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Supersymmetric Gauge Theory

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Vacuum structure of spontaneously broken $\mathcal{N}=2$ supersymmetric gauge theory

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We analyze the vacuum structure of spontaneously broken $\mathcal{N}=2$ supersymmetric gauge theory with the Fayet-Iliopoulos term. Our theory is based on the gauge group $SU(2)\times U(1)$ with $N_f=1,2$ massless quark hypermultiplets having the same $U(1)$ charges. In the classical potential, there are degenerate vacua even in the absence of supersymmetry. It is shown that this vacuum degeneracy is smoothed out, once quantum corrections are taken into account. In the $N_f=1$ case, the effective potential is found to be the so-called runaway type, and there is neither a well-defined vacuum nor a local minimum. On the other hand, in the $N_f=2$ case, while there is also the runaway direction in the effective potential, we find the possibility that there appears a local minimum with broken supersymmetry at the degenerate dyon point.

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I. INTRODUCTION

There has been much progress in understanding the dynamics of strongly coupled $\mathcal{N}=1,2$ supersymmetric (SUSY) gauge theories. The exact effective superpotential can be derived for $\mathcal{N}=1$ SUSY QCD (SQCD) by using the holomorphicity properties of the superpotential and the gauge kinetic function [1]. Seiberg and Witten derived the exact low energy Wilsonian effective action for $\mathcal{N}=2$ SUSY $SU(2)$ Yang-Mills theory [2], and generalized their discussion to the case with up to four massive quark hypermultiplets [3]. The key ingredients which allow us to derive the exact results are duality and holomorphicity. One can write down the prepotential and the gauge couplings in terms of the meromorphic differential on the Riemann surface with genus 1 whose properties are determined by the dynamical scale and the hypermultiplet masses.

The results by Seiberg and Witten were extended to the case of the explicit soft SUSY breaking terms by using the spurion technique. If these terms do not change the holomorphicity and duality properties of the theory, we can derive the exact effective action for $\mathcal{N}=1$ and $\mathcal{N}=0$ (nonsupersymmetric) SUSY gauge theories up to the leading order for the soft SUSY breaking terms. In Refs. [4–6], the exact superpotential and the phase structure in $\mathcal{N}=1$ SQCD were discussed based on the $\mathcal{N}=2$ SUSY gauge theory with some soft breaking terms. In Refs. [7–10], the vacuum structure of nonSUSY gauge theory was investigated in which soft SUSY breaking terms directly break $\mathcal{N}=2$ SUSY to $\mathcal{N}=0$. As further extensions, the method to introduce nonholomorphic soft SUSY breaking terms was recently discussed [11].

In this paper, we study a spontaneously broken $\mathcal{N}=2$ SUSY gauge theory. It is well known that, in the framework of $\mathcal{N}=2$ SUSY theory, the only possibility to break SUSY spontaneously is to introduce the Fayet-Iliopoulos (FI) term [12]. Therefore, in the following, we consider the gauge theory which includes $U(1)$ gauge interaction together with the FI term.

The simplest example of this type of theory is $\mathcal{N}=2$ SUSY QED (SQED) with the FI term [13]. At the classical level, although SUSY is spontaneously broken in the Coulomb branch, there are degenerate vacua (moduli space) which are parametrized by the vacuum expectation value of the scalar field $a$ in the $U(1)$ vectormultiplet. The direction of this vacuum degeneracy in the absence of SUSY is called the “pseudoflat” direction. However, it is expected that this direction is lifted up, once quantum corrections are taken into account. By virtue of $\mathcal{N}=2$ SUSY, the effective action is found to be one loop exact, and the effective gauge coupling is given by $e(a)^2\sim 1/\log(A_L/a)$, where $A_L$ is the Landau pole. Note that there are two singular regions in moduli space, namely, the ultraviolet region such as $|a|\gg A_L$, and the massless singular point at the origin $a=0$. Since the effective potential is described as $V(e(a))=1/\log(a/a_0)$, the potential minimum emerges at the origin, where SUSY is formally restored. However, since this point is the singular point, we conclude that there is no well-defined vacuum in this theory.

In this paper, we investigate the vacuum structure of a more interesting theory with spontaneous $\mathcal{N}=2$ SUSY breaking. Our theory is based on the gauge group $SU(2)\times U(1)$ with $N_f=1,2$ massless quark hypermultiplets having the same $U(1)$ charges. In the ultraviolet region, the behavior of the effective potential can be well understood based on the perturbative discussion, since the $SU(2)$ gauge interaction is weak there. On the other hand, it is expected that the behavior of the effective potential in the infrared region is drastically changed compared with SQED, because of the presence of the $SU(2)$ gauge dynamics.

The paper is organized as follows. In the next section, we briefly discuss the classical structure of our theory. It is shown that the classical potential has the pseudoflat direction. In Sec. III, the low energy effective action is discussed. In subsection A, we first make our framework clear, and give

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general formulas of the effective action. The effective potential can be read off from this effective action, and is explicitly presented in subsection B. In subsection C, we give the explicit formulas for the periods and the effective gauge couplings which are necessary to analyze the effective potential. In Sec. IV, the effective potential is numerically analyzed, and the vacuum structures of our theory are investigated for both cases of $N_f = 1$ (subsection A) and $N_f = 2$ (subsection B). In Sec. V, we give our conclusions. Some formulas and technical details used in our analysis are summarized in Appendices A and B.

II. CLASSICAL STRUCTURE OF $\mathcal{N}=2$ SU(2)×U(1) GAUGE THEORY

In this section, we briefly discuss the classical structure of our theory. The complete analysis of the classical potential was originally addressed in Ref. [12].

We describe the classical Lagrangian in terms of $\mathcal{N}=1$ superfields: adjoint chiral superfield $A_i$, superfield strength $W_i$, and vector superfield $V_i$ in the vectormultiplet ($i = 1, 2$ denote the index of the U(1) and the SU(2) gauge symmetries, respectively), and two chiral superfields $Q_i^\alpha$ and $\tilde{Q}_i^\alpha$ in the hypermultiplet [$i = 1, \ldots, N_f$ is the flavor index, and $\alpha = 1, 2$ is the SU(2) color index]. The classical Lagrangian is given by

$$L = L_{HM} + L_{VM} + L_{FI},$$

where

$$L_{HM} = \int d^4 \theta \left( Q_i^\alpha e^{v^2 V_i^\dagger + 2 V_i^\dagger Q_i^\alpha + \tilde{Q}_i^\alpha e^{-v^2 V_i^\dagger + 2 V_i^\dagger \tilde{Q}_i^\alpha}} \right),$$

$$L_{VM} = \frac{1}{2 \pi} \text{Im} \left[ \tau_{22} \left( \int d^4 \theta A_2^\dagger e^{v^2 V_2^\dagger} - 2 V_2^\dagger \right) + \frac{1}{4 \pi} \text{Im} \left[ \tau_{11} \left( \int d^4 \theta A_1^\dagger A_1 \right) + \frac{1}{2} \int d^2 \theta W_2^2 \right] \right],$$

$$L_{FI} = \int d^4 \theta \xi V_1,$$

and

$$V = \frac{1}{8^2} \text{tr} \left[ A_2^\dagger A_2 \right]^2 + \frac{g^2}{2} \left( q_i^\alpha T^a q_i^\dagger - \tilde{q}_i^\dagger T^a (\tilde{q}_i^*)^\dagger \right)^2 + q_i^\dagger A_i^\dagger A_i^\dagger [A_2^\dagger A_2 \right],$$

