Explicit CP Violation of the Higgs Sector in the Next-to-Minimal Supersymmetric Standard Model

愛媛大学 教育学部 谷本盛光, 愛知教育大学 松田正久

1. Introduction

The physics of CP violation has attracted much recent attention in the light that the B-factory will go on line in the near future at KEK and SLAC. The central subject of the B-factory is the test of the standard model(SM), in which the origin of CP violation is reduced to the phase in the Kobayashi-Maskawa matrix[1]. However, there has been a general interest in considering other approaches to CP violation since many alternate sources exist. The next-to-MSSM(NMSSM) was studied by many authors especially in the interests of mass spectra of Higgs sectors[2,3]. The detailed analysis of the mass spectra in this model was studied by Ellis et al.[3], in which CP violation in the Higgs sector was neglected. The additional singlet N could cause explicit CP violation in the Higgs sector even at tree level. In this report, we study the explicit CP violation of the Higgs sector in the NMSSM phenomenologically.

2. CP violation in Higgs Potential

The model we discuss is the MSSM to which a gauge singlet Higgs scalar N has been added with the requirement that the superpotential contains only cubic terms[2,3] as follows:

$$W = h_U Q u^c H_2 + h_D Q d^c H_1 + h_E L e^c H_1 + \lambda H_1 H_2 N - \frac{1}{3} k N^3 + \cdots \ , \qquad (1)$$

where Q, L, u^c, d^c and e^c are usual notations of quarks and leptons, and the ellipsis stands for possible nonrenormalizable terms. The effective scalar potential is given as

$$\begin{aligned}
V_{\text{Higgs}} &= V_F + V_D + V_{soft} \ , &(2)\\
V_F &= |\lambda|^2[(|H_1|^2 + |H_2|^2)|N|^2 + |H_1 H_2|^2] + |k|^2|N|^4 \\
&\quad -(\lambda k^* H_1 H_2 N^{*2} + H.c.) - |\lambda|^2(H_1^0 H_2^0 H^{+*} H^{-*} + H.c.) \ , &(3)\\
V_D &= \frac{g^2}{8}(H_2^\dagger \hat{\sigma} H_2 + H_1^\dagger \hat{\sigma} H_1)^2 + \frac{g'^2}{8}(|H_2|^2 - |H_1|^2)^2 \ , &(4)\\
V_{soft} &= m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_N^2 |N|^2 - (\lambda A_\lambda H_1 H_2 N + H.c.) \\
&\quad -(\frac{1}{3} k A_k N^3 + H.c.) \ , &(5)
\end{aligned}$$

where $H_1 \equiv (H_1^0, H^-)$, $H_2 \equiv (H^+, H_2^0)$, $H_1 H_2 \equiv H_1^0 H_2^0 - H^- H^+$ and $\hat{\sigma} \equiv (\sigma^1, \sigma^2, \sigma^3)$. The radiative effect of the top-quark and top-squark is significant for the mass spectra of the Higgs bosons as pointed out by some authors in the MSSM[4]. This leading-log radiatively induced potential is given as follows:

$$V_{\rm top} = \frac{3}{16\pi^2}\left[(h_t^2|H_2|^2 + M_{sq}^2)^2 \ln\frac{(h_t^2|H_2|^2 + M_{sq}^2)}{Q^2} - h_t^4|H_2|^4 \ln\frac{h_t^2|H_2|^2}{Q^2}\right], \qquad (6)$$

where we have assumed degenerate squarks: $M_{\tilde{t}_L} = M_{\tilde{t}_R} = M_{sq} \gg m_t$. The potential $V_{\rm top}$ should be added to $V_{\rm Higgs}$ in eq.(2).

In general, λ, k, A_λ and A_k are complex, however, by redefining the global phase of the fields H_2 and N, we can take

$$\lambda A_\lambda \geq 0\,, \qquad kA_k \geq 0\,, \qquad (7)$$

without loss of any generality. If we allow CP violation explicitly in the Higgs scalar sector, λk^* is a complex.

