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A Magnetic Model of Matter

A speculation probes deep within the structure of nuclear particles and predicts a new form of matter.

Julian Schwinger

And now we might add something concerning a certain most subtle Spirit, which pervades and lies hid in all gross bodies.

—Newton

Although electromagnetic phenomena are the best understood of all nature's manifestations, there are still great mysteries in this and related areas. Here are four of them:

1) The fundamental electromagnetic equations of Maxwell show an intrinsic symmetry between electric and magnetic quantities which, incidentally, is unique to the four dimensions of space and time. Yet no magnetic counterpart to electric charge is known experimentally. How can one account for this, while retaining the qualitative idea of reciprocity between electric charge and magnetic charge?

2) The unit of electric charge is universal. It is observed, with fantastic precision, to be identical on all charged particles, despite wide variations in their other characteristics. What unknown general principle is at work?

3) A new periodic table is coming into being through the artificial creation of subnuclear particles and their tentative grouping into families. Two approximate but significant properties have been recognized, isotopic spin and hypercharge, which serve also to specify the electric charge of the particle. What is the dynamical meaning of these properties that are related to but distinct from electric charge? In addition, more inclusive classification schemes have been proposed, which lend themselves to the interpretation that nuclear particles have constituents with fractional electric charges. In view of the strict regularity noted in 2), how can such models have physical significance?

4) The behavior of all particles with respect to strong, electromagnetic, and weak interactions has seemed consistent with a general symmetry property in which the interchange of left and right, symbolized by P(parity), is combined with the exchange of positive and negative charge, C. But recently, phenomena have been observed that indicate a weak violation of this CP symmetry. What dynamical mechanism is responsible?

I shall put forward a speculative hypothesis, which has in its favor only one argument—that it does connect and give tentative answers to all these questions. However wide of the truth this hypothesis may be, it can serve to bring into better focus the nature of the quest for order and understanding that underlies the activity of the high-energy physicist.

It began long ago when Dirac (*1*) pointed out that, according to the quantum laws of atomic physics, the existence of a magnetic charge would lead to a quantization of electric charge in which only integral multiples of a fundamental unit could occur. I have never seriously doubted that here was the missing general principle referred to in 2). And Dirac himself noted the basis for the reconciliation called for in 1). The law of reciprocal electric and magnetic charge quantization is such that the unit of magnetic charge, deduced from the known unit of electric charge, is quite large. It should be very difficult to separate opposite magnetic charges in what is normally magnetically neutral matter. Thus, through the unquestioned quantitative asymmetry between electric and magnetic charge, their qualitative relationship might be upheld.

What is new is the proposed contact with the mysteries noted under 3) and 4), which are testimonials to the advance of experimental science. This appears if one considers the properties of particles that carry both electric and magnetic charges. Now the conditions of charge quantization are less stringent, and fractional electric charge becomes a physical possibility, consonant with the integral charges necessarily carried by magnetically neutral particles. Such dual-charged particles supply a physical realization for the constituents used in the empirical models of the so-called hadrons (*2*), which are the strongly interacting nuclear particles. Furthermore, in the introduction of particles with definite ratios between electric and magnetic charges, a mechanism for CP violation has made its appearance. Electric and magnetic charges, like electric and magnetic fields, behave oppositely under spatial reflection, whereas the equations of electromagnetism are symmetrical between positive and negative charges, when both types are considered together. If the dual-charged particles, and their antiparticles, realize a certain ratio between electric and magnetic charge, but not its negative value, the rule of CP invariance is broken. This physical model requires further elaboration to explain, rather paradoxically,

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why the observed violation of *CP* invariance is so remarkably weak. The same refinement is also relevant in the establishment of the detailed correspondence with the empirical mass spectrum that relates to the meaning of isotopic spin and hypercharge. We now turn from this brief survey to more specific but elementary discussions of the various items.

