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Existence of Magnetic Charge

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A status report is presented on the existence of quarks carrying the Dirac unit of magnetic charge $g = (137/2)e$. The Paschen-Back effect in dyonium is discussed. From the dyonium model, Akers predicted the existence of a new η meson at 1814 MeV with $I^G(J^{PC}) = 0^+(0^{-+})$. Experimental evidence now confirms the existence of the meson resonance.

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1. INTRODUCTION

In this paper, I discuss the recent experimental evidence for quarks carrying the Dirac unit of magnetic charge $g = (137/2)e$. There is evidence (Akers, 1985, 1987*a*) that quarks with Dirac charges are involved with the Zeeman splitting of meson states.

Akers (1985) presented an analysis of the Zeeman splitting and suggested it was due to the interaction of a magnetic monopole with the magnetic dipole moment of a *c*-quark. Later, Akers (1987*a*) suggested that the interaction involved a pair of dyons with electric and magnetic charges (Ze, g) and $(-Ze, -g)$, where Z may be integral or fractional (Schwinger, 1969).

From an analysis of the meson spectrum, Akers (1987*a*,*b*) presented a model of the Paschen-Back effect in dyonium. The dyonium model was introduced by Schwinger (1969) and Barut (1971, Barut and Bornzin, 1971). In Section 2, I review the Paschen-Back effect and discuss the prediction of a new η meson at 1814 MeV. In Section 3, I present the recent experimental evidence (Bisello *et al.*, 1989) confirming the existence of the η resonance. Concluding remarks are presented in Section 4.

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2. PASCHEN-BACK EFFECT IN DYONIUM

The discovery of Zeeman splitting in meson spectroscopy was made by Akers (1985), who predicted the existence of a new η meson at 1814 MeV with $I^G(J^{PC}) = 0^+(0^{-+})$ from the spectrum. The existence of this meson would be evidence for the presence of magnetic charge on quarks for isospin $I = 0$ mesons as shown in Figure 1. The masses for $I = 0$ mesons are shown in Figure 1 with corresponding quantum numbers J^{PC} along the horizontal axis. The experimental masses are from the Particle Data Group (1988). However, the $\eta(1814)$ meson needs to be listed as a confirmed resonance (Bisello *et al.*, 1989) in the data base at Lawrence Berkeley Laboratory.

The spectrum of Figure 1 indicates a splitting of the meson states, which is due to the Zeeman effect, about the mass $M_0c^2 = 2397$ MeV of the dyon. The dyon mass is derived from the classical Dirac mass of the magnetic monopole. In addition, the magnetic monopole mass has been derived from a Lagrangian of the Yang-Mills and Higgs field theory of strong interactions (Akers, 1987*c*). The results of magnetostrong theory (Akers, 1987*c*) will be taken up at a latter date.

In studying the energy spectrum of dyonium, Barut and Bornzin (1971) were able to consider the free-particle bound states from the Schrödinger and Dirac equations. Akers (1987*a*) also considered the free-particle bound

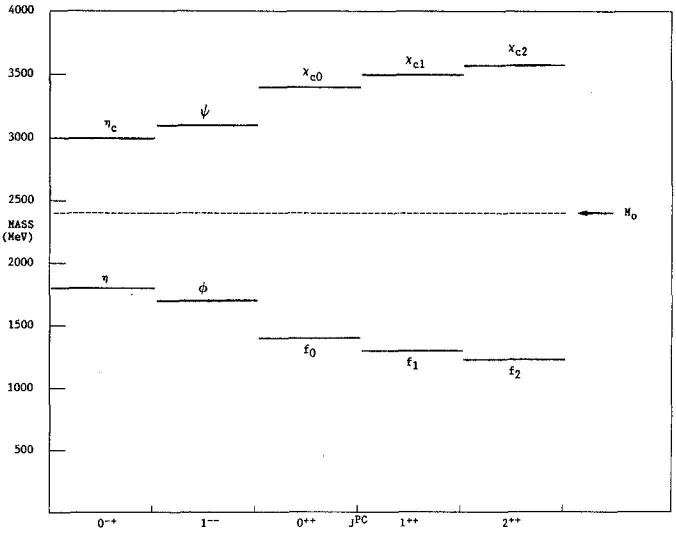

Fig. 1. Zeeman splitting of isospin $I = 0$ mesons. The dashed line represents the mass $M_0c^2 = 2397$ MeV of the magnetic monopole. The experimental masses are indicated by solid lines.

