Monopoles, Anomalies, and Electroweak Symmetry Breaking

John Terning
with Csaba Csaki, Yuri Shirman
in progress
Outline

* Motivation
* A Brief History of Monopoles
* Anomalies
* Models
* LHC
* Conclusions
Hierarchy Problem Now

SUSY

Technicolor
Hierarchy Problem Now

- SUSY
- Extra Dimensions
- Technicolor
Hierarchy Problem Now

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- Extra Dimensions
- Technicolor
  - flat
  - curved
Hierarchy Problem Now

- SUSY
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- small
- large
- discrete
- Little Higgs
- MCH
- RS
- Higgsless
- gaugephobic
The Vision Thing

magnetic hypercharge

electric hypercharge

consistent theory of massless dyons? chiral symmetry breaking -> EWSB?
J.J. Thomson

\[ J = q \ g \]

Figure 1. Static configuration of an electric charge and a magnetic monopole.

The quantization of charge follows by applying semiclassical quantization of angular momentum:

\[ J \cdot \hat{R} = e g c = n \hbar \]
\[ n = 0, \pm 1, \pm 2, \ldots \]

or

\[ e g = m' \hbar c, \quad m' = n^2 \]

(2.4a)

(2.4b)

(Here, and in the following, we use \( m' \) to designate this "magnetic quantum number." The prime will serve to distinguish this quantity from an orbital angular momentum quantum number, or even from a particle mass.)

2.3. Classical scattering

Actually, earlier in 1896, Poincaré [3] investigated the motion of an electron in the presence of a magnetic pole. This was inspired by a slightly earlier report of anomalous motion of cathode rays in the presence of a magnetized needle [32]. Let us generalize the analysis to two dyons (a term coined by Schwinger in 1969 [11]) with charges \( e_1, g_1 \) and \( e_2, g_2 \), respectively. There are two charge combinations

\[ q = e_1 e_2 + g_1 g_2, \quad \kappa = -e_1 g_2 - e_2 g_1 c. \]

(2.5)

Then the classical equation of relative motion is (\( \mu \) is the reduced mass and \( v \) is the relative velocity)

\[ \mu \frac{d^2}{dt^2} r = q r r^{-3} - \kappa v \times r r^{-3}. \]

(2.6)

The constants of the motion are the energy and the angular momentum,

\[ E = \frac{1}{2} \mu v^2 + q r, \quad J = r \times \mu v + \kappa \hat{r}. \]

(2.7)

Note that Thomson’s angular momentum (2.3) is prefigured here. Because

\[ J \cdot \hat{r} = \kappa, \]

the motion is confined to a cone, as shown in figure 2. Here the angle of the cone is given by

\[ \cot \chi = \frac{l}{|\kappa|}, \quad l = \mu v_0 b, \]

(2.8)

where \( v_0 \) is the relative speed at infinity, and \( b \) is the impact parameter. The scattering angle \( \theta \) is given by

\[ \cos \theta = \cos \chi | | \sin \left( \xi/2 \cos \chi/2 \right) | |, \]

(2.9a)
Dirac

charge quantization

Proc. Roy. Soc. Lond. A133 (1931) 60
non-local action?

\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + *G_{\mu\nu} \]

\[
G_{\mu\nu}(x) = 4\pi (n \cdot \partial)^{-1} \left[ n_\mu *j_\nu(x) - n_\nu *j_\mu(x) \right] \\
= \int (dy) \left[ f_\mu(x - y) *j_\nu(y) - f_\nu(x - y) *j_\mu(y) \right] \\
= \partial_\mu f^\mu(x) = 4\pi \delta(x) \\
f^\mu(x) = 4\pi n^\mu (n \cdot \partial)^{-1} \delta(x)
\]

Phys. Rev. 74 (1948) 817
dyons

\[ q_1 g_2 - q_2 g_1 = \frac{n}{2} \]

Science 165 (1969) 757
while if the fermions are massless then the coupling terms to write a low-energy Lagrangian below the mass scale of the fermions that will correct the after the Witten effect.

One can check that this Lagrangian indeed correctly reproduces the Maxwell equations from the proper generalization of this Lagrangian incorporating the non-Lorentz invariant kinetic mixing ensures that the term can always be rotated away.

For our work we will need to generalize the Zwanziger action to include the CP violating parameter which makes calculations very difficult.

\begin{align*}
\mathcal{L} &= -\frac{1}{2n^2e^2} \{[n \cdot (\partial \wedge A)] \cdot [n \cdot (\partial \wedge B)] - [n \cdot (\partial \wedge B)] \cdot [n \cdot (\partial \wedge A)]
+ [n \cdot (\partial \wedge A)]^2 + [n \cdot (\partial \wedge B)]^2 \} - J \cdot A - \frac{4\pi}{e^2} K \cdot B.

