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Abstract

We show that in $SU(3)_C \times SU(3)_L \times U(1)_X$ model, with the values of relative phases of the vev's such that CP violation is nonzero, the leading contribution to the electric dipole moment of neutron is due to the one-loop diagrams which come from exchanging the charged Higgs bosons and the new quark D in the first family. The estimated result together with current experimental bounds on d_n shows that CP violation is very small.

PACS number(s): 13.40.Em, 12.60.Cn, 12.60.Fr, 14.65.Bt

1 Introduction

Recently, an interesting model based on the gauge group $SU(3)_C \times SU(3)_L \times U(1)_X$ has been proposed[1,2] as a possible explanation of the family replication question and its some phenomenological implications have been investigated[3,4,5,6]. Comparing with other electroweak models of $SU(3) \times U(1)$ suggested some years ago with different choices of particle content[7], this model has minimal particle content and some new interesting features. In this model, the third quark family is treated differently from the first two, and the anomaly cancellation requires that the number of families be equal to the number of quark colours. By matching the gauge coupling constants at the electroweak scale, the mass of the new heavy neutral gauge boson Z_2 is bounded to be less than 1.7 Tev and the mass upper bound for the new charged gauge bosons ($Y^{\pm\pm}$ and $Y^{\pm}$) is 330 Gev[3]. Unlike most extensions of the standard model, in which the masses of the new gauge bosons are not bounded from above, this model would be either realized or ruled out in the future high energy colliders.

In this paper, we estimate the size of the electric dipole moment (edm) d_n of the neutron in this model. It is well known that the neutron electric dipole moment can play an important role in helping us to identify the sources of CP violation[8]. In particular, any positive result of EDM around the experimental limit[9] ($d_n = -(3 \pm 5) \times 10^{-20}$ e-cm) will demonstrate the presence of a CP-violation source above and beyond the standard Kobayashi-Maskawa mechanism. In such an eventuality, models in which the CP-violation is brought about by the exchange of Higgs bosons[10] (whether involving spontaneous breaking of the CP symmetry or not) are likely to receive even closer scrutiny as candidate theories of CP violation. In the $SU(3)_C \times SU(3)_L \times U(1)_X$ model, there are several Higgs multiplets and spontaneous CP

violation occurs via complex vacuum expectation values.

This paper is organized as follows. Section 2 outlines the model and in particular, its relative Higgs sector. Section 3 calculates the edm of neutron. The numerical results and discussions are presented in the section 4.

2 Description of the Model

We outline the model presented by Frampton[1]. The fermions transform under $SU(3)_C \times SU(3)_L \times U(1)_X$ according to

$$l_{1,2,3} = \begin{pmatrix} e^- \\ \nu_e \\ e^+ \end{pmatrix}, \begin{pmatrix} \mu^- \\ \nu_\mu \\ \mu^+ \end{pmatrix}, \begin{pmatrix} \tau^- \\ \nu_\tau \\ \tau^+ \end{pmatrix} : (1, 3^*, 0) \tag{1}$$

$$q_{1,2} = \begin{pmatrix} u \\ d \\ D \end{pmatrix}, \begin{pmatrix} c \\ s \\ S \end{pmatrix} : (3, 3, -1/3) \tag{2}$$

$$q_3 = \begin{pmatrix} b \\ t \\ T \end{pmatrix} : (3, 3^*, 2/3) \tag{3}$$

$$u^c, c^c, t^c : (3^*, 1, -2/3) \tag{4}$$

$$d^c, s^c, b^c : (3^*, 1, 1/3) \tag{5}$$

$$D^c, S^c : (3^*, 1, 4/3) \tag{6}$$

$$T^c : (3^*, 1, -5/3), \tag{7}$$

where new quarks D, S, and T carry electric charge Q=-4/3, -4/3, and 5/3 respectively.The Higgs multiplets required for the symmetry breaking and fermion masses are given by

$$\Phi = \begin{pmatrix} \phi^{++} \\ \phi^+ \\ \phi^0 \end{pmatrix} : (1, 3, 1) \tag{8}$$

$$\Delta = \begin{pmatrix} \Delta_1^+ \\ \Delta^0 \\ \Delta_2^- \end{pmatrix} : (1, 3, 0) \tag{9}$$

$$\Delta' = \begin{pmatrix} \Delta'^0 \\ \Delta'^- \\ \Delta'^{--} \end{pmatrix} : (1, 3, -1) \tag{10}$$

and

$$\eta = \begin{pmatrix} \eta_1^{++} & \eta_1^+/\sqrt{2} & \eta^0/\sqrt{2} \\ \eta_1^+/\sqrt{2} & \eta'^0 & \eta_2^-/\sqrt{2} \\ \eta^0/\sqrt{2} & \eta_2^-/\sqrt{2} & \eta_2^{--} \end{pmatrix} : (1, 6, 0). \tag{11}$$

The non-zero vacuum expectation value (VEV) of ϕ^0 breaks $SU(3)_L \times U(1)_X$ into $SU(2)_L \times U(1)_Y$ and electroweak breaking is achieved by VEVs of Δ^0 and Δ'^0. The sextet η is needed to obtain a realistic lepton mass spectum.

