A REGULAR THEORY OF MAGNETIC MONOPOLES AND ITS IMPLICATIONS

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A regular charge-monopole theory is derived from simple and self-evident postulates. It is shown that this theory provides explanations for effects of strong and nuclear interactions. The theory is compared with Dirac's monopole theory. Applications to strong and nuclear interactions are compared with quantum chromodynamics. The results favor the regular charge-monopole theory and indicate difficulties of the other ones. An experiment that may provide further evidence helping to decide between the regular charge-monopole theory and quantum chromodynamics is suggested.

1. Introduction

Classical electrodynamics is regarded as a well established part of physics. The equations of Maxwell and the Lorentz law of force are the equations of motion of a system of electromagnetic fields and electrically charged matter. The fields part of these equations consists of two kinds of entities - namely, the electric and the magnetic fields. On the other hand, the massive matter part contains a single kind of electromagnetic entity - the electric charge.

The idea of magnetic monopoles (called just monopoles in the literature) aims to restore the symmetry between electricity and magnetism. Let us examine the electromagnetic fields tensor[1,2]

$$F^{\mu\nu}_{(e)} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}. \tag{1}$$

In this work subscripts $_{(e)}$ and $_{(m)}$ denote quantities related to charges and monopoles, respectively. Units where the speed of light $c = 1$ are used. The Lorentz

metric is diagonal and its entries are $(1, -1, -1, -1)$. Greek indices run from 0 to 3. The symbol $_{,\mu}$ denotes the partial differentiation with respect to x^μ. **i**, **j** and **k** denote unit vectors in the x, y and z directions, respectively.

Duality transformations cast a system of fields and charges into a system of fields and monopoles. These transformations are (see [2], pp. 252, 551)

$$\mathbf{E} \to \mathbf{B}, \quad \mathbf{B} \to -\mathbf{E} \tag{2}$$

and

$$e \to g, \quad g \to -e, \tag{3}$$

where g denotes the monopole strength. (In this work, duality is used in its restricted form of a duality rotation by $\pi/2$.) Eq. (3) represents relations between Lorentz scalars (see a discussion of this issue in Section 4) whereas (2) takes a relativistic tensorial form

$$F^{*\mu\nu}_{(m)} = \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}F_{(e)\alpha\beta}. \tag{4}$$

Here $\varepsilon^{\mu\nu\alpha\beta}$ is the completely antisymmetric unit tensor of the fourth rank. Entries of the monopole dependent fields tensors of (4) are

$$F^{*\mu\nu}_{(m)} = \begin{pmatrix} 0 & -B_x & -B_y & -B_z \\ B_x & 0 & E_z & -E_y \\ B_y & -E_z & 0 & E_x \\ B_z & E_y & -E_x & 0 \end{pmatrix}. \tag{5}$$

Historically, classical electrodynamics of charges and fields has been formulated after a lot of experimental data have been accumulated. Results of these experiments have guided physicists how to construct the theory. Thus, in the case of electrodynamics of charges and fields, development has taken the inductive way. (The addition of the Maxwell term makes an exception.) Unfortunately, monopoles have not been detected in laboratories. Hence, one cannot follow the historical course of classical electrodynamics of charges and fields. Therefore, the deductive course must be adopted and the theory should be derive from an appropriate set of postulates.

Consider two postulates pertaining to this topic:

(A) The theory of monopoles and fields takes a form which is completely dual to the theory of charges and fields.

(B) Electromagnetic fields of a system of monopoles and those of a system of charges have identical dynamical properties.

Hereafter, these postulates are called postulate (A) and (B), respectively. Upper case letters denote postulates and numbers denote other kinds of items.

One may be tempted to use both postulates (A) and (B) as fundamental elements of the theory. However, it turns out that this goal is unattainable because different sets of equations of motion are obtained from postulate (A) (without (B)) and from postulate (B) (without (A)). Section 4 contains a discussion of this topic.

In Section 2, a regular charge-monopole theory is derived from postulate (A). The relevance of this theory to strongly interacting particles (called hadrons) and to nuclear interactions is discussed in Section 3. A comparison of results obtained in Sections 2 with the Dirac monopole theory (which is consistent with postulate (B)) is presented in Section 4. A comparison of the results of Section 3 with quantum chromodynamics (QCD) is shown in Section 5. Concluding remarks are the contents of the last Section.

2. A Regular Charge-Monopole Theory

Postulate (A) means that classical electrodynamics of charges and their associated fields is a cornerstone of the charge-monopole theory developed here. For this reason, let us examine the equations of motion of classical electrodynamics of charges and fields as well as some of its fundamental relations. The equations of motion of the fields are Maxwell equations. Their tensorial form is (see [1], pp. 74, 67 or [2], pp. 551)

$$F^{\mu\nu}_{(e)\ ,\nu} = -4\pi j^{\mu}_{(e)} \tag{6}$$

and

$$F^{*\mu\nu}_{(e)\ ,\nu} = 0. \tag{7}$$

where $F^{*\mu\nu}_{(e)}$ takes the same form as (5) but here it represents fields of charges. The Lorentz law of force is the equation of motion of charges (see [2], p. 572)

$$ma^{\mu}_{(e)} = eF^{\mu\nu}_{(e)}v_{\nu}, \tag{8}$$

where v^{μ} denotes the particle's 4-velocity, m is its rest mass and e is its charge.

The fields used in (6) and in (7) can be derived from a regular 4-potential

$$F_{(e)\mu\nu} = A_{(e)\nu,\mu} - A_{(e)\mu,\nu}. \tag{9}$$

(Point infinities associated with the introduction of elementary classical point charges are beyond the scope of this work. A regular solution of point infinity problems is presented in [3].)