where $A_2, A_1, q_i^\dagger, \tilde{q}_i^\dagger$ are scalar components of the corresponding chiral superfields, respectively. The potential minimum is obtained by solving the stationary conditions with respect to these scalar components. There are some solutions, and one example is given by

$$q_i^\dagger = 0, \quad \tilde{q}_i^\dagger = 0, \quad \xi = 0, \quad j \neq 1,$$

$$A_2 + A_1 = \left( \begin{array}{cc} a_2/2 & 0 \\ 0 & -a_2/2 \end{array} \right) + \left( \begin{array}{cc} a_1 & 0 \\ 0 & a_1 \end{array} \right) = \left( \begin{array}{cc} 0 & 0 \\ 0 & z \end{array} \right),$$

where $a_1$ and $a_2$ are complex parameters and $z$ is an arbitrary constant. In this example, the gauge symmetry SU(2)×U(1) is broken to U(1). The potential energy is given by

$$V = \frac{\xi^2}{2} \left( e^2 g^2 \right) = \frac{\xi^2}{2} \left( e^2 g^2 \right).$$

Note that the classical potential has the pseudopotential direction parametrized by $a_1$ or $a_2$ with the condition $a_1 + i a_2 = 0$. We expect that this direction is lifted up, once quantum corrections are taken into account, and the true nondegenerate vacuum is selected out after the effective potential is analyzed. This naive expectation seems natural if we notice that the above potential energy is described by the bare gauge couplings, which should be replaced by the effective one (nontrivial functions of moduli parameters) in the effective theory.

III. QUANTUM STRUCTURE OF $\mathcal{N}=2$ SU(2)×U(1) GAUGE THEORY

A. Effective action

In this subsection, we describe the low energy Wilsonian effective Lagrangian of our theory. If we could completely integrate the action to zero momentum, the exact effective Lagrangian $L_{\text{EXACT}}$ could be obtained, which is described by light fields, the dynamical scale, and the coefficient of the FI term $\xi$. However, this is highly nontrivial and a very difficult task. In the following discussion, suppose that the coefficient $\xi$, the order parameter of SUSY breaking, is much smaller than the dynamical scale of the SU(2) gauge interaction.
Then we consider the effective action up to the leading order of $\xi$. The exact effective Lagrangian, if it could be obtained, can be expanded with respect to the parameter $\xi$ as

$$L_{\text{exact}} = L_{\text{SUSY}} + \xi L_1 + O(\xi^2).$$  \hspace{1cm} (8)

Here, the first term $L_{\text{SUSY}}$ is the exact effective Lagrangian containing full SUSY quantum corrections. The second term is the leading term of $\xi$, which is nothing but the FI term at tree level.\footnote{Considering all the symmetries of our theory, we find that the FI term is tree-level exact [13].} Analyzing the effective Lagrangian up to the leading order of $\xi$, we obtain the effective potential of the order of $\xi^2$. The coefficient of $\xi^2$ in the effective potential includes full SUSY quantum corrections. Therefore, in our aim, what we need to analyze the effective potential is nothing but the effective Lagrangian $L_{\text{SUSY}}$.

Except for the FI term, the classical SU(2) $\times$ U(1) gauge theory has moduli space, which is parametrized by $a_2$ and $a_1$. On this moduli space except for the origin, the gauge symmetry is broken to U(1)$_c$. Here $U(1)_c$ denotes the gauge symmetry in the Coulomb phase originated from the SU(2) gauge symmetry. Before discussing the effective action of this theory, we should make it clear how to treat the U(1) gauge interaction part. In the following analysis, this part is, as usual, discussed as a cutoff theory.\footnote{There is a possibility that the nontrivial fixed point and the strong coupling phase exist in QED [14]. This problem is very difficult, and is out of our scope (see also Ref. [13] for related discussions).} Thus, the Landau pole is inevitably introduced in our effective action of this theory, we should make it clear how to treat the U(1) gauge interaction part. In the following analysis, this part is, as usual, discussed as a cutoff theory.\footnote{This detail is necessary for the monodromy transformation [9].}

The part $L_{\text{HM}}$ is described by a light hypermultiplet with appropriate quantum number $(n_e, n_m)_n$, where $n_e$ is electric charge, $n_m$ is magnetic charge, and $n$ is the U(1) charge. This part should be added to the effective Lagrangian around a singular point on moduli space, since the hypermultiplet is expected to be light there and enjoys correct degrees of freedom in the effective theory. The explicit description is given by

$$L_{\text{HM}} = \int d^4 \theta (M^1 e^{2n_v V_{2D} + 2n_V} + 2n_V + 2n_V)$$

$$\times M + \bar{M} e^{-2n_m V_{2D} - 2n_V - 2n_V} + \sqrt{2} \left( \int d^2 \theta \bar{M} (n_a A_{2D} + n_a A_2 + n A_1) M + H.c. \right),$$

\hspace{1cm} (11)

where $M$ and $\bar{M}$ denote light quark or light dyon hypermultiplet, that is, the light Bogomol'nyi-Prasad-Sommerfield (BPS) state, and $V_{2D}$ is the dual gauge field of U(1)$_c$.

In order to obtain an explicit description of the effective Lagrangian, let us consider the monodromy transformation of our theory. Suppose that moduli space is parametrized by the vectormultiplet scalars $a_2$, $a_1$ and their duals $a_{2D}$, $a_{1D}$ which are defined as $a_{iD} = \partial F / \partial a_i$ ($i = 1, 2$). These variables are transformed into their linear combinations by the monodromy transformation. In our case, the monodromy transformation is subgroup of $Sp(4, \mathbb{R})$, which leaves the effective Lagrangian invariant, and the general formula is found to be

$$L_{\text{VM}} = \sum_{i,j} \left( M^1 a_{2D}^{\prime} + p a_{2D} + qa_{2D} \right) W_{ij}$$

$$\left( \begin{array}{c}
\begin{array}{c}
M^1 a_{2D}^{\prime} + p a_{2D} + qa_{2D} \\
\gamma a_{2D} + \delta a_2 + qa_1 \\
\alpha a_{1D} + \beta a_2 + pa_1 \\
\end{array}
\end{array} \right) ,$$

\hspace{1cm} (12)

where $(\alpha, \beta, \gamma, \delta, p, q) \in SL(2, \mathbb{Z})$ and $p, q \in \mathbb{Q}$. Note that this monodromy transformation for the combination $(a_{2D}, a_2, a_1)$ is exactly the same as that for SQCD with massive quark hypermultiplets, if we regard $a_1$ as the same mass of the hypermultiplets such that $m = \sqrt{2} a_1$. This fact means that the U(1) gauge interaction part plays the only role as the mass...
term for the SU(2) gauge dynamics. This observation is consistent with our assumption. On the other hand, the SU(2) dynamics plays an important role for the U(1) gauge interaction part, as can be seen in the transformation law of $a_{1D}$. This monodromy transformation is also used to derive dual variables associated with the BPS states. As a result, the prepotential of our theory turns out to be essentially the same as the result in Ref. [3] with understanding the relation $A_1 = m/\sqrt{2},$

$$F(A_2, A_1, \Lambda_N, \Lambda_L) = F^{(SW)}_{SU(2)}(A_2, m, \Lambda_N)\big|_{A_1 = m/\sqrt{2} + C A_1^2},$$

where the first term is the prepotential of $\mathcal{N}=2$ SQCD with hypermultiplets having the same mass $m$, and $C$ is the free parameter. The freedom of the parameter $C$ is used to determine the scale of the Landau pole relative to the scale of the SU(2) dynamics.