Our discussion is concentrated on the neutral Higgs sector because there is no CP violation in the charged Higgs sector. Since the contribution of $V_{\rm top}$ is not important for qualitative studies of the explicit CP violation, we discuss the magnitude of CP violation without $V_{\rm top}$ in sections 2 and 3. However, $V_{\rm top}$ contributes significantly to the mass spectra of the Higgs bosons, so we include this effect in the numerical analyses in section 4. Neglecting $V_{\rm top}$ for simplicity, we can write

$$\begin{aligned}\langle V_{\rm neutral}\rangle &= \lambda^2(|x|^2|v_1|^2 + |x|^2 v_2^2 + |v_1|^2 v_2^2) + k^2|x^4| - v_2(\lambda k^* v_1 x^{*2} + \lambda^* k v_1^* x^2)\\ &\quad + \frac{g^2+g'^2}{8}(|v_1^2| - v_2^2)^2 + m_{H_1}^2|v_1^2| + m_{H_2}^2 v_2^2 + m_N^2|x^2|\\ &\quad - \lambda A_\lambda v_2(v_1 x + v_1^* x^*) - \frac{kA_k}{3}(x^3 + x^{*3})\,, \end{aligned} \qquad (8)$$

where VEV's of the neutral Higgs scalar fields are defined as follows:

$$v_1 \equiv \langle H_1^0\rangle\,, \qquad v_2 \equiv \langle H_2^0\rangle\,, \qquad x \equiv \langle N\rangle\,. \qquad (9)$$

We also introduce a phase for λk^* as follows:

$$\lambda k^* = \lambda k e^{i\varphi}\,, \qquad (10)$$

where λ and k in RHS are redefined as positive real number. The neutral Higgs scalar masses are given by 5×5 mass marix.

Decomposing the neutral Higgs fields into their real imaginary components

$$H_1^0 \equiv \frac{S_1 + iP_1}{\sqrt{2}}\,, \qquad H_2^0 \equiv \frac{S_2 + iP_2}{\sqrt{2}}\,, \qquad N \equiv \frac{X + iY}{\sqrt{2}}\,, \qquad (11)$$

shifting H_1^0, H_2^0, N by their expectation values, and expanding the neutral Higgs scalar part of $V_{\rm Higgs}$, we get the mass matrix of the neutral Higgs scalars. After expressing

P_1 and P_2 in terms of the neutral Goldstone boson $G^0 \equiv \cos\beta P_1 - \sin\beta P_2$ and its orthogonal state $A \equiv \sin\beta P_1 + \cos\beta P_2$, we get 5×5 mass matrix for the Higgs bosons A, Y, S_1, S_2 and X as follows:

$$M^2_{\rm Higgs} = \begin{bmatrix} M^{AY}_{AY} & M^{AY}_{S_1S_2X} \\ (M^{AY}_{S_1S_2X})^T & M^{S_1S_2X}_{S_1S_2X} \end{bmatrix}, \tag{12}$$

where M^{AY}_{AY}, $M^{AY}_{S_1S_2X}$ and $M^{S_1S_2X}_{S_1S_2X}$ are 2×2, 2×3 and 3×3 submatrices, respectively. The matrix M^{AY}_{AY} is the one for the Higgs pseudoscalars A and Y as follows:

$$M^{AY}_{AY} = \begin{pmatrix} \frac{\lambda x v^2}{v_1 v_2}(A_\lambda + kx\cos\varphi) & \lambda v(A_\lambda - 2kx\cos\varphi) \\ \lambda v(A_\lambda - 2kx\cos\varphi) & \frac{\lambda v_1 v_2}{x}A_\lambda + 3A_k kx + 4\lambda k v_1 v_2\cos\varphi \end{pmatrix}. \tag{13}$$