Maxwell's Equations

The form of these equations for the electric field $\mathbf{E}$ and the magnetic field $\mathbf{H}$, in which c is the speed of light,

$$\nabla \times \mathbf{H} - \frac{1}{c}\frac{\partial}{\partial t}\mathbf{E} = \frac{4\pi}{c}\mathbf{j}_e$$
$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$
$$-\nabla \times \mathbf{E} - \frac{1}{c}\frac{\partial}{\partial t}\mathbf{H} = \frac{4\pi}{c}\mathbf{j}_m$$
$$\nabla \cdot \mathbf{H} = 4\pi\rho_m$$

makes evident the symmetry

$$\mathbf{E} \to \mathbf{H},\ \mathbf{H} \to -\mathbf{E} \qquad \rho_e \to \rho_m,\ \rho_m \to -\rho_e$$

with the electric and magnetic currents, $\mathbf{j}_e$ and $\mathbf{j}_m$, following the pattern of the charge densities ρ_e and ρ_m. This is a particular example of the invariance expressed by the rotation through the arbitrary angle θ.

$$\mathbf{E}' = \mathbf{E}\cos\theta + \mathbf{H}\sin\theta$$
$$\mathbf{H}' = -\mathbf{E}\sin\theta + \mathbf{H}\cos\theta$$
$$\rho_e' = \rho_e\cos\theta + \rho_m\sin\theta$$
$$\rho_m' = -\rho_e\sin\theta + \rho_m\cos\theta$$

In purely electromagnetic considerations, the observed absence of magnetic charge is equally well described as the coexistence of electric and magnetic charge in the universal ratio indicated by

$$\rho_m/\rho_e = \tan\theta$$

We also note that the following combinations formed from electric charges e_1,e_2 and magnetic charges g_1,g_2 are invariant under the redefinitions produced by the rotation through the angle θ:

$$e_1e_2 + g_1g_2,\quad e_1g_2 - e_2g_1$$

Charge Quantization

Here is an elementary argument in support of the existence of charge quantization (*3*). Consider the nonrelativistic behavior of a particle with mass m, carrying electric charge e_1 and magnetic charge g_1, which moves with velocity $\mathbf{v}$ in the field of a stationary body that possesses charges e_2 and g_2. There is an equivalent description for the relative motion of two particles with arbitrary masses. The equation of motion is

$$m\frac{d\mathbf{v}}{dt} = e_1(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{H}) + g_1(\mathbf{H} - \frac{1}{c}\mathbf{v}\times\mathbf{E})$$

where the following forms of the field strengths at the point with vector $\mathbf{r}$, of magnitude r,

$$\mathbf{E} = e_2\frac{\mathbf{r}}{r^3},\quad \mathbf{H} = g_2\frac{\mathbf{r}}{r^3}$$

assign the origin of coordinates to the position of the stationary body. The explicit statement

$$m\frac{d\mathbf{v}}{dt} = (e_1e_2 + g_1g_2)\frac{\mathbf{r}}{r^3} + (e_1g_2 - e_2g_1)\frac{1}{c}\mathbf{v}\times\frac{\mathbf{r}}{r^3}$$

involves just the invariant charge combinations that were noted. The associated moment equation is

$$\mathbf{r}\times m\frac{d\mathbf{v}}{dt} = (e_1g_2 - e_2g_1)\frac{1}{c}\frac{\mathbf{r}\times(\mathbf{v}\times\mathbf{r})}{r^3} = (e_1g_2 - e_2g_1)\frac{1}{c}\frac{d}{dt}\frac{\mathbf{r}}{r}$$

and we recognize the conserved angular momentum vector

$$\mathbf{J} = \mathbf{r}\times m\mathbf{v} - (e_1g_2 - e_2g_1)\frac{1}{c}\frac{\mathbf{r}}{r}$$

The quantization of the component of this angular momentum along the connecting line of the particles then gives the charge quantization condition ($2\pi\hbar$ is Planck's constant)

$$(e_1g_2 - e_2g_1)/\hbar c = \nu$$

where ν is an integer. The exclusion of (integer + ½) values, which were admitted by Dirac, seems plausible in this purely orbital situation, but it requires a rather subtle argument in support. Equally subtle is the suggestion that, if there are dual-charged particles, rather than just electrically charged particles and magnetically charged particles, the integer ν must be even (*4*).

