Comment on unconfined quarks and gluons

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(Received 26 December 1979)

It is argued that it might be impossible to implement quasiconfinement of quarks and gluons by spontaneously breaking the color gauge symmetry to give the gluons a small mass μ in a theory which otherwise looks like quantum chromodynamics. Rather it is suggested that the gauge symmetry will be dynamically restored, and the theory will remain exactly confining.

De Rújula, Giles, and Jaffe[1] (DGJ) have proposed a fascinating mechanism for hiding unconfined quarks and gluons at high mass without doing much violence to either the confined-quark picture of ordinary hadron spectroscopy or to the short-distance properties of the underlying theory. Their idea was to have a set of colored Higgs mesons which develop a very *small* vacuum expectation value (VEV) μ, much smaller than the inverse confinement radius Λ. This would softly break the gauge symmetry and give the gluons a mass term of order μ. They then argued quite plausibly that color would be unconfined, but that the physical masses of unconfined quarks and gluons would be inversely proportional to μ, of order Λ^2/μ, going to infinity as $\mu \to 0$ where the theory would be exactly confining.

In this note, I will adopt a very naive picture of confinement and use it to argue that the DGJ mechanism does not really work. Rather, I suspect that the gauge symmetry in such a system is dynamically restored, and the theory is actually confining.

The argument goes as follows. First let me imagine adding to the standard quantum-chromodynamics (QCD) theory some set of scalar fields with color. The precise color-SU(3) representation will not matter very much. The scalar fields may have Yukawa couplings to the quarks, and they will certainly interact among themselves. I will assume that none of these couplings are large.

To begin, I will assume that the scalar fields have a mass square small compared to Λ^2, but positive so that the theory in tree approximation does not spontaneously break the gauge symmetry. Many particle theorists would agree that this theory confines quarks and probably the colored scalar mesons as well. I will assume that it does.

This theory presumably describes the usual baryon and meson bound states of quarks, slightly modified by the effect of the scalar mesons on the QCD confining force. In addition, there will be bound states involving the confined scalar mesons. In all of the states, the scalar mesons are confined inside a region of size roughly $1/\Lambda$. The scalar particles are far off their mass shell.

In fact, the mass term is not very important for the confined scalar fields. It is a small perturbation. I can take the mass to zero, and nothing much happens. In the scalar meson bound states, there are not even the large spin-spin forces associated with the breakdown of chiral symmetry in a quark-antiquark bound state. The scalar bound states just get a bit lighter when the mass in the Lagrangian is reduced to zero. The mass of the bound state is still of order Λ.

Now suppose the mass squared is reduced further, to a negative mass squared $-m^2$, but with $m^2 \ll \Lambda^2$. Again, I think, nothing much happens except that the scalar-meson bound states get a bit lighter. The negative mass squared is a small perturbation which does not change the confining nature of the theory.

This interpretation conflicts with the straightforward interpretation of the tree-approximation Hamiltonian, which suggests that the gauge symmetry is spontaneously broken. But in a theory which confines at distances of order $1/\Lambda$, a tree approximation which purports to determine the structure of the vacuum at distances of order $1/m$, much larger than $1/\Lambda$, is quite likely to be spurious. The scalar fields simply do not spread out far enough to discover that they are supposed to develop a VEV. The mass term is irrelevant if the mass is small compared to Λ.[2]

As m is increased, the scalar-meson bound states continue to decrease in mass until eventually for an $m^2 = m_c^2 \simeq \Lambda^2$, the lightest physical scalar-meson bound state becomes massless. It is this physical requirement which, I think, signals the onset of spontaneous symmetry breakdown.

The crucial question is: What happens as m^2 is increased beyond the critical point m_c^2? The gauge symmetry breaks spontaneously, but what is the nature of the transition to the broken-symmetry phase? If the phase transition is second order, the Higgs-meson VEV turns on gradually as m^2 increases above m_c^2. If this happens, DGJ can obtain a small VEV by tuning the negative mass squared $-m^2$ appropriately. On the other hand, if the phase transition is first order, the Higgs-meson VEV turns on immediately of order Λ. If this happens, the DGJ mechanism is not particularly relevant because the liberated quarks will have a typical hadronic mass.[3]

No one knows enough about confinement to be sure what happens at $m^2 \simeq m_c^2$. I suspect a first-order phase transition because I think perturbation theory is not completely irrelevant for $m^2 \simeq \Lambda^2$. My picture is that for $m^2 \simeq \Lambda^2$, there is a local minimum of the effective action at $\phi^2 \simeq m^2/\lambda$, as suggested by the classical potential, but that for $m^2 < m_c^2$ there is a lower minimum at $\phi^2 = 0$ induced by quantum effects. If this is the situation, the phase transition will be first order.

One might hope to save the DGJ mechanism by introducing a negative mass term $-m^2$ with $m^2 > \Lambda^2$ in such a way that it would induce a small VEV μ. Typically (for large m) one expects $m^2 \simeq \lambda\mu^2$ where λ is a scalar-meson self-coupling. Perhaps with a large value of λ, one could force a small VEV on this theory.

This may be possible, though for large λ perturbation theory is not a reliable guide to the nature of the spontaneous breakdown. But the real problem in the present context is that for large λ, there is no reason to expect the theory to look like QCD. For example, the large λ affects the momentum dependence of the gauge coupling. This defeats the purpose of the DGJ mechanism, which was to let quarks get out without drastically modifying the QCD predictions at short distances.

Thus, if the transition to the broken-symmetry phase is first order, DGJ has no starting point. It is not possible to give colored scalar fields a VEV small compared to Λ in a theory which otherwise resembles QCD. And the rest of the DGJ argument, while interesting, is probably moot.

In fairness, I must point out that while I believe the arguments presented here are convincing, they are certainly not rigorous.

I am grateful to S. Coleman, H. D. Politzer, and E. Witten for useful conservations. I would like to especially thank the authors of Ref. 1 for several fruitful and friendly arguments. It is a pleasure to have colleagues who can disagree so constructively. This research was supported in part by the National Science Foundation under Grant No. PHY77-22864 and in part by the Alfred P. Sloan Foundation.

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[1]A. De Rújula, R. C. Giles, and R. L. Jaffe, Phys. Rev. D 17, 285 (1978).

[2]DGJ argue that the scalar fields do spread out far enough to feel the effect of a small negative mass term inside the "bag" which forms between color sources separated by a large distance. I believe that the classical potential is irrelevant inside such a bag because there is a color electric field of order Λ^2. Such an electric field will induce quantum corrections to the effective action which overwhelm the small classical negative mass term.

[3]This description of the nature of the question was developed in discussions with S. Coleman, R. Giles, and R. Jaffe.