Electroweak symmetry breaking from Monopole Condensation

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Outline

- Brief intro to monopoles and Rubakov-Callan
- A toy model for EWSB
- Detour on anomalies
- Non-abelian magnetic charges
- A model with a heavy top
- Basic phenomenology

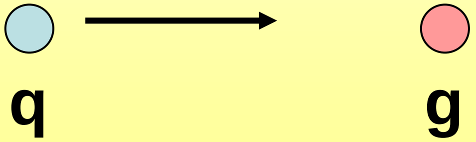
A Brief History of Monopoles

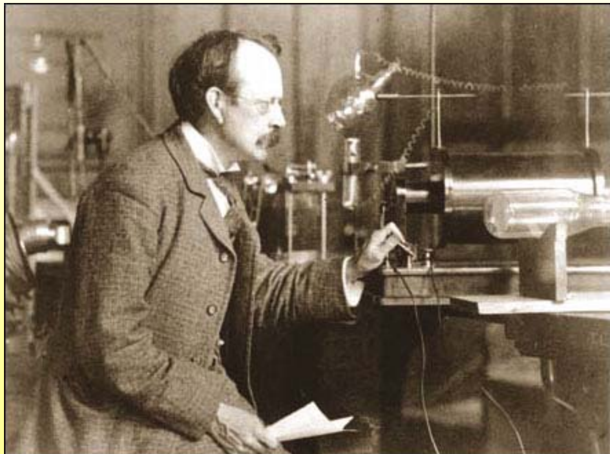
- J.J. Thomson 1904: monopole + charge

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

- Implies Dirac quantization

- Implies the Rubakov-Callan effect





A Brief History of Monopoles

- J.J. Thomson 1904: monopole + charge

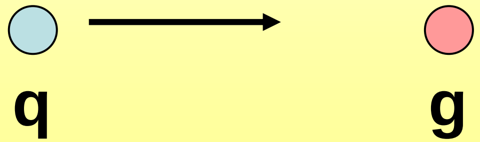
$$\vec{J} = \int d^3r \frac{1}{c} \vec{r} \times (\vec{E} \times \vec{B})$$

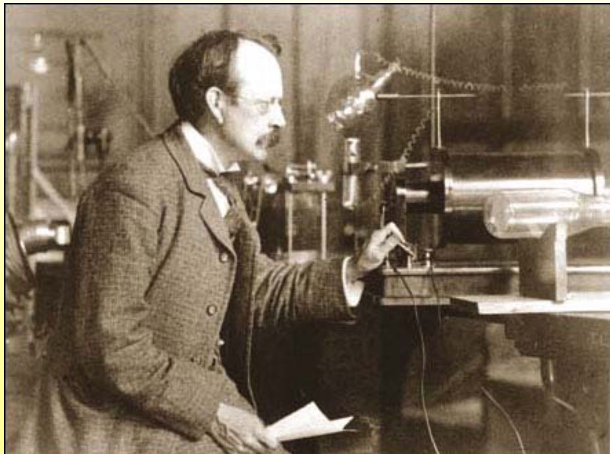
$$\vec{E} = \frac{q\vec{r}}{r^3}$$

$$\vec{B} = \frac{g(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^3}$$

- Implies Dirac quantization

- Implies the Rubakov-Callan effect





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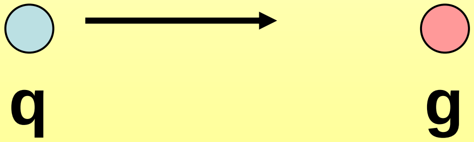
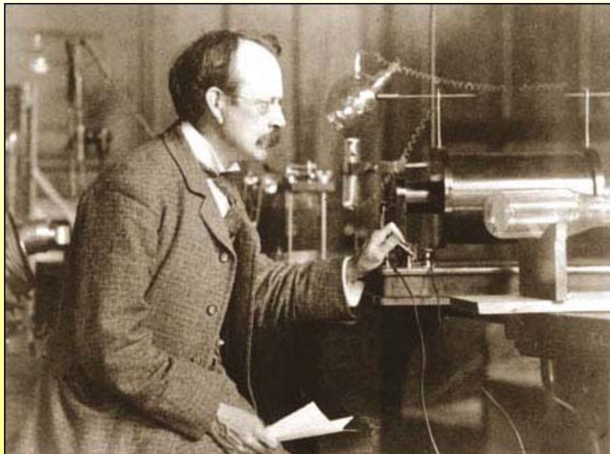




