Nonaxion solution of the problem of *CP* conservation in strong interactions

N. V. Krasnikov and V. A. Matveev
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 11 February 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 6, 270–272 (20 March 1982)

A new model based on the gauge group SU(9) ⊗ SU(2) ⊗ U(1) furnishes a natural explanation of why the *CP* nonconservation is slight in strong interactions, without hypothesizing the existence of an axion. Supersymmetry models can also explain the absence of strong *CP* violation.

PACS numbers: 11.30.Er, 11.30.Ly, 12.40. – y

The complicated structure of the vacuum in quantum chromodynamics[1-4] can disrupt *CP* invariance in strong interactions.[5] At the moment, some of the most popular models which offer an explanation for the problem of strong *CP* conservation are models that have an axion: a light pseudoscalar particle.[6-8] Unfortunately, the standard version[7,8] of the axion model has been refuted by experimental data (at a 90% confidence level).[9] On the other hand, some models which have been proposed recently[10-12] have a very light axion, which essentially does not interact with ordinary matter. The existence of such an "invisible" axion does not contradict experiment.[1)]

In this letter we wish to propose a model, without axions, in which the *CP* problem is resolved by introducing a hypothetical new strong interaction of the technicolor type.[14,15] We will also show that the supersymmetry models can explain the lack of a strong *CP* violation.

Our model is based on the gauge group SU(9) ⊗ SU(2) ⊗ U(1), where SU(2) ⊗ U(1) is the ordinary Weinberg-Salem electroweak group. At an energy $\mu \sim 10$ TeV, the SU(9) group is broken down to the group[2)]

$$SU(9) \overset{\mu}{\to} SU(3) \otimes SU(6),$$

where SU(3) is the ordinary color gauge group of strong interactions, and SU(6) is the technicolor gauge group of the new, strong interactions with a mass scale $\Lambda_6 \sim 400$ GeV. To avoid the γ_5 electroweak anomalies in this model, we must triple the number of lepton isodoublets. In place of the ordinary triplet of colored quarks, say $u = (u_1, u_2, u_3)$, we introduce the colored SU(9) 9-plet $u' = (u_1, u_2, u_3, X_1, X_2, X_3, X_4, X_5, X_6) = (u, X)$, where X_i $(i = 1, \ldots, 6)$ are techniquarks which transform by a sixtet transformation of the SU(6) group. In this new model, in contrast with the technicolor models in Refs. 13–15, there is a standard isodoublet $\phi = (\phi_1^0, \phi_1^-)$ of Higgs fields. On the other hand, the Yukawa coupling $\overline{(u', d')}_L \phi u'_R$, which gives rise to the mass of the u quark in the Weinberg-Salem model under the assumption of a nonzero vacuum expectation value $\langle\phi_1^0\rangle$, is not present. At the classical level, the Lagrangian of the model has the global symmetry, $u'_R \to e^{i\alpha} u'_R$, which is disrupted by the instantons of the SU(9) group:

$$\sim \partial^\mu J^R_\mu = -\frac{g_9^2}{32\pi^2} F\tilde{F},$$

$$J^R_\mu = \bar{u}'_R \gamma_\mu u'_R ,$$

$$F\tilde{F} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} F^a_{\mu\nu} F^a_{\alpha\beta}, \tag{1}$$

where $F^a_{\mu\nu}$ is the stress tensor of the SU(9) gauge group. Because of the global classical symmetry $u'_R \to e^{i\alpha} u'_R$, the physics becomes independent of the parameter θ in the effective strong-interaction Lagrangian

$$L_{eff} = L_{SU(9)} + \frac{i\theta g^2}{32\pi^2} F\tilde{F}.$$

A similar result could be derived for ordinary quarks also, but in the absence of a Yukawa coupling $\overline{(ud)}_L \phi e u_R$ in the standard model, we would have a massless u quark, which would contradict the phenomenology.[5] The incorporation of a new, strong interaction SU(6) gives rise to a mass for the u quark, by virtue of the assumed presence of a quark condensate for the techniquarks X. The effective four-fermion Lagrangian, which describes the interaction between the u and X quarks, is

$$L = \frac{g_9^2}{2M_9^2}\left[\bar{u}\gamma_\mu l_a X \bar{X}\gamma^\mu l_a u - \frac{1}{6}\bar{u}\gamma_\mu u \bar{X}\gamma^\mu X\right], \tag{2}$$

where l_a is the complete set of real 3×6 matrices. Using Fierz transform, we can write (2) as

$$L = -\frac{g_9^2}{2M_9^2}(\bar{X}X\bar{u}u - \bar{X}\gamma_5 X\bar{u}\gamma_5 u + \dots).$$

Condensation of the techniquarks, $\langle X\bar{X}\rangle \neq 0$, leads to a nonzero mass for the u quark:

$$m_4 = -\frac{g_9^2}{2M_9^2}\langle \bar{X}X\rangle = -\frac{\langle \bar{X}X\rangle}{2\mu^2},$$

$$M_9 = g_9 \mu . \tag{3}$$

If the mass scale is $\Lambda_6 \sim 400$ GeV, then [13-15]

$$\langle \bar{X}X\rangle \sim (0.25 \times 400\ \text{GeV})^3.$$

If we choose the parameter μ, which characterizes the breakdown of the SU(9) group to SU(3) $\otimes$ SU(6), to be ~10 TeV, we find the mass of the u quark to be ~5 MeV. An analysis based on current algebra leads to a similar mass for the u quark.[5,16]

