Hidden Sector on Magnetized D7-brane Model

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Around the end of the semester, I begin to consider the hidden sector of the magnetized D7-brane model, which was constructed by Chin-san in his master's thesis.

6.2 ポテンシャル解析

簡単のために磁場が 0 の場合でポテンシャルの解析をする。例としてオービフォルドの射影演算子と磁場が

$$P_{++-},\quad P'_{+--},\quad M^{(1)}=\left(\begin{array}{c|cc} 0 & & \\ \hline & 0\times\mathbf{1}_N & \\ & & 0\end{array}\right),\quad M^{(2)}=\left(\begin{array}{c|cc} H & & \\ \hline & 0\times\mathbf{1}_N & \\ & & 0\end{array}\right),\quad M^{(3)}=\left(\begin{array}{c|cc} 0 & & \\ \hline & H\times\mathbf{1}_N & \\ & & H\end{array}\right) \tag{6.5}$$

の場合について具体的に考える。ただし実線は $D7_C, D7_D$ の区別を表している。このとき、場の構成は

$$\Phi_1=\left(\begin{array}{c|c} & \\ \hline & Q\end{array}\right),\quad \Phi_2=\left(\begin{array}{c|c} & X \\ \hline & \end{array}\right),\quad \Phi_3=\left(\begin{array}{c|c} & \\ \hline \widetilde{Q} & \end{array}\right) \tag{6.6}$$

となる。

He already studied the hidden sector but he set the all flux to zero.

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となる。

He already studied the hidden sector but he set the all flux to zero.

My goals are

- Introduce the flux in the hidden sector and develope the model.
- Upgrade to SUGRA and stabilize the moduli, which related to my *Sotsuron*.

Introduction & Review

There are several problems in the Standard Model. I list them though briefly.

- Quantization of the gravity
- Origin of $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Hierarchy problem
- Origin of three-flavors (generations)
- Strong (QCD) CP violation, etc.

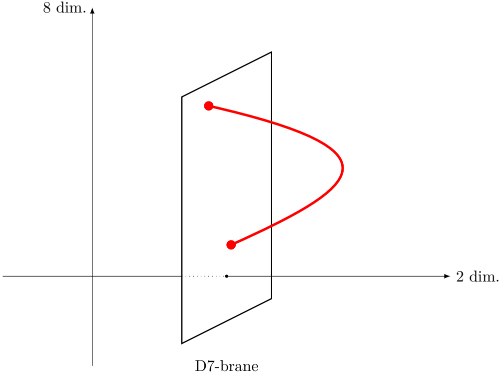
(Most of them can be found in Kikuchi-san's master's thesis, Hokkaido univ..)

Superstring theory is one of the candidate for solving these problems.

We are interested in its effective field theory, Super Yang-Mills theory.

In D7-brane model,

- the endpoints of a string behave SYM particles.
- the brane is an 8-dimensional objects and the particles appear to be localized when viewed from other dimensions.



Lagrangian

$$\mathcal{L} = \frac{1}{g^2}\,\mathrm{Tr}\left[-\frac{1}{4}F^{MN}F_{MN} + \frac{i}{2}\bar{\lambda}\Gamma^M D_M \lambda\right]$$

- M, N run $0, 1, \cdots, 9$.
- F_{MN} is a field strength defined as $F_{MN} \equiv \partial_M A_N - \partial_N A_M - i[A_M, A_N]$. (We assume the gauge group G is non-abelian, then the commutator does not vanish.)
- λ is a majorana-weyl spinor satisfying a majorana condition and a positive chirality condition:

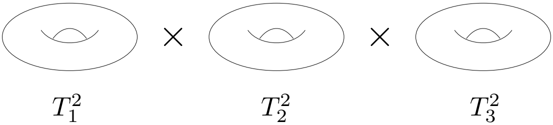
$$\lambda^C = \lambda\,, \quad \Gamma\lambda = +\lambda.$$

[1] H. Abe, T. Kobayashi, K. Sumita, and S. Uemura, Nucl. Phys. B **863** (2012) 1–18, arXiv:1204.5327 [hep-th].
[2] D. Cremades, L. E. Ibanez, and F. Marchesano, JHEP **05** (2004) 079, arXiv:hep-th/0404229.

