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Weak-Interaction Singlet and Strong *CP* Invariance

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Strong *CP* invariance is *automatically* preserved by a spontaneously broken chiral $U(1)_4$ symmetry. A weak-interaction singlet heavy quark Q, a new scalar meson σ^0, and *a very light axion* are predicted. Phenomenological implications are also included.

Recent attempts[1-4] to incorporate the observed *CP*-invariance violation[5] in unified gauge theories of the weak and electromagnetic interactions can be classified into three broad categories:

(i) *Hard CP-invariance violation.*—The Lagrangian itself violates *CP* invariance, i.e., it contains complex Yukawa or scalar self-coupling constants. Though the exact meaning of *CP*-invariance property can only be given after all the physical particles acquire masses, one may include theories with complex coupling constants in this category. Effective complex gauge-boson couplings to quarks[1] and the complex Higgs scalar couplings[2] of Weinberg belong to this category.

(ii) *Dynamical CP-invariance violation.*—The theory conserves *CP* in the tree approximation, but it is not conserved when radiative corrections are included.[3] This theory is attractive in the sense that it automatically gives a small *CP*-invariance–violating phase, but has a drawback in the uncertainty of estimating radiative corrections. Further, there is a danger of too small[6] a *CP*-invariant–violating phase in the final result.

(iii) *Spontaneous CP-invariance violation.*—Before spontaneous symmetry breaking, the Lagrangian conserves *CP*, i.e., one can always find appropriate *CP* phases for various fields which made the Lagrangian *CP* invariant. In general, we can start with real coupling constants. The spontaneous symmetry breaking introduces complex vacuum expectation values which make the final Lagrangian *CP*-invariance violating.[4]

I wish to point out that a *simple* theory should belong to one of these classifications for *completeness* of the gauge theory of weak and electromagnetic interactions. (Of course, one can treat the *CP*-invariance violation separately from the known weak- and electromagnetic-interaction theory by introducing a superweak interaction.[7])

For some time, the above picture of weak and electromagnetic interactions had not seemed to induce any difficulties when quantum chromodynamics (QCD) was considered as the gauge theory of strong interactions. However, the recently discovered instanton solutions of QCD and associated quantum effects[8] lead to an effective interaction

$$\mathcal{L}_{\text{int}} = (\theta/32\pi^2)F_{\mu\nu}{}^a\tilde{F}^{a\mu\nu}, \tag{1}$$

which violates both P and T invariance but preserves C invariance. A limit on the parameter θ is about $<10^{-9}$–10^{-10} from a recently given bound on the electric dipole moment of neutron, $d_n < 1.24\times10^{-25}\ e\cdot\text{cm}$. To guarantee strong *CP* invariance *automatically,* Peccei and Quinn observed[9] that the effective Lagrangian (1) can be rotated away if the Lagrangian has a chiral U(1) invariance denoted as $U(1)_A$, becuase the corresponding chiral current satisfies $\partial_\mu J_5{}^\mu = (g^2/16\pi^2) F_{\mu\nu}{}^a \tilde{F}^{a\mu\nu}$. Other alternatives[10] starting from $\theta = 0$ are not in general automatic because one cannot remove (1) by insisting upon *CP*invariance in the Lagrangian. Though the Lagrangian conserves *CP*, Eq. (1) will still come about at higher orders of weak interactions.

In this paper, I wish to discuss an *automatic theory for strong CP conservation* introducing the $U(1)_A$ symmetry in the Lagrangian. If this $U(1)_A$ is not broken, the symmetry is realized in the Wigner-Weyl manner and the only possible way of relating this unbroken $U(1)_A$ symmetry with flavor-conserving gluons is to have at least one massless quark. This can be easily checked by introducing additional spinless mesons that do not generate vacuum expectation values. The massless-quark possibility has been recently discussed.[11] On the other hand, the broken $U(1)_A$ symmetry implies a Goldstone boson (the so-called axion).[12] However, the Peccei-Quinn-Weinberg-Wilczek axion (PQWW axion) seems not to exist.[13]

