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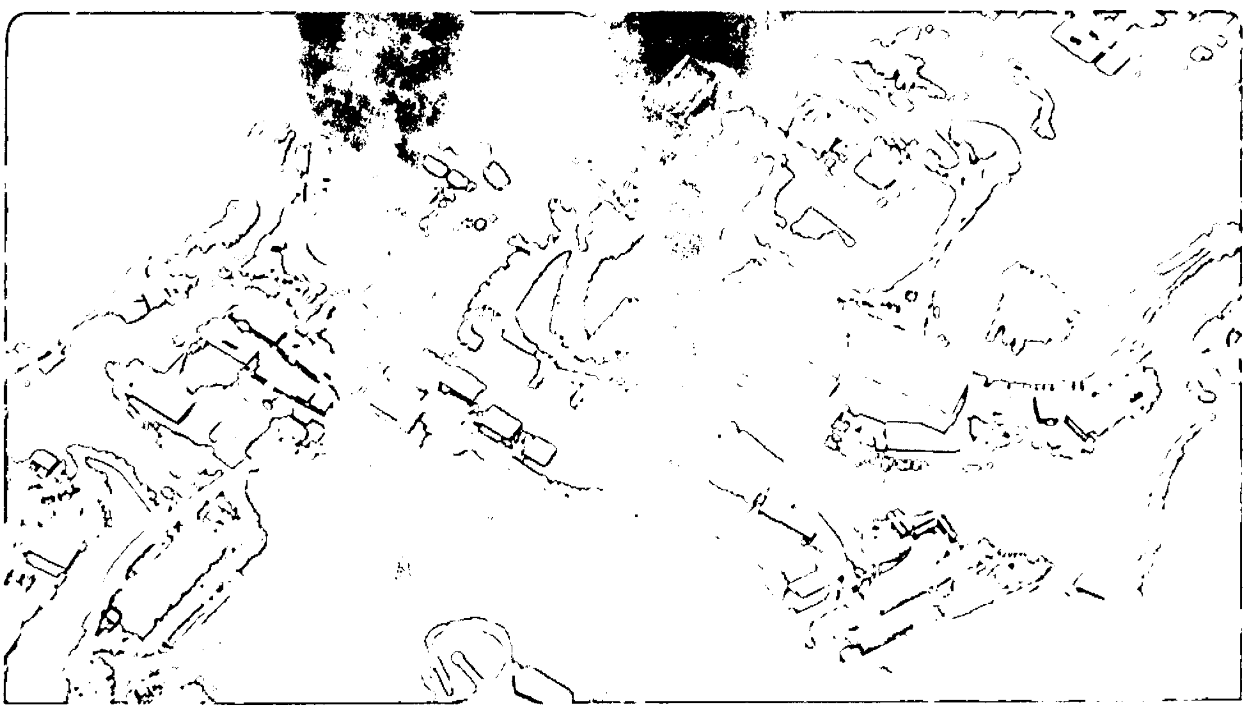

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DISCLAIMER

MINIMALLY MODIFIED, UNBROKEN QCD WITH FRACTIONALLY CHARGED STATES†

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ABSTRACT

We discuss a modification of QCD which does not tamper with confinement but still has fractionally charged states formed out of quarks and, in the case we focus on, a proposed neutral, color-triplet of massive scalars. The model has a number of attractive features, however all such models appear to have difficulty with achieving a sufficiently low cosmological abundance before freeze-out, unless one makes some unconventional assumptions.

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Ever since the proposal of the quark model by Gell-Mann and Zweig, there has been an interest in trying to observe fractionally charged states (FCS). On the other hand, quantum chromodynamics (QCD) (the quark model transformed into a gauge field theory) is believed to demand quark confinement. So if FCS are observed (and in the past few years the experiments of La Rue, Phillips, and Fairbank[1] claim to have done so) some modification of the standard conception of QCD would be required (assuming the FCS are hadronic).

Probably the most direct alternative, but also the most drastic, is to assume that FCS are really free quarks which supposedly can exist if one allows for spontaneous breaking of color symmetry[2,3] at a scale $\mu < \Lambda_{QCD}$. A nice feature[4] of these theories is that the "reluctant" liberation of quarks (or di-quarks in the glow model) allows reduction of the concentration of the FCS, objects "x", to the value

$$\frac{n_x}{n_{baryon}} \approx 10^{-20} \text{ or } r_x \equiv \frac{n_x}{n_\gamma} \approx 10^{-30}, \qquad (1)$$

which is consistent with the upper bounds[5] and the claimed observations.[1] However, the lack of glueball type states of small mass $\approx \mu$ is a severe argument[6] against such theories.

