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CP NON-CONSERVATION IN SUPERSYMMETRICAL MODELS WITH EXTRA NEUTRAL CURRENTS. THE $W^{\pm}\to \ell^{\pm}\nu_{\ell}$ DECAY

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Models with additional neutral vector bosons arise in most versions of compactification of higher dimensional theories[1].

For instance, the heterotic $E_8 x E_8$ string may yield a supersymmetric E_6 grand-unified theory [2]. The E_6 group is then broken down to some subgroup G.

In the simplest case, G is rank 5 with only one extra neutral vector boson Z_E :

$$G = SU_c(3) \times SU_L(2) \times U_Y(1) \times U_E(1) \times [N=1 \ SUSY] \qquad (1)$$

and no further symmetry breaking is introduced at intermediate scales.

To compare (1) with the usual standard model, processes that are experimentally accessible and most likely to give different results in the presence of the added Z_E have been studied [3].

However, the existence of Z_E also implies [4] a new Majorana particle: its superpartner $\tilde{Z}_E$. Such a state is added to the four Majorana particles that already appear in the minimal supersymmetric model [5] — that is, the superpartners of the two neutral gauge bosons ($\tilde{\gamma}$ and $\tilde{Z}$) and of the two neutral Higgs scalars ($\tilde{H}_1^0$ and $\tilde{H}_2^0$)— and to the SU(3)xSU(2)xU(1) scalar singlet $\tilde{N}$.

Since supersymmetry is expected to be broken at present energies (1 TeV), the physical (massive) states χ_i of the neutral fermions — the neutralinos — should be some mixture of all these S = 1/2 neutral states [4] :

$$\chi_L^i = N^{ij} \psi_L^j \ ; \ \psi_j = (\tilde{\gamma}, \tilde{Z}, \tilde{Z}_E, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{N}) . \qquad (2)$$

Here N_{ij} are elements of the neutralino mixing matrix, which are determined by the specific mechanism of supersymmetry breaking.

As it will become clear further on, we can neglect the Higgs superpartners in Eq.(2). The number of neutral Higgs scalars and their superpartners is therefore irrelevant to our result.

If CP conservation is not imposed, the N_{ij} in (2) are in general some complex numbers. It is then possible to use the CP-violating asymmetry

$$a_W = \left| \frac{\Gamma(W^+ \to e^+ \nu) - \Gamma(W^- \to e^- \nu)}{\Gamma(W^+ \to \ell^+ \nu) + \Gamma(W^- \to \ell^- \nu)} \right| \qquad (3)$$

induced by them to disentangle new physics produced by the extra neutralino .

A non-zero value of a_W requires at least 1-loop radiative corrections in order to have an absorptive part in the amplitude and a mixing leading to at least one surviving CP-violating phase.

Such a phase is available neither in the standard model nor in the presence of massive neutrinos.

In the minimal supersymmetric extension of the standard model, the photino and the higgsinos effectively decouple (their couplings being zero or of the order of the leptons masses) and only the $\tilde{Z}$ appears in the loop corrections to the $W^\pm \to \ell^\pm \nu_\ell$ decay. Consequently, the only phase present can always be rotated away, and again $a_W = 0$. This is a result of interest because it would provide an indirect test of the N = 1 supersymmetric standard model.

Instead, the presence of an additional neutral boson, by enlarging the neutralino mixing matrix (see Eq.(2)), gives a non-vanishing result. Note that the additional neutral boson Z_E does not provide by itself any contribution to the asymmetry a_W .

a_W is thus a senstive probe for the existence of an additional neutralino and—by means of supersymmetry— for the presence of an associated extra neutral boson.

Three diagrams contribute to the absorptive part of the supersymmetrical 1-loop corrections to (3) with, respectively, $(\tilde{e}_L - \tilde{\nu})$, $(\tilde{W}^\pm - \chi)$ and $(\tilde{H}^\pm - \tilde{H}^0)$ as the intermediate states that are put on mass shell (no diagram with $\tilde{e}_R$ -exchange contributes because of chirality).

The $(\tilde{H}^\pm - \tilde{H}^0)$ diagram is proportional to the neutrino mass and therefore vanishes.

Similarly, the χ_i in the $(\tilde{W}^\pm - \chi)$ diagram couples to the $W^\pm$ only by the $\tilde{Z}$ and not by the $\tilde{Z}_E$ (no $Z - Z_E$ mixing is assumed because of its smallness as it is suggested by neutral current data and present measurement on the Z mass [6]): no remaining phase is thus expected from this diagram.

Hence, only the $(\tilde{e}_L - \tilde{\nu})$ diagram of the figure contributes.