The matrix $M^{S_1S_2X}_{S_1S_2X}$ is the one for the Higgs scalars S_1, S_2 and X as follows:

$$M^{S_1S_2X}_{S_1S_2X} = \begin{pmatrix} \begin{array}{c}\bar{g}^2 v_1^2 + \frac{\lambda v_2 x}{v_1} \\ +\frac{\lambda v_2 x}{v_1}(A_\lambda + kx\cos\varphi)\end{array} & \begin{array}{c}v_1 v_2(2\lambda^2 - \bar{g}^2) \\ -\lambda x(A_\lambda + kx\cos\varphi)\end{array} & \begin{array}{c}2\lambda^2 v_1 x \\ -\lambda v_2(A_\lambda + 2kx\cos\varphi)\end{array} \\ \begin{array}{c}v_1 v_2(2\lambda^2 - \bar{g}^2) \\ -\lambda x(A_\lambda + kx\cos\varphi)\end{array} & \begin{array}{c}\bar{g}^2 v_2^2 \\ +\frac{\lambda v_1 x}{v_2}(A_\lambda + kx\cos\varphi)\end{array} & \begin{array}{c}2\lambda^2 v_2 x \\ -\lambda v_1(A_\lambda + 2kx\cos\varphi)\end{array} \\ \begin{array}{c}2\lambda^2 v_1 x \\ -\lambda v_2(A_\lambda + 2kx\cos\varphi)\end{array} & \begin{array}{c}2\lambda^2 v_2 x \\ -\lambda v_1(A_\lambda + 2kx\cos\varphi)\end{array} & \begin{array}{c}\frac{\lambda v_1 v_2}{x}A_\lambda \\ -A_k kx + 4k^2x^2\end{array} \end{pmatrix}, \tag{14}$$

where $\bar{g}^2 \equiv (g^2 + g'^2)/2$. The matrix $M^{AY}_{S_1S_2X}$ is the mixing terms of the scalar and pseudoscalar components as follows:

$$M^{AY}_{S_1S_2X} = \begin{pmatrix} \frac{k\lambda v_1 x^2}{v}\sin\varphi & \frac{k\lambda v_2 x^2}{v}\sin\varphi & 2k\lambda v x\sin\varphi \\ -2k\lambda v_2 x\sin\varphi & -2k\lambda v_1 x\sin\varphi & -2k\lambda v_1 v_2\sin\varphi \end{pmatrix}. \tag{15}$$

This submatrix is zero if CP is conserved, that is to say, $\varphi = 0$.

3. Explicit CP Violation in Special Limiting Cases

In general, CP symmetry is violated due to the scalar and pseudoscalar mixing of eq.(15). Its magnitude depends on the values of the Higgs potential parameters, especially, x. Following analyses of the Higgs mass spectra by Ellis et al.[3], we study the magnitude of CP violation in the special limiting cases: (A) $x \gg v_1$, v_2 with λ and k fixed and (B) $x \gg v_1$, v_2 with λx and kx. These limits are discussed in the phenomenological standpoint.

(A) Limits of $x \gg v_1,\ v_2(\lambda,\ k$ fixed)

In this limit with $A_\lambda, A_k \simeq O(x)$, the matrix M^2_{Higgs} in eqs.(12)~(15) becomes very simple. Remaining only the terms of order $O(x^2)$, the Higgs scalar X and the Higgs pseudoscalar Y almost decouple from other Higgs bosons since these mixing terms are at most order $O(x)$. The masse squares of X and Y bosons are an order of $O(x^2)$ and then, those mixing is negligible small. The effect of X and Y contributes to our result in the order of v_1/x and v_2/x through the mixings. Therefore, it is enough for CP violation to consider 3×3 submatrix as to A, S_1 and S_2. Then, the mass matrix is given in the $A-S_1-S_2$ system as follows:

$$M^2_{\text{Higgs}} = \begin{bmatrix} 2\lambda x A_\sigma/\sin 2\beta & \lambda k x^2 \cos\beta\sin\varphi & \lambda k x^2 \sin\beta \sin\varphi \\ \lambda k x^2\cos\beta\sin\varphi & \bar{g}^2 v^2\cos^2\beta + \lambda x A_\sigma \tan\beta & (\lambda^2 - \frac{\bar{g}^2}{2})v^2\sin 2\beta - \lambda x A_\sigma \\ \lambda k x^2 \sin\beta\sin\varphi & (\lambda^2 - \frac{\bar{g}^2}{2})v^2 \sin 2\beta - \lambda x A_\sigma & \bar{g}^2 v^2 \sin^2\beta + \lambda x A_\sigma \cot\beta \end{bmatrix} \tag{16}$$

