Symmetry Principles toward Solutions of the $\mu$ Problem

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Abstract

We stress that a natural solution of the $\mu$ problem requires two ingredients: a symmetry that would enforce $\mu = 0$ as well as the occurrence of a small breaking parameter that generates a nonzero $\mu$. It is suggested that both the Peccei-Quinn symmetry and the spontaneously broken $R$ symmetry may be the sources of the needed $\mu$ term in the minimal supersymmetric standard model provided that they are spontaneously broken at a scale $10^{10} - 10^{12}$ GeV. To solve the strong CP problem with a hidden sector confining group, both of these symmetries are needed in superstring models with an anomalous $U(1)_A$. 

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1. Introduction

It is often assumed that one can understand many aspects of the low energy electroweak phenomena from supergravity interactions at high energies governed by an underlying superstring theory [1]. Even though there does not exists a standard superstring model, it is a general expectation that one of numerous string vacua might coincide with the minimal supersymmetric standard model (MSSM) in supergravity [2]. Nevertheless, the attractive MSSM has a few outstanding theoretical parameter problems: the cosmological constant problem [3], the strong CP problem [4], and the $\mu$ problem [5]. From the top–down approach, these may be solved by the theory. But from the bottom–up approach, these need explanations and constitute very interesting and challenging problems. In this paper, we address two of these problems: the strong CP problem and the $\mu$ problem.

The strong CP problem seems to have an inherent solution in string models due to the existence of the model-independent axion [6]. However, the model-independent axion is known to have the axion decay constant problem if it is designed to solve the strong CP problem [7]. Apart from this cosmological problem, the need for a hidden sector confining group to break supersymmetry at the intermediate scale requires another axion to settle the QCD vacuum angle at zero. However, the string models are known to have no continuous global symmetry. Therefore, there does not exist any room for the additional axion at the string level. Thus the prospect for a solution of the strong CP problem through an invisible axion looks doomed.

On the other hand, the MSSM admits

$$W_\mu = \mu H_1 H_2$$

in the superpotential, where $H_1$ and $H_2$ are two Higgs doublets with $Y = -1/2$ and $Y = 1/2$ and $\mu$ is a free parameter whose magnitude is in principle different from the magnitude of $m_{3/2} \sim M_{SUSY}$ characterizing the soft SUSY breaking terms in supergravity. Electroweak phenomenology suggests that $\mu$ is nonzero and falls in the 100 GeV region similar to the magnitude of soft parameters. In addition, axion phenomenology suggests that $\mu$ cannot be
zero, or there results an unwanted 0.1 MeV axion. Theoretically, however, one expects that 
$\mu$ is of order the Planck scale unless it is forbidden by some symmetry. At present, there 
exist several suggestions toward a solution of the $\mu$ problem [1][3][4].

In this paper, we will try to understand these two outstanding problems from symmetry 
principles, which will work as a guideline for future construction of superstring models.

2. The Peccei–Quinn and $R$ Symmetries

From the early days of the $\mu$ problem [5], it was suggested that a symmetry, presumably a
Peccei-Quinn symmetry with an invisible axion [10], may be needed toward a solution of 
the problem. The reason is simple. Consider the following Yukawa super-potential

$$W_Y = d^c_L F_d q_L H_1 + u^c_L F_u q_L H_2$$

(2)

where $F_{d,u}$ is the $3 \times 3$ Yukawa coupling matrix, $q_L$ is a column vector of three SU(2) doublet 
superfields, $d^c_L$ and $u^c_L$ are column vectors of up- and down-type anti-quark superfields. A 
Peccei–Quinn symmetry\(^1\)

$$H_1 \rightarrow e^{i\alpha} H_1, \quad H_2 \rightarrow e^{i\alpha} H_2, \quad \{q_L, d^c_L, u^c_L\} \rightarrow e^{-i\alpha \{q_L, d^c_L, u^c_L\}}$$

$$W \rightarrow W.$$ (3)

forbids $W_\mu$. One can introduce the Peccei–Quinn symmetry to understand the smallness of $\mu$, 
and break it at $10^{10} - 10^{12}$ GeV, generating an electroweak scale $\mu$ through nonrenormalizable 
interactions generated by gravity [3]. The Peccei–Quinn symmetry seems to be a necessity 
to fix the scale of $\mu$ at $M_{SU(3)}$.