We need to know the masses of the charged Higgs bosons and their quark couplings in the model in order to calculate the edm of neutron. Therefore, we present the relevant masses and mass eigenstates of the charged Higgs bosons investigated by C. S. Huang and me [6] as following (we have set w=0 for the sake of simplicity in reference [6]): The mininum of the

potential is achieved for

$$< \Phi >= \begin{pmatrix} 0 \\ 0 \\ u\exp(i\alpha)/\sqrt{2} \end{pmatrix} \tag{12}$$

$$< \Delta >= \begin{pmatrix} 0 \\ v\exp(i\alpha+\beta)/\sqrt{2} \\ 0 \end{pmatrix} \tag{13}$$

$$< \Delta' >= \begin{pmatrix} v'/\sqrt{2} \\ 0 \\ 0 \end{pmatrix} \tag{14}$$

The phases α and β are measure of CP violation.

In addition, the relevant masses and mass eigenstates of the charged physical Higgs bosons are

$$H_1^{\pm} = \exp(\pm i(2\alpha+\beta))sin\theta_2\Delta_2^{\pm} + cos\theta_2\phi^{\pm} \tag{15}$$

with a common mass given by $m^2_{H_1^{\pm}} = fv'(u^2+v^2)/(\sqrt{2}uv)$,

$$H^{\pm\pm} = \exp(\pm i\alpha)sin\theta_1\phi^{\pm\pm} + cos\theta_1\Delta'^{\pm\pm} \tag{16}$$

with a mass given by $m^2_{H^{\pm\pm}} = fv(u^2+v'^2)/(\sqrt{2}uv')$,

where $tg\theta_1 = v'/u$ and $tg\theta_2 = u/v$.

3 The edm of the Neutron

The EDM of a particle is defined by one of its electromagnetic form factors. In particula a spin-$\frac{1}{2}$ particle f, the form factor decomposition of the matrix element of the electroma current J_μ is:

$$< f(p')|J_\mu(0)|f(p) >= \bar{u}(p')\Gamma_\mu(q)u(p),$$

where

$$\Gamma_\mu(q) = F_1(q^2)\gamma_\mu + F_2(q^2)i\sigma_{\mu\nu}q^\nu/(2m) + F_A(q^2)(\gamma_\mu\gamma_5 q^2 - 2m\gamma_5 q_\mu) + F_3(q^2)\sigma_{\mu\nu}\gamma_5 q^\nu/(2m),$$

where $q = p' - p$ and m denotes the mass of f.

The EDM of f is then given by:

$$d_f = -F_3(0)/2m$$

Thus in the $SU(3)_C \times SU(3)_L \times U(1)_X$ model, the lowest order non-zero $d_u(d_d)$ can through the one-loop graphs Fig.(a). The relevant terms of quark-quark-Higgs boson coup in Lagrangian after the spontaneously symmetry breaking are:

$$\begin{aligned}
\mathcal{L} = &\textstyle\sum_k[\bar{u}(a_{11}^{h_k} + \gamma_5 b_{11}^{h_k})u + \bar{d}(a_{11}^{'h_k} + \gamma_5 b_{11}^{'h_k})d]h_k \\
&+ \textstyle\sum_k\sum_{i=2}^3\{[\bar{u}(a_{1i}^{h_k} + \gamma_5 b_{1i}^{h_k})u^i + \bar{d}(a_{1i}^{'h_k} + \gamma_5 b_{1i}^{'h_k})d]h_k + H.C.\} \\
&+\{[\textstyle\sum_{i=1}^3 \bar{d}^i(a_{i1} + b_{i1}\gamma_5)u + \sum_{i=2}^3 \bar{d}(a_{1i} + \gamma_5 b_{1i})u^i]H_2^- \\
&+ \textstyle\sum_{i=1}^2[\bar{N}^i(c_{i1} + \gamma_5 d_{i1})dH_1^- + \bar{N}^i(e_{i1} + \gamma_5 f_{i1})uH_1^{--}] + H.C.\},
\end{aligned}$$

where $u = (u, c, t), d = (d, s, b), N = (D, S)$ and $A^\mu, h_k, H_2^-, H_1^-, H^{--}$ are the photon , ne Higgs bosons and charged Higgs bosons respectively.

The parameters a_{i1}, b_{i1} etc. are proportional to the coefficient of the Yukawa coupling. In particular, the parameters a_{i1}, b_{i1} etc. with i=1 are proportional to the mass of the corresponding quarks. The contributions to d_u and d_d of Fig.(a) are proportional to $m_j Im(a_{ij} b^*_{ij})$, therefore, the dominant contributions are the ones where $H^{++}(H_1^+)$ is exchanged between D and u (d) quarks for charged Higgs boson-quark couplings (We do not consider the diagrams that D quark is replaced by S quark because the coefficient of the Yukawa coupling in the latter case is relatively small.). Here, we consider only these dominant contributions(see Figs. (b), (c), (d) and (e)).

