Electroweak Symmetry Breaking from Monopole Condensation

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We argue that the electroweak symmetry of the standard model (SM) could be broken via condensation of magnetic monopole bilinears. We present an extension of the SM where this could indeed happen, and where the heavy top mass is also a consequence of the magnetic interactions.

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All currently viable models of electroweak symmetry breaking are fine-tuned at some level, while theories of electroweak symmetry breaking that are not fine-tuned, like technicolor, are generically not viable, due to difficulties with electroweak precision observables and flavor changing neutral currents. In this Letter we explore a model of monopole condensation which is not fine-tuned and could potentially avoid some of the difficulties of technicolor models. It is known [1,2] that there are consistent supersymmetric field theories with both magnetic and electric massless charged particles. These supersymmetric theories are expected to reach IR fixed points. However, in more general theories of massless magnetic and electric charges, it may be possible that one type of charge outweighs the other in the running of the coupling and that a fixed point cannot be reached. In this case, either the electric or magnetic coupling is driven into the strongly coupled regime. We then might expect to enter a Higgs or a confining phase. Because of electromagnetic (EM) duality these can be the same thing, since an electrically charged Higgs condensate confines magnetic charges and vice versa [3]. Here we would like to see how a bilinear condensate of magnetically charged fermions could break the electroweak gauge group down to electromagnetism.

Thomson [4] calculated the angular momentum of the EM field in the presence of an electric charge q (in units of e) and a magnetic charge g (in units of $4\pi/e$). He found $|J| = qg$ pointing from the charge to the magnetic monopole. Later Dirac [5] showed that in a quantum mechanical theory a monopole could be thought of as a gauge configuration with an unobservable singular string, with the result that qg is quantized in units of half integers. This result also quantizes the angular momentum found by Thomson as one would expect. Dirac was also able to write down a Lagrangian [6] for the interaction of electric and magnetic charges. A new nonlocal contribution to the field strength tensor was required to account for the EM interactions of the monopole via the Dirac string.

Schwinger extended the idea of monopoles to include dyons [7] which have both electric and magnetic charge. Two dyons must satisfy a generalized charge quantization condition [8]:

$$q_1 g_2 - q_2 g_1 = \frac{n}{2}, \tag{1}$$

where n is an integer. Later, Zwanziger [9] was able to rewrite Dirac's Lagrangian in a local but non-Lorentz invariant form. Zwanziger's Lagrangian contains two gauge fields: one that couples to electric and one to magnetic charges; however, the form of the kinetic terms is such that there are only two propagating degrees of freedom. This description is very useful when considering explicit calculations of quantum effects involving monopoles.

Rubakov and Callan [10] showed that, in addition to EM interactions, monopoles and charges must have other nontrivial interactions in order to maintain the consistency of the theory. Consider low-energy s-wave scattering of a charge off a monopole. In a head-on collision, there are no EM forces on the particles, but simple forward scattering would result in a final state where the angular momentum vector has flipped sign, which would not conserve angular momentum. There must be new unsuppressed contact interactions in order to unitarize low-energy s-wave scattering, which one might not expect from a low-energy effective field theory approach. In the case of an electron and a scalar monopole with minimal charge, new chirality violating operators of the form $e_L \bar{e} M^* M$ must be present, which are not suppressed by a high scale (i.e., the operator is marginal). This interaction allows the helicity flip of the electron to compensate the flip of the EM angular momentum.

The aim of this Letter is to find a matter content of monopoles and/or dyons that could potentially give rise to realistic natural electroweak symmetry breaking. For this the spectrum must satisfy the following properties: to have strong dynamics in the IR the monopoles and dyons should be massless; to avoid the hierarchy problem, the monopoles and dyons should be fermionic; all anomalies (including the mixed electric and magnetic anomalies [11]) should cancel; an $SU(2)_R$ custodial symmetry should protect the T parameter; to avoid confinement of the electric charges, the magnetic charges should be vectorlike with respect to $U(1)_{em}$, so that the condensates can be magnetically neutral; the Dirac-Schwinger quantization condition (1) should be satisfied.

To satisfy these conditions it is sufficient to add to the standard model (SM) one generation of fields which, in addition to the usual quantum numbers, also carry magnetic hypercharge. These fields would be analogous to techniquarks, whose dynamics gives rise to electroweak symmetry breaking, and the role of the technicolor interactions is played by the strong magnetic force. While the condensate will be formed through the strong magnetic interaction, we will require that the condensate itself is *magnetically* neutral (just as the quark condensates of QCD are color neutral). Otherwise the magnetic hypercharge would be broken, implying electric confinement via the dual Meissner effect, which would be obviously unacceptable. This is the reason for requiring a vectorlike set of magnetic charges.