B. Effective potential

The effective potential can be read off from the above Lagrangian with the FI term such that

$$V = b_{11}|F_1|^2 + b_{12}(F_1^2 + F_1^1 + F_2^2) + b_{22}|F_2|^2$$

$$+ \frac{1}{2}b_{11}D_1^2 + b_{21}D_1^3 + \frac{1}{2}b_{22}D_2^2 + (D_2 + nD_1)(|M|^2 + |\tilde{M}|^2 + |F_M|^2 + |\tilde{F}_M|^2 + a_2M\tilde{M} + a_2\tilde{M}M)$$

$$+ a_2MF_M + H.c.) + \sqrt{2}(nF_1M\tilde{M} + na_1MF_M)$$

$$+ na_1\tilde{M}F_M + H.c.) + \xi D_1,$$

where $F_j (j = 1, 2, M, \tilde{M})$ denotes the auxiliary field of the corresponding chiral multiplet, $D_j (j = 1, 2)$ denotes the auxiliary field of the corresponding vector multiplet $V_j$, and the effective gauge coupling is defined as $b_{ij} = (1/4\pi) Im \tau_{ij}$. Eliminating these auxiliary fields by using their equations of motion,

$$D_1 = \frac{1}{\det b}((-b_{21} - nb_{22})(|M|^2 - |\tilde{M}|^2) - \xi b_{22})$$

$$D_2 = \frac{1}{\det b}((-b_{11} - nb_{12})(|M|^2 - |\tilde{M}|^2) + \xi b_{12})$$

$$F_1 = \frac{\sqrt{2}}{\det b}(b_{12} - nb_{22})(M\tilde{M})^\dagger,$$

$$F_2 = \frac{\sqrt{2}}{\det b}(b_{12} - nb_{11})(M\tilde{M})^\dagger,$$

$$F_M = -\sqrt{2}(a_2^1 + na_1^1)\tilde{M}^\dagger,$$

$$F_{\tilde{M}} = -\sqrt{2}(a_2^1 + na_1^1)M^\dagger,$$

where $\det b = b_{22}b_{11} - b_{12}b_{21},$ we obtain

$$V = \frac{b_{22}}{2\det b} \xi^2 + S(a_2, a_1)(|M|^2 - |\tilde{M}|^2)^2 + 4|M\tilde{M}|^2$$

$$+ 2T(a_2, a_1)(|M|^2 + |\tilde{M}|^2) - U(a_2, a_1)(|M|^2 - |\tilde{M}|^2),$$

where $S, T,$ and $U$ are defined as

$$S(a_2, a_1) = \frac{1}{b_{22}} + \frac{(b_{12} - nb_{22})^2}{2b_{22}\det b},$$

$$T(a_2, a_1) = |a_2 + na_1|^2,$$

$$U(a_2, a_1) = \frac{b_{12} - nb_{22}}{\det b} \xi.$$

The stationary conditions with respect to the hypermultiplets,

$$\frac{\partial V}{\partial M} = M\{2S(|M|^2 - |\tilde{M}|^2) + 2T - U\} + 4SM^\dagger(M\tilde{M}) = 0,$$

$$\frac{\partial V}{\partial \tilde{M}^\dagger} = \tilde{M}\{-2S(|M|^2 - |\tilde{M}|^2) + 2T + U\} + 4S\tilde{M}(M\tilde{M})$$

$$= 0,$$

lead to three solutions as follows:

1. $M = \tilde{M} = 0$; $V = \frac{b_{22}}{2\det b} \xi^2.$

2. $|M|^2 = -\frac{2T - U}{2S}$, $M = 0$;

$$V = \frac{b_{22}}{2\det b} \xi^2 - S|M|^4.$$

3. $M = 0$, $|\tilde{M}|^2 = -\frac{2T + U}{2S}$;

$$V = \frac{b_{22}}{2\det b} \xi^2 - S|\tilde{M}|^4.$$
The solution Eq. (23) or Eq. (24), in which the light hypermultiplet acquires the vacuum expectation value, is energetically favored, because of det $b > 0$ and $S(a_2, a_1) > 0$. Since the hypermultiplet appears in the theory as the light BPS state around the singular point on moduli space, the potential minimum is expected to emerge there. On the other hand, the solution Eq. (22) describes the potential energy away from the singular points, which smoothly connects with the solution Eq. (23) or Eq. (24).

C. Periods and effective couplings

It was shown that the effective potential is described by the periods $a_{2D}$, $a_2$, and the effective gauge coupling $b_{ij}$. In this subsection, we derive the periods and the effective gauge couplings in order to give an explicit description of the effective potential. As already discussed, the periods are the same as that of SQCD, which were derived in both cases with the massless [15–18] and the massive [9,19–21] hypermultiplets. There are some different descriptions of the periods with such as the Weierstrass functions [9], the hypergeometric functions [19], the modular functions [20], and the elliptic integrals [21]. In our analysis, we use the integral representation. On the other hand, the effective coupling $\tau_{ij}$ is described in terms of the Weierstrass functions.

We first review how to obtain the periods $a_{2D}$ and $a_2$. The elliptic curves of $\mathcal{N} = 2$ SQCD with hypermultiplets having the same mass $m$ were found to be [3]

$$y^2 = x^2 (x-u) + P_{N_f}(x,u,m,\Lambda_{N_f}),$$

where the polynomials $P_{N_f}(N_f=1,2)$ are given by

$$P_1 = \frac{\Lambda_1^3}{4} mx^3 - \frac{\Lambda_1^6}{64},$$

$$P_2 = -\frac{\Lambda_2^4}{64} (x-u) + \frac{\Lambda_2^2}{4} m^2 x - \frac{\Lambda_2^4}{32} m^2.$$

In this case, the mass formula of the BPS state with the quantum number $(n_e,n_m)_n$ is given by $M_{BPS} = \sqrt{2} |n_m a_{2D} + n_e a_2 + n m|/\sqrt{2}$. If $\lambda$ is a meromorphic differential on the curve Eq. (25) such that

$$\frac{\partial \lambda}{\partial u} = \frac{\sqrt{2}}{8 \pi} \frac{dx}{y},$$

the periods are given by the contour integrals

$$a_{2D} = \oint_{\alpha_1} \lambda, \quad a_2 = \oint_{\alpha_2} \lambda,$$

where the cycles $\alpha_1$ and $\alpha_2$ are defined so as to encircle $e_2$ and $e_3$, and $e_1$ and $e_3$, respectively (see Fig. 1). Meromorphic differentials are given by

$$\lambda^{(N_f=1)} = -\frac{\sqrt{2}}{4\pi} \frac{y \ dx}{x^2} = \frac{\sqrt{2}}{4\pi} \frac{dx}{2y} \left[ 3x - 2u + \frac{m \Lambda_1^2}{4x} \right],$$

$$+ \frac{dx}{2y} \left[ \frac{\Lambda_1^2}{4} \right],$$

$$\lambda^{(N_f=2)} = -\frac{\sqrt{2}}{4\pi} \frac{y \ dx}{x^2 - \frac{\Lambda_4^2}{64}} = -\frac{\sqrt{2}}{4\pi} \frac{dx}{y} \left[ x - u + \frac{m^2 \Lambda_2^2}{4 \left( x + \frac{\Lambda_2^2}{8} \right)} \right].$$

