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Charge Spectra of Dyonic Quarks

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Considering quarks as dyons, we analyze different possibilities for free fractional electric charges and monopoles to coexist. For nonvanishing vacuum angle θ, electric charges of dyons are not exactly fractional, but carry extra charges proportional to θ. The average extra charge vanishes for mesons, but not for baryons.

1. INTRODUCTION

Although magnetic monopoles (Dirac, 1931, 1948) continue to be sought, very little experimental evidence has been presented so far for their existence. Since the report of Price *et al.* (1975, 1978), there has been growing interest in the theory of magnetically charged particles. At the same time it has become clear that a better understanding of monopoles and dyons can be achieved in non-Abelian gauge theory, where they appear as classical solutions of the system (Wu and Yang, 1969) and have a definite topological meaning (Arafune *et al.*, 1975; Coleman, 1977). At present it is widely recognized (Dokos and Tomaras, 1980) that monopoles and dyons are intrinsic parts of all current grand unified theories (GUTs) (Georgi and Glashow, 1972). Consequently, monopoles and dyons have become objects of utmost interest and of potential importance particularly in connection with the issue of quark confinement in QCD (Mandelstam, 1976; t'Hooft, 1978). The possible physical implications of the topological structure of monopoles and dyons in connection with color confinement have been investigated by many authors (Jackiw and Rebbi, 1976; Nambu, 1974; Kogut and Surskind, 1975; Rana *et al.*, 1988) and it has been speculated that the color confinement could occur through a dual-Meissner effect generated by some kind of magnetic condensation of the vacuum. In view of the potential role of dyons in connection with the issue of quark confinement, quarks

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have been interpreted (Rana *et al.*, 1988, 1989) as dyons and the hadron spectrum has been explained accordingly (Barut, 1986; Anderson, 1988). Based on the dyonium model (Barut and Bornizin, 1971; Schwinger, 1969), Akers (1987) analyzed the Paschen–Back effect in the dyonium model and predicted the existence of a dyonic quark as an η-meson resonance at 1814 MeV, confirmation of which has now been experimentally claimed by Bisallo *et al.* (1989).

In the present paper, considering quarks as dyons, we demonstrate that in both the experiments performed at SLAC on fractional electric charge (LaRue *et al.*, 1981) and monopoles (Cabrera, 1982) the same single-particle dyons possessing fractional electric charge and the magnetic charge of one Dirac unit (g_D) might have been observed. It is suggested that for the simultaneous validity of these experimental results, the exact gauge symmetry is not $SU(3)_c \times U(1)_{em}$, but $SU(3)_c \times U(1)'_{em} \times U'(1)$. This leads to values of the primed charges on baryon supermultiplets different from the usual electromagnetism, which further leads to the existence of a new long-range force, hitherto undetected, different from usual electromagnetism. The charge spectra of dyonic quarks is discussed and it is shown that the average primed charge of mesons is vanishing while that for baryons is not, except for the vanishing prime charge on the whole baryon supermultiplet. The possibility of dyonic quarks is also discussed in terms of a nonzero vacuum angle θ and it is demonstrated that if θ in nonzero, then the electric charges of quarks (dyons) are not exactly $\pm(1/3)e$, $\pm(2/3)e$, and that they will also carry extra charges proportional to θ. Two different possibilities for the hadron spectrum are discussed and it is demonstrated that the present model is almost equivalent to that of Huazhong Zhang (1987) predicting the discovery of new mesons.

