Electroweak symmetry breaking from Monopole Condensation

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Outline

- Introduction
- A toy model
- Rubakov-Callan
- Non-abelian magnetic charges
- A model with a heavy top
- Basic phenomenology

Idea: use strong interactions between monopoles and electric charges to break electroweak symm.

Similar to: Schwinger 1960's theory of strong interactions using interactions of dyons (in the paper where he coined the term "dyon"

Would be like a technicolor-type theory built on U(1) dyons ("monocolor")

Could have some advantages wrt. technicolor

- Rubakov-Callan for top mass
- No new gauge group needed, just SM
- Different phenomenology…

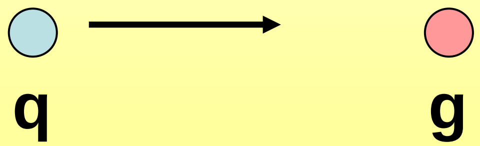
The most important formula for monopoles

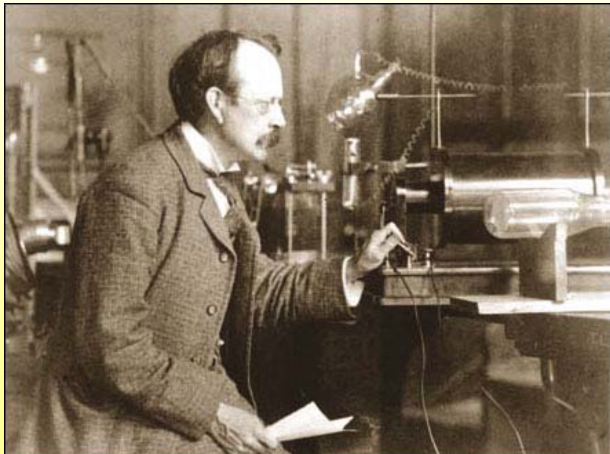
- J.J. Thomson 1904: monopole + charge

$$\vec{J} = qg\vec{n}$$

- Implies Dirac quantization

- Implies the Rubakov-Callan effect





What kind of theory could be interesting?

- If only electric charges: U(1) IR free

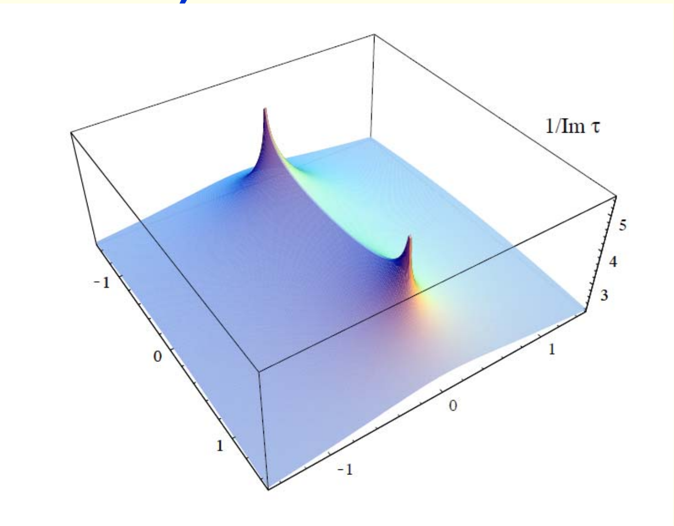
- If only magnetic charges: dual U(1) IR free (free magnetic phase)

- Need electric and magnetic charges at the same time

- Argyres-Douglas: this is possible (in N=2 SUSY at very special points…)