where $A_\sigma \equiv A_\lambda + kx\cos\varphi$ is defined conveniently and A_σ is taken to be of $O(x)$. By rotating this matrix using U_0 with

$$U_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix}\ , \tag{17}$$

we get simple form of the matrix $M'^2_{\text{Higgs}} = U_0^T M^2_{\text{Higgs}} U_0$ in the new basis of $A - S'_1 - S'_2$ as follows:

$$M'^2_{\text{Higgs}} = \begin{bmatrix} \frac{2\lambda x A_\sigma}{\sin 2\beta} & \lambda k x^2 \sin\varphi & 0 \\ \lambda k x^2 \sin\varphi & (\bar{g}^2\cos^2 2\beta + \lambda^2 \sin^2 2\beta)v^2 & (\lambda^2 - \bar{g}^2)v^2 \sin 2\beta\cos 2\beta \\ 0 & (\lambda^2 - \bar{g}^2)v^2\sin 2\beta\cos 2\beta & (\bar{g}^2 - \lambda^2)v^2\sin^2 2\beta + \frac{2\lambda x A_\sigma}{\sin 2\beta} \end{bmatrix}. \tag{18}$$

In this matrix, the (2-2), (2-3), (3-2) components are very small because these are order of $O(v^2)$ but others are $O(x^2)$. Therefore, the submatrix of $S'_1 - S'_2$ system is almost diagonal one. Since this matrix has a hierarchical structure, one should investigate these mass eigenvalues carefully. In order to get the condition of positive eigenvalues, we take the determinant of this matrix:

$$Det[M'^2_{\text{Higgs}}] \geq 0\ , \tag{19}$$

which gives a constraint $\lambda k x^2 \sin\varphi \leq O(xv)$. Since λ and k are constants, we get

$$\sin\varphi \leq O(v/x)\ , \tag{20}$$

which means the scalar-pseudoscalar mixing vanishes in the $x \to \infty$ limit. Therefore, it is concluded that CP violation is minor in this limit.

(B) Limits of $x \gg v_1,\ v_2(\lambda x,\ kx$ fixed)

This limit leads the NMSSM to the MSSM without the Higgs singlet field as discussed Ellis et al.[3]. In this limit with $A_\lambda, A_k \simeq O(v)$, the X and Y boson decouple from other bosons, and then the matrix $M^2_{\rm Higgs}$ in eqs.(12)~(15) reduces to the same 3×3 matrix in eq.(16). However, masses of X and Y are same order of other Higgs bosons in contrast with the case (A). Using the same orthogonal matrix in eq.(17), we get also the similar matrix as the one in eq.(18) for the $A - S_1' - S_2'$ system as follows:

$$M'^2_{\rm Higgs} = \begin{bmatrix} \frac{2\overline{\lambda}A_\sigma}{\sin 2\beta} & \overline{\lambda}\,\overline{k}\sin\varphi & 0 \\ \overline{\lambda}\,\overline{k}\sin\varphi & (\overline{g}^2\cos^2 2\beta + \lambda^2\sin^2 2\beta)v^2 & (\lambda^2 - \overline{g}^2)v^2\sin 2\beta\cos 2\beta \\ 0 & (\lambda^2 - \overline{g}^2)v^2\sin 2\beta\cos 2\beta & (\overline{g}^2 - \lambda^2)v^2\sin^2 2\beta + \frac{2\overline{\lambda}A_\sigma}{\sin 2\beta} \end{bmatrix}, \tag{21}$$

where the definitions $\overline{\lambda} \equiv \lambda x$ and $\overline{k} \equiv kx$ are fixed to be constants, while λ and k are order of $O(1/x)$. In contrast with the matrix of eq.(16), this matrix has not a hierarchical structure in the considering limit since $\overline{\lambda}$ and $\overline{k}$ are finite numbers. Therefore, the submatrix of $S_1' - S_2'$ in eq.(21) are far from the diagonal matrix in general. Now, let us discuss the magnitude of CP violation for the special case of $\tan\beta$.

