A way to observe free quarks

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It might be possible to detect relict free quarks after they have been knocked out of matter by an intense proton beam.

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There is no solid theoretical basis for the widely popular idea of absolute quark confinement. All attempts to date to prove absolute confinement by quantum chromodynamics have been unsuccessful. On the other hand, several studies of the infrared asymptotic behavior of the Green's functions of quantum chromodynamics[1–5] suggest that it might be possible to arrange a situation in which, despite the strong infrared singularity of the gluon propagator, a mass shell and corresponding asymptotic states for quarks exist.[3–5] It would then be possible in principle to observe quarks. The infrared asymptotic behavior of the gluon propagator[1,2] $D(k) \cong M^2/(k^2)^2$ in the approximation of the exchange of a single dressed gluon leads to the following long-range quark-antiquark interaction potential[4]:

$$V(r) \underset{r\to\infty}{=} \frac{g^2M^2}{6\pi} r = a^2 r. \tag{1}$$

This result would appear to support the hypothesis of absolute confinement, but it must be kept in mind that expression (1) was derived in the approximation of the exchange of only a single gluon, while the actual potential must incorporate all possible exchanges. We do not rule out the possibility that when all possible exchanges are taken into account the behavior in (1) will change at sufficiently large distances, and there will ultimately be a Coulomb decay in the limit $r \to \infty$ (see also Ref. 6). As a result, the potential may assume the form shown in Fig. 1. The linearly increasing part of the potential is described by the expression $a^2 r$, where $a = 420$ MeV (from the spectrum of charmonium, etc.), and at large r the potential falls off as G^2/r. Since the

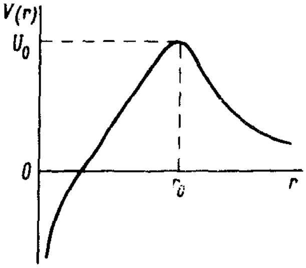

FIG. 1. Possible shape of the quark-antiquark potential.

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potential is quite wide, tunneling is negligible, and the maximum height of the potential, U_0, determines the energy threshold for the production of free quarks. From experiments on e^+e^- annihilation[7] we infer that this threshold is $E_0 \geqslant 35$ GeV in the c.m. frame. We note that the height of the potential may also be significantly less than E_0, since a quark moving between the production point and the potential barrier intensely emits gluons, which then hadronize, forming a jet. At this point, we do not have even a classical chromodynamic theory for the emission of free quarks, but working by analogy with electromagnetic radiation theory we may assume that the emission intensity is inversely proportional to the square of the quark's mass. If we make literal use of the electrodynamic expressions for radiation with a charge G determined by the Coulomb decay at $r > r_0$, we find the following energy condition for quark production:

$$E \geqslant 2M + U_0 + \frac{2U_0^3}{3M^2}, \tag{2}$$

where M is the mass of the quark, and the last term gives the radiative loss. Since b quarks with a mass of 4.5 GeV are not produced below 35 GeV, we can estimate the barrier height to be $U_0 \geqslant 8$ GeV. The dimensions of the quark can then be characterized by the parameter $r_0 \geqslant 10^{-12}$ cm (Fig. 1). In this interpretation, the failure of searches for quark production at high energies can be attributed to the fact that the production threshold has not been reached. It would thus be very interesting to see experiments at higher energies.

I wish to call attention to a possibility for observing quarks which has not been discussed previously. The search would be carried out with an intense-beam accelerator at a comparatively modest energy (below the production threshold). Let us first consider how a quark or antiquark interacts with a nucleon or a nucleus. Since a nucleus is colorless, its interaction is determined by the polarization in the color field: $H_{\text{in}} = \mathbf{dE}$, where $\mathbf{E} = -\partial V/\partial x$. The induced dipole moment $\mathbf{d}$ is also proportional to $\mathbf{E}$, and we conclude from this picture that the interaction potential corresponds to an attraction and is a square well of size $r_0 \simeq 10^{-12}$ cm with some constant depth V_0. Pursuing these arguments, we can estimate the cross section for the interaction of quarks with nucleons and nuclei to be $\sigma = 2\pi r_0^2 = 6 \times 10^{-24}$ cm^2, or much larger than ordinary nuclear cross sections. Cross sections of this type are characteristic of the "anomalons" observed in experiments involving the collisions of heavy nuclei.[8] An anomalon is a fragment of the incident nucleus with a range of 1.5–2.5 cm in matter (depending on the particular medium). Some investigators (see Ref. 9, for example) interpret this entity as a nucleus with an attached quark. A characteristic feature of the production of anomalons is an energy threshold on the order of 1 GeV/nucleon in a heavy-ion beam. Working from our picture we can explain in a qualitative way why quarks can be freed in the form of anomalons during the fragmentation of a nucleus. If we assume that the potential barrier is not very high, say 8 GeV, then the energy required to overcome this barrier is already available in experiments in which anomalons are observed, and the emission of a quark attached to a nucleus would be inconsequential [see (2)] because of the large mass of the nucleus. Pursuing this interpretation, we can estimate the cross section for the quark-nucleus interaction to be $\sigma = 7 \times 10^{-24}$ cm^2, where we are adopting a range of 1.5 cm in matter with the density of water, in agreement with the theoretical estimate given above. Working from the values of a, r_0, and nuclear sizes, we would expect the well depth V_0 to be some tens or hundreds of MeV. We cannot offer a more precise estimate at this point, but qualitatively we would expect V_0 to increase with increasing atomic number. Relict quarks would thus be more likely to accumulate in heavy materials than in light materials. These arguments can explain the differences in the results of different experimental searches for quarks in matter. In Ref. 10, where fractional charges $\pm e/3$ were detected in an abundance of 10^{-20} per nucleon in niobium and tungsten, the atomic numbers of the materials were higher than that of the iron used in Ref. 11, where no effect was observed above a level of 3×10^{-21} per nucleon.

The idea underlying the experiment which we are proposing here is to knock relict quarks out of matter with an intense proton beam and then detect them. We of course mean u and d quarks with masses $\leqslant 350$ MeV. In estimating the number of events we work from the experimental result of Ref. 10, according to which there are 6×10^3 quarks in a gram of a heavy material, and from the estimated cross section for a proton-quark interaction, $\sigma = 6\times 10^{-24}$ cm^2. At a beam intensity of 10^{13} p/s, a target length of 2 cm, and a target density of 20 g/cm^3 (W,Pt,Au,U) we then find one event a day. If, on the other hand, it proves to be correct to interpret anomalons as bound states of quarks with nuclei, then the concentration of quarks in the target will increase in the course of the experiment as a result of the production of anomalons, and this effect would increase the count rate substantially. This experiment is realistic, especially if the quark interpretation of anomalons is correct. The beam would have to have an energy sufficient to ionize anomalons with a high probability, 70 GeV, for example. The detector must have little mass so that a quark with a cross section $\sim 10^{-23}$ cm^2 does not stick to it. The general plan might follow the principle of searching for particles in the kinematically forbidden region, as in the first experimental search for quarks as Serpukhov.[12] In the previous experiments, we might note, the beam intensities were not adequate to detect the effect.

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