F &= \frac{1}{n^2} (\{n \wedge [n \cdot (\partial \wedge A)]\} - \ast \{n \wedge [n \cdot (\partial \wedge B)]\})
\end{align*}

Phys. Rev. D3 (1971) 880
shown by Witten to be violating physical parameter at zero mass. In what follows we will find both the electric and magnetic terms. Disregarding cancellations that occur for particular values of the magnetic charge even with zero mass. The gauge anomaly in units of a fundamental charge. There are also five well-known conditions on electric and magnetic charges if we label the electric and magnetic charges of particle $p$. It is well known that there is a charge consistency constraint in a theory with both electric and magnetic charges. In a CP-invariant theory this requires that both types of charges can be expressed as integers. Finally we apply this analysis to the various types of gauge anomalies how the axial anomaly can be calculated for a dyon making use of contributions and find new conditions that must be satisfied even in a CP-conserving theory.

2 Review of tools we will be using here to circumvent this problem are direct loop calculations. Since it is impossible to write a local and Lorentz invariant Lagrangian for coexisting monopoles and dyons, direct loop calculations are quite difficult. This argument is too naive for two reasons. First, since the magnetic charge also couples to zero momentum fields, we will be using a noncanonical holomorphic normalization of the gauge fields:

\[ \mathcal{L}_{\text{free}} = -\frac{1}{4e^2} F_{\mu\nu} F_{\mu\nu} - \frac{\theta}{32\pi^2} F_{\mu\nu}^* F_{\mu\nu} \]

Thus it is important to be very clear what the exact meaning of these transformations are. One can see that a shift in the angle becomes delocalized and other possible force carriers. In general, there are the conditions come from the charges of fermions that arise from requiring anomaly cancellations. The gauge anomaly depends on variables in the path integral for example nicely described in Witten's work.

There exist some very special theories usually different powers of \( \tau \) functions. Even though this does not leave the phase \( \theta \) transformation group one, this is often referred to as a Toduality. Even though this does not leave the phase \( \theta \) corresponds to shifts in the angle one might naively expect that different powers of \( \tau \) functions, different powers of \( \tau \) correspond to changes of variable. Let us review in detail how this comes.

\[ q_{\text{eff},j} = q_j + g_j \frac{\theta}{2\pi} \]

't Hooft-Polyakov

topological monopoles

Nucl. Phys., B79 1974, 276
JETP Lett., 20 1974, 194
`t Hooft-Mandelstam

magnetic condensate confines electric charge

Phys. Rept. 23 (1976) 245
new unsuppressed contact interactions!

JETP Lett. 33 (1981) 644
Seiberg-Witten

massless fermionic monopoles

$\mathcal{N} = 2$

hep-th/9407087
Argyres-Douglas

CFT with massless electric and magnetic charges

hep-th/9505062
### Toy Model

Is this anomaly free?

<table>
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\[ q_i g_j - q_j g_i = \frac{n}{2} \]

Is this anomaly free?
\[ \mathcal{L} = -\frac{1}{2n^2e^2} \{ [n \cdot (\partial \wedge A)] \cdot [n^* (\partial \wedge B)] - [n \cdot (\partial \wedge B)] \cdot [n^* (\partial \wedge A)] + [n \cdot (\partial \wedge A)]^2 + [n \cdot (\partial \wedge B)]^2 \} - J \cdot A - \frac{4\pi}{e^2} K \cdot B. \]
E-M Duality

\[ \vec{E} \rightarrow \vec{B} \]

\[ \vec{B} \rightarrow -\vec{E} \]

\[ *F^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \]

\[ F^{\mu\nu} \rightarrow *F^{\mu\nu} \]
Shift Symmetry

\[ \mathcal{L}_{\text{free}} = -\frac{1}{4e^2} F^{\mu\nu} F_{\mu\nu} - \frac{\theta}{32\pi^2} F^{\mu\nu} * F_{\mu\nu} \]

\[ \theta \rightarrow \theta + 2\pi \]

\[ \tau \equiv \frac{\theta}{2\pi} + \frac{4\pi i}{e^2} \]
$L_{\text{free}} = -\text{Im} \frac{\tau}{32\pi} (F^{\mu\nu} + i * F^{\mu\nu})^2$