The 4-potential is an important quantity of the system's dynamics, because it is used in the charge-fields interaction term of the Lagrangian density (see [1], p. 71 or [2], p. 596)

$$L_{int} = -j^{\mu}_{(e)} A_{(e)\mu}. \tag{10}$$

The reader should note the difference between the inhomogeneous Maxwell equations (6) and the homogeneous ones (7). As a matter of fact, the homogeneous equation (7) represents internal mathematical relations between field components (see [1], pp. 66,67). On the other hand, the inhomogeneous Maxwell equations (6) are associated with charge-fields interaction and are derived from the Lagrangian density (see [1], pp. 73-75 or [2], pp 597).

Let us now use postulate (A) and obtain the equations of motion of a system of monopoles and their associated fields (namely, a system that does not contain electric charges). This goal is achieved from the application of the duality relations (2) - (4) to (6) - (8). The results are

$$F^{*\mu\nu}_{(m)\ ,\nu} = -4\pi j^{\mu}_{(m)}, \tag{11}$$

$$-F^{\mu\nu}_{(m)\ ,\nu} = 0. \tag{12}$$

and

$$ma^{\mu}_{(m)} = gF^{*\mu\nu}_{(m)} v_{\nu}. \tag{13}$$

One should note that $F^{*\mu\nu}_{(m)}$ of (11) takes the form of (5) and $F^{\mu\nu}_{(m)}$ of (12) takes the form of (1). Like in the case of charges, the fields of monopoles can be derived from an appropriate 4-potential

$$F^{*}_{(m)\mu\nu} = A_{(m)\nu,\mu} - A_{(m)\mu,\nu}. \tag{14}$$

For this system, the interaction part of the Lagrangian density is analogous to (10)

$$L_{int} = -j^{\mu}_{(m)} A_{(m)\mu}. \tag{15}$$

The reader should note that in the monopole case, the fields tensors take the opposite role, with respect to that of charges. Thus, $F^{*\mu\nu}_{(m)}$ of (11) is related to the interaction term (15) whereas $F^{\mu\nu}_{(m)}$ of (12) represents mathematical relations. At this point we have the equations of motion of two noninteracting systems: a system of charges and their associated fields and another system which consists of monopoles and their associated fields. The rest of this Section is devoted to the

equations of motion of a combined system containing charges, monopoles and their fields.

Due to the linearity of electrodynamics, one may split the electromagnetic fields into a sum of field quantities and examine their effects separately. An important kind of split is the one which examines bound fields and radiation fields separately. (A decomposition of the electromagnetic fields of a system of charges into these components can be found in [3].) The first kind of fields is significant near the charges and decays rapidly at larger distances. Radiation fields decay slower at larger distances and become dominant there. They represent an entity which is distinguished from charges. In classical physics they take the form of radiation energy and in quantum mechanics they appear as real photons.

Radiation fields emitted from a specific source have the following properties

$$B^2 - E^2 = 0 \tag{16}$$

and

$$\mathbf{E} \cdot \mathbf{B} = 0. \tag{17}$$

(These relations are obtained from eq. (66.8) of [1], p. 172 and from eqs. (9.4) and (9.5) of [2], p. 392.) Relations (16) and (17) are just a reformulation of the Lorentz scalar $F^{\mu\nu}F_{\mu\nu}$ and the pseudoscalar $F^{*\mu\nu}F_{\mu\nu}$, respectively. An observation of these quantities proves that in the case of radiation fields, they remain invariant under the duality transformation (2). This result indicates that radiation fields of charges and radiation fields of monopoles may be regarded as one and the same entity. This result is also obtained from the equations of motion of radiation fields. These equations are the *homogeneous* Maxwell equations

$$F^{\mu\nu}_{(e)\ ,\nu} = 0 \tag{18}$$

and

$$F^{*\mu\nu}_{(e)\ ,\nu} = 0. \tag{19}$$

Let us examine the simple example of linearly polarized monochromatic plane wave (see [1], pp. 114-117 or [2], pp. 273-278) which propagates in the z-direction. Taking the electric charge point of view, a vector potential of the fields is

$$\mathbf{A}_{(e)} = -iAe^{i\omega(z-t)}\mathbf{i}. \tag{20}$$

Thus, we have

$$\mathbf{E} = -\frac{\partial A_{(e)}}{\partial t} = \omega A e^{i\omega(z-t)}\mathbf{i} \tag{21}$$

and

$$\mathbf{B} = \nabla \times A_{(e)} = \omega A e^{i\omega(z-t)}\mathbf{j}. \tag{22}$$

(Obviously, the real part of these equations represents the quantities that should be accounted for.) The direction of the linear polarization is that of the electric field (21).

Let us now take the monopole point of view. Here one examines a vector potential which is parallel to the y-axis

$$\mathbf{A}_{(m)} = -iAe^{i\omega(z-t)}\mathbf{j}. \tag{23}$$

Using the duality relations (2) as well as (14), one finds

$$\mathbf{B} = -\frac{\partial A_{(m)}}{\partial t} = \omega A e^{i\omega(z-t)}\mathbf{j} \tag{24}$$

and

$$\mathbf{E} = -\nabla \times A_{(m)} = \omega A e^{i\omega(z-t)}\mathbf{i}. \tag{25}$$

It follows that (21) equals (25) and (22) equals (24).

