Holographic monopole catalysis of Baryon number

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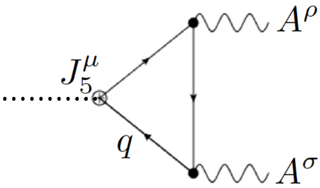
with K.M. Lee, C. Park, H.U. Yee
+work under progress

Anomaly and fermion number violation

- The fermion numbers are often not conserved due to ABJ anomaly, when the background fields are topologically nontrivial. ('t Hooft 1976)

$$\partial_\mu j_5^\mu = -\frac{g^2}{16\pi^2}\mathrm{tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$



Anomaly and fermion number violation

- In the EW gauge theory $B + L$ is not conserved :

$$\Delta B = \Delta L = 2N_f \Delta N_{\rm CS}$$

  with $N_{\rm CS} = \int {\rm d}^3 x \Omega_{\rm CS}(A)$. The amplitude is highly suppressed, ${\rm Amp} \sim e^{-8\pi^2/g^2}$.
- The rate is however enhanced at temperature higher than the EW phase transition temperature due to sphalerons. (Kuzmin+Rubakov+Shaposhnikov; Arnold+McLerran)
- EW baryogenesis via leptogenesis?

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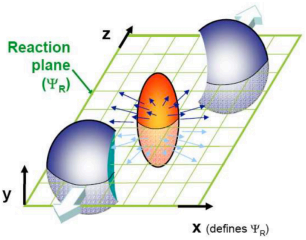
chiral magnetic effects

- In medium the currents are spontaneously generated due to ABJ anomaly under the external magnetic fields (Fukushima+Kharzeev+Warringa '08; DKH '11):



$$J_V^\alpha = \delta^{\alpha i}\frac{q^2 B^i}{2\pi^2}\mu_A + \delta^{\alpha 0}\, q\, n$$

$$J_A^\alpha = \delta^{\alpha i}\frac{q^2 B^i}{2\pi^2}\mu + \delta^{\alpha 0}\, q\, n_A$$

Monopole Catalysis of Baryon decay: Callan-Rubakov

- In V-A theory the baryon number is not conserved in the presence of magnetic monopoles. (Callan-Rubakov)

$$\mathrm{Monopole} + p \longrightarrow \mathrm{Monopole} + e^{+}$$

- The rate is given by the QCD scale, so not suppressed.
- Non-suppression is easy to see in the skyrmion picture. (Callan-Witten)

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Monopole Catalysis of Skyrmion decay: Callan-Witten

- In the Skyrme picture baryons are topological solitons, admitted by the chiral Lagrangian of pions,

$$U(x) : R^{(3,1)} \mapsto \mathcal{M} = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R / \mathrm{SU}(2)_V .$$

- The baryon number current is identified as

$$B^\mu = \frac{1}{24\pi^2} \epsilon^{\mu\nu\alpha\beta} \mathrm{Tr}\left(U^{-1}\partial_\nu U U^{-1}\partial_\alpha U U^{-1}\partial_\beta U \right)$$

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Monopole Catalysis of Skyrmion decay: Callan-Witten

- Since the electromagnetic interaction acts on U by

$$U \to e^{iQ} U e^{-iQ} \quad , \quad Q = \begin{pmatrix} \frac{2}{3} & 0 \\ 0 & -\frac{1}{3} \end{pmatrix}$$

the gauge-invariant baryon current becomes

$$\begin{aligned} B^{\mu} &= \frac{1}{24\pi^2} \epsilon^{\mu\nu\alpha\beta} \mathrm{Tr}\left(U^{-1}\partial_\nu U U^{-1}\partial_\alpha U U^{-1}\partial_\beta U\right) \\ &\quad - \frac{1}{24\pi^2} \epsilon^{\mu\nu\alpha\beta} \partial_\nu \left[3A_\alpha^{EM} \mathrm{Tr}\left(Q(U^{-1}\partial_\beta U + \partial_\beta U U^{-1})\right)\right] \end{aligned}$$

Monopole Catalysis of Skyrmion decay: Callan-Witten

- Magnetic monopole unwinds the Skyrmion because of the angular momentum barrier and only the neutral pions pass through the core

$$U(t) = \exp\left[\frac{2i}{f_\pi}\pi^0(t)\sigma^3\right]$$

- Outside the core there are radial flux into the magnetic monopole, whose potential $A^{EM} = -\frac{i}{2}(1-\cos\theta)d\phi$,

$$\frac{dB}{dt} = \int \mathrm{d}\vec{S}\cdot\vec{B} = \frac{1}{\pi f_\pi}(\partial_t \pi^0)$$

Baryons in holographic QCD

- Holographic QCD is an attempt to describe QCD in terms of hadrons, the relevant degrees of freedom at low energy.
- In the large color and large 't Hooft coupling limit QCD is described by a 5D flavor gauge theory, hQCD.
- It gives a unified picture for all anomaly-related baryon number violation and furthermore it predicts a new process for the baryon number violation. (HLPY '08)
- We consider the Witten-Sakai-Sugimoto model, based on Type IIA string theory with $D4-D8-\bar{D}8$ branes. But, it works for any hQCD models.

