_0 is the bare mass. Differentiating both sides, one finds

$$m_0^2 \partial_\mu W_\mu = g \partial_\mu g_\mu.$$

In our case, the spin-1 χ is coupled to the strangeness current, which is not exactly conserved ($\partial_\mu j \neq 0$) when weak interactions are taken into account. It follows that m_0^2 cannot vanish for the χ. The argument does not seem to lead to any conclusive restriction on the *physical* mass, however, so we shall not make use of it.

[5] L. B. Leipuner, W. Chinowsky, R. Crittenden, R. Adair, B. Musgrave, and F. T. Shively, Phys. Rev. **132**, 2285 (1963).

[5a] *Note added in proof*. For the same reason the fifth interaction cannot explain the $K_2 \to 2\pi$ decays observed by J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964). Note that in this latter experiment the effect of Leipuner *et al.* is not seen.

[6] We are much indebted to Dr. William Wagner for suggesting K-mesonic atoms as a possible source of information.

[7] Note that the atomic levels themselves are shifted very little by the fifth interaction because the nucleus is not strange and χ exchange between nucleus and K occurs rarely.

TABLE I. Limits on m_χ.

Experiment	Range of m_χ excluded by experiment
K-mesonic atoms (Sec. II-A)	$m_\chi < 10^4$ eV
Long-range pp potential (II-B)	Anomalous moment $K_\chi g_\chi/2m_\chi < 0.03 g_\chi/2m_\chi$ if $m_\chi < 10^3$ eV
K_1 regeneration from a K_2 beam (II-C)	$m_\chi < 2\times10^{-5}$ eV
Lamb shift (IV-A)	8 eV $< m_\chi < 2\times10^6$ eV
"Ice-bucket" experiment (IV-A)	10^{-12} eV $< m_\chi < 10^{-5}$ eV
$\pi^0 \to \gamma+\chi$ (IV-B)	$m_\chi < 1.4\times10^8$ eV
$\chi \to e^+ + e^-$ (IV-C)	10^6 eV $< m_\chi < 2.8\times10^8$ eV

competition from χ emission (the χ does not couple to electrons and thus would not be reabsorbed by them).

Little experimental work on K-mesonic atoms has been reported, but what does exist shows no evidence of the χ. Eisenberg and Kessler[8] have searched K^- capture in emulsion for Auger electrons with energies exceeding 15 keV. Their findings are quite consistent with standard electromagnetic theory; thus they are inconsistent with the massless χ by an order of magnitude. Of course, this result does not rule out the χ if it is too massive to be emitted in K-mesonic transitions (i.e., as a very crude estimate, $m_\chi \gtrsim 10^4$ eV is allowed). In another experiment, Kopelman *et al.*[9] studied how long it takes the K to cascade down and get recaptured by the nucleus. They obtained along time, inconsistent with emission of massless or very light χ's. Their result does not even show signs of the expected speed-up from Stark mixing,[10] however, so perhaps one must reserve judgment on the understanding of this particular experimental situation.

B. Long-Range pp Potential

Although nucleons have strangeness zero, they do have internal currents of $\bar{K}$'s, Σ's, etc., which allow them to couple to the χ via "strangeness form factors" and anomalous magnetic moments, just as the neutron couples to photons. At low-momentum transfers, the dominant term is the anomalous magnetic moment, and χ exchange between nucleons has the same spin dependence as the usual magnetic-magnetic interaction. If the χ is massless, the ratio of χ exchange to magnetic-magnetic photon exchange in the potential between two protons is

$$R=[g_\chi K_\chi/e(1+K_\gamma)]^2, \qquad (1)$$

where $g_\chi K_\chi/e(1+K_\gamma)=g_\chi K_\chi/2.79e$ is the ratio of strange anomalous moment to electromagnetic total moment. Putting in numbers, one finds $R=1.8K_\chi^2$.