$L_c = \frac{1}{4\pi} \int d^4B_\mu \partial_\nu * F^{\mu\nu}$

$\tilde{L} = \text{Im} \frac{1}{32\pi\tau} \left( \tilde{F}^{\mu\nu} + i * \tilde{F}^{\mu\nu} \right)^2$

$\tilde{F}_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$
\( \tau \equiv \frac{\theta}{2\pi} + \frac{4\pi i}{e^2} \)

\[ S : \tau \rightarrow -\frac{1}{\tau} \quad T : \tau \rightarrow \tau + 1 \]

\[ \tau' = \frac{a\tau + b}{c\tau + d} \]

\[ K^\mu \rightarrow aK'^\mu + cJ'^\mu, \quad J^\mu \rightarrow bK'^\mu + dJ'^\mu \]

\[ ad - bc = 1 \]

not a symmetry
\[ \frac{d\tau}{d \log \mu} = \beta \]

\[ \left( \begin{array}{cc} a & -b \\ -c & d \end{array} \right) \left( \begin{array}{c} q \\ g \end{array} \right) = \left( \begin{array}{c} n \\ 0 \end{array} \right) \]

\[ n = \gcd(q, g) \]

\[ c = g/n, \quad d = q/n \quad \text{and} \quad aq - bg = n \]

\[ \frac{d\tau'}{d \log \mu} = i \frac{n^2}{16\pi^2} \]

\[ \frac{d\tau}{d \log \mu} = \frac{i}{16\pi^2} (q + g\tau)^2 \]
\[ \frac{d\tau}{d \log \mu} = \frac{i}{16\pi^2} (q + g\tau)^2 \]

\[ \beta_e = \mu \frac{de}{d\mu} = \frac{e^3}{12\pi^2} \sum_j \left[ \left( q_j + \frac{\theta}{2\pi} g_j \right)^2 - g_j^2 \frac{16\pi^2}{e^4} \right] \]

\[ \beta_\theta = \mu \frac{d\theta}{d\mu} = -\frac{16\pi}{3} \sum_j \left[ q_j g_j + \frac{\theta}{2\pi} g_j^2 \right] \]

Argyres, Douglas  hep-th/9505062
\[
\frac{\text{Im} (\tau)}{4\pi} \partial_\mu (F^{\mu\nu} + i * F^{\mu\nu}) = J^\nu + \tau K^\nu
\]

\[
K^\mu \rightarrow aK'^\mu + cJ'^\mu , \quad J^\mu \rightarrow bK'^\mu + dJ'^\mu
\]

\[
(F^{\mu\nu} + i * F^{\mu\nu}) \rightarrow \frac{1}{c\tau^* + d} (F'^{\mu\nu} + i * F'^{\mu\nu})
\]

\[
\frac{\text{Im} (\tau')}{4\pi} \partial_\nu (F'^{\mu\nu} + i * F'^{\mu\nu}) = J'^\mu + \tau' K'^\mu
\]
\[ L = \frac{-\text{Im} \frac{\tau}{8\pi n^2}}{\{ [n \cdot \partial \wedge (A + iB)] \cdot [n \cdot \partial \wedge (A - iB)] \}} \]

\[ -\text{Re} \frac{\tau}{8\pi n^2} \{ [n \cdot \partial \wedge (A + iB)] \cdot [n \cdot * \partial \wedge (A - iB)] \} \]

\[ + \text{Re} [(A - iB) \cdot (J + \tau K)] \]

\[ F = \frac{1}{n^2} (\{ n \wedge [n \cdot (\partial \wedge A)] \} - * \{ n \wedge [n \cdot (\partial \wedge B)] \}) \]

\[ (A + iB) \rightarrow \frac{1}{c\tau^* + d} (A' + iB') \]
Axial Anomaly from SL(2,Z)

\[(q, g) \rightarrow (n, 0)\]

\[
\partial_\mu j^\mu_A(x) = \frac{n^2}{16\pi^2} F'_\mu\nu * F'_\mu\nu
\]

\[
= \frac{n^2}{32\pi^2} \text{Im} \left( F'_\mu\nu + i * F'_\mu\nu \right)^2
\]
\[ \partial_{\mu} j_A^\mu(x) = \frac{n^2}{32\pi^2} \text{Im} \left( c\tau^* + d \right)^2 \left( F^{\mu\nu} + i F_{\mu\nu} \right)^2 \]

\[ = \frac{1}{16\pi^2} \text{Re} \left( q + \tau^* g \right)^2 F^{\mu\nu} \ast F_{\mu\nu} + \frac{1}{16\pi^2} \text{Im} \left( q + \tau^* g \right)^2 F^{\mu\nu} F_{\mu\nu} \]