The first case is the one with $\tan\beta = 0$ and ∞. Since $\sin 2\beta = 0$, the submatrix of the $S_1' - S_2'$ system is exactly diagonal. The scalar-pseodoscalar mixing is occured only in the $A - S_1'$ submatrix. The mixing angle is given as follows:

$$\tan 2\theta_{AS_1'} = \frac{2\overline{\lambda}\,\overline{k}\sin\varphi}{(\overline{g}^2\cos^2 2\beta + \lambda^2\sin^2 2\beta)v^2 - \frac{2\overline{\lambda}A_\sigma}{\sin 2\beta}} \simeq -\frac{\overline{k}}{A_\sigma}\sin\varphi\sin 2\beta\,. \tag{22}$$

Thus, the scalar-pseudoscalar mixing vanishes in $\tan\beta = 0$ or ∞ limit since it is proportional to $\sin 2\beta$ even if $\sin\varphi \simeq 1$. Then, the CP violation effect is expected generally to vanish. However, we should pay attention to an exceptional case that the CP violating effect depends on $\tan\beta$ significantly. We will discuss this case in analyses of the electric dipole moments of the section 4.

The second case is the one of $\tan\beta = 1$, which gives $\cos 2\beta = 0$. In this case, the scalar-pseodoscalar mixing is also occured only in the $A - S_1'$ submatrix since the $S_1' - S_2'$ submatrix is exactly diagonal. Then, the $S_1' - S_1'$ component is $\lambda^2 v^2$ which is order of $O(v^4/x^2)$. This hierarchical structure of the mass matrix gives strong constraint for the mixing angle as discussed in the limitting case (A). Applying the positivity condition of the Higgs scalar mass in eq.(21) leads

$$\sin\varphi \le O(\frac{v}{x})\,. \tag{23}$$

Thus, CP violation also vanishes in the case of $\tan\beta = 1$.

In order to get the finite CP violation, we should choose the region of $\tan\beta \neq 0$, 1 and ∞. If we could adjust the parameter such as

$$2\overline{\lambda}A_\sigma \simeq \overline{g}^2 v^2 \cos^2 2\beta \sin 2\beta \ , \tag{24}$$

by choosing the suitable $\tan\beta$, the large scalar-pseudoscalar mixing is expected. However, since the radiative correction $V_{\rm top}$ becomes significant in this situation, we shall give the numerical analyses in section 4.

4. Numerical Discussion of Explicit CP violation

In our interest, we present numerical study of the similar case to the MSSM spectroscopy, but the case with CP violation. This is just the limit in case (B).

In the previous section, we have neglected the radiatively induced potential $V_{\rm top}$ for simplicity because the qualitative result is not changed even if we include it. Now, we should include the $V_{\rm top}$ term in our numerical analyses. In the leading-log approximation, this potential contributes only to the mass matrix element $M^{S_2}_{S_2}$ in eq.(14) as follows:

$$M^{S_2}_{S_2} = (\overline{g}^2 + \Delta)v_2^2 + \frac{\lambda v_1 x}{v_2}(A_\lambda + kx\cos\varphi) \ , \tag{25}$$

where

$$\Delta = \frac{3h_t^4}{4\pi^2}\left[\ln\left(\frac{M_{sq}^2}{m_t^2}\right) + p\right] \ , \tag{26}$$

where p denotes non-logarithmic terms. In the following calculations, we fix $\Delta = 0.5$, which corresponds to $M_{sq} = 3$TeV and $m_t = 175$GeV with $p = 1$.