[8] Y. Eisenberg and D. Kessler, Phys. Rev. **130**, 2352 (1963).

[9] J. B. Kopelman, M. M. Block, and C. R. Sun, Bull. Am. Phys. Soc. **9**, 34 (1964).

[10] T. B. Day, Nuovo Cimento **18**, 381 (1960).

Now the magnetic-magnetic potential between two protons at molecular distances has been checked to one part in a thousand by Ramsey,[11,12] in a microwave study. From Eq. (1) we deduce that $K_\chi \lesssim 0.03$, unless χ is so massive that the factor $e^{-m_\chi r}$ in the χ-exchange potential cuts off before molecular distances are reached (i.e., $m_\chi \gtrsim 10^3$ eV). Of course, the limit obtained on K_χ is not an impossibly low one, especially when we remember that the scalar electromagnetic moment is only $0.06e/2m$, but it does seem rather small and will be useful later in limiting anomalous regeneration of K_1^0 via χ exchange between K_2^0 and nuclei.

C. K_1 Regeneration from a K_2 Beam

Consider a K_2 beam approaching a bubble chamber. If m_χ is sufficiently small, the K_2's will undergo long-range interactions with nuclei in the chamber by means of χ exchange. We shall study the interaction between a single nucleus and K_2, and then add up the coherent interactions between many nuclei and K_2.

In strong interactions, K_2 and K_1 are distinguished by their opposite behavior under charge conjugation, and χ is negative under charge conjugation just like the photon. Therefore, K_2 can turn into K_1 by emitting a χ. The nucleus can absorb this χ by means of its anomalous "strange" magnetic moment, as discussed in Sec. II-B, or possibly through higher moments or inelastic effects. At low-momentum transfers, such as we are interested in, these latter effects can be neglected and only the "strange" magnetic moment matters.

At this point, let us recall the Pauli theory for an electron in the Coulomb field of a hydrogen atom. The effective potential in this theory includes the "spin-orbit" term[13]

$$\begin{aligned} V_{\text{eff}} &= -(1+2K)(\mu_0/2)\boldsymbol{\sigma}\cdot\mathbf{E}\times\mathbf{v} \\ &= -[(1+2K)e^2/4mr^3]\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}, \end{aligned} \qquad (2)$$

where $\mathbf{E}=e\mathbf{r}/r^3$ is the electric field, $\mathbf{v}$ is the electron velocity, μ_0 is $e/2m$, and the complete magnetic moment is $(1+K)$ times the Dirac moment. Now the χ-exchange potential between K^0 and a nucleus is completely analogous to (2), with K^0 replacing the nucleus as source, χ exchange replacing γ exchange, and the nucleus replacing the electron as the spinning object. Mathematically, we must substitute g_χ^2 for e^2, $2K_\chi$ for $1+2K$, nucleon mass for electron mass, and K velocity in the laboratory (or equivalently nuclear velocity in the K rest frame) for electron velocity. We find

$$V_{\chi\,\text{exchange}} = -(K_\chi g_\chi^2/2m_N r^3)\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}. \qquad (3)$$

When the effects of many nuclei on a K_2 are added

[11] N. F. Ramsey, Phys. Rev. **85**, 937 (1952).

[12] We are greatly indebted to Dr. Ramsey for informing Dr. Ne'eman about this work, and to Dr. Ne'eman for passing the information on to us.

[13] For the dependence on K, see, for example, R. P. Feynman, *Quantum Electrodynamics* (W. A. Benjamin, Inc., New York, 1962), p. 52.

together, the spin-orbit terms cancel unless the nuclear spins are polarized. Under standard operating conditions for the bubble chamber, for instance at 25°K in a magnetic field of 10^4 G, the excess of nuclear spins along the field is about one in 10^5. As a result, only about 10^{-5} of the nuclei act together to produce a coherent χ-exchange potential. From the directional properties of $\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}$, one sees that the coherent potential is greatest for K's passing through the chamber off-center, and vanishes when there are as many nuclei to the left as to the right.

