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PREDICTIONS FOR THE ELECTRIC DIPOLE MOMENTS IN SUPERSTRING-BASED MODELS

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A B S T R A C T

In superstring inspired E_6 unified theories, the CP violating interactions of the scalar leptons may give rise to large values of the electron and neutron electric dipole moments without upsetting other phenomenological constraints.

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Certainly, there are many problems to be overcome before a four-dimensional field theory in agreement with the physical reality is consistently derived from a ten-dimensional $E_8 \times E_8$ string theory¹⁾ valid at the Planck scale. However, some general implications²⁾ of the superstring inspired unified theories lead to phenomenological predictions which can be already tested³⁾⁻⁹⁾.

One such prediction is that the matter fields should be accommodated in a 27 representation of E_6 , which, besides the usual quarks and leptons (including a right-handed neutrino) contains an isosinglet neutral lepton N and two 5-plets, $(\bar{h}\bar{h}\bar{h}H^{-}\bar{H}^0)$ and $(hhhH^0H^+)$, transforming as the 5 and 5* representations of $SU(5)$, respectively. In contrast to any ordinary grand unified theory, in the superstring-based models the colour triplet isosinglet fields h and $\bar{h}$ may be light¹⁰⁾ ($M_{h,\bar{h}} \approx 10^2-10^3$ GeV) without necessarily causing proton instability. Some physical implications of the existence of a light h and $\bar{h}$ have already been considered^{5),7)-9)}.

In the present note we discuss the possibility that the interactions of the h and $\bar{h}$ with the usual forms of matter violate CP conservation. We calculate the electric dipole moments (EDM) of the electron (d_e) and the neutron (d_n) induced by h , $\bar{h}$ exchange processes and find that they could be much larger than in the standard model [see Ref. 11) for a review], actually very close to the present experimental upper limits¹²⁾

$$\begin{aligned} d_e^{\text{exp}} &< 3 \times 10^{-24} \text{ e.cm} \\ d_n^{\text{exp}} &< 4.6 \times 10^{-25} \text{ e.cm} \end{aligned} \quad (1)$$

Furthermore, it is easy to argue that the considered effect will not substantially contribute to the CP violation in the K meson system.

The interactions of the h and $\bar{h}$, often called (scalar) leptoquarks, are described by the following superpotential:

$$\bar{\lambda} L Q \bar{h} + \lambda e^c u^c h + \lambda' \bar{\nu}^c d^c h + f N h \bar{h} \quad (2)$$

The last term is important in mixing h and $\bar{h}$ and giving them a mass $\sim f \langle N \rangle$ through a soft supersymmetry breaking three-scalar coupling³⁾. In addition to the terms in Eq. (2), the underlying E_6 symmetry would also allow the diquark couplings QQh and $u^c d^c \bar{h}$, but to avoid a catastrophe with proton decay one must assume that they

are not present. The more optimistic "string phenomenologists" hope that a discrete symmetry originated in the topological structure of the compactified internal manifold forbids these couplings³⁾. This kind of discrimination of couplings would, of course, be out of the question in the ordinary GUT's where the Yukawa coupling constants are uniquely determined by the gauge symmetry; on the other hand, in the superstring models the discrimination is possible due to extraordinary symmetry breaking mechanism that is believed to work there¹³⁾.

The superpotential (2) leads to the following lepton-quark-leptoquark couplings:

$$\begin{aligned} & \bar{\lambda}_{ij}^k (\bar{\ell}_{iR}^c u_{jL} - \bar{\nu}_{iR}^c d_{jL}) \bar{h}_k \\ & + \lambda_{ij}^k \bar{\ell}_{iR} u_{jL}^c h_k + \lambda'_{ij}{}^k \bar{\nu}_{iR} d_{jL}^c h_k + h.c. \end{aligned} \quad (3)$$

where i, j and k are family indices. Since there are left-handed and right-handed couplings between a given pair of lepton and quark, and the associated coupling constants are independent, it is obvious that a CP violation can be generated already by one-loop diagrams. Indeed, in the Figure, we present the diagrams which contribute to the EDM of the electron and the up quark. Let us recall that in the standard model with the Kobayashi-Maskawa (KM) mechanism¹⁴⁾ for CP violation one must go beyond two loops in order to get a non-vanishing result for a quark EDM¹⁵⁾ and thus the moments predicted are necessarily small. For the neutron a two-quark mechanism¹⁶⁾ gives the dominant contribution but even so the result¹⁷⁾ is seven orders of magnitude below the experimental limit. In our mechanism, one could expect larger values.