In Fig.1, we display a plot of the experimentally allowed region in the $\cos\varphi - \lambda$ plane for fixed values of the other parameters, which are

$$x = 10v, \quad k = 0.1, \quad A_\lambda = v, \quad A_k = v, \quad \tan\beta = 10 \ . \tag{27}$$

One experimental constraint is that the two Higgs bosons have not been produced in the decay of a real Z^0. The lower boundary(small λ) in Fig.1 corresponds to $m_{h_1} + m_{h_2} = m_{Z^0}$, where m_{h_1} and m_{h_2} are two lightest Higgs boson masses. The other constraint is that a light Higgs boson has not been produced in the $Z^0 \to Z^{0*}h$ process, where h is a physical Higgs boson. If $h = \sum_{i=1}^5 \alpha_i \Phi_i$, where α_i and Φ_i denote mixing factors and neutral Higgs boson fields S_1, S_2, A, X, Y, respectively, the cross section for this process is approximately proportional to $|\alpha_1\cos\beta + \alpha_2\sin\beta|^2 m_h^{-1}$. The non-observation of this process gives the upper boundary(large λ) in Fig.1 by $m_h \geq (60\text{GeV})|\alpha_1\cos\beta + \alpha_2\sin\beta|^2$. In addition, the pseudoscalar and scalar bosons should be heavier than 24GeV and 44GeV, respectively. This constraints are satisfied in the allowed region of Fig.1.

In Fig.2, the allowed region of λ is shown in the case of $\tan\beta = 1 \sim 100$ at $\cos\varphi = 0$. Other parameters are fixed as given in eq.(27). It is remarked that the allowed region vanishes below $\tan\beta \simeq 1.5$. This result is consistent with the qualitaive discussion of (B) in section 3, in which φ is constrained to be very small at $\tan\beta \simeq 1$, but $\varphi \simeq \pi/2$ is allowed at $\tan\beta = \infty$. In both results of Figs. 1 and 2, we fix $k = 0.1$, which gives the most wide allowed area of λ. As far as we take $k = 0.03 \sim 0.2$, the allowed region is obtained.

The electric dipole moment(EDM) of electron or neutron is very important quantities to constrain the phase φ. In our scheme, the EDM of electron is calculated in the two-loop level as shown by Barr and Zee[5]. The neutron EDM is also predicted in two-loop level. Both three gluon operator proposed by Weinberg[6] and quark-gluon operator by Gunion and Wyler[7] are taken into account in our calculation. Since the estimation of the hadronic matrix elements is model-dependent, the ambiguity with a few factors should be taken into consideration in the prediction of the neutron EDM. Here, we use the model proposed by Chemtob[8,9]. The recent experimental upper limit of the electron EDM is $4 \times 10^{-27}\mathrm{e}\cdot\mathrm{cm}$[10] and that of the neutron EDM is $11 \times 10^{-26}\mathrm{e}\cdot\mathrm{cm}$. It should be remarked that the Barr-Zee operator and the quark-gluon operator are exceptional CP violating operators as discuussed in (B) of section 3. Since these operators have a term which is proportional to $\tan^2\beta$, this term contributes to the EDM significantly at $\tan\beta \gg 1$ even if the scalar-pseusoscalar mixing is very small. In fact, we find the large predicted EDM at $\tan\beta = 10$ in Figs. 3 and 4. In these figures, we give the numerical predictions of the electron EDM and the neutron EDM in the allowed region of λ in Fig.1. The upper(lower) boundary of the predictions corresponds to the upper(lower) one of λ in Fig.1. Those predictions lie around experimental upper limits except for the region of $\cos\varphi \simeq \pm 1$. If the small λ, $O(0.01)$, is taken, our predictions are below the experimental limits even if the phase φ is a maximal one $\pi/2$. We expect both electron EDM and neutron EDM will be observed around $10^{-27} \sim 10^{-26}\mathrm{e}\cdot\mathrm{cm}$ in the near future.

