# $CP$-Violation in SUSY and $T$-odd Asymmetry

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## Abstract

$T$-violation in the gaugino pair production processes by $e^+e^-$ annihilation is discussed in the supersymmetric standard model. $T$-odd correlations among the momenta and/or spins of initial and final state particles are expected as $T$ violation effect.

Since the discovery of $CP$-violation in the $K_0-\bar{K}_0$ system in 1964, $CP$-violation is expected to appear in other places than $K_0$, and is extensively investigated both experimentally and theoretically. So far, however, the nature has not disclosed her secret of violation of $CP$ in any other places. The efforts of disclosing $CP$-violation are mainly made in the low energy experiments. Can the high energy $e^+e^-$ and $p\bar{p}$ colliders have a chance to observe $CP$-violation? The question can be answered affirmatively if the supersymmetry is the true symmetry of the nature at the energy scale accessible by the human being.

It is well-known that the supersymmetric standard models [1, 2] have new sources of $CP$-violation [3-9]. They are coming from the mass matrices of SUSY partners, and produce complex couplings with $Z$-boson. For example, the nondiagonal coupling of the charginos ( $w_{h,\ell}$ ) with $Z$ is

$$
\begin{aligned}
&L_{int}(\text{chargino}-Z)\\
&\quad = eZ_\mu \overline{w}_h \gamma^\mu (G_L P_L + G_R P_R) w_\ell + \text{h.c.},\\
&G_L = \frac{\sin 2\theta_L}{2\sin 2\theta_W} e^{-i\beta_L},\\
&G_R = \frac{\sin 2\theta_R}{2\sin 2\theta_W} e^{i(\gamma_2-\gamma_1-\beta_R)},
\end{aligned}
\tag{1}
$$

where $P_{L,R} = (1 \mp \gamma_5)/2$, and the coupling of the neutralinos ($\chi_i$; $i = 1 \sim 5$) with $Z$ is

$$
\begin{aligned}
&L_{int}(\text{neutralino}-Z)\\
&= \frac{e}{\sin\theta_W} \bar{\chi}_i \gamma_\mu (O_Z P_L - \eta_i \eta_j O_Z^* P_R)_{ij} \chi_j,
\end{aligned}
\tag{2}
$$

where $N$ is a complex orthogonal matrix diagonalizing the neutralino mass matrix $M_N$ as

$$N^t M_N N = \text{diag}(m_1, m_2, m_3, m_4),$$

and $\eta_i$ is a $C$-parity of $\chi_i$. It was shown by many authors [3-7, 10-12] that these complex couplings produce a large electric dipole moment of the neutron (*EDMN*). The recent experimental upper bounds [13, 14] are

$$
\begin{aligned}
d_n &< 2.6 \times 10^{-25} \text{e} \cdot \text{cm}, && \text{(Leningrad 1986)}\\
&= -0.3 \pm 0.4 \times 10^{-25} \text{e} \cdot \text{cm}, && \text{(Grenoble 1989)}
\end{aligned}
$$

which constrain the phase and the masses of SUSY particles. For the neutralinos, we have

$$
\begin{aligned}
&\frac{100\text{GeV}}{\tilde{m}_u} \sum_i \frac{\Delta m_i}{\tilde{m}_u} \times \text{Im}\left(N_{4i}(N_{1i} + \frac{5}{3}\tan\theta_W N_{2i})\right) < 10^{-2};\\
&\Delta m_i/2 = m_i - m_\chi,
\end{aligned}
\tag{3}
$$

where $\tilde{m}_u$ is the scalar u-quark mass, and $m_\chi$ is an average value of the neutralino masses. If the imaginary parts of the elments of $N$ are of order unity, and the neutralinos have masses of order 100 GeV, the scalar quarks have to have masses of order 1 TeV. The contribution of the winos to *EDMN* is very similar to that of neutralinos, and we have a similar constraint to (3).

These complex coupligs will produce $T$-odd efects at the tree level of reaction processes [15-18]. In the process $e^+e^- \to w_h^+ + w_\ell^-$ [15] mediated by $Z$-boson, the relative phase $\delta_c$ between $G_L$ and $G_R$ forces its cross section to contain a term,

$$\left((g_L^e)^2 - (g_R^e)^2\right)|G_L||G_R| \sin\delta_c [\mathbf{s}_h \cdot (\mathbf{p}_- \times \mathbf{p}_h)], \tag{4}$$

where $\mathbf{s}_h$ and $\mathbf{p}_h$ are the spin and the momentum in $CM$ system of $w_h$, and $\mathbf{p}_-$ is the momentum of the initial electron. Clearly the vector product $\mathbf{s}_h \cdot (\mathbf{p}_- \times \mathbf{p}_h)$ violates $T$, and we could anticipate to observe a $T$-odd effect. It may be difficult to measure the spin of $w_h$, but instead the momentum of the particle into which $w_h$ decays can be observed to get the $T$-odd effect. For example, if the wino decay into a charged lepton and neutral particles, a vector product formed by $\mathbf{p}_-$ and the momenta of the charged leptons from $w_l^-$ and $w_h^+$, $\mathbf{p}_1$ and $\mathbf{p}_2$, will appear in the cross section to produce an asymmetry

$$A_T = \frac{d\sigma_Z(\mathbf{p}_- \cdot (\mathbf{p}_1 \times \mathbf{p}_2) > 0) - d\sigma_Z(\mathbf{p}_- \cdot (\mathbf{p}_1 \times \mathbf{p}_2) < 0)}{d\sigma_Z(\mathbf{p}_- \cdot (\mathbf{p}_1 \times \mathbf{p}_2) > 0) + d\sigma_Z(\mathbf{p}_- \cdot (\mathbf{p}_1 \times \mathbf{p}_2) < 0)}, \tag{5}$$

whose non-vanishing value shows $T$ violation at the tree level.

Similarly $T$-odd effect results in the production process of two different neutralinos $\chi_i, \chi_j$ by $e^+e^-$ annihilation mediated by $Z$-boson [18] from the term in the cross section

$$\left((g_L^e)^2 - (g_R^e)^2\right)|O_Z|^2 \sin 2\delta_Z m_j [\mathbf{s}_i \cdot (\mathbf{p}_- \times \mathbf{p}_i)], \tag{6}$$

where $\mathbf{s}_i$ and $\mathbf{p}_i$ are the spin and the momentum of $\chi_i$, and $\delta_Z = \arg(O_Z)$. The $T$ odd asymmetry like (5) may have a non-vanishing value when we observed the momenta of $\ell^+, \ell^-$ from the decay $\chi_i \to \ell^+ + \ell^- + \chi_j$ ( we assume $m_i > m_j$ ).

It is well-known that these $T$-od asymmetries mean $T$-violation only at the tree level. The final state interactions produce $T$-odd asymmetry at one-loop level or more. Although the effect of the final state interactions is expected to be smaller than the tree level one, we can not conclude the existence of $T$-violation from the non-vanishing $T$-odd asymmetry. There could be, however, a way to get rid of the final state interactions [19]; that is, taking a quantity odd under $CP$ as well as $T$. The $CP$- and $T$-odd asymmetry does mean $CP$-violation because the effect of the final state interactions is even under $CP$. There need a further study to look for the best quantity which can be easily tested by experiments, and from which $CP$-violation can be definitely deduced. If such a quantity could be tested in the future high energy collider experiments, and its asymmetry were larger than order of $10^{-4}$, it could be concluded that there would be $CP$-violation originating from *New Physics* beyond the standard model since the standard $CP$-violation model predicts the asymmetry less than order of $10^{-4}$.

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