quantities are not large and then insensitive to uncertainties in the calculations.

The above numbers are relevant to the subclass of decays selected by the specific character of the experimental design and a more universal expression of the results is necessary. For the kinematic region such that $\vec{p}_\mu \cdot \vec{p}_\nu = 0$, we have $P_n = (-3.0 \pm 4.7) \times 10^{-3}$. We can also express the result in terms of the value of ξ , the conventional ratio of form factors used in discussion of $K_{\mu 3}$ decays; taking $\text{Re} \xi = 0$, we find $\text{Im} \xi = -0.016 \pm 0.025$.

According to the calculations of Zhitnitskii, CP nonconservation in the Higgs sector leads to a polarization, for P_n where $\vec{p}_\mu \cdot \vec{p}_\nu = 0$ and T_μ is of the order of 100 MeV, such that

$$P_n = \frac{(m_\mu m_K)}{(8m_0^2)^{1/2}} \frac{v_2^2}{v_3^2} = -4.63 \times 10^{-3} \frac{v_2^2}{v_3^2},$$

where the value of m_0 is set equal to 2 GeV by the measured $K^0-\bar{K}^0$ CP -nonconserving effects and v_2^2/v_3^2 is defined by the gauge transformation properties of the Higgs doublets and not otherwise determined experimentally: Zhitnitskii expects this number to be of the order of one. For this experiment, the limits set are of the magnitude expected and serve to constrain the free parameter to be less than two.

Somewhat stronger constraints can be invoked if we compound these results with those from our

previous measurements⁶ of P_n from the $K_{\mu 3}$ decays of K_L^0 mesons where we found $\text{Im} \xi = 0.001 \pm 0.030$. The experiments are quite similar and the uncertainties are almost wholly statistical. Therefore, we feel that it is permissible to add the results of the two measurements to derive a value of $\text{Im} \xi = -0.010 \pm 0.019$ and $P_n = (-1.85 \pm 3.60) \times 10^{-3}$. Although this null result cannot exclude the possibility that the CP -nonconserving effects which are known from observations of the $K^0-\bar{K}^0$ system derive from CP -nonconserving phases in the Higgs sector, we can conclude that such mechanisms do not make unusually large contributions to $K_{\mu 3}$ decays.

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Superstrong Force with a Heavy Axion

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A new, superstrong force (analogous, to, but much stronger than, quantum chromodynamics) is introduced to the Peccei-Quinn extension of the standard model of weak and electromagnetic interactions. Strong CP nonconservation is naturally suppressed and the resulting heavy axion is compatible with the present experimental bounds. The strength of this new force and some of its properties are discussed.

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The discovery of pseudoparticle solutions¹ in non-Abelian gauge theories has far-reaching consequences in quantum chromodynamics (QCD). The QCD vacuum must have a nontrivial topological structure,² labeled by a new parameter θ_c , and the effective QCD Lagrangian becomes

$$L_{\text{eff}} = L_{\text{QCD}} + (i\theta_c g^2/32\pi^2) G_{\mu\nu}^a \tilde{G}^{a\mu\nu}, \quad (1)$$

where $\tilde{G}^{a\mu\nu}$ is the dual of the QCD field stress

tensor $G^{a\mu\nu}$ and g is the QCD coupling constant. The presence of the second term violates P and CP invariances, both of which are known to be excellent symmetries of strong interactions. In fact, the experimental bound on the electric dipole moment of the neutron³ implies $\theta_c < 10^{-8}$. This means that θ_c must be extremely small if not exactly zero. It is possible, although highly unlikely, that nature just so happens to have a

very tiny θ_c . Furthermore, there are no experiments that can be performed to find out if nature has made this accidental choice. It seems more likely that $\theta_c=0$ in nature because this is dictated by the presence of some symmetry.

One way to achieve this is to have a new global chiral U(1) symmetry on the QCD Lagrangian. Invariance under this chiral rotation renders theories with different θ values all equivalent to one another. Then it follows that the effective θ , namely θ_c , is exactly zero. There are at least two ways to realize this U(1) symmetry. One way is to have a massless quark, the u quark being the only possible candidate. Unfortunately, if the u quark is massless, our present understanding of current algebra must be modified somewhat in order to be compatible with experiments. Again, in this case, there are no experiments that can be performed to test directly the masslessness of the u quark.