2. DYONIC QUARK

The detection of free fractional electric charges (quarks) (LaRue *et al.*, 1981) and magnetic monopoles (Cabrera, 1982) would impact two cherished ideas of physics: the confinement model for quarks and Maxwell's equations. Thus the experimental pursuit of these two putative objects is important and interesting. There have been interesting citings of both quarks and monopoles, but each lost its plausibility as time passed without independent experimental confirmations. However, two experiments performed at SLAC supported the existence of quarks (LaRue *et al.*, 1981) with electric charges $\pm(1/3)e$ and $\pm(2/3)e$ and an event best explained as a monopole with a magnetic charge of one Dirac unit $g_D = 1/2e$ (Cabrera, 1982). If both these observations are correct, the situation is puzzling in view of Dirac's quantization condition and a result of 't Hooft (1976), showing that an observation of a magnetic monopole would exclude free fractionally charged quarks and even the confined quarks, if these quarks are confined by a color confinement mechanism and the monopoles are soliton solutions of gauge field theory. Such a simultaneous existence of quarks and monopoles would also conflict with the presently accepted views in particle physics that the color force confines quarks and that the exact gauge symmetry is $SU(3)_c \times U(1)_{em}$. This observation would lead to the existence of a new long-range force, different from usual electromagnetism, which may be either confined color or/and some new interaction. Rana *et al.* (1988, 1989) made an attempt to reconcile these two experiments and analyzed the compatibility of the simultaneous existence of fractional electric charge and a monopole having one Dirac unit of magnetic charge and stated that in both these experiments the same single particle, a dyon, might have been observed. The existence of such dyonic quarks has been shown (Rana *et al.*, 1988, 1989) to resolve many other problems.

3. COMPATIBILITY OF SIMULTANEOUS EXISTENCE OF MONOPOLE AND FREE QUARK

To discuss the compatibility of both the observations of LaRue *et al.* (1981) and that of Cabrera (1982), let us first discuss why a conflict exists. Dirac (1931, 1948) offered a theoretical explanation for the quantization of electric charge and showed that the mere existence of a magnetic monopole anywhere in the universe will imply the quantization of electric charge. By examining the properties of charged particles in the field of a magnetic monopole, he derived the following condition:

$$qg = \tfrac{1}{2}n \tag{1}$$

where q is the electric charge of a particle, g is the magnetic charge, and n is an integer. This condition shows that if a monopole possessing one Dirac unit of magnetic charge exists, then the only possible electric charge is $q = ne$, which is true for all color singlets. For quarks, the quantization rule is changed, as they have color charges in addition to the usual electromagnetic charges. If the monopoles have color magnetic charges, the angular momentum of a charged particle in the field of monopole will be

$$\sum_{\alpha} G^{\alpha} Q^{\alpha} + qg = \tfrac{1}{2}n \tag{2}$$

where G is color magnetic charge of the monopole and Q is the color charge of quarks. Thus, color fields make it possible for noninteger charges and a monopole with magnetic charge g_D to exist. In the case of confined color, the objects observed by LaRue *et al.* must be color singlets all of which should obey the original Dirac quantization condition if $SU(3)_c \times U(1)_{em}$ is a local gauge theory. If a monopole of magnetic charge g_D exists, then all color singlets must have integer charges and hence there is a strong likelihood that the observation of either the Dirac monopole or fractional charged objects (maybe both) will turn out to be an artifact. However, it is interesting to ask in principle whether the conditions (1) and (2) can be made compatible within our present theoretical framework.

The problem of the compatibility of the simultaneous existence of fractional charges and monopoles can be analyzed (Rana *et al.*, 1988, 1989) by keeping in view the results of Witten (1979) and Wilczek (1982) that monopoles are necessarily dyons carrying one unit of Dirac magnetic charge g_D and nonintegral electric charge. For dyons the Dirac quantization condition (1) is modified to the following chirality quantization condition

$$\mu_{ij} = e_i e_j - e_j g_i = n/2 \tag{3}$$

where e_i and g_i are the electric and magnetic charges of the ith dyon, μ_{ij} is the magnetic coupling parameter (Joshi and Rajput, 1981; Rajput and Parkash, 1976, 1978) between the ith and jth dyons, and n is an integer. Actually n should be an even integer in this equation because half-integer values of n are forbidden (Zwanziger, 1968) by the requirement of chirality invariance and locality in the commutation rules of the quantized fields associated with dyons. At the first stage, we may ignore this requirement; then the quantization condition (3) is satisfied for the first generation of quarks. Thus, these experiments about the observations of quarks and monopoles are compatible if we assume that in both experiments the same single particle, a dyon with fractional electric charge and magnetic charge g_D, might have been observed. In such a situation we do not need to consider the existence of a new long-range force or enlarge the exact gauge symmetry. However, such a simple interpretation is not possible if we stay with the requirement of the locality of dyonic fields, which does not permit half-integral values on the right-hand side of the chirality quantization condition (3).

