Fate of Chiral Symmetries in Supersymmetric Quantum Chromodynamics

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Supersymmetric Quantum Chromodynamics (SQCD)

with N_c-colors and N_f-flavors

$$SU(N_c)\times SU(N_f)_L\times SU(N_f)_R\times U(1)_V\times U(1)_A$$

Seiberg PR D49 **1994**,NP B435 **1995**

Chiral $SU(N_f)$ *Symmetry*

Electric

- $N_f < N_c$
- $N_f = N_c$
- $N_f = N_c + 1$

vectorial $SU(N_f)_{L+R}$

Magnetic

- $N_c + 2 \le N_f \le 3N_c/2$
- $3N_c/2 < N_f < 3N_c$ — **the N=2 duality**

chiral $SU(N_f)_L\times SU(N_f)_R$

"magnetic" quarks

Electric

$N_c + 2 \le N_f \le 3N_c/2$

mesons and baryons

In the "electric" phase ($N_f \ge N_c + 2$):

Since anomaly-matching is not satisfied, we expect *spontaneous breakdown* of chiral symmetries

$$\Rightarrow SU(N_c)_{L+R}\times SU(N_f-N_c)_L\times SU(N_f-N_c)_R$$

Anomalous U(1) and Superpotential

Veneziano & Yankielowicz PL 113B **1983**
Taylor, Veneziano & Yankielowicz NP B218 **1983**

S :2-Body Composite of Chiral Gauge Superfields

$$\delta_{anomalous} L = \delta_{anomalous} W_{eff}\big|_{\text{F-term}} \propto S\big|_{\text{F-term}}$$

$T_{i=1\sim N_f}^{j=1\sim N_f}$:Mesons, $B^{[i_1 \cdots i_{N_c}]}$:Baryon, $\overline{B}_{[i_1 \cdots i_{N_c}]}$:Anti-baryon

Masiero, Pettorino, Roncadelli & Veneziano NP B261 **1985**
Yasuè PR D35. D36: PTP 78 **1987**

Effective Superpotential for $N_f \geq N_c$

$$W_{eff} = S\left\{\ln\left[\frac{S^{N_c-N_f}\det(T)f(Z)}{\Lambda^{3N_c-N_f}}\right]+N_f-N_c\right\}$$

$$Z \equiv BT^{N_f-N_c}\overline{B}/\det(T)$$

$$\xrightarrow{\text{Classical Limit}} \left.\begin{matrix} Z=1 \\ f(Z)=0 \end{matrix}\right\} \Rightarrow f(Z)=(1-Z)^{\rho} \quad (\rho>0)$$

$$(*)\rho = 1 \text{ for } N_f = N_c+1$$

$$W_{eff} = S\left\{\ln\left[\frac{S(\det(T)-BT\overline{B})}{\Lambda^{3N_c-N_f}}\right]+1\right\} \Rightarrow W_{eff} = \frac{\det(T)-BT\overline{B}}{\Lambda^{2N_f-3}}$$

Strategy

⇒Slightly broken SUSY vacuum, where

⇒Symmetry behavior of our superpotential is more visible.

⇒ Universal scalar masses, which **respect** *global symmetry* and only **break** *SUSY*

⇒The consistency with SQCD is checked in its SUSY limit

Conditions on $\pi_i = \langle 0|T_i^i|0\rangle, \pi_\lambda = \langle 0|S|0\rangle$

Honda & Yasuè PTP 101; PL B466 **1999**

$i = 1 \sim N_c$

$$A_T W^*_{eff:i}\frac{\pi_\lambda}{\pi_i}(1-\alpha) = A_S W_{eff:\lambda}(1-\alpha) + \beta X_B + M^2_{SUSY}\left|\frac{\pi_i}{\Lambda}\right|^2 \quad (A_{T,S} \leftarrow \text{Kähler})$$

$$\alpha = z f'(z)/f(z) \quad \beta = z\alpha' \quad z = \langle 0|Z|0\rangle \quad M^2_{SUSY} = \mu_L^2 + \mu_R^2 + A'_T\Lambda^2\sum_{i=1}^{N_f}\left|W_{eff:i}\right|^2$$

$$X_B = A_T\sum_{a=1}^{N_c} W_{eff:a}\frac{\pi_\lambda}{\pi_a} - \left(A_B W_{eff:B}\frac{\pi_\lambda}{\pi_B} + A_B W_{eff:\bar{B}}\frac{\pi_\lambda}{\pi_{\bar{B}}}\right) \quad W_{eff:i} = \frac{\partial W_{eff}}{\partial \pi_i} \text{ etc.}$$

