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THE DEMON OF LOCAL SUSY

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ABSTRACT

We discuss the Dipole Electric Moment Of the Neutron (DEMON) in locally supersymmetric models, with particular attention to axionless theories with $\theta = 0$ at the Planck scale. We find that the DEMON in these theories should be near, but not above, the present experimental upper bound of 16×10^{-25} e.cm.

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It has been recognized for some time now ¹⁾ that softly broken supersymmetric models, in general, can result in potentially large values of the dipole moment of the neutron (DEMON). Recently, detailed calculations ²⁾⁻⁴⁾ have confirmed the numerical estimates in Ref. 1). These results are of particular importance to advocates of locally supersymmetric models with a large (tens of GeV) gravitino mass, as these theories look like globally supersymmetric models with soft supersymmetry breaking at low energy. In this paper we show that a large class of models (including those which we favour) predict a DEMON which is at the level of the experimental upper limit ⁵⁾ of 6×10^{-25} e.cm, although much lower values are possible in models with an axion.

The most general superpotential involving only Higgs doublets and quark and lepton superfields is

$$W = y_U^{ij} \bar{H} Q_i \bar{U}_j + y_D^{ij} H Q_i \bar{D}_j + y_E^{ij} H L_i \bar{E}_j + \mu H \bar{H} \quad (1)$$

where i and j are generation indices. The most general soft breaking terms we can add to the Lagrangian are ⁶⁾

$$\mathcal{L}_{\text{soft}} = \sum_a m_a^2 |\phi_a|^2 + m_{3/2} \sum_n (A_n W_n + h.c.) + \sum_\alpha \left(\frac{1}{2} m_\alpha \lambda_\alpha \lambda_\alpha + h.c. \right) \quad (2)$$

where λ_α is a gauge fermion [gluino ($\alpha=3$), wino ($\alpha=2$), or bino ($\alpha=1$)], W_n is any term in W , and ϕ_a is any scalar (Higgs, squark, or slepton). The A 's are expected to be of order one in locally supersymmetric models, while m_a and m_α should be of order $\frac{m_3}{2}$ ⁷⁾⁻¹⁰⁾.

Without loss of generality, we can assume μ , the Higgs VEVs, all quark masses, and $m_{3/2}$ are real. If the A_n all have the same phase (as predicted by simple models of local SUSY breaking), then, without loss of generality, the A_n can all be chosen real as well. However, there is no more freedom to choose the phases of the gaugino masses. These phases violate CP, and can produce a large DEMON ¹⁾⁻⁴⁾.

Thus, we must ensure that the phases of the gaugino masses are not too large. The breakdown of $SU(2) \times U(1)$ cannot occur at the tree level in ^{10),12),13)} models with a natural gauge hierarchy ¹¹⁾, while radiatively induced breaking is facilitated by large, bare gaugino masses. These masses can come from non-minimal kinetic terms ^{7),10)}

$$\mathcal{L} = \int d^2\theta f_{\alpha\beta}(\hat{Z}) \hat{W}^\alpha \hat{W}^\beta \quad (3)$$

where $\hat{W}^\alpha$ is the superspace Yang-Mills field strength (here α is an adjoint group index) and $f_{\alpha\beta}$ is an a priori arbitrary analytic function of all chiral superfields. We have indicated explicitly its possible dependence on $\hat{Z}$, a chiral superfield which participates in the breaking of local SUSY and whose F component has a VEV of order $m_{\frac{3}{2}}M$, where $M = M_P/\sqrt{8\pi} = 2.4 \times 10^{18}$ GeV. In general, we can write $f_{\alpha\beta}$ as a power series in $(\hat{Z}/M)$:

$$f_{\alpha\beta}(\hat{Z}) = f_{\alpha\beta} \sum_{n=0}^{\infty} a_n \left(\frac{\hat{Z}}{M} \right)^n \quad (4)$$