These results indicate explicitly that one may identify radiation fields of charges with radiation fields of monopoles without arriving at any contradiction. Henceforth, radiation fields of charges and radiation fields of monopoles are regarded as one and the same entity and are denoted by the subscript $_{(w)}$. Thus, for example, $F^{\mu\nu}_{(e,w)}$ denotes the tensor of bound and radiation fields of charges and the radiation fields of monopoles. The symbol $F^{\mu\nu}_{(m,w)}$ is analogous.

Let us examine bound fields of charges and bound fields of monopoles. A simple example is the system which consists of one charge and one monopole. The interaction term of the Lagrangian density is required. Again, due to the linearity of electrodynamics, one may write the interaction part of a system which consists of many charges and many monopoles as a sum of two body interactions. There are several restrictions imposed on the form of the required quantity:

I. Since the action is a Lorentz scalar, all terms of the Lagrangian density must be Lorentz scalars too.

II. Due to the linearity of electrodynamics, the charge-monopole interaction term must be a sum of bilinear quantities containing two factors, one is related to charges and the other is related to monopoles.

III. Due to the notion of a charge and of a monopole, a system of one motionless charge and one motionless monopole does not change in time.

The charge-charge interaction term (10) satisfies requirements I and the appropriate analogue of II. Relation (15) is the monopole version of (10). An observation of a system of one motionless charge and one motionless monopole proves that, unlike the case of radiation fields, bound fields of these objects differ substantially. Thus, the Lorentz scalar (16) $B^2 - E^2 < 0$ for the case of a charge and $B^2 - E^2 > 0$ for the case of a monopole.

A simple analysis[4] proves that in the case of bound fields, one cannot create an interaction term that satisfies I, II and III as well as some other self-evident postulates. Thus, the following conclusion is obtained:

1. Charges do not interact with bound fields of monopoles and monopoles do not interact with bound fields of charges. Charges interact with all fields of charges and with radiation fields emitted from monopoles. Monopoles interact with all fields of monopoles and with radiation fields emitted from charges.

Henceforth, this conclusion is referred to as conclusion 1. Conclusion 1 yields the following form of the Lorentz force exerted on charges

$$ma^{\mu}_{(e)} = eF^{\mu\nu}_{(e,w)}v_{(e)\nu}. \tag{26}$$

The corresponding force exerted on monopoles is

$$ma^{\mu}_{(m)} = gF^{*\mu\nu}_{(m,w)}v_{(m)\nu}. \tag{27}$$

Explicit expressions of the Lagrangian of the system and of the energy-momentum tensor can be found in [4]. Since fields of charges and fields of monopoles have different dynamical properties, it is suggested that fields of monopoles be called magnetoelectric fields[4].

It is interesting to note that conclusion 1 can be obtained even without the requirement of having a regular interaction term of the charge-monopole Lagrangian density. It can be shown[5] that the same result is obtained if one uses the postulate that, like the electric charge, the magnetic monopole is a Lorentz scalar and not a pseudoscalar (see [2], p. 253).

Conclusion 1 is the main result of the theoretical analysis carried out in this section. It explains why postulates (A) and (B) which are written in the introduction, cannot be used together as elements of a charge-monopole theory. Indeed, if postulate (B) is adopted (like in Dirac's charge-monopole theory[6-8]) then the Lorentz force exerted on a charge must be $eF^{\mu\nu}_{(e,m,w)}v_{(e)\nu}$, contrary to (26). Physical implications of conclusion 1 are discussed in the next section. In what follows, the monopole theory outlined here is called the regular charge-monopole theory.

3. A Discussion of Experimental Data

Consider the 4 different kinds of interactions known in physics: strong, electromagnetic, weak and gravitational. The gravitational interaction is practically blind to many features of matter and "sees" only the matter's energy-momentum tensor and that of electromagnetic fields. For this reason, it is not mentioned here any more. Table 1 shows 2 conservation properties of the other interactions,

	strong	electromagnetic	weak
parity	yes	yes	no
flavor	yes	yes	no

Table 1:
Validity of parity and flavor conservation
under three kinds of interactions

The meaning of parity conservation is that if, for example, a theory of the specific kind of force contains a Hamiltonian then this Hamiltonian commutes with the parity operator. Parity conservation indicates similarity between strong and electromagnetic interactions. Flavor is a property of elementary constituents of matter: each one of the 3 kinds of charged leptons (electrons, muons and tau mesons) and each one of the 6 kinds of quarks has its own flavor. Hereafter, the symbol q is sometimes used as a notation of a quark. All these objects are spin 1/2 Dirac particles and each one of them has its own antiparticle (generally, an antiparticle is denoted by a bar over the particle's symbol). Table 1 shows that strong and electromagnetic interactions cannot alter flavor properties of matter. Moreover, experiments show that these interactions "see" quarks and leptons as very small objects whose radius is less than $10^{-16}cm$. As a matter of fact, it is a common belief that leptons and quarks are pointlike (see [9], pp. 264, 276, 277). Experiments also show that strong and electromagnetic interactions can perform a process called pair production. This process results in the creation of a particle and an antiparticle of the same kind, thereby obeying flavor conservation. Pair production is seen in the creation of separate charged leptons, like an electron and a positron or, for example, in the creation of mesons which are $q\bar{q}$ bound systems. Table 1 indicates that strong and electromagnetic interactions are similar with respect to flavor conservation too.

On the basis of these results it is postulated here that

(C) Strong interactions are interactions between magnetic monopoles. Thus, all charged leptons have a unit of electric charge $\pm e$ and no magnetic monopole, whereas quarks have both electric charge and a magnetic monopole unit $-g$.

Applications of the regular charge-monopole theory and of postulate (C) to

experimental data are discussed briefly in this Section. As shown below, several fundamental properties of the relevant data can be explained in a qualitative manner. This point can be put in a different way. Postulate (C) can be *refuted* if it fails to explain qualitative properties of experimental data.