In this paper, we also suggest that $R$ symmetry can be used as another symmetry in 
addition to the Peccei–Quinn symmetry [2]. With $\mu = 0$, we assign an $R$ symmetry,

$$\{H_1, H_2\} \rightarrow \{H_1, H_2\},$$

\(^1\)For the heavy quark axion, $H_{1,2} \rightarrow H_{1,2}$, and hence it cannot be used for the small $\mu$ term.

\(^2\)The use of $R$ symmetry for the $\mu$ term has been suggested before [11][12].
\{q_L, d_L^c, u_R^c\} \rightarrow e^{i\beta} \{q_L, d_L^c, u_R^c\},
\quad W \rightarrow e^{2i\beta} W \quad \text{(4)}

so that ordinary quarks and Higgs doublets carry vanishing \(R\) charge.

### 3. \(R\) Violation and the \(\mu\) Term

As a simple example, consider the Polonyi super-potential \[13\],

\[ W_{\text{Polonyi}} = m^2(z + \tilde{m}) \quad \text{(5)} \]

where \(\tilde{m}\) is of order of the Planck scale \((M = M_{\text{Pl}}/\sqrt{8\pi})\) and \(m\) is of the order of intermediate SUSY breaking scale \((M_I)\). Supersymmetry is broken at the scale \(m(\sim M_I)\), \(F_z = m^2 + (m^2/M^2)z^*(z + \tilde{m})\) with \(z = (\sqrt{3} - 1)M\) and \(\tilde{m} = (2 - \sqrt{3})M\). With \(\tilde{m} = 0\), \(W = W_Y + W_{\text{Polonyi}}\) has the \(R\) symmetry with \(z\) transforming under \(R\) as

\[ z \rightarrow e^{2i\beta} z. \quad \text{(6)} \]

The field \(z\) gets mass through \(m\) of order \(O(m^2/M) = O(m_{3/2})\). From the supergravity Lagrangian, we note \[14\] that the \(z\) field interacts with the other observable sector fields through gravitation only, and hence it has the severe cosmological problem \[15\]. The hypothetical \(R\) symmetry is broken by nonzero \(\tilde{m}\). To see the effect of \(R\) symmetry violation, we can assign \(R\)-charge 2 to \(m^2\tilde{m}\). Thus, we expect that this model generates through gravitational interaction a super-potential \((m^2\tilde{m})H_1H_2/M^2\), producing \(\mu \sim m_{3/2}\). Any supergravity model, with super-potential \(W = \text{cubic terms} + \text{constant}\), realizes this kind of \(R\) breaking and accordingly generates a nonzero \(\mu\) term.

Let us briefly discuss the models discussed by Guidice and Masiero \[8\] and by Casas and Munoz \[9\] from this \(R\) symmetry argument. Guidice and Masiero suggest a Kähler potential

\[ K = (H_1H_2 + h.c.) + \cdots \quad \text{(7)} \]

where \(\cdots\) denotes \(\phi^*\phi\), etc. In supergravity models, the Guidice and Masiero solution gives an \(H_1H_2\) term in the scalar potential, not to the superpotential. However, its effect can be absorbed in the superpotential through the transformation,
\[ K(\phi, \bar{\phi}) \rightarrow K(\phi, \bar{\phi}) - F(\phi) - \bar{F}(\bar{\phi}), \quad W(\phi) \rightarrow e^{F(\phi)} W(\phi). \] (8)

Therefore, the solutions discussed in Refs. [8,9] can be studied in the framework of Ref. 7. Casas and Munoz assume that the superpotential \( W_0 \) does not contain the \( \mu \) term. But the gravitational interaction can generate a term \( W_0 H_1 H_2 / M^2 \). They assume \( \langle W_0 \rangle \sim M^2 m_{3/2} \) to generate \( \mu \sim M_W \) and relate it to the scale of supersymmetry breakdown. The effective superpotential \( W_0 H_1 H_2 / M^2 \) preserves the \( R \) symmetry, and \( \langle W_0 \rangle \neq 0 \) breaks the \( R \) symmetry and there results a pseudo-Goldstone boson, which is hidden in the fields describing \( W_0 \). This solution may have the Polonyi problem too [13].