states of isospin $I=0$ mesons of Figure 1. Their energy eigenvalues are

$$\begin{aligned} E_{nm_Lm_I} = {} & M_0c^2 + nm_Ig_ME^{z}_{nm_Lm_I} + nm_Lm_Ig_ME^{\mathrm{so}}_{nm_Lm_I} \\ & + nm_Ig_ME^{\mathrm{hf}}_{nm_Lm_I}\{(8\pi/3)|\Psi_{nL}(0)|^2\langle\mathbf{I}\cdot\mathbf{S}\rangle \\ & + \langle[3(\mathbf{I}\cdot\mathbf{R})(\mathbf{S}\cdot\mathbf{R}) - \mathbf{I}\cdot\mathbf{S}]/R^3\rangle\} \end{aligned} \tag{1}$$

where **I** and **S** are the intrinsic spins of the dyons with angular momentum 1/2 each (Osborn, 1982; Akers, 1987*c*). The intrinsic spin **I** is not to be confused with the isospin I of the mesons. M_0c^2 is the mass of the dyon and is the first term in the Dirac equation. The second term is the Zeeman effect due to the electric and magnetic dipole moments interacting with their respective fields. The third and fourth terms in equation (1) are, respectively, the spin-orbit and hyperfine energy splittings. g_M is the Landé g-factor. Finally, the wave function in equation (1) is the hydrogen-type function with the "Bohr" radius a_0 of the system (Ze, g) and $(-Ze, -g)$.

In a strong magnetic field due to the presence of magnetic charge g, the level splitting of the Zeeman and spin-orbit terms is called the Paschen-Back effect (Baym, 1969). The good quantum numbers of the dyonium system are then m_L and m_I (Anderson, 1971). $m_I = -1/2,\ 1/2$ for $I = 1/2$; $m_L = -L, \ldots, 0, \ldots, L$.

Akers (1987*a*) fitted the coefficients $E^{z}_{nm_Lm_I}$, $E^{\mathrm{so}}_{nm_Lm_I}$, and $E^{\mathrm{hf}}_{nm_Lm_I}$ to the center-of-mass splittings in the spectrum of charmonium. For the $n=1$ shell structure of equation (1), the coefficients are

$$E^{z}_{1m_Lm_I} = 670\ \mathrm{MeV}, \qquad E^{\mathrm{so}}_{11m_I} = 926\ \mathrm{MeV}$$

$$E^{\mathrm{hf}}_{10m_I} = 43.5\ \mathrm{MeV}, \qquad E^{\mathrm{hf}}_{11m_I} = 70\ \mathrm{MeV}$$

For example, to calculate the mass of the $\Psi(3097)$ meson from equation (1), the quantum numbers are $m_L = 0$ and $m_I = 1/2$. One has $g_M = 2$ and $\langle\mathbf{I}\cdot\mathbf{S}\rangle = 1$. Therefore,

$$\begin{aligned} E &= M_0c^2 + m_Ig_ME^{z}_{10m_I} + m_Ig_ME^{\mathrm{hf}}_{10m_I}(8\pi/3)|\Psi_{10}(0)|^2\langle\mathbf{I}\cdot\mathbf{S}\rangle \\ &= 2397 + (1/2)2(670) + (1/2)2(43.5)(8\pi/3)(1/4\pi)1 = 3096\ \mathrm{MeV} \end{aligned}$$

In Table I, the masses for isospin $I=0$ mesons are calculated from equation (1). The experimental masses are shown in parentheses next to the calculated values. The experimental masses are from the Particle Data Group (1988). Mesons with resonances not established are shown in brackets. The theoretical values for these mesons are within experimental uncertainties. To illustrate, in Figure 2, the theoretical mass of $f_0(1379)$ is shown along with the experimental measurements by publication date.