Each differential has the single pole at $x = 0$ for $N_f=1$ and $x = -\Lambda_2/8$ for $N_f=2$. For both cases, the residue is given by

$$\text{Res} \lambda^{(N_f)} = \frac{1}{2\pi i} \left( -\frac{m}{\sqrt{2}} \right).$$

We calculate the periods by using the Weierstrass normal form for later convenience. In this form, the algebraic curve is rewritten by new variables $x = 4X + u/3$ and $y = 4Y$, such that

$$Y^2 = 4X^3 - g_2^{(N_f)} X - g_3^{(N_f)} = 4(X - a_1)(X - a_2)(X - a_3),$$

where $g_2^{(N_f)}$ and $g_3^{(N_f)}$ are explicitly written by

$$g_2^{(1)} = \frac{u^2}{3} - \frac{m \Lambda_1^2}{3},$$

$$g_3^{(1)} = \frac{1}{16} \left( \frac{m u \Lambda_1^2}{2} + \frac{\Lambda_1^6}{12} + \frac{2u^3}{27} \right),$$

$$g_2^{(2)} = \frac{1}{16} \left( \frac{4}{3} u^2 + \frac{\Lambda_2^4}{16} - \frac{m^2 \Lambda_2^2}{2} \right),$$

$$g_3^{(2)} = \frac{1}{16} \left( \frac{m^2 \Lambda_2^2}{32} - \frac{u}{12} m^2 \Lambda_2^2 - \frac{u \Lambda_2^2}{96} + \frac{2u^3}{27} \right).$$
Converting the Seiberg-Witten differentials of Eqs. (30) and (31) into the Weierstrass normal form and substituting them into Eq. (29), we obtain the integral representations of the periods as follows ($a_{2D}$ and $a_2$ are denoted by $a_{21}$ and $a_{22}$, respectively):

\begin{align}
    a_{21}^{(N_f-1)} &= -\frac{\sqrt{2}}{4\pi} \left( -u I_1^{(i)} + 12 I_2^{(i)} + \frac{m\Lambda_1^3}{16} I_3^{(i)}(c) \right), \\
    a_{21}^{(N_f-2)} &= -\frac{\sqrt{2}}{4\pi} \left( -4 I_1^{(i)} + 8 I_2^{(i)} + \frac{m^2\Lambda_2^2}{8} I_3^{(i)}(c) \right),
\end{align}

where $c$ is the pole of the differentials, and $c = -u/12$ for $N_f = 1$ and $c = -u/12 - \Lambda_2^2/32$ for $N_f = 2$. Integrals $I_1^{(i)}, I_2^{(i)},$ and $I_3^{(i)}$ are defined as

\begin{align}
    I_1^{(i)} = \frac{1}{2} \int_{a_i} \frac{dX}{Y}, \quad I_2^{(i)} = \frac{1}{2} \int_{a_i} \frac{XdX}{Y}, \quad I_3^{(i)}(c) = \frac{1}{2} \int_{a_i} \frac{dX}{Y(c)}.
\end{align}

The roots $e_i$ of the polynomial defining the cubic are chosen so as to lead to the correct asymptotic behavior for large $|u|$, and

\begin{align}
    a_{2D}^{(N_f)}(u) &\sim \frac{4 - N_f}{2\pi} \sqrt{2u} \log \frac{u}{\Lambda_2^2}, \\
    a_2^{(N_f)}(u) &\sim \frac{\sqrt{2}u}{2}.
\end{align}

A correct choice is the following:

\[
    N_f = 1 \quad \text{case:} \quad e_1 = \frac{1}{48} \left( -24\Lambda_1^3 m + 32u^2 + 2^{1/3}H(u,m,\Lambda_1)^{2/3} \right) / H(u,m,\Lambda_1)^{1/3}, \\
    e_2 = \frac{1}{96} \left( 8(1-3i)(3\Lambda_1^3 m - 4u^2) - 2^{1/3}i(-i + \sqrt{3})H(u,m,\Lambda_1)^{2/3} \right) / 2^{2/3}H(u,m,\Lambda_1)^{1/3}, \\
    e_3 = \frac{1}{96} \left( 8(1+3i)(3\Lambda_1^3 m - 4u^2) + 2^{1/3}i(i + \sqrt{3})H(u,m,\Lambda_1)^{2/3} \right) / 2^{2/3}H(u,m,\Lambda_1)^{1/3},
\]

\[
    H(u,m,\Lambda_1) = 27\Lambda_1^6 + 128u^3 + 3\Lambda_1^3[-48mu + \sqrt{3}\sqrt{27\Lambda_1^6 - 256(m^2 - u)u^2} + 32\Lambda_1^3(8m^3 - 9mu)];
\]

\[
    N_f = 2 \quad \text{case:} \quad e_1 = \frac{u}{24} - \frac{\Lambda_2^2}{64} = \frac{1}{8} \sqrt{u + \frac{\Lambda_2^2}{8} + \Lambda_2 m} \sqrt{u + \frac{\Lambda_2^2}{8} - \Lambda_2 m}, \\
    e_2 = \frac{u}{24} - \frac{\Lambda_2^2}{64} + \frac{1}{8} \sqrt{u + \frac{\Lambda_2^2}{8} + \Lambda_2 m} \sqrt{u + \frac{\Lambda_2^2}{8} - \Lambda_2 m}, \quad e_3 = -\frac{u}{12} + \frac{\Lambda_2^2}{32}.
\]

Fixing the contours of the cycles relative to the positions of the poles, which is equivalent to fix the U(1) charges (baryon numbers) for the BPS states, the final formulas are given by

\[
    a_{21}^{(N_f-1)} = -\frac{\sqrt{2}}{4\pi} \left[ -u I_1^{(i)} + 12 I_2^{(i)} + \frac{m\Lambda_1^3}{16} I_3^{(i)}(c) - \frac{u}{12} \right], \\
    -\frac{m}{\sqrt{2}} \delta_{12}, \quad \text{with the integral} \quad I_1^{(i)}(i = 1,2) \text{ explicitly given by}
\]

\[
    I_1^{(i)} = \int_{e_2}^{e_3} \frac{dX}{\sqrt{e_2 - e_1}},
\]

\[
    \delta_{12} = \frac{1}{2} \int_{a_{12}} \frac{dX}{Y}, \quad I_2^{(i)} = \frac{1}{2} \int_{a_{12}} \frac{XdX}{Y}.
\]
\[ I_2^{(1)} = \int_{e_2}^{e_3} e X \, dX = \frac{i e_1}{e_2 - e_1} K(k') + i \sqrt{e_2 - e_1} E(k'), \]

\[ I_3^{(1)} = \int_{e_2}^{e_3} \frac{dX}{Y(X - c)} = -\frac{i}{(e_2 - e_1)^{3/2}} \frac{1}{k + c} K(k') + \frac{4k}{1 + k} \frac{1}{c^2 - k^2} \Pi_1\left( \nu, \frac{1 - k}{1 + k} \right), \]

where \( k^2 = (e_3 - e_1)/(e_2 - e_1), \) \( k'^2 = 1 - k^2 = (e_2 - e_3)/(e_2 - e_1), \) \( \tilde{c} = (c - e_1)/(e_2 - e_1), \) and \( \nu = -[(k + \tilde{c})/(k - \tilde{c})]^2 [(1 - k)/(1 + k)]^2. \) The formulas for \( I_1^{(1)} \) are obtained from \( I_i^{(1)} \) by exchanging the roots, \( e_1 \) and \( e_2. \) In Eqs. (46)–(48), \( K, E, \) and \( \Pi_1 \) are the complete elliptic integrals [22] given in Appendix A.