A more interesting case is provided in models with hidden sector confining gauge groups [16]. The \( \mu \) term generated in this scenario has been discussed in Ref. [11]. We will elaborate this mechanism after presenting general classifications of \( R \) breaking mechanisms.

In string derived supergravity models, there exist only cubic terms in the superpotential. One can then define an \( R \) symmetry. This \( R \) symmetry could be broken in various ways:

(a) vacuum expectation values of \( R \neq 0 \) scalar fields, (b) \( F \) terms of \( R = 0 \) chiral fields, (c) a constant in the effective superpotential, or (d) gaugino condensation.

Vacuum expectation values of \( R \neq 0 \) scalar fields – Let the chiral fields carrying nonzero \( R \) quantum numbers be \( B_i \) with \( R = R_i \). Then the effective superpotential of the form

\[
\frac{1}{M^{n-1}} \prod_{i=1}^{n} B_i H_1 H_2, \quad \sum_{i=1}^{n} R_i = 2
\]

(9)

\(^3\)In this model there is no symmetry that forbids the \( \mu \)-term and dangerous renormalizable operators like, for example, \( Z_i H_1 H_2 \) in \( W_0 \) with nonvanishing vacuum expectation values of gauge singlets \( Z_i \). Thus, a full solution of the \( \mu \) problem is not achieved.

\(^4\)The most popular attempts of supersymmetry breaking in superstring models rely on this idea [17].

\(^5\)In such theories a pseudo-Goldstone boson \( \chi \) does appear. Its mass can be estimated by standard perturbative methods.
preserves the $R$ symmetry. The $R$ symmetry is broken by the vacuum expectation values of $B_1, B_2, \cdots, B_n$, and $\mu$ is generated

$$\mu = \frac{\langle B_1 B_2 \cdots B_n \rangle}{M^{n-1}}.$$  \hspace{1cm} (10)

For the argument of $R$ symmetry toward a naturally small $\mu$ to make any sense, $\langle B_i \rangle \ll M$.

$F$ terms of chiral fields -- Let us suppose that $A_i$ carry vanishing $R$ quantum numbers so that $A_{iF}$ carries $R = -2$. Then $A_i^* H_1 H_2$ needed for the $D$-term does not carry $R$ quantum number and generates a $\mu$ term

$$\frac{1}{M} \int d^2 \bar{\theta} d^2 \theta A_i^* H_1 H_2 = \int d^2 \theta W_\mu$$  \hspace{1cm} (11)

where $\mu = A_{iF}^* / M \sim m_{3/2}$. The dilaton superfields, moduli fields and chiral fields corresponding to flat directions can have vanishing $R$ quantum numbers, since they do not appear in the superpotential only as multiplicative factors of terms involving the interaction of the matter fields. For $B_i$ fields carrying $R = \pm 1$, one needs two $B$'s, e.g. $B_1(R = 1)$ and $B_2(R = -1)$ to have a $D$-term,

$$\frac{1}{M^2} \int d^2 \bar{\theta} d^2 \theta B_1^* B_2^* H_1 H_2.$$  \hspace{1cm} (12)

In this case,

$$\mu \sim (1/M^2)(B_{1F}^* \langle B_2^* \rangle + \langle B_1^* \rangle B_{2F}^*).$$  \hspace{1cm} (13)

Since $\langle B_i \rangle \ll M$ for $R$ symmetry to solve the $\mu$ problem, the $\mu$ term generated by $B_i$'s are insignificant compared to the one arising from the $A_i$ terms.