To obtain an effective four-dimensional theory, we need to compactify the extra dimensions. Now $\mathbb{R}^6$ to $T^2 \times T^2 \times T^2$.

$$\mathrm{d}s^{10} = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + g_{mn}\mathrm{d}x^m \mathrm{d}x^n$$

$$g_{mn} = \begin{pmatrix} g^{(1)} & 0 & 0 \\ 0 & g^{(2)} & 0 \\ 0 & 0 & g^{(3)} \end{pmatrix}, \quad g^{(i)} = (2\pi R_i)^2 \begin{pmatrix} 1 & \mathrm{Re}\ \tau_i \\ \mathrm{Re}\ \tau_i & |\tau|^2 \end{pmatrix}$$



An area of the i-th torus is $\mathcal{A}^{(i)} = 4\pi^2 R_i^2\ (\mathrm{Im}\ \tau_i)$.

[1] H. Abe, T. Kobayashi, K. Sumita, and S. Uemura, Nucl. Phys. B **863** (2012) 1–18, arXiv:1204.5327 [hep-th].
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Procudure

$$\mathcal{L} = \frac{1}{g^2}\,\mathrm{Tr}\left[-\frac{1}{4}F^{MN}F_{MN} + \frac{i}{2}\bar{\lambda}\Gamma^M D_M \lambda\right]$$

$$\Big\Downarrow \quad \text{4-dim. } \mathcal{N}=1 \text{ superspace [3]}$$

$$\mathcal{L} = \int \mathrm{d}^4\theta\, \mathcal{K} + \left\{\int \mathrm{d}^2\theta\, \left(\frac{1}{4g^2}\mathcal{W}^\alpha \mathcal{W}_\alpha + \mathcal{W}\right) + \text{ h.c. }\right\},\ S = \int \mathrm{d}^{10}X\,\sqrt{-G}\mathcal{L}$$

$$\Big\Downarrow \quad \text{Compactify } \mathbb{R}^6 \text{ to } T^2\times T^2\times T^2$$

$$\mathcal{L} = \sum_{\text{KK modes}} \int \mathrm{d}^4\theta\, \mathcal{K} + \left\{\int \mathrm{d}^2\theta\, \left(\frac{1}{4g^2}\mathcal{W}^\alpha \mathcal{W}_\alpha + \mathcal{W}\right) + \text{ h.c. }\right\},\ S = \int \mathrm{d}^4x\,\mathcal{L}$$

where

$$\begin{cases} \mathcal{K}(V,\phi_i) = \dfrac{2}{g^2}h^{\bar{i}j}\,\mathrm{Tr}\left[\bar{\phi}_{\bar{i}}\phi_j + \sqrt{2}\left\{\left(\bar{\partial}_{\bar{i}}\phi_j + \dfrac{1}{\sqrt{2}}\left[\langle\bar{\phi}_{\bar{i}}\rangle, \phi_j\right] + \text{ h.c. }\right) + \cdots\right.\right. \\ \mathcal{W}(\phi_i) = \dfrac{1}{g^2}\varepsilon^{ijk}\,\mathrm{Tr}\left[\sqrt{2}\left(\partial_i\phi_j - \dfrac{1}{\sqrt{2}}\left[\langle\phi_i\rangle, \phi_j\right]\right)\phi_k - \dfrac{2}{3}\phi_i\phi_j\phi_k\right] \end{cases}$$

$$\mathcal{L} = \sum_{\text{KK modes}} \int \mathrm{d}^4\theta\, \mathcal{K} + \left\{ \int \mathrm{d}^2\theta \left(\frac{1}{4g^2} \mathcal{W}^\alpha \mathcal{W}_\alpha + \mathcal{W} \right) + \text{ h.c. } \right\}$$

Some features

- This theory contains infinite number of fields.

  $\longrightarrow$ Find the massless particles. (Zero mode equations)

- We will not care about Lorentz invariance on the extra dimension.

  $\longrightarrow$ Assign the VEV $\langle A_m \rangle$ along the extra dimensions.

$$\Downarrow$$

Break the gauge symmetry $U(N) \to U(n_1) \times U(n_2) \times \cdots\cdots.$

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[3] N. Arkani-Hamed, T. Gregoire, and J. Wacker, JHEP **03** (2002) 055, arXiv:hep-th/0101233.

