Effects of *CP*-odd supersymmetric phases in the supersymmetric version of the standard model

A. A. Iogansen and N. G. Ural'tsev
V. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR, 188350, Gatchina

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That component of the coefficient of the *CP*-odd operator $O_6 = g_s^3/[(16\pi^2) G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} f_{abc}]$ which would be induced by a possible *CP*-odd phase associated with a soft breaking of supersymmetry is calculated in the supersymmetric version of the standard model. A limitation on the magnitude of the *CP*-breaking supersymmetric phase, $\theta < 10^{-3}$–10^{-4}, is found from the limitation on the value of d_n.

1. The only positive experimental information we have on the nature of *CP* breaking comes from decays $K^0 \to 2\pi$, so there are fundamentally different possibilities for explaining this breaking.

Regardless of the details of the model, heavy-particle effects can be taken into account in a renormalizable theory by integrating over the corresponding degrees of freedom. As a result, local operators of various dimensionalities appear in the low-energy effective action. In the simplest cases, the effect is greatest for the operators of minimal dimensionality.

Effects stemming from standard *CP*-odd operators of dimensionality 4, 5, and 6 have been discussed in detail in the literature (e.g., Ref. 1). Weinberg[2] recently called attention to a purely gluon *CP*-odd operator

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$$O_6 = \frac{g_s^3}{16\pi^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} \tilde{G}^c_{\rho\mu}. \quad (1)$$

In the present letter we consider additional contributions to the coefficient (C_6) of the operator O_6 in the low-energy effective action which arise in a supersymmetric version of the standard model with a soft breaking of supersymmetry (SUSY).

2. In the supersymmetric model of electroweak interactions (Ref. 3, for example), an additional source of *CP* breaking is the possible presence of *CP*-odd phases in terms which break the supersymmetry softly. The latter include gaugino masses and increments in the Lagrangian which are proportional to a superpotential which depends on scalar components of the superfields. It can be shown that the presence of a *CP*-odd phase in the gaugino masses reduces to a change in the *CP*-odd phase in terms which break supersymmetry softly in the scalar-field sector. These terms are of the form

$$\Delta L = m_{3/2} A [h^f_D \tilde{Q}^{+i}_{Lf} H^{(1)}_i \tilde{D}^f_R + h^f_U \tilde{Q}^{+i}_L H^{(2)}_i \tilde{U}^f_R] + \text{H.a.} + \mu \bar{\tilde{g}} \tilde{g}, \quad (2)$$

where $\widetilde{Q}^i_L$, $\widetilde{D}^f_R$, and $\widetilde{U}^f_R$ are scalar quarks; $\tilde{g}$ is a gluino, $H^{(1),(2)}_i$ are Higgs doublets; f is the generation index; $h^f_{U,D}$ are Yukawa constants; $m_{3/2}$ is the gravitino mass; $\mu = \gamma_3 m_{3/2}$; and the parameters A and γ_3 are associated with the breaking of the supersymmetry.

Expression (2) induces *CP*-odd contributions to the mass matrix of the scalar quarks. This is the effect in which we are interested below. The contribution to the coefficient of the operator O_6 is determined by two-loop diagrams which incorporate vertices representing a Yukawa coupling of the gluino, the quark, and the scalar quark. The calculations are more convenient in an external-field formalism. Only one diagram arises in this case. Calculations involving some technical intricacies lead to the expression

$$\Gamma = \frac{m\mu g_s^2}{16\pi^2} O_6 \frac{\mathrm{Im} M^2_{LR}}{M_2^2 - M_1^2} \left\{ -\frac{2}{3}(m^2 C_V + \mu^2 C_F) \cdot I_{266} + \right\}$$

$$\left\{ + \frac{3}{2} C_V (I_{264} + I_{246}) + \frac{1}{2} C_V (m^2 I_{248} + \mu^2 I_{284}) \right\} \Big|^{M^2 = M_2^2}_{M^2 = M_1^2}, \quad (3)$$

where $C_F = 4/3$ and $C_V = 3$ are Casimir operators for the $SU(3)$ group, $M^2_{1,2}$ are the eigenvalues of the mass matrix of scalar quarks, M^2_{LR} is an off-diagonal element of this matrix, and

$$I_{knl}(M^2, \mu^2, m^2) = \int \frac{d^4k d^4p}{\pi^4} (k^2 + \mu^2)^{-n} (p^2 + m^2)^{-l} ((p+k)^2 + M^2)^{-k}, \quad (4)$$

3. Expression (5) simplifies greatly for relatively light quarks ($m^2 \ll \mu^2, M^2$), say the b quark. In this case the leading contribution corresponds to the emission of two gluons by a virtual quark and gives us

$$\Gamma = \frac{g_s^2}{32\pi^2 m_b \mu^3} O_6 \mathrm{Im} M^2_{LR} \frac{f(x_2) - f(x_1)}{x_2 - x_1}, \quad (5)$$

where $x_{1,2} = M_{1,2}^2/\mu^2$ and

$$f(x) = C_F \frac{2}{3}\left[\frac{1+x}{2(1-x)^2} + \frac{x}{(1-x)^3}\ln x\right] - C_V \frac{5}{3}\left[\frac{1}{1-x} + \frac{x}{(1-x)^2}\ln x\right]. \qquad (6)$$

In the limit $x_1 \to x_2$ we have $(f(x_2) - f(x_1))/(x_2 - x_1) \to f'(x)$. Numerically, with $\mu = M$ we have $f'(1) = 0.8$.

The QCD renormalization of the coefficient of the operator O_6 has been discussed in detail elsewhere.[4,5] The contribution from heavier quarks to this coefficient turns out to be suppressed in comparison with that of relatively light quarks. Numerically, we thus restrict the discussion to the b-quark contribution, for which the QCD-renormalization factor is ~ 0.3. In this case, with a mass $\mu = 120$ GeV for the gluino, with a mass $M = 100$ GeV for a scalar quark, and with $|A| = |\gamma_3| \approx 2$, we have

$$d_n = 2 \cdot 10^{-22} \sin\theta \;\; e\cdot\text{cm}, \qquad (7)$$

where $\theta = \arg A/\gamma_3$. In (7) we used the methods of Refs. 4 and 5 to estimate the contribution to d_n from O_6.

The contribution of SUSY phases to d_n was estimated previously[6] in terms of the electric dipole moment of the quarks. Because of factors associated with chirality, however, both the electric dipole moment of the light quarks and their chromoelectric dipole moment contain the mass of a light quark. They accordingly make a smaller contribution to the electric dipole moment of the neutron (despite the circumstance that these operators formally have a dimensionality of 5). The SUSY phases also induce a θ term which generally leads to a larger contribution to the electric dipole moment. We are thus obliged to assume that there is an axial mechanism in some form or other. When there is an explicit CP-breaking, however, a minimization with respect to θ leads to an effective value $\theta_{\text{eff}} \neq 0$ proportional to the extent of the explicit breaking of CP. It was shown in Refs. 4 and 5 that, because of the zero axial charge of the operator O_6, the corresponding "induced" contribution to d_n is parametrically suppressed in the presence of light quarks. For the operators of dimensionality 5 mentioned above, however, the presence of an axial mechanism can substantially reduce the resultant value of d_n.

Using the limitation $d_n < 2\times 20^{-25}$ $e\cdot$cm on the electric dipole moment of the neutron, we find a limitation $\theta < 10^{-3}$–10^{-4} on the magnitude of the CP-odd SUSY phase, for superparticle masses $\simeq 100$ GeV and for typical parameter values of the diagrams with light superparticles.

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