$Constants$ $in$ $W_{eff}$ -- As discussed above the constant in the superpotential breaks the $R$ symmetry. In string motivated supergravity models, this constant arises from the vacuum expectation values of $A_i B_j B_k$ where $R(A_i) = 0$ and $R(B_j, B_k) = 1$ or more generally $R(A_i) + R(B_j) + R(B_k) = 2$. For this to generate a gravitino mass scale $\mu$, we require

$$\langle A_i \rangle \sim M, \quad \langle B_i \rangle \sim M_I.$$  \hspace{1cm} (14)
Thus to obtain a reasonable $\mu$, the scalar components of chiral fields participating in the cubic superpotential with nonzero $R$ should have vacuum expectation values not exceeding the intermediate scale.

*Gaugino condensation* – Gauginos are assigned with $R = +1$ so that gauge bosons carry the vanishing $R$ quantum number. Therefore, the gaugino condensation in the hidden sector breaks supersymmetry and can generate a $\mu$ term through

$$\frac{1}{M^2} \langle \Psi^a \Psi^a \rangle H_1 H_2$$

where the (chiral) gauge boson multiplet is $\Psi^a = i\lambda^a + \cdots$. The magnitude of $\mu$ is

$$\mu \sim \frac{\Lambda^3_h}{M^2}.$$  

### 4. Solutions of the Strong CP and $\mu$ Problems in String Models

This leads us to the discussion on the anomalous $U(1)$ symmetry [19] in string models and generation of the $\mu$ term through the Peccei–Quinn symmetry [11]. The anomalous gauge $U(1)$ becomes a global $U(1)_P$ by removing the massive anomalous gauge boson [20]. It obtains mass by absorbing the model-independent axion. Frequently, string models are referred to having no global symmetry, which led some to assume an approximate $U(1)_{PQ}$ in some string models [21]. However, the class of string models with an anomalous $U(1)_{A}$ have one $U(1)_P$ global symmetry below the string scale for a solution of the strong CP problem. The $U(1)_P$ symmetry has the $P$–(gauge boson)–(gauge boson) anomaly, [20,11],

$$\partial_\mu J^\mu_P = \frac{1}{32\pi^2} \sum_i F_{\mu\nu}(G_i) F^{\mu\nu}(G_i)$$  

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6One can obtain the same effect by generalizing the gauge kinetic function [18].

7The reason that the global symmetry results is similar to that an $SU(2)$ global symmetry results if an $SU(2)$ gauge symmetry without Yukawa couplings is broken by the vacuum expectation value of a doublet Higgs field.
where $G_i$ is the gauge group. With one nonabelian gauge group $U(1)$, $U(1)_P$ is the needed Peccei–Quinn symmetry for the solution of the strong CP problem. But the hidden sector confining group needed for SUSY breaking invalidates the strong CP solution by the invisible axion since the axion in general gets a mass of order $(\text{coupling}) \times \Lambda^2_h$ where $\Lambda_h$ is the scale of the hidden sector confining gauge group. In Ref. [11], it was pointed out that $U(1)_R$ can be used to obtain the invisible axion. We elaborate briefly how this idea can be made successful.

With $U(1)_P$ and $U(1)_R$ symmetries, one may consider a potential of the form

$$V = -\Lambda^4_{QCD} \cos(\theta_c + \nu_0 \theta_h) - \Lambda^4_h \cos(\theta_c + \nu_h \theta_h) + V_R(\theta_c, \theta_h)$$

(18)

where $\theta_c (= a_c/v_c)$ is the QCD vacuum angle and $\theta_h (= a_h/v_h)$ is the hidden sector vacuum angle. The Goldstone bosons corresponding to these symmetries are $a_c$ and $a_h$ with decay constants $v_c$ and $v_h$, respectively. We assume that $U(1)_R$ has the $R - SU(3)_c - SU(3)_c$ and $R - G_h - G_h$ anomalies which are parametrized by $\nu_0$ and $\nu_h$, respectively. The $U(1)_P$ has both $U(1)_P - SU(3)_c - SU(3)_c$ and $U(1)_P - G_h - G_h$ anomalies. Without $V_R$, both $\theta_h$ and $\theta_c$ are settled to zero. One can expect the appearance of nontrivial $V_R$, and there exists a possibility that $\theta_c$ is not settled to zero. However, to study the extra potential $V_R$, one must consider the original $U(1)_P \times U(1)_R$ symmetry. Let us consider the following chiral and gauge fields as a simple example,

$$\begin{array}{cccccc}
A & B & \Psi^a & H_1 & H_2 \\
P & 2 & -1 & 0 & 1 & 1 \\
R & 0 & 1 & 1 & 0 & 0 \\
\end{array}$$