•Dirac 1930: Dirac string/monopole

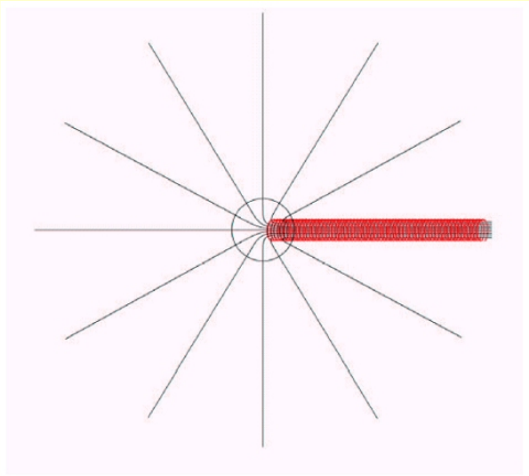


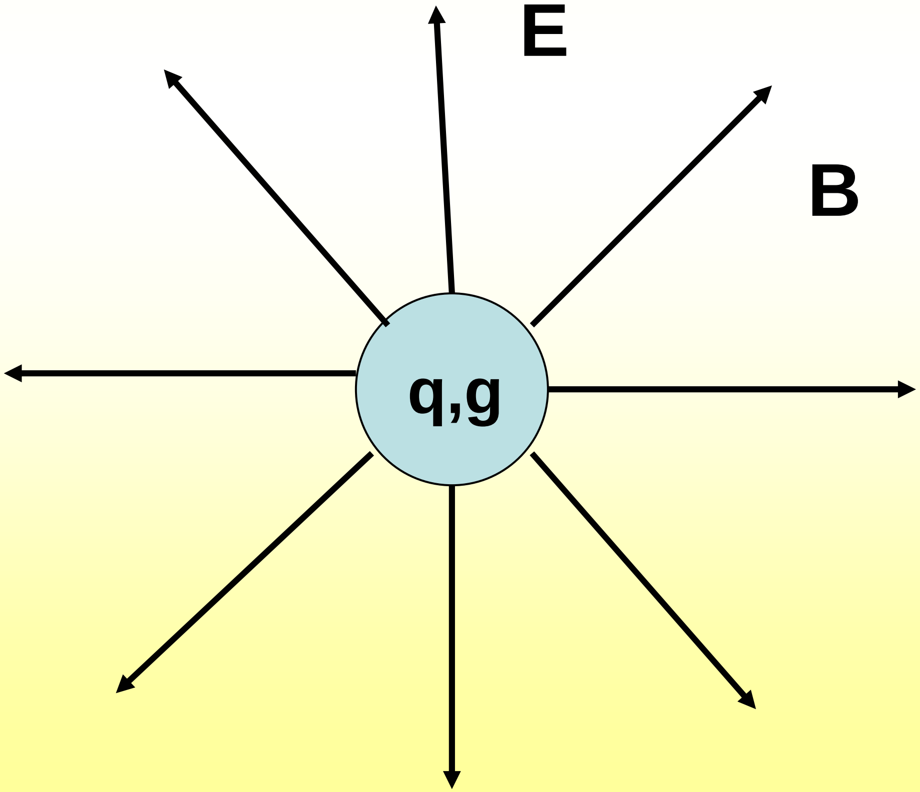
Figure 2: The vector potential of a monopole is singular on a string. When the string carries an integer number of flux quanta it can be gauged away.