The other way to realize this global U(1) symmetry is that suggested by Peccei and Quinn⁴ [to be called U(1)_{PQ}]. The simplest version of a realistic model that contains this U(1)_{PQ} symmetry combines QCD with the standard weak-electromagnetic interaction model⁵ which contains two Higgs doublets. Weinberg⁶ and Wilczek⁷ observed that, as a result of U(1)_{PQ}, a light pseudoscalar Higgs boson (the axion) must be present. Unfortunately, such an axion (with a typical mass around 100 keV) seems to have been ruled out by experiments. In fact, the experimental bound on the mass of such an axion is roughly $m_a \gtrsim 50$ MeV.⁸ A number of modifications of this model have been suggested by various authors so that the resulting modified models satisfy the present experimental bounds on the axion.⁹ Here I propose a new model for the axion by extending the Peccei-Quinn model to include a new, as yet unobserved, superstrong interaction. The new interaction (to be called QC'D) raises the axion

mass by a huge factor so that the axion's existence is compatible with the present experimental bound. Here I shall consider only a simple version of this new force, whose properties can be extrapolated from QCD. This new force offers many interesting properties and dramatic signatures for detection, some of which I shall briefly discuss.

The Lagrangian is given by

$$L = L_{\text{QCD}} + L_{\text{WS}} + L_{\text{QC'D}} + L_{\text{Yukawa}} - V(\varphi_1, \varphi_2), \quad (2)$$

where L_{WS} is the standard Weinberg-Salam-Glashow-Iliopoulos-Maiani model. The new interaction QC'D has its own fermions which are in the fundamental representations of a gauge group G and are singlets under the QCD color SU(3) group. The gauge group G is unbroken and its fermions are confined at a distance scale much smaller than that in QCD. The QC'D fermions are left-handed doublets and right-handed singlets under the weak SU(2) gauge group, to be called (P_i, N_i) , just like the ordinary quark doublets (p_j, n_j) , where i and j are generation indices (capital letters to be used for QC'D objects and small letters for QCD), so that the lightest pair is (U, D) in QC'D and is (u, d) in QCD. The Higgs potential is chosen such that spontaneous symmetry breaking takes place ($f^2 = f_1^2 + f_2^2$, $x = f_1/f_2$):

$$\begin{aligned} \varphi_1 &= \frac{f_1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \exp\left(\frac{ixa}{f}\right), \\ \varphi_2 &= \frac{f_2}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \exp\left(\frac{ia}{xf}\right), \end{aligned} \quad (3)$$

where a is to be identified as the axion field.^{6,7} The Yukawa couplings are such that φ_1 (φ_2) gives masses to P_i (N_i) and p_j (n_j) so that the flavor-changing neutral current is naturally suppressed. Following Peccei and Quinn, the Lagrangian has an additional chiral U(1) symmetry so that, after symmetry breaking, the axion part of the Lagrangian has the U(1)_{PQ} symmetry explicit in it:

$$\begin{aligned} L_a &= \frac{1}{2}(\partial_\mu a)^2 - \sum_i M_{P_i} \bar{P}_i \exp(ixa\gamma_5/f) P_i - \sum_i M_{N_i} \bar{N}_i \exp(ia\gamma_5/xf) N_i \\ &\quad - \sum_k m_{l_k} \bar{l}_k \exp(ia\gamma_5/xf) l_k - \sum_j m_{p_j} \bar{p}_j \exp(ixa\gamma_5/f) p_j - \sum_j m_{n_j} \bar{n}_j \exp(ia\gamma_5/xf) n_j, \end{aligned} \quad (4)$$

where the leptons l_k are also included. The axion couplings to usual quarks, usual leptons, and QC'D fermions are determined by Eq. (4). The axial current associated with this residual chiral U(1) symmetry is

$$J_{5\mu} = f \partial_\mu a + \frac{1}{2} x (\sum_i \bar{P}_i \gamma_\mu \gamma_5 P_i + \sum_j \bar{p}_j \gamma_\mu \gamma_5 p_j) + (2x)^{-1} (\sum_i \bar{N}_i \gamma_\mu \gamma_5 N_i + \sum_j \bar{n}_j \gamma_\mu \gamma_5 n_j + \sum_k \bar{l}_k \gamma_\mu \gamma_5 l_k). \quad (5)$$