4. DYONS IN TERMS OF FRACTIONAL ELECTRIC CHARGE AND MAGNETIC CHARGE OF ONE DIRAC UNIT

In view of the above situation we consider the following possibilities based on the assumption that quarks are dyons.

(a) Color is unbroken and quarks carry fractional electric charges and magnetic charge g_D. In this case a dyon possesses chromomagnetic charge g^a and color electric charge e^a besides its usual magnetic charge g and fractional electric charge e. Then the chirality quantization condition (3) will be modified for a system of dyons in the following form:

$$\mu_{ij}^a + \mu_{ij} = n \tag{4}$$

where

$$\mu_{ij}^a = e_i^a g_j^a - e_j^a g_i^a$$

is the color chirality of the dyons and n is an integer. If we assume the possibility that the dyon charges are purely colored, i.e., having color electric and magnetic charges, then this condition leads to the following form of color chirality:

$$\mu_{ij}^a = e_i^a g_j^a - e_j^a g_i^a = P \tag{5}$$

which ensures the integral quantization of color chirality that guarantees the color confinement. Since we are interested in the dyonic quarks carrying nonvanishing $U(1)$ charge and the usual electromagnetic charge besides its color charge, we consider a system of dyonic quarks having magnetic charges of one Dirac unit and fractional electric charges e_i, $e_j = \pm(1/3)e$ and $\pm(2/3)e$ along with the color charges. Then the total chirality (3) reduces to the following form of total color chirality:

$$\sum_a \mu_{ij}^a = (P - \mu_{ij}) \tag{6}$$

We may summarize the different values for the total color chirality for a different combination of quark–quark and quark–antiquark pairs [u, d, s, c, b, and t quarks of the $SU(6)$ quark model in Table I]. We can further have other combinations with the help of equation (6) and Figure 1. Since P is an even integer, we write the color chirality in the following form from Table I:

$$\mu_{ij}^a = P,\ P \pm \tfrac{2}{3},\ P \pm \tfrac{1}{2},\ P \pm \tfrac{1}{6} \tag{7}$$

which demonstrates the nonquantization of color chirality leading to nonconfinement of color. Table I also gives the color chirality separately for quark–quark and quark–antiquark systems in the following form:

$$\begin{aligned} \mu_{ij}^a &= P,\ P \pm \tfrac{1}{2} && \text{for quark–quark system} \\ &= P \pm \tfrac{1}{6},\ P \pm \tfrac{1}{3},\ P \pm \tfrac{2}{3} && \text{for quark–antiquark system} \end{aligned} \tag{8}$$

which demonstrates that though for the quark–quark system of dyons the usual chirality is quantized and the total color chirality having nonintegral values is not quantized, for the quark–antiquark system of dyons neither the usual chirality nor color chirality is quantized. With the help of Table I and equation (6), we construct Table II, which shows the usual chirality and color chirality for the mesons in $SU(4)$ symmetry and demonstrates that the meson

Table I

(q, q) System	e_i	e_j	n	μ_{ij}
$(u\,d)$	2/3	−1/3	1	$P-1/2$
$(u\,s)$	2/3	−1/3	1	$P-1/2$
$(u\,e)$	2/3	2/3	0	P
$(u\,b)$	2/3	1/3	1	$P-1/2$
$(u\,t)$	2/3	2/3	0	P
$(u\,\bar{d})$	2/3	1/3	1/3	$P-1/6$
$(u\,\bar{s})$	2/3	1/3	1/3	$P-1/6$
$(u\,\bar{c})$	2/3	−2/3	4/3	$P-2/3$
$(u\,\bar{b})$	2/3	−1/3	1/3	$P-1/6$
$(u\,\bar{t})$	2/3	−2/3	4/3	$P-2/3$
$(d\,u)$	−1/3	2/3	−1	$P+1/2$
$(s\,u)$	−1/3	2/3	−1	$P+1/2$
$(d\,s)$	−1/3	−1/3	0	P
$(d\,c)$	−1/3	2/3	−1	$P+1/2$
$(d\,b)$	−1/3	−1/3	0	P
$(d\,t)$	−1/3	2/3	−1	$P+1/2$
$(d\,\bar{u})$	−1/3	−2/3	1/3	$P-1/6$
$(d\,\bar{s})$	−1/3	1/3	−2/3	$P+1/3$
$(d\,\bar{c})$	−1/3	−2/3	1/3	$P-1/6$
$(d\,\bar{b})$	−1/3	1/3	−2/3	$P+1/3$
$(d\,\bar{t})$	−1/3	−2/3	1/3	$P-1/6$