(possible dependence on other fields has not been written explicitly). The a_n are a priori arbitrary complex numbers, although they are real in extended supergravities. The VEV of $f_{\alpha\beta}$ is related to the bare vacuum angle θ :

$$[\text{Im} \langle f_{\alpha\beta} \rangle]_A = f_{\alpha\beta} \theta \frac{g^2}{32\pi^2} \quad (5)$$

where the subscript A means the A component of $f_{\alpha\beta}$. A possible, axionless solution^{1),10)} to the strong CP problem can be found by supposing that the unknown quantum gravitational dynamics (extended supergravity ?) which determines $f_{\alpha\beta}$ chooses $[\text{Im} \langle f_{\alpha\beta} \rangle]_A = 0$. Then we need only be concerned with finite renormalizations of θ which come from SUSY breaking¹⁾ (more on these below). If we do suppose $[\text{Im} \langle f_{\alpha\beta} \rangle]_A = 0$, it is natural to expect $[\text{Im} \langle f_{\alpha\beta} \rangle]_F = 0$ as well. This will happen, for example, if all the a_n are real (as in extended supergravities), and if both $\langle \hat{Z} \rangle_A$ and $\langle \hat{Z} \rangle_F$ are real (as in simple models of local SUSY breaking). Real $\langle \hat{Z} \rangle_F$ results in a real $m_{\frac{3}{2}}$ and real A_n in Eq. (2), while $\langle f_{\alpha\beta} \rangle_F$ is just the bare gaugino mass. Thus if the solution to the strong CP problem lies in quantum gravity, then it is reasonable to expect $[\text{Im} \langle f_{\alpha\beta} \rangle]_F = 0$, and hence no CP violating phases in bare gaugino masses.

What about radiative contributions to gaugino masses ? Here the situation is more delicate. We know our ultimate Lagrangian must contain hard CP violation to explain the cosmological baryon asymmetry (CBA), and that hard CP violation represented by the Cabibbo-Kobayashi-Maskawa angles provides a good description of the $K^0-\bar{K}^0$ system. These phases can feed into radiative gaugino masses.

There need not be any dangerous (imaginary) contributions to gaugino masses from one-loop diagrams involving superheavy particles [as suggested in Ref. 4)],

as there is no need to have (or reason to expect) CP violation to appear in the mass matrices of these particles. (It need only be present in their Yukawa couplings to quarks and leptons.) So we do not need to worry about CP violation other than that present in the quark and squark mass matrices.

The contribution (Fig. 1) to the imaginary part of gaugino masses coming from one loop of quarks and squarks (or leptons and sleptons) vanishes if all the A_n are equal. In this case, the quark and squark mass matrices are diagonalized by the same unitary transformation, and all CP violation cancels out of Fig. 1. In general, though, we expect the A_n to be different. Even if they are all equal at the GUT or Planck scale (more on this below), they will be renormalized and differ at the weak scale¹³⁾. In the general case of arbitrary (but all real) A_n , the imaginary part of the gluino mass is roughly

$$\text{Im}(m_3) \simeq \left(\frac{\alpha_3}{\pi}\right) m_{3/2} \left(\frac{m_b^2 m_s^2 \text{ or } m_t^2 m_c^2}{m_{3/2}^4} \right) " \sin \delta " \quad (6)$$

where we have assumed that all scalar masses are of order $m_{3/2}$, and " $\sin \delta$ " stands for some combination of angular factors. This result is achieved by noting (see Fig. 2) that we need at least four quark mass insertions (three on the quark line and one on the scalar line, or vice versa) involving more than one generation to get a non-zero imaginary part. Which quark masses appear depends on whether the CKM CP violation resides in the up and/or the down quark sector (more on this below).