•Dirac quantization:

$$qg = \frac{n}{2}$$

•Schwinger generalized quantization condition to dyons

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



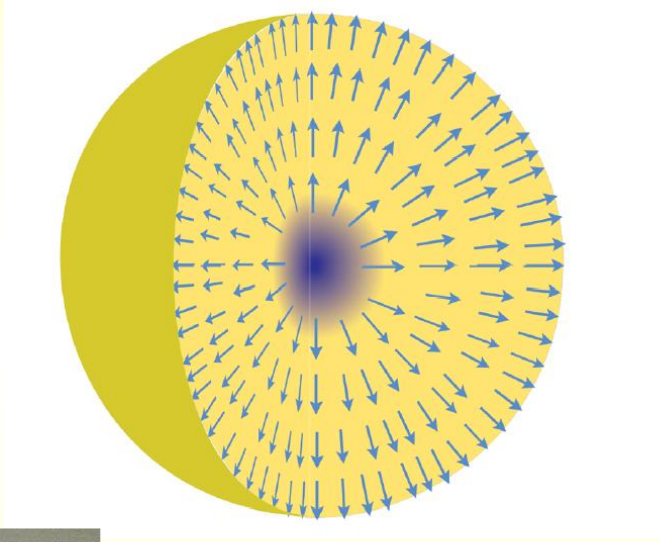
- Schwinger also tries to write theory of strong inter’s using a model of hadrons with monopoles and dyons

- Our proposal in similar spirit, try to replace “technicolor-type” interactions with strong U(1) effects from dyons

- To our knowledge only known attempt to connect monopoles with “low-scale” particle pheno

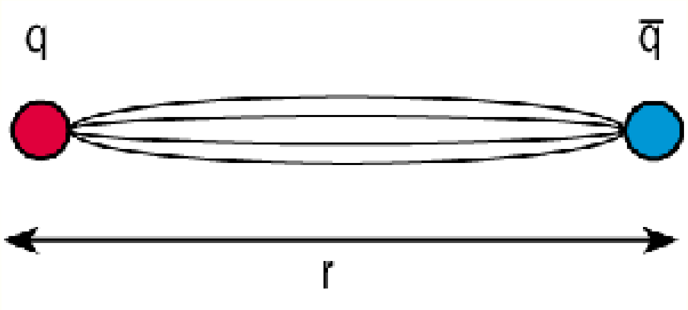
•1974: ‘t Hooft Polyakov monopole

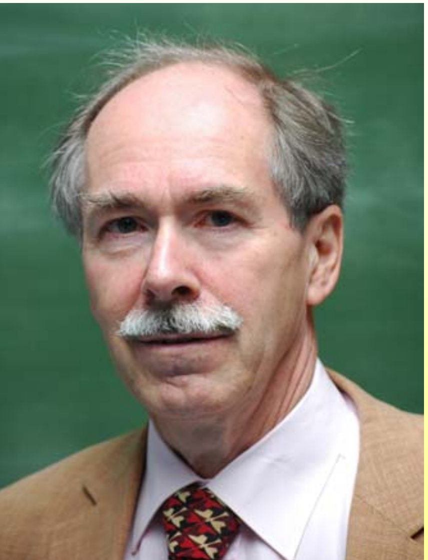
•Topological monopoles without singularity

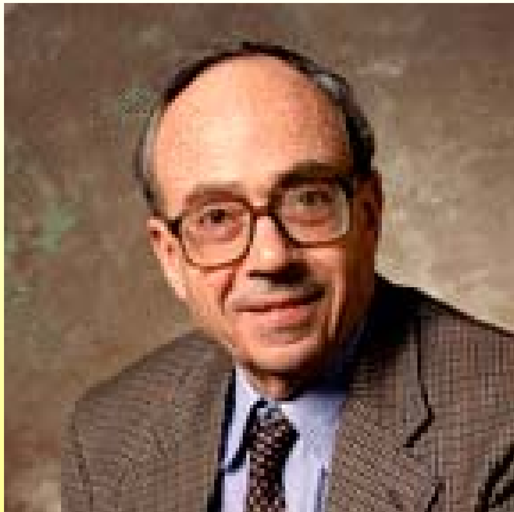


•1976: ‘t Hooft – Mandelstam: condensation of magnetic charges causes electric confinement