First,caculating the diagrams in Figs. (b) and (c), we obtain:

$$d_u = \frac{2m_D}{16\pi^2 m^2_{H^{++}}} Im(e_{11} f^*_{11})\{-eQ_{H^{++}} I_u^{(1)}(m_{H^{++}}, m_D, m_u) + eQ_D I_u^{(2)}(m_{H^{++}}, m_D, m_u)\}, \tag{21}$$

where $Q_D = -4/3$ and $Q_{H^{++}} = 2$,

$$I_u^{(1)}(m_{H^{++}}, m_D, m_u) = \int_0^1 dx \frac{x(1-x)}{1 - x + \rho_D^2 x - \rho_u^2 x(1-x)} \tag{22}$$

and

$$I_u^{(2)}(m_{H^{++}}, m_D, m_u) = \int_0^1 dx \frac{x^2}{1 - x + \rho_D^2 x - \rho_u^2 x(1-x)} \tag{23}$$

where $\rho_i = m_i / m_{H^{++}}$, i=D,u. In Eq.(21)

$$e_{11} = \tfrac{1}{2}[h^1_D cos(\alpha) sin(\theta_1) + h^1_u cos(\theta_1) + i h^1_D sin(\alpha) sin(\theta_1)], \tag{24}$$

$$f_{11} = \tfrac{1}{2}[-h^1_D cos(\alpha) sin(\theta_1) + h^1_u cos(\theta_1) - i h^1_D sin(\alpha) sin(\theta_1)], \tag{25}$$

where h^1_u and h^1_D are the coefficients of the Yukawa interactions which are related to the

masses of u quark and D quark *respectively*[3]. From Eq.(24), Eq(25), one has

$$\begin{aligned} Im(e_{11} f^*_{11}) &= \tfrac{1}{2} h^1_D h^1_u sin(\theta_1) cos(\theta_1) sin(\alpha) \\ &= \tfrac{1}{4} g^2 \frac{m_u m_D}{m^2_{Y^{++}}} sin(\alpha). \end{aligned} \tag{26}$$

where $m_{Y^{++}}$ is the mass of the new charged gauge boson Y^{++}. Similarly, calaulating the diagram in Fig.(d) and (e), we obtain:

$$d_d = \frac{2m_D}{16\pi^2 m^2_{H_1^+}} Im(c_{11} d^*_{11})\{-eQ_{H^+} I_d^{(1)}(m_{H^+}, m_D, m_d) + eQ_D I_d^{(2)}(m_{H^+}, m_D, m_d)\}, \tag{27}$$

where $Q_{H^+} = 1$,

$$I_d^{(1)}(m_{H^+}, m_D, m_d) = I_u^{(1)}(m_{H^+}, m_D, m_d), \tag{28}$$

and

$$I_d^{(2)}(m_{H^+}, m_D, m_d) = I_u^{(2)}(m_{H^+}, m_D, m_d). \tag{29}$$

In Eq.(27)

$$c_{11} = \tfrac{1}{2}[h^1_D cos(\theta_2) + h^1_d sin(\theta_2) cos(2\alpha + \beta) + i h^1_d sin(2\alpha + \beta) sin(\theta_2)], \tag{30}$$

$$d_{11} = \tfrac{1}{2}[-h^1_D cos(\theta_2) + h^1_d sin(\theta_2) cos(2\alpha + \beta) + i h^1_d sin(2\alpha + \beta) sin(\theta_2)], \tag{31}$$

where h^1_d is the coefficient of the Yukawa interactions which is related to the mass of d quark[3].

From Eq.(30), Eq.(31), one has

$$I_m(c_{11} d^*_{11}) = -\tfrac{1}{4} g^2 \frac{m_d m_D}{m^2_{Y^+}} \sin(2\alpha + \beta) \tag{32}$$

where m_{Y^+} is the mass of the new charged gauge boson Y^+.

One may then use either the nonrelativistic-quark-model result $d_n = \frac{4}{3} d_d - \frac{1}{3} d_u$ or "naive dimentional analysis"[11] which gives $d_n \approx d_q$. Therefore, we can obtain the neutron electric dipole moment.

4 Results

First, let us define $d_u = d_u^{max} sin(\alpha)$ and $d_d = d_d^{max} sin(2\alpha + \beta)$.

d_u^{max} and d_d^{max} are numerically computed in terms of the charged Higgs bosons $m_{H^{++}}$ and $m_{H_1^+}$, the D quark mass m_D and the new charged gauge bosons $m_{Y^{++}}$ and m_{Y^+} respectively. By matching the coupling constants at the symmetry breaking scale and using $\sin^2\theta_W(m_Z) = 0.2333$, it is found that the breaking scale is less than 1.7 Tev[3,12]. Therefore, the mass of the new quark D is expected to be less than 10 Tev and the mass upper bound for the new charged gauge bosons (Y^{++} and Y^+) is 330Gev[3]. From the collider experiments[13] and muon decay[14], $m_{Y^{++}}$ and m_{Y^+} are greater than 210 Gev (95% C.L.) and 270 Gev (90% C.L.) respectively. Furthermore, from the analyses on oblique corrections , one obtains an upper bound for the charged Higgs masses, namely $m_{H^{\pm\pm}}, m_{H_2^\pm} \leq O(1Tev)$[4], which leads to $m_{H_1^+} \leq 300Gev$. In our computation, the following ranges are assumed: $0.8Tev \leq m_D \leq 10Tev, 50Gev \leq m_{H^{++}} \leq 1000Gev, 50Gev \leq m_{H_1^+} \leq 300Gev, 210Gev \leq m_{Y^{++}} \leq 350Gev, 270Gev \leq m_{Y^+} \leq 350Gev$ and fixed masses $m_u = m_d = 0.3Gev$. The results are given in Fig.(1)-(6).