Table II

Mesons	(q, q) System	Electromagnetic charges	Chirality m_{ij}	Color chirality μ_{ij}^a
K^+ (K^{*+})	$(u\,\bar{s})$	2/3, 1/3	±1/3	$P\pm1/6$
K^0 (K^{*0})	$(d\,\bar{s})$	−1/3, 1/3	±2/3	$P\pm1/3$
K^- (K^{*-})	$(\bar{u}\,s)$	−2/3, −1/3	±1/3	$P\pm1/6$
$\bar{K}^0$ $(\bar{K}^{*0})$	$(\bar{d}\,s)$	1/3, −1/3	±2/3	$P\pm1/3$
π^+ $(^+)$	$(u\,\bar{d})$	2/3, 1/3	±1/3	$P\pm1/6$
π^- $(^-)$	$(d\,\bar{u})$	−1/3, −2/3	±1/3	$P\pm1/6$
π^0 $(^0)$	$(u\,\bar{u})$	2/3, −2/3	±4/3	$P\pm2/3$
η^0 $(^0)$	$(d\,\bar{d})$	−1/3, 1/3	±1/3	$P\pm1/3$
η^0 $(^0)$	$(s\,\bar{s})$	−1/3, 1/3	±2/3	$P\pm1/3$
ψ	$(c\,\bar{c})$	2/3, −2/3	±4/3	$P\pm2/3$
D^+	$(c\,\bar{d})$	2/3, 1/3	±1/3	$P\pm1/6$
D^0	$(c\,\bar{u})$	2/3, −2/3	±4/3	$P\pm2/3$
$\bar{D}^0$	$(u\,\bar{c})$	2/3, −2/3	±4/3	$P\pm2/3$
D^-	$(d\,\bar{c})$	−1/3, −2/3	±1/3	$P\pm1/6$
F^+	$(c\,\bar{s})$	2/3, 1/3	±1/3	$P\pm1/6$
F^-	$(s\,\bar{c})$	−1/3, −2/3	±1/3	$P\pm1/6$