The model can be improved in our present discussion. When the experimental uncertainties are reduced, the energy coefficients for $n=2$

Table I. Energies of Free-Particle Bound States for $I = 0$ Mesons[a]

	Energy, MeV				
Quantum numbers	1^1S_0	1^3S_1	1^3P_0	1^3P_1	1^3P_2
J^{PC}	0^{-+}	1^{--}	0^{++}	1^{++}	2^{++}
$m_L = 1,\ m_I = \frac{1}{2}$			3415 (3415)	3505 (3510)	3551 (3555)
$m_L = 0,\ m_I = \frac{1}{2}$	2980 (2980)	3096 (3097)	2798	2890	2936
$m_L = -1,\ m_I = \frac{1}{2}$			2613	2521	2475
$m_L = -1,\ m_I = -\frac{1}{2}$			2181	2273	2318 (2300)
$m_L = 0,\ m_I = -\frac{1}{2}$	1814 (1800)	1698 (1680)	1996	1904	1858 [1810]
$m_L = 1,\ m_I = -\frac{1}{2}$			1379 (1400)	1287 (1285)	1241 (1270)

[a] The usual spectroscopic notation is shown, along with established experimental masses in parentheses and nonestablished resonances in brackets.

states in equation (1) may be fitted with the 2^1S_0 and 2^3S_1 states of charmonium. Moreover, the Paschen-Back effect of the dyonium model should be extended to include nonisoscalar mesons as well as the baryon spectrum. Earlier theoretical study by Chang (1972) was done on a composite model of baryons based upon quarks carrying magnetic charges. In Section 4, I will return to a short discussion of Chang's work on the electric dipole moments (EDM) of hadrons generated by magnetic charges.

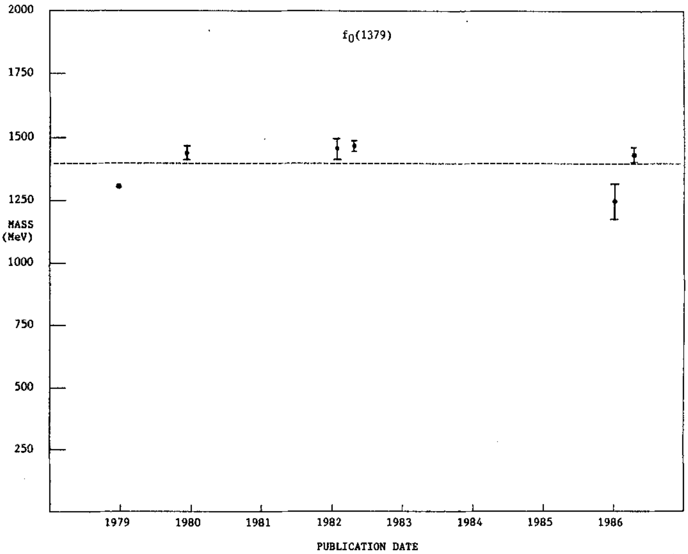

Fig. 2. The mass of the $f_0(1379)$ is represented by the dashed line. The theoretical value is in excellent agreement with the experimental data represented by the dots with error bars.

Table II

Experiment	Meson mass, GeV	$I^G(J^{PC})$	Reference
Zeeman splitting	1.814	$0^+(0^{-+})$	Akers (1985, 1987*a*)
$J/\psi \to \gamma\rho\rho$	1.8	$0^+(0^{-+})$	Bisello *et al.* (1989)
$J/\psi \to \gamma\omega\omega$	1.77	0^-	Bisello *et al.* (1987)
$J/\psi \to \gamma\rho\rho$	1.8	0^-	Baltrusaitis *et al.* (1985)
$J/\psi \to \gamma\omega\omega$	1.8	0^-	Baltrusaitis *et al.* (1986)
$J/\psi \to \phi K^{\pm}K_s\pi^{\pm}$	1.8	?	Köpke (1986)
$e^+e^- \to e^+e^-K_s^0K^{\pm}\pi^{\pm}$	1.8	?	Berger *et al.* (1985)
$J/\psi \to \gamma\rho\rho$	1.8	0^-	Wermes (1984)