It is obvious that a classical theory cannot go far in explaining properties of matter. Thus, additional postulates are used below, where required. These postulates look natural and rely on fundamental properties of matter. Putting them in the status of postulates does not negate the possibility of proving them by means of a more profound theory. Up to now, only postulates (A) and (C) are used.

1. The regular charge-monopole theory of Section 2 predicts that electromagnetic-like forces come in pairs, one is charge related and the other pertains to monopoles. If, for example, 3 different kinds of such interactions are found in Nature then the regular monopole theory is refuted (or has to find rescue in an additional postulate which is analogous to the one stating that "monopoles do not exist").

Up to now, nothing is said on specific properties of magnetic charges. The following postulate fills this gap.

(D) Like the case of electric charge, the elementary unit g of magnetic charge is quantized. Moreover, the size of g is rather big $g^2 \gg e^2 \simeq 1/137$. Experimental data indicate that $g^2 \simeq 1$ (see [9], p. 20).

The reader should note that in Dirac's charge-monopole theory which is derived in accordance with postulate (B) of the introduction, there is a numerical relation between the size of the elementary electric charge and of its magnetic counterpart and $g^2 = 137/4$[6-8]. This relation, which imposes a restriction on the size of the elementary magnetic charge, does not hold in the regular charge-monopole theory derived in Section 2. Here the size of the elementary magnetic unit is a free parameter.

Let us proceed further, using postulate (D).

2. Experiments show that elementary particles that have just electric charges, like the electron, do not participate in strong interactions[10]. Moreover, the electric charge of proton's quarks is not identical to the corresponding quantity of the neutron. It turns out that energetic electrons interact *differently* with quark constituents of protons and neutrons (see [10], p. 200 and [11]). On the other hand, energetic real photons interact strongly with quark targets of protons and neutrons and, in these interactions, protons and neutrons look very much alike[12]. These properties of Nature fit like a glove Conclusion 1

of the regular charge-monopole theory outlined in Section 2. Indeed, one has just to replace the terms 'electric charge' by 'electron', 'magnetic charge' by 'quark' and use Postulate (D) which means that the monopole charge of quarks dominates the process. The reader should note that Conclusion 1 is obtained from a pure theoretical analysis that relies on simple postulates which have (at least apparently) no relevance to the experimental data mentioned here. Further aspects of this issue are discussed in Section 5.

In order to proceed further, we need the following postulate, which relies on well established experimental data (see [9], pp. 275-277)

(E) Quarks are spin 1/2 Dirac particles.

This postulate enables us to make further deductions.

3. Theory predicts and experiments show bound states of an electron and a positron, called positronium. Now, by the postulates which we already have at hand, one predicts strongly bound $q\bar{q}$ states whose total spin and parity are analogous to the states of the positronium. The fact that there are 6 different kinds of quarks, all of which are assumed to have the same elementary magnetic charge, indicates that mesonic states are much richer than the positronium ones, because the quarks of a $q\bar{q}$ pair may or may not have the same type of flavor. This prediction is supported by experimental data of mesons[13].

4. Mesons whose quantum states cannot be created by a $q\bar{q}$ system are called exotic. Binding forces between 2 mesons, namely a $qq\bar{q}\bar{q}$ system, are expected to be much weaker than the $q\bar{q}$ bond. This conclusion is analogous to the relation between the value of the binding energy of electrons in atoms and that of the molecular (or van der Waals) forces between neutral atoms (and neutral molecules). In particular, the lowest $q\bar{q}$ state (called π meson) has a total spin=0 and is analogous to an atom of a noble gas. Thus, one expects that if bound states of a π meson and another hadron exist at all then their binding energy must be very small. Also in this case, predictions are supported by experimental data[13].

A set of particles called baryons is found in Nature. Proton and neutron are the lowest energy states of baryons. Quantum states of baryons are characterized by means of 3 quarks, called valence quarks. In order to explain bound states of this kind by means of magnetic monopole forces, one makes another postulate. Thus, by analogy of atoms, it is assumed that

(F) Baryons have a core whose magnetic charge is $+3g$.

This assumption provides an explanation of baryons, using the baryonic core and 3 quarks attracted to it by the dual Coulomb force which exists between magnetic monopoles. The sign of the monopole charge of the core and that of quarks is defined here in order to keep an analogy with the sign of the electric charge of nuclei and electrons, respectively.

The structure of the baryonic core is beyond the scope of the present work. It may be an elementary object or, more probably, a complex system of closed shells of strongly interacting objects whose overall magnetic charge is $+3g$ (see a remark on this issue in the last Section).

Experiments show that baryons do have a core. Thus, it is found that in an appropriate Lorentz frame, quarks and antiquarks carry only about one half of the nucleon's momentum (see [9], p. 282). Hence, something else exists in a nucleon and here it is called a core.

Postulate (F) leads to further predictions.

5. Like in the case of mesons, bound states of baryons that cannot be created by 3 quarks are called exotic. Arguments that correspond to those of point 4 above lead to the claim that *strongly* bound states that make exotic baryons do not exist.

This prediction is confirmed experimentally. The lowest bound state of a baryon and another hadron is the deuteron which consists of one proton and one neutron. The binding energy of the deuteron is about 2.2 MeV, whereas gaps between baryonic energy levels are measured by hundreds of MeV. Other bound states of baryons are nuclei. Here the binding energy is generally about 8 MeV per nucleon. Another aspect of this point is the similarity between the form of the nuclear forces and the van-der-Waals ones. This is the reason for the success of the nuclear liquid drop model[14].