From the Figs., we can see that $|d_u^{max}|(d_d^{max})$ decreases slowly when the D quark mass m_D decreases and the charged Higgs mass $m_{H^{++}}(m_{H_1^+})$ increases. But obviously, $|d_u^{max}|(d_d^{max})$ decreases quadratically when the charged gauge boson mass $m_{Y^{++}}(m_{Y^+})$ increases. In addition, $|d_u^{max}|$ is slightly larger than d_d^{max} and they are of the same order of magnitude (10^{-22} e-cm) in the range of reasonable values for model parameters. It is easy to see from Figs. that $d_n^{max} = \frac{1}{3}(4d_d^{max} - d_u^{max})$ is about 2×10^{-22} e-cm which exceeds the experimental limit[9] by 3 orders of magnitude. In order to let d_n within the experimental limit, if we know the exact values of $m_D, m_{H^{++}}, m_{H_1^+}, m_{Y^{++}}, m_{Y^+}, m_u$ and m_d, we can let

$|d_n| = |\frac{1}{3}(4d_d^{max} sin(\alpha) - d_u^{max} sin(2\alpha + \beta))| < 10^{-25}$ e-cm by the way of exactly selecting value of β ($\beta = arcsin(\frac{4d_d^{max}}{d_u^{max}} sin(\alpha) - 2\alpha + \epsilon_1)$ when we use the nonrelativistic-quark-model result $d_n = (\frac{1}{3}(4d_d - d_u)$, obviously, this way is not natural; When we consider the "naive dimensional analysis" which gives $d_n \approx d_q$, we must let $\alpha = k\pi + \epsilon_2$ and $\beta = m\pi + \epsilon_3$ (where $\epsilon_i < 10^{-3}$ with i=1,2,3 and $k, m = \pm 1, \pm 2, \pm 3, ...$). Therefore, CP violation is very small.

In conclusion, we have estimated the edm of the neutron in the $SU(3)_C \times SU(3)_L \times U(1)_X$ model. Different form the other models, the dominant contributions to d_n come from exchanging the charged Higgs bosons due to the existence of a new quark D in the first family with charge -4/3 and a not too heavy mass (O(Tev)) in this model. In order not to get into conflict with the experiment bound $d_n = -(3 \pm 5) \times 10^{-25}$ e-cm[9], one can resort to small enough CP-violating phases or even postulate some definite phase relation to produce cancellations between d_u and d_d.

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Figure Captions

Fig.(a) The one-loop contributions to the neutron electric dipole moment. Figs.(b) and (c), the dominant one-loop contributions to the d_u. Figs. (d) and (e), the dominant one-loop contributions to the d_d.

Fig.1 d_u^{max} (in the unit of 10^{-22} e-cm) versus m_{H++}, we have taken $m_{Y++} = 300$ Gev and

$m_D = 5$ Tev.

Fig.2 d_u^{max} (in the unit of 10^{-22} e-cm) versus m_D, we have taken $m_{Y++} = 300$ Gev and $m_{H++} = 250$ Gev.

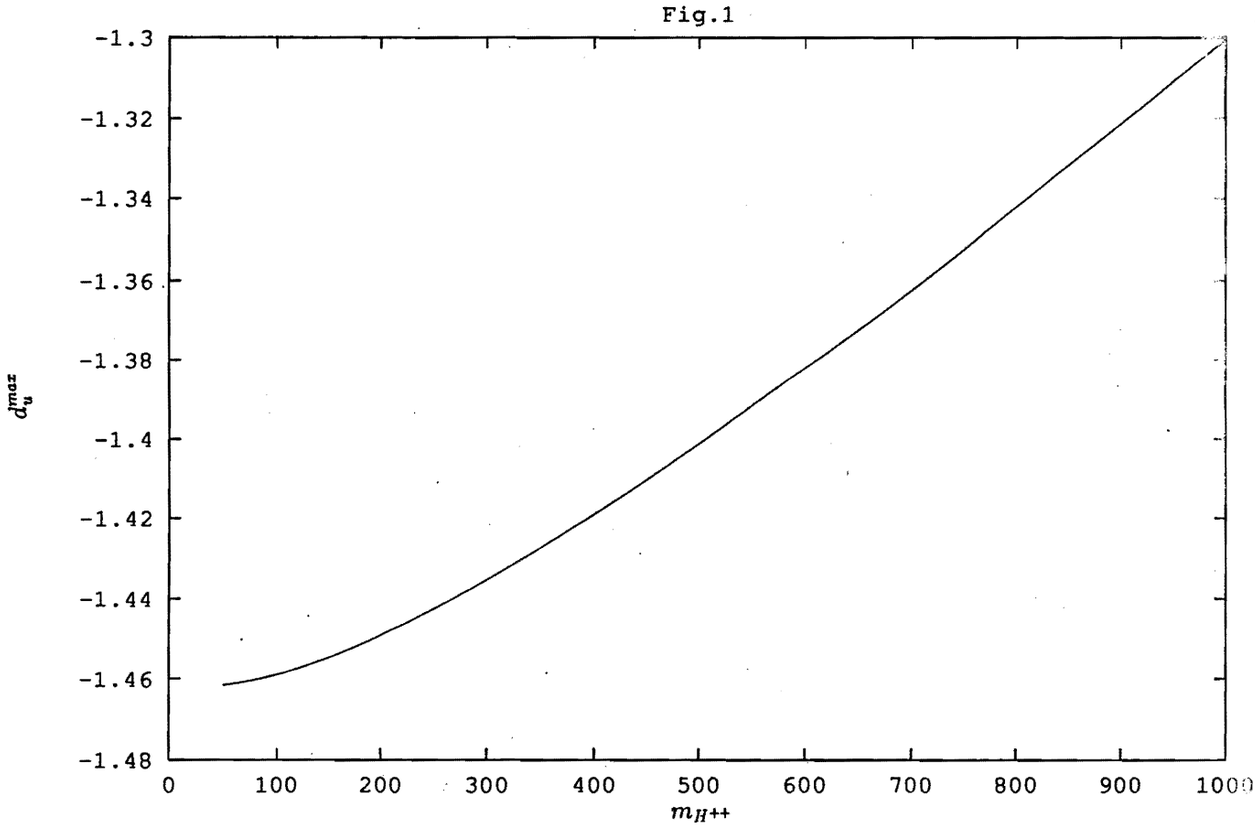
Fig.3 d_u^{max} (in the unit of 10^{-22} e-cm) versus m_{Y++}, we have taken $m_D = 5$ Tev and $m_{H++} = 250$ Gev.