Let us estimate the sum of $\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}$ terms for a K_2 with $v\sim c$ approaching a bubble chamber a few centimeters off center. We suppose the bubble chamber has a $(10\text{ cm})^3$ volume, $\sim 10^{24}$ nuclei/cm^3, and one in 10^5 of the nuclear spins aligned, and we give K_χ the small value 0.01 to avoid any conflict with the limit imposed by Ramsey's experiment (Sec. II-B). The result is

$$\text{Total } V_{\chi\,\text{exchange}}\sim(10^{27}\text{ nuclei})\times(10^{-5}\text{ fraction of aligned spins})\times(10^{-24}\text{ eV/nucleus})\sim10^{-2}\text{ eV}. \quad (4)$$

Since this off-diagonal matrix element connecting K_2 to K_1 is much greater than the diagonal matrix element distinguishing K_1 from K_2 ($|m_{K_1}-m_{K_2}|\sim4\times10^{-5}$ eV), the eigenvectors of K^0 are each 50% K_2 and 50% K_1, and the mass eigenvalues are split by $2V\sim2\times10^{-2}$ eV. An initially pure K_2 beam would thus oscillate rapidly between K_2 and K_1, and many K_1 decays would occur as the beam approached and entered the chamber. This behavior is not observed, so again we must reject the possibility that m_χ is very small.

Now as m_χ is increased, several factors act to cut down K_1 regeneration: the K_2 beam doesn't exchange χ's with the bubble chamber until it gets closer than $r\sim1/m_\chi$; only the nearby parts of the chamber, amounting to a volume $\sim m_\chi^{-3}$, contribute to the potential when $1/m_\chi\lesssim10$ cm, and the left- and right-hand $\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}$ contributions cancel for K_2 inside the chamber except in a peripheral region of thickness $1/m_\chi$. Taking these factors into account, we estimate[14] that masses $m_\chi\lesssim(1\text{ cm})^{-1}$ produce too much K_1 regeneration and can be ruled out.

III. ANOMALOUS K_1 REGENERATION

In a recent experiment, Leipuner *et al.*[5] claim to observe anomalously large K_1 regeneration from a K_2 beam in a hydrogen bubble chamber. The anomalous K_1's appear at very small angles with $\cos\theta\geq0.999$, indicating that the momentum transfer $|t|$ to the hydrogen target is less than $(30\text{ MeV})^2$. Other studies of K_1 regeneration in iron[15] show that the anomaly cannot increase strongly when heavier nuclei are used as targets.

If we did not have the stringent limitations on m_χ recorded in Sec. II and IV, it would be possible to explain the results of Leipuner *et al.*, in terms of χ-exchange contributions to the reaction $K_2+(\text{nucleus})\rightarrow K_1+(\text{nucleus})$. The χ would need to have $m_\chi<30$ MeV to explain why the effect is concentrated at small angles. The failure of the effect to increase strongly in heavier nuclei would be explained naturally since χ-exchange couples to nuclei only through the "strange" magnetic moment, which cancels in closed shells and does not increase proportionately to the number of nucleons.

The result of Leipuner *et al.* could then emerge in either of two ways. One possibility is K_1 regeneration in the collective field of many nuclei, as described in Sec. II-C, with m_χ just on the borderline between too much K_1 regeneration and too little [i.e., for the choice of K_χ in Sec. II-C, we would have $m_\chi\sim(1\text{ cm})^{-1}$]. In this case, however, most of the K_1's would be produced at the extreme sides of the chamber, where the $\boldsymbol{\sigma}\cdot\mathbf{r}\times\mathbf{v}$ contributions from different nuclei do not cancel.