5. Summary

We have studied the explicit CP violation of the Higgs sector in the MSSM with a gauge singlet Higgs field. The magnitude of CP violation is discussed in the limiting cases of $x \gg v_1,\ v_2$ and $x \ll v_1,\ v_2$. We have shown that the large CP violation is realized in the region of $\tan\beta \geq 1.5$ for the case of $x \gg v_1,\ v_2$ with the fixed values of λx and kx. In other cases, the explicit CP violation is minor for the Higgs sector. Since CP violation in the Higgs sector does not ocuur in the MSSM without a gauge singlet Higgs field, CP violation is an important signal of the existence of the gauge singlet Higgs field. In the present case of the Higgs sector, the predictions of the electron EDM and the neutron EDM lie around the experimental upper limits. Our results suggest that these EDM's will be observed in the near future if CP is explicitly violated through the Higgs sector in the NMSSM. Furthermore, we have found that the large CP violation effect reduces the magnitude of the lightest Higgs boson mass in the order of a few ten GeV. Thus, the explicit CP violation due to the gauge singlet Higgs boson will give us interesting phenomena in the forthcoming experiments.

References

[1] M.Kobayashi and T.Maskawa, Prog. Theor. Phys. **49**, 652(1973).

[2] P. Fayet, Nucl. Phys. **B90**, 104(1975);
R.K. Kaul and P. Majumdar, Nucl. Phys. **B199**, 36(1982);
R. Barbieri, S. Ferrara and C.A. Sávoy, Phys. Lett. **119B**, 343(1982);
H.P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. **120B**, 346(1983);
J.M. Frère, D.R.T. Jones and S. Raby, Nucl. Phys. **B222**, 11(1983);
J.P. Derendinger and C.A. Savoy, Nucl. Phys. **B237**, 307(1984).

[3] J. Ellis, J.F. Gunion, H.E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. **D39**, 844(1989).

[4] Y. Okada, M. Yamaguchi, and T. Yanagida, Prog. Theor. Phys. **85**, 1(1991);
J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. **257B**, 83(1991);
H. Haber and R. Hempfling, Phys. Rev. Lett. **66**, 1815(1991);
R. Barbieri, M. Frigeni and F. Caravaglios, Phys. Lett. **258B**, 167(1991);
A. Yamada, Phys. Lett. **263B**, 233(1991);
P. Binétruy and C.A. Savoy, Phys. Lett. **277B**, 453(1992);
T. Elliott, S.F. King and P.L. White, Phys. Rev. **D49**, 2435(1994).

[5] S.M. Barr and A. Zee, Phys. Rev. Lett. **65**, 21(1990);
S.M. Barr, Phys. Rev. Lett. **68**, 1822(1992); Phys. Rev. **D47**, 2025(1993);
D. Chang, T.W. Kephart, W-Y. Keung and T.C. Yuan, Phys. Rev. Lett. **68**, 439(1992).

[6] S. Weinberg, Phys. Rev. Lett. **63**, 2333(1989).

[7] J.F. Gunion and D. Wyler, Phys. Letts. **248B**, 170(1990).

[8] M. Chemtob, Phys. Rev. **D45**, 1649(1992).

[9] T.Hayashi, Y.Koide, M.Matsuda and M.Tanimoto, Prog. Theor. Phys. **91**, 915(1994).

[10] E.D. Commins, S.B. Ross, D. DeMille and B.C. Regan, Phys. Rev. **A50**, 2960(1994).