We assume that "the lightest field is massless." This assumption implies

$$\partial_i f_j^{(i)} - \frac{1}{2}\left[\langle A_i \rangle , f_j^{(i)}\right] = 0$$

$$\text{where} \quad \phi_j(x^\mu, \boldsymbol{z}, \bar{\boldsymbol{z}}) \equiv f_j^{(1)}(z_1, \bar{z}_1) f_j^{(2)}(z_2, \bar{z}_2) f_j^{(3)}(z_3, \bar{z}_3) \phi_j^{(0)}(x^\mu)$$

for each torus, and we assign the VEV along the extra dimensions as

$$\langle A_i \rangle = \frac{\pi}{\operatorname{Im} \tau_i}(M^{(i)} \bar{z}_i + \bar{\zeta}).$$

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for each torus, and we assign the VEV along the extra dimensions as

$$\langle A_i \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i}(M^{(i)}\bar{z}_i + \bar{\zeta}).$$

The "massless condition" is rewritten as

$$\left[\partial_i - \frac{\pi}{2\mathrm{Im}\,\tau_i}(M^{(i)}\bar{z}_i + \bar{\zeta}^{(i)})\right] f_j^{(i)} = 0 \qquad \text{Zero mode equations}$$

Zero mode equation(s)

$$\left[\partial_i - \frac{\pi}{2\mathrm{Im}\,\tau_i}(M^{(i)}\bar{z}_i + \bar{\zeta}^{(i)})\right] f_j^{(i)} = 0$$

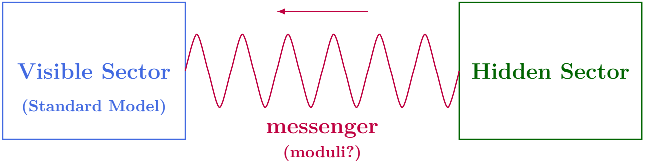
- The degeneracy of the solution $f_j^{(i)}$ depend on the backgrounds $M^{(i)}$ and ζ^i, and the orbifold conditions.
- The degeneracy corresponds to the *flavor* on the Standard Model.
- Once the solutions are obtained, we can evaluate the Yukawa matrix (Higgs & Quark coupling) and CKM matrix (mixing of flavors).

$\longrightarrow$ These facts are related to Chin-san's and Shimada-kun's works.

Hidden sector

From now on, we will consider the hidden sector, that is decoupled from the visible (or SM) sector.

- If supersymmetry is broken in the visible sector, some phenomenological problems will arise:
  - It is difficult to give gauginos mass.
  - Squarks and sleptons will become too light, so that they will already be observed.
- Thus, we think that the supersymmetry breaking occurs in a "hidden sector" of particles.



We assume that the gauge group is broken as
$U(N+2) \to U(1)_X \times U(N) \times U(1)_Y$ due to the flux

$$M^{(1)} = \left(\begin{array}{c|cc} M_X^{(1)} & & \\ \hline & M_N^{(1)} \times \mathbf{1}_N & \\ & & M_Y^{(1)} \end{array}\right) \begin{array}{c} X \\ N \\ Y \end{array}$$

$$M^{(2)} = \left(\begin{array}{c|cc} H & & \\ \hline & M_N^{(2)} \times \mathbf{1}_N & \\ & & M_Y^{(2)} \end{array}\right) \begin{array}{c} X \\ N \\ Y \end{array}$$

$$M^{(3)} = \left(\begin{array}{c|cc} M_X^{(3)} & & \\ \hline & H \times \mathbf{1}_N & \\ & & H \end{array}\right) \begin{array}{c} X \\ N \\ Y \end{array}$$

These flux determines the particles existing in its effective 4D theory.

There are two kinds of potentials in this theory, F-term potential and D-term potential, but the former one is already vanished by the VEV $\langle A_i \rangle$ assignment, at least perturbatively.

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The remaining one is

$$
\begin{aligned}
V_D = &\frac{1}{2}\left(\frac{M_X^{(1)}}{\mathcal{A}^{(1)}} + \frac{M_X^{(3)}}{\mathcal{A}^{(3)}} + (\text{matter})\right)^2 \\
&+ \frac{1}{2}\left(\frac{M_Y^{(1)}}{\mathcal{A}^{(1)}} + \frac{M_Y^{(2)}}{\mathcal{A}^{(2)}} + (\text{matter})\right)^2 \\
&+ \frac{1}{2}\left(\frac{M_N^{(1)}}{\mathcal{A}^{(1)}} + \frac{M_N^{(2)}}{\mathcal{A}^{(2)}} + \frac{M_N^{(3)}}{\mathcal{A}^{(3)}} + (\text{matter})\right)^2 .
\end{aligned}
$$

Example: fluxless model

Before introducing flux, we investigate the model without the magnetic flux.