Fig.4 d_d^{max} (in the unit of 10^{-22} e-cm) versus $m_{H_1^+}$, we have taken $m_{Y+} = 300$ Gev and $m_D = 5$ Tev.

Fig.5 d_d^{max} (in the unit of 10^{-22} e-cm) versus m_D, we have taken $m_{Y+} = 300$ Gev and $m_{H_1^+} = 80$ Gev.

Fig.6 d_d^{max} (in the unit of 10^{-22} e-cm) versus m_{Y+}, we have taken $m_D = 5$ Tev and $m_{H_1^+} = 80$ Gev.

Fig.1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$m_{H^{++}}$

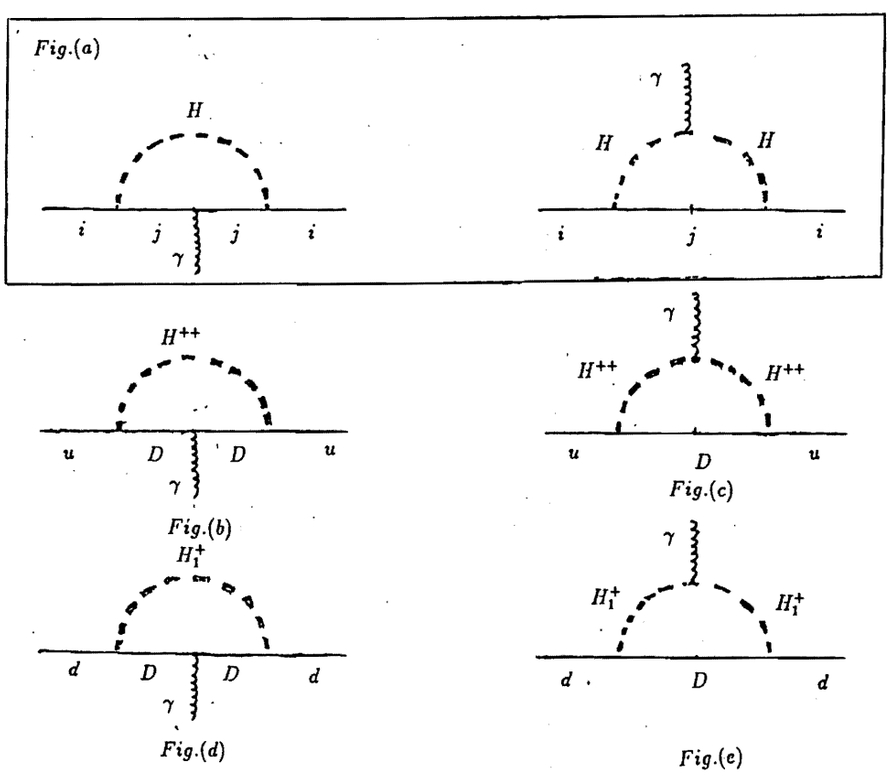
Fig.(a)
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Fig.(c)
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Fig.(e)

