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HIGGS MIXING AND CP VIOLATION

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HIGGS MIXING AND CP VIOLATION

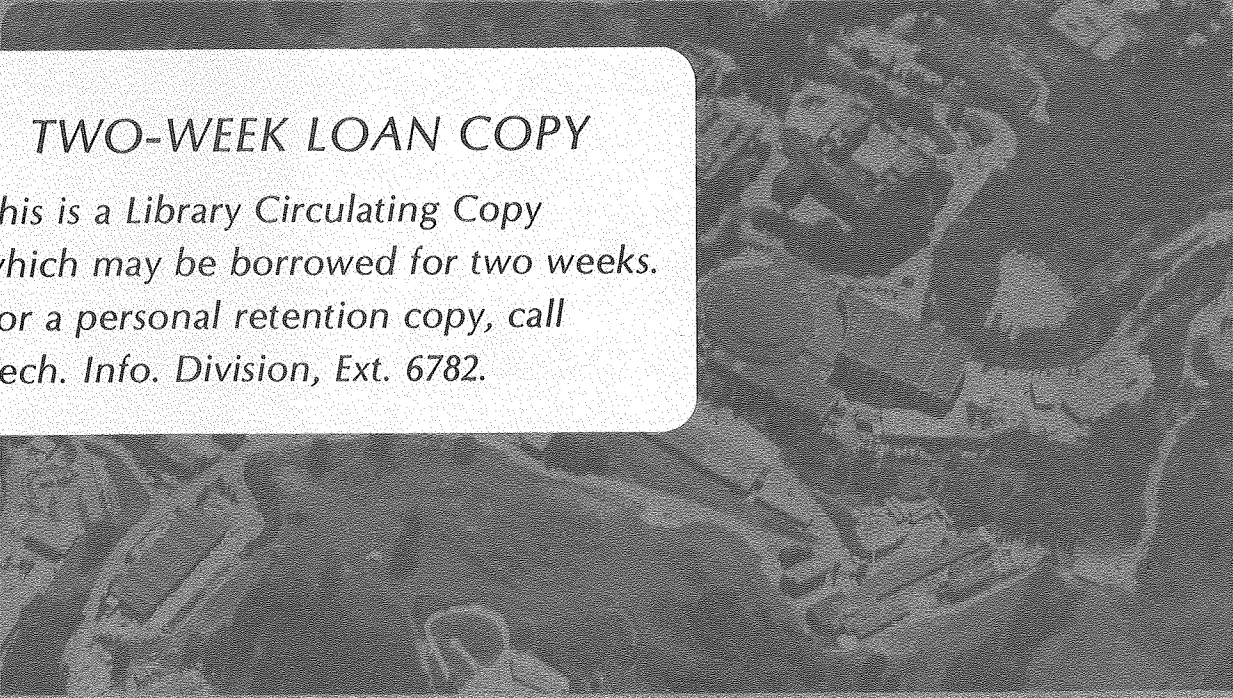
K. Shizuya and S.-H.H. Tye

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## Higgs mixing and CP violation

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(Received

The enlarged Higgs sector (i.e. three or more doublets) in the Weinberg-Salam model is studied in a systematic approach. Its CP violating effects are analyzed in terms of the Higgs-fermion couplings and charged-Higgs particle masses. Their results are compared with that in the Kobayashi-Maskawa model. The analysis is also applicable to composite Higgs particles.

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## I. INTRODUCTION

There are two straightforward ways to introduce CP violation into the standard  $SU(2)_L \times U(1)$  gauge model<sup>1</sup> of weak and electromagnetic interactions. One way is to enlarge the quark sector to six (or more) flavors, as originally observed by Kobayashi and Maskawa (K-M).<sup>2</sup> They suggested a systematic way (via the K-M quark-mixing matrix) to study the CP violating and other weak interaction effects. The discovery of the b quark<sup>3</sup> certainly indicates that the K-M mechanism of CP violation is present in nature. Details of this mechanism have been studied extensively.<sup>4-8</sup>

The other way of introducing CP violation into the  $SU(2)_L \times U(1)$  model is to enlarge the Higgs sector.<sup>9-10</sup> If we want natural suppression of flavor-changing neutral currents, three (or more) Higgs doublets are needed, as originally observed by Weinberg.<sup>10</sup> Its phenomenological consequences have been discussed by Weinberg and others.<sup>11</sup> However, as the number of Higgs doublets increases, the Higgs structure becomes extremely complicated. In this work we study these Higgs effects in a systematic fashion. The parametrization scheme introduced earlier<sup>12</sup> is followed and extended. We evaluate the CP violating effects in various systems and discuss them in relation to earlier estimates.<sup>10-11</sup>

Before we present the calculations, a few words on our motivation seem appropriate.