In this new model, effects of both the condensation of the techniquarks X and the nonzero vacuum expectation value $\langle\phi_0\rangle \neq 0$ contribute to the mass of the intermediate bosons. The primary purpose of the expanded SU(9) group—strong interactions—is to give the u quark a mass in a dynamic fashion while retaining the global symmetry $u'_R \to e^{i\alpha} u'_R$, whose presence is responsible for the lack of a strong *CP* violation. The model predicts the existence of light pseudoscalar mesons consisting of techniquarks (analogs of the ordinary pseudoscalar mesons) with a mass ~5–100 GeV. The phenomenological properties of these mesons are similar to the properties of the "standard" pseudoscalar technimesons.[15] Dimopoulos[17] introduced some new strong interactions for the purpose of increasing the mass of the axion. As a result of the spontaneous symmetry breaking $SU(9) \to SU(6) \otimes SU(3)$, an effective renormalization parameter $\delta\theta \neq 0$ arises, but it is constructed from diagrams which are associated with the exchange of heavy intermediate bosons, $SU(9)/SU(3) \otimes SU(6)$, and it is given in order of magnitude by $\delta\theta \sim (m_4/\mu)^2 \sim 10^{-12}$, which is considerably smaller than the experimentally allowed limit.[18,19]

Finally, we wish to call attention to the fact that the supersymmetry theories[20] can furnish a natural explanation for the absence of a *CP* violation. The Lagrangian L^s_{QCD}, which describes the supersymmetry generalization of quantum chromodynamics in the Wess–Zumino gauge, can be written as follows, after auxiliary fields are eliminated:

$$L^s_{QCD} = -\frac{1}{4}(G^a_{\mu\upsilon})^2 + \frac{i}{2}\bar{G}D_G G + \sum_{k=1}^{N}\Big\{\bar{q}_k(i\hat{D} - m_k)q_k + |(D_\mu\Lambda_k)|^2 + |(D_\mu R_k)|^2$$

$$- \frac{1}{\sqrt{2}}(\bar{q}_{Lk}G_R\Lambda_k + \bar{q}_{Rk}G_L R_k + \text{H.a.}) - \frac{g^2}{8}(\Lambda^+_k\lambda_a\Lambda_k - R^+_k\lambda_a R_k)^2\Big\}. \qquad (4)$$

Here the Majorana field G is a superpartner of the gluon field A^a_μ, and the scalar fields (Λ_k, R_k) are superpartners of the quark field q_k. It is easy to see that Lagrangian (4) has t the Peccei–Quinn symmetry[6]:

$$G \to \exp(i\alpha\gamma_5)G \;, \quad \Lambda_k \to \exp(i\alpha)\Lambda_k, \qquad R_k \to \exp(-i\alpha)R_k\,. \qquad (5)$$

Because of the symmetry in (5), there is no *CP* violation in the sypersymmetry quantum chromodynamics.

We wish to thank V. M. Lobashev, A. N. Tavkhelidze, and C. Jarlskog for useful discussions.

[1)]The "invisible" axion[10–12] is very similar to the "pseudon" which was discussed many years ago in papers of M. A. Markov, G. V. Domogatskiĭ, and others.[13]

[2)]The conditions for the coalescence of the SU(3) and SU(6) coupling constants α_3 and α_6 at $\mu \sim 10$ TeV are $\alpha_3(\mu^2/\Lambda_3^2) = \alpha_6(\mu^2/\Lambda_6^2)$ and are satisfied.

1. A. A. Belavin *et al.*, Phys. Lett. 59B, 85 (1975).
2. G. 't Hooft, Phys. Rev. Lett. 37, 8 (1976).
3. C. G. Callan, R. F. Dashen, and D. J. Gross, Phys. Lett. 63B, 334 (1976).
4. R. Jackiw and C. Rebbi, Phys. Rev. Lett. 37, 172 (1976).
5. As a review see, for example: N. V. Krasnikov, V. A. Matveev, and A. N. Tavkhelidze, Fiz. Elem. Chastits At. Yadra. 12, 100 (1981) [Sov. J. Part. Nucl. 12, 38 (1981)].
6. R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
7. S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
8. F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).
9. See, for example: S. H. Tye, in Proceedings of the VPI Workshop on Weak Interactions as Probes of Unification.

10. J. E. Kim, Phys. Rev. Lett. 43, 103 (1979).
11. M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. **104B**, 199 (1981).
12. M. V. Wise, H. Georgi, and S. L. Glashow, Phys. Rev. Lett. 47, 402 (1981).
13. M. A. Markov, Neĭtrino (Neutrinos), Izd. Nauka, 1964; Nguyen Van Hieu, Zh. Eksp. Teor. Fiz. 47, 116 (1964) [Sov. Phys. JETP **20**, 79 (1965); [G. V. Domogatskiĭ, Yad. Fiz. 8, 759 (1968) [Sov. J. Nucl. Phys. 8, 442 (1969)].
14. L. Susskind, Phys. Rev. **D 20**, 2619 (1979); S. Weinberg, 19, 1277 (1979).
15. As a review of the technicolor concepts see, for example: P. Sikivie, "An introduction to technicolour," CERN Preprint TH 2951, 1980.
16. See, for example: S. Weinberg, in: A Festchrift for I. I. Rabi (ed. L. P. Motz), New York, 1977.
17. S. Dimopoulos, Phys. Lett. **84B**, 435 (1979).
18. V. Baluni, Phys. Rev. **D** 19, 2227 (1979).
19. R. J. Crewther *et al.*, Phys. Lett. **88B**, 123 (1979).
20. See, for example: E. Witten, Nucl. Phys. **B188**, 513 (1981).

Translated by Dave Parsons
Edited by S. J. Amoretty