I shall try only to indicate what is involved in these arguments through the following consideration on behalf of integer quantization. Since matter is normally magnetically neutral, any purely magnetically charged particle, for example, has an oppositely charged counterpart somewhere. If one is interested in an electric charge e, at the point $\mathbf{r}$, which is in the neighborhood of the magnetic charge g at the origin, it should not be necessary to refer to the compensating charge $-g$ at the point $\mathbf{R}$, if the latter is sufficiently remote from the origin. But, on examining the additional electromagnetic angular momentum of this system, which is

$$-(eg/c)\left[\frac{\mathbf{r}}{r} - \frac{\mathbf{r}-\mathbf{R}}{|\mathbf{r}-\mathbf{R}|}\right]$$

we see that the angular momentum associated with the charge $-g$ does not vanish as this particle recedes to infinity but contributes an additive constant. The total angular momentum of the three-particle system is integral, as we confirm by noting that the electromagnetic angular momentum vanishes when $\mathbf{R}\to 0$ and the magnetic charge is neutralized. On shifting our viewpoint between the physically equivalent two-particle system and the three-particle system with an infinitely remote compensating charge, paradoxical transitions between (integer + ½) and integer values of the angular momentum will be avoided if $eg/\hbar c$ is restricted to integral values.

It can be useful to regard

$$-\frac{1}{c}(e_1g_2 - e_2g_1)$$

as the radial component of a spin angular momentum vector $\mathbf{S}$ (*5*)

$$-\frac{1}{c}(e_1g_2 - e_2g_1) = \mathbf{S}\cdot\mathbf{r}/r$$

The complete spin vector is introduced by defining the momentum $\mathbf{p}$

$$m\mathbf{v} = \mathbf{p} + \mathbf{S}\times\mathbf{r}/r^2$$

which gives

$$\mathbf{J} = \mathbf{r}\times\mathbf{p} + \mathbf{S} = \mathbf{L} + \mathbf{S}$$

The properties of $\mathbf{p}$ and $\mathbf{S}$ are indeed those suggested by this familiar combination involving the orbital angular momentum vector $\mathbf{L}$. On introducing the radial momentum p_r according to

$$\mathbf{p} = \frac{\mathbf{r}}{r}p_r + \frac{\mathbf{L}\times\mathbf{r}}{r^2}$$

we infer the kinetic energy

$$T = \tfrac{1}{2}m\mathbf{v}^2 = \frac{1}{2m}\left(p_r^2 + \frac{\mathbf{J}^2 - (\mathbf{J}\cdot\mathbf{r}/r)^2}{r^2}\right)$$

where

$$\mathbf{J}\cdot\frac{\mathbf{r}}{r} = \mathbf{S}\cdot\frac{\mathbf{r}}{r} = -\nu\hbar$$

The total angular momentum spectrum is, correspondingly

$$\mathbf{J}^2 = j(j+1)\hbar^2,\ j = |\nu|,\ |\nu|+1, \ldots$$

In the present experimental situation, with only electric charge known, the consideration of a hypothetical magnetic charge g gives the electric charge quantization condition

$$eg/\hbar c = 2n$$

in which the evenness of the integer $\nu = 2n$ is assumed. From the observed unit of electric charge, as measured by

$$e^2/\hbar c \simeq 1/137$$

we deduce a unit of magnetic charge, on choosing $n = 1$

$$g_0^2/\hbar c \simeq 4(137)$$

Forces between magnetic charges are superstrong, in comparison with the strong nuclear forces for which coupling constants are ~ 10. The above electric-charge quantization condition also governs the total electric charge of a magnetically neutral aggregate of dual-charged particles. Let e_a,g_a denote the various dual-charge assignments, which obey

$$\sum_a g_a = 0 \quad , \quad \sum_a e_a = e$$

Allowing for the possibility that the smallest magnetic charge g_0 resides on a particle with electric charge e_0, we conclude from

$$\sum_a (e_a g_0 - e_0 g_a)/\hbar c = \sum_a 2n_a$$

that

$$eg_0/\hbar c = 2n$$

The importance of the latter remark is that the electric charge on a dual-charged particle need not be an integral multiple of the charge unit. Let us imagine a situation in which all particles are dually charged with a universal charge ratio