•Dual of Meissner effect where electric condensation confines magnetic fields



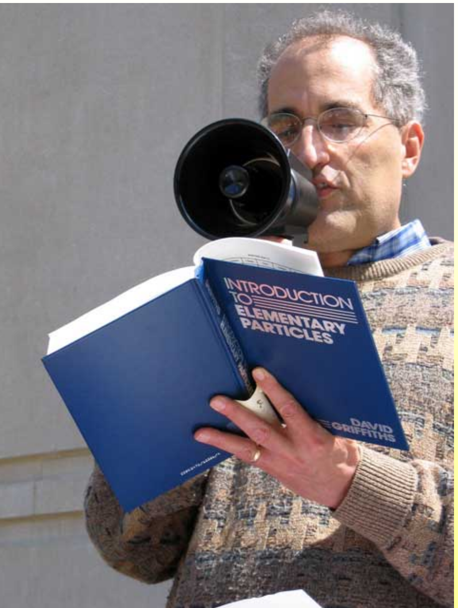




- Witten effect: magnetically charged objects pick up electric charge in the presence of θ

$$q \to q + \frac{\theta}{2\pi} g$$

- θ can be physical in U(1) theories, if fermions massive



- Heuristic proof by Coleman $\mathcal{L}_\theta = \frac{\theta e^2}{8\pi^2}\vec{E}\cdot\vec{B}$

- Monopole field plus arbitrary field:

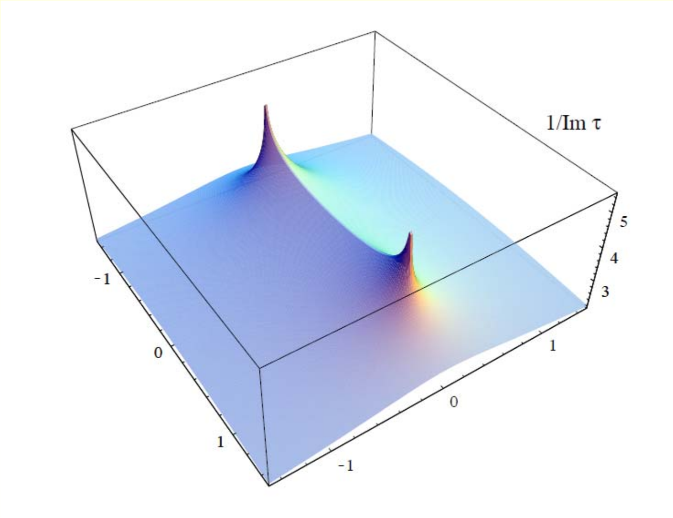
$$\vec{E} = -\nabla\phi$$
$$\vec{B} = \nabla\times\vec{A} + \frac{g}{4\pi}\frac{\vec{e}_r}{r^2}$$