(19)

where $P$ and $R$ are the charges of $U(1)_P$ and $U(1)_R$. The potential $V_R$ arises from effective super-potential

$$\int d^2 \theta W_{\text{eff}} = \int d^2 \theta \{W_1 + \int d^2 \theta g_1 \bar{g}_2\}$$

(20)

where $W_1$ and $g_1$ are the composite superfield operator constructed from (left-handed) chiral fields only and $\bar{g}_2$ is constructed from (right-handed) anti-chiral fields only. From the $U(1)_P \times$
$U(1)_R$ symmetry, we argue that $W_1$ carries vanishing $P$ and 2 units of $R$ while $g_1\bar{g}_2$ carries vanishing $P$ and $R$. Thus $W_1$ can contain $ABB$, $BBH_1H_2/M$, $\Psi^a\Psi^a$, etc. On the other hand $g\bar{g}$ can contain $A^*H_1H_2/M$, $A^*B^*B^*\Psi^a\Psi^a/M^3$, etc. From $W_1$ and $g_1\bar{g}_2$, we do not expect to generate a potential containing $a_c$ and $a_h$ since these phase fields do not appear in $\sum_i |\partial W_{\text{eff}}/\partial z_i|^2$ and $|W_{\text{eff}}|^2$. Thus $V_R(\theta_c, \theta_h) = \text{(constant)}$. The constant is chosen so that the potential is zero at the minimum of the potential. Note, however, that $V_R$ can contain the scalar partners of the phase fields.

To see the $a_c$ and $a_h$ independence of $V_R$, we observe that $W_{\text{eff}}$ must preserve $U(1)_P \times U(1)_R$, which is the case for $U(1)_P$ if nonperturbative effects of gravitational interaction are supposed to respect it. Namely, we do not consider the argument based on wormholes, otherwise the axion solution of the strong CP problem is not attractive. Also, it is assumed that the $U(1)_R$ symmetry in some string models is valid up to dim=10 operators. This extra assumption is needed for the strong CP, but not for a solution of the $\mu$ problem. Suppose $z_i$ carries $P$ and $Q$ charges so that it transforms under $U(1)_P$ and $U(1)_R$ as

$$z_i \longrightarrow e^{i[\alpha_c P(z_i) + \alpha_h R(z_i)]} z_i \quad (21)$$

where $\alpha_c$ and $\alpha_h$ are the rotation angles. The $U(1)_P$ and $U(1)_R$ symmetry of $W_{\text{eff}}$ implies

$$P : W_{\text{eff}} \longrightarrow W_{\text{eff}} \quad (22)$$

$$R : W_{\text{eff}} \longrightarrow e^{i\alpha_h R} W_{\text{eff}} \quad (23)$$

where $R = \sum_i R(z_i) = 2$. The nonlinear realization of this transformation is represented by Goldstone fields $a_c$ and $a_h$. $W_{\text{eff}}$ does not depend on $a_c$ but depends on $a_h$, which can be factored out as

$$W_{\text{eff}} = (W_{\text{eff}})_{\text{radial}} e^{2i\alpha_h v_h} \quad (24)$$

with the following transformation

$$a_h \longrightarrow a_h + \alpha_h v_h \quad (25)$$
where \((W_{\text{eff}})_{\text{radial}}\) does not contain \(a_h\). \(|W_{\text{eff}}|^2\) is independent of \(a_c\) and \(a_h\). \(\partial W_{\text{eff}}/\partial z_i\) carries \(P = -P(z_i)\) and \(R = 2 - R(z_i)\) and can be written
\[
\left(\frac{\partial W_{\text{eff}}}{\partial z_i}\right)_{\text{radial}} \exp \left[i \left(-P(z_i) \frac{a_c}{v_c} + (2 - R(z_i)) \frac{a_h}{v_h}\right)\right]
\]
(26)
where \((\partial W_{\text{eff}}/\partial z_i)_{\text{radial}}\) does not depend on \(a_c\) and \(a_h\). Therefore, \(\sum_i |\partial W_{\text{eff}}/\partial z_i|^2\) does not depend on \(a_c\) and \(a_h\).