Another and in some ways the simplest alternative[7,8] is to assume x is a new, fractionally charged lepton, a possibility which is allowed in such grand unified theories (GUTs) as those based[9] on SU(7). (These models also allow for new fractionally charged hadrons.) The lack of observation of such new leptons in colliding beams or other experiments is readily accounted for if $m_x \gtrsim 50$ GeV. However, it is extremely difficult[7] to avoid cosmological x concentrations far larger by many orders of magnitude than (1).

We would like to focus our attention on the possibility that x is a new hadron, but rather than breaking QCD, we prefer the simpler, more conventional approach of having x a color-singlet hadron.[10] There are a number of ways of doing this but we wish to focus specifically on modifying QCD in a minimal way, merely by introducing a color triplet of electrically neutral, massive scalars ϕ. Then $x \equiv (\bar{\phi}q)$ or (ϕqq) is a color-singlet hadron carrying fractional electric charge. We believe this to be the simplest approach consistent with confined QCD. For example, adding such a neutral scalar triplet clearly is not going to contribute to anomalies.

Although for simplicity we have assumed that the mass term for ϕ is positive, still our ϕ bears some analogy to the Glashow-Weinberg-Salam Higgs scalars h, which like the left-handed leptons belong in the fundamental [2] representation of $SU(2)_L$, but are an $SU(3)_C$ singlet. The analogy can be carried further in the complementarity[11] approach where $SU(2)_L$ is viewed as unbroken and the physical leptons are $SU(2)_L$ singlet composites $(h_i^\dagger \psi_{iL})$. Being aware of the usual arguments unfavorable to fundamental scalars,[12] we can just as well have these scalars ϕ be composite at some higher energy scale as has been suggested for h.

One of the main motivations for our proposal is that ϕ's form strongly bound meson-like $\bar{\phi}\phi$ and baryon-like $\phi\phi\phi$ neutral states which one might hope could account for the small concentration of ϕ-quark bound states. Before discussing this issue we note that since the x's are not elementary, the point-like $\gamma x\bar{x}$ vertex does not occur. Production of $x\bar{x}$ pairs in e^+e^- experiments can still proceed via a quark loop, annihilation into 3 gluons, and then ϕ pair creation, however such a process would be reduced by $\alpha_s^6 \approx 10^{-4} - 10^{-6}$. Better bounds would come from purely hadronic experiments, particularly if the large c and b

production cross sections are confirmed. At any rate if $m_\phi \gtrsim 10$ GeV, present bounds are well avoided.

There are essentially two independent reasons why the models in which FCS ≡ lepton = $L_{1/3}$ fail to yield the small ratio (1). The first point concerns the $L_{1/3} - \bar{L}_{1/3}$ asymmetry. An important observational fact[13] is that there is a baryon excess

$$A_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_q - n_{\bar{q}}}{n_\gamma} \approx 10^{-10} . \qquad (2)$$

If (1) is satisfied we must have $\frac{n_x - n_{\bar{x}}}{n_\gamma} = \frac{n_L - n_{\bar{L}}}{n_\gamma} \lesssim 10^{-30}$. If we do not wish to attribute the baryon asymmetry to initial conditions (or to spatial separation of matter and antimatter), we can adopt the explanation that it is generated at some early stage of the big bang when $T \approx m_X$, the scale of grand unification, by baryon- and lepton-number violating processes. Since $m_X \gtrsim 10^5$ GeV in all known schemes, $m_L \approx m_q$ on that scale and it is extremely difficult to understand, particularly in GUTs incorporating $L_{1/3}$, why the same mechanism does not simultaneously yield $\frac{n_L - n_{\bar{L}}}{\gamma} \approx \frac{n_q - n_{\bar{q}}}{\gamma} \approx 10^{-10}$ with 20 orders of magnitude violation of (1)! Even in the case of no asymmetry large concentrations of the new stable particles would freeze out at the decoupling temperature T_f when the $L\bar{L}$ annihilation rate falls behind the expansion rate of the universe. Rather elaborate mechanisms[7] need to be postulated by which practically all the L's get reconcentrated in super massive protostars, followed by ionization of L-nuclei states and almost complete $L\bar{L}$ annihilation.

