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Comments and Addenda

The section Comments and Addenda is for short communications which are not appropriate for regular articles. It includes only the following types of communications: (1) Comments on papers previously published in **The Physical Review** *or* **Physical Review Letters**. *(2) Addenda to papers previously published in* **The Physical Review** *or* **Physical Review Letters**, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section must be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts follow the same publication schedule as articles in this journal, and page proofs are sent to authors.*

Interpretation of new evidence for free quarks

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Taking the recent results of LaRue, Fairbank, and Phillips at face value and assuming the fractional charge observed on three out of nine niobium balls was due to quarks, it is concluded that these three balls contained at least three $\bar{d}$ quarks and two u quarks on their surfaces. It is shown that this result is not inconsistent with the negative results of other quark searches provided that primordial quarks are predominantly positively charged, the u-d mass difference is less than the electron mass, and total confinement is invalid. A cosmological proof is given that primordial quarks must be positively charged.

The combined results of LaRue, Fairbank, and Hebard[1] and LaRue, Fairbank, and Phillips[2] give evidence for fractional charge on three out of nine niobium balls in a modified Millikan oil-drop experiment. Whenever a fractionally charged ball was scrubbed or exposed to an electric discharge, there was a change in the nature of the fractional charge. This strongly suggests that the fractional charge must have resided on the surface as suggested in Ref. 2. Reference 2 also suggests that the heat treatment 1800 °C for 17 hours could have swept positively charged quark impurities to the surface. Before heat treatment the balls were multicrystalline; after heat treatment they were single crystals.

In the remainder of this paper it will be assumed that the fractional charges observed in this Stanford experiment are due to appropriate u and d quarks. The observations can be explained as follows.

Ball 3 had a residual charge of $-\frac{1}{3}$ which changed to zero after scrubbing in acetone and alcohol. The simplest explanation is that a u quark of $+\frac{2}{3}$ charge was scrubbed off the surface. (A residual charge of $-\frac{1}{3}$ is indistinguishable from $+\frac{2}{3}$.) Appropriate quark combinations such as two $\bar{d}$ or two u plus one $\bar{d}$ could give the same result.

Ball 6 has a more complex history. Initially with residual charge $q_r = +\frac{1}{3}$, it changed to $q_r = 0$ after washing in acetone and alcohol. Later, after experiencing an unplanned electric discharge, it "picked up" a new fractional charge $q_r = +\frac{1}{3}$. Then after a second unplanned electric discharge, q_r went back to zero and remained zero after a third discharge (this time intentionally induced). But how can ball 6 pick up a quark by electric discharge if free quarks are so rare? This question is resolved by assuming it had originally three positively charged surface quarks, one u and two $\bar{d}$'s. As indicated in Fig. 1, the washing removes one $\bar{d}$, the first discharge removes the u quark, the second discharge removes the final $\bar{d}$, and subsequent discharges will have no further effect.

Ball 9 originally had $q_r = +\frac{1}{3}$, and after remeasurement (with no washing or discharges) still had $q_r = +\frac{1}{3}$. This could be explained in terms of a single $\bar{d}$ on the surface.

The remainder of this paper will show that these

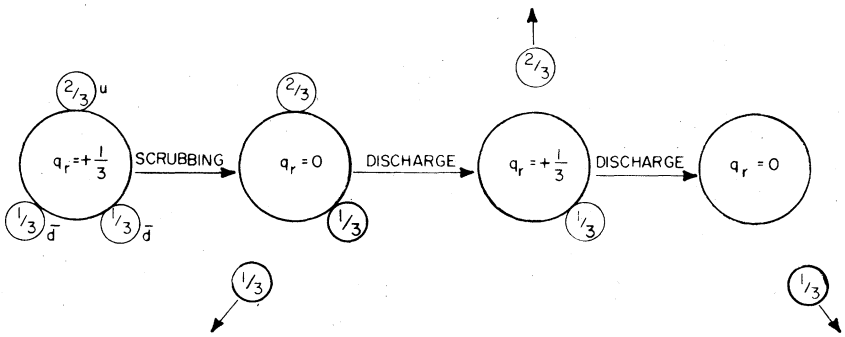

FIG. 1. History of ball 6. The one-by-one release of positive surface quarks gives rise to a residual charge which changes from $+\frac{1}{3}$ to 0 to $+\frac{1}{3}$ to 0.

