PHYSICAL REVIEW D VOLUME 22, NUMBER 1 1 JULY 1980

More on unconfined quarks and gluons

A. De Rújula,* R. C. Giles, and R. L. Jaffe
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 7 March 1980)

Georgi has recently argued that our model of quasiconfinement may not be realizable in quantum chromodynamics. Though he raises very relevant issues, his arguments fail to resolve the crucial question of the nature of the transition between confining and nonconfining phases.

In a recent paper[1] Georgi has raised some interesting questions regarding the possibility that "quasiconfinement" occurs in quantum chromodynamics (QCD). By quasiconfinement we mean a scenario, discussed in detail in Ref. 2, for liberating colored quarks with very large masses while preserving the successful standard phenomenology of QCD at presently accessible energies. In Ref. 2 we associated such a failure of confinement with an appropriate spontaneous breakdown of the color gauge symmetry. Hadronic phenomena at ordinary mass scales were shown to be modified by terms proportional to Λ^2/M^2 where Λ (~300 MeV) is the dynamical scale of QCD and M is the physical mass ($M \gg \Lambda$) of the lightest color-nonsinglet hadron. The breakdown of the gauge symmetry was evident only for processes that probe large distance scales of order M/Λ^2. In particular, nonsinglet color states were found to be extended objects of size $\sim M/\Lambda^2$. The particular phenomenological realization of these ideas presented in Ref. 2 was obtained in a modified MIT bag model. Gluons were given a small mass μ inside the bag via a Higgs mechanism and M was found to be proportional to Λ^2/μ.

In the context of renormalizable field theory a gluon mass can only arise from spontaneous symmetry breakdown—in practice by a Higgs mechanism. It is convenient to discuss the symmetry breaking in terms of the parameter m_0^2 (in Georgi's notation), the squared mass of the Higgs field in the original Lagrangian.

At the level of tree graphs, $m_0^2 > 0$ corresponds to no symmetry breaking and, presumably, confinement, while $m_0^2 < 0$ leads to spontaneous breakdown, the acquisition of masses by gluons and, presumably, no confinement. Though quantum corrections may modify this picture, we nevertheless expect that, as in weak-interaction gauge theories, large negative m_0^2 ($m_0^2 \ll -\Lambda^2$) leads to spontaneous breakdown with $\mu^2 \gg \Lambda^2$. The critical question is what happens as m_0^2 increases toward zero from below: What is the nature and location of the transition from the Higgs phase to the confining phase?

Georgi makes two important observations: First, this phase transition may occur at a finite negative value m_c^2 of the Higgs-field squared mass rather than at zero as in Ref. 2. Second, the phase transition at m_c^2 may be first order, with M, the mass of colored states, approaching some finite value of order Λ as m_0^2 goes to m_c^2, rather than second order, with $M \to \infty$ as m_0^2 goes to m_c^2 as occurred in Ref. 2. If the phase transition is first order there is no close connection between confining and Higgs phases, quasiconfinement does not occur, and the mechanism of Ref. 2 does not apply. We agree with Georgi: *A priori* one does not know whether m_c^2 vanishes or not nor whether the transition is first or second order.

Unfortunately, the nature of the phase transition is a very difficult problem to address directly. Like the analysis of the dynamics of the confining phase itself, it requires nonperturbative techniques. As we have described in Ref. 2, quasiconfinement arises naturally in the bag model which, though not a field theory, constitutes a rather minimal dynamical model of confining forces in a field-theoretic framework. Also, the behavior of massive electrodynamics in two space-time dimensions as a function of the photon mass μ has been investigated by Parke and Steinhardt.[3] They find a smooth transition to confining theory as $\mu \to 0$. Finally, a series of lattice-gauge-theory models with nonlinear Higgs (generalized nonlinear σ models) structure have been studied by Fradkin and Shenker.[4] For Higgs fields in the fundamental representation, their work indicates no discontinuous transition from Higgs regimes to confining regimes.