It would seem that the hadronic $x = \bar{\phi}q$ model offers a panacea for all these difficulties. The main advantage is that the binding of the Coulomb-like states $\bar{\phi}\phi$ and $\phi\phi\phi$ are (with SU(3) factors and reduced masses properly accounted for):

$$B_{\bar\phi\phi} = \frac{1}{2}\frac{4}{3}\alpha_s\left(\frac{m_\phi}{2}\right) = \frac{1}{3}\alpha_s m_\phi$$

$$B_{\phi\phi\phi} = \frac{3}{2}\frac{2}{3}\alpha_s^2 m_\phi\frac{2}{3} = \frac{2}{3}\alpha_s^2 m_\phi, \qquad (3)$$

and these can get to be very large as compared with $\bar\phi q$ or ϕqq bindings which are reduced due to the lightness of the quark mass. If all states are in thermal equilibrium as $T \to \Lambda_{QCD}$ (which we denote hereafter merely by Λ), as one would naively expect for the strongly interacting ϕ's and q's, we can use the standard formula[14] for the equilibrium concentration (assuming vanishing chemical potentials),

$$n_{\phi eq} = \frac{1}{(2\pi)^3}\int_0^\infty 4\pi\, p^2 dp\left[\exp\left(\frac{\sqrt{m_\phi^2+p^2}}{T}\right) - 1\right]^{-1}, \qquad (4)$$

which for $T < m_\phi$ we can approximate without significant error by the nonrelativistic result

$$r_{\phi eq} = \frac{n_{\phi eq}}{n_\gamma} \approx \frac{1}{.24(2\pi)^{3/2}}\, \chi^{3/2} e^{-\chi},\ \chi = \frac{m_\phi}{T}, \qquad (5)$$

where we have divided by $n_\gamma \approx .24\, T^3$. Then

$$r_\phi\big|_{T\approx\Lambda} \approx \frac{1}{.24(2\pi)^{3/2}}\left(\frac{m_\phi}{\Lambda}\right)^{3/2}\exp\left(-\frac{m_\phi}{\Lambda}\right), \qquad (6a)$$

if $A_\phi = \frac{n_\phi - \bar n_\phi}{n_\gamma} = 0$. If A_ϕ is significant, then assuming all excess ϕ's are bound into $\phi\phi\phi$ states by $T \approx \Lambda$, the ϕ concentration is controlled by

$$r_\phi\big|_{T\approx\Lambda} \approx A_\phi e^{-2/3\alpha_s^2 m_\phi/\Lambda}. \qquad (6b)$$

Since n_ϕ at $T \approx \Lambda$ is also the number of $\bar x = \phi\bar q$ and $x = \phi qq$ states eventually formed (since q's far outnumber ϕ's at this point by construction), we expect to satisfy (1) if

$$m_\phi \gtrsim 75\,\Lambda \approx 15 \text{ GeV, case a} \qquad (7a)$$

or

$$m_\phi \gtrsim 70\,\frac{\Lambda}{\alpha_s^2} \approx 700 \text{ GeV, case b with } A_\phi \approx A_B \approx 10^{-10}. \qquad (7b)$$

We note incidentally that the Coulomb approximation used in (3) is better at high temperatures above the deconfinement $T \approx \Lambda$, when the linear confining forces are absent. We verify also that the Debye screening length ℓ_D of the gluon and quark plasma which exists above the deconfinement temperature is larger that the size of the bound $\bar\phi\phi$ system so that the Coulomb approximation is also valid from this aspect. This follows from noting that $\ell_D \approx \sqrt{\frac{T}{n\alpha_s}}$ ($n \sim T^3$ is the plasma number density) so that for temperatures on the order of and below the binding energy of the $\bar\phi\phi$ system ℓ_D is larger than the Bohr radius $r_B \approx \frac{1}{m_\phi\alpha_s}$.

In the case of A_ϕ = ϕ asymmetry $\neq 0$ the ϕ excess could form $\phi\phi\phi$ "baryons" (which are really bosonic). Since from the estimates of Eq. (3) the decay $\phi\phi\phi \to \phi\phi q + \phi\bar q$ is energetically forbidden, we find quite surprisingly that the $\phi\phi\phi$ lowest states are absolutely stable (ignoring possible GUT effects). Being far more massive than ordinary baryons (by $3m_\phi > 100$ GeV) we expect them to collapse much earlier than normal matter and their bosonic nature could allow for peculiar condensate formations. The bounds on missing mass in the universe and the non-observation of heavy isotopes formed by {A, Z($\phi\phi\phi$)} would suggest that A_ϕ is considerably smaller than A_B though we are not forced to conclude $A_\phi \lesssim 10^{-20} A_B$.