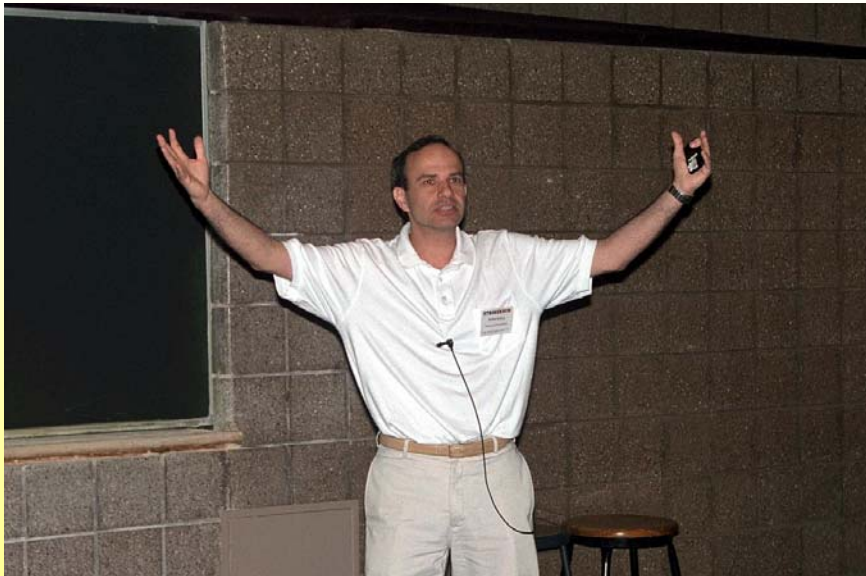
- The Lagrangian, integrating by parts:

$$L_\theta = \frac{\theta e^2}{8\pi}\int dV(-\nabla\phi)\cdot(\nabla\times\vec{A} + \frac{g}{4\pi}\frac{\vec{e}_r}{r^2}) =$$
$$-\frac{\theta e^2 g}{32\pi^3}\int dV\,\phi\nabla(\frac{\vec{e}_r}{r^2}) = \frac{\theta e^2 g}{8\pi^2}\int dV\,\phi\delta(\vec{r})$$

- Like a charge at the origin, q→q+$\theta/(2\pi)$ g

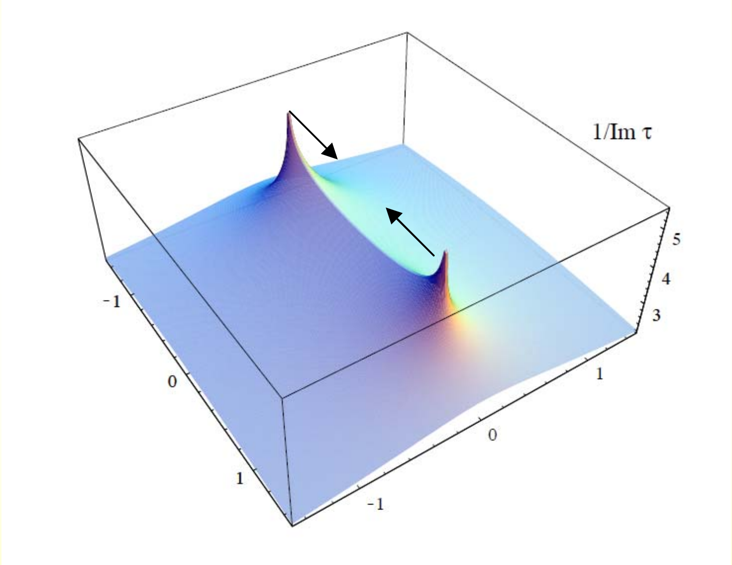
•1994: Seiberg, Witten: monopoles in N=2 SUSY theories can become massless (and condense if broken to N=1)





•Argyres Douglas (and also Intriligator and Seiberg):

