Quarks, Magnetic Monopoles and Negative Mass.

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Several principal unsolved questions confronting elementary-particle physics may have a rational explanation by postulating the existence of dually charged particles with both electric and magnetic charge and by identifying these particles with the quarks (1). First, the introduction of magnetic charge, besides electric charge, would much more satisfactorily account for the intrinsic symmetry in between electric and magnetic quantities exhibited by Maxwell's equations. Second, the existence of magnetic monopoles would explain the extremely accurate observed quantization of electric charge in units of the elementary charge (2). Third, the introduction of dually charged quarks would make unnecessary the unphysical concept of color (3) which otherwise seems unavoidable if quarks are believed to be spin-$\frac{1}{2}$ particles satisfying Fermi-Dirac statistics.

NAMBU (4) and PARISI (5) have speculated that quarks may be monopoles attached to the ends of magnetic strings. These magnetic strings are thought to be similar to the Abrikosov flux lines in the Landau-Ginzburg theory of superconductivity. According to this picture a dual string is nothing but a mathematical idealization of a magnetic-flux tube in equilibrium against the pressure of the surrounding charged superfluid of the Higgs scalar field, which it displaces. However, more recently LINDE (6) and VELTMAN (7) have shown that the Higgs mechanism may be at variance with astronomical data because it would lead to a long-range force many orders of magnitude larger than the gravitational force. Another serious problem of the Nambu model is its failure to account for the existence of baryons, since each magnetic string must have exactly two opposite charged magnetic monopoles attached to its ends.

The question for the reality of magnetic monopoles has been given a new perspective by PARKER (8), who has shown that the inclusion of nonlinear gravitational effects resulting from the Einstein-Maxwell equations exludes the existence of magnetic mono-

(1) J. SCHWINGER: *Science*, **165**, 757 (1969).
(2) P. A. M. DIRAC: *Proc. Roy Soc.*, A **133**, (1931); *Phys. Rev.*, **74**, 817 (1948).
(3) H. FRITZSCH, M. GELL-MANN and H. LEUTWYLER: *Phys. Lett.*, **47** B, 365 (1973).
(4) Y. NAMBU: *Phys. Rev. D*, **10**, 4262 (1974).
(5) G. PARISI: *Phys. Rev. D*, **11**, 970 (1975).
(6) A. D. LINDE: *JETP Lett.*, **19**, 183 (1974).
(7) M. VELTMAN: *Phys. Rev. Lett.*, **34**, 777 (1975).
(8) L. PARKER: *Phys. Rev. Lett.*, **34**, 412 (1975).

poles with positive gravitational mass, but not of negative gravitational mass and for which the Dirac charge quantization rule or the dual quantization rule by SCHWINGER [1] apply. The principle of equivalence then automatically requires that the inertial mass of the magnetic monopoles must be also negative. We therefore put forward the hypothesis that the dually charged particles by SCHWINGER have a negative inertial mass.

There are a number of compelling reasons to introduce the concept of negative masses into physics.

1) Negative inertial masses enter through the two possible signatures for the square root of the Einstein factor $(1-v^2/c^2)^{-\frac{1}{2}}$, and the mass-energy relation should actually be written as follows:

$$E = \pm \frac{m_0 c^2}{\sqrt{1-v^2/c^2}} = \pm mc^2 , \tag{1}$$

permitting both signs.

2) In quantum theory the negative sign of the square root has a profound effect, it leads to the Dirac equation having both positive- and negative-energy states.

3) Einstein's gravitational-field equations have solutions with negative gravitational masses, as can be seen for example by the following solution of the field equations given by the line element:

$$ds^2 = c^2\left(1 + \frac{2G|m|}{rc^2}\right)dt^2 - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2) - \frac{dr^2}{1 + 2G|m|/rc^2}, \tag{2}$$

which is obtained from Schwarzschild's solution by the substitution $m \to -|m|$. The principle of equivalence then implies that a negative gravitational mass must be connected to a negative inertial mass. Whereas the Schwarzschild metric is gravitationally attractive for any test particle, the opposite is true for a test particle in the field of the metric given by the line element of eq. (2).