3. EXPERIMENTAL EVIDENCE FOR η(1814)

In the 1- to 2-GeV mass region, particle physicists are searching for evidence of a $J^{PC} = 0^{++}$ or 0^{-+} glueball. Recent experiments in J/ψ decays reveal structures in the 1.4- to 1.9-GeV mass region. The Mark-III Collaboration has found peaks at 1.55 and 1.8 GeV in $J/\psi \to \gamma\rho\rho$ (Baltrusaitis *et al.*, 1986). These resonances were seen in earlier experiments (Wermes, 1984), as shown in Table II. Baltrusaitis *et al.* (1986) assigned the spin parity of the 1.8-GeV structure as $J^P = 0^-$, which was consistent with the predicted quantum numbers by Akers (1985, 1986).

Another recent experiment (Bisello *et al.*, 1987) has confirmed the presence of the signal around 1.8 GeV/c^2 and its pseudoscalar character. From the list of experiments in Table II, we have confirmation of a pseudoscalar meson at 1.8 GeV. The most convincing evidence for a new η resonance comes from $J/\psi \to \gamma\rho\rho$ decays in experiments recently done by the DM2 Collaboration (Bisello *et al.*, 1989). Their analysis of branching ratios into $\rho^0\rho^0$ and $\rho^+\rho^-$ supports an $I^G = 0^+$ assignment. In addition to the 1.8-GeV resonant state, they have found other states at 1.5 and 2.1 GeV with $J^{PC} = 0^{-+}$. Bisello *et al.* (1989) have suggested radial excitations of the η(548) and η'(958) in recent models to account for these resonant states.

4. CONCLUSION

I summarize the evidence for the discovery of quarks carrying the Dirac unit of magnetic charge $g = (137/2)$. The presence of Zeeman splitting in meson states is due to magnetic fields generated by magnetic charges on the quarks. From the theoretical model (Akers, 1987*a*), it was suggested that the magnetic dipole moments of the quarks interacted with the magnetic fields. The energy splittings of Figure 1 are calculated from the dyonium model based upon the Zeeman effect and spin-dependent forces. Other models give a description of $q\bar{q}$ systems; however, they do not explain the symmetry of Figure 1. For a review of meson spectroscopy and quark models see the paper by Diekmann (1988).

It has not been the intent of the present theoretical work to account for the entire mesonic "zoo." Spin-dependent potential models (Choi, 1986), QCD models (Godfrey and Isgur, 1985), and bag models all contribute to our understanding of the meson spectrum. The dyonium model has given us a contribution with the idea that quarks carry magnetic charges.

Recently, Barut (1986, 1987) and Anderson (1988) considered the magnetic nature of quarks. They indicated that it is possible for quarks with magnetic sources to account for the hadron mass spectrum. Perhaps the most interesting contributions on the subject have come from the earlier papers by Chang (1972), Kim (1976), and Satikov and Strazhev (1979). The magnetic nature of quarks is investigated with regard to the baryon mass spectrum in the work by Chang (1972). Chang solved the difficulty in explaining the electric dipole moments (EDM) of the baryons with the introduction of magnetic isospin. Akers (1987*c*) also introduced magnetic monopoles associated with an isospin of $I=1$. However, Chang (1972) assigned a physical spin of $J=0$ to the magnetic monopole in his model, whereas Akers suggested a spin of $J=1/2$. A magnetic monopole with $J=0$ would not have an intrinsic electric dipole moment. Therefore, it would be worth investigating the EDM of particles to determine the internal dynamics of the quarks carrying magnetic charges. An experimental investigation is strongly recommended.

In the research of Kim (1976), the magnetic charge is equivalent to the color degree of freedom. Kim follows the conjecture by Schwinger (1969) that dyons are quarks with both electric and magnetic charges of fractional units. Likewise, Satikov and Strazhev (1979) identify the magnetic charge with the color quantum number. A theory of the strong interactions called magnetostrong theory (Akers, 1987*c*) will carry these ideas of color (magnetic) charge further along by incorporating them into a Lagrangian of the Yang-Mills and Higgs fields. These ideas will be presented in a future paper.

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