Another issue is the existence of antiparticles in the system. This is a relativistic effect which may be found more easily in a system where interaction energies are very high. Thus, experiments show that, beside the 3 valence quarks, antiquarks exist in nucleons, too. Here antiquarks are associated with the existence of additional $q\bar{q}$ pairs in the baryonic wave function (see [9] pp. 282). It turns out that antiquarks occupy a rather narrow region of the variable x used for characterizing relations between Lorentz invariant quantities of experiments (see [9], p. 281).

Now, a narrow x pertains to a small Fermi motion in the volume occupied by the baryon. Thus, due to the uncertainty principle, one concludes that antiquarks occupy a larger volume than quarks do (see [9], pp. 266-271).

The magnetic monopole theory discussed here explains this point very easily:

6. If $q\bar{q}$ pairs are found in a baryonic wave function then quarks are attracted

to the core and antiquarks are pushed away from it. This result is related to the fact that near the center, the field of the core's magnetic charge is not completely screened by quarks. Hence, antiquarks, whose magnetic charge takes the same sign as that of the core, are pushed away to outer regions.

Let us examine the interaction between quarks in a baryon. Like the interaction between electrons in an atom, this interaction is repulsive and increases the energy of baryonic states. Hence, if in certain quantum states, this interaction is reduced then these states should have a higher binding energy. Since electrons and quarks are spin-1/2 Dirac particles, their total quantum state is antisymmetric. Now, electronic states whose total spin is symmetric have a spatial state which is completely antisymmetric. These states yield a smaller repulsive energy between electrons than corresponding states where the spatial part is symmetric. Indeed, let us examine 2 electrons and $\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2$ be chosen as a dynamical coordinate. Hence, for $\mathbf{r}_{12} = 0$, an antisymmetric wave function must vanish. This property indicates that at a region where $\mathbf{r}_{12}$ is very small and the repulsive interaction is highest, spatially antisymmetric wave functions yield a smaller contribution. This effect is related to the Hund rule in atomic states[15,16]. Antisymmetric spatial wave function of 3 quarks must be created from 3 different single particle wave functions. Hence, excited single particle wave functions are used and the system's kinetic energy increases. Let us have a very rough estimate of this quantity. For this purpose, consider 2 terms of the state $J^P = 3/2^+$, where the spin and isospin are symmetric

$$\psi = \psi_1 + \psi_2. \tag{28}$$

Here ψ_1 is the obvious state $\psi_1 = \phi_1\phi_2\phi_3$, where the ϕ_i are single particle S-waves, ϕ_1 is the ground state and the other ones are the first and the second radial excitations, respectively. $\psi_2 = \phi_1(\chi_1\chi_2, L = 1)$. χ_i are single particle P-waves which are coupled to the antisymmetric state[17] $L = 1$. For each of these χ_i, one finds from the spatial angular momentum

$$1 = l = \mid \mathbf{r} \times \mathbf{p} \mid \Longrightarrow p_T = \frac{1}{0.8} fm^{-1} \simeq 250 MeV, \tag{29}$$

where p_T is the momentum component which is perpendicular to $\mathbf{r}$ and $0.8fm$ is an estimate of the effective radius. Using the relation between momentum and kinetic energy, $\Delta P > \Delta E_k$, one finds from (29) that the increase of the kinetic energy of ψ_2 is about 500 MeV. Here the Hamiltonian is evaluated for $J^P = 3/2^+$ functions. As is well known, the lowest state obtained after diagonalization of the Hamiltonian matrix, is lower than the diagonal entry of each of the basis functions. To this reduction one has to add the expected contribution of the magnetic monopole analogue of the Hund effect.

Hence,

7. The mass of the Δ_{1232} baryon, which is higher than the nucleonic mass by about 300 MeV, is understood.

Conclusion 1 and the related equations of motion (26) and (27) indicate that static electric field of a charge and electric field of a moving monopole have different dynamical properties. The same conclusion holds for the corresponding magnetic fields. A special case of this distinction is found in the electric field of a polar dipole (which is made of two displaced electric charges having equal strength and opposite sign) and that of an axial electric dipole of a spinning monopole. The *axial* electric dipole of spinning monopoles is discussed here.

The neutron is known to be a spin-1/2 electrically neutral composite particle. Its nonvanishing magnetic dipole moment demonstrates that not all effects of its electrically charged constituents vanish. The duality relations between electric charges and magnetic monopoles provide the basis for the following statement. If quarks are dyons (namely, particles that have both electric and magnetic charge) and strong interactions are interactions between magnetic monopoles then, it is highly reasonable that neutrons (and protons) should have a large *axial* electric dipole moment which is associated with spinning monopoles. Indeed, it is extremely unlikely that the overall electric dipole moment of a system of spinning monopoles vanishes whereas the total spin is nonzero. This discussion indicates that the very low upper bound measured for the electric dipole moment of the neutron[18,19] should not be regarded as a major argument against a hadronic theory where quarks are magnetic monopoles obeying (26) and (27). Indeed, all experiments carried out for the measurement of the electric dipole moment of the neutron are eventually based on the interaction of electric field of charge with the searched electric dipole moment of the neutron[18,19].

Thus, the very low upper bound measured for the electric dipole moment of neutrons is, as a matter of fact, an upper bound for its *polar* electric dipole moment. These measurements provide no information on the magnitude of the neutron's *axial* electric dipole moment. Hence, results of measurements of the neutron's electric dipole moment are not incompatible with the regular charge-monopole theory presented in this work whose main results are (26) and (27).