The model has only three-particles, $Q, \tilde{Q}, X$:

$$\Phi^{(1)} = \left(\begin{array}{c|c} \phantom{\tilde{Q}} & \\ \hline & \\ & Q \end{array}\right)\begin{array}{c} X \\ N \\ Y \end{array}$$

$$\Phi^{(2)} = \left(\begin{array}{c|c} \phantom{\tilde{Q}} & X \\ \hline & \\ & \end{array}\right)\begin{array}{c} X \\ N \\ Y \end{array}$$

$$\Phi^{(3)} = \left(\begin{array}{c|c} & \\ \hline \tilde{Q} & \\ & \end{array}\right)\begin{array}{c} X \\ N \\ Y \end{array}$$

Both fermions Q and $\tilde{Q}$ couple with the gauge group $SU(N)$ and they can be confined in the low energy theory, like QCD.

To prove the above phenomena, we evaluate realization group (RG) equation for gauge coupling g. It is known that the β-function

The β-function for $SU(N)$ Yang-Mills theory, with n_f Weyl fermions and n_s complex scaler fields:

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\left(\frac{11}{3}C(G) - \frac{2}{3}n_f C(R_f) - \frac{1}{3}n_s C(R_s)\right)$$

In this case,

$$C(SU(N)) = N,\ n_f C(R_f) = 2N \quad \text{then} \quad \beta(g) = -\frac{7N}{48\pi^2}g$$

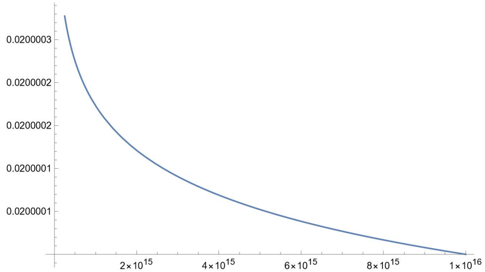
The RG equation is

$$\frac{\mathrm{d}}{\mathrm{d}\ln \mu/\mu_0} g = -\frac{7N}{48\pi^2} g, \quad g(\mu_0) = g_0$$

where the 2nd relation is the “initial condition” explained later.

The solution is

$$g(\mu) = \frac{g_0}{\left[1 + (7N g_0^3/48\pi^2)\ln \mu/\mu_0\right]^{1/2}}$$



Rough plot of the solution.

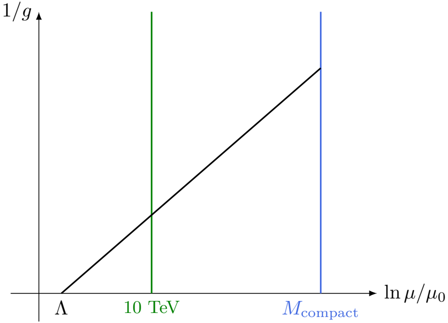
(Vertical line: $g(\mu)$, Horizontal line: μ)

$$g(\mu) = \frac{g_0}{\left[1 + (7Ng_0^3/48\pi^2)\ln\mu/\mu_0\right]^{1/2}}$$

From the solution, we can evaluate the confinement scale Λ:

$$\Lambda = \mu_0 \exp\left[-\frac{1}{7Ng_0^3/48\pi^2}\right].$$

If $N = 2, g_0 = 1/50, \mu_0 = 10^{16}$ GeV, then $\Lambda \sim 10^{-10^5} \sim 0$.



Some notes

- I choose the parameter $N = 2, g_0 = 1/50, \mu_0 = 10^{16}$ GeV by referring the Nakano-san's thesis.
- This result contradict with our assumption that the fermions are confined and construct the meson $M = \mathrm{tr}\,\tilde{Q}Q$. (I guessed that we assume it for F-term SUSY breaking, but I do not know why actually.)
- To obtain a desirable result, we should tune the initial gauge coupling g_0, since other parameters change Λ very little. If Λ is around 10 TeV, the coupling should be lower than $g \sim 1.57$ at the compactified scale $\mu = 10^{16}$ GeV, with $SU(2)$.