Non-zero $\text{Im}(m_3)$ gives a non-zero θ of order $\text{Im}(m_3)/\text{Re}(m_3)$ when the gluino is rotated to make its mass real. Assuming $\text{Re}(m_3)$ is of order $m_{3/2}$, we get

$$\delta\theta \simeq \frac{\text{Im}(m_3)}{m_{3/2}} \quad (7)$$

Combining Eqs. (6) and (7), it is easy to see that $\delta\theta \gg 10^{-9}$ (and hence produces too large a DEMON) if we use $m_t^2 m_c^2$ in Eq. (6). If we use $m_b^2 m_s^2$, and take the worst case estimates $\alpha_3 \simeq 0.15$, $m_{3/2} \simeq 20 \text{ GeV}$ (there are no charged scalars lighter than this), we get

$$\delta\theta \simeq \left(\frac{\alpha_3}{\pi}\right) \frac{m_b^2 m_s^2}{m_{3/2}^4} " \sin \delta " \simeq 2 \cdot 10^{-7} " \sin \delta " \quad (8)$$

which is compatible with experiment^{5),14)} for " $\sin \delta$ " ≤ 0.01 . [The reader who is still worried about θ should remember that we can add a harmless, phantom axion¹⁵⁾ to the model, if necessary. Axion models always yield an effective θ of order $\text{Im}(m_{12})/m_K \simeq O(10^{-17})$ (here we disagree with comments made in Ref. 4).]

There is also a direct contribution to the DEMON from the diagrams of Fig. 3. The gluino contributes an amount of order

$$\text{DEMON} \simeq e \left(\frac{\alpha_3}{\pi} \right) m_{u,d} \frac{\text{Im}(m_3)}{m_{3/2}} \quad (9)$$

Using the same (worst case) values of parameters as before, with $m_b^2 m_s^2$ in Eq. (6), this gives the safe value

$$\text{DEMON} \simeq 10^{-27} \text{ "sin } \delta" \text{ e.cm} \quad (10)$$

If we use $m_t^2 m_c^2$ with $m_t \simeq 50 \text{ GeV}$, we get a DEMON of $10^{-23} \text{ "sin } \delta" \text{ e.cm}$. This is also acceptable if "sin δ ", a combination of CKM angles, is less than 0.05.

The winos and binos contribute to the DEMON as well, but not as much since their couplings are weaker.

Let us summarize our conclusions up to this point. If we assume that the a_n of Eq. (4) are real (as in extended supergravities), and that $\langle \hat{Z} \rangle_A$ and $\langle Z \rangle_F$ are real (as in simple models of local SUSY breaking), we get $\theta = \text{Im}(m_3) = \text{Im}(A_n) = \text{Im}(m_{\text{gaugino}}) = 0$ at the Planck scale. If all hard CP violation is in the couplings of Higgs fields to down quarks, then the renormalized value of θ is about 10^{-9} (worst case estimate with "sin δ " $\simeq 0.01$). If we insist on hard CP violation in the up quark sector (and there is no reason to do so), we need an axion to suppress θ . The direct contribution to the DEMON is clearly acceptable for "down" CP violation, borderline for "up" CP violation.

The previous discussion applies in the case of general, real values of A_n . As we said, though, these contributions to the DEMON vanish if all the A_n are equal. If they are almost equal, we get suppression factors of ΔA . So it is of interest to examine the values of A_n in different models.

One simple method of SUSY breaking is to add to the superpotential of ordinary matter some terms whose sole function in life is to break local SUSY ⁹⁾ spontaneously. This yields A_n of the form

$$A_n = A - 3 + d_n \quad (11)$$

where A is a universal number (assumed real) and d_n is the number of fields multiplied together in term n . We have argued elsewhere ¹⁶⁾ that a very attractive resolution of quark-lepton mass hierarchies can be found by assuming

that the mass terms for the third generation are produced by the usual, renormalizable Higgs couplings, but that second and first generation masses come only from non-renormalizable couplings. This gives different A_n for different generations.