Seiberg-Witten

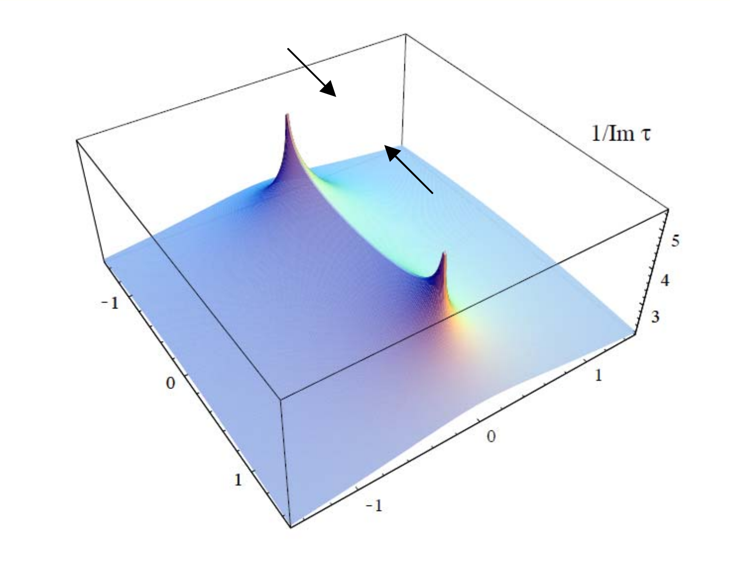
- 1994: Seiberg, Witten: monopoles in N=2 SUSY theories can become massless (and condense if broken to N=1)



Argyres-Douglas

•Argyres Douglas (and also Intriligator and Seiberg):

•The points where monopoles and dyons are massless can coincide. Expect a fixed point (4D CFT)



What we need for an interesting theory

- Want massless monopoles (relevant for IR dynamics)
- Should be fermionic (to avoid hierarchy problem)
- Should be chiral (to have quantum # of Higgs)
- All anomalies should cancel
- All Dirac quantization obeyed
- Magnetic charges should be vectorlike (to avoid confinement of electric charges)

A toy model

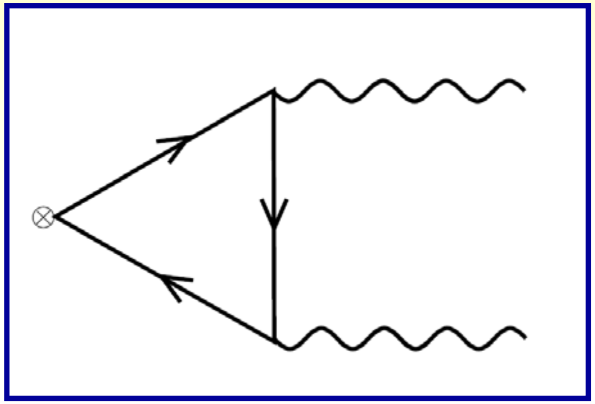
- An extra generation with magnetic hypercharges

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q	$\square$	$\square$	$\frac{1}{6}$	3
L	1	$\square$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\square}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

- All anomalies cancel, Dirac quantization OK

How many anomaly cancellation conditions?

- Global symmetries: what is the chiral anomaly in the presence of dyons?



- Need to cancel electric and magnetic separately!

- Charges (q_i,g_i) and global charge q_{Xi}:

$$\sum q_{Xi} q_i^2 = 0, \quad \sum q_{Xi} q_i g_i = 0, \quad \sum q_{Xi} g_i^2 = 0$$

- Similarly for gauge symmetries: all mixed $U(1)U(1)_{el}U(1)_{mag}$ have to cancel

$$\sum_j q_j^2 g_j = 0$$
$$\sum_j q_j g_j^2 = 0$$
$$\sum_j g_j^3 = 0$$

For a detailed explanation of this see talk by

Yuri Shirman

Thursday afternoon 3:15pm

A toy model

- An extra generation with magnetic hypercharges

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- All anomalies cancel, Dirac quantization OK

What IR phase?

3 possibilities

- **Conformal fixed point** – if β- function like 1-loop: expect fixed point, not interesting for EWSB

- **IR-free** – electric charge outweighs magnetic charge, like in QED. Magnetic coupling becomes very large, forming of condensates and mass gap

- **Free magnetic** Magnetic charge outweighs electric

- **Assume:** not a fixed point. In this case plausible that it is IR free (more electric fields) - condensation

Possible condensates

- Don't carry magnetic charge
- Have quantum number of Higgs

$$Q\bar{D} \sim (1,2,\frac{1}{2}) \sim H, \quad Q\bar{U} \sim (1,2,-\frac{1}{2}) \sim H^*,$$
$$L\bar{E} \sim (1,2,\frac{1}{2}) \sim H, \quad L\bar{N} \sim (1,2,-\frac{1}{2}) \sim H^*.$$

