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Comment on recent evidence for unbound quarks

Lawrence W. Jones
The University of Michigan, Ann Arbor, Michigan 48104
and Westfied College, London N.W. 3
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Recent possible positive evidence for quarks in stable matter is examined in the context of published negative quark searches. It is concluded that quarks may either be constrained to exist only in nuclei produced by high-energy fission or may be primordial constituents of matter.

A recent paper by the Stanford low-temperature group reports two niobium pellets, each of about 9×10^{-5} g, with third-integral electric charge.[1] This is interpreted as evidence for unpaired or unbound quarks in stable atomic matter. The purpose of this paper is to explore the relationship of the result to the previous body of experimental data relating to quarks of fractional electric charge.

There are two classes of experiments with stable matter: Those such as the Stanford experiment wherein a sample of gross matter is studied for a net electric charge (basically refinements of the Millikan oil-drop experiment), and those wherein a sample of matter is treated so as to "concentrate" the quarked matter. Of the oil-drop group of experiments, the Stanford measurement is among the most sensitive published, exploring possible quark concentrations $\rho\simeq10^{-20}$ quarks per nucleon (Q/N). An earlier published measurement by Garris and Ziock[2] was sensitive at a level of $\rho\lesssim5\times10^{-20}$ Q/N, but reported an ambiguous result (actually favoring $|q|=\pm\frac{1}{3}$ for 11 out of 12 iron samples) due to systematic difficulties. Negative results were reported by Morpurgo,[3] Johnston,[4] and Stover[5] at levels of $(1-5)\times10^{-19}$ Q/N, and by others at less significant levels. A subsequent report by the University of Genoa group sets limits of $\rho<3\times10^{-21}$ Q/N on iron.[6] Hillas reported no evidence for quarks at a level of 10^{-22} Q/N in a different sort of experiment wherein the net charge on a cylinder of bulk gas (nitrogen or argon) was sought, in order to explore the equality of proton- and electron-charge magnitudes.[7]

In the other class of quark searches in stable matter, samples are evaporated, ionized, or otherwise fragmented and the atoms (or molecules) analyzed with an ion beam or mass spectrograph apparatus.[8] These searches assume that quarks would be incorporated into an otherwise free atom or molecule, and that this particle behaves as predicted simply on the basis of its fractional electric charge. Cook *et al.* have studied sea water and a wide variety of rock samples, and have set limits to ρ of $10^{-22}-10^{-24}$ Q/N. Stevens *et al.* have studied lunar soil samples and deep ocean sediment, and have set limits to ρ of $10^{-21}-10^{-22}$ Q/N. Had quarks been found by these experiments, both the existance of quarks and the experimenters' assumptions concerning the behavior of quarked matter would have been established. However, a negative result may only prove that quarked matter does not behave as assumed. For example, a quarked nucleus may interact with neighboring nuclei through a long-range chromodynamic force to form an aggregate of matter, perhaps analogous to an ion in a polar solvent. In such a case, evaporation or ionization of the quarked atom might be strongly inhibited. Were this true, the negative results here might not contradict the recent Stanford results. In this context, it is disturbing that one niobium pellet lost its fractional charge through "handling" in the Stanford experiments.[1]

The searches for quarks in cosmic rays may be related to stable-matter searches assuming that (1) The incident cosmic-ray flux has remained constant since the since the earth was formed, and (2) there has been mixing of the crustal material of the earth to a limited depth y (g/cm^2) over the age of the earth. If quarks are produced by cosmic-ray interactions in the upper atmosphere and rain onto the earth with a flux ϕ [(cm^2 sr sec)$^{-1}$], then

$$\phi=\frac{Ny}{\pi t}\rho\,,$$

where t is the accumulation time and N is Avogadro's number. For $t=4\times10^9$ (1.2×10^{17} sec) and $y\geqslant3\times10^4$ g cm^{-2}, $\phi\geqslant5\times10^{10}\rho$. The mixing depth y is quite uncertain; over this time it could be as much as 5×10^7 g/cm^2 (the mixing depth of crustal plates) or as little as 3×10^5 g cm^{-2} (the average depth of oceans). The depth of the atmosphere and the probable stopping and capture mean free path of produced quarks together with glaciation and surface erosion make values of y less than $\sim3\times10^4$ g cm^{-2} highly unlikely for even the most favorable stable parts of the earth's crust. The Stanford results thus imply a cosmic-ray flux ϕ of $\gtrsim5\times10^{-10}$ quarks per (cm^2 sr sec).