$$g/e = \tan\theta$$

Then the integer in any charge-quantization condition vanishes, and no further restrictions appear. Of course, as the use of the angle θ signals, this situation is just a charge-rotated version of pure electric charges, where no charge quantization exists. But it emphasizes the weakening of charge quantization that the consideration of dual-charged particles entails. Suppose there are two kinds of dual-charged particles with a common magnetic charge g_0, but different electric charges, e_1 and e_2. The charge quantization condition is

$$(e_1 - e_2)\, g_0/\hbar c = 2n$$

which asserts that $e_1 - e_2$ is a multiple of the charge unit but does not determine the individual charges. Alternatively, by forming a composite of the particle having charges e_1,g_0 with the antiparticle of charges $-e_2$, $-g_0$, we produce a magnetically neutral particle with electric charge $e_1 - e_2$, which must submit to normal charge quantization. If there are dual-charged particles with magnetic charges different from g_0, they must carry integral multiples of this smallest value to be consistent with the reciprocal quantization enforced on magnetic charge by the electrical charge unit e. If we compare the charges e_3,$2g_0$, for example, with e_1,g_0, the charge quantization condition asserts that

$$(e_3 - 2e_1)\, g_0/\hbar c = 2n$$

The conclusion that $e_3 - 2e_1$ is a multiple of e is again equivalent to the production of a magnetically neutral composite whose electric charge must have e as a unit. In this way it is seen that the electric charge on a dual-charged particle with magnetic charge g_0 provides a new charge unit that is distinct from the known unit e.

Hadron Models

We are being led to a picture in which hadronic matter is viewed as a magnetically neutral composite of dual-charged particles that are based electrically upon a new unit of charge. Such a picture must have enough variety to account for the two different kinds of hadrons: mesons, which are Bose-Einstein particles, and baryons, which are Fermi-Dirac particles. In perhaps the simplest kind of model, all dual-charged particles are alike, at least with regard to statistics, which must be Fermi-Dirac if baryons are to be built from them. It would not do to have only one value of magnetic charge, for then magnetically neutral composites could be produced in only one way, namely, by the combination of particle and antiparticle. That would only manufacture mesons. But it is enough to have just two different values of magnetic charge, which we take to be $2g_0$ and $-g_0$. Now a magnetically neutral composite is also formed from three constituents, of magnetic charges $2g_0, -g_0, -g_0$, and this is a Fermi-Dirac particle. It is satisfactory that this pattern of magnetic charge is unsymmetrical, in contrast with the meson pattern illustrated by g_0, $-g_0$, for it means that the antibaryon, with constituent magnetic charges $-2g_0, g_0, g_0$, is a fundamentally different particle. Magnetic charge thus supplies an interpretation for the empirical property of nucleonic charge. The latter could be identified, for example, with the total magnetic charge on doubly charged constituents measured in units of $2g_0$.

As in the unification of neutron and proton into the nucleon, which was the first use of isotopic spin, it is natural to regard the three values of magnetic charge as three choices available to the fundamental dual-charged particle. And the heuristic power of the theoretical reciprocity between electric and magnetic charges becomes apparent in the suggestion that the electric charge of this fundamental particle has the same threefold option: $2e_0, -e_0, -e_0$. On equating the nonvanishing difference of these charge values to the known unit e, we identify the new charge unit

$$e_0 = \tfrac{1}{3} e$$

The pattern of fractional electric charges, $\tfrac{2}{3}, -\tfrac{1}{3}, -\tfrac{1}{3}$, is just the one used in the empirical models. It has now been traced back to the qualitative symmetry between electric and magnetic charge, and the requirement of magnetic neutrality. We should note the consistency of the hypothesis that the electric-charge pattern is independent of the magnetic charge, which again states that $2e_0$ differs from $-e_0$ by an integer. Incidentally, the relation between the electric-charge unit of dual-charged particles and the unit of pure electric charge has its magnetic analog in