\[ = \frac{1}{16\pi^2} \left\{ \left[ \left( q + \frac{\theta}{2\pi} g \right)^2 - g^2 \frac{16\pi^2}{e^4} \right] F^{\mu\nu} \ast F_{\mu\nu} \right\} \]

\[ + \left[ qg + \frac{\theta}{2\pi} g^2 \right] F^{\mu\nu} F_{\mu\nu} \]
Axial Anomaly

\[ \partial_\mu j_A^\mu (x) = \frac{1}{16\pi^2} \left\{ \left[ q^2 - g^2 \frac{16\pi^2}{e^4} \right] F^{\mu\nu} * F_{\mu\nu} + qg F^{\mu\nu} F_{\mu\nu} \right\} \]
\[ \mathcal{L}_{\text{anom}} = c \Omega G^{\alpha \mu \nu} * G^\alpha_{\mu \nu} \]

\[ \Omega = \Omega_A + i \Omega_B \]

\[ \Omega \rightarrow \frac{1}{c \tau^* + d} \Omega' \]
$L_{\text{anom}} = \frac{n \cdot \text{Tr} \, T^a(r) \cdot T^a(r)}{16\pi^2} \Omega'_A \, G^{a\mu\nu} \cdot G^a_{\mu\nu}$

$= \frac{n \cdot \text{Tr} \, T^a(r) \cdot T^a(r)}{16\pi^2} \text{Re} \, \Omega' \, G^{a\mu\nu} \cdot G^a_{\mu\nu}$

$= \frac{n \cdot T(r)}{16\pi^2} \text{Re} \, (c\tau^* + d) \, \Omega \, G^{a\mu\nu} \cdot G^a_{\mu\nu}$

$= \frac{T(r)}{16\pi^2} \left[ \left( q + \frac{\theta}{2\pi} \right) \Omega_A + g \frac{4\pi}{e^2} \Omega_B \right] \, G^{a\mu\nu} \cdot G^a_{\mu\nu}$
\[
L_{\text{anom}} = \frac{n^3}{16\pi^2} \Omega' A \ F'_{\mu\nu} \ast F'_{\mu\nu} = \frac{n^3}{32\pi^2} \text{Re}[\Omega'] \text{Im}\left[(F'_{\mu\nu} + i * F'_{\mu\nu})^2\right] \\
= \frac{n^3}{32\pi^2} \text{Re}[(c\tau^* + d) \Omega] \text{Im}\left[(c\tau^* + d)^2 (F_{\mu\nu} + i * F_{\mu\nu})^2\right] \\
= \frac{1}{16\pi^2} \left[\left(q + \frac{\theta}{2\pi} g\right)^3 - \left(q + \frac{\theta}{2\pi} g\right) \frac{16\pi^2}{e^4} g^2\right] \Omega_A F_{\mu\nu} \ast F_{\mu\nu} \\
- \frac{1}{16\pi^2} \left[-\left(q + \frac{\theta}{2\pi} g\right)^2 \frac{4\pi}{e^2} g + \frac{64\pi^3}{e^6} g^3\right] \Omega_B F_{\mu\nu} \ast F_{\mu\nu} \\
- \frac{1}{8\pi^2} \left[\left(q + \frac{\theta}{2\pi} g\right)^2 \frac{4\pi}{e^2} g \Omega_A + \left(q + \frac{\theta}{2\pi} g\right) \frac{16\pi^2}{e^4} g^2 \Omega_B\right] F_{\mu\nu} F_{\mu\nu}
\]
$U(1)^3$ Anomaly

\[ \sum_j q_j^3 = 0 \]

\[ \sum_j q_j g_j^2 = 0 \]

\[ \sum_j q_j^2 g_j = 0 \]

\[ \sum_j g_j^3 = 0 \]
### Toy Model

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\[
\sum_j q_j^3 = 0, \quad \sum_j g_j^3 = 0, \quad \sum_j g_j^2 q_j = 0, \quad \sum_j q_j g_j = 0, \quad \sum_j q_j = 0, \quad \sum_j g_j = 0, \\
\sum_j \text{Tr} T^a_{r_j} T^b_{r_j} q_j = 0, \quad \sum_j \text{Tr} \tau^a_{r_j} \tau^b_{r_j} q_j = 0, \quad \sum_j \text{Tr} T^a_{r_j} T^b_{r_j} g_j = 0, \quad \sum_j \text{Tr} \tau^a_{r_j} \tau^b_{r_j} g_j = 0
\]
### Dynamics