Fig.3

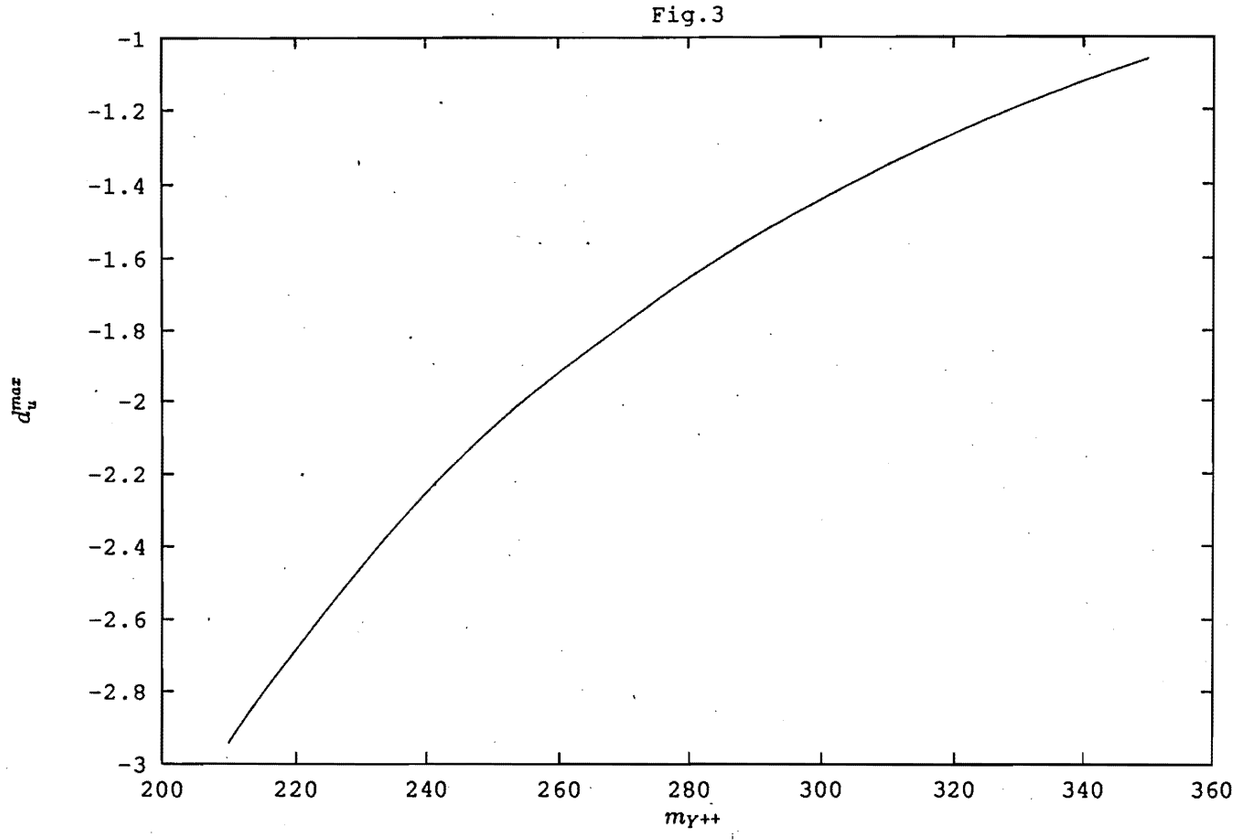
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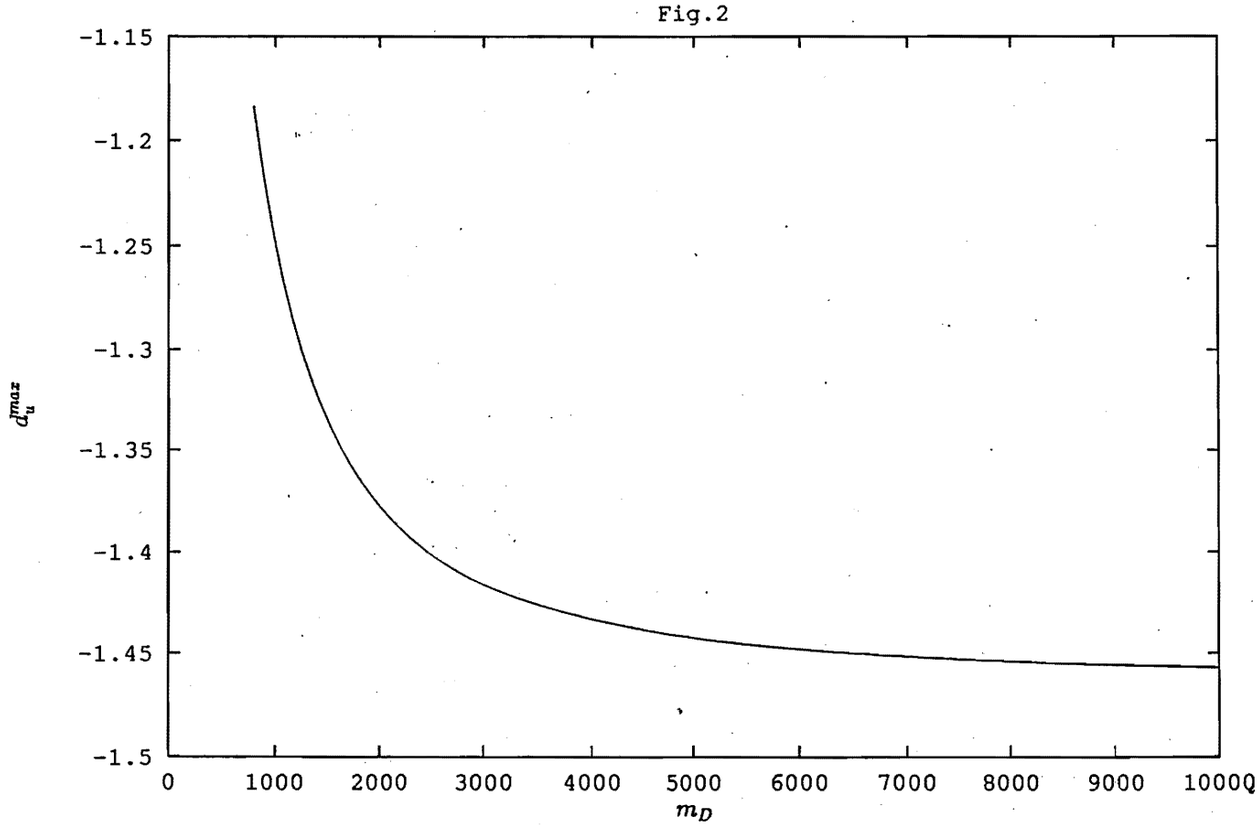