Next let us consider the effective coupling defined as Eq. (10). The effective couplings \( \tau_{22} \) and \( \tau_{12} = \tau_{21} \) are obtained by

\[ \tau_{22} = \left. \frac{\partial a_{2 \alpha}}{\partial a_2} \right|_{a_2} = \frac{\omega_1}{\omega_2}, \]

\[ \tau_{12} = \left. \frac{\partial a_{2 \alpha}}{\partial a_1} \right|_{a_2} = \frac{\partial a_{2 \beta}}{\partial a_1} \bigg|_u = \left. \tau_{22} \frac{\partial a_2}{\partial a_1} \right|_u = -\frac{2z_0}{\omega_2}, \]

where \( \omega_i \) is the period of the Abelian differential,

\[ \omega_i = \oint_{a_i} \frac{dX}{Y} = 2I_1^{(i)}(i = 1, 2), \]

and \( z_0 \) is defined as

FIG. 2. The contour of the integral Eq. (53).

FIG. 3. The effective gauge couplings \( b_{ij} \) for \( a_1 = \sqrt{2} \) along the real \( u \) axis.

FIG. 4. The flow of the singular points on the \( u \) plane for fixed \( a_1 \) in the case \( \text{Im} a_1 = 0. \) The left figure shows the positions of the singular points for \( a_1 = 0, \) the upper figures shows the evolutions of the singular points for \( a_1 > 0, \) and the lower figures show them as \( a_1 < 0 \) is decreasing.
Here $F(\phi, k)$ is the incomplete elliptic integral of the first kind given in Appendix B. The effective coupling $\tau_{11}$ is described in terms of the Weierstrass function. First consider the period $a_{11D}$ by using the Riemann bilinear relation [23],

$$
\int_{a_1}^{a_2} \phi \int_{a_2}^{a_1} \omega = \int_{a_1}^{a_2} \phi \int_{a_2}^{a_1} \omega = 2 \pi i \sum_{n=1}^{N_p} \text{Res}_{\phi} \phi \int_{s_n^+}^{s_n^-} \omega,
$$

(53)

where $\phi$ and $\omega$ are meromorphic and holomorphic differentials, respectively, $N_p$ is the number of poles ($N_p=1$ in our case), and $s_n^+$ are poles of $\phi$ on the positive and negative Riemann sheets. Substituting $\phi = \partial \Lambda_{SW}^{(N)} / \partial a_1$ and $\omega = \partial \Lambda_{SW}^{(N)} / \partial a_2$ into Eq. (53), we obtain (see Fig. 2 for the definition of the contour)

$$
a_{11D}^{(N)} = - \sum_{n=1}^{N_p} \int_{s_n^+}^{s_n^-} \Lambda_{SW} + \tilde{C},
$$

(54)

where $\tilde{C}$ is a constant independent of $a_2$. The effective coupling $\tau_{11}$ is obtained by differentiating Eq. (54) with respect to $a_1$ with $a_2$ fixed. This integral can be evaluated by the uniformization method discussed in Appendix B. After regularizing the integral by using the freedom of the constant $\tilde{C}$, we finally obtain (see also Appendix B for details)

$$
\tau_{11} = - \frac{1}{\pi i} \left[ \log \sigma(2z_0) + \frac{4z_0^2}{\omega_2} I_{1D}^{(2)} \right] + C,
$$

(55)

where $\sigma$ is the Weierstrass sigma function, and $C$ is the constant in Eq. (13).

Note that, since the gauge coupling $b_{11}$ is found to be a monotonically decreasing function of large $|a_1|$ with fixed $u$, and vice versa (see, for example, Fig. 3 in the case of fixed $a_1$), the scale of the Landau pole is defined as $|a_1| = \Lambda_L$ at which $b_{11} = 0$. The large $\Lambda_L$ required by our assumption is realized by taking an appropriate value for $C$. In the following analysis, we fix $C = 4 \pi i$, which corresponds to $\Lambda_L \sim 10^{17-18}$ for fixed $\Lambda_N \sim O(1)$.

In the $N_f=1$ case, we plot the effective couplings $b_{ij}$ along real $u$ axis in Fig. 3. Here, the dynamical scale is normalized as $\Lambda_1 = (256/27) \Lambda_L$, and the parameter $a_1 = \sqrt{2}$ is fixed. As expected, in the figure of $b_{22}$, there are three singular points: the dyon point ($u \sim -2.6$), the monopole point ($u \sim -2.4$), and the quark singular point ($u \sim -4.2$). While the existence of the quark singular point is understood based on the perturbative discussion, the appearance of the dyon and the monopole singular points is the result from the SU(2) dynamics. Note that, in addition to the quark singular point, there appear two singular points in the figures of $b_{12}$ and $b_{11}$. This result means that the SU(2) dynamics plays an important role for the U(1) gauge interaction part in the infrared region on the moduli space, as pointed out in subsection A.

### IV. POTENTIAL ANALYSIS

Based on the results given by the previous sections, let us now investigate the vacuum structure of our theory. Since the effective potential is the function of two complex moduli parameters $u$ and $a_1$, it is a very complicated problem to figure out behaviors of the effective potential in the whole parameter space. However, note that for our aim it is enough to evaluate the potential energy just around the singular points, since these points are energetically favored [see Eqs. (22)–(24)]. The singular points on the moduli space parameterized by $u$ flow according to the variation of $a_1$. In the following discussion, we evaluate the effective potential along the flow of the singular points, and examine which point is energetically favored on the line of the flow.

![FIG. 5. The effective potential around the (2,1)$_1$ dyon point for $a_1 = 0$ and $\xi = 0.1, 0.3, 0.5$ (from left to right) along the real $u$ axis.](image)

![FIG. 6. The left figure shows the effective potential for $a_1 = 1/8$ (left), 0 (middle), −1/8 (right). The right figure shows the evolution of the potential energy along the flow of the (2,1)$_1$ dyon point.](image)
A. Vacuum structure in the $N_f=1$ case

Here we analyze the vacuum structure of our theory in the $N_f=1$ case. Let us first discuss the flow of the singular points. In the following analysis, the dynamical scale is fixed as $\Lambda_1=(256/27)^{1/6}$. The singular points on the $u$ plane are given by the solutions of the cubic polynomial [3].

$$\Delta = \frac{\Lambda_1^6}{16} - u^3 + m^2 u^2 + \frac{9}{8} \Lambda_1^3 m u - \Lambda_1^3 m^2 - \frac{27}{256} \Lambda_1^6$$

$$= 0.$$  \hspace{1cm} (56)