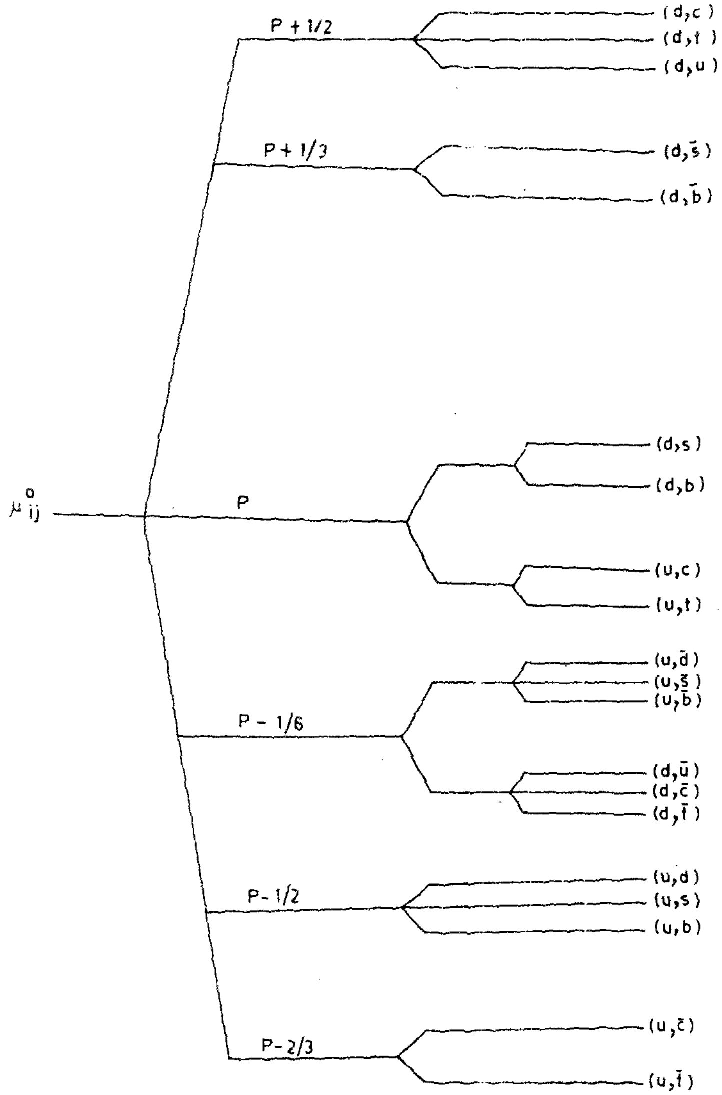

Fig. 1. Total color chirality for mesons in the $SU(6)$ quark model [see equation (6)].

states lead to nonquantization of the usual chirality as well as color chirality for the system of two dyons. Thus, the meson states of $SU(4)$ symmetry, being built up from quarks with usual but fractional charges, do not possess the color magnetic charge. If these states contain chromomagnetic charge besides the fractional charge, then the total chirality will not be quantized and the color will not be confined, since the nonconfinement of chromomagnetic charge implies the confinement of color electric charge and vice versa. This shows that electric and magnetic colors are constituents of the same entity, the dyon. Furthermore, if we accept that Wilson's (1974) lattice approximation describes the most essential long-range feature of color theory, then the color charges will be screened at hadronic distances of the order of 1 GeV^{-1}. However, since we have a large amount of evidence about the confinement of color (Nelson and Manohar, 1983) and there is no indication that observed fractional charges carry color, we propose the following alternative possibility.

(b) Exact gauge symmetry is not $SU(3)_c \times U(1)_{\mathrm{em}}$ and there exists new massless bosons (Wilson, 1974; Lee and Yang, 1955) associated with a long-range force corresponding to the group $U'(1)$ different from the usual $U(1)$. In this case a dyon will carry primed electric and magnetic charges e' and g' besides its usual electric and magnetic charges e and g and color charges e^a and g^a, respectively. In other words, there will exist a gauge symmetry $SU(3)_c \times U(1)_{\mathrm{em}} \times U'(1)$. A similar possibility was considered by Corrigan and Olive (1976), Olive (1976), Goddard *et al.* (1977), Rubakov (1983), and Barr *et al.* (1983). However, it is worthwhile to mention here that in their analyses the chirality quantization condition was not taken into account, while we insist on this condition in view of its fundamental importance in dyonic theory. Further, two primed charges (e' and g') on a dyon besides its usual electric and magnetic charges (e, g) and color charges (e^a, g^a) will give rise to new conserved quantum numbers outside $SU(3)_c \times U(1)_{\mathrm{em}}$ and hence the quantization condition (4) is further modified to the form

$$\mu_{ij}^a + \mu_{ij} + \mu'_{ij} = n \tag{9}$$

where

$$\mu'_{ij} = e'_i g'_j - e'_j g'_i$$

is the primed chirality corresponding to the new gauge group $U'(1)$. For absolute color confinement, we have

$$\mu_{ij}^a = 0 \qquad \text{or integer} \tag{10}$$

and hence the condition (4) reduces to

$$\mu_{ij} + \mu'_{ij} = \text{integer} \tag{11}$$

which corresponds to the unbroken gauge group $U(1)_{\mathrm{em}} \times U'(1)$. This equation gives the possibility for the existence of dyons with magnetic charges g_{D} and fractional electric charges $\pm(1/3)e$ and $\pm(2/3)e$, but ensures the existence of primed electric and magnetic charges, implying the existence of some new long-range force different from usual electromagnetism. The existence of such undetected local gauge symmetry and its associated primed charges has exciting consequences for monopole experiments and cosmology, providing a way to have an agreement between weak mixing angle predictions (at the cosmological level) and phenomenological values.