As pointed out above, a nucleon is expected to have a nonvanishing *axial* electric dipole moment, due to its spinning quarks. In this way, one finds an explanation for the tensor interaction between nucleons[20,21]

$$V_T = \{3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{r})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{r}) - r^2 \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2\} U(r), \tag{30}$$

where $\boldsymbol{r}=\boldsymbol{r}_2-\boldsymbol{r}_1$ and $\boldsymbol{\sigma}$ is the spin operator. This expression is a generalization of

the dipole-dipole interaction between two static point dipoles $\boldsymbol{\mu}_1$ and $\boldsymbol{\mu}_2$ (see [2], p 143).

$$V_{DIPOLE} = -\{3(\boldsymbol{\mu}_1 \cdot \boldsymbol{r})(\boldsymbol{\mu}_2 \cdot \boldsymbol{r}) - r^2 \boldsymbol{\mu}_1 \cdot \boldsymbol{\mu}_2\}/r^5. \tag{31}$$

Evidently, the nuclear tensor interaction cannot be exactly a dipole-dipole one, because nucleons are not point dipoles but composite particles whose size is not much smaller than the distance between nucleons in a nucleus. For this reason the form of the function $U(r)$ of (30) is determined phenomenologically. It is interesting to note that the *sign* of $U(r)$ of (30) is negative (see [21], p. 103), like the sign of (31). It can be concluded that

8. The origin of the nuclear tensor force is understood.

The size of the nucleonic volume inside a nucleus can be deduced from the nucleonic quarks' momentum. It is found that the larger the number of nucleons A in a nucleus, the larger is the mean self volume of nucleons of this nucleus. In other words, as the nucleus becomes heavier its nucleons swell. This property is compatible with the EMC effect[22,23].

On the other hand, the success of the nuclear liquid drop models is an indication that nuclear density is practically constant (see [14] and [20], pp. 6,7). The swelling of the mean volume occupied by quarks of a nucleon with the increase of the number A of nucleons in nuclei, is compatible with screening properties of electrodynamics. Consider a nucleon N_i in a nucleus. A part of the wave function of quarks of neighboring nucleons penetrates into the volume occupied by N_i. Thus, the attracting field of the core of N_i is partially screened by quarks belonging to neighboring nucleons. It follows that, in this case, quarks of N_i "see" a weaker field attracting them to the core of N_i and settle in a larger volume. As the number of nucleons of a nucleus, A, increases, the average number of neighbors of a typical nucleon increases too and the screening effect becomes more significant. This situation explains the EMC effect. Thus,

9. screening effects cause self volume of quarks of each nucleon to increase inside rather large nuclei.

The 3 valence quarks of the proton are uud. Thus, one may write a truncated sum of terms of the proton's full wave function as follows:

$$\psi_{proton} = \lambda_0 \phi_0(uud) + \lambda_1 \phi_1(uudu\bar{u}) + \lambda_2 \phi_2(uuddd\bar{d}). \tag{32}$$

Here ϕ_0 of (32) denotes a wave function of the 3 valence quarks (and the completely full "sea" of negative energy states of quarks). In ϕ_1, one u quark is excited from

the "sea" into a positive energy state. ϕ_2 is analogous. Every ϕ_i is normalized and each of the λ_i is a numerical coefficients. Obviously, each of these terms has the proton's quantum numbers. Since the valence quarks of the proton contain 2 u quarks and only one d quark, it is obvious that the additional d quark of ϕ_2 finds a lower energy state than the additional u quark of ϕ_1. Hence, the absolute value of the coefficient λ_2 should be greater than that of λ_1. It can be concluded that

10. the regular charge-monopole theory provides an explanation for the extra $\bar{d}$ found in a proton, called flavor asymmetry[24].

The 10 issues pointed out in this Section should be considered as an illustration of the ability of the regular charge-monopole theory to explain phenomena related to strong interaction.

4. A Comparison of Magnetic Monopole Theories

This Section contains a discussion of the Dirac monopole theory and its comparison with the regular charge-monopole theory outlined in Section 2. An introductory part is needed for clarifying some general aspects. A physical theory is a mathematical structure that has a physical domain of validity [25]. Hence, in principle, a theory can be refuted if its mathematical structure leads to a contradiction. Its physical meaning can be rejected if it fails to explain results of physical measurements carried out within its domain of validity. It should be pointed out that in the latter case, the theory cannot be saved by an attempt to gerrymander its validity domain[25]. The foregoing arguments indicate that one cannot refute a theory by means of another theory. Indeed, assume that theories A and B yield contradictory predictions within a common validity domain. In this case it may be concluded that at least one of these theories is wrong but it is still unknown which theory is the wrong one. Thus, a comparison with experimental data is required.

There is another aspect of a theory which is not directly connected to its correctness and has also a subjective personal side. It is generally accustomed to regard a theory as a neat one if it relies on a minimal set of postulates which are based on general properties of Nature. One also generally expects that a neat theory is more likely to be correct when compared to another theory which does not look neat. For this reason, the specific postulates used by theories are mentioned too.

The origin of problems of the Dirac charge-monopole theory is that it does not start with the simple case of a system of monopoles without charges. As shown in Section 2, an examination of this case together with postulate (A) leads to the regular charge-monopole theory where the Lorentz force takes the form of (26) and (27). Let us turn to some problematic points of the Dirac charge-monopole theory. These points show that Dirac's charge-monopole theory differs drastically from electrodynamics.