This leads me to consider a phenomenologically different axion. I will consider the gauge group $SU(2)_L \otimes U(1) \otimes SU(3)_C$ for weak, electromagnetic, and strong interactions. The known six leptons and six quarks are represented in the Kobayashi-Maskawa picture.[1] One Higgs doublet is sufficient to complete this picture. *CP* is not conserved by scheme (i). In addition, I will introduce a weak-interaction–singlet quark Q and a weak-interaction–singlet, complex Higgs Scalar σ with zero weak hypercharge so as to have a symmetry $U(1)_A$. Further, a discrete symmetry R is introduced as

$$R: \; Q_L \to -Q_L, \; Q_R \to +Q_R, \; \sigma \to -\sigma;$$
$$\text{all the other fields are invariant.} \tag{2}$$

This guarantees the absence of a bare-mass term $m\bar{Q}Q$. The invariant Yukawa coupling of Q and the Higgs potential V are taken to be

$$\mathcal{L}_y = f \bar{Q}_L \sigma Q_R + f^* \bar{Q}_R \sigma^* Q_L, \tag{3}$$

$$V(\varphi,\sigma) = -\mu_\varphi{}^2 \varphi^+\varphi - \mu_\sigma{}^2 \sigma^*\sigma + \lambda_\varphi(\varphi^+\varphi)^2 + \lambda_\sigma(\sigma^*\sigma)^2 + \lambda_{\varphi\sigma}\varphi^+\varphi\sigma^*\sigma. \tag{4}$$

It is trivial to see that (3) and (4) are invariant under a $U(1)_A$ transformation

$$Q \to e^{i\gamma_5\alpha} Q, \quad \sigma \to e^{-2i\alpha}\sigma, \tag{5}$$

which can be used to rotate away the interaction (1) provided Q belongs to a nontrivial representation of $SU(3)_C$. The remaining U(1) invariance from (3) and (4) gives the Q-type baryon-number conservation. For specific illustrations Q is assumed to be a color triplet. Also for a finite range of parameters we have $\langle\varphi\rangle_0 \neq 0$ and $\langle\sigma\rangle_0 \neq 0$ to generate quark masses. Therefore, the $U(1)_A$ is spontaneously broken and is realized by the existence of the axion a that does not couple to ordinary quarks at the tree level. With a nonvanishing $\lambda_{\varphi\sigma}$, the standard Higgs is mixed with $\mathrm{Re}\sigma$, but not with a. In the following, $\lambda_{\varphi\sigma} = 0$ is assumed.

Though R (or gauge) symmetry forbids the light-quark coupling $\bar{q}\sigma q$, R symmetry is broken spontaneously and such a coupling will be present at higher orders. This induced coupling can be estimated by a diagram given inside the box of Fig. 1,

$$-i\left(\frac{g_s{}^2}{4\pi^2}\right)^2 \frac{m_q}{v'} \ln\left(\frac{m_Q}{m_q}\right) \bar{q}\gamma_5 q\, a, \tag{6}$$

where g_s is the color coupling constant, $v' = \langle\sigma\rangle_0$. The mass of the axion is estimated[12,14] by the current-algebra approach (cf. Fig. 1 for the role of an instanton),

$$m_a = \frac{\sqrt{Z}}{1+Z} \frac{\alpha_s{}^2}{\pi^2} \frac{f_\pi}{v'} m_\pi \ln\left(\frac{m_Q{}^2}{m_u m_d}\right), \tag{7}$$

with $Z = \langle m_u \bar{u}u\rangle / \langle m_d \bar{d}d\rangle$. If $m_Q = 100$ GeV, $f = 0.001$ (or $v' = 100$ TeV), $\alpha_s = 0.15$, and $2m_u \approx m_d \approx 10$ MeV, the axion mass is about 2.7 eV. For this particular set of values the lifetime of axion is about 1.0×10^{16} (0.95×10^{12}) yr for $e_Q = 0$ $(e_Q = -\frac{1}{3})$.