As one can see easily, in classical Newtonian mechanics two particles of negative mass would show attraction for forces which are repulsive for positive-mass particles. *Vice versa*, two negative-mass particles would show repulsion for forces which are attractive for positive-mass particles. In quantum mechanics this behavior in general remains unchanged except that there the phenomenon of exchange forces can lead to an attraction of particles which in the classical case would repel each other. For particles of opposite mass interacting via a force which for positive masses would be attractive, the positive-mass particle would be attracted towards the negative-mass particle and the negative-mass particle repelled from the positive-mass particle resulting in a self-accelerated motion. *Vice versa*, for a force which for positive masses would be repulsive, the positive-mass particle would be repelled from the negative-mass particle and the negative-mass particle attracted towards the positive-mass particle, again resulting in a self-accelerated motion albeit of opposite direction.

A phenomenon which bears directly on the physical reality of negative masses is the zitterbewegung of elementary particles first studied by SCHRÖDINGER [9], and it was recognized by DE BROGLIE [10] that the oscillatory part of the zitterbewegung results from the admixture of negative-energy and hence negative-mass states to the wave function. Although the direct connection of the spin and zitterbewegung had

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(9) E. SCHRÖDINGER: *Berl. Ber.*, 416 (1930), 418 (1931).
(10) L. DE BROGLIE: *L'électron magnétique* (Paris, 1934).

been already recognized by SCHRÖDINGER, it was first shown by HÖNL [11] that the spin can be hereby understood as the result of the superposition of a positive mass with a virtual positive-negative mass dipole. In the classical limit, the translation of a mass dipole produces an angular momentum and it is this fact which leads to the spin phenomenon. This of course is of no surprise, since the Dirac equation describing the spin phenomenon is connected to states of negative energy and hence negative mass.

The occurrence of negative masses in quantum theory is different from the one in classical mechanics. Since the Klein-Gordon equation describing Bose particles is obtained from the squared expression for the relativistic energy equation thus removing the ambiguity of the two signatures in eq. (1), it is here assumed that Bose particles, and which in the classical limit are associated with real force fields, can only occur with positive mass. In contrast the Dirac equation is derived from the unsquared relativistic energy equation thus permitting both signs in eq. (1) and it is therefore assumed that Fermi particles can occur with both positive or negative mass.

In his model of dually charged quarks SCHWINGER [1] assumes the following quantization condition:

$$eg_0/\hbar c = 2n\,, \qquad n = 1, 2, \ldots, \tag{3}$$

where $e^2/\hbar c$ is the electric and $g_0^2/\hbar c$ the magnetic coupling constant resulting from the electric monopole of charge e and the magnetic monopole of charge g_0. Since from observation $e^2/\hbar c \simeq 1/137$, a unit of magnetic charge g_0 is deduced by putting in eq. (3) $n = 1$ hence

$$g_0^2/\hbar c \simeq 4 \times 137 = 548\,. \tag{4}$$

The quark hypothesis assumes fractionally charged particles in units of e given by $\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}$. If one therefore redefines the fundamental electric charge by $e_0 = \frac{1}{3}e$, the electric charge of the quarks in units of e_0 would be $2, -1, -1$. According to SCHWINGER the magnetic charge of the quarks in units of g_0 would then be $2, -1, -1$.

Electric and magnetic charges, like electric and magnetic fields, behave opposite under spatial reflection, whereas the equations of electromagnetism are symmetric between positive and negative charges, when both types are considered together. Hence, if the dually charged particles and their antiparticles have a certain fixed ratio between their electric and magnetic charge, but not its negative value, the rule of CP invariance is broken. However, the weakness of the observed CP violation suggests the existence of large magnetic charge exchange currents flowing in between the dually charged particles. Large magnetic charge exchange currents are also consistent with our negative-mass hypothesis for the quarks, since it seems that only a magnetic charge exchange force can account for the binding of oppositely charged negative-mass magnetic monopoles. As it was stated, forces which are attractive in between positive-mass particles will be repulsive for negative-mass particles. Neglecting the much smaller electric charge for the dually charged particles it follows that the magnetic force will predominate. Since this magnetic Coulomb force for oppositely charged magnetic monopoles would be attractive for positive-mass particles, it would be repulsive for negative-mass particles and would not lead to a bound state. If, however, the magnetic interaction is accompanied by a large magnetic charge exchange current, a Heisenberg-type magnetic charge exchange force will result and which can become larger than the ordinary Wigner-type force. A Heisenberg-type charge exchange force is repulsive for oppositely charged positive-mass particles and hence attractive for negative-mass