Since 1964 a very wide variety of cosmic-ray experiments has been carried out, seeking quarks among air showers, under lead shielding, and as unaccompanied particles (the latter at sea level, on mountain tops, and underground). Separate experiments[9] on unaccompanied particles have set 90% C.L. upper limits to ϕ of 5×10^{-11} to 3×10^{-10} quarks per (cm^2 sr sec)$^{-1}$ for quarks of charge $\frac{1}{3}$, $\frac{2}{3}$, or $\frac{4}{3}\,e$. Weighted combinations of the published limits are $\phi\leq1.1\times10^{-11}$ for $\frac{1}{3}e$ and $\phi\leq2.4\times10^{-11}$ for $\frac{2}{3}e$. The search for quarks among air showers[10] has also been undertaken by several groups with limits ranging from $\phi<1.2\times10^{-11}$ to 1×10^{-10} (90% C.L.). The weighted combination of these results gives $\phi\leq0.71\times10^{-11}$ for $\frac{1}{3}e$ and $\phi\leq1.4\times10^{-11}$ for $\frac{2}{3}e$. The Stanford results are thus not compatible with the cosmic-ray limits by about two orders of magnitude.

Searches for free quarks in beams from accelerators[11] are more sensitive than cosmic-ray searches by two to six orders of magnitude for quark masses of less than 20 GeV, for a wide range of assumptions concerning production kinematics.

If the Stanford results and all other experiments are taken at face value, the following must be assumed: (1) Unpaired quarks may exist in nuclei, but not as free particles; and (2) matter containing quarks behaves anomalously as regards evaporation. The compatibility with other stable-matter experiments is eased if the quarked nuclei of large A are stable and these of small A are forbidden. Thus Hillas,[7] Chupka,[12] and others[8] established their most stringent limits ($\rho<10^{-22}$ Q/N) for light elements: air, water, argon, etc. Most of the other samples were rock and other materials composed principally of nuclei with $A\lesssim30$. The Genoa group's recent limit was for iron.[6]

Longo has suggested a model[13] wherein quarks may exist in nuclei but not as free particles. Briefly, he suggests that the color force field of a quark in a nucleus may be shielded by polarization of the nuclear quarks so that the field strength at the nuclear surface may be too weak to produce quark pairs from the vacuum, whereas the separation of isolated quark pairs would always produce pairs from the vacuum, leaving color-neutral free hadrons as the only observables.

This model could explain why free quarks are not observed in accelerator beams or with cosmic rays. It could also help explain the fact that quarked matter is not easily evaporated or ionized. An alternative which could lead to the same consequences would be a model wherein the mass of an unpaired quark was a function of its nuclear environment; whereas a free quark might be very massive, quarks bound in nuclei might be lighter, so that the effective mass of the quark decreases as the atomic weight increases.[14] If the color-gluon field is indeed long range, it could add to the electrostatic bonding of a quarked nucleus into a crystal lattice and inhibit its separation. Further, if the quarked nuclei could only exist for $A\gtrsim60$–90, even this constraint would be eased.

On the other hand, such assumptions beg other questions. If free quarks cannot exist, but quarked (colored) nuclei can, then such quarked nuclei could only be formed by the interaction of an energetic particle (cosmic ray) with a heavier nucleus within which a quark pair is produced and which then undergoes fission, resulting in two quarked nuclei. The interaction of energetic cosmic rays with light nuclei (C, N, O) almost never result in fission, and they are rarely fission fragments. Alternatively, if the quark mass depends on nuclear size, with free quarks much heavier than quarks in nuclei, the steep dependence of the quark abundance on effective quark mass ($m^{-5.33}$ as noted below) may lead to the same consequence.