$$g_0 = \tfrac{1}{3} g$$

The unit of pure magnetic charge has a magnitude given by

$$g^2/\hbar c \simeq 36(137)$$

We come now to a very important question. What name shall we give to the fundamental dual-charged particle (*6*)? The particle ending *-on* is obligatory. As evidenced by the use of the provisional phrase "dual-charged particle," the basic aspect that should be commemorated in the name is the dualistic or dyadic character of the charge that the particle bears. There are various short Greek and Latin combining forms that could be applied: *bi-*, *di-*, *duo-*, *dyo-*, as well as longer words such as *dyadikos-*, of two. Dyadikon surely has a ring to it. But being mindful that mesotron became shortened to meson, I believe that dyon is a better choice. The symbol D will not often lead to confusion with deuterium, particularly if we add labels that indicate the electric and magnetic charges, for which we use e and g as units. Thus ${}^{2/3}D^{-1/3}$ is the dyon with electric charge $-\frac{1}{3}e = -e_0$ and magnetic charge $\frac{2}{3}g = 2g_0$.

What is the mass of a dyon? Let us be clear about this; any estimate is sheer guesswork. We do not have the wit to connect the known properties of the composites—hadrons—with the unknown properties of the constituents—dyons. The interaction strength far surpasses anything for which such skill exists. But a beginning must be made. Consider the nonrelativistic behavior of two widely separated dyons, of common mass M_D, that are combined in a hydrogenlike structure. The energy expression is

$$H = \frac{1}{2m}\left[p_r^2 + \frac{\mathbf{J}^2 - (\nu\hbar)^2}{r^2}\right] + (g_1g_2 + e_1e_2)/r$$

where m is the reduced mass, $\frac{1}{2}M_D$. Hydrogen energy levels depend only upon the principal quantum number $n = n_r + l + 1$, where l is here given by

$$l(l+1) = j(j+1) - \nu^2$$

As an initial approximation, let us ignore the fine structure of order $eg_0/\hbar c \sim 1$, and the hyperfine structure of order $e^2/\hbar c \simeq 1/137$. The appearance of the formulas will also be simplified by the adoption of atomic units for which $\hbar = c = 1$. With the specific choice

$$g_1g_2 = -g_0^2$$

the Bohr formula supplies the total mass, or better, the squared mass as

$$M^2 = (2M_D)^2\left[1 - \frac{1}{4}\frac{g_0^4}{n^2}\right]$$

This result is valid only when the second term is small compared to unity, corresponding to very large quantum numbers, $n \gg n_0$, where

$$n_0 = \tfrac{1}{2}\, g_0^2 \simeq 2(137)$$

But, *faute de mieux*, let us abandon caution and extrapolate down to zero mass! That is reached at $n = n_0$. The neighboring states identified by $n = n_0 + k$, where $k = 1, 2, \ldots,$ are approximately represented by

$$M^2 = (2M_D)^2(2/n_0)k$$

This formula can be compared with empirical meson mass spectra (*7*). Simple but accurate representations of the mass splittings within the known families of $9 = 3 \times 3$ particles enable one to remove this mass structure, and the resulting squared masses are proportional to an integer with actual values of 0, 1, 2, or 3. The scale is supplied by the mass of the ρ-meson, which gives the identification

$$(2M_D)^2 = \tfrac{1}{2}\, n_0 m_\rho^2$$

The specific value of n_0 noted above refers to the individual magnetic charge magnitude g_0. If $2g_0$ were considered, n_0 would be four times larger. We shall use a weighted mean of these values, which effectively equates n_0 to 4(137), and then

$$M_D \sim (137/2)^{1/2}\, m_\rho \sim \text{6 billion electron volts}$$

I would not risk more than three groschen on the likelihood of this estimate, but at least it is an optimistic one, in relation to current accelerator plans.