[11] H. HÖNL: *Ergeb. exak. Naturwiss.*, **26**, 291 (1952).

particles, and thus could bring the negative-mass particles into a bound state. The occurrence of a strong magnetic charge exchange current can be described by an effective coupling constant $g^2/\hbar c$ for which $g^2/\hbar c \ll g_0^2/\hbar c$. In calculating the binding energy for the negative-mass quarks we will use the nonrelativistic Schrödinger equation. This, of course, can be only justified as a crude approximation but which may suffice for this first exploratory study. The Schrödinger equation for two particles of positive mass m in the field of a mutually attractive potential $-g^2/r$ is given by

$$\nabla^2\psi + \frac{m}{\hbar^2}\left(W + \frac{g^2}{r}\right)\psi = 0 . \tag{5}$$

From eq. (5) it follows for the binding energy W in the lowest state

$$W = -\frac{mg^4}{4\hbar^2} . \tag{6}$$

Adding to this the total rest mass energy $2mc^2$, one obtains for the total ground-state energy

$$E = 2mc^2\left[1 - \frac{1}{8}\left(\frac{g^2}{\hbar c}\right)^2\right]. \tag{7}$$

From this equation it follows that a bound state of two positive-mass particles will have a positive energy and hence positive mass only as long as $g^2/\hbar c < \sqrt{8} \simeq 2.8$. For $g^2/\hbar c > \sqrt{8}$, the resulting bound state would have negative energy and hence negative mass. We now consider the low-lying meson states consisting of a bound quark-antiquark pair with each quark having the mass $m = -|m_q|$. Substituting into eq. (5) and eq. (6) $g^2 \to -g^2$, $m \to -|m_q|$ one obtains

$$\nabla^2\psi + \frac{|m_q|}{\hbar^2}\left(-W + \frac{g^2}{r}\right)\psi = 0 \tag{8}$$

and

$$W = \frac{|m_q|g^4}{4\hbar^2} . \tag{9}$$

Since the total rest mass energy for two negative-mass quarks would be given by $-2|m_q|c^2$, the total energy of the resulting ground state is

$$E = 2|m_q|c^2\left[\frac{1}{8}\left(\frac{g^2}{\hbar c}\right)^2 - 1\right]. \tag{10}$$

In analogy to the binding of two positive-mass particles, eq. (10) is valid for two negative-mass particles and shows that the binding of two negative-mass particles will lead to a negative-energy state and negative mass only as long as $g^2/\hbar c < \sqrt{8}$. For $g^2/\hbar c > \sqrt{8}$, the total energy will become positive and hence the mass of the bound state although the constituent particles have a negative mass. In case of positive-mass particles interacting via an attractive potential $-g^2/r$, the energy cannot become smaller than $-4mc^2$ since otherwise the particles would dive into the negative-energy continuum of the Dirac equation resulting in pair production (Klein paradox), requiring that $g^2/\hbar c < \sqrt{24} \simeq 4.9$. If we assume that the same inequality also holds for negative-mass particles, which similarily would otherwise rise into the positive-energy continuum of negative-mass particles obeying the Dirac equation, it follows that

$$4.9 > g^2/\hbar c > 2.8 . \tag{11}$$

To estimate the value of the coupling constant $g^2/\hbar c$ one needs a value of $|m_q|$. The parton model suggests that $|m_q| \simeq 320\,\text{MeV}/c^2$ [12] and the magnetic moments of nucleons and electromagnetic processes likewise suggest a quark mass of $|m_q| \simeq 330\,\text{MeV}/c^2$ [13]. Putting $E = \overline{m}c^2$, where $\overline{m} \simeq 680\,\text{MeV}/c^2$ is the average meson mass, and putting $|m_q| \simeq 330\,\text{MeV}/c^2$, we thus obtain