(c) As another alternative for the compatibility of simultaneous observations of fractional charges and monopoles we consider quarks as dyons when the vacuum angle of the world is nonzero. In this case dyons carry extra charges proportional to θ (besides the usual fractional charges) but the quark–antiquark pair still remains neutral. Of course, since θ is very small ($\theta < 10^{-9}$), it seems difficult to test this point experimentally at present. Then for dyons with electric and magnetic charges given by

$$\pm(\tfrac{2}{3})e \mp e\frac{\theta}{3}; \qquad \pm(1/3)e \mp e\frac{\theta}{3}; \qquad \pm\frac{1}{3e} \tag{12}$$

the quantization condition (4) yields

$$\begin{aligned} \mu_{ij} &= \pm\tfrac{1}{3} \\ \mu'_{ij} &= \pm\tfrac{2}{3} \end{aligned} \tag{13}$$

showing the quantization of chirality and primed chirality in the units of 1/3, which ultimately ensures the absolute color confinement. Thus, the existence of a new long-range force is linked with nonzero θ, which in turn is linked with CP violation and the study of monopoles and dyons in SUSY GUTs.

5. CHARGE SPECTRA OF DYONIC QUARKS IN TERMS OF PRIMED CHARGES

If we assume that the primed magnetic charge g' on a dyon is related to the primed electric charge e' in the same manner as its usual magnetic charge is linked with unit electric charge, i.e., $g = 1/2e$, then equation (11) takes the following form for the allowed integral values of the chirality:

$$e'_u - e'_d = me' = n_{ud}e' \tag{14}$$

where $e' = 1/2g'$ and $m = n_{ud}$ is an integer. Then the primed charges of isospin multiplets of baryons and mesons can be calculated. Following equation (14), the primed charges of the proton and the neutron are given by

$$\begin{aligned} e'_p &= (u,\ u,\ d)' = 2e'_u + e'_d \\ e'_n &= (u,\ u,\ d)' = e'_u + 2e'_d \end{aligned} \tag{15}$$

and the average primed charge of a nucleon is

$$q'_N=\tfrac{1}{2}(e'_p+e'_n)=\tfrac{3}{2}(e'_u+e'_d) \tag{16}$$

If we set integral values of the chirality in equation (11) and then consider two dyons each with prime electric charges e'_u and prime magnetic charges g'_i and g'_j, respectively, then equation (11) reduces to the form

$$g'_j-g'_i=n_u/e'_u \tag{17}$$

where n_u is an integer. Similarly, for two dyons with primed electric charges $e'_i=e'_j=e'_d$ and primed magnetic charges g_i and g'_j, respectively, we obtain

$$g'_j-g'_i=n_d/e'_d \tag{18}$$

Comparing equations (17) and (18), we obtain the following relation:

$$n_u/n_d=e'_u/e'_d \tag{19}$$

If we take a system of two dyons carrying primed electric charges $e'_i=e'_j=e'_s$ (third generation of quarks) and primed magnetic charges g'_i and g'_j, respectively, we get

$$g'_j-g'_i=n_s/e'_s \tag{20}$$

and similar results for other generations of the $SU(6)$ quark model.

Thus we arrive at the following relations

$$n_u/e'_u=n_d/e'_d=n_s/e'_s=n_c/e'_c=n_b/e'_b=n_t/e'_t \tag{21}$$

where all n_u, n_d, n_s, n_c, n_b, and n_t are integers. Substituting this relation into equations (15), we obtain the results

$$\begin{aligned} e'_p&=[n_{ud}e'/(n_u-n_d)](2n_u+n_d) \\ e'_n&=[n_{ud}e'/(n_u-n_d)](n_u+2n_d), \qquad n_u\neq n_d \end{aligned} \tag{22}$$

which give the following nonvanishing value of the average primed charge of the isospin doublet of nucleons:

$$q'_N=\tfrac{3}{2}[n_{ud}e'/(n_u-n_d)](n_u+n_d) \tag{23}$$

Similarly, with the help of equations (15) and using three quark combinations for other baryons, we get the following values of average primed charges of the Δ, Σ, Φ, and Ω isospin multiplets of baryons:

$$\begin{aligned}
q'_\Delta &= \tfrac{3}{2}(e'_u/n_u)(n_u+n_d)\\
q'_\Sigma &= (e'_u/n_u)(n_u+n_d+n_s)\\
q'_\Phi &= \tfrac{1}{2}(e'_u/n_u)(n_u+n_d+4n_s)\\
q'_\Omega &= 3(e'_u/n_u)n_s
\end{aligned} \tag{24}$$

The quark–antiquark combination of mesons yields a vanishing average primed charge. In equations (24) the total chirality number in terms of n_u, n_d, and n_s is vanishing, i.e.,

$$n_u+n_d+n_s=0 \tag{25}$$

showing that all the hadrons are color singlets. The sum of the average primed charges of the baryon decuplet as well as the baryon octet (or as we call it, the baryon supermultiplet) are also vanishing.