Most of Ref. 1 is devoted to an argument that $m_c \neq 0$. It is observed that dynamical effects scaled by Λ may overwhelm a small Lagrangian mass m_0 regardless of whether m_0^2 is positive or negative. While this does not seem to occur in perturbation theory, it nevertheless may be so. If it is so it means the phase transition occurs at $m_c^2 \neq 0$ but says nothing about its order.

Having located the phase transition at m_c^2, let us discuss it in terms of an *effective* potential $V_{eff}(\phi)$ which includes whatever nonperturbative effects shift the transition from $m_0^2 = 0$ to $m_0^2 = m_c^2$. Since for $m_0^2 > m_c^2$ the gauge symmetry is in effect unbroken (in actuality it is broken then dynamically restored), gluons in the effective Lagrangian should be massless when $m_0^2 > m_c^2$. For $m_0^2 < m_c^2$ the gluons should obtain a mass, breaking the symmetry and liberating color. The order of the phase transition depends on the shape of the effective Higgs potential for $m_0^2 \cong m_c^2$. For the phase transition to be first order the effective potential must be of the form shown in Fig. 1. Then as m_0^2 passes through m_c^2, $\langle\phi\rangle$ jumps discontinuously from zero to a certain $\langle\phi_0\rangle$. If $\langle\phi_0\rangle$ is a typical hadronic mass and cannot possibly be made smaller, the effective gluon mass cannot be made small and the mass of colored particles cannot be made large. Quasiconfinement does not occur. We do not know how to say anything rigorous about $V_{eff}(\phi)$. Georgi says: "My picture is that for $m_c \sim O(\Lambda)$, there is a local minimum of the effective action at $\phi^2 \sim |m_0^2|/\lambda$, as suggested by the classical potential, but for $m_0^2 > m_c^2$ there is a *lower minimum* (the emphasis is ours) at $\phi^2 = 0$ induced by quantum effects. If this is the situation, the transition will be first order." He gives no support for this scenario. While this may be so, none of the authors involved in this controversy knows how to reliably estimate quantum effects that may or may not produce an extra minimum at the origin, nor whether such a minimum is deeper than the $\phi \neq 0$ ones.

In summary, we believe that Georgi's comments are useful insofar as they serve to focus consideration of quasiconfinement on a single precise question, namely, the nature of the confining phase transition. We do not as yet know how to answer this question. Georgi's prejudices, while interesting, clearly do not provide a satisfactory resolution of these problems.

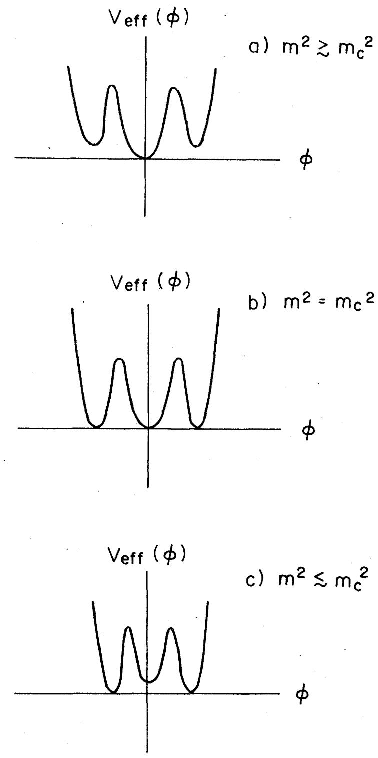

FIG. 1. Behavior of an effective potential leading to a first-order phase transition.

We thank Howard Georgi for many pleasant conversations on these matters. We would also like to thank Sidney Coleman for his characteristically trenchant comments. This work was supported in part through funds provided by the U. S. Department of Energy (DOE) under Contract No. EY-76-C-02-3069.

*On leave from CERN, Geneva, Switzerland.

[1]H. Georgi, Phys. Rev. D 22, 228 (1980).
[2]A. De Rújula, R. C. Giles, and R. L. Jaffe, Phys. Rev. D 17, 285 (1978).
[3]S. Parke and P. Steinhardt, Ann. Phys. (N.Y.) 114, 215 (1978).
[4]E. Fradkin and S. H. Shenker, Phys. Rev. D 19, 3682 (1979).