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Citation of published version:

Kitazawa, N., Maru, N., Okada, N. (2000): Dynamical Supersymmetry Breaking with Gauged $\mathbf{U(1)_R}$ Symmetry. *Physical Review D,* 62(7).
DOI: https://doi.org/10.1103/PhysRevD.62.077701

PHYSICAL REVIEW D, VOLUME 62, 077701

Dynamical supersymmetry breaking with gauged $U(1)_R$ symmetry

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(Received 5 November 1999; revised manuscript received 3 April 2000; published 8 September 2000)

We propose a simple model of dynamical supersymmetry breaking in the context of minimal supergravity with gauged $U(1)_R$ symmetry. The model is based on the gauge group $SU(2)\times U(1)_R$ with three matters. Since the $U(1)_R$ symmetry is gauged, the Fayet-Iliopoulos D term appears due to the symmetry of supergravity. On the other hand, the superpotential generated dynamically by the SU(2) gauge dynamics leads to a runaway potential. Since the supersymmetric vacuum condition required by the D term potential contradicts the one required by the superpotential, supersymmetry is broken. The supersymmetry breaking scale is controlled by the dynamical scale of the SU(2) gauge interaction. We can choose the parameters in our model for a vanishing cosmological constant. Our model is phenomenologically viable with the gravitino mass of order 1 TeV or 10 TeV.

PACS number(s): 12.60.Jv, 11.30.Na, 12.60.Cn

The supersymmetric extension is one of the most promising ways to provide a solution to the gauge hierarchy problem beyond the standard model [1]. However, since none of the superpartners have been observed yet, supersymmetry should be broken at low energies. The origin of supersymmetry breaking still remains as the one of the biggest mysteries in supersymmetric theories.

The models of spontaneous supersymmetry breaking at the tree level were proposed many years ago [2]. However, since these models had dimensionful parameters given by hand, there was no explanation for the hierarchy between the scale of the supersymmetry breaking and the Planck scale. A more complete model may be the model in which the origin of the scale of supersymmetry breaking can be explained by the model itself. An example of such a model is the dynamical supersymmetry breaking model [3]. While this model has no dimensionful parameter from the beginning, the dimensionful parameter is induced by nonperturbative gauge dynamics. It seems possible to extend such a model into the supergravity model, if the four dimensional space-time is flat.

In this paper, we propose a simple model of dynamical supersymmetry breaking in the context of the minimal supergravity with gauged $U(1)_R$ symmetry. Our model is based on the gauge group $SU(2)\times U(1)_R$. Since the $U(1)_R$ symmetry is gauged, the Fayet-Iliopoulos D term appears due to symmetry of supergravity. On the other hand, the nonperturbative effect of the SU(2) gauge dynamics generates the superpotential dynamically, which leads to the run away potential. Since the supersymmetric vacuum condition required by the D term potential contradicts the one required by superpotential, supersymmetry is broken. Supersymmetry breaking scale is controlled by the scale of the SU(2) gauge dynamics. Analyzing the potential minimum, we find that the cosmological constant can vanish, if the parameters in our model are appropriately chosen. The mass spectrum of the model is also discussed. The scalars with nonzero $U(1)_R$ charges get soft supersymmetry breaking masses at the tree level by the vacuum expectation value of the D term. These masses are the same order of the magnitude of the gravitino mass. On the other hand, for the gauginos in the minimal supersymmetric standard model we can consider two possibilities. One is to introduce the higher dimensional term in the gauge kinetic function. The other is to consider the anomaly mediation scenario [4] without nontrivial gauge kinetic function. The gaugino masses are found to be the same order of the gravitino mass or a few orders smaller than the gravitino mass in the former case or the latter case, respectively.

Our model is based on the gauge group $SU(2)\times U(1)_R$ with the following matter contents:[1]

	SU(2)	$U(1)_R$
Q_1	**2**	-1
Q_2	**2**	-1
S	**1**	$+4.$

The general renormalizable superpotential at the tree level is

$$W=\lambda S[Q_1 Q_2], \tag{1}$$

[1]In the following, we do not discuss the cancellation of the gauge anomaly $[U(1)_R]^3$ and the mixed gravitational anomaly of $U(1)_R$. The discussion depends on the full particle contents of the theory, and it is beyond the main subject of this paper [7]. Here, we simply assume that these anomalies are canceled, if all particle contents are considered with the appropriate $U(1)_R$ charge assignment.

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where square brackets denote the contraction of the SU(2) index by the ϵ-tensor, λ is a dimensionless coupling constant. We assume that λ is real and positive in the following.

It is known that the superpotential is generated dynamically by nonperturbative (instanton) effect of the SU(2) gauge dynamics [5]. The total effective superpotential is found to be

$$W_{eff}=\lambda S[Q_1Q_2]+\frac{\Lambda^5}{[Q_1Q_2]}, \tag{2}$$

where the second term is the dynamically generated superpotential, and Λ is the dynamical scale of the SU(2) gauge interaction. Note that the supersymmetric vacuum lies at $\langle S\rangle\to\infty$ and $\langle Q_1\rangle,\langle Q_2\rangle\to 0$, if only the F-term potential is considered.