I would like to start a discussion on introducing magnetic flux.

The flux $M_A^{(i)}$ should satisfy a D-flat condition, but $\cdots\cdots$.

Discussion (?)

There are at least two ways to compute the D-flat condition:

1. Find potential vanishing condition naively:

$$\sum_{i=1,3} \frac{M_X^{(i)}}{\mathcal{A}^{(i)}} = \sum_{i=1,2} \frac{M_Y^{(i)}}{\mathcal{A}^{(i)}} = \sum_{i=1,2,3} \frac{M_N^{(i)}}{\mathcal{A}^{(i)}} = 0$$

2. Substitute the area of tori $\mathcal{A}^{(i)} \longrightarrow T^i$ and then evaluate $\partial_i V_D = 0$.

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2. Substitute the area of tori $\mathcal{A}^{(i)} \longrightarrow T^i$ and then evaluate $\partial_i V_D = 0$.

I guess the 2nd way is plausible, but

it conclude that we cannot assign the flux in this setup!

(The word "plausible" means that the first orders of the fluctuation δT^i vanish if we assume the 2nd way, rather than vanishing the zeroth order in the 1st way. Non vanishing first order terms occurs the shifts of the VEV $\langle T^i \rangle$.)

[5] L. E. Ibáñez and A. M. Uranga, Cambridge University Press, 2012.
[6] H. Abe, T. Kobayashi, K. Sumita, and S. Uemura, Phys. Rev. D **96** (2017) 026019, arXiv:1703.03402 [hep-th].

In $D7$-brane model, the relation between Kähler moduli and the area of the torus is

$$T_i = \mathcal{A}^{(j)}\mathcal{A}^{(k)} \longrightarrow \mathcal{A}^{(i)} = \sqrt{\frac{T_j T_k}{T_i}}$$

$$\Downarrow$$

$$V_D = \frac{1}{2}\left(V_X + (\text{matter})\right)^2 + \frac{1}{2}\left(V_Y + (\text{matter})\right)^2$$
$$V_X \equiv M_X^{(1)}\sqrt{\frac{T_1}{T_2 T_3}} + M_X^{(3)}\sqrt{\frac{T_3}{T_1 T_2}}$$
$$V_Y \equiv M_Y^{(1)}\sqrt{\frac{T_1}{T_2 T_3}} + M_Y^{(2)}\sqrt{\frac{T_2}{T_1 T_3}}$$

A D-flat condition should be

$$\partial_{T_i} V_D = 0 \quad \text{for } i = 1, 2, 3$$

$$\Downarrow$$

$$\begin{cases} M_X^{(1)} T_1 - M_X^{(3)} T_3 = 0, \\ M_X^{(1)} T_1 + M_X^{(3)} T_3 = 0, \\ M_Y^{(1)} T_1 - M_Y^{(2)} T_3 = 0, \\ M_Y^{(1)} T_1 - M_Y^{(2)} T_2 = 0, \\ M_Y^{(1)} T_1 + M_Y^{(2)} T_2 = 0. \end{cases}$$

$\longrightarrow$ all flux are zero:

$$M_X^{(1)} = M_X^{(3)} = M_Y^{(1)} = M_Y^{(2)} = 0$$

1. Find potential vanishing condition naively:

$$\sum_{i=1,3} \frac{M_X^{(i)}}{\mathcal{A}^{(i)}} = \sum_{i=1,2} \frac{M_Y^{(i)}}{\mathcal{A}^{(i)}} = \sum_{i=1,2,3} \frac{M_N^{(i)}}{\mathcal{A}^{(i)}} = 0 \qquad \clubsuit$$

2. Substitute the area of tori $\mathcal{A}^{(i)} \longrightarrow T^i$ and then evaluate $\partial_i V_D = 0$.

Thus, to introduce the flux, we may need to take the 1st way (?)

$$\clubsuit \implies \begin{cases} \dfrac{\mathcal{A}^{(3)}}{\mathcal{A}^{(1)}} = -\dfrac{M_X^{(3)}}{M_X^{(1)}} \\ \dfrac{\mathcal{A}^{(2)}}{\mathcal{A}^{(1)}} = -\dfrac{M_Y^{(2)}}{M_Y^{(1)}} \\ M_N^{(1)} M_X^{(3)} M_Y^{(2)} - M_N^{(2)} M_X^{(3)} M_Y^{(1)} - M_N^{(3)} M_X^{(1)} M_Y^{(2)} = 0 \end{cases}$$

The ratio of the torus is determined from the visible sector.