The divergence of this current is zero except for the QCD and the QC'D anomalies^{2,10}

$$\partial^\mu J_{5\mu} = (1/32\pi^2)(x + x^{-1})(ng^2 \tilde{G}_{\mu\nu}^a G^{a\mu\nu} + Ng'^2 \tilde{F}_{\mu\nu}^b F^{b\mu\nu}), \quad (6)$$

where n (N) is the number of QCD (QC'D) doublets and $F_{\mu\nu}^b$ ($\tilde{F}_{\mu\nu}^b$) is the field stress tensor (its dual) of QC'D. These anomalies actually render the axion massive. The QC'D coupling g' is taken to be much larger than the QCD coupling g and, as we shall see below, the U and D masses $M_{U,D}$ are taken to be much larger than the u, d masses $m_{u,d}$. Hence the QC'D anomaly provides the dominant contribution to the axion mass and it is a good approximation to ignore the QCD anomaly contribution in Eq. (6).

To obtain some idea of the QC'D contribution to the axion mass, let us introduce the scale parameter $\Lambda_{c'}$ in QC'D. The corresponding scale parameter in QCD has the value $\Lambda_c \sim 0.2$ GeV. If $M_{U,D} \ll \Lambda_{c'}$, then the axion mass is dictated by the chiral symmetry limit and the standard current-algebra method can be applied.¹⁰ In general, both the anomaly and the chiral symmetry breaking by the fermion masses are important. With use of a U(2) nonlinear sigma model involving the QC'D pions and " η " meson with an explicit U(1)-symmetry-breaking interaction,¹⁰ the axion mass is given by (assuming $N=1$)

$$f^2 m_a^2 \simeq F_\pi^2 M_\pi^2 (M_\eta^2 - M_\pi^2) / M_\eta^2, \quad (7)$$

where π and η are the isospin triplet and singlet pseudoscalar mesons in QC'D. For simplicity, $Z = M_U / M_D \simeq 1$ and $x \simeq 1$. Scaling from QCD, the QC'D pion decay constant is $F_\pi \simeq \frac{1}{2} \Lambda_{c'}$, and the U(1) breaking due to the anomaly is $M_\eta^2 - M_\pi^2 \simeq 7 \Lambda_{c'}^2$. As is clear from Eq. (7), if $\Lambda_{c'} \gg M_U$, the axion mass is obtained by using current-algebra methods,¹⁰

$$f^2 m_a^2 \simeq \left(x + \frac{1}{x}\right)^2 \frac{Z}{(1+Z)^2} F_\pi^2 M_\pi^2 \simeq M_U V_U + M_D V_D, \quad (8)$$

where $V_U \simeq V_D \simeq \langle 0 | \bar{U} \exp(i a \gamma_5 / f) U | 0 \rangle \simeq \Lambda_{c'}^3$. If $M_U \gg \Lambda_{c'}$, the meson mass is the sum of the fermion mass, the antifermion mass, and the binding energy; using our experience from QCD and intuitive dimensional arguments, I use $M_\pi \simeq 2(M_U + \Lambda_{c'})$ as an order-of-magnitude estimate. This completes the estimate of the axion mass in terms of M_π and $\Lambda_{c'}$. Given M_π and $\Lambda_{c'}$, properties of QC'D are essentially determined. We shall come back to this later.

In the model described above, there are two θ angles which may induce large CP -nonconserving effects, namely θ_c in QCD and $\theta_{c'}$ in QC'D. The U(1)_{PQ} symmetry allows us to make one rotation so that either the effective θ_c or the $\theta_{c'}$ (or both) remains nonzero and CP invariance remains broken.

Depending on the mass of M_U (assuming $M_U \ll M_D$, it is possible to have $M_U < m_u \simeq 5$ MeV), the CP nonconservation may be suppressed somewhat. However, this is still far from sufficient in providing a natural suppression in the value of the electric dipole moment of the neutron. Also, the lightest QC'D fermion is stable in this case, which may be difficult to reconcile with cosmological constraints. What is actually more likely to happen is that QCD and QC'D are unified into a bigger gauge group at some scale M somewhere between 10^2 and 10^{14} GeV. This implies that θ_c must be equal to $\theta_{c'}$, at least at the tree level. Hence the possibility of a nonzero $\Delta\theta = \theta_{c'} - \theta_c$ must come from radiative corrections. This implies that the neutron electric dipole moment can arise only from high-order-loop diagrams. Of course, the exact value depends on the details of the model. Experience from the Kobayashi-Maskawa model¹¹ leads us to believe that radiative corrections at very high orders may be needed to induce a nonzero value of $\Delta\theta$. If this is the case, the neutron electric dipole moment induced by $\Delta\theta$ would be too small to be observed.