(1) The significance of pinpointing the origin of CP violation in the Weinberg-Salam model is obvious. An enlarged Higgs sector seems to be the only viable alternative to the K-M mechanism. Naive estimates of CP violating effects from the Higgs sector seem to have already<sup>11</sup> ruled out the model. However, a careful analysis shows that this is not the case,

as we shall see.

(2) Recent investigations of the issue of matter-antimatter asymmetry in the universe from the viewpoint of grand unification seem to indicate that three Higgs doublets may be needed in the Weinberg-Salam model.<sup>13</sup>

(3) It is possible that the Higgs structure arises dynamically.<sup>14</sup> If this is the case, we expect their couplings to fermions to behave like that of elementary Higgs particles at low energies (i.e. energies below 10 to 100 GeV), while the couplings among the composite Higgs particles themselves are determined dynamically and may be rather involved. By parametrizing the dominant CP violating effects into the Yukawa couplings, our systematic approach may be well-suited for the study of composite Higgs-induced CP violating effects at low energies.

The formalism is discussed in Sec. II while the application is discussed in Sec. III.

## II. FORMALISM

The most general  $SU(2) \times U(1)$ -symmetric Higgs potential invariant under reflections  $\psi_i \rightarrow -\psi_i$  of each Higgs doublet  $\phi_i(x) = (\psi_i^+(x), \psi_i^0(x))$  ( $i=1, \dots, n$ ) has the form<sup>10</sup>

$$V(\phi) = \sum_i \mu_i^2 (\phi_i^+ \phi_i) + \sum_{i,j} a_{ij} (\phi_i^+ \phi_i) (\phi_j^+ \phi_j) + \sum_{i,j} b_{ij} (\phi_i^+ \phi_j) (\phi_j^+ \phi_i) + \sum_{i,j} c_{ij} (\phi_i^+ \phi_j)^2, \quad (1)$$

where  $b_{ii} = c_{ii} = 0$  by definition. Hermiticity requires that  $a_{ij}$  and  $b_{ij}$  be real and symmetric while  $c_{ij}$  need only be Hermitian; correspondingly they consist of  $2n^2$  real parameters. After spontaneous symmetry breakdown,  $\phi_i$  are not necessarily mass eigenstates. The charged components  $\psi_i(x)$  of  $\phi_i(x)$  can be related to their mass eigenstates  $H_i^+(x)$  by a rotation:

$$(\psi_i^+(x), \psi_i^0(x)) = Y_{ij} (H_j^+(x), H_j^0(x)),$$

where  $H_j^0(x)$  are not necessarily the mass eigenstates of the neutral Higgs fields. Let  $H_1^+(x)$  be a massless Goldstone boson to be absorbed into the  $W^+$ . Then, at the tree level, all the neutral fields  $H_j^0(x)$  have vanishing vacuum expectation values except for  $\langle H_1^0(x) \rangle = v \neq 0$ . (In general,  $H_i^+(x)$  ( $i=2, \dots, n$ ) are massive fields.) It is convenient to fix the arbitrary overall phases of  $(\psi_i^+, \psi_i^0)_i$  ( $i=1, \dots, n$ ) and  $(H_1^+, H_1^0)$  so that the vacuum expectation values  $\langle \psi_i^0 \rangle_i$  and  $\langle H_1^0 \rangle = v$  become real. We remove  $(n-1)$  (unphysical) phases in the unitary matrix  $Y$  by adjusting the overall phases of  $(H_i^+, H_i^0)$  ( $i=2, \dots, n$ ). Then the  $Y$  matrix can be expressed in terms of  $\frac{n}{2}(n-1)$  angles and  $\frac{1}{2}(n-1)(n-2)$  (observable) phases<sup>12</sup>, in exact analogy with the K-M quark-mixing matrix<sup>3</sup>  $K$ . For  $n=3$ , they are written as