Fig.2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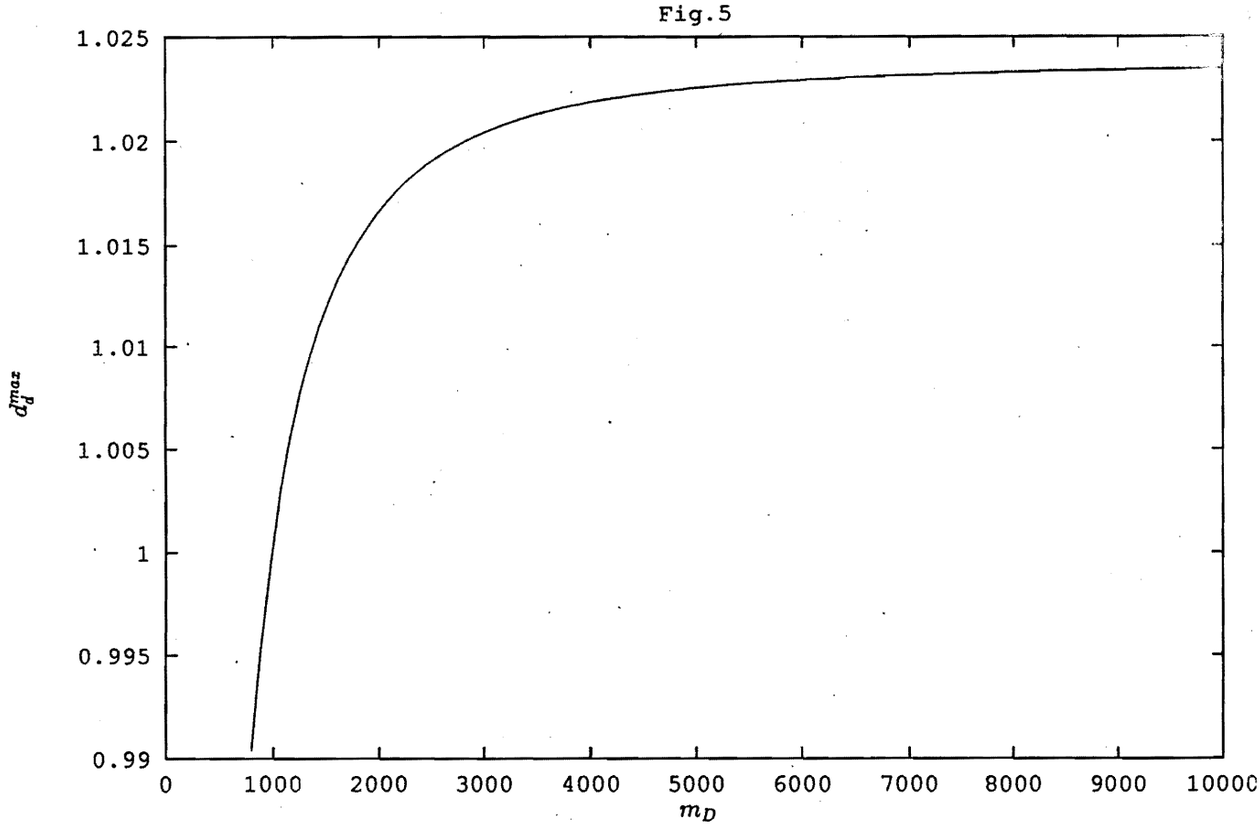
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