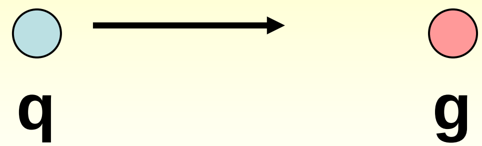
- Assume some of these condensates generated

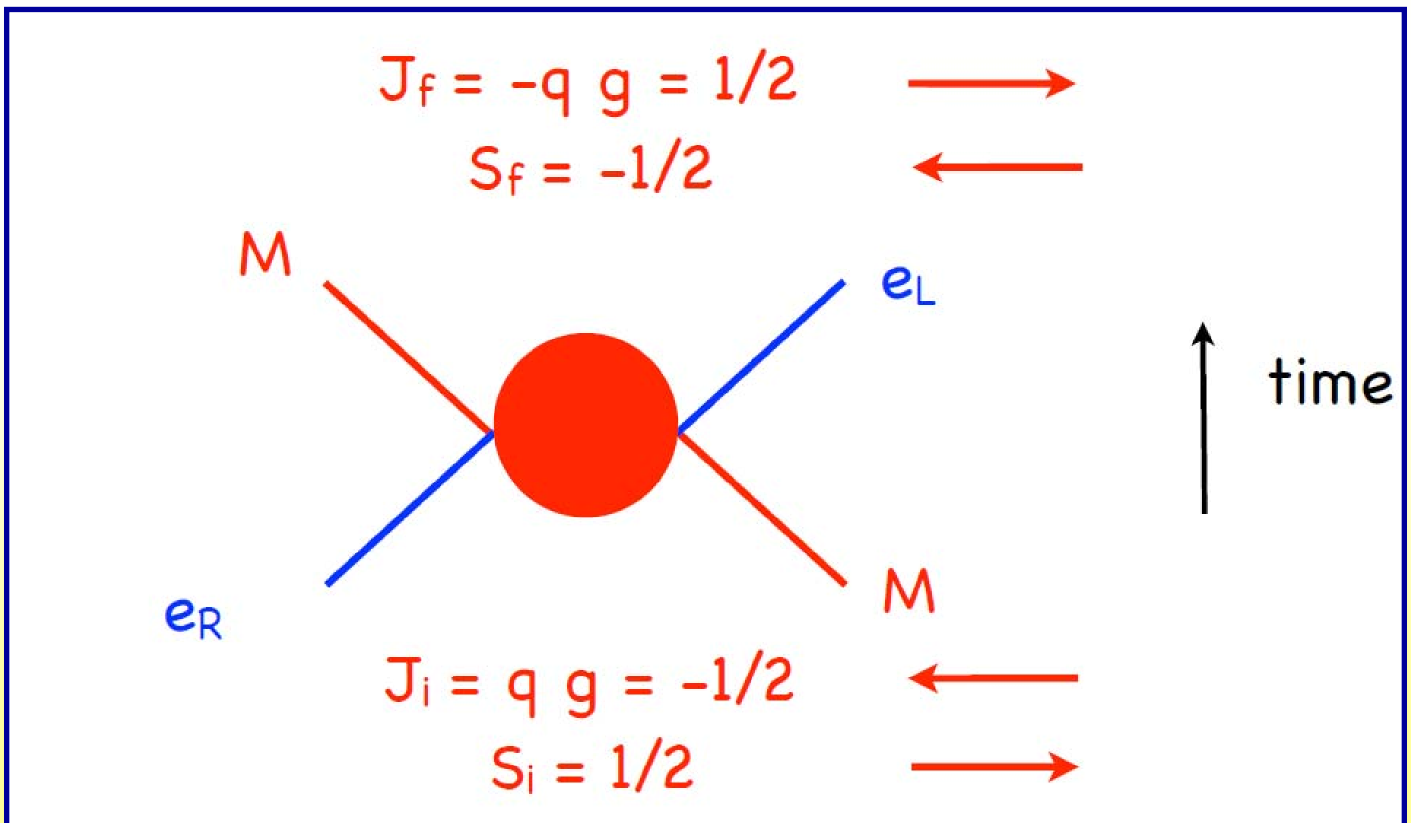
$$\langle U_L\bar{U}\rangle \sim \langle D_L\bar{D}\rangle \sim \langle N_L\bar{N}\rangle \sim \langle E_L\bar{E}\rangle \sim \Lambda^d_{mag}$$