Next, let us consider the D term potential. The gauged $U(1)_R$ symmetry is impossible in the globally supersymmetric theory, since the generators of the $U(1)_R$ symmetry and supersymmetry do not commute with each other. On the other hand, in the supergravity theory the $U(1)_R$ symmetry can be gauged as if it were a usual global symmetry [6,7]. However, there is a crucial difference that the Fayet-Iliopoulos D term of the gauged $U(1)_R$ symmetry appears due to the symmetry of supergravity. This fact is easily understood by the standard formula for supergravity theories [8]. Using the generalized Kähler potential $G=K+\ln|W|^2$, the D term is given by $D=\Sigma_i q_i(\partial G/\partial z_i)z_i$, where q_i is the $U(1)_R$ charge of the field z_i. Note that the contribution from the superpotential leads to the constant term, since the superpotential has $U(1)_R$ charge 2.

With the above particle contents, the D term potential is found to be

$$V_D=\frac{g_R^2}{2}(4S^\dagger S-Q_1^\dagger Q_1-Q_2^\dagger Q_2+2M_P{}^2), \tag{3}$$

where $M_P=M_{pl}/\sqrt{8\pi}$ is the reduced Planck mass, g_R is the $U(1)_R$ gauge coupling, and the minimal Kähler potential, $K=S^\dagger S+Q_1^\dagger Q_1+Q_2^\dagger Q_2$, is assumed.[2] Note that the supersymmetric vacuum condition required by the D term potential contradicts the one required by the effective superpotential of Eq. (2). Therefore, supersymmetry is broken. This consequence remains correct, if there is no other superfields which have negative $U(1)_R$ charges. We give some comments on this point in the final part of this paper.

Let us analyze the total potential in our model. Here, note that the cosmological constant should vanish. This requirement comes not only from the observations of the present universe but also from the consistency of our discussion. Since it is not clear whether the superpotential discussed above can be dynamically generated even in the curved space, the space-time should be flat for our discussion to be correct. Note that we cannot take the usual strategy, namely, adding a constant term to the superpotential, since such a term is forbidden by the $U(1)_R$ gauge symmetry. It is a nontrivial problem whether we can obtain the vanishing cosmological constant in our model.

Assuming that the potential minimum lies on the D flat direction of the SU(2) gauge interaction, we take the vacuum expectation values such that $\langle S\rangle=s$ and $\langle Q_i^\alpha\rangle=v\,\delta_i^\alpha$, where i and α denote the flavor and SU(2) indices, respectively. Here, we can always make s and v real and positive by symmetry transformations. The total potential is given by

$$V(v,s)=e^K\left[(\lambda v^2+sW)^2+2v^2\left(\lambda s-\frac{\Lambda^5}{v^4}+W\right)^2-3W^2\right]+\frac{g_R^2}{2}(4s^2-2v^2+2)^2, \tag{4}$$

where K and W are the Kähler potential and superpotential, respectively, which are given by

$$K=s^2+2v^2, \tag{5}$$

$$W=\lambda s v^2+\frac{\Lambda^5}{v^2}. \tag{6}$$

Here, all dimensionful parameters are taken to be dimensionless with the normalization $M_P=1$. The first line in Eq. (4) comes from the F term (except for W^2 term) and the remainder is the D term potential.

Since the potential is very complicated, it is convenient to make some assumptions for the values of parameters. First, assume that $g_R\gg\lambda,\Lambda$. Since the D term potential is proportional to g_R^2 and positive definite, the potential minimum is expected for V_D to be small as possible. If we assume $s\ll 1$ and $v\sim 1$, the potential can be rewritten as

$$V\sim e^2(\lambda^2-3\Lambda^{10}). \tag{7}$$

It is found that $\lambda\sim\sqrt{3}\Lambda^5$ is required in order to get the vanishing cosmological constant.

Let us consider the stationary conditions of the potential. Using the assumptions $s\ll 1$ and $v=1+y$ ($|y|\ll 1$), the stationary conditions can be expanded with respect to s and y. Considering the relations $g_R\gg\lambda\sim\Lambda^5$, the condition $\partial V/\partial y=0$ leads to

$$y\sim s^2-\frac{e^2\lambda^2}{2g_R^2}. \tag{8}$$

Using this result, the expansion of the condition $\partial V/\partial s=0$ leads to

$$s\sim\frac{\lambda\Lambda^5}{8\lambda^2-\Lambda^{10}}. \tag{9}$$

By the numerical analysis, the above rough estimation is found to be a good approximation. The result of numerical calculations is the following.

$$y\sim 4.7\times 10^{-3}, \tag{10}$$

$$s\sim 6.8\times 10^{-2}. \tag{11}$$

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[2]This assumption is justified by our final result with $\Lambda\ll M_P$ which means that the SU(2) gauge interaction is weak at the Planck scale.