Let us present a simple model for our fermion mass mechanism. The relevant parts of the superpotential are

$$\begin{aligned}
 W = & \bar{H} \left[y'_3 T_3 T_3 + y'_2 M^{-1} \Sigma T_2 T_2 + y'_1 M^{-2} \Sigma^2 T_1 T_1 \right] \\
 & + H \left[\bar{F}_3 (y_{33} T_3 + y_{32} T_2 + y_{31} T_1) \right. \\
 & + M^{-1} \Sigma \bar{F}_2 (y_{23} T_3 + y_{22} T_2 + y_{21} T_1) \\
 & \left. + M^{-2} \Sigma^2 \bar{F}_1 (y_{13} T_3 + y_{12} T_2 + y_{11} T_1) \right] \quad (12)
 \end{aligned}$$

Here the $\bar{F}_i (T_i)$ are $\bar{5}$'s (10 's) of $SU(5)$, and Σ is a 24 . The y (y') are complex (real) numbers of order one ^{*)}. Equation (12) is schematic : terms with Σ should include different contractions of $SU(5)$ indices (each with its own set of y 's), which produce novel fermion mass relations ¹⁶⁾ (like $|m_s/m_u| = 2/3$). The most important feature of Eq. (12) for the present discussion is that the up quark sector is strictly diagonal, and hence contains no CP violation. If we add terms to break local SUSY spontaneously, we get different A_n 's for different generations. This is potentially important, since it means that $|A|$ [defined in Eq. (11)] can be larger than three [as required, for example, to break $SU(5)$ in the model of Ref. 17)], while removing the dangerous, charge breaking minima found in Ref. 18). For example, suppose $A = -3.1$. Then we see from Eq. (11) that the A_n corresponding to the first two generations are -2.1 and -1.1 , both safe values from the point of view of Ref. 18). A_n for the third generation is -3.1 , but this is subject to renormalization and we can get this $|A_n|$ less than three at the weak scale as well. On the other hand, the A_n relevant to $SU(5)$ breaking in Ref. 17) are not subject to significant renormalization since they correspond to very small Yukawa couplings of order 10^{-12} . Thus this model is acceptable on all fronts ; it would yield a θ of 10^{-9} (worst case estimate with "sin δ " = 0.01).

*) The y must be chosen, however, so that the field redefinitions which make the quark mass matrix real and diagonal do not entail an over-all chiral rotation which changes θ ; otherwise, we need an axion.

Finally, we would like to comment on our general philosophy of putting some couplings in and leaving others out. This is, of course, somewhat unappealing. We would like to write down the most general couplings, all of order one, consistent with local symmetries. All such theories proposed to date have one feature in common : they do not describe Nature. Since we are forced to adopt theories where some couplings (like quark-lepton Yukawa couplings) seem unnaturally small, it seems to us that the best available strategy is to consider only theories where small couplings are more than small : they are zero. These zeros, we believe, will be much easier to explain in a fundamental theory ($N = 8$ supergravity ?) than numbers like $m_e/M_W \approx 10^{-6}$. Of course, global SUSY is essential to make sure that large, unwanted couplings are not generated radiatively, and local SUSY is essential to explain the existence of non-renormalizable couplings whose shadows describe our world at low energies.

We have seen that models of the type we favour, within the context of our philosophy for constructing them, can solve the strong CP problem while yielding an acceptable DEMON. The DEMON, however, cannot be too small, and could be the first apparition of local SUSY to our experimental colleagues.

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FIGURE CAPTIONS

Figure 1 A radiative contribution to the real part of gaugino masses. The cross on the quark line represents a quark mass ; the cross on the scalar line represents a squared mass proportional to a quark mass coming from the $A_n W_n + \text{h.c.}$ terms in Eq. (2).

Figure 2 A radiative contribution to the imaginary part of gaugino masses requires at least four mass insertions.

Figure 3 Direct contribution to the DEMON. The cross represents the imaginary part of the gluino mass.

- Figure 1 -

- Figure 2a -

- Figure 2b -

- Figure 3 -