Another possibility would involve larger m_χ for which the collective exchange potential is negligible. The K_1-regeneration potential would then become sizable only in the immediate neighborhood of individual nuclei [remember, Eq. (3) grows like r^{-2}], and K_1 regeneration would depend on the occasional encounters of K_2 with such regions, occurring with equal probability over the entire bubble chamber. In a hydrogen chamber, this effect can be described in terms of the cross section for $K_2+p\rightarrow K_1+p$. The cross section is easily estimated from the Rosenbluth formula by changing e to g_χ in the vertex, t^{-1} to $(t-m_\chi^2)^{-1}$ in the propagator, and keeping only the anomalous magnetic moment $K_\chi g_\chi/2m$. One finds

$$d\sigma/d\Omega\simeq g_\chi^4K_\chi^2|t|q^2/M^2(t-m_\chi^2)^2, \quad (5)$$

where q is the K momentum and M the proton mass.[16] At the small angles where most of the cross section is concentrated, $t\simeq-q^2\theta^2$, so

$$d\sigma/d\Omega\simeq g_\chi^4K_\chi^2q^4\theta^2/M^2(q^2\theta^2+m_\chi^2)^2. \quad (6)$$

The integrated cross section is approximately

$$\sigma_I\equiv\int d\Omega\frac{d\sigma}{d\Omega}\simeq\frac{2\pi g_\chi^4K_\chi^2}{M^2}\ln\left(\frac{2q}{m_\chi}\right)\simeq\frac{K_\chi^2}{4}\ln\left(\frac{2q}{m_\chi}\right)\times10^{-28}\text{ cm}^2. \quad (7)$$

[14] At $1/m_\chi\sim1$ cm, only about 10^{-3} of the nuclei in the chamber are near enough to exchange χ's, so the total potential is reduced to $\sim10^{-5}$ eV. This is already slightly smaller than the K_1-K_2 mass difference and thus only a fraction of the K_2's exposed to such a potential will convert to K_1. Furthermore, the maximum potential will not be felt by K_2's entering the central parts of the chamber, because of the left-right cancellation. Further increase of m_χ reduces the K_1 production very rapidly.

[15] R. H. Good, R. P. Matsen, F. Muller, O. Piccioni, W. M. Powell, H. S. White, W. B. Fowler, and R. W. Birge, Phys. Rev. **124**, 1223 (1961).

[16] Incidentally, the forward differential cross section does not become infinite when $m_\chi=0$ because the K_1-K_2 mass difference prevents momentum transfer t from approaching zero. This effect has been left out of Eqs. (6) and (7).

Equating σ_I with the anomalous effect of Leipuner *et al.*, with m_χ in the relevant range 2×10^{-5} eV$<m_\chi<3\times10^7$ eV, we find we must take K_χ between $\frac{1}{2}$ and 2.

To summarize, it is possible to explain the experiment of Leipuner *et al.* by χ exchange. The explanation is untenable, however, because it contradicts other experimental evidence (Table I) against small m_χ, and if $m_\chi\leq10^3$ eV, it also contradicts the Ramsey limit $K_\chi\lesssim0.03$.

IV. EVIDENCE AGAINST $m_\chi<2m_\pi$

A. Vacuum Polarization

In ordinary vacuum polarization, the largest contribution comes from the process (virtual γ) $\rightarrow e^+ + e^- \rightarrow$ (virtual γ). This process can also be thought of as providing an electron-pair exchange correction to the one-photon exchange potential between two particles. For example, the Coulomb potential is corrected as follows:

$$V=\frac{Q_1Q_2}{r}+Q_1Q_2\alpha\int_{2m_e}^{\infty}dm'C(m')\frac{e^{-m'r}}{r}, \tag{8}$$

where the extra factor α in the correction term, and its short range $r\sim1/2m_e$, are exhibited explicitly.