$$g^2/\hbar c \simeq 4 , \tag{12}$$

satisfying inequality (11). The same estimate can be made for baryons which consist of three quarks. In this case one has three interacting pairs, hence

$$E \simeq 3|m_q|c^2\left[\frac{1}{8}\left(\frac{g^2}{\hbar c}\right)^2 - 1\right] , \tag{13}$$

which for the proton rest mass of $m_p = E/c^2 \simeq 940\,\text{MeV}/c^2$ again leads to $g^2/\hbar c \simeq 4$. Comparing this result with the Schwinger magnetic-monopole coupling constant $g_0^2/\hbar c \simeq 4 \times 137 = 548$ it follows that $g_0/g \simeq 12$, which can serve as a measure for the magnitude of the magnetic charge exchange current and which seems to be consistent with the smallness of the CP violation.

The Regge behavior of hadrons could perhaps be explained by the trapping of the magnetic flux in a curved space created by f-dominated strong gravity [14] of the gluon field energy. According to Gauss's law flux trapping would result in a constant force field for the quark interaction as it has been suggested by several authors [15,16]. Such a metric flux trapping would not be limited to two quarks as the magnetic string model by NAMBU [4] but would rather work for any number of quarks in a bound system. The metric trapping of the magnetic flux by f-dominated gravity may also explain the success of hadron models based on massless strings. The massless-string model has the unphysical feature to be only realizable in 25 dimensions and one may expect that a quantum-mechanical object trapped in its own curved space will require no more space-time dimensions than it intrinsically has like our universe which by inclusion of quantum effects should remain four dimensional. The negative-mass hypothesis also seems to explain Zweig's rule, forbidding the annihilation of quark-antiquark pairs inside hadrons which would lead to negative-mass bosons and which are excluded as stated above.

The negative-mass hypothesis seems to make it plausible why it is so difficult to produce free quarks. By inelastic collisions of hadrons one simply pumps in more energy going into the binding field of the gluons increasing their energy. The production of free quarks would then rather require to lower the total energy of the bound quark

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(13) J. J. J. KOKKEDE: *The Quark Model* (New York, N. Y., 1969).
(14) C. J. ISHAM, A. SALAM and J. STRATHDEE: *Phys. Rev. D*, **3**, 867 (1971).
(15) J. KOGUT and L. SUSSKIND: *Phys. Rev. Lett.*, **34**, 767 (1975).
(16) B. J. HARRINGTON, S. Y. PARK and A. YILDIZ: *Phys. Rev. Lett.*, **34**, 168 (1975).

system. The absence of certain quark states like the two- and four-quark systems could be explained by the fact that such systems would have a positive mass but a nonvanishing magnetic charge and thus be forbidden. This means only systems having $3n$ ($n = 1, 2, 3 \ldots$) quarks would be permitted and which are the states represented by nuclear matter. For mesons composed of a quark with its antiquark only the states composed of $2n$ ($n = 1, 2, 3 \ldots$) quarks would be permitted and which would cover the known mesons and meson resonances. Any reaction leading to objects of positive mass which would have a magnetic monopole would thus be forbidden by nonlinear gravitational effects. For example, the pick-up reaction in a meson-nucleon collision, whereby the nucleon would acquire an additional quark, is forbidden if, as it is to be expected, the resulting nucleon-quark configuration would be a bound-state system of positive mass. It seems more likely that a meson-meson collision would be more inclined to produce free quarks since here a two-body exchange reaction could lead to a bound meson and two free quarks. The collision of a negative-mass with a positive-mass particle will increase the velocity of the negative-mass particle and which would explain why cosmic-ray quarks would have little tendency to accumulate in solid matter.

It is however possible that quarks could be set free in very strong magnetic fields. For $g^2/\hbar c = 4$, which is the value of the coupling constant corrected for the magnetic charge exchange current, one computes a quark magnetic charge of $g \simeq 1.1 \cdot 10^{-8}$ e.s.u. The interquark magnetic field is then given by $H = g/r^2$, which for $r = 3 \cdot 10^{-13}$ cm yields $H \simeq 10^{17}$ G. Such a field may not be attainable even in neutron stars, but the possibility that it could be reached in the cores of quasars cannot be excluded.