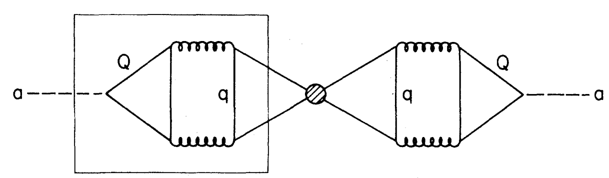

FIG. 1. Diagram for axion coupling to an ordinary quark q through the new quark Q and the gluon (curly lines) loops. The blob in the center is the 't Hooft instanton interaction which could be used for computation of m_a if a reliable method were available for estimating its effects. In the absence of such a method, the diagram is not to be interpreted as an orthodox Feynman diagram.

The main decay mode is $a \to 2\gamma$. For this kind of heavy quark Q, another possible diagram (Fig. 2) does not contribute significantly to the axion mass compared to (7), being presumably down by (a rough estimate) $\sim \pi^2(\mu/m_Q)^{3/2}[\alpha_s^2 \ln(m_Q^2/m_u m_d)]^{-1} \sim 0.023$ for $\mu \approx 1$ GeV. In the following, I will neglect the direct heavy-quark coupling to instantons.

There can be many variations of the present model even for the case of nontrivial weak interactions, but they are more complicated and the essential features are contained in the present example.

With the above estimate of the axion properties, I proceed to discuss the phenomenological implications of the heavy quark Q, a new scalar σ^0, and the axion a.

The new heavy quark Q.—In principle, the color content and the charge of Q can be arbitrary. Color content is assumed to be the same as light quarks (i.e., 3). If its charge is $\frac{2}{3}$ or $-\frac{1}{3}$, the heavy-quark system can be observed in high-energy e^+e^- machines, such as PEP and PETRA, for $10 < m_Q \lesssim 20$ GeV. If its charge is 0, there can be fractionally charged color-singlet hadrons such as $Q\bar{u}$, $Q\bar{d}$, Quu, Qud, etc. Hence, the observation of fractionally charged matter[15] will not disprove the idea of quark confinement. The lightest of these fractionally charged hadrons, $Q\bar{u}$, Quu, and QQu, and a neutral baryon QQQ are absolutely stable. (For this stability consideration, the case of charged Q also applies.) The search for stable heavy particles by Cutts *et al.*[16] at Fermilab sets a limit of 10 GeV and hence $m_Q \gtrsim$ GeV. These stable particles can be observed at a higher-mass search. The implications of a stable charged baryon for hypernuclei and x-ray spectra have been discussed in the literature.[17] If the stable charged particles are produced in e^+e^- annihilation, they can be identified by the presence of a high-momentum track with a very low v/c as measured by time-of-flight information. Heavy mesons formed out of $Q\bar{Q}$ are not stable and they decay to ordinary hadrons through gluon emission. If there is an asymmetry in the new baryon number B_Q in the universe, this will show up as stable particles through cosmic rays. If this asymmetry is hidden somewhere in the universe as neutral stable particles (QQQ), it will be very hard to observe them but they still contribute to the mass of the universe.

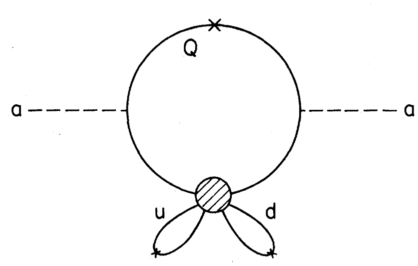

FIG. 2. Possible 't Hooft instanton interaction with a heavy quark.

The new scalar σ^0.—By the spontaneous symmetry breaking of $\mathrm{U}(1)_A$, σ will be split into a scalar boson σ^0 of mass $(2\mu_0)^{1/2}$ and an axion a. This σ^0 is *not* a Higgs meson, because it does not break the gauge symmetry, but the phenomenology of it is similar to the Higgs because of its coupling to quark as m_Q/v'. If this scalar mass is $\gtrsim 2m_Q$, we will see spectacular final state of stable particles such as $(Q\bar{u})$ and $(\bar{Q}u)$. If its mass is $\lesssim 2m_Q$, the effective interaction through loops $(c/v')F_{\mu\nu}{}^a F^{a\mu\nu}\sigma^0$, with numerical constant c, will describe the decay $\sigma^0 \to$ ordinary hadrons. The order of magnitude of its lifetime is $\tau(\sigma^0) \approx \tau(\pi^0)(v'/f_\pi)^2(m_{\pi^0}/m_{\sigma^0})^3 \approx 2\times 10^{-10}$ sec for $v' \approx 10^5$ GeV and $m_{\sigma^0} \approx 10$ GeV. This kind of particle can be identified as a jet in pp high-energy collisions, since there can be no missing leptons. The estimate of production cross section for this kind of jet is given in the literature.[18] If Q is charged, σ^0 can be seen by producing $\bar{Q}Q$ resonance in e^+e^- annihilation and looking for a hard monochromatic γ from its decay.[19]