Here, we used the values of $\Lambda=10^{-3}$, $\lambda\sim1.8\Lambda^5$ and $g_R=10^{-12}$. For these values of the parameters, we can obtain the vanishing cosmological constant. Note that the numerical values of Eqs. (10) and (11) are almost independent of the actual value of Λ, if the condition $g_R\gg\Lambda^5$ is satisfied and the ratio λ/Λ^5 is fixed. This can be seen in the approximate formulas of Eqs. (8) and (9). We can choose the value of Λ in order to get a phenomenologically acceptable mass spectrum.

Now we discuss the mass spectrum in our model. Using the above values of parameters, the gravitino mass is estimated as

$$m_{3/2}=\langle e^{K/2}W\rangle\sim3.0\times\frac{\Lambda^5}{M_P^4}. \tag{12}$$

The gravitino mass contributes to the masses of scalar partners via the tree level interactions of supergravity. Note that there is another contribution, if scalar partners have nonzero $U(1)_R$ charges. In this case, they also get the mass from the vacuum expectation value of the D term, and it is estimated as

$$m_{D\ term}^2=qg_R^2\langle D\rangle\sim\left(7.3\times\frac{\Lambda^5}{M_P^4}\right)^2 q, \tag{13}$$

where q is the $U(1)_R$ charge. This mass squared is always positive for the scalar partners with positive $U(1)_R$ charges. The mass is the same order of the magnitude of the gravitino mass. This is because g_R is cancelled out in the above estimation [see Eq. (8)]. For gaugino masses, we can consider two cases. One is to introduce a gauge invariant higher dimensional term $S([Q_1Q_2])^2/M_P^5$ in the gauge kinetic function. In this case, gaugino masses are found to be the same order of the gravitino mass. The other is to consider the anomaly mediation of supersymmetry breaking [4] without the nontrivial gauge kinetic function.[3] In this case, gaugino masses are given by the gravitino mass times beta functions, which are a few orders smaller than the gravitino mass. Considering the experimental bound on gaugino masses in the minimal supersymmetric standard model [9], the gravitino mass is taken to be of the order of 1 TeV or 10 TeV in the former case or the latter case, respectively. From this phenomenological constraint, the dynamical scale of the SU(2) gauge interaction is found to be of the order of 10^{15} GeV for both cases. This means that we have to fine-tune $\lambda\sim10^{-15}$ to have the vanishing cosmological constant at tree level.[4] This fine-tuning is also necessary in order to get the soft supersymmetry breaking masses of the same order of the gravitino mass.

Finally, we give some comments. Our model has the same structure of the supersymmetry breaking model with the anomalous U(1) gauge symmetry [10]. In the model, the Fayet-Iliopoulos D term is originated from the anomaly of the U(1) gauge symmetry [11]. On the other hand, in our model the origin of the D term is the symmetry of supergravity with the gauged $U(1)_R$ symmetry. The D-term appears even if the $U(1)_R$ gauge interaction is anomaly free.

The mechanism of the supersymmetry breaking in our model cannot work unless there are other superfields with negative $U(1)_R$ charges. However, when our model is combined with the visible sector, for example, the minimal supersymmetric standard model, it is highly nontrivial whether all the gauge anomalies can be cancelled out with only semipositive $U(1)_R$ charged superfields in the visible sector [7]. The easiest way to remain correct in our discussion is to give up the cancellations of all the anomalies, and consider the Green-Schwarz mechanism [12] by introducing the dilaton field as it is done in the model with anomalous U(1) gauge symmetry [10]. In this case, one can construct a full model combined with our hidden sector [14]. Although new Fayet-Iliopoulos D term appears due to the $U(1)_R$ gauge anomaly, its magnitude is suppressed compared with that of the gauged $U(1)_R$ symmetry. Hence, our results obtained above is little changed.

Unfortunately, the introduction of the dilaton field in the model causes new difficult problems such as the stabilization of the dilaton potential, the vacuum expectation value of the dilaton F term and so on [13]. Therefore, it is likely expected to construct the model with our supersymmetry breaking mechanism without the Green-Schwarz mechanism. Indeed, we can construct the anomaly free model with some extensions of the model presented in this paper [14].

We would like to thank Hitoshi Murayama for helpful comments. This work was supported in part by the Grant-in-aid for Science and Culture Research form the Ministry of Education, Science and Culture of Japan (#11740156, #3400, #2997). N.M. and N.O. are supported by the Japan Society for the Promotion of Science for Young Scientists.

[3]The higher dimensional term $S([Q_1Q_2])^2/M_P^5$ in the gauge kinetic function can be forbidden to all orders by the discrete symmetry.

[4]This small Yukawa coupling is consistent with our discussion in the following sense. Since S has the vacuum expectation value, the mass for Q_i is generated through the Yukawa coupling in Eq. (2). The relation $\lambda\langle S\rangle\ll\Lambda$ is needed not to change our result from the SU(2) gauge dynamics.

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