All anomalies cancel if the magnetic charges are proportional to the usual B-L charges. This is because B-L is an independent anomaly-free U(1) in the SM; thus, if we pick magnetic charges proportional to B-L all mixed anomalies will cancel. However, it turns out that the simplest such model would not generate a top quark mass via Rubakov-Callan operators, and so we will study a modified version with non-Abelian magnetic charges [12,13].

We will assume that the global structure of the gauge group is $SU(3)_c \times SU(2)_L \times U(1)_Y/Z_6$ [just like the SU(5) grand unified theory], in which case the monopoles can carry non-Abelian magnetic charges for both the color and electroweak groups. In such theories the generalized Dirac quantization condition is

$$4\pi(T_c^8 g\beta_c + T_L^3 g\beta_L + Yg) = 2\pi n, \qquad (2)$$

where β_L and β_c are parameters that fix the relative strength of magnetic couplings under different gauge groups. Furthermore, the non-Abelian magnetic charges contribute $\beta_c T^8 g + \beta_L T_L^3 g$ to the angular momentum of the gauge fields. We will take $\beta_c \neq 0$ for the quarklike monopoles and $\beta_c = 0$ for the leptonlike monopoles. The choice $\beta_L = 1$ means that only the photon couples to the magnetic charge of the monopoles, while the Z does not. This is a preferred choice, because this way the W and Z do not have large magnetic couplings to new particles; thus it is plausible that the deviations of the W and Z couplings, masses, and widths from the SM predictions are small, as expected from electroweak precision data at LEP. Note that, since the W and Z become massive, the magnetic charges coupled to them would be confined through the Meissner effect. However, the choice $\beta_L = 1$ for all the fields ensures that the magnetic charges point in the QED direction, orthogonal to W and Z, and thus no confinement will occur. From now on we will assume that $\beta_L = 1$ for all fields carrying magnetic charge. In this case the magnitude of the effective magnetic charge is just the same as the magnetic hypercharge $g_{em} = Y^{mag} = g$. Aside from the ordinary quarks, leptons, and gauge bosons, the field content of the model is given by

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q_L	$\mathbf{3}^m$	$\mathbf{2}^m$	$\frac{1}{6}$	$\frac{1}{2}$
L_L	1	$\mathbf{2}^m$	$-\frac{1}{2}$	$-\frac{3}{2}$
U_R	$\mathbf{3}^m$	1^m	$\frac{2}{3}$	$\frac{1}{2}$
D_R	$\mathbf{3}^m$	1^m	$-\frac{1}{3}$	$\frac{1}{2}$
N_R	1	1^m	0	$-\frac{3}{2}$
E_R	1	1^m	-1	$-\frac{3}{2}$

where the superscript m reminds us that there is a corresponding non-Abelian magnetic charge $\beta_a \neq 0$. With $\beta_c = 1$ [with $T^8 = \mathrm{diag}(1/3, 1/3, -2/3)$] the Dirac-Schwinger quantization conditions are satisfied for all the fields in the model. The normalization was chosen to obtain the minimal magnetic charge $\frac{1}{2}$. Finally, all anomalies are still canceled: the $U(1)_{em}$ magnetic charges are still proportional to B-L, and so any combination of anomalies will cancel. Custodial symmetry emerges because the magnetic hypercharges of the right-handed singlets are universal. From the point of view of the strong magnetic hypercharge interactions there is an $SU(2)_L \times SU(2)_R$ symmetry, which is weakly broken by electric hypercharge as in the SM.

There are no tools to directly analyze the IR properties of this theory, except perhaps lattice simulations. There are two plausible low-energy phases of this model. One possibility would be an IR fixed point, similar to those of Argyres and Douglas [2]. In this phase the theory would not break electroweak symmetry. The other plausible option is that the full nonperturbative β function of the theory is very different from the naive one-loop β function, and that the electric hypercharge from 3 + 1 generations actually dominates over the contributions of the magnetic hypercharge from 1 generation. In this case the electric hypercharge would become weaker as one goes towards the IR, while the magnetic hypercharge would keep increasing (and by our hypothesis its contribution to the β function would keep decreasing). In such a scenario the theory is driven to a very strongly interacting magnetic theory, and magnetic charges could condense as quarks do in QCD. Such chiral symmetry breaking is observed in strongly coupled U(1) theories on the lattice [14]. The charges in the inline table above have been chosen such that the plausible condensates (while magnetically neutral) have the right (electric) quantum numbers to play the role of the SM Higgs vacuum expectation value:

$$\langle U_L \bar{U} \rangle \sim \langle D_L \bar{D} \rangle \sim \langle N_L \bar{N} \rangle \sim \langle E_L \bar{E} \rangle \sim \Lambda_{mag}^d, \qquad (3)$$

where Λ_{mag} is the scale dynamically generated by the strong magnetic hypercharge interactions and d is the *a priori* unknown scaling dimension of the bilinear operators. In the rest of this Letter we will assume that the low-energy dynamics of the theory is indeed of this type: magnetic interactions generate a mass gap of order $\Lambda_{\rm mag}$, all particles carrying magnetic hypercharge pick up a dynamical mass of this order, and the condensates in (3) are formed giving rise to electroweak symmetry breaking as in ordinary QCD and technicolor theories.