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$$
\left(\frac{1}{6}\right)^2 \alpha_Y 3^2 \alpha_m = \frac{1}{4}
$$

$$
\alpha_m \sim 98
$$
Quark Masses

technicolor: fail

\[
\begin{align*}
T_L & \quad 1 \quad M^2 \\
S_L & \quad \frac{1}{M^2} \\
T_R & \quad S_R
\end{align*}
\]
Quark Masses

Standard Model

$\log(M)$

$\frac{1}{M^2}$
Callan–Rubakov

$J_f = q g = -1/2$
$S_f = -1/2$

$J_i = q g = -1/2$
$S_i = -1/2$

New dimension 4, four particle operator
Four Fermion Ops

\[ J_f = q \ g = 1/2 \]
\[ S_f = -1 \]

\[ U_R \quad \quad \quad t_L \]

\[ J_i = q \ g = 2 \]
\[ S_i = 1 \]

\[ t_R \quad \quad \quad U_L \]

\[ \text{time} \]
Four Fermion Ops

\[
J_f = q g = 1/2
\]
\[
S_f = -1
\]
\[
U_R \quad t_L
\]
\[
J_i = q g = 2
\]
\[
S_i = 1
\]
fail!

\[
t_R \quad U_L
\]

\[\text{time}\]
Four Fermion Ops

\[ J_f = q \ g = 2 \]
\[ S_f = 0 \]

\[ U_R \quad t_R \quad \rightarrow \]

\[ t_L \quad U_L \quad \rightarrow \]

\[ J_i = q \ g = 1/2 \]
\[ S_i = 0 \]

\[ \uparrow \text{time} \]
Four Fermion Ops

\[ J_f = q \ g = 2 \]
\[ S_f = 0 \]
\[ U_R \leftrightarrow t_R \]
\[ J_i = q \ g = 1/2 \]
\[ S_i = 0 \]
\[ \text{fail!} \]
non-Abelian magnetic charge

\[ Q = T^3 + Y \]

\[ Q_m = T^3_m + Y_m \]

explicit examples known in GUT models

EWSB is forced to align with the monopole charge
non-Abelian magnetic charge

\[ Q = T^3 + Y \]

\[ e^{2\pi i Q} = e^{2\pi i T^3} e^{2\pi i Y} \]
\[ = \text{diag}(e^{i \frac{1}{2} 2\pi}, e^{-i \frac{1}{2} 2\pi}) \]
\[ = Z \]

\[ (SU(2)_L \times U(1)_Y)/Z_2 \]
The Model

\[(SU(3)_c \times SU(2)_L \times U(1)_Y)/Z_6\]

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<td>1</td>
<td>(-\frac{1}{3})</td>
<td>1</td>
</tr>
<tr>
<td>(N_R)</td>
<td>1</td>
<td>0</td>
<td>(-3)</td>
<td>0</td>
<td>(-3)</td>
</tr>
<tr>
<td>(E_R)</td>
<td>1</td>
<td>(-1)</td>
<td>(-3)</td>
<td>(-1)</td>
<td>(-3)</td>
</tr>
</tbody>
</table>

\[\alpha_m = \frac{1}{4\alpha} \approx 32\]
Four Fermion Ops

\[ J_f = \frac{1}{3} + \frac{2}{3} \cdot 1 \]

\[ S_f = +1 \]

\[ U_L \quad \quad \quad t_R \]

\[ t_L \quad \quad \quad U_R \]

\[ J_i = \frac{1}{3} + \left( \frac{1}{2} + \frac{1}{6} \right) \cdot 1 \]

\[ S_i = -1 \]
Four Fermion Ops

\[ J_f = \frac{1}{3} + \frac{2}{3} \cdot 1 \]
\[ S_f = +1 \]

\[ J_i = \frac{1}{3} + \left( \frac{1}{2} + \frac{1}{6} \right) \cdot 1 \]
\[ S_i = -1 \]

hooray!
New U(1): weaker coupling but less elegant

embed in a GUT?
Phenomenology

uncontrolled perturbation theory

Ginzburg, Schiller hep-th/9802310
ATLAS has a trigger for monopoles

CMS does not

pair production, unconfined, highly ionizing
but it won't work

ATLAS has a trigger for monopoles

CMS does not

pair production, unconfined, highly ionizing
Bremstrahlung

Grojean, Weiler, JT
Fireball

Preliminary

Grojean, Weiler, JT
Conclusions

Monopoles are still fascinating after all these years

Anomalies for monopoles can be easily calculated

Monopoles can break EWS and give the top quark a large mass

The LHC could be very exciting