1. The Dirac theory yields a kind of irregularity which is not found in other parts of classical electrodynamics. Indeed, let us examine a magnetic charge density ρ_m and the Dirac's vector potential, which is used for fields of charges *and* for fields of monopoles

$$4\pi\rho_m = \nabla \cdot \mathbf{B} = \nabla \cdot (\nabla \times \mathbf{A}) = 0. \tag{33}$$

This relation states that monopoles do not exist if the vector potential $\mathbf{A}$ is regular. Hence, in Dirac's monopole theory the vector potential must be singular. For this reason, Dirac has introduced the notion of a string that extends from a monopole g to infinity or ends at another monopole having a magnetic charge $-g$. Moreover, the system should obey what is called Dirac's veto which forbids charges from entering regions of space occupied by strings (see [6], p. 1374). Strings are a *new* notion introduced into the theory. Thus, the following postulate enables their acceptability.

(A') Strings connected to monopoles account for the irregularities of the theory. Charges are not allowed to enter regions of space occupied by strings.

2. Unlike ordinary classical electrodynamics and the regular charge-monopole theory outlined in Section 2, Dirac's charge-monopole theory cannot be derived from a regular Lagrangian[4,26]. Hence, the definition of canonical variables is unclear and the ordinary method of constructing the Hamiltonian cannot be used. For this reason, the form of quantum mechanics of Dirac's charge-monopole theory is not self-evident. Analogous conclusions have already been published[27-29].

Let us examine the angular momentum of a Dirac charge-monopole system. A ring made of an insulating material is placed in the (x, y) plane and its center coincides with the origin. The ring is covered uniformly with charge density ρ and it can rotate around the z-axis. A monopole g moves along the z-axis from $-\infty$ towards ∞ (see fig. 1) and carries its string along its path. The motion is legitimate according to Dirac's veto, because charges of the ring do not touch the z-axis. Now, the motion of the monopole is accompanied with a circular electric field which is dual to the circular magnetic field of a uniformly moving charge. Due to Dirac's monopole theory, this field accelerates charges along the ring. Hence, the value of the angular momentum of the ring at the final time differs from its value at the initial time. It turns out that this variation of the angular momentum is compensated by the interaction part of a charge-monopole system (see [2], p. 256 and [6], pp. 1365, 1366. Note the different units used in [2] and [6]). Thus, in

Dirac's monopole theory, the angular momentum of a static system of a charge and a monopole is

$$\mathbf{j} = eg\mathbf{r}/r \tag{34}$$

where $\mathbf{r}$ denotes the radius vector from the charge to the monopole. This angular momentum depends on the *direction* of the line connecting the charge and the monopole but is *independent of the distance between the particles*. It follows that

3. in Dirac's charge-monopole theory there is an interaction dependent quantity whose value does not vanish even if the particles are infinitely far apart. This result is strange and unconvincing.

4. Eq. (34) as well as other arguments yield the results that in Dirac's monopole theory, a magnetic charge g transforms not like a scalar but like a pseudoscalar (see [2], p. 253). It is not clear how this outcome affects the theory. In particular, by analogy with charges (see [1], p. 70, [2], p. 549), one expects that the monopole 4-current is $\rho_m v^\mu/\gamma$, where ρ_m is the monopole density and $\gamma = (1 - v^2)^{-1/2}$. Now, one expects that the 4-current behaves like a 4-vector, contrary to the pseudoscalar property assigned to monopoles.

Assume that, in spite of what is said in item 2 of this section, one finds a way for introducing monopoles into quantum mechanics. In this case, the self consistency of the theory is doubtful because the theory is not derived from a regular Lagrangian. The following example illustrates this issue. Let us examine a spin 1/2 charged particle which is attracted to a center of force by a non-electromagnetic interaction (henceforth denoted by NEMI). NEMI is much stronger than all electromagnetic forces and the latter are evaluated by perturbation calculations. A peculiar feature of NEMI is that its spin-orbit interaction is very strong and its $l = 3$ $j = 7/2$ state is its ground state. An external field of the NEMI performs a split of the m states,

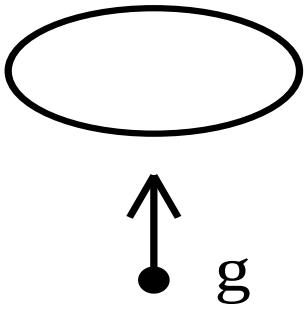

Figure 1: A monopole g moves through a ring (see text).

which is analogous to the Zeeman effect. Thus, the state $l = 3$, $j = 7/2$, $m_j = 7/2$ is the ground state. This is a quantum mechanical analogue of the ring of fig. 1. A magnetic monopole g moves along the z-axis from $z = -Z_0$ to $z = Z_0$ and returns back along a semicircle whose center is at the origin (Z_0 is very large). Evidently, the final state equals the initial one, except for the energy gained by the monopole while moving along the z-axis. (Energy involved with the motion along the arc can be ignored because on this line the magnetic field of the magnetic dipole of the $j = 7/2$ charge behaves like r^{-3}.) Hence,

5. quantum mechanics of the Dirac monopole theory does not conserve energy.

6. Another aspect related to the Dirac monopole theory is the usage of measurement of fields by charges and by monopoles. It can be shown that if the laboratory is located in a noninertial frame of reference (like a rotating laboratory) then fields measured by charges and fields measured by monopoles are *different* entities [30]. Hence, it is not clear why, in Dirac's charge-monopole theory, these different entities are derived from the same 4-potential.

7. Beside the foregoing theoretical difficulties, there is the experimental situation stating that, in spite of prolonged efforts, Dirac monopoles have not been detected[13,31]. This outcome has been predicted on the basis of S-matrix considerations[27] and by using the regular charge-monopole theory outlined in Section 2[32]. This is probably the only monopole related prediction that still holds till now.