The relevant lagrangian is obtained in two steps: first the standard model action is supplemented by new terms giving rise to the additional neutral current — their structure being determined by the gauge group of the low-energy model [3]; secondly, the lagrangian thus obtained is supersymmetrically extended following the usual procedure [5]: the super-partner $\tilde{Z}_E$ of the extra $U_E(1)$ gauge boson is added, its coupling being left unchanged. The massive states χ_i are introduced in the lagrangian by expressing the interaction eigenstates Ψ_i in terms of them (Eq.(2)). Thus, the lagrangian responsible for the CP-violating diagram in the figure is:

$$\mathcal{L} = \frac{e}{2c_W} c_i \tilde{e}_L (\bar{e}_L \chi_i) + \frac{e}{2c_W s_W} d_i \tilde{\nu} (\bar{\nu}_L \chi_i) + \frac{ie}{\sqrt{2} s_W} \tilde{\nu}^* \partial_\alpha \tilde{e}_L W^+_\alpha + h.c., \quad (4)$$

where

$$c_i = N_{i2}^* + \frac{1}{3} N_{i3}^*; \quad d_i = N_{i2}^* + \frac{s_W}{3} N_{i3}^*, \quad (5)$$

$$s_W = \sin\theta_W, \quad c_W = \cos\theta_W.$$

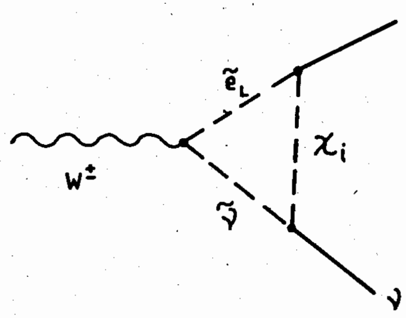

Fig. The ($\tilde{e}_L - \tilde{\nu}$) loop diagram responsible for CP-violation in $W^\pm \to e^\pm \nu_e$ decays.

N_{i2} and N_{i3} are strongly model dependent. Our phenomenological analysis requires that neither of them is zero.

The interference of the absorptive part of the diagram in the figure with the tree level diagram implies for the asymmetry

$$a_W = \frac{2e^2}{c_W^2 s_W} \left| c_i^* d_i \right| I.\sin\delta, \quad (6)$$

where I (the absorptive part of the loop) is given by

$$I = \frac{\lambda^{1/2}}{8\pi M_W^2} \left[\kappa + \frac{1}{2}(1-\kappa^2) \ln \frac{1+\kappa}{1-\kappa} \right], \quad (7)$$

where

$$\kappa = \lambda^{1/2} \left[M_W^2 - 2m_{\chi_i}^2 - m_{\tilde{e}_L}^2 - m_{\tilde{\nu}}^2 \right] \quad (8)$$

$$\lambda = \left[M_W^2 - (m_{\tilde{e}_L} + m_{\tilde{\nu}})^2 \right] \left[M_W^2 - (m_{\tilde{e}_L} - m_{\tilde{\nu}})^2 \right]$$

and δ is the CP violating phase defined by

$$c_i^* d_i = \left| c_i^* d_i \right| e^{i\delta}. \quad (9)$$

For maximal CP violation (i.e., $\sin\delta = 1$) the asymmetry (6) is a function of the three masses of the superparticles in the loop. These three masses appear as the only adjustable parameters and any bound on a_W is reflected by bounds on them.

The sneutrino mass has to be assumed much lighter than M_W, otherwise, for the existing bounds on $m_{\tilde{e}_L}$ [7], a non-zero a_W would not be kinematically allowed. This assumption is also compatible with the current bounds on $m_{\tilde{\nu}}$: $m_{\tilde{\nu}} \gtrsim 1.7$ GeV. In this case the main contribution to the asymmetry comes from the diagram in which χ is the lightest superparticle.

Neglecting the $\tilde{\nu}$ and χ masses ($m_{\tilde{\nu}}, m_\chi \ll M_W$) we obtain

$$a_W = \frac{\alpha}{c_W^2 s_W} \left| c_i^* d_i \right| \frac{M_W^2 - m_{\tilde{e}_L}^2}{M_W^2} \sin\delta. \quad (10)$$

For $m_{\tilde{e}_L} = (2/3) M_W$ and $|N_{i2}| = |N_{i3}| = 1/2$, (10) gives ($\sin\delta = 1$)

$$a_W = .42 \times 10^{-3} \quad (11)$$

that is a number comparable to other CP-violating asymmetries that have been already experimentally observed /8/.

While the approximate number of $W^{\pm}$'s needed to measure a_w ($N \geq 1/a_w^2 B$) is — for a branching ratio B of .IO — probably too large for the expected production rate per year at LEP II /9/, it should be within reach of a hadronic supercollider /IO/.

Once mixing between the neutralinos is assumed, there remain only two possibilities for a_w to be zero: either the masses of the virtual sleptons are large enough to push the threshold for the decay higher than the W mass or there is no extra gaugino and (1) is not a correct extension of the standard model.

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CP-нарушение в суперсимметричных моделях с дополнительными нейтральными токами. Распад $W^{\pm} \to \ell^{\pm}\nu_{\ell}$

Существование по крайней мере одного дополнительного нейтрального векторного бозона приводит к появлению однопетлевой (SUSY) поправки к распаду $W^{\pm} \to \ell^{\pm}\nu_{\ell}$, которая нарушает CP-инвариантность. Существующие границы для масс слептонов допускают, чтобы величина соответствующей асимметрии достигала порядка 10^{-3}.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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CP Non-Conservation in Supersymmetrical Models with Extra Neutral Currents. the $W^{\pm} \to \ell^{\pm}\nu_{\ell}$ Decay

The existence of at least one extra neutral vector boson provides a 1-loop (SUSY) correction to the $W^{\pm} \to \ell^{\pm}\nu_{\ell}$ decay which violates CP invariance. The existing bounds for the slepton masses allow the corresponding asymmetry to be as large as 10^{-3}.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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