6. HADRONIC SPECTRUM IN TERMS OF DYONIC QUARKS

The third possibility discussed earlier for the reconciliation of both the experiments (LaRue *et al.*, 1981; Cabrera, 1982) in terms of dyonic quarks relies on the assumption of a nonzero vacuum angle θ of the world. In this situation, for the charge spectra of dyonic quarks, we may consider the following two possibilities by using (12):

$$\begin{aligned}
q_g^u &= 1/(3e), & q_e^u &= (2/3)e - e\theta/3\\
q_g^d &= 1/(3e), & q_e^d &= -(1/3)e - e\theta/3\\
q_g^s &= 1/(3e), & q_e^s &= -(1/3)e - e\theta/3\\
q_g^{\prime u} &= -2/(3e), & q_e^{\prime u} &= (2/3)e + 2e\theta/3\\
q_g^{\prime d} &= -2/(3e), & q_e^{\prime d} &= -(1/3)e + 2e\theta/3\\
q_g^{\prime s} &= -2/(3e), & q_e^{\prime s} &= -(1/3)e + 2e\theta/3
\end{aligned} \tag{26}$$

or

$$\begin{aligned}
q_g^u &= -1/(3e), & q_e^u &= -(2/3)e + e\theta/3\\
q_g^d &= -1/(3e), & q_e^d &= (1/3)e + e\theta/3\\
q_g^s &= -1/(3e), & q_e^s &= (1/3)e + e\theta/3\\
q_g^{\prime u} &= 2/(3e), & q_e^{\prime u} &= -(2/3)e - 2e\theta/3\\
q_g^{\prime d} &= 2/(3e), & q_e^{\prime d} &= (1/3)e - 2e\theta/3\\
q_g^{\prime s} &= 2/(3e), & q_e^{\prime s} &= -(1/3)e - 2e\theta/3
\end{aligned} \tag{27}$$

With either of these possibilities, we may construct two meson octets, one baryon octet, and one baryon decuplet. The two meson octets may be identified with the 0^- meson octet and the 1^- meson octet, respectively:

0^- meson octet:

$$\begin{array}{llll} K^+(\bar{s}u), & K^0(\bar{s}d), & \pi^+(\bar{d}u), & \pi^0[(\bar{u}u-\bar{d}d)/\sqrt{2}] \\ \pi^-(\bar{u}d), & K^0(\bar{d}s), & K^-(\bar{u}s), & \eta^0[(\bar{u}u+\bar{d}d-2\bar{s}s)/\sqrt{2}] \end{array} \tag{28}$$

1^- meson octet:

$$\begin{array}{c} K^{*+}(\bar{s}'u'), \quad K^{*0}(\bar{s}'d'), \quad \rho^+(\bar{d}'u'), \quad \rho^-(\bar{u}'d'), \\ \bar{K}^{*0}(\bar{d}'s'), \quad K^{*-}(\bar{u}'s'), \quad \rho^0[(\bar{u}'u'-\bar{d}'d')/\sqrt{2}] \\ \omega^-[(\bar{u}'u'+\bar{d}'d'-2\bar{s}'s')/\sqrt{6}] \end{array} \tag{29}$$

To construct the baryons we need both q and q' quarks; $\frac{1}{2}^+$ baryons may possibly be constructed as follows:

$\frac{1}{2}^+$ baryons:

$$\begin{array}{c} \rho(ud'u), \quad \eta(u'dd), \quad \Sigma^+(s'uu), \quad \Phi^0(ssu'), \quad \Phi^-(ssd') \\ \Sigma^0[s'(ud+du)/\sqrt{2}] \quad \Lambda^0[s'(ud-du)/\sqrt{2}], \quad \Sigma^-(s'dd) \end{array} \tag{30}$$