For simplicity, we consider the case $\text{Im} a_1 = 0$ in the following. The flow of the singular points is sketched in Fig. 4. For $a_1=0$, there are three singular points at $u_1 = 1/2$, $u_2 = \exp(i\pi/3)$ and $u_3 = \exp(-i\pi/3)$, respectively. These singular points correspond to the appearance of the BPS states with quantum numbers $(n_c,n_m) = (2,1)$, $(1,1)$, and $(0,1)$, respectively. In this case, there is nonanomalous $Z_3$ symmetry on the moduli space. The $(2,1)_1$ dyon point is moving to the left on real $u$ axis, as $a_1$ is increasing. The $(1,1)_1$ dyon point and the $(0,1)_0$ monopole point are moving to the right and approaching real $u$ axis, and eventually collide on the real $u$ axis for $a_1 = (3/4\sqrt{2})\Lambda_1$. This collision point is called the Argyres-Douglas (AD) point [24], at which the two collapsing states are simultaneously massless, and the theory is believed to transform into the superconformal theory. After the collision and for $a_1 > (3/4\sqrt{2})\Lambda_1$, quantum numbers of two BPS states, $(n_c,n_m) = (1,1)_1$ and $(0,1)_0$, change into $(1,0)_1$ and $(0,1)_0$, respectively, due to the conjugation of monodromy [21]. As $a_1$ is increasing further, both of the singular points, $u_2$ and $u_3$, are moving to the right on the real $u$ axis ($u_2$ approaches the infinity faster than $u_3$). On the other hand, as $a_1$ is decreasing from $a_1=0$, the dyon point $u_1$ is moving to the right on the real $u$ axis. The dyon point $u_2$ and the monopole point $u_3$ are approaching the imaginary $u$ axis to the infinites, $u_2 \rightarrow +i\infty$ and $u_3 \rightarrow -i\infty$, respectively.

Before analyzing the vacuum structure, let us see the dependence of the effective potential on the SUSY breaking parameter $\xi$. For $a_1=0$, the effective potential around the dyon singular point $u_1$ is depicted in Fig. 5, with various values of $\xi$. In the left figure, the top figure with the cusp and the bottom figure show the effective potential without and with the dyon condensation, respectively. Note that the cusp is smoothed out in the effective potential including the dyon condensation. This fact means that the dyon really enjoys the correct degrees of freedom in the effective theory around the singular point. We can see that values of the potential minimum and the width of the dyon condensation are controlled by the scale of $\xi$, as expected.

Now we investigate the vacuum structure by varying the values of $a_1$. In the following analysis, the SUSY breaking parameter is fixed as $\xi = 0.1$. First, let us see the evolution of the potential energy along the flow of the $(2,1)_1$ dyon point ($u_1$). The effective potentials for $a_1 = 1/8$, $0$, and $-1/8$ from left to right are depicted in Fig. 6. We can check that the potential minimum appears on the singular point for fixed $a_1$. The right figure shows the evolution of the potential energy along the flow of the singular point. We can find that, as $a_1$ is decreasing, the potential energy is monotonically decreasing. Therefore the effective potential is not bounded from below along the flow of the $(2,1)_1$ dyon point.

Next we investigate the effective potential around the other two singular points. For $a_1 < (3/4\sqrt{2})\Lambda_1$, the effective potential has the $CP$ symmetry, and is invariant under the transformation $u \leftrightarrow u^*$. Hence the potential energies on these points are degenerate. As $a_1$ is increasing, the potential energy is monotonically decreasing toward the AD point ($a_1 = (3/4\sqrt{2})\Lambda_1$), at which two singular points collide. For $a_1 > (3/4\sqrt{2})\Lambda_1$, two singular points appear again, the $(0,1)_0$ monopole point and the $(1,0)_1$ quark singular point. The effective potential for various values of $a_1 > (3/4\sqrt{2})\Lambda_1$ is depicted in Fig. 7. For $a_1 > (3/4\sqrt{2})\Lambda_1$, all the singular points are on the real $u$ axis. From the left figure, we see that there appears the potential minimum only on the quark singular point (the left minimum corresponds to the minimum around $(2,1)_1$ dyon point already depicted in Fig. 6). The $(0,1)_0$ monopole condensation is too small for the effective poten-

FIG. 7. The left figure shows the effective potential along the real $u$ axis for $a_1 = 2/\sqrt{3}$ (left), $2.5/\sqrt{3}$ (middle), and $3/\sqrt{3}$ (right). The right figure shows the evolution of the potential energy along the flow of the quark singular point.

FIG. 8. The evolutions of the potential energies along the flows of the singular points.
tial to have its minimum on the monopole point. Since, as \( a_1 \) is increasing further, the potential energy on the quark singular point is monotonically decreasing as depicted in the right figure, we find that the effective potential is not bounded from below along the flow of this singular point.\(^4\)

In the case \( \text{Im} \, a_1 = 0 \), the evolutions of the potential energies along the flows of the singular points are simultaneously sketched in Fig. 8. The effective potential is found to be the runaway type, and is monotonically decreasing toward the boundary of the defined region of moduli space. We can analyze the effective potential for general complex values of \( a_1 \), and find that the same results come out. In conclusion, there is neither well-defined vacuum nor local minimum in the effective theory.

**B. Vacuum structure in the \( N_f = 2 \) case**

Next, we analyze the vacuum structure for the \( N_f = 2 \) case. Again, let us first consider the flow of the singular points. In the following analysis, the dynamical scale is fixed as \( \Lambda_2 = 2 \sqrt{3} \). In the \( N_f = 2 \) case, the discriminant of the algebraic curve can be easily solved such that

\[
\begin{align*}
u_1 &= -m\Lambda_2 - \frac{\Lambda_2}{8} \frac{1}{a_1 - m/\sqrt{3}}, \\
u_2 &= m\Lambda_2 - \frac{\Lambda_2}{8} \frac{1}{a_1 - m/\sqrt{3}}, \\
u_3 &= m^2 + \frac{\Lambda_2}{8} \frac{1}{a_1 - m/\sqrt{3}}. 
\end{align*}
\]

(57)

We investigate the case \( \text{Im} \, a_1 = 0 \), for simplicity. The flow of the singular points is sketched in Fig. 9. For \( a_1 = 0 \), the singular points appear at \( u_1 = u_2 = -1 \) and \( u_3 = 1 \). Here, at \( u = -1 \), two singular points degenerate. For nonzero \( a_1 > 0 \),\(^5\) this singular point splits into two singular points \( u_1 \) and \( u_2 \), which correspond to the BPS states with quantum numbers \((1,1)_{-1}\) and \((1,1)_{1}\), respectively. As \( a_1 \) is increasing, these singular points, \( u_1 \) and \( u_2 \), are moving to the left and the right on the real \( u \) axis, respectively. Two singular points, \( u_2 \) and \( u_3 \), collide and degenerate at the AD point \((u = 3\Lambda_2^2/8)\) for \( a_1 = \Lambda_2/2\sqrt{3} \). As \( a_1 \) is increasing further, there appear two singular points \( u_2 \) and \( u_1 \) again, and quantum numbers of the corresponding BPS states, \((1,1)_{1}\) and \((0,1)_{0}\), change into \((1,0)_{1}\) and \((1,-1)_{1}\), respectively. The singular point \( u_2 \) is moving to the right faster than \( u_3 \).

We investigate the vacuum structure by varying the values of \( a_1 \). For \( 0 < a_1 < \Lambda_2/2\sqrt{3} \), the effective potential is plotted in Fig. 10. While the potential minima appear at two singular points \( u_1 \) and \( u_2 \), the monopole condensation is too small for the potential to have a minimum at the singular point \( u_3 \). The top and bottom figures in the middle show the effective potential without and with the dyon condensations, respectively. The cusps are smoothed out in the bottom figure, as in the case \( N_f = 1 \). The evolutions of the potential energies on the singular points \( u_2 \) and \( u_3 \) are depicted in Fig. 11. We find that both of them are decreasing toward the point \( a_1 = 0 \), and thus the effective potential is bounded from below, at least, along the real \( u \) axis.