The axion a.—Newton's law of gravitation will not be affected if the mass of axion, m_a, is heavy enough so that[20]

$$g_{aN\bar{N}}{}^2 e^{-m_a r} \lesssim \tfrac{1}{10} G_{\mathrm{N}} m_p{}^2,$$

where $g_{aN\bar{N}}$ is the axion-nucleon coupling and r is the typical distance scale ~ 1 cm for the measurement of Newton's constant $G_{\mathrm{N}} \cong 3.6\times 10^{-38}$ GeV^{-2}. With use of Eq. (6) as a rough guess on

$$g_{aN\bar{N}} \sim (\alpha_s{}^2/\pi^2)(f_\pi/v')\ln(m_Q/m_q) g_{\pi N\bar{N}} \sim 1\times 10^{-8} g_{\pi N\bar{N}}$$

(for $\alpha_s \approx 0.15$, $v' \approx 10^5$ GeV, $m_Q = 100$ GeV, and $m_q \approx 10$ MeV), a very crude bound on the axion mass is $m_a \gtrsim 10^{-3}$ eV. Reasonable estimates of axion mass satisfy this bound.

Because of a suppression of axion coupling to hadrons by a factor of $\alpha_s{}^2/\pi^2$ (also v' can be adjusted to suppress it) compared to the PQWW axion, it will be relatively harder to observe by hadrons of light quarks. I guess that the axion coupling is suppressed by about a factor of 100.

The decay process $K^+ \to \pi^+ a$ or $\psi \to a\gamma$ is suppressed by a factor of 10^4 relative to the previous[13] estimate of the branching ratios, and at present they give no useful information.

Any processes involving leptons are almost completely suppressed. Such processes can only occur for neutral quark Q by (Q-quark loop)–(gluon loop)–(light-quark loop)–(W or Z boson)–lepton, or by Higgs charged-lepton loops. Therefore, the axion does not contribute to the anomalous magnetic moment of the muon, cannot give spin-spin interaction in atoms and molecules, and cannot mimic $\nu_e e \to \nu_e e$ and $\bar{\nu}_e e \to \bar{\nu}_e e$ elastic scatterings in reactor experiment[21] which was one of the serious evidence against the PQWW axion. There can, however, be a very small contribution to this 1974 experiment, $\bar{\nu}_e \mathrm{D} \to np\bar{\nu}_e$ by $a\mathrm{D} \to np$, of Reines *et al.*[21] but this is about 10^{-5} times smaller than the measured background.[13]

The axion production and interaction cross section in beam-dump experiments is 10^8 times smaller than the estimate given before,[13] and hence, 10^5 times smaller than the best experimental bound,[22] 10^{-68} cm^4/nucleon.

Cosmological and astrophysical considerations limit[23] the mass of the PQWW axion. In the present case, since the axion is not supposed to have decayed to two photons after the decoupling from $ap \rightleftarrows \gamma p$, it could not have changed the entropy of the universe (number of photons/number of nucleons), or not distort the radiation background spectrum. Further, the axion would not change the standard prediction of deuterium abundance because $a\mathrm{D} \to pn$ would have ceased much earlier than $\gamma \mathrm{D} \to pn$. Stellar evolution may be affected by the existence of a light axion by the Primakoff process, but it is not known at present what kind of upper limit on the axion mass (a region of a zero axion mass which allows no Primakoff process will be allowed) will upset the present stellar evolution theory.