Very large magnetic fields, in principle, could be produced in the focus of a laser beam. The average magnetic field in a laser beam is given by the Poynting vector $S = c\bar{H}^2/4\pi$. The maximum concentration of the light flux increases in inverse proportion with the square of the wavelength and which determines the smallest possible size of the focal spot. Let us assume a short-wavelength X-ray laser beam of $\sim 10^{13}$ erg with a pulse length of 10^{-9} s and a wavelength of $\lambda = 10^{-10}$ cm concentrated onto the area of $\lambda^2 \sim 10^{-20}$ cm^2. It follows that $S = 10^{42}$ erg/cm^2 s and hence $H \simeq 2 \cdot 10^{16}$ G thus approaching the critical value of 10^{17} G. Furthermore, hadron collisions taking place in a strong magnetic field may enhance quark production by the tunnel effect. The required X-ray laser radiation could possibly be produced by atomic excitation using novel methods for the generation of ultrastrong ion beams ([17]).

The energy set free by nucleon fission into the three constituent quarks of a nucleon with mass m_p would be given by

$$E = (m_p - 3m_q)c^2 = (m_p + 3|m_q|)c^2 \,, \tag{14}$$

where one must take into account the negative value of m_q. Since $m_p \simeq 3|m_q|$ one can write for eq. (14)

$$E \simeq 2m_p c^2 \,. \tag{15}$$

In gravitational collapse only a fraction of the rest mass energy can be converted into energy of the escaping radiation and which seems to be insufficient to explain the large energy release presumably taking place in quasars. However, nucleon fission into quarks according to eq. (15) could easily account for the unexplained energy source of quasars.

([17]) F. WINTERBERG: *Plasma Phys.*, **17**, 69 (1975).

Although the quark production would be accompanied by setting free a very large amount of energy there would be an even more exciting prospect in regard to the « ash » of that reaction, that is the negative-mass quarks. For this remember that the tensile strength of solid matter is given by

$$\sigma \simeq Ne^2/r\,, \tag{16}$$

where r is the atomic radius being approximately equal to the lattice distance and N the atomic number density. Since $N \simeq r^{-3}$ we have

$$\sigma \simeq e^2/r^4\,. \tag{17}$$

By order of magnitude, r is given by the Bohr radius $r = \hbar^2/me^2$ (m electron mass). Therefore if a crystal lattice of solid matter is doped with quarks, by gradually replacing electrons with quarks, the average distance in between the atoms of a crystal lattice will decrease due to the fact that $|m_q|/m \sim 10^3$ and that the localization of a mass in a force field is determined by Heisenberg's uncertainty principle which is unchanged in going to negative masses. If, for example, a crystal is doped by replacing one out of 300 electrons with three quarks of equal electric charge, the average lattice distance would decrease by a factor 10 and according to eq. (17) the tensile strength increase by a factor 10^4, which for solid matter would give $\sigma \sim 10^{14}$ dyn/cm^2. Since also the melting point of solid material is determined by the factor e^2/r^4 this would at the same time increase the melting point from $\sim 10^3$ °K up to $\sim 10^7$ °K.

One may ultimately consider the case where a substantial fraction of the electrons is removed from the crystal lattice and replaced by negative-mass quarks. Since $m_p \simeq 3|m_q|$ and since three quarks can make up for one negative-electron charge, average electric and magnetic charge neutrality combined with the balance of the positive-mass nuclei against the negative-mass quarks could then lead to a state of a macroscopic body approaching zero rest mass but still with a high tensile strength. It is furthermore conceivable that the body could have either positive or negative mass depending on the balance in between positive-mass nuclei, negative-mass quarks and the mutual binding energy.

If it is assumed that by this method a macroscopic body with approaching zero rest mass can be actually built then it is easy to see that it would be ideally suited for the easy attainment of relativistic velocities as they have been contemplated for interstellar space flight by photon rockets.