$$K = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 + s_2 s_3 e^{i\delta} & c_1 c_2 s_3 - s_2 c_3 e^{i\delta} \\ -s_1 s_2 & c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix} K, \quad (2a)$$

$$Y = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 + s_2 s_3 e^{i\delta} & c_1 c_2 s_3 - s_2 c_3 e^{i\delta} \\ -s_1 s_2 & c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix} Y \quad (2b)$$

where  $c_i = \cos \theta_i$  and  $s_i = \sin \theta_i$ . Both  $K$  and  $Y$  have three angles and one phase  $((\theta_i)_K, \delta_K)$  and  $((\theta_i)_Y, \delta_Y)$ . The subscripts  $K$  and  $Y$  are appended to emphasize the distinction.

Diagonalization of the charged-Higgs mass matrix at the tree level leads to the relation

$$M_i^2 + 2v^2 \sum_j a_{ij} (Y_{j1})^2 = \sum_j |Y_{ij}|^2 M_j^2 \quad (3)$$

$$2v^2 (b_{ik} + c_{ik}) = \frac{1}{2} y_{ij} y_{kj}^* M_j^2 \quad (i \neq k), \quad (4)$$

where  $M_j^2$  ( $j=1, \dots, n$ ) is the mass of the  $j^{\text{th}}$  charged Higgs field ( $M_1^2 = 0$ ) and  $y_{ij} \equiv Y_{ij}/Y_{i1}$ . It is clear from the above that all  $c_{ij}$  are real when all the phases  $(\delta_i)_Y$  in the  $Y$  matrix vanish. In particular, for  $n=3$ , we find that

$$\begin{aligned} \text{Im}(c_{12}) &= -(t_2)_Y \text{Im}(c_{13}) = (t_1^2 s_2^2)_Y \text{Im}(c_{23}) \\ &= + \frac{1}{2} \{(M_2^2 - M_3^2)/v^2\} \{(s_2 s_3 c_3 / c_1 c_2) \sin \delta\}_Y \end{aligned} \quad (5)$$

where  $(t_i)_Y = \tan(\theta_i)_Y$ .

The phases of  $H_i^0(x)$  (relative to  $H_1^+(x)$ ) are still arbitrary. It is convenient to adjust the phases  $\epsilon_j$  of  $H_j^0(x) = e^{i\epsilon_j} \tilde{H}_j^0(x)$  in such a way that the  $\tilde{H}^0$ - $\tilde{H}^0$  coupling in  $V(\phi)$ ,  $\tilde{H}_i^0 F_{ij} \tilde{H}_j^0$ , has real  $F_{ij}$  components. We express  $\tilde{H}_j^0(x)$  in terms of real fields,  $\tilde{H}_j^0(x) = \xi_j(x) + i\chi_j(x)$ . Then, in the mass matrix of the neutral Higgs fields at the tree level, (i)  $\chi_1(x)$ , which is a Goldstone boson to be absorbed by  $Z^0$ , is decoupled from the rest; (ii)  $\xi_1(x)$  has no mixing with  $\chi_i(x)$  ( $i=1, \dots, n$ ). The  $\xi_1(x)$  can be brought into its mass eigenstate by a translation, and  $\xi_i(x)$  and  $\chi_i(x)$  ( $i=2, \dots, n$ ) are related to their mass eigenstates by means of a  $2(n-1) \times 2(n-1)$  orthogonal matrix.

The mixing between  $\xi$  and  $\chi$  leads to CP violation as well as P violation. However, this mixing vanishes as  $(\delta_Y)_i$  go to zero, as is easily seen. In this sense, the neutral Higgs sector gives rise to no additional CP-violating phase factor (other than  $\delta_Y$ ).

The coupling of the Higgs sector to the quark sector has to be constructed in such a way that the flavor-changing neutral current interaction due to the neutral Higgs exchange is naturally suppressed. This is done by



imposing some discrete symmetry on the Yukawa couplings so that different Higgs fields  $\phi_i$  couple to the charge 2/3 and -1/3 right-handed quarks.