We should check whether the conjecture above agrees with our experience in QCD-like theories. The Dirac quantization condition determines the strength of the magnetic interaction, $\alpha^{\rm mag} = \alpha^{-1}/4 \sim 32$, while one would naively expect condensation to happen for $\alpha^{\rm mag} \sim 4\pi$. However, we do not have any experience with theories containing massless electric and magnetic charges, and such theories have not been studied in lattice simulations. If lattice simulations were to confirm the naive expectation, one can still use the mechanism outlined above for electroweak symmetry breaking, except that one would need to use a U (1) different from hypercharge, for which the coupling constant can be freely adjusted to be $\alpha^{\rm mag} \sim 4\pi$.

Now, let us consider the scattering of an ordinary SM right-handed up-type quark u_R on N_L. The angular momentum of the EM field is $\frac{2}{3} \times \frac{-3}{2} = -1$, while the spin of the incoming particles is $+1$. After the particles scatter forward, the angular momentum of the field flips, which can be compensated by the simultaneous chirality flip of the up-type quark and the monopole. Thus the interaction

$$\lambda^{(u)}_{ij} u^i_R L_L (q^j_L N_R)^\dagger \tag{4}$$

should be present, which, after monopole condensation, can give rise to the large top mass. In fact, a large mass for at least one of the up-type quarks is required by the consistency of the theory, while most extensions of the standard model would still be self-consistent with a 10 GeV top quark. Why there is only one heavy up-type quark is not explained. Indeed, monopole interactions cannot break anomaly-free flavor symmetries; thus, the appearance of a single heavy quark mass requires the existence of nontrivial flavor physics in the underlying UV theory. This UV physics has to break all nonanomalous flavor symmetries (just as Yukawa couplings do in the SM), and will leave its imprint on the low-energy physics in the form of the coefficients $\lambda^{(u)}_{ij}$. In usual technicolor models the effects of such high-scale flavor violation would be strongly suppressed at low energies. Here, however, we can use the Rubakov-Callan operators to transmit the high-scale flavor violation to low scales without a large suppression, thereby decoupling the scale of flavor physics from the electroweak scale. On the other hand, operators with four ordinary quarks do not involve strong magnetic charges, so they are suppressed by the UV scale of flavor physics; thus, flavor changing neutral currents could potentially be suppressed while keeping a heavy top mass. The detailed discussion of the UV flavor physics is beyond the scope of this Letter; however, a simple way to ensure unitarity in all possible scattering channels is for every element of $\lambda^{(u)}_{ij}$ to have approximately the same value, which (since it is approximately a rank one matrix) would only give one heavy mass, similar to what we observe in the real world.

What about the other quarks and leptons? There are no four-fermion Rubakov-Callan operators that can generate the masses for the down-type quarks or leptons. Instead we find that the following Rubakov-Callan-type scattering process involving six fermions,

$$d_R + E_L + u_L + d^\dagger_L \to u_L + E_R, \tag{5}$$

is allowed. A down-type mass is then generated from the corresponding operator by closing the up-quark loop. While this diagram appears naively to be quadratically divergent, the Rubakov-Callan operator will not be generated for very energetic external legs, which will provide the appropriate cutoff. We obtain a simple estimate for the heaviest down-type quark mass of $m_b \sim m_t/(16\pi^2)$, which is just a one-loop suppression relative to the top mass. There are similar operators for the charged leptons. Neutrinos in this model are necessarily much lighter than other fermions since they are electrically neutral and cannot obtain Dirac masses through Rubakov-Callan operators at any loop order.

We will discuss the phenomenology of this model elsewhere; however, there should be a variety of interesting signatures that can be searched for at the LHC. Monopole annihilation into multiphoton final states with roughly a picobarn cross section [15] would be relatively easy to find at the LHC with 1 $\rm fb^{-1}$ of data since there is no standard model background.

In summary, we have presented a novel approach to electroweak symmetry breaking, where the necessary condensate is generated via strong magnetic interactions, which can also imply the existence of heavy up-type quarks.

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