Because the anomaly-matching at least requires dynamical symmetry breakdown	$\pi_{i=1} \neq 0$

$$\left|\frac{\pi_{i=2\sim N_c}}{\pi_1}\right| = 1 + \frac{\left(M^2_{SUSY}/\Lambda^2\right)\left(|\pi_1|^2 - |\pi_i|^2\right)}{G_S W_{eff:\lambda}(1-\alpha) + \left(M^2_{SUSY}/\Lambda^2\right)|\pi_i|^2 + \beta X_B}$$

$\pi_{i=2\sim N_c} = 0$ is **NO**⇒ $\pi_{i=2\sim N_c} = \pi_1$ is **OK**⇒***SU*(*N*$_c$)$_{L+R}$?**

Symmetry Breaking

Input	Output $\varepsilon = \not{SUSY} = \left|1-z\right|$	
$\left|\pi_{i=1\sim N_c}\right| \equiv \Lambda_T^2 \sim \Lambda^2$	$\left|\pi_B\right| = \left|\pi_{\bar{B}}\right| \equiv \Lambda_B^{N_c} \sim \Lambda^{N_c}$	$\left|\pi_{i=N_c+1\sim N_f}\right| = \varepsilon \left|\pi_{i=1\sim N_c}\right|$ $\left|\pi_\lambda\right| \sim \Lambda^3 \varepsilon^{1+\frac{\rho}{N_f-N_c}}$

In the SUSY Limit ($\varepsilon \to 0$)

$SU(N_c)_{L+R}$	$SU(N_f-N_c)_L \times SU(N_f-N_c)_R \times U(1)'_A$
$\left|\pi_{i=1\sim N_c}\right| = \Lambda_T^2 \quad \left|\pi_B\right| = \left|\pi_{\bar{B}}\right| = \Lambda_B^{N_c}$	$\left|\pi_{i=N_c+1\sim N_f}\right| = \left|\pi_\lambda\right| = 0$

$$G = SU(N_c) \times SU(N_f)_L \times SU(N_f)_R \times U(1)_V \times U(1)_A \Rightarrow$$
$$H = SU(N_c)_{L+R} \times SU(N_f - N_c)_L \times SU(N_f - N_c)_R \times U(1)'_V \times U(1)'_A$$

Consistent anomaly-matching property due to the emergence of the Nambu-Goldstone superfields

massless bosons⇒**broken** part: G/H

massless fermions⇒**unbroken** part: H

Anomaly-matching is a dynamical consequence

Our superpotential is consistent with	Holomorphic **decoupling**
	instanton calculus for SQCD with $N_f = N_c$ reproduced by massive quarks with flavors of $SU(N_f - N_c)$

Summary

Dynamical breakdown of chiral symmetries

determined by

$$\begin{cases} W_{eff} = S\left(\ln\left[\dfrac{S^{N_c-N_f}\det(T)(1-Z)^{\rho}}{\Lambda^{3N_c-N_f}} \right] + N_f - N_c \right) \\ Z = \dfrac{BT^{N_f-N_c}B}{\det(T)} \ \& \ \rho>0 \end{cases}$$

SQCD ($N_c+2 \leqq N_f \leqq 3N_c/2$)	QCD ($N_f=2$)
$SU(N_f)_L \times SU(N_f)_R$	$SU(2)_L \times SU(2)_R$
"magnetic" quarks	proton & neutron
$SU(N_c)_{L+R} \times SU(N_f-N_c)_L \times SU(N_f-N_c)_R$	$SU(2)_{L+R}$
Nambu-Goldstone superfields	Nambu-Goldstone bosons

Indications of Spontaneous Chiral Symmetry Breaking

- Dynamical evaluations of condensates — **Appelquist, Nyffeler & Selipsky** PL B425 **1998**
- Instable SUSY vacuum in the "magnetic" phase — **Arkani-Hamed & Rattazzi** PL B454 **1999**
- Slightly different effective superpotential in the "electric" phase — **Pronin & Stepanyantz** hep-ph/9902163 **1999**

Chiral $SU(N_f)$ Symmetry

$N_f < N_c$	Electric: $SU(N_f)_{L+R}$	
$N_f = N_c$	Electric: $SU(N_f)_{L+R}$	$SU(N_f)_L \times SU(N_f)_R$
$N_f = N_c + 1$	Electric	$SU(N_f)_L \times SU(N_f)_R$
$N_c + 2 \le N_f \le 3N_c/2$	Electric: $SU(N_c)_{L+R} \times \cdots$	Magnetic: $SU(N_f)_L \times SU(N_f)_R$
$3N_c/2 < N_f < 3N_c$		Magnetic: $SU(N_f)_L \times SU(N_f)_R$
	mesons, baryons	**"magnetic" quarks**