Then the general form of the charged-Higgs-quark coupling is given by

$$\mathcal{L}_Y = 2^{3/4} G_F^{1/2} \left[ \sum_{i,j} y_{ij} H_j^+ (\bar{p}_R M_i^{(p)} K n_L - \bar{p}_L K M_i^{(n)} n_R) + \text{h.c.} \right]$$

where  $p = (u, c, t)$  and  $n = (d, s, b)$  are the charge +2/3 and -1/3 quark mass-eigenstates, and  $y_{ij} = Y_{ij}/Y_{11}$  as before. The mass matrix  $M_i^{(p)}$  is nonzero for only one  $\phi_i$ , for which  $M_i^{(p)} = \text{diag.}(m_u, m_c, m_t)$ ; similarly,  $M_i^{(n)} = \text{diag.}(m_d, m_s, m_b)$  for only one  $\phi_i$  coupling to  $n_R$ .

### III. PHENOMENOLOGY

Let us discuss the CP-violating effects in the Higgs sector. For simplicity, we take  $\delta_K = 0$  and  $(s_3)_K > 0.1$ .<sup>5</sup>

(1) The  $K^0$ ,  $B^0$  and  $T^0$  systems. The box diagrams (1a) in Figure 1 are responsible for the  $K^0$ - $\bar{K}^0$  mixing. The contribution of the charged-Higgs-boson exchange turns out to be CP-conserving. To obtain CP-violating effects in the  $K^0$ - $\bar{K}^0$  system, we consider diagram (1b). In this case, the  $K^0$  decay is not chirally suppressed. Let us define  $\langle 0 | \bar{d} \gamma_5 s | K^0 \rangle = F_K m_K$ , where  $F_K$  is expected to be larger than the kaon decay constant  $f_K$ . It is straightforward to evaluate the diagrams.

From this, we obtain a prediction for the CP-violating effects in the  $B(b\bar{d})$  system. In the production of B mesons in  $e^+e^-$  annihilation  $e^+e^- \rightarrow B^0\bar{B}^0$ , the final state may go to  $B^0\bar{B}^0$  or  $\bar{B}^0B^0$  via  $B^0$ - $\bar{B}^0$  mixing (which is estimated to be close to maximum). In a reasonable approximation, the asymmetry in the Higgs model is given by

$$a_B = \frac{N(\bar{B}^0 B^0) - N(B^0 \bar{B}^0)}{N(\bar{B}^0 B^0) + N(B^0 \bar{B}^0)} \sim \left( \frac{F_B f_K m_B}{F_K f_B m_S} \right)^2 \epsilon_K$$

where  $\epsilon_K \sim 2 \cdot 10^{-3}$  in the K system.<sup>16</sup> If we take  $F_B \sim F_K$  and  $f_B \sim 0.5$  GeV,  $m_B = 5$  GeV and  $m_S = 0.3$  GeV,  $a_B \sim 2\%$ , which is certainly measurable.<sup>17</sup> If we let<sup>18</sup>  $F_B = f_B m_B (m_d + m_b)^{-1}$  and  $F_K = f_K m_K (m_s + m_d)^{-1}$ , the asymmetry  $a_B \sim 0.2$ , which is huge. The analogous asymmetry  $a_T$  in the  $T^0$ - $\bar{T}^0$  system is comparable to  $a_B$  while the asymmetry  $a_D$  in the  $D^0$ - $\bar{D}^0$  system is too small to be observed ( $a_D \sim 10^{-3}$ ).

In our choice of parametrization, CP violation can also arise via the Higgs self-interaction. The diagram in Figure 2 gives such a contribution. However, if we assume all Higgs self-couplings are weak (so that perturbative calculations make sense), then the CP-violating effects from diagrams of this type may contribute at most a few percent of that observed in the K system. Hence, in our parametrization, essentially all CP-violating effects in the Higgs sector come from  $\delta_Y$ . This verifies the practical usefulness of our approach.

(2)  $\epsilon'/\epsilon$ . It is reasonable to assume that the  $\Delta I = 1/2$  enhancement over the  $\Delta I = 3/2$  channel in K decays is due to QCD effects<sup>19</sup>, where the charged W boson is exchanged in "Penguin diagrams", then  $\epsilon'/\epsilon$  induced in the Higgs sector is very small. The largest value one can reasonably expect<sup>11</sup> is  $\epsilon'/\epsilon \sim 3\%$ . However,  $\epsilon'/\epsilon$  in the K-M model is also estimated<sup>8</sup> to be 0.3 to 3%. Hence, this does not provide a good test of the Higgs mixing.