The above discussion leads us to consider the gauge group $G \otimes \text{SU}(2)_L \otimes \text{U}_Y(1)$ where the fermions *either* are spectators of the gauge group G or have vectorlike interactions under G . (The fermion content must be chosen so that it is free of the weak-interaction anomalies.) The Higgs representations (e.g., two Higgs doublets) are chosen so that the Peccei-Quinn mechanism is in effect: $\bar{\theta}_c = \theta_c + \arg \det m = 0$. The gauge group G is broken into QCD $\otimes$ QC'D at the mass scale M . The Yukawa couplings of QCD quarks (q) and QC'D fermions (Q) are related since both q and Q come from fermion representations of G . For example, if q_i and Q_i with the same $\text{SU}(2)_L \otimes \text{U}_Y(1)$ family quantum numbers belong to the same irreducible representation of G , their "current quark" masses must come from the same Yukawa couplings, which guarantees that (i) at least at the tree level, the Yukawa couplings of each (q_i, Q_i) pair to each of the two Higgs doublets have equal magnitude and phase, and (ii) $\bar{\theta}_c = \bar{\theta}_{c'} = 0$. Since QC'D is a stronger force than QCD, radiative corrections would in general enhance the Q_i mass relative to the q_i mass. Such enhancement can be substantial. Also, it is possible that a very small but nonzero effective $\bar{\theta}_c$ ($\leq 10^{-8}$) may be introduced by radiative corrections.

As is clear from Eq. (8) and Ref. 10, the axion would not get a mass from QC'D if the fermions U and/or D are massless. Hence QC'D cannot be

FIG. 1. The M_π - $\Lambda_{c'}$ parameter space expected for the superstrong force QC'D. The axion masses of $m_a = 50$ MeV, 100 MeV, 1 GeV, and 10 GeV are shown. $M_U = M_D = 100$ and 10 GeV are shown. The lower bound on M_π is not shown.

identified as the force introduced by Weinberg and Susskind.¹² In general, in order to have natural CP invariance in QCD there must be an explicit chiral $U(1)$ symmetry left in the Lagrangian after both symmetry breaking and fermion mass generation have taken place. Otherwise, strong CP nonconservation would remain a problem.¹³

To study the phenomenology of QC'D, we must obtain some idea of the ranges of values that $\Lambda_{c'}$, $M_{U,D}$, and M_π are expected to take. Let us consider the following constraints: (1) If $M_\pi \leq 18$ GeV, then $e^+e^- \rightarrow \pi^+\pi^-$ could have been observed. The dominant decay mode " $\pi^+ \rightarrow l^+\nu$ ", where l^+ is the heaviest lepton permitted by phase space, would provide a clean signal. Also, the dominant decay mode of " π^0 " is to two photons. (2) The axion mass must be bigger than (roughly) 50 MeV.⁸ This provides a lower bound on $\Lambda_{c'}$, > 3 GeV as shown in Fig. 1. (3) The coupling of the QC'D pions to the W^+ and Z^0 bosons contributes a mass term to the gauge bosons as follows: $M_W^2 = (g_w^2/4)[f^2 + F_\pi^2] > g_w^2 F_\pi^2/4$, where g_w is the weak $SU(2)$ gauge coupling. This implies that $\Lambda_{c'} < 500$ GeV. As F_π increases and f decreases correspondingly, the axion-fermion coupling strength increases. (4) If the QC'D fermions are very heavy, they would induce an unacceptably strong ϕ^4 coupling.¹⁴ In the absence of fine tuning of the parameters in the Higgs potential, we expect $M_{U,D} < 100$ GeV. This is shown in the figure.

Although some of the constraints mentioned above are not rigorous bounds, they do provide an indication of the ranges of values in which we should expect QC'D to emerge if it exists. It is encouraging that near-future accelerators can reach essentially the whole allowed parameter

space shown in the figure. For small $\Lambda_{c'}$, the QC'D vector meson mass should be comparable to that of the QC'D pion mass. Since its dominant couplings are via weak and electromagnetic interactions, it can show up as a resonance in both e^+e^- annihilation and Drell-Yan experiments. Its excited resonance should show up at roughly $2\Lambda_{c'} > 6$ GeV above it.

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