Next, we examine whether the effective potential is bounded in all the directions for general complex \( a_1 \) values. As an example, let us consider the case \( \text{Re} \, a_1 = 0 \). For \( a_1 \neq 0 \), the two singular points \( u_1 \) and \( u_2 \) appear on the imaginary \( u \)-axis with \( \text{Re} \, u = -1 \). The effective potential is depicted in Fig. 12 along this axis for \( a_1 = i(\sqrt{2}/4) \). There appear two potential minima at the singular points. The right figure shows the evolution of the potential energy along the flow of the singular point \( u_1 \),\(^6\) and we find that the effective potential for \( a_1 = 0.3 \) (left), \( a_1 = 0.4 \) (middle), and \( a_1 = 0.5 \) (right).

\(^4\)To be correct, there is a possibility that the local minimum may exist near the AD point. However, our description of the effective theory is not applicable around the point, since the condensations of two BPS states are well overlapped. For detailed discussions in this situation, see the next subsection B.

\(^5\)We consider only the case \( a_1 > 0 \), since the result for \( a_1 < 0 \) can be obtained by exchanging \( u_1 \leftrightarrow u_2 \), as can be seen from the first two equations in Eq. (57).

\(^6\)Two potential minima for fixed \( a_1 \) are degenerate, since the effective potential has the CP symmetry under the exchange \( u \leftrightarrow u^\dagger \) in the case \( \text{Re} \, a_1 = 0 \).
potential is also bounded in this direction. We can check that
the effective potential is bounded from below for all the val-
ues of small $|a_1|$. Therefore the effective potential seems to
have the local minimum at the points $u = -1$ and $a_1 = 0$.

However, note that our description is not applicable for
small $|a_1|$, since the condensations of two dyon states are
going to overlap with each other (see Fig. 10). Unfortunately,
we have no knowledge about the correct description of
the effective theory in this situation. Nevertheless, we con-
clude that the local minimum must appear with broken
SUSY in the limit $a_1 \to 0$ from the result in the following.
In this limit, the effective potential without the dyon condens-
ations is depicted in Fig. 13. We can find that there appears
the potential minimum at $u = -1$, and the value of the effec-
tive potential on the cusp is nonzero, $V \sim 0.0061 > 0$. If we
had the correct description of the effective theory for $a_1 = 0$,
this cusp might be smoothed out. However, there is no rea-
son that SUSY is restored at $u = -1$, because the correct
effective theory must have no singularity for the Kähler met-
ic. Therefore there is the promising possibility of the ap-
pearance of the local minimum with broken SUSY at $u =
-1$ and $a_1 = 0$.

Finally, let us get back to the case $\text{Im} a_1 = 0$. For $a_1 > \Lambda_2/\sqrt{2}$, the effective potential has two minima only at
two singular points $u_1$ and $u_2$. The monopole condensation is
too small for the effective potential to have a minimum at $u_1$.
The plot of the effective potential is similar to Fig. 7. While
the evolution of the potential energy along the singular point
$u_1$ is the same as for $0 < a_1 < \sqrt{2}/\Lambda_2$, the potential energy
on the quark singular point $u_2$ is monotonically decreasing,
as $a_1$ is increasing. Thus there is a runaway direction along
the flow of the quark singular point. We can find the same
global structure along the flow of the quark singular point for
general complex $a_1$ values.

The evolutions of the potential energies along the flows
of the singular points are simultaneously sketched in Fig. 14.
The global structure of the effective potential is the same as
in the case $N_f = 1$, namely, the runaway type. However, we
find the promising possibility that there exists the local mini-
mum with broken SUSY in the theory. Since there is no
well-defined vacuum on the runaway direction, this mini-
mum with broken SUSY is the unique and promising candi-
deate for the vacuum in the theory. Unfortunately, we have no
knowledge of the correct description about the effective theory
around the degenerate dyon point.

V. CONCLUSION

We analyzed the vacuum structure of spontaneously
broken $\mathcal{N}=2$ SUSY gauge theory with the Fayet-Iliopoulos
term. Our theory is based on the gauge group
$SU(2) \times U(1)$ with $N_f = 1,2$ massless quark hypermultiplets
having the same $U(1)$ charges. The $U(1)$ gauge interaction
was necessary introduced to include the Fayet-Iliopoulos
term in the theory. It was shown that there are degenerate
vacua in the classical potential even in the absence of SUSY.
This degeneracy is expected to be smoothed out, once quan-
tum corrections are taken into account. Then, we investi-
gated the effective potential, and analyzed the vacuum struc-
ture of the theory.

The effective action was formulated up to the leading or-
der for the SUSY breaking parameter $\xi$. In our framework,
the $U(1)$ gauge interaction part was treated as the cutoff
theory under the assumption that the $U(1)$ gauge interaction
has no effect on the $SU(2)$ gauge dynamics. Thus the moduli
space in the theory was restricted within the region smaller
than the cutoff scale, the Landau pole. Considering the
monodromy transformation, we found that the prepotential
consistent with the assumption was the same as the one in
SQCD with massive quark hypermultiplets.

The effective potential was the function of the moduli
parameters. Examining the minimum of the effective poten-
tial, we found that the singular points on the moduli space
were energetically favored, because of the condensations of
the light BPS states. The singular points on the $u$ plane
flowed according to the values of the moduli parameter $a_1$.
Thus we analyzed the effective potential along the flows of
the singular points, and examined which point was energeti-
cally favored on the line of the flow.

In the $N_f = 1$ case, the effective potential was found to be
the runaway type and monotonically decreasing toward the
ultraviolet region in the moduli space. We observed that
there was neither well-defined vacuum nor the local mini-
mum in this case. In the $N_f = 2$ case, there was also the
runaway direction along the flow of the quark singular point, and the global structure was the same as in the $N_f=1$ case. However, we found the promising possibility that the local minimum with broken SUSY appears at the degenerate dyon point. Therefore this point is the promising candidate for the global minimum. Note that the behavior of the effective potential without the dyon condensations is different in two cases $N_f=1,2$. If we consider the extended version of our theory with $N_f=3,4$ quark hypermultiplets, we may find the global minimum in the theory. Although this extension makes our analysis much more complicated and difficult, it will be interesting.

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APPENDIX A

In this appendix, we demonstrate the derivations of the integrals $I_l^{(j)}$ in Eqs. (46)–(48). The complete elliptic integrals are given as follows:

\[ K(k) = \int_0^1 \frac{dx}{\sqrt{(1-x^2)(1-k^2x^2)}} , \]  
\[ E(k) = \int_0^1 \left( \frac{1-k^2x^2}{1-x^2} \right)^{1/2} dx , \]  
\[ \Pi_1(\nu,k) = \int_0^1 \frac{dx}{\sqrt{(1-x^2)(1-k^2x^2)}} , \quad \nu = 1 + \frac{1}{1+k^2} . \]

The integrals $I_l^{(j)}$ are described in terms of the above complete elliptic integrals through some steps of changing variables in the integrations.