In general, we expect that \(\nu_0\) and \(\nu_h\) are different, and both \(\theta_h\) and \(\theta_c\) can be settled to zero by the dynamical fields \(a_h\) and \(a_c\). The mass matrix \(M^2\) of \(a_c\) and \(a_h\) satisfies
\[
\text{Det } M^2 = (\nu_0 - \nu_h)^2 \frac{\Lambda_{\text{QCD}}^4 \Lambda_h^4}{v_c^2 v_h^2}
\]
(27)
from which we expect an invisible axion, with mass \(\sim (\text{coupling constant}) \times \Lambda_{\text{QCD}}^2 / \Lambda_h\), because \(\nu_0 \neq \nu_h\) and \(\Lambda_h\), \(v_c\) and \(v_h\) are of the same order. The other boson gets a mass of order \((\text{coupling constants}) \times \Lambda_h^2\).

The \(\mu\) term given in Eq. (1) is supersymmetric. In principle, it can arise without supersymmetry breaking. Thus it can arise from a term \(AH_1 H_2\) in the superpotential with \(\langle A \rangle \neq 0\), and \(\mu\) can be of order string scale. In the above, we argued that a Peccei–Quinn symmetry spontaneously broken at the intermediate mass scale \(M_I\) excludes this possibility. Then there exist many possibilities for generating the \(\mu\) term of order of \(M_{\text{SUSY}}\).

Recently, the \(\mu\) term has been calculated in some string models\[22\] indicating the presence of terms as described in the paper of Guidice and Masiero\[8\]. The contribution of terms in the superpotential to the \(\mu\) term will, however, be dominant unless they are forbidden by a symmetry.

A general expression for the \(\mu\) term can be written as
\[
\mu = A + m_{3/2} O(1) - F^n \partial_n \xi(M^n) + \tilde{\mu}
\]
(28)
where \(F^n\) is the auxiliary component of \(n\)-th modulus, and \(M^n\) is the anti-modulus\[22\]. The \(A\) term must be absent, presumably by the Peccei–Quinn symmetry as mentioned above. The \(m_{3/2}\) term arises from the Guidice–Masiero or the Casas–Munoz form\[8,11\]. The rest
arise from $D$ terms; thus involve anti-chiral fields. $\xi$ arises from moduli couplings and $\tilde{\mu}$ arises from the Yukawa and gauge couplings. In any case, these are at most of order $m_{3/2}$, since to obtain a superpotential $W_{\mu}$ one must take $\int d^2\bar{\theta}$ on the $D$-term which will pick up the $F$-term ($\sim M_\xi^2$) of anti-chiral fields.

Notice, that the absence of $A$ in Eq. (28) is crucial for the solution of the $\mu$ problem and has to be guaranteed by a symmetry, as e.g. the anomalous $U(1)$ symmetry in the models discussed above.

5. Conclusion

We have seen that there can be many sources for the $\mu$ term in supergravity. To understand its magnitude in a natural scheme, however, one needs a symmetry. Both the $R$ symmetry and the Peccei–Quinn symmetry are suggested for a natural solution of the $\mu$ problem. Without such a symmetry principle, one does not have a handle to remove specific (large) terms in the super-potential. We have shown that string models with the anomalous $U(1)_A$ with specific $P$ and $R$ charges are the best candidates toward the solution of both the strong CP problem and the $\mu$ problem.

ACKNOWLEDGMENTS

This work is supported in part by the Korea Science and Engineering Foundation through Center for Theoretical Physics, Seoul National University (JEK), KOSEF–DFG Collaboration Program (JEK, HPN), the Basic Science Research Institute Program, Ministry of Education, 1994, BSRI-94-2418 (JEK) and European Union grants SC1-CT91-0729 and SC1-CT92-0789 (HPN).
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