Quarked nuclei may have been formed through the fissioning of heavy nuclei by cosmic rays during the time between the formation of the heavy elements and the condensation of these elements to form the earth. During this time, t_B, this material may have been exposed to the full cosmic-ray flux. The value of ρ (quarks per nucleon) should then be given by

$$\rho=4\pi t_B\left[\int_{E_T}^{\infty}\frac{d\phi_c}{dE}\,\sigma_Q(E,m_Q)\,dE\right]f_Q f_F\,.$$

The factor f_Q is the fraction of quark production in a lead (or heavier) nucleus which results in unpaired quarks in each of two fission fragments, compared with the production of otherwise "free" quarks—assuming they could exist. The factor f_F is the fraction of niobium of fission origin, estimated[15] to be no greater than 10^{-5}. The cross section for "free" quark-pair production $\sigma_Q\,(E,m_Q)$ may be taken from the calculation of Gaisser and Halzen,[16] and the primary cosmic-ray flux $d\phi_c/dE$ is taken as $2.3E^{-2.67}$ (cm^2 sr sec)$^{-1}$ with E in GeV.[17] The threshold E_T for quark production may be approximated by

$$E_T\simeq 2m_Q{}^2/m_p\simeq 2m_Q{}^2,$$

(where E_T and m_Q are in GeV) and the production cross section is a function of $(E-E_T)/m_Q$ and is proportional to $m_Q{}^{-2}$. If spin factors are set equal to unity, the integral in square brackets is given approximately by

$$5.1\times10^{-30}(m_Q)^{-5.33}\ (\text{sr sec})^{-1},$$

where m_Q is in GeV. The time t_B is uncertain between 10^8 and 10^{10} years; 10^9 may be taken as a guess. The factors f_Q and f_F are taken as 10^{-2} and 10^{-5}, so that

$$\rho \cong 6 \times 10^{-19} (m_Q)^{-5.33} \text{ quarks/nucleon.}$$

With these assumptions, the Stanford result of $\rho \simeq 10^{-20}$ leads to $m_Q \simeq 2.2$ GeV. It should be noted that if the product $(f_Q f_F t)$ is increased by 3500, even $m_Q = 10$ GeV yields the Stanford result, and a reduction in σ_Q (e.g., in accord with a statistical model) would require a lower m_Q to yield the Stanford ρ value.

Therefore if quarked niobium resulted from the cosmic-ray fission of heavy elements before the earth formed, quarks must be so light and their production cross section through this process must be so large that they would be readily observed in fission fragments from heavy-element targets at Fermilab and the CERN SPS.

The Stanford group notes that the two spheres on which fractional charge was observed had been heat-treated on a tungsten substrate, and that the tungsten might have contained the quarks in a relatively rich concentration. The heat treatment process coats the niobium with a thin surface layer of tungsten. However, recent reports cite results of electrostatic levitometer searches for quarks in tungsten granules.[18] While the 90%-C.L. upper-limit concentration is only 6×10^{15} quarks per nucleon, this is 30 times the quark concentration needed to provide the observed quarks on the tungsten surface of the Stanford spheres.

The mechanism sketched above is more probable than the alternative wherein quarked nuclei would be made by the fissioning of heavy nuclei by cosmic rays which had penetrated the earth's atmosphere following the formation of the earth. The attenuation of the primary flux in the atmosphere, 3×10^{-4}, and the crustal mixing depth y suppress such quark production more than would be offset through any gain in integration time.

A final possibility exists that quarks are a primordial constituent of matter (made in the "big bang") but cannot be made by cosmic rays or accelerators with cross sections thus far explored, either because of large mass or low production cross section.[19] Zeldovich and Okun[20] calculated that quark concentration would be 10^{-9}–10^{-18} Q/N, and Feinberg[21] notes that observations of the 3°K radiation may constrain ρ to 10^{-10}–10^{-13} Q/N. As the primary cosmic-ray flux beyond the geomagnetic cutoff is only of order unity per (cm^2 sr sec), cosmic-ray-flux limits would be insensitive to primordial quarks in the concentration reported by the Stanford experiments by nine orders of magnitude. One must additionally explain, however, the negative results of the more sensitive experiments with stable matter.

Further discussion of production calculations and summaries of earlier experimental results has been published.[22]

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model.

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