From the Figure we obtain for the electric dipole moment of a fermion f

$$d_f = - \frac{e}{16\pi^2} \text{Im}(\lambda \bar{\lambda}) m_F \int_0^1 dx \frac{Q_F(1-x)^2 + Q_B x(1-x)}{x m_B^2 + (1-x) m_F^2 - x(1-x) m_f^2} \quad (4)$$

where m_F and m_B are the masses and Q_F and Q_B the electric charges of the loop fermion and boson, respectively. One notices here an interesting interconnection between lepton and quark worlds: the EDM of a lepton is scaled by a quark mass and vice versa. However, this does not mean that the moments of leptons are in general larger than those of quarks. In fact, for small m_F the integral in Eq. (4) is dominated by the term $(Q_F/m_B^2) \log(m_F/m_B)$ which counterbalances the linear dependence on m_F . Clearly, the EDM of the down quark is expected to be very small, since it is proportional to a neutrino mass (which is necessarily in

the range 1 eV to 10^2 eV in this model^{5),8),9)} and the leading term, the one where the photon couples to the internal fermion, vanishes ($Q_V=0$). For the EDM of the electron we obtain

$$d_e = \begin{cases} 7.8 \times 10^{-22} \text{Im}(\lambda\bar{\lambda})_1 & \text{e.cm} \\ 2.6 \times 10^{-19} \text{Im}(\lambda\bar{\lambda})_3 & \text{e.cm} \end{cases}, \quad (5)$$

where the two numbers correspond to the graphs with the u quark or the t quark in the loop, respectively. The figures in Eq. (5) satisfy the experimental bound of Eq. (1) if

$$\begin{aligned} \delta_1 \equiv \text{Im}(\lambda\bar{\lambda})_1 &< 4 \times 10^{-3} \\ \delta_3 \equiv \text{Im}(\lambda\bar{\lambda})_3 &< 10^{-5} \end{aligned} \quad (6)$$

The indices in the couplings in Eqs. (5) and (6) remind us of the quark generation involved. For the EDM of the u quark, and therefore for that of the neutron, we obtain

$$d_n = \begin{cases} -1.4 \times 10^{-22} \text{Im}(\lambda\bar{\lambda})_1 & \text{e.cm} \\ -1.4 \times 10^{-19} \text{Im}(\lambda\bar{\lambda})_3 & \text{e.cm} \end{cases}, \quad (7)$$

which in turn implies the bounds

$$\begin{aligned} \text{Im}(\lambda\bar{\lambda})_1 &< 3 \times 10^{-3} \\ \text{Im}(\lambda\bar{\lambda})_3 &< 3 \times 10^{-8} \end{aligned} \quad (8)$$

In our estimate we have taken $m_u = 5$ MeV, $m_t = 40$ GeV, $m_e = 0.5$ MeV, $m_\tau = 1.8$ GeV and $m_B = 100$ GeV.

Let us recall the standard model result¹⁷⁾

$$d_n = 1.6 \times 10^{-28} \delta_{KM} \text{e.cm}, \quad (9)$$

where $|\delta_{KM}| = 4 \times 10^{-5}$ is a combination of KM angles and phase that plays the role of $\text{Im}(\lambda\bar{\lambda})$. It is interesting to point out that a δ_3 of this order of magnitude, i.e., $\delta_3 \approx 10^{-5}$, is already excluded by Eqs. (8). Furthermore, assuming that $\text{Im}(\lambda\bar{\lambda}) \approx \text{Re}(\lambda\bar{\lambda})$ one can see that our most stringent bound implies

$$\lambda, \bar{\lambda} < 2 \times 10^{-4} \quad (10)$$

which is consistent with and slightly smaller than the values derived^{5),9)} from the analysis of some rare decays.

Another prediction of our mechanism is the fact that the EDM of the electron and of the neutron are related to each other. Depending on whether we consider the first or the third generations, we obtain from Eqs. (5) and (7)

$$-d_e/d_n \simeq \begin{cases} 5 \\ 0.02 \end{cases}, \quad (11)$$

where the relative sign is another consequence of the fact that the dominant contribution is proportional to Q_F , the electric charge of the loop fermion. In the standard model these two quantities are totally independent, since one does not expect any relation between the KM mixings in the quark and lepton sectors. On the contrary, with the mechanism we are considering and if the third generation couplings are complex, it is possible that $d_n \approx -50 d_e$. Furthermore, this mechanism could induce large EDM without any significant increase of CP violation in the kaon system, where only down quark transitions are involved. Similarly, we do not predict any considerable CP violation in the $B^0-\bar{B}^0$ system, but we do so for the $D^0-\bar{D}^0$ and $T^0-\bar{T}^0$ transitions.

In conclusion, assuming that light leptoquark particles exist, as they do according to some models based on superstrings, and if their interactions with quarks and leptons violate CP conservation, then, as we have shown, the electric dipole moments of the electron and neutron will be related and may have values close to the present experimental upper limits, without upsetting other phenomenological constraints.

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FIGURE CAPTION

Fig. 1a Diagram contributing to the electric dipole moment of the electron.
 There is another diagram where the photon couples to the internal
 fermion line.

Fig. 1b Similar to a, but for the up quark.

(a)

(b)