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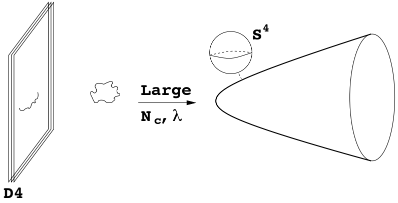
Witten-Sakai-Sugimoto model

- N_c stack of $D4$ branes over $R^3 \times S^1$ describes pure $SU(N_c)$ YM. (Witten '98)

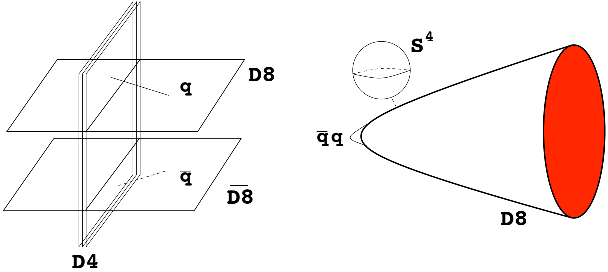


$$ds^2 = \left(\frac{U}{R}\right)^{3/2}\left(\eta_{\mu\nu}dx^\mu dx^\nu + f(U)d\tau^2\right) + \left(\frac{R}{U}\right)^{3/2}\left(\frac{dU^2}{f(U)} + U^2 d\Omega_4^2\right)$$

with $R^3 = \pi g_s N_c l_s^3$ and $f(U) = 1 - U_{KK}^3/U^3$

Witten-Sakai-Sugimoto model

- Adding flavors was done by Sakai-Sugimoto (2004).



- Spontaneous chiral symmetry breaking is geometrically realized:

$$SU(N_F)_L \times SU(N_F)_R \mapsto SU(N_F)_V \, .$$

Introduction and Review

- Effective action on D8 is a $U(N_F)$ gauge theory,

$$S_{D8} = -\mu_8 \int \mathrm{d}^9 x \, e^{-\phi} \sqrt{-\det\left(g_{MN} + 2\pi\alpha' F_{MN}\right)} + \mu_8 \int \sum C_{p+1} \wedge \mathrm{Tr}\, e^{2\pi\alpha' F} \,,$$

- The gauge fields contain pions and whole tower of vector mesons:

$$A_\mu(x,z) = \alpha_\mu(x)\psi_0(z) + \beta_\mu(x) + \sum_{n\geq 1} B_\mu^{(n)} \psi_n(z) \,,$$

where with $\xi = \exp(i\pi(x)/f_\pi)$

$$\alpha_\mu = \left\{\xi^\dagger, \partial_\mu \xi\right\}, \quad \beta_\mu = \left[\xi^\dagger, \partial_\mu \xi\right] .$$

Baryons in holographic QCD

- In 5D YM there is a topologically conserved current, $d\,{}^*J = 0 = DF$,

$$J^M = \frac{1}{24\pi^2}\epsilon^{MNLPQ}\,\mathrm{tr} F_{NL}F_{PQ}\,.$$

- One can define the baryon current

$$B^\mu = \frac{1}{8\pi^2}\int \mathrm{d}z\epsilon^{\mu\nu\rho\sigma}\mathrm{tr} F_{\nu\rho}F_{\sigma z}\,.$$

- In the gauge $A_z = 0$ one may write with $U = \exp(2i\pi/f_\pi)$

$$A_\mu(x,z) = U^{-1}\partial_\mu U\psi_0(z) + \sum_{n\geq 1} B_\mu^{(n)}\psi_n(z)\,.$$

Then, the baryon current becomes the Skyrme current

$$B^\mu = \frac{1}{24\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr} U^{-1}\partial_\nu UU^{-1}\partial_\rho UU^{-1}\partial_\sigma U$$

holographic monopole catalysis

- The instanton number is also not conserved in the presence of monopole (cf. Skyrme number violation of Callan-Witten '84):

$$DF \neq 0 \longrightarrow d\,{}^{*}j_B \neq 0\,.$$

- In SS model the external $U(1)_{\rm em}$ background gives a BC,

$$A(+\infty) = A(-\infty) = QA^{EM}, \quad Q = \mathrm{diag}\,(2/3, -1/3)\,.$$

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Baryon number violation

- In hQCD the baryon number current is given as

$$B^\mu = \int_{-\infty}^{+\infty} dz\, j_B^\mu = \frac{1}{8\pi^2} \int_{-\infty}^{+\infty} dz\, \epsilon^{\mu\nu\alpha\beta}\, \mathrm{Tr}\,(F \wedge F)_{\nu\alpha\beta z}$$