Stanford results can in a natural way be compatible with the negative results of previous quark searches. We must of course give up on total quark confinement. This is consistent with the fact that a proof of color and quark confinement in quantum chromodynamics does not exist.[3]

The total mass involved in the Stanford experiment was 7×10^{-4} g which yields a quark abundance in niobium of $\sim10^{-20}$ quarks per nucleon. It is pointed out in Ref. 2 that this abundance is not inconsistent with other Millikan oil-drop type of experiments. But an abundance of $\sim10^{-20}$ seems inconsistent with upper limits of $\sim10^{-22}$ reported by Cook *et al.*[4] and Stevens *et al.*,[5] who used ion-beam and mass-spectrometer approaches to analyze sea water, air, and rock samples (even from the moon). The negative results of these two groups can be made consistent with Refs. 1 and 2, provided the free quarks are not being produced in cosmic rays, they are only positively charged, and their rest mass is several GeV/c^2. In the next paragraph we shall explain why free quarks should not be in the cosmic rays and why they should be positively charged.

There is the additional problem of getting the observed abundance of 10^{-20} compatible with the nonobservation of quark production by high-energy accelerators.[6] This author has previously proposed that free-quark pair production in nuclear matter is effectively quenched by the presence of spectator quarks which induce quark recombination in the interaction region.[7] However, quark pair production in vacuum by $e^- + e^+ \rightarrow q^- + q^+ + X$ is permitted and has not been ruled out by experiment. This method of quark production could only take place during the first second of the "big bang." We are thus forced to conclude that most of the existing free quarks must have been produced primordially. An estimate which the authors feel contains "large ambiguities" has been made of the abundance of primordial quarks.[8] If the free-quark mass is several times that of the nucleon mass, the free quarks were "frozen out" at a time when the number of quarks and antiquarks in the universe were equal to each other to about one part in 10^8.[8,9] If one uses 10^8 for the entropy per nucleon and a quark-quark cross section of tens of mb, Ref. 8 gives $\sim10^{-14}$ for the ratio of quarks (or antiquarks) per nucleon. The approach used in Ref. 8 completely ignores any possibility of confinement or processes which simulate confinement such as suggested in Ref. 7. L. W. Jones has pointed out that such a low primordial abundance would not be detected in cosmic-ray experiments.[10]

During the fourth minute of expansion of the universe the remaining neutrons would be absorbed into helium nuclei.[11] At this age of the universe, kT is high enough so that more than 10^{-3} of the quarks and protons could undergo charge exchange each time a collision took place. The only available charge-exchange reactions would be

$$d^{(-1/3)} + p \rightarrow u^{(2/3)} + n \quad \text{and} \quad \bar{u}^{(-2/3)} + p \rightarrow \bar{d}^{(1/3)} + n\,,$$

where the superscript denotes charge. The positive quarks are too far below the 20-MeV threshold for charge exchange, viz.,

$$u^{(2/3)} + {}^4\text{He} \rightarrow d^{(-1/3)} + {}^3\text{He} + p$$

is energetically forbidden. After repeated collisions the end result is transformation of the negative quarks into positive quarks. We conclude that primordial quarks must be positively charged for the same sort of reason that primordial nucleons must be positively charged.

In this discussion we have assumed a u-d mass difference less than the electron mass. This is because both types are needed to explain the Stanford observations, and thus both types must be stable. If the above explanations are correct, we see that there is nothing special about niobium or the thin tungsten layer on some of the balls in the Stanford experiment.

Note added in proof. After this paper was submitted, I received a report by R. V. Wagoner and G. Steigman [Phys. Rev. D 20, 825 (1979)] which predicts a primordial quark to a nucleon ratio of 10^{-20} provided $M_q > 15$ GeV.

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