8. It should be mentioned that, in addition to the problematic points of the Dirac monopole theory, this theory explains a basic phenomenon of Nature which is charge quantization. However, Dirac's value of the elementary monopole unit $g^2 \simeq 34$ appears to be very high.

Charge quantization clearly cannot be derived from the regular monopole theory of Section 2. However, it can be argued that it is very far from being self-evident that a proof of charge quantization is an inseparable part of the validity domain of an acceptable charge-monopole theory.

5. Problems of Quantum Chrodynamics

At present, quantum chrodynamics (QCD) is regarded as the theory of strong interactions (see [9], p. 20). It relies on several postulates that have not been used previously. By analogy with the discussion in Section 3, these postulates are described below.

A". It uses the Young-Mills idea which extends the gauge procedure and enables the replacement of complex numbers of the phase by matrices belonging to a certain group. In the case of QCD, the group is SU_3.

B". It relies on a certain procedure called after Higgs, which enables the theory to take an acceptable form. The Higgs procedure requires the existence of particles called Higgs mesons.

C". It assigns to each quark a new kind of charge called color. There are 3 kinds of color, called red, green and blue, each of which has its own anticolor. The theory further assumes that particles found in laboratories must be white, namely, they should have equal amount of positive and negative values of each color or equal amount of all the 3 colors.

Let us make a list of problematic points of QCD. The list has a certain resemblance to some of the points discussed in Section 3, where the utilization of the regular charge-monopole theory to strong interactions is described.

1. In spite of a long experimental search, the Higgs mesons have not been found [13].

2. QCD provides no explanation to the participation of real photons in strong interactions. It should be pointed out that the approach called Vector Meson Dominance as well as similar ideas have been discussed recently. It is proved that these approaches have no theoretical basis[33].

3. QCD does not rule out the existence of exotic states (see, e.g. [13] pp. 754, 755, [34]). However, the validity of these states is not established by experiments.

4. The fact that quarks carry only about one half of the nucleon's momentum is explained in Section 3 by the introduction of the baryonic core (see the discussion that follows postulate (F)). In QCD, this is explained by the claim that gluons (the QCD analogue of electromagnetic bound fields) carry the rest of the momentum. These different explanations can be tested by an analysis of sufficient data obtained from colliding beams of π mesons and electrons. Here, the monopole theory used in Section 3 predicts that quarks of a π meson should carry all momentum whereas QCD expects that gluons of the $q\bar{q}$ pair of the π meson should take a portion of the momentum.

6. Concluding Remarks

This work shows how a regular charge-monopole theory can be derived from the self-evident duality postulate. It is also shown that this theory can be applied to the field of strongly interacting particles. This application relies on very simple and self-evident postulates and explains several qualitative properties of strong and nuclear interaction. Thus, it removes the asymmetry between electricity and magnetism in contemporary electrodynamics.

The idea that baryons contain a magnetic charge has already been published. Even before the discovery of quarks, it has been suggested by Dirac that nucleon constituents contain monopoles [8]. Schwinger has proposed a model of hadrons where quarks are dyons[35,36]. This course has been examined by other authors, too [37,38]. However, since all these authors have used the Dirac charge-monopole theory, they could not overcome difficulties. For example, the Dirac monopole theory cannot explain why electrons do not "see" the monopole field but real photons do "see" it (see item 2 of Section 3). Similarly, it cannot explain why the axial electric dipole moment associated with spinning monopoles is not detected in neutron measurements (see the discussion that follows item 7 of section 3).

Problems and difficulties of the Dirac monopole theory are discussed in Section 4. These difficulties and the failure of the experimental quest for Dirac monopoles, indicate that it is unlikely that the Dirac charge-monopole theory is correct. Several kinds of experimental data which are not explained by QCD are discussed in Section 5. The data certainly belongs to the domain of validity of QCD or to the wider theory called the Standard Model. Thus, the interaction of a real photon with a hadron belongs to the combined domain of electrodynamics and QCD, both of which are elements of the Standard Model. As proved elsewhere [33], QCD does not provide an acceptable explanation for this phenomenon.

Other points, like the failure to detect the Higgs mesons as well as exotic states of hadrons belong to the validity domain of QCD. Moreover, QCD has not predicted the EMC effect [22]. It is shown in Section 3 how easily the monopole theory of hadrons explains the similarity between the van der Waals forces and the nuclear ones, as well as the nuclear tensor force, including its sign. On the other hand, in spite of intensive work carried out during more than 30 years, standard textbooks on QCD[9,10] do not discuss these topics.

Similarly, if the baryonic core is assumed to consist of a magnetic monopole central object and closed shells of inner quarks then the enhancement found in the cross section of very high energy collisions[39,40] is understood. These experiments indicate the existence of an energy threshold above which additional quarks at the nucleonic target begin to participate in the interaction with the projectile. The analysis of deep inelastic scattering of electrons on π mesons may provide new

evidence concerning the different interpretations of the portion of momentum carried by nucleonic quarks. In QCD the rest of the momentum is ascribed to gluons whereas in the monopole theory outlined here, it is ascribed to the baryonic core that carries also 3 units of monopole charge. In the case of mesons, there is no core and the monopole theory predicts that all momentum is carried by quarks and antiquarks. On the other hand, according to the QCD approach, a portion of the π meson's momentum is expected to be carried by gluons.

A theory differs from a model by the fact that a theory is expected to fit accurately results of experiments carried out within its validity domain. For this reason, it can be concluded that QCD's inability to describe correctly well established experimental data casts doubts on its correctness.

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