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



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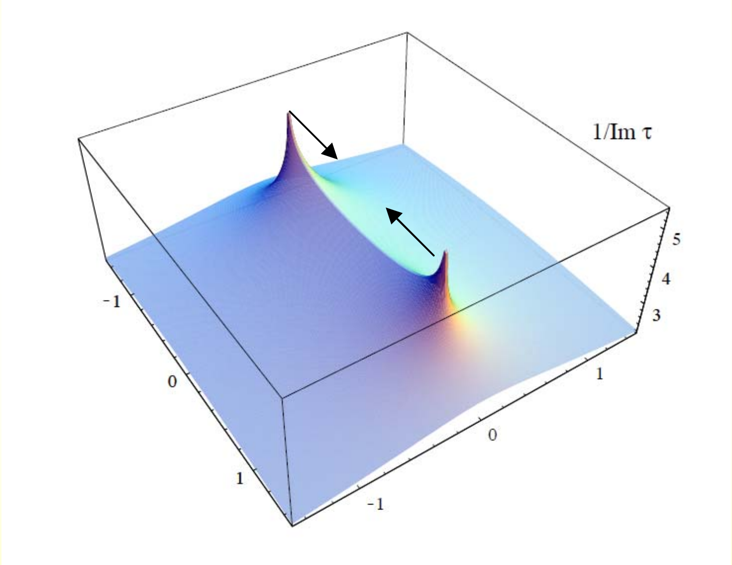
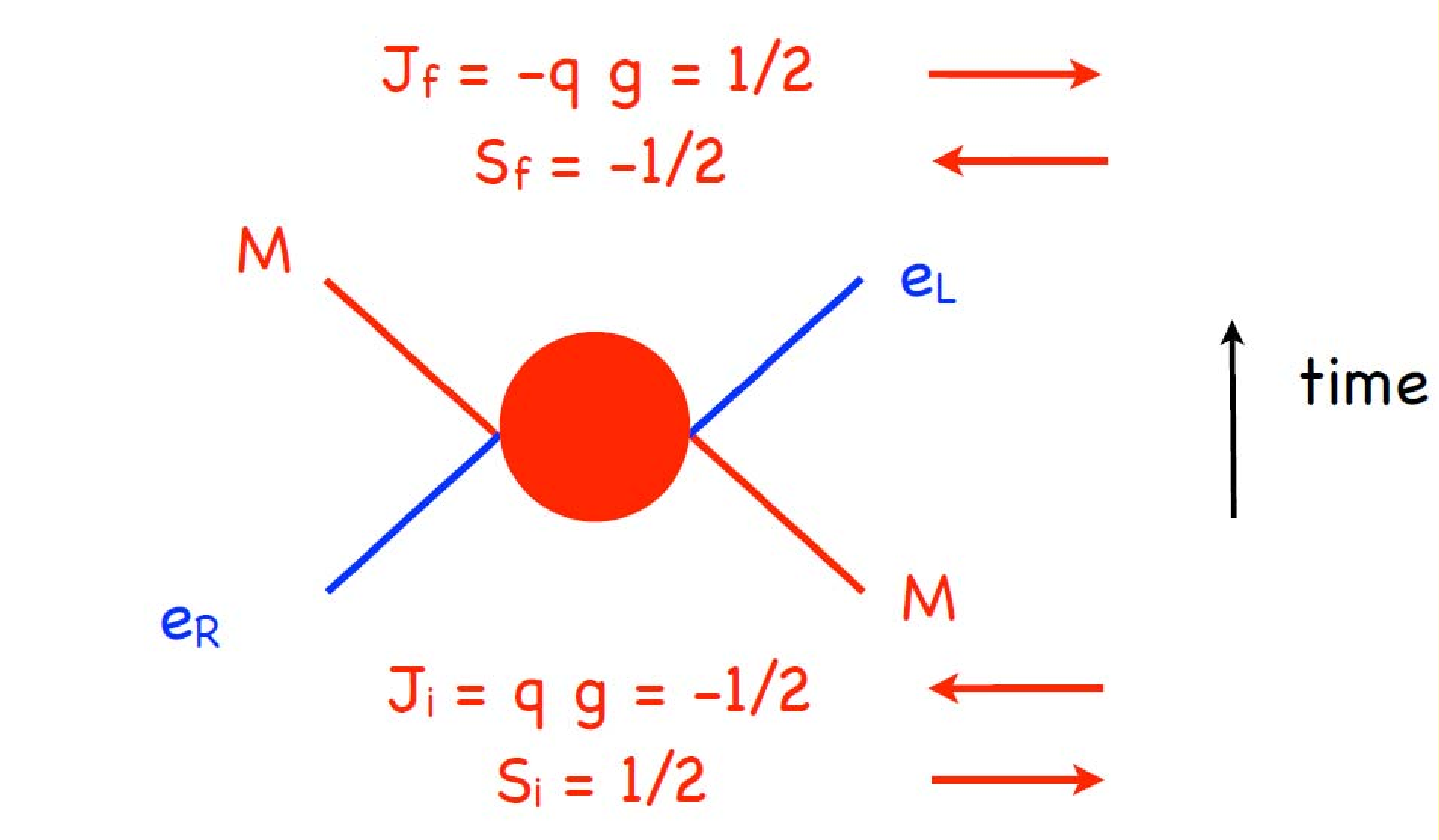