Break the gauge group $U(8) \to U(3)_C \times U(1)_l \times U(2)_L \times U(2)_R$

$$M^{(1)} = \left(\begin{array}{cc|cc} m_c^{(1)} \times \mathbf{1}_3 & & & \\ & m_l^{(1)} & & \\ \hline & & m_L^{(1)} \times \mathbf{1}_2 & \\ & & & m_R^{(1)} \times \mathbf{1}_2 \end{array}\right)$$

$$M^{(2)} = \left(\begin{array}{cc|cc} H \times \mathbf{1}_3 & & & \\ & H & & \\ \hline & & m_L^{(2)} \times \mathbf{1}_2 & \\ & & & m_R^{(2)} \times \mathbf{1}_2 \end{array}\right)$$

$$M^{(3)} = \left(\begin{array}{cc|cc} m_c^{(3)} \times \mathbf{1}_3 & & & \\ & m_l^{(3)} & & \\ \hline & & H \times \mathbf{1}_2 & \\ & & & H \times \mathbf{1}_2 \end{array}\right)$$

with Wilson line, and orbifolds $\mathbb{Z}_2 \times \mathbb{Z}_2'$.

There are five models $(m_c^{(i)}, m_l^{(i)}, m_L^{(i)}, m_R^{(i)})$ that have successfully realized the Yukawa matrix and CKM matrix to some extent.

For example,

$$\frac{\mathcal{A}^{(2)}}{\mathcal{A}^{(1)}} = \frac{1}{10},\ \frac{\mathcal{A}^{(3)}}{\mathcal{A}^{(1)}} = 1.$$

Thus, we should choose flux to satisfy

$$\frac{M_X^{(3)}}{M_X^{(1)}} = -1,\ \frac{M_Y^{(2)}}{M_Y^{(1)}} = -\frac{1}{10},$$

$$M_N^{(1)} M_X^{(3)} M_Y^{(2)} - M_N^{(2)} M_X^{(3)} M_Y^{(1)} - M_N^{(3)} M_X^{(1)} M_Y^{(2)} = 0$$

$$\Downarrow$$

Future works!

Summary

Summary

- I study the hidden sector of the magnetized D7-brane model.
- If the flux are zero, we need *artificial* tune for the initial parameter of the RG equation, for the consistency.
- If we rewrite a D-term potential in terms of Kähler moduli T^i, it conclude that we can *not* introduce a flux.

Future Works

- Which conditions we should impose for the D-flat condition?
- Determine the flux which consistent with the visible sector.
- Identify particles which are created by the flux and study the potential.

Appendix

Questions

I list them below:

- Why particles do not appear symmetrically in the flux model?
  $\longrightarrow$ Next page.
- If matters are created, its theory becomes far from *asymptotic free* in general. Thus, the flux-less is the best for the confinement?

$$\Phi^{(1)} = \left(\begin{array}{c|c} & \\ \hline & ? \\ & Q \end{array}\right) \begin{array}{l} X \\ N \\ Y \end{array}$$

$$\Phi^{(2)} = \left(\begin{array}{c|c} & X \\ \hline & \\ ? & \end{array}\right) \begin{array}{l} X \\ N \\ Y \end{array}$$

$$\Phi^{(3)} = \left(\begin{array}{c|c} & ? \\ \hline \tilde{Q} & \\ & \end{array}\right) \begin{array}{l} X \\ N \\ Y \end{array}$$

References

[1] H. Abe, T. Kobayashi, H. Ohki, and K. Sumita, *Superfield description of 10D SYM theory with magnetized extra dimensions*, Nucl. Phys. B **863** (2012) 1–18, arXiv:1204.5327 [hep-th].

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[4] S. P. Martin, *A Supersymmetry Primer*, arXiv:hep-ph/9709356, `http://arxiv.org/abs/hep-ph/9709356`.

[5] L. E. Ibáñez and A. M. Uranga, *String Theory and Particle Physics: An Introduction to String Phenomenology*. Cambridge University Press, Cambridge, 2012.

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