The χ is a spin-one particle and is negative under charge conjugation, just like the photon. Vacuum polarization can therefore receive a contribution from (virtual γ) $\rightarrow\chi$ (for example, via K^+K^-, which couples to both γ and χ) $\rightarrow$ (virtual γ). This new process can be thought of as providing a χ-exchange correction to the one-photon exchange potential (it also provides a K^+K^- exchange potential, for example, but this has a very short range in an on-the-mass-shell theory and can safely be neglected). Thus to the Coulomb potential between two charged particles, one must add:

$$\delta V=Q_1Q_2\alpha g_\chi^2C_\chi(e^{-m_\chi r}/r). \tag{9}$$

We have estimated the residue of the χ-exchange pole, for the purpose of obtaining C_χ, by ordinary techniques of field theory. In our estimate, χ is joined to the charge line at each vertex by $\chi\rightarrow K^+K^-\rightarrow\gamma\rightarrow$ (charge line). After current conservation is imposed, the calculation is still logarithmically divergent so we introduce a cut-off mass Λ. The result for $m_\chi\ll m_K$ is

$$C_\chi\approx(1/36\pi^2)(\ln\Lambda/m_K)^2. \tag{10}$$

It is now clear that δV is not likely to be more than a 10^{-4} correction to the Coulomb potential, so its effects will be noticeable only in relatively precise measurements. The Lamb shift provides a useful example. The potential δV will shift an atomic level with wave function ψ by approximately

$$\Delta E=\int\bar{\psi}\delta V\psi d^3x. \tag{11}$$

For example, the $2P$ level in hydrogen undergoes the shift

$$\Delta E(2P)=\int_0^\infty r^2dr\left(-e^2\alpha g_\chi^2C_\chi\frac{e^{-m_\chi r}}{r}\right)\left[\frac{re^{-r/2a}}{(2a)^{3/2}\sqrt{3}a}\right]^2=\frac{-e^2\alpha g_\chi^2C_\chi}{4a(1+am_\chi)^4}, \tag{12}$$

where a is the Bohr radius. Similarly, the $2S$ level in hydrogen undergoes the shift

$$\Delta E(2S)=[-e^2\alpha g_\chi^2C_\chi/4a(1+am_\chi)^4](1+2a^2m_\chi^2). \tag{13}$$

The difference

$$D=\Delta E(2P)-\Delta E(2S)=e^2\alpha g_\chi^2C_\chi am_\chi^2/2(1+am_\chi)^4 \tag{14}$$

represents a correction to the Lamb shift, and must be bounded by 0.1 Mc/sec to maintain the agreement between experiment and standard quantum electrodynamics. If we take $\ln(\Lambda/m_K)=2$ for purposes of estimating C_χ, D is large and the 0.1 Mc/sec agreement is very badly violated when m_χ lies between about 2 MeV and 8 eV, so we can rule out these values of m_χ.[17]

The behavior of D can be given a simple qualitative explanation. We begin with the usual observation that δV is most important at small r ($r\lesssim1/m_\chi$), where it influences the $2S$ more than the $2P$ level. As m_χ is decreased from high values, δV overlaps an increasing area of the atom and thus D grows until δV covers the whole atom ($m_\chi a\sim1$). When m_χ is decreased beyond this point, most of the further growth of δV occurs outside the atom, with the result that $\Delta E(2S)$ and $\Delta E(2P)$ approach constant values. The remaining changes of δV inside the atom are towards a strictly $1/r$ behavior which shifts $2P$ as much as $2S$, so D slowly subsides back to zero.

As m_χ is reduced still further to about 10^{-5} eV ($1/m_\chi\sim1$ cm), the χ-exchange potential conflicts with another very precise measurement: the Cavendish "ice-bucket" experiment which accurately verifies the $1/r$ form of the Coulomb potential. The result of the modern version of this experiment, performed by Plimpton and Lawton,[18] is usually stated in terms of an $r^{-1-\delta}$ form for the Coulomb potential, and reads:

$$|\delta|<2\times10^{-9}. \tag{15}$$

For our purposes, we compare the experiment with the potential

$$V=(Q_1Q_2/r)(1+\alpha g_\chi^2C_\chi e^{-m_\chi r}) \tag{16}$$

(ordinary vacuum polarization is entirely negligible at the distances, of order centimeters, involved in this experiment). The second term in parentheses is compatible with the Plimpton-Lawton experiment if it is

[17] If $\ln(\Lambda/m_K)$ exceeds two, more stringent limits on m_χ are obtained.