(3) The contribution of charged-Higgs-boson exchange (Figures 3a and 3b, etc.) to the neutron electric dipole moment  $D_n = \frac{1}{3} (4D_d - D_u)$  is given by

$$D_d = em_d Z \{ c_1^2 m_u^2 \ln(m_H^2/m_u^2) + s_1^2 c_2^2 m_c^2 \ln(m_H^2/m_c^2) + s_1^2 s_2^2 m_t^2 \ln(m_H^2/m_t^2) \\ - (c_1^2 m_u^2 + s_1^2 c_2^2 m_c^2 + s_1^2 s_2^2 m_t^2) (\frac{3}{4} + t_3^2 (x - t_3)^{-1} \ln x) \}$$

$$D_u = -\frac{1}{2} em_u Z \{ c_1^2 m_d^2 \ln(m_H^2/m_d^2) + s_1^2 c_3^2 m_s^2 \ln(m_H^2/m_s^2) + s_1^2 s_3^2 m_b^2 \ln(m_H^2/m_b^2) \\ - (c_1^2 m_d^2 + s_1^2 c_3^2 m_s^2 + s_1^2 s_3^2 m_b^2) (3 + t_3^2 (x - t_3)^{-1} \ln x) \},$$

where  $m_H \equiv m_{H_2} \gg m_q$ ,  $x = m_{H_3}/m_{H_2} \geq 1$ ,  $c_i = (c_i)_K$ ,  $s_i = (s_i)_K$ ,  $t_3^2 = (t_3)_Y$  and  $Z = (G_F/(6\sqrt{2}\pi^2 m_H^2))(1 - t_3^2/x) \text{Im}(y_{12} y_{22}^*)$  ( $= \text{Im} A/(24\pi^2)$  in ref. 9). The neutral Higgs fields also contribute to  $D_n$ .<sup>11</sup> However, there are too many unknown parameters in the neutral Higgs sector to obtain any reliable estimate. Assuming that the neutral Higgs contribution to  $D_n$  is comparable to that of the charged Higgs sector, we obtain an order-of-magnitude estimate of the electric dipole moment of the neutron,  $D_n \sim 10^{-25 \pm 2}$  e cm.

Our results are summarized in Table I, where the values given are the probable ranges expected. Our estimates are in essential agreements with the previous calculations.<sup>10,11</sup> This is due to the lack of information on the structure of the Higgs sector. If the Higgs model is correct, we expect future experiments will be able to determine the various parameters in the Higgs sector. This will render our systematic approach much more useful than the parametrization used in earlier calculations.<sup>10,11</sup>

In summary, we find that the asymmetry in the  $(\bar{B}^0 - B^0)$  or  $(T^0 - \bar{T}^0)$  system provides the best place to distinguish the "Higgs" model from the K-M model. The discovery of the electric dipole moment of the neutron at the level of  $10^{-27}$  e cm or larger would certainly be considered as a decisive test. It is likely that CP-violating effects in the K system

arise from both the KM model and the Higgs model. In this case, CP violating effects in other systems are expected to be somewhere between those predicted by the two models.

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17. A particular mode of the asymmetry is the semi-leptonic decay of  $B^0 \rightarrow \ell^- \bar{\nu} + x$  versus  $\bar{B}^0 \rightarrow \ell^+ x + x$ , where  $N(\ell^+ \ell^+) \neq N(\ell^- \ell^-)$ . See ref. 4; A. Pais and S. B. Treiman, Phys. Rev. D12, 2744 (1975). However, other modes can also be used to measure the asymmetry, e.g.,  $B^0 \rightarrow \psi K^- \pi^+$  versus  $\bar{B}^0 \rightarrow \psi K^+ \pi^-$ .
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Caption for Table I

CP-violating effects in the Kobayashi-Maskawa model and the "Higgs" model.

$a(B^0-\bar{B}^0)$  is the charge asymmetry in the neutral B system;  $a(T^0-\bar{T}^0)$  that in the neutral top meson system.  $\epsilon'/\epsilon$  is in the K system.  $D_n$  is the electric dipole moment of the neutron. See text for details on estimates and uncertainties. The predictions of the K-M model are taken from the references indicated. The readers should consult them for details of their estimates and uncertainties. The top quark mass is taken to be  $m_t \lesssim 30$  GeV.