- Λ_{mag} is a dynamical of order few x 100 GeV

The Rubakov-Callan effect

$$\vec{J} = qg\vec{n}$$





The Rubakov-Callan effect

•Even though no interaction between monopole and charge, angular momentum changes

•There has to be a contact interaction between monopoles and charges which is marginal

The quantum picture

- Dirac equation in the presence of monopole peculiar for J=0

- For electron, positive helicity purely outgoing
  negative helicity purely incoming

- For positron just the opposite

- This is because $\vec{J}_{em} = -\frac{1}{2}\vec{n}$ and $\vec{J}_{tot} = \vec{J}_{em} + \vec{\sigma}$

- Need boundary condition at core of monopole – chirality should flip (or electric charge…)

But for toy model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q	$\square$	$\square$	$\frac{1}{6}$	3
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- **No** Rubakov-Callan generated
- Want something like $t_R U_L \rightarrow t_L U_R$
- J_{in}=3 x 2/3=2
- J_{fin}=-3 x 1/6 =-1/2
- Can not compensate with chirality flips…
- Need to modify model such that minimal Dirac charge is allowed

Need for non-abelian magnetic charges

- Question similar to early 80’s: can you have minimal Dirac charge with down quark e=-1/3?

- Naively contradicts Dirac quantization

- If monopole also carries color magnetic charge then possible

- This is what happens for GUT monopole

- Need to embed magnetic field into non-abelian groups as well – “non-abelian monopoles”

GUT monopole:

$$Y = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & -\frac{3}{2} & \\ & & & & -\frac{3}{2} \end{pmatrix}$$

•Specific U(1) transformations:

$$e^{\pm i\frac{2\pi}{3}Y} = \begin{pmatrix} \omega & & & & \\ & \omega & & & \\ & & \omega & & \\ & & & -1 & \\ & & & & -1 \end{pmatrix} \subset SU(3)\times SU(2)$$

•Monopole also carries **discrete** SU(3)xSU(2) magnetic charges

•Group really SU(3)xSU(2)xU(1)/Z_6

Conserved quantity in presence of monopole

$$\begin{array}{l} \text{SU(3)} \\ \\ \text{SU(2)} \end{array} \left(\begin{array}{c|c} 1 & \\ \hline & -1 \end{array}\right) \quad \boxed{\propto \frac{1}{3}T_8 + (Y + T_3)}$$

• The actual conserved quantity

$$\boxed{J_z^{tot} = (\vec{L} + \vec{S})_z + Q + \frac{1}{3}T_8}$$

• Leads to non-trivial Dirac quantization

Non-abelian monopoles

- Magnetic field not aligned with $U(1)_Y$

$$\vec{B}^a_Y = \frac{g}{g_Y}\frac{\hat{r}}{r^2}\,,$$
$$\vec{B}^a_L = \delta^{a3}_L\,\frac{g\,\beta_L}{g_L}\,\frac{\hat{r}}{r^2}$$
$$\vec{B}^a_c = \delta^{a8}_c\,\frac{g\,\beta_c}{g_c}\,\frac{\hat{r}}{r^2}$$

- Dirac quantization loop

$$\int_{loop} e\,q\,A^\mu dx_\mu$$

- Now replaced by

$$\int_{loop}\left(g_c\,T^a_c G^{a\mu} + g_L\,T^a_L\,W^{a\mu} + g_Y Y\,B^\mu\right) dx_\mu$$

- The gauge field for Dirac calculation:

$$\vec{A}_Y = \frac{g}{g_Y} \frac{1-\cos\theta}{r\sin\theta} \hat{e}_\phi \; .$$

$$\vec{A}_L^a = \delta_L^{a3} \frac{g\,\beta_L}{g_L} \frac{1-\cos\theta}{r\sin\theta} \hat{e}_\phi$$

$$\vec{A}_c^a = \delta_c^{a8} \frac{g\,\beta_c}{g_c} \frac{1-\cos\theta}{r\sin\theta} \hat{e}_\phi$$