- With the right b.c. it gives the correct (gauged) baryon number current.
- In a general background A_L and A_R with $\xi_\pm^{-1} = P\exp(-\int_0^{\pm\infty} A_z)$ and $\xi_+^{-1}\xi_- = U$ we write

$$A_\mu(x,z) = A_{L\mu}^{\xi_+}(x)\psi_+(z) + A_{R\mu}^{\xi_-}(x)\psi_-(z) + (\text{excited modes}),$$

where
$A_{L\mu}^{\xi_+} = \xi_+ A_{L\mu}\xi_+^{-1} + \xi_+\partial_\mu\xi_+^{-1}, A_{R\mu}^{\xi_-} = \xi_- A_{R\mu}\xi_-^{-1} + \xi_-\partial_\mu\xi_-^{-1}.$

Baryon number violation

- Then the baryon current becomes

$$
\begin{aligned}
B^\mu \;=\;& \frac{1}{24\pi^2}\,\epsilon^{\mu\nu\alpha\beta}\,\mathrm{Tr}\,\left(U^{-1}\partial_\nu U U^{-1}\partial_\alpha U U^{-1}\partial_\beta U\right)\\
&-\frac{1}{8\pi^2}\,\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}\,\partial_\nu\left(U^{-1}A_{L\alpha}\partial_\beta U + A_{R\alpha}U^{-1}\partial_\beta U - U^{-1}A_{L\alpha}UA_{R\beta}\right)\\
&-\frac{1}{8\pi^2}\,\epsilon^{\mu\nu\alpha\beta}\,\mathrm{Tr}\left(\partial_\nu A_{L\alpha}\,A_{L\beta} + \frac{2}{3}A_{L\nu}A_{L\alpha}A_{L\beta} - (L\leftrightarrow R)\right)\,.
\end{aligned}
$$

- We find a unified formula for the baryon number violation

$$
\partial_\mu B^\mu = \frac{1}{32\pi^2}\left(\mathrm{Tr}F_L\tilde{F}_L - \mathrm{Tr}F_R\tilde{F}_R\right) + \frac{i\delta^{(3)}(\vec{x})}{2\pi}\int_{-\infty}^{+\infty}dz\,\mathrm{Tr}\left(QF_{tz}\right),
$$

Baryon number violation

- The first term is the famous baryon number violation in chiral gauge theories, found by 't Hooft.
- The second term gives

$$\partial_\mu B^\mu = -\frac{i\delta^{(3)}(\vec{x})}{2\pi}\,\mathrm{Tr}\,(QA_t)\Big|_{-\infty}^{+\infty}$$
$$= -\frac{i\delta^{(3)}(\vec{x})}{2\pi}\left[\mathrm{Tr}\left(QU^{-1}\partial_t U\right) + \mathrm{Tr}\left(QU^{-1}A_{Lt}U\right) - \mathrm{Tr}\left(QA_{Rt}\right)\right] \quad .$$

- For the monopole catalysis of instanton-baryon decay, $U = \exp(2i\pi/f_\pi)$, we have from the first one

$$\frac{dB}{dt} = \frac{1}{\pi f_\pi}(\partial_t \pi^0)\,.$$

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Baryon number violation

- We found also that the nonzero axial chemical potential induces baryon number violation in the presence of magnetic monopole:

$$\frac{dB}{dt} = \frac{\mu_5}{6\pi}$$

- In the early universe before the QCD confinement we do have fluctuations of topological charges.
- The average of the topological charges is zero but its root-mean-square is non-zero or $\mu_5 \neq 0$, which might give enough baryon asymmetry, assuming there is a magnetic monopole in our universe. (Work under progress.)

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Conclusion and Outlook

- The baryons are realized as instanton solitons in hQCD.
- The baryon number violation due to anomaly is reproduced in holographic QCD.
- The monopole catalysis of baryon decay is easily seen in hQCD, as the violation of the Bianchi identity.
- The holographic QCD provides a unified picture of all known baryon number violation due to anomaly.
- It also gives a new mechanism to violate the baryon number, which might explain the baryon asymmetry of our universe. (Work under progress)

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