$\frac{3}{2}^+$ baryons may be obtained as

$$\begin{array}{c} \Delta^{++}(uuu'), \quad \Delta^+(u'ud), \quad \Delta^0(udd'), \quad \Delta^-(ddd') \\ \Sigma^{*+}(suu'), \quad \Sigma^{*-}(sdd'), \quad \Omega^-(sss') \\ \Phi^{*0}(ss'u), \quad \Phi^{*-}(ss'd) \end{array} \tag{31}$$

Since c and b quarks may have the same charge as those of u and d quarks, respectively, one may predict the following new mesons:

$$\begin{array}{c} D^{*+}(\bar{d}'c'), \quad D^{*-}(\bar{c}'d'), \quad D^{*0}(\bar{u}'c') \\ \bar{D}^{*0}(\bar{c}'u'), \quad F^{*+}(\bar{s}'c'), \quad F^{*-}(\bar{c}'s'), \quad \eta^*(\bar{c}'c) \end{array} \tag{32}$$

In all these states the θ terms cancel out in the electric charge.

7. DISCUSSION

The possibility of reconciling experiments about the observation of fractional electric charge (LaRue *et al.*, 1981) and monopole (Cabrera, 1982) in terms of dyons and the confinement of color has been discussed using the simple and fundamental process of chirality quantization given by equation (3), which is an entirely new observation and is essential for all dyonic systems. The quantization condition (9) shows that the exact gauge symmetry is not $SU(3)_c \times U(1)_{\mathrm{em}}$ but $SU(3)_c \times U(1)_{\mathrm{em}} \times U'(1)$, leading to values of the primed charges on the baryon supermultiplet (baryon octet + decuplet) that are different from the usual electromagnetic ones. A similar possibility has also been discussed by Rubakov (1983), Minakata (1985), among others, in entirely different approaches. The heavy fermionic sector responsible for inducing the fractional electric charges on monopoles (fermion fractionization) comes into the picture only as a result of the supersymmetrization of GUTs, while our results are valid for any GUT model. Further, it has been shown that the average primed charge of mesons is vanishing, while it is nonvanishing for baryons except for the vanishing primed charge for the whole baryon supermultiplet. Equation (25) demonstrates that the total chirality is vanishing and leads to the fact that all the hadrons are color singlets. Considering the possibility of dyonic quarks, it has been demonstrated that if the vacuum angle θ of the world is nonzero, the electric charges of quarks are not exactly given by $\pm(1/3)e$ and $\pm(2/3)e$; instead, they will carry extra charges proportional to θ, but the quark–antiquark pair still remains neutral. Considering the two different possibilities in equations (26) and (27) to construct the hadron spectrum, it has been shown that the meson octet, baryon octet, and decuplet constructed here are essentially similar to those constructed by Huazhong Zhang (1987). Constructing the hadronic spectrum in terms of dyonic quarks, it has been shown that the present model can predict the existence of new mesons. Since both q and q' quarks are needed to construct baryons, this model does not seem to be consistent with $SU(3)$ flavor phenomenology and runs into difficulty in giving predictions corresponding to the well-known Gell-Mann–Okubo mass formula. The present model also conflicts with the standard model, where left-handed quarks and leptons form an $SU(2)$ weak isospin doublet.

There has been considerable interest in identifying quarks as dyons. The most interesting contribution to this subject have come from the work of Chang (1972), Kim (1976), and Satikov and Strazhev (1979). Recently, Barut (1986) and Anderson (1988) considered the magnetic nature of quarks and suggested that it is possible for quarks with magnetic sources to account for the hadron mass spectrum. Akers (1985) presented an analysis of Zeeman splitting and found evidence for quarks with the Dirac unit of magnetic charge involved in the Zeeman splitting of meson states. Further, based on the dyonium model (Barut, 1986; Anderson, 1988; Barut and Bornizin, 1971; Schwinger, 1969), Akers (1987) presented a model of the Paschen–Back effect in dyonium and predicted the existence of a new η-meson at 1814 MeV. The experimental evidence for dyonic quarks with magnetic charge g_{D} in terms of this η-meson resonance at 1814 MeV with $I^G\ (J^{PC}) = 0^+\ (0^{-+})$ and $I = 0$ has been confirmed by Bisallo *et al.* (1989).

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