Let us return to what was termed the fine and hyperfine structure of the mass spectrum. The hyperfine structure is an electric-charge dependence which causes the interaction strength to vary by a fraction

$$\sim e^2/g_0^2$$

The corresponding change in squared mass is

$$\sim M_D^2\, e^2/g_0^2 \sim (1/137)\, m_\rho^2$$

That is indeed the magnitude observed for the charge dependence as illustrated by the K-mesons

$$m_{K^0}^2 - m_{K^\pm}^2 \simeq 0.7 \times 10^{-2}\, m_\rho^2$$

but the sense of the splitting is opposite to what one would expect from the simple mechanism considered. The fine structure is represented by a variation in n or k that is of the order of unity. Such is the qualitative empirical situation, as illustrated by a comparison of the K-meson, which belongs to the $k = 0$ nonuplet, with the ρ-meson, a member of the $k = 1$ nonuplet:

$$m_K^2 \simeq 0.4\, m_\rho^2$$

But the quantitative details are wrong. Only the value of the electric charge would seem to be relevant, whereas observed mass spectra are labeled by and give meaning to the properties of isotopic spin and hypercharge. Something is missing.

Charge Exchange

Are other known phenomena omitted in this dynamical scheme? Although conventional electromagnetic and strong interactions have been given a generalized electromagnetic interpretation, there is no reference to the so-called weak interactions. This type of interaction can be viewed as a mechanism of electric-charge exchange among members of the same particle family, including the lepton family (L) of electron, muon, and neutrino. It is possible, but not necessary, to regard this charge exchange as proceeding through the intermediary of an unknown, heavy, charged boson, as has been proposed several times under different names. The commonly employed symbol is W(weak), which we use in writing some typical particle reactions

$$L^+ \leftrightarrow L^0 + W^+, \quad {}^{-1/3}D^{2/3} \leftrightarrow {}^{-1/3}D^{-1/3} + W^+$$

There is a striking analogy with electromagnetic emission and absorption of photons (which motivated my own early speculations in this direction) since the observed interactions are essentially vectorial in character and have a certain universality in strength. In more detail, these weak interactions are known to be *CP*-conserving, but *C*- and *P*-violating, in a way that depends upon the sign of the electric charge that is exchanged. It would seem that they destroy the charge rotational invariance of the Maxwell equations and thereby help to establish the absolute distinction between electric and magnetic charge.

I find it natural to imagine a magnetic analog of these processes, with a correspondingly stronger coupling, that could be mediated by a boson of unit magnetic charge, S (strong). A typical magnetic charge-exchange process for the dyon is

$${}^{2/3}D^{-1/3} \leftrightarrow {}^{-1/3}D^{-1/3} + {}^{+}S$$

It is entirely possible that both S and W are fictitious and should be understood only as a shorthand for the direct exchange of charge between pairs of particles of various types. We shall not dwell on the conceivable magnetic counterparts of leptons, except to wonder if the neutral neutrino(s) could be common to both families. The mechanism represented by the magnetic particle S produces a rapid exchange of magnetic charge among the dyons that constitute a hadron. It may be that the result is a very short time scale averaging out of the magnetic charge on an individual dyon. Indeed, that is what is suggested by a naive view of the empirical baryon situation. The pattern of low-lying multiplets is correctly represented if we unite a three-valued electric label with a two-valued spin index and consider only totally symmetrical arrangements of three such index pairs as though three constituents were in a symmetrical orbital state and obeyed Bose-Einstein statistics. Conflict with the physical Fermi-Dirac statistics of dyons is avoided if we recognize the additional three-valued magnetic labels and combine them in a totally antisymmetric arrangement. This implies that each of the three magnetic assignments is equally probable for an individual dyon, thus giving an average magnetic charge of zero.

A mechanism for magnetic charge exchange is also indicated if large violations of *CP* invariance are to be avoided. Particularly relevant is the remarkable precision with which it is known that the neutron does not have an electric dipole moment (*8*). The associated length is measured to be $\lesssim 10^{-22}$ centimeter, in contrast with $\sim 10^{-14}$ centimeter for the magnetic dipole moment. We compare this situation with an elementary model in which a dyon, considered to be a particle with spin of ½, possesses intrinsic magnetic and electric dipole moments proportional to its spin vector and its electric and magnetic charge, respectively. Such models have often been applied to nucleon magnetic moments, with the paradoxical result that the constituents have masses smaller than the nucleon mass, rather than the much larger values that are required physically. This is an artifact of an overly naive nonrelativistic attitude, however, and it is removed if the magnetic (and electric) energy is incorporated as an added term in the relativistic expression for the squared mass of the composite particle. Then it is the mass of the composite particle that sets the scale, and one empirical factor of the order of unity gives a reasonable account of neutron and proton magnetic moments. The analogous electric dipole moment is proportional to the sum of dyon magnetic charges multiplied by spin vectors. Since the total magnetic charge is zero, the electric dipole moment would vanish if all three dyons were dynamically the same and therefore had identical average spin vectors. But surely the dyon of magnetic charge ⅔ is in a different environment than a dyon of magnetic charge −⅓ and should have a somewhat different average spin; this would lead to an unacceptable electric dipole moment, unless a mechanism restores the equivalence of all dyons by a rapid exchange of magnetic charge which effectively destroys the correlation between spin and magnetic charge.