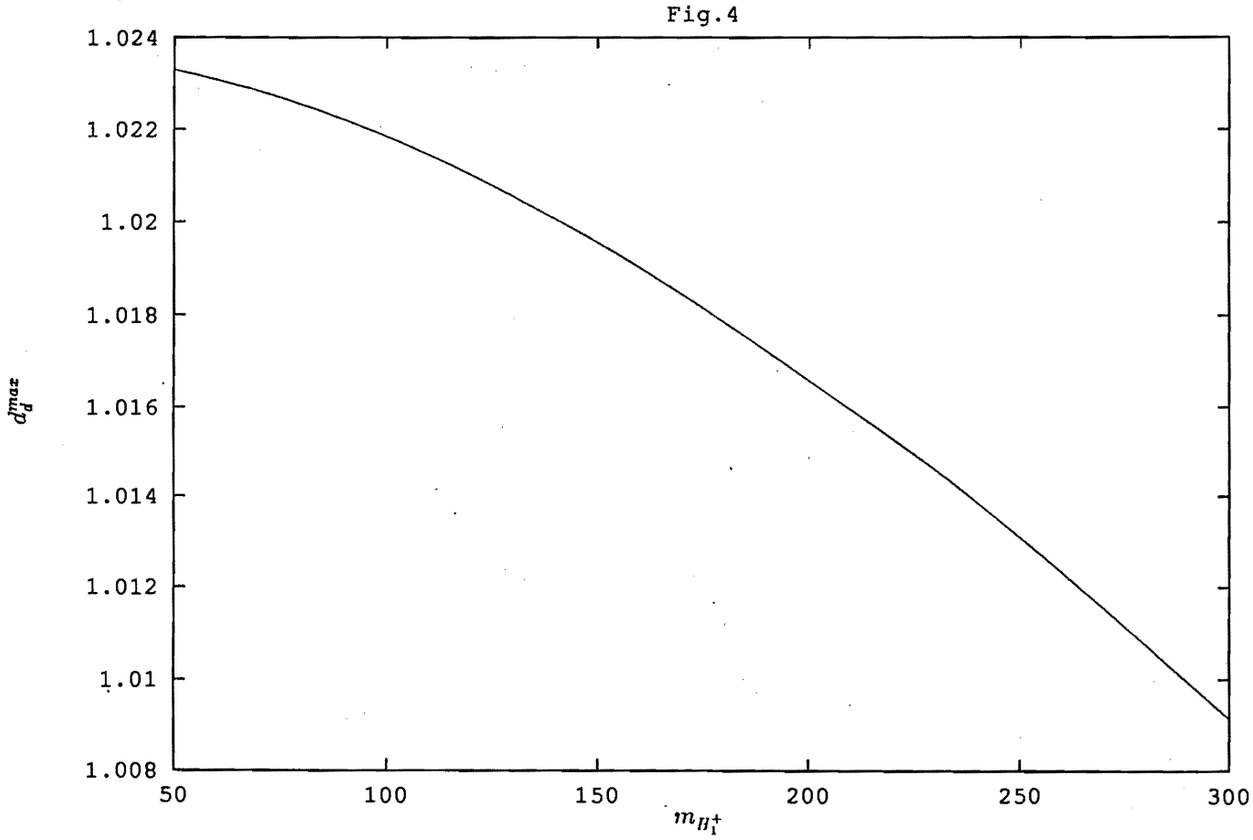
Fig.4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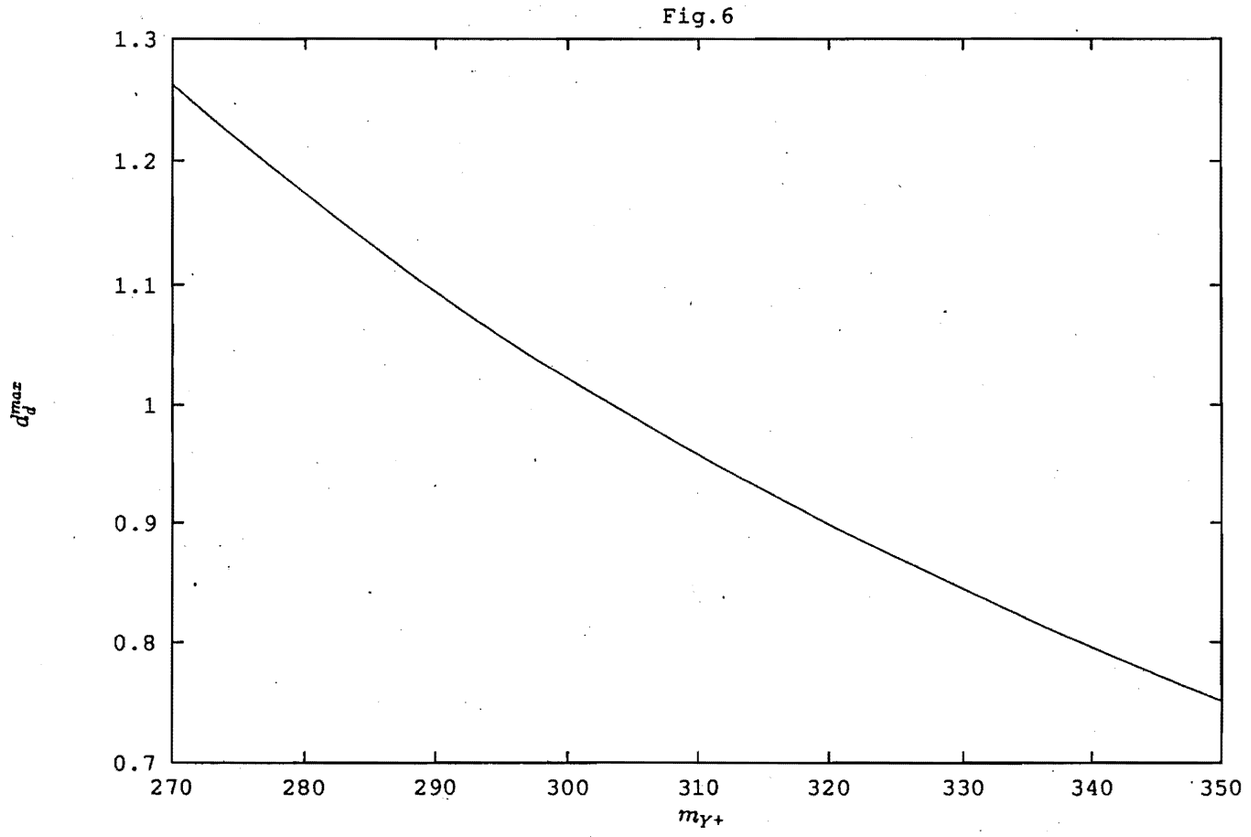
Fig.6