Table I

	K-M model	"Higgs" model
$a(B^0-\bar{B}^0)$	$4 \times 10^{-4}$ (ref. 6)	0.5 to 20%
$a(T^0-\bar{T}^0)$	$< 10^{-5}$ (ref. 6)	0.5 to 20%
$\epsilon'/\epsilon$	0.3 to 3% (ref. 8)	<3%
$\frac{D_n}{e}$ (in cm)	$10^{-30}$ (ref. 7)	$10^{-25 \pm 2}$

Figure Captions

- Figure 1. (a) The standard box diagram where a pair of boson fields ( $HW$ ,  $WW$  or  $HH$ ) are exchanged between a pair of left-handed quark-antiquark. The  $HH$  pair exchange conserves CP invariance. Crossed diagrams must be included.
- (b) Exchange of a pair of charged Higgs fields by a left-handed and a right-handed quark-antiquark system. This box diagram can give CP violating effects.

Figure 2. A two loop diagram where the self-interacting Higgs vertex can give CP violating effects.

Figure 3. The lowest order diagrams which involve the charged Higgs particles and contribute to the electric dipole moment of the neutron.

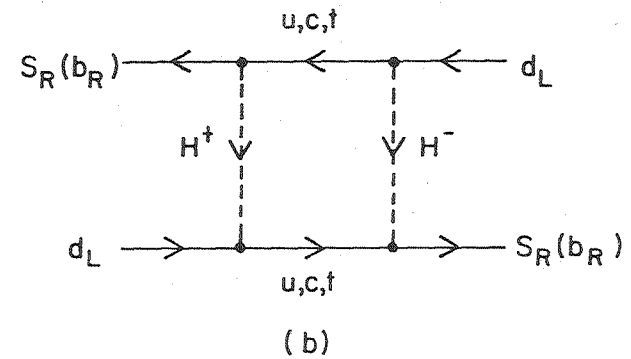
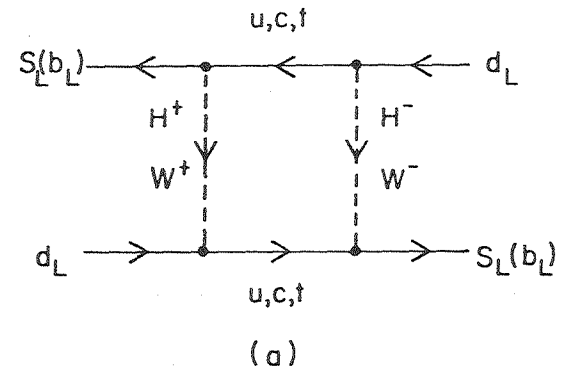
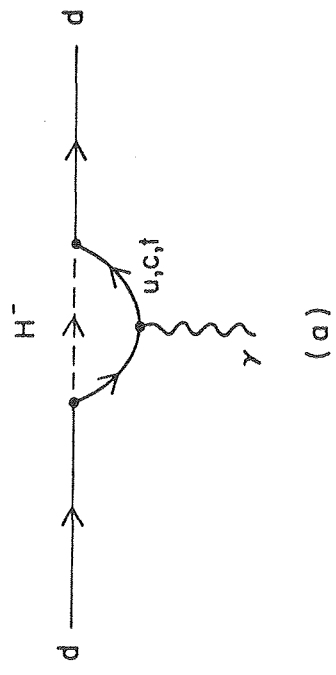


Fig. 1



(a)

(b)

Fig. 3

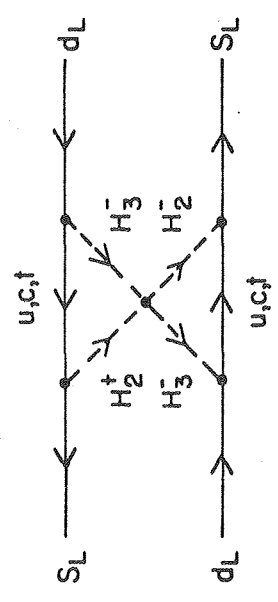


Fig. 2