The same mechanism for magnetic charge exchange will tend to suppress those effects of order $eg_0/\hbar c$ that were called fine structure. The exchange mechanism itself produces mass splittings, however. Among the consequences of these couplings is a displacement in the masses of the individual dyons. There is a plausible expression for the exchange interaction that produces a mass splitting of a threefold electric multiplet into a doublet and a singlet, which gives an elementary account of the empirical properties of isotopic spin and hypercharge. These considerations are too quantitative and too uncertain to merit further comment here. Suffice it to say that the general outlines of a mechanism have appeared, which may meet the challenge posed by the regularities observed in the properties of hadronic strong, electromagnetic, and weak interactions.

Summary

A conceivable dynamical interpretation of the subnuclear world has been erected on the basis of the speculative but theoretically well-founded hypothesis that electric and magnetic charge can reside on a single particle. I hope that these suggestive, if inadequate, arguments will be sufficiently persuasive to encourage a determined experimental quest for the portal to this unknown new world of matter, for

Nothing is too wonderful to be true, if it be consistent with the laws of nature, and in such things as these, experiment is the best test of such consistency.

—Faraday

References and Notes

P. A. M. Dirac, *Proc. Roy. Soc. London Ser. A* **133**, 60 (1931); *Phys. Rev.* **74**, 817 (1948).

2. The term hadron has been introduced in opposition to lepton, which designates particles, other than the photon and graviton, that do not have strong interactions. Lepton was well chosen since the Greek combining form *lepto-* includes "small, weak" among its meanings. But, unfortunately, the meanings of *hadro-* are limited to "ripe, thick," which this is, a bit.
3. The argument was presented for particles with either electric or magnetic charge in *Symmetry Principles at High Energy*, A. Perlmutter, J. Wojtaszek, G. Sudarshan, B. Kursunoglu, Eds. (Freeman, San Francisco, 1966). Also noted there is the charge-quantization condition for dual-charged particles, under the assumption that particles carry both charges *e,g* and *e,–g*. I was not yet ready to face the apparently strong violation of *CP* invariance that occurs if only one of these particles exists.
4. Both arguments are presented in the language of the new theory of sources [J. Schwinger, *Phys. Rev.* **173**, 1536 (1968)]. A discussion that employed the more conventional and more cumbersome methods of operator field theory was given some time ago by T.-M. Yan [thesis, Harvard University (1968)]. It has been duplicated recently by D. Zwanziger [*Phys. Rev.* **176**, 1489 (1968)], although this author does not recognize that two different factors of 2 are involved.
5. Comments in this direction were made by A. Goldhaber [*Phys. Rev.* **140**, B1407 (1965)]. I came to this approach from the opposite direction, by asking how the spin of a particle could be removed in favor of its helicity, the spin component along the momentum direction. The mathematical problem is the same, with position and momentum vectors interchanged.
6. Unfortunately, the field of choice is not free of prior incursions. In the interests of an obscure literary reference that celebrates the empirical aspect of triadism, an untraditional and unmellisonant term was introduced and has found favor in some circles. I prefer to respect tradition and, more important, to emphasize the theoretical basis of the otherwise mysterious empirical characteristics.
7. J. Schwinger, *Phys. Rev. Lett.* **20**, 516 (1968).
8. W. Dress, J. Baird, P. Miller, N. Ramsey, *Phys. Rev.* **170**, 1200 (1968); C. Schull and R. Nathans, *Phys. Rev. Lett.* **19**, 384 (1967).