- Dirac quantization: every component of matrix has to obey

$$4\pi\left(T_c^8\, g\,\beta_c + T_L^3\, g\,\beta_L + Y g\right) = 2\pi n$$

A model with a heavy top

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

- We choose β_L=1 and β_c=1 for colored monopoles
- Dirac quantization now satisfied with minimal (1/2) Dirac charge

- Since β_L=1 magnetic field actually points always in direction of QED photon

- Can instead just look at QED electric and magnetic charges

	$SU(3)_c$	$U(1)_{em}^{el}$	$U(1)_{em}^{mag}$
U_L	$\square^m$	$\frac{2}{3}$	$\frac{1}{2}$
D_L	$\square^m$	$-\frac{1}{3}$	$\frac{1}{2}$
N_L	1	0	$-\frac{3}{2}$
E_L	1	-1	$-\frac{3}{2}$
U_R	$\square^m$	$\frac{2}{3}$	$\frac{1}{2}$
D_R	$\square^m$	$-\frac{1}{3}$	$\frac{1}{2}$
N_R	1	0	$-\frac{3}{2}$
E_R	1	-1	$-\frac{3}{2}$

- Quantization condition now will be: $$T_c^8 g\beta_c + qg = \frac{n}{2}$$

- Dyons: $$(q_1 g_2 - q_2 g_1) + (T_{c1}^8 g_2 \beta_{c2} - T_{c2}^8 g_1 \beta_{c1}) = \frac{n}{2}$$

- With this embedding:

$$\alpha^{mag} = \frac{\alpha^{-1}}{4} \sim 32$$

- Rubakov-Callan now generated:

- $u_R N_L \rightarrow u_L N_R$ satisfies the RC condition

- Initial spin +1, EM field J= 2/3 x (-3/2)=-1

- Final spin -1, EM field J= - 2/3 x (-3/2)=1

- Operator needs to be present: $\lambda_{ij}^{(u)} u_R^i N_L \left(u_L^j N_R\right)^\dagger$

- Gauge invariant version: $\lambda^{(u)}_{ij} u^i_R L_L \left(q^j_L N_R\right)^\dagger$

- Some up-type quarks have to have large masses

- BUT: don't expect RC to break global symmetry

- Need to assume flavor physics at high scales breaks all flavor symmetries

- RC can be used to transmit flavor violation to low scales

- Can decouple flavor and EWSB scales via RC

- Down-type masses: 6-fermion RC operator

$$d_R + E_L + u_L + d_L^\dagger \rightarrow u_L + E_R$$

- After closing up up-quark leg get down mass

- $m_b \sim m_t/(16\pi^2)$

- Similarly for charged leptons. Neutrinos strongly suppressed

- PNGB's: RC can save us again, can transmit symmetry breaking:

$$Q_L E_R (L_L D_R)^\dagger$$
$$Q_L N_R (L_L U_R)^\dagger$$

Basic Phenomenology

- After EWSB theory vectorlike, expect monopoles to pick up mass of order Λ_{mag}~500 GeV – TeV

- Since monopole points in QED direction, not confined, like “ordinary” QED monopole

- No magnetic coupling to Z

- Electric coupling is there, expect EWPO (S,T) like a heavy fourth generation – could be OK?

•**At LHC:** likely pair produced. Due to strong force strong attraction, will always annihilate at LHC. Large radiation, then annihilation. Lots of photons, some of them hard. Cross section ~ pb **(A. Weiler)**

•**Cosmic ray** bounds? SLIM upper bound on monopole flux 1.3 10^{-15} cm^{-2} sr^{-1} s^{-1}. Implies 1 mb bound on cross section, not strong.

•**Dark matter?** Monopole number conserved, baryon type monopole UUDE or UDDN could be stable

Summary

- Use strong interactions from magnetic sector of U(1) to break EWS via condensation

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- **Rubakov-Callan operators can transmit high scale flavor violation, separate flavor scale**

Summary

•Use strong interactions from magnetic sector of U(1) to break EWS via condensation

•Monopoles can be aligned with QED, then no coupling to Z, not confined, minimal Dirac charge.

•Rubakov-Callan operators can transmit high scale flavor violation, separate flavor scale

•Should be visible at the LHC, lots of photons… CMS will trigger on it! First model to be tested?