The Rubakov-Callan effect



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

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

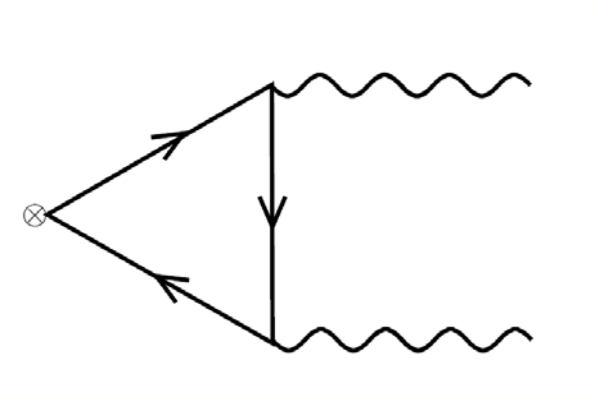
- An extra generation with magnetic hypercharges

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
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

A detour on anomalies with monopoles

- What is the chiral anomaly in the presence of dyons?



- Assume, can calculate anomalies for fields independently

- Then can do SL(2,Z) rotation where field is just an electron

SL(2,Z)

•A set of field redefinitions that leaves physics unchanged (but Lagrangian NOT invariant, no sym)

•S-duality: has effect of $$g \longrightarrow \frac{1}{g}$$

•Also exchanges electric and magnetic charges

•T-duality: shift of θ: $$\theta \longrightarrow \theta + 2\pi$$

•Together SL(2,Z). Can introduce "holomorphic" coupling parameter τ, under SL(2,Z) $$\tau \longrightarrow \frac{a\tau+b}{c\tau+d}$$

$$\tau \equiv \frac{\theta}{2\pi} + \frac{4\pi i}{e^2}$$

- Here a,b,c,d are integers and ad-bc=1
- The transformation of charges:

$$\begin{pmatrix} a & -b \\ -c & d \end{pmatrix} \begin{pmatrix} q \\ g \end{pmatrix} = \begin{pmatrix} n \\ 0 \end{pmatrix}$$

- Where n=gcd(q,g) can always be achieved
- In this frame anomalies easy, just usual

$$\begin{aligned} \partial_\mu j_A^\mu(x) &= \frac{n^2}{16\pi^2} F'^{\mu\nu}\, {}^*F'_{\mu\nu} \\ &= \frac{n^2}{32\pi^2} \mathrm{Im} \left(F'^{\mu\nu} + i\, {}^*F'^{\mu\nu} \right)^2 \end{aligned}$$

- To transform back need SL(2,Z) for fields

- Maxwell equations:

$$\frac{\text{Im}(\tau)}{4\pi}\partial_\mu\left(F^{\mu\nu}+i\,{}^*F^{\mu\nu}\right)=J^\nu+\tau K^\nu$$

- Will be SL(2,Z) covariant if fields transform (New?):

$$\left(F^{\mu\nu}+i\,{}^*F^{\mu\nu}\right)\rightarrow\frac{1}{c\tau^*+d}\left(F'^{\mu\nu}+i\,{}^*F'^{\mu\nu}\right)$$