[18] S. J. Plimpton and W. E. Lawton, Phys. Rev. **50**, 1066 (1936).

either very small at $r\sim$centimeters ($m_\chi \gg 1$/cm) or essentially constant over the apparatus (m_χ very small). Putting in numbers in a very crude fashion, one finds that the intermediate masses $m_\chi \sim 10^{-5}$ eV ($1/m_\chi \sim 1$ cm) to $m_\chi \sim 10^{-12}$ eV ($1/m_\chi \sim 10^7$ cm) are incompatible with experiment.

B. $\pi^0 \to \gamma + \chi$

The decay[19] $\pi^0 \to 2\gamma$ is relatively slow for an electromagnetic process. Very likely, the explanation is that the decay has to proceed through rather massive intermediate states.[20] In this case, intermediate states involving strange particle pairs may be competitive, and these pairs would couple to χ's more strongly than to γ's, so we are led to consider the possibility of π^0 decay into χ's.

The decay $\pi^0 \to 2\chi$ happens to be inhibited, since π^0 has isotopic spin one, χ has isotopic spin zero, and the χ coupling conserves isotopic spin. The electromagnetic interactions needed to violate isotopic spin bring a factor α into each matrix element, more than offsetting the advantage gained by replacing double-photon emission ($\sim\alpha$ in the matrix element) with double-χ emission ($\sim g_\chi^2$ in the matrix element), and the net result is the negligible branching ratio

$$\text{Rate } (\pi^0 \to 2\chi)/\text{Rate } (\pi^0 \to 2\gamma) \sim (g_\chi^2)^2 \sim 1/100. \quad (17)$$

In the decay $\pi^0 \to \chi + \gamma$, however, the photon coupling supplies the necessary violation of isotopic spin, and if strange particle pairs are sufficiently well represented in intermediate states we may have a ratio as large as

$$R = \text{Rate } (\pi^0 \to \chi + \gamma)/\text{Rate } (\pi^0 \to 2\gamma) \sim g_\chi^2/\alpha \sim 10. \quad (18)$$

The admittedly uncertain theoretical estimate (18) can be compared with experiments which limit the branching ratio R. The best limit[19] is obtained from absolute rates of the various processes that occur when π^-'s stop in hydrogen:

$$\begin{aligned} \pi^- + p &\to n + \pi^0, & \pi^0 &\to \gamma + \gamma, & &\text{(a)} \\ &\to n + \pi^0, & \pi^0 &\to \gamma + e^+ + e^-, & &\text{(b)} \quad (19) \\ &\to n + \gamma, & & & &\text{(c)} \\ &\to n + e^+ + e^-. & & & &\text{(d)} \end{aligned}$$

Samios,[21] for example, reports measurements of the total number of π^- stops [(a)+(b)+(c)+(d)+ negligible processes], the total number of $e^+ e^-$ pairs [(b)+(d)], and the ratio of (b) to (d) [(b) is distinguished from (d) by kinematical considerations]. Combining these measurements with our very accurate knowledge[22] of the ratios (a)/(b) and (c)/(d), one has a complete specification of (a) through (d) which should agree with the total number of π^- stops—*unless* some fraction of π^0's decay into $\gamma+\chi$. In this case, either $m_\chi < 2m_e$, so that χ cannot decay into an $e^+ e^-$ pair and too few electron pairs would be seen, or $m_\pi > m_\chi > 2m_e$, in which event $\chi \to e^+ + e^-$ via an intermediate photon is the main decay mode of χ and too many $e^+ e^-$ pairs would be seen (if m_χ is a substantial fraction of m_π, the $e^+ e^-$ pairs would also have a different energy from the usual Dalitz pairs).