First, demonstrate the derivation of Eq. (46):

\[ I_1^{(1)} = \int \epsilon_2 \frac{dX}{Y} = \int_{\epsilon_2 \sqrt{4(X-e_1)(X-e_2)(X-e_3)}}^{\epsilon_3} \frac{dX}{\sqrt{4(X-e_1)(X-e_2)(X-e_3)}} \]
\[ = \frac{i}{2\sqrt{e_2-e_1}} \int_0^{k^2} \frac{dt}{(t(1-t-k^2))^{1/2}} , \]  
where we changed the variable $X$ by $t = -(X-e_2)/(e_2 - e_1)$. Further, changing the variable $t$ by $t = 1 + k^2/(\zeta^2 - 1/2k)$ and rescaling $\zeta$ as $x = 2k(1+k)/(1-k)\zeta$, we obtain

\[ I_1^{(1)} = \frac{i}{\sqrt{e_2-e_1}} \frac{2}{1+k} K \left( \frac{1-k}{1+k} \right) . \]

Using the relation

\[ \frac{2}{1+k} K \left( \frac{1-k}{1+k} \right) = K(k') , \]  
we obtain Eq. (46). Repeating the same steps for the integral $I_2^{(1)}$, we obtain
\[ I_3^{(1)}(c) = \int_{\tilde{c}}^{c} \frac{dX}{Y} = -\frac{i}{(e_2-e_1)^{3/2}} \frac{1}{c+k} \frac{1}{1+k} \times \int_{-1}^{1} \frac{dx}{\left[1-\frac{(1-k)^2}{1+k} \frac{x^2}{(1-x^2)}\right]^{1/2}} \times \left[1 - \frac{2k}{c+k} \frac{1}{1+k} \frac{1}{c-k} \frac{1}{1+k} \frac{x}{c+k} \right]. \tag{A7} \]

where \( \tilde{c} = (c-e_1)/(e_2-e_1) \). Using the relations Eq. (A4), we obtain Eq. (48).

**APPENDIX B**

In this appendix, we show the derivations of the effective couplings in terms of the Weierstrass functions. It is convenient to introduce the uniformization variable \( z \) through the map with the Weierstrass \( \wp \) function,

\[ (\wp(z), \wp'(z)) = (X, Y). \tag{B1} \]

Using this map, the half-period \( \omega_i/2 \) is mapped into the root \( e_i = \wp(\omega_i/2) \) \( (\omega_3 = \omega_1 + \omega_2) \). The inverse map is defined as

\[ z = \psi^{-1}(x_0) = \int_{x_0}^{\psi} \frac{dX}{Y} = -\frac{1}{\sqrt{e_2-e_1}} F(\phi, k), \tag{B2} \]

where we changed the integration variable \( X \) by \( t^2 = (e_2 - e_1)/(X - e_1) \), and \( F(\phi, k) \) is the incomplete elliptic integral given by

\[ F(\phi, k) = \int_{0}^{\phi} \frac{dt}{\sqrt{(1-t^2)(1-k^2t^2)}} \quad \sin^2 \phi = \frac{e_2-e_1}{x_0-e_1}. \tag{B3} \]

We derive the effective couplings, \( \tau_{12} \) and \( \tau_{11} \), by using the map of Eq. (B1). The effective coupling \( \tau_{12} \) is described by

\[ \tau_{12} = \left. \frac{\partial a_{2D}}{\partial a_1} \right|_{a_2} = \left. \frac{\partial a_{2D}}{\partial a_1} \right|_{a_2} - \tau_{22} \left. \frac{\partial a_2}{\partial a_1} \right|_{a_2}. \tag{B4} \]

The partial derivative of the periods \( a_{2D} \) and \( a_2 \) with respect to \( a_1 \) can be calculated by using Eqs. (29)–(31) as

\[ \left. \frac{\partial a_{2i}}{\partial a_1} \right|_{a_2} = \int_{a_1}^{a_2} \frac{d\phi}{\omega_i} \frac{1}{2} \log [\wp(z) - \wp(\omega_j)] + 2z \wp'(z), \tag{B7} \]

where \( \wp(z) = c, \wp'(z) \) is the Weierstrass zeta function, and we used the definition of the Weierstrass sigma function, \( \wp(z) = (d/dz) \log \wp(z) \), and the relation

\[ \wp'(z_0) \wp(z) = \wp'(z_0) = \wp'(z_0) \wp(z) - \wp'(z_0) \wp(z + \omega_j) + 2 \wp'(z_0). \tag{B8} \]

Taking into account that \( Y \) corresponds to \( \wp'(z) \) under the map of Eq. (B1), the pole \( \wp'(z_0) \) can be easily obtained as

\[ \wp'(z_0)^2 = -\frac{N_f (2(N_f-1) A_{N_f}^{4-N_f})}{32}. \tag{B9} \]

Using the pseudoperiodicity of the Weierstrass sigma function,

\[ \wp(z_0 + \omega_i) = -\wp(z_0) \exp \left[ 2z_0 \frac{\omega_i}{2} \right] \left( z_0 + \frac{1}{2} \omega_i \right), \tag{B10} \]

we obtain

\[ \left. \frac{\partial a_{2i}}{\partial a_1} \right|_{a_2} = \left. \frac{1}{\pi i} \omega_i \wp'(z_0) - 2z_0 \wp(\omega_i/2). \tag{B11} \]

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The zeta function at half period can be described by the integral representations such as
\[
\zeta \left( \frac{\omega_1}{2} \right) = -l_2^{(i)}.
\] (B12)

Substituting Eq. (B11) into Eq. (B4) and using the Legendre relation
\[
\omega_1 \zeta \left( \frac{\omega_2}{2} \right) - \omega_2 \zeta \left( \frac{\omega_1}{2} \right) = i \pi,
\] (B13)
we finally obtain
\[
\tau_{12} = -\frac{2z_0}{\omega_2}.
\] (B14)

Next we derive the effective coupling \(\tau_{11}\), which is given by differentiating \(a_{1D}\) of Eq. (54) with respect to \(a_1\) with \(a_2\) fixed such as
\[
\tau_{11} = \int_{x_n}^{x_0} \left[ \frac{\partial \lambda_{SW}}{\partial u} \bigg|_{a_1} \frac{\partial u}{\partial a_1} \bigg|_{a_2} + \frac{\partial \lambda_{SW}}{\partial u} \bigg|_{a_2} \frac{\partial u}{\partial a_2} \bigg|_{a_1} \right] + \frac{\partial \tilde{C}}{\partial a_1}.
\] (B15)

The integral can be evaluated by using the map (B1). Although the integral contains divergence, it can be regularized by using the freedom of the integration constant \(\tilde{C}\). Let us demonstrate this regularization by introducing the regularization parameter \(\epsilon\) as follows:
\[
\tau_{11} = -\int_{x_n^+}^{x_0^+} \left[ \frac{\partial \lambda_{SW}}{\partial u} \bigg|_{a_1} \frac{\partial u}{\partial a_1} \bigg|_{a_2} + \frac{\partial \lambda_{SW}}{\partial u} \bigg|_{a_2} \frac{\partial u}{\partial a_2} \bigg|_{a_1} \right] + \frac{\partial \tilde{C}}{\partial a_1}
\]
\[+ \frac{\omega_1}{\pi i} \left[ \log \sigma(2z_0) - \frac{4z_0^2}{\omega_2} \left( \frac{\omega_2}{2} \right) \right] + \frac{1}{\pi} \log \sigma(\epsilon) + \frac{1}{2} \frac{\partial \tilde{C}}{\partial a_1}.
\] (B16)

The divergence part, \(\log \sigma(\epsilon)\), can be subtracted by taking the integration constant such that \(\tilde{C} = Ca_1 - a_1/2 - a_1/\pi \log \sigma(\epsilon)\), and we finally obtain Eq. (55) with the relation of Eq. (B12).