However, upon closer scrutiny we realize that even this model, as well as any similar hadronic x model, is probably not viable regardless of the A_ϕ asymmetry. The crucial assumption that ϕ's, quarks, $\phi\bar{\phi}$ and $\phi\phi\phi$ bound states are all in thermal equilibrium all the way down to $T = \Lambda \approx 200$ MeV is most likely false. To see the difficulty we use the standard[13-15] rate equation

$$\frac{df}{d\theta} = D^{-1} M_P m_\phi \langle v\sigma \rangle (f^2 - f_{eq}^2), \tag{8}$$

where $f = \frac{n_\phi}{T^3}$, $\theta = \frac{T}{m_\phi}$, $D = \sqrt{\frac{8\pi^3}{90} N}$ (N being the number of effective degrees of freedom), $\langle v\sigma \rangle$ is the average of the relative velocity times the $\phi\bar{\phi}$ cross section, and M_P is the Planck mass. This equation has been numerically investigated[15] for various types of particles and conditions, but there also exists a reasonably accurate analytic approximation. We define the freeze-out temperature T_f by

$$\frac{df_{eq}}{d\theta} = D^{-1} M_P m_\phi \langle v\sigma \rangle f_{eq}^2, \text{ at } \theta = \theta_f = \frac{T_f}{m_\phi}, \tag{9}$$

then f approximately follows

$$\frac{df}{d\theta} = D^{-1} M_P m_\phi \langle v\sigma \rangle f^2, \; \theta < \theta_f, \tag{10}$$

with the initial condition $f(\theta_f) = f_{eq}(\theta_f)$. So the freeze-out temperature is given by

$$\chi_f^{-1/2} e^{-\chi_f} = \frac{(2\pi)^{3/2} D}{M_P m_\phi \langle v\sigma \rangle}, \tag{11}$$

and we must make some estimate of $\langle v\sigma \rangle$. Taking as a reasonable upper limit a typical hadronic cross-section ≈ 300 GeV^{-2}, we find

$$\chi_f \approx 45 \Rightarrow T_f \approx .33 \text{ GeV, (case a, } m_\phi = 15 \text{ GeV)} \tag{12a}$$

$$\chi_f \approx 48 \Rightarrow T_f \approx 15 \text{ GeV, (case b, } m_\phi = 700 \text{ GeV).} \tag{12b}$$

Hence the freeze-out temperature is well above (considering it appears

in an exponential) the value of Λ we used to estimate m_ϕ, and indeed the residual abundance of ϕ's at T_f is found to be

$$r_\phi(\theta_f) = \frac{f_\phi(\theta_f)}{.24} \approx \frac{D\chi_f^2}{.24 M_P m_\phi \langle v\sigma \rangle} \approx 10^{-18} \text{ to } 10^{-19}. \tag{13}$$

Thus although the annihilation and bound-state formation processes are efficient in reducing the density of ϕ's, they are not sufficiently efficient if one assumes even what is probably the upper limit on reasonable cross sections. Actually since above Λ we are dealing with a plasma of quarks and gluons, it is probably a more reasonable estimate to assume that $\langle v\sigma \rangle \approx \frac{\alpha_s^2}{m_\phi^2}$, which would considerably increase the residual abundance. Note also that the result (13) argues against the assumption of complete bound-state formation used in arriving at Eqs. (6b) and (7b) in the case of a ϕ asymmetry. What one would need is instead of a Coulomb potential, a rising, confining potential which would give an essentially infinite cross section.

Since by $T \to \Lambda$ the $\phi\bar{\phi}$ collisions are quite rare but ϕq collisions are far more frequent (by $10^{18} - 10^{19}$), we expect that all these residual ϕ's (13) will form x's. We then find using (10) that

$$f(\theta) = [f(\theta_f)^{-1} + D^{-1} M_P m_\phi \langle v\sigma \rangle (\theta_f - \theta)]^{-1}, \tag{14}$$

so that at present with $\theta \approx 0$,

$$r_x(0) \approx r_\phi(0) = r_\phi(\theta_f)(1 + \chi_f)^{-1} \approx 10^{-19} \text{ to } 10^{-21}, \tag{15}$$

which is still about 10 orders of magnitude too large compared with (1). Since r_ϕ is inversely proportional to m_ϕ and $\langle v\sigma \rangle$, one must increase either or both of these to make up the 10 orders of magnitude. But, for example, an $m_\phi \approx 10^{10}$ GeV (assuming no reduction in $\langle v\sigma \rangle$!) would give an extremely heavy x of ≈ 10^{-14} g which would presumably be difficult to avoid detecting unless one argued that such a large mass would force concentration in the cores of astronomical bodies. We wish to emphasize that although we have focused on the neutral, scalar ϕ model in our analysis, the result is general since the numbers change very little whether the ϕ is neutral or integrally charged, or has or has not spin.

It thus appears that one must make some rather unconventional assumptions about either the underlying particle physics or the history of the FCS particle during stellar evolution in order to accomodate such a FCS into the presently accepted framework of QCD on the one hand and big bang cosmology on the other. It may also be amusing to note that if the existence[16] of a magnetic monopole with minimal magnetic charge is confirmed, no unconfined, fractionally charged objects (not carrying some other charge coupled to long-range fields) will be consistent with the Dirac quantization condition eg = n/2. Needless to say, all these objections should serve only as a further incentive to search for FCS.

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