In Samios' study, the stopped π^- are accurately accounted for by the individual processes (a), (b), (c), and (d), and one obtains the branching ratio $R = 0.04 \pm 0.05$ for decay into $\chi+\gamma$. Actually, this 10% limit applies to the case $m_\chi < 2m_e$; for $m_\chi > 2m_e$, a better limit of order 0.1% is obtained since nearly all χ would then decay into $e^+ + e^-$, whereas normal $\pi^0 \to \gamma+\gamma$ decays convert into Dalitz pairs only about 1% of the time.

Comparing these limits on the $\pi^0 \to \chi + \gamma$ decay with the theoretical estimate (18), we may conclude that $m_\chi > m_\pi$ with some confidence even though the theoretical estimate was quite uncertain.

C. More on the Production of χ, and Detection of $\chi \to e^+ + e^-$

In any process where electric charge is accelerated, photon emission occurs. Most of the photons have low energies, but with sizable accelerations one obtains energetic photons (more than 1 MeV, say) in $\sim\alpha/\pi = 0.3\%$ of all events.

Analogously, in processes where strangeness is accelerated, χ emission occurs, unless too little energy is available to produce the extra $m_\chi c^2$. In processes where strange particles are scattered or produced in pairs, the analogy to photon emission is very close and energetic χ's are typically emitted in $g_\chi^2/\pi \sim 3\%$ of the events. In processes where strangeness is violated, such as K decay, the analogy is less close because of the absence of current conservation,[22a] but the probability of energetic χ emission is still expected to be of order 3% or greater.

Although χ's are so easily produced, we have thus far paid relatively little attention to how one might detect them directly. For χ masses in the range $0 \leq m_\chi < 2m_e$, there were reasons for this neglect. The main decay mode is $\chi \to 3\gamma$ (remember, χ is negative under charge conjugation). This decay is slow and not conspicuous. If χ's are absorbed instead of decaying, the events might be mistaken for photon absorptions at first sight.

In the range $2m_e < m_\chi < 2m_\pi$, by contrast, $\chi \to e^+ + e^-$ is the main decay mode. It proceeds rapidly via an intermediate photon (the $\chi\gamma$ coupling can be estimated

[19] We are greatly indebted to Dr. Hans Kobrak, who pointed out the significance of π^0 decays for our inquiry, and provided the information on the relevant experiments.

[20] For a recent statement of this idea, see J. B. Bronzan and F. E. Low, Phys. Rev. Letters **12**, 522 (1964).

[21] N. Samios, Phys. Rev. Letters **4**, 470 (1960); Phys. Rev. **121**, 275 (1961).

[22] D. W. Joseph, Nuovo Cimento **16**, 997 (1960).

[22a] *Note added in proof*. For a study of this case, see S. Weinberg, Phys. Rev. Letters **13**, 495 (1964).

using an intermediate K^+K^- state as in Sec. IV-A), and shows up as a conspicuous electron pair at or near the point of χ production. Thus, to take K decays as an example, 3% or more of all decays would involve χ's—$K^+ \to \mu^+ + \nu + \chi$, $K_1^0 \to \pi^+ + \pi^- + \chi$, and so forth—and the χ's would make easily detectable $e^+ e^-$ pairs at the point of K decay. One can put experimental limits of a few tenths of a percent or better on the fraction of such decays,[23,23a] however, allowing us to rule out m_χ in the range $2m_e < m_\chi < 2m_\pi$. At higher χ masses, this method is not applicable because the main decay mode becomes $\chi \to 2\pi$ which is not so conspicuous.