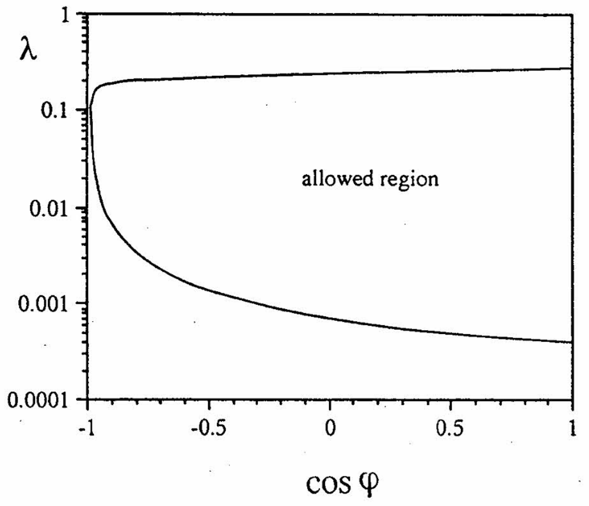

Fig. 1

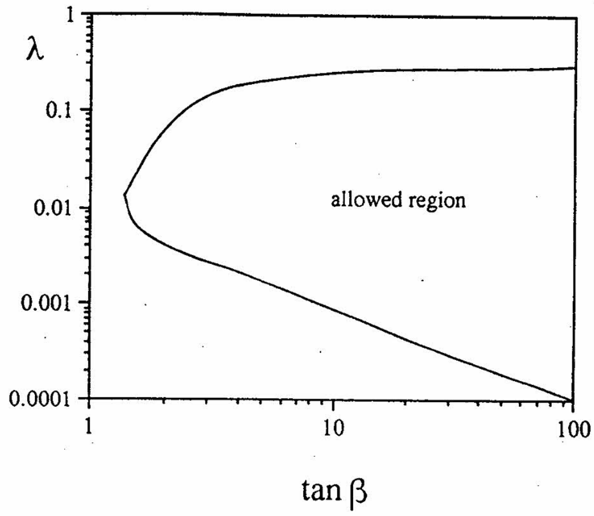

Fig. 2

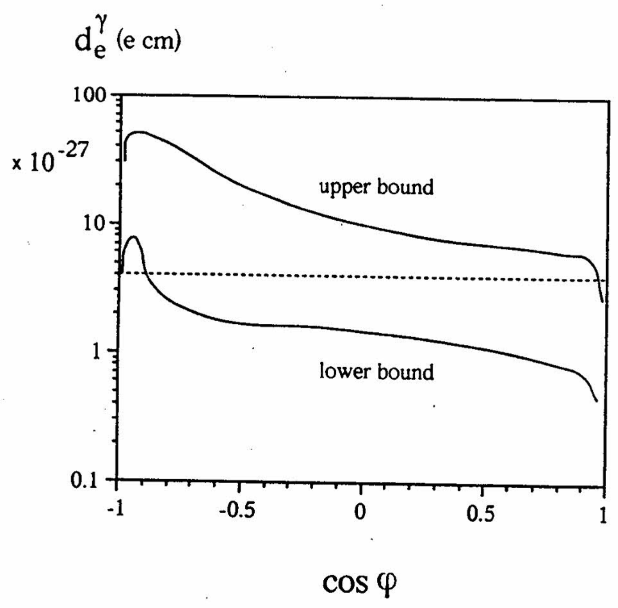

Fig. 3

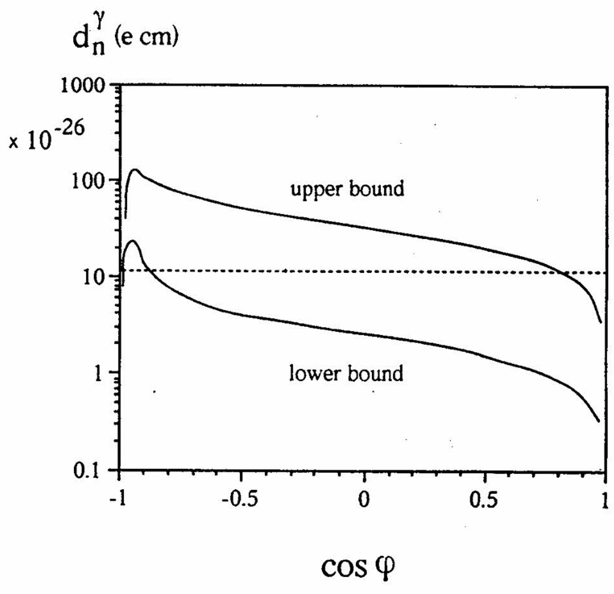

Fig. 4