What are the possible experiments to prove the present scheme? Probably high-precision experiments of the axion search will do. But the easier verification of the weak-interaction singlets Q and σ^0 in pp or $\bar{p}p$ machines (e^+e^- annihilation machine also if Q is charged) will shed light on the whole idea of the spontaneously broken chiral $\mathrm{U}(1)_A$ invariance and the multiple vacuum structure of QCD.

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[14]Estimates of the axion mass have been given by Weinberg (Ref. 12), Wilczek (Ref. 12), W. A. Bardeen and S.-H. H. Tye [Phys. Lett. 74B, 229 (1978)], and J. Kandaswamy *et al.* [Phys. Rev. D 17, 1430 (1978)]. The effective coupling of the axion to the light quarks enables one to obtain, by the current-algebra approach of Bardeen and Tye, the estimate of the axion mass which is given in Eq. (7). Another possible diagram (Fig. 2) which has a direct heavy-quark coupling to an instanton will not be important since the effective instanton interaction to a sufficiently heavy quark Q will be down by $(m_Q \rho)^2$ compared to the ones without the heavy quark. A rough estimate shows that the contribution of the diagram in Fig. 2 is comparable to that in Fig. 1 for a 5–10-GeV heavy quark.

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Fusion Cross Sections for $\alpha + {}^{40,44}$Ca and the Problem of Anomalous Large-Angle Scattering

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Fusion cross sections for the reactions $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca have been measured between 10 and 27 MeV (lab) via the detection of the γ radiation of the evaporation residues. At maximum the cross sections are about 1170 mb for $\alpha + {}^{44}$Ca and about 970 mb for $\alpha + {}^{40}$Ca. This difference supports recent optical-model and semiclassical interpretations that the well-known anomalous large-angle scattering results from different absorption strengths for these two systems.

Cross sections for the elastic and inelastic scattering of projectiles and targets such as ^{16,18}O + ^{28}Si, $\alpha + {}^{40,44}$Ca, and others in the vicinity of closed-shell nuclei differ by orders of magnitude at backward angles.[1] These enhanced back-angle cross sections are under intense study by many experimental and theoretical groups; it is hoped that the great sensitivity of this effect leads to a better, more detailed understanding of heavy-ion collisions in general. At present, however, the interpretation of the anomalous large-angle scattering (ALAS) has led to controversies; in particular, resonance versus potential "explanations" have been suggested. Recently, optical-model studies[2,3] and a semiclassical investigation by Brink and Takigawa[4] have shown that the elastic $\alpha + {}^{40,44}$Ca scattering is described by the interference between the wave reflected at the nuclear radius (i.e., the outer potential barrier) and the wave reflected at the internal angular momentum barrier. Scattering from the internal barrier can give rise to orders-of-magnitude enhancement of the cross section at backward angles (such as observed for $\alpha + {}^{40}$Ca scattering) provided the absorption is moderate enough to permit sufficient transparency for this wave through the outer potential barrier[4] (i.e., the surface region). In case of strong absorption this contribution is suppressed and no back-angle enhancement of the cross section is observed (as, e.g., for $\alpha + {}^{44}$Ca); the "normal" wave, reflected at the nuclear radius, then dominates the cross section over the entire angular range.

In this Letter, for the first time, we report direct experimental evidence that the strengths of absorption for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca are considerably different in the region of the nuclear surface. This is obtained through the measurement of $\alpha + {}^{40,44}$Ca fusion cross sections.

An α-particle beam of a few nanoamperes from the FN tandem accelerator at the University of Köln was focused on 2.6-mg/cm^2-thick ^{40}Ca and ^{44}Ca targets. The γ radiation was registered with two Ge(Li) detectors (80 cm^3) at $+90°$ and $-90°$ to the beam direction. Two monitor detectors were placed at $+5°$ and $-5°$ to the beam direction to control the beam current integration, the beam spot position on the target, and possible target inhomogeneities. Depending on Doppler broadening a resolution of 2 to 5 keV (full width at half maximum) was achieved for the γ lines in the spectra. A careful dead-time correction and an absolute efficiency calibration with radioactive sources were made.

To obtain fusion cross sections all ground-state