- Chiral anomaly:

$$\begin{aligned}\partial_\mu j^\mu_A(x) &= \frac{1}{16\pi^2}\text{Re}\,(q+\tau^*g)^2\,F^{\mu\nu}\,{}^*F_{\mu\nu}+\frac{1}{16\pi^2}\text{Im}\,(q+\tau^*g)^2\,F^{\mu\nu}\,F_{\mu\nu}\\ &= \frac{1}{16\pi^2}\left\{\left[\left(q+\frac{\theta}{2\pi}g\right)^2-g^2\frac{16\pi^2}{e^4}\right]F^{\mu\nu}\,{}^*F_{\mu\nu}+\left[qg+\frac{\theta}{2\pi}g^2\right]F^{\mu\nu}\,F_{\mu\nu}\right\}\end{aligned}$$

- Need to cancel all terms separately!

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

- Can argue similarly for gauge symmetries
- Need some Lagrangian formulation
- Use Zwanziger Lagrangian (local, gauge invariant but not Lorentz invariant)
- Two gauge fields, A electric, B magnetic
- Equations of motion Lorentz invariant

•We found a trivial generalization including θ term

$$
\begin{aligned}
\mathcal{L} \;=\; & -\mathrm{Im}\frac{\tau}{8\pi n^2}\{[n\cdot\partial\wedge(A+iB)]\cdot[n\cdot\partial\wedge(A-iB)]\} \\
& -\mathrm{Re}\frac{\tau}{8\pi n^2}\{[n\cdot\partial\wedge(A+iB)]\cdot[n\cdot^{*}\partial\wedge(A-iB)]\} \\
& -J\cdot A-\frac{4\pi}{e^2}K\cdot B
\end{aligned}
$$

•Using this we showed (similarly) that mixed gauge anomalies should cancel too:

$$
\begin{aligned}
\sum_j q_j^2\, g_j &= 0 \\
\sum_j q_j\, g_j^2 &= 0 \\
\sum_j g_j^3 &= 0
\end{aligned}
$$

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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

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

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

- Low energy phase:

  Conformal fixed point – if 1 loop beta function reliable expect fixed point, not interesting for EWSB

  Mass gap generated – if 1 loop beta function like QED. Need to assume that small coupling drives the beta function. The bigger the coupling, the smaller contribution to beta. In that case forming of condensates and mass gap seems inevitable

- Assume second scenario realized. Don't have evidence this is indeed the case, but don't see argument that this could be impossible

- No Rubakov-Callan generated in this case
- 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

•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”

Non-abelian monopoles

- Magnetic field not aligned with $U(1)_Y$
- Also contained partly in SU(3), SU(2)
- This is what happens to GUT monopole
- Group really $SU(3)\times SU(2)\times U(1)/Z_6$

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

- Dirac quantization loop

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

- Now replaced by

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

•The gauge field for Dirac calculation:

$$\vec{A}_Y = \frac{g}{g_Y} \frac{1-\cos\theta}{r\sin\theta}\,\hat{e}_\phi\ .$$
$$\vec{A}^a_L = \delta^{a3}_L \frac{g\,\beta_L}{g_L} \frac{1-\cos\theta}{r\sin\theta}\,\hat{e}_\phi$$
$$\vec{A}^a_c = \delta^{a8}_c \frac{g\,\beta_c}{g_c} \frac{1-\cos\theta}{r\sin\theta}\,\hat{e}_\phi$$

•Dirac quantization: every component of matrix has to obey

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

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

	$SU(3)_c$	$U(1)^{el}_{em}$	$U(1)^{mag}_{em}$
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: $T^8_c g\beta_c + qg = \frac{n}{2}$

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

- 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: $\lambda_{ij}^{(u)} u_R^i L_L \left(q_L^j N_R\right)^\dagger$

•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 w/o Higgs – could be OK?

•CP violation? Dyons generically break CP… But low-energy effects vanish in limit of fermion masses vanish – proportional to neutrino masses.

•At LHC: likely pair produced. Due to strong force large radiation, then annihilation. Lots of photons, some of them hard. Cross section ~ pb

•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

•Could try to 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 (hard) photons…