V. COMMENTS ON MASSIVE χ's

There are many other effects of light or massless χ's which would be harder to observe than the cases we have mentioned, but nevertheless interesting. For example, the reader may have noticed that exchange of massless χ's would produce a Coulomb-like attraction between particles of opposite strangeness such as K^0K^- or Σ^+K^+, leading to Bohr-type bound states. But we hope everyone is convinced by now that $m_\chi > 2m_\pi$, and we proceed to a brief discussion of higher χ masses.

A massive χ would appear as an $I=0$, $J^P=1^-$ resonance which is produced and decays, mainly into strongly interacting particles, at a rate intermediate between the rates characteristic of strong and electromagnetic interactions. Since χ couples directly to the strangeness current, decays to strange particle pairs would be somewhat preferred if $m_\chi > 2m_K$.

Ne'eman[1] has suggested the ϕ as a possible candidate, in view of its preference for $K\bar{K}$ decays and rather small decay rate.[24] The ω is not such a good candidate because its interactions are quite strong. It is also conceivable that χ is lighter than these well-known vector mesons, but has been missed in the past because of its relatively weak couplings.

We close with a comment concerning the current that χ couples to. In general, isotopic spin and hypercharge conservation only allow χ to couple to a linear combination of the baryon (B) and hypercharge (Y) currents. The reason for taking the linear combination to be *precisely* the strangeness current $S=Y-B$ was to make a light or massless χ hard to observe—had it coupled to nonstrange currents as well, it would have been too easily produced. Our finding that m_χ must exceed $2m_\pi$ removes this motivation, allowing χ to couple to a more general linear combination of Y and B currents.[25]

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[23] A discussion of the experimental situation with Dr. J. van Putten was very helpful.

[23a] *Note added in proof.* For the particular decay $K^+ \to \pi^+ + e^+ + e^-$, the very low branching ratio

$$\frac{\Gamma(K^+ \to \pi^+ + e^+ + e^-)}{\Gamma(K^+ \to \text{total})} \leq 1.1 \times 10^{-6}$$

has now been established [U. Camerini, D. Cline, W. F. Fry, and W. M. Powell, Phys. Rev. Letters **13**, 318 (1964)].

[24] In Ref. 3, we dissociated the χ-strange current interaction from the additional possibility, mentioned by Ne'eman, of a χ-muon current interaction. This additional possibility can indeed be ruled out if ϕ is χ. The decay width for $\phi \to \mu^+ + \mu^-$ would be

$$\Gamma = g_\chi^2 (m_\phi/3)[1 + O(m_\mu/m_\phi)^2] \sim 30 \text{ MeV}$$

if the muon had strangeness, but the experimental full width for ϕ is only 3 MeV [N. Gelfand, D. Miller, M. Nussbaum, J. Ratau, J. Schultz *et al.*, Phys. Rev. Letters **11**, 438 (1963)], and the mode $\phi \to \mu^+ + \mu^-$ occurs in less than 1.3% of ϕ decays. [A. Barbaro-Galtieri and R. Tripp, University of California Report No. UCRL-11428, 1964 (unpublished). This work will appear in the Proceedings of the International Conference on High Energy Nuclear Physics, Dubna, USSR, 1964 (to be published). We would like to thank Dr. Barbaro-Galtieri for informing us of her work in advance of publication.]

[25] In particular, it is conceivable that χ could have a strong coupling to the B (singlet) current, and substantially weaker coupling to the Y (octet) current. The current-current product which appears in lowest order (g_χ^2) mass splittings would then have a strong **1** component, a weaker **8** component, and a still weaker **27** component, which would help to explain why SU(3) symmetry violation is mainly octet. In view of its strong coupling to the B current, χ could then be ω. This theory, however, goes beyond Ne'eman's original intentions inasmuch as it uses χ coupling to explain several things [strong singlet vector meson-baryon current coupling, octet dominance of SU(3) violation] which the bootstrap mechanism may be able to account for without introduction of a new interaction.