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ПИСЬМА В ЖУРНАЛ ЭКСПЕРИМЕНТАЛЬНОЙ И ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

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SUSY MODEL WITH *R*-PARITY VIOLATION AND LONG-LIVED CHARGED SLEPTON

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We construct a SUSY electroweak model with superweak R-parity violation. The scale of R-parity violation in our model is determined by the Majorana mass of the neutrino and is very small, leading to the existence of a long-lived ($T \geq O(10^{-4})$ sec) lightest superparticle. If the lightest superparticle is a right-handed charged slepton, as can occur within the gaugino-dominated scenario, then the phenomenology of such a model differs in a drastic way from the standard SUSY phenomenology; in particular, long-lived charged sleptons can form bound states with ordinary matter — quasistable supermatter (SUSY analogs of mu-atoms and muonium). We also discuss possible manifestations of the existence of such a long-lived charged particle at LEP2, TEVATRON and LHC.

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Supersymmetric electroweak models offer the simplest solution of the gauge hierarchy problem [1]–[4]. In real life supersymmetry has to be broken and the masses of superparticles have to be lighter than $O(1)$ Tev provided the supersymmetry solves the gauge hierarchy problem [4]. Supergravity gives a natural explanation for the supersymmetry breaking, namely, taking the supergravity breaking into account in the hidden sector leads to soft supersymmetry breaking in the observable sector [4]. For the supersymmetric extension of the Weinberg–Salam model, soft supersymmetry breaking terms usually consist of the gaugino mass terms, squark and slepton mass terms with the same mass at the Planck scale and trilinear soft scalar terms proportional to the superpotential [4]. Another standard assumption is that the "Minimal Supersymmetric Standard Model" (MSSM) conserves R-parity [4]. In the MSSM the superpartners of the standard model states are R-odd while all standard model states are R-even. As a consequence of R-parity conservation the new supersymmetric states can only be produced in pairs and supersymmetric states can't decay into ordinary particles, so the lightest superparticle (LSP) is stable. This has very important consequences for the search for supersymmetry.

Namely, experimental searches for new supersymmetric particles are based on pair production of superparticles, and the typical SUSY signature involves missing p_T momentum as a signal for SUSY particle production. However R need not be conserved in supersymmetric extensions of the Weinberg–Salam model. Moreover, the most general form for the renormalized superpotential in the MSSM contains terms which explicitly violate R; this leads in general to the nonconservation of lepton number and to proton decay. The phenomenology of the models with R-violation has been discussed in Refs. [5]–[13] under the assumption that the lightest superparticle is electrically neutral ($U(1)$ gaugino or neutral higgsino). Although for the short-lived gaugino the missing p_T momentum signature dissapears, typically such models predict an excess of multileptons due to superparticle decays, which allows one to discover SUSY even for the case of R-parity breaking. If the lightest superparticle decays outside the detector the phenomenology coincides with the standard one.

In this paper we construct a SUSY $SU(3)\otimes SU(2)_L\otimes U(1)$ model with R-parity violation. In our model the scale of R-breaking is determined by the neutrino Majorana mass, and as a consequence the lightest superparticle is long-lived ($T_{lsp} \geq O(10^{-4})$ sec). We assume that the lightest superparticle is a charged right-handed slepton. The situation when the lightest superparticle is a right-handed slepton is realized within supergravity-motivated models in the gaugino-dominated scenario (at the GUT scale the slepton and squark masses are small compared to the gaugino masses). Long-lived charged slepton can form bound states with ordinary leptons and nuclei — quasistable supermatter (analogs of muonium and mu-atoms). We discuss the manifestations of the existence of a quasistable charged slepton at LEP2, TEVATRON and LHC. For the case when the lightest superparticle is a neutralino the phenomenology coincides with the standard one and is not very interesting. We also construct a $SU(3)\otimes SU(2)_L\otimes SU(2)_R\otimes U(1)$ model with a naturally small R-violation.

Consider an electroweak $SU(3)\otimes SU(2)_L\otimes U(1)$ supersymmetric model with a right-handed neutrino. The superpotential of the model has the form (here we have restricted ourselves to the third generation)

$$W = W_m + W_1 \ , \tag{1}$$

$$W_m = h_t Q H_1 \bar{t} + h_b Q H_2 \bar{b} + h_\nu L H_1 \bar{\nu} + h_\tau L H_2 \bar{\tau} \ , \tag{2}$$

$$W_1 = \mu H_1 H_2 + \frac{M_\nu \bar{\nu}\bar{\nu}}{2} + \lambda H_1 H_2 \bar{\nu} \tag{3}$$

Here $Q = (t,b)_L$, $L = (\nu,\tau)_L$, $H_1 = (H_{11}, H_{12})$, $H_2 = (H_{21}, H_{22})$, $\bar{t} = t^c_R$, $\bar{b} = b^c_R$, $\bar{\nu} = \nu^c_R$, $\bar{\tau} = \tau^c_R$, $H_1 H_2 = \epsilon^{ij} H_{1i} H_{2j}$. The superpotential W_m conserves R-parity while the term $\lambda\bar{\nu}H_1H_2$ in the superpotential W_1 violates R-parity. We shall consider the most interesting case when the right-handed τ-slepton is the lightest superparticle. Such situation takes place in the so-called gaugino-dominated scenario [14]–[16]. Actually, in supergravity-motivated models the standard assumption is that at the GUT scale soft supersymmetry breaking terms have a very simple structure: all squark and slepton masses are equal, the gaugino masses are also equal, and the trilinear soft supersymmetry breaking term is proportional to the superpotential. In such a scenario the lightest superpartner of quarks and sleptons is the right-handed slepton [17, 18]. For the case when Yukawa coupling constants of the leptons are negligible, all the right-handed sleptons are degenerate in mass. In terms of soft supersymmetry breaking parameters m_0 (common squark and slepton mass at the

GUT scale) and $m_{1/2}$ (common gaugino mass) the right-handed slepton mass is given by the formula [18]

$$\tilde{m}^2_{E_R} = m_0^2 + 0.14 m_{1/2}^2 - 0.22\cos(2\beta) M_Z^2 \quad (4)$$

For the case of the third generation the τ-lepton Yukawa coupling is the largest one among the leptons, and taking the nonzero Yukawa coupling into account leads to a decrease of the corresponding right-handed slepton masses [18], so the right-handed τ-slepton is the lightest superparticle among the squarks and sleptons. For the gaugino masses, an account of evolution from the GUT scale to the observable electroweak scale leads to the formula [18]

$$M_i = \frac{\tilde{\alpha}_i(M_Z)}{\alpha_{GUT}} m_{1/2} \quad (5)$$

The gaugino associated with the $U(1)$ gauge group is the lightest sparticle among the gauginos, and numerically its mass is given by the formula

$$M_1 \approx 0.43 m_{1/2} \quad (6)$$

Comparing formulas (4) and (6), we find that for the gaugino-dominated scenario [14]–[16] ($m_0 \ll m_{1/2}$; to be precise, for $m_0 \leq 0.17 m_{1/2}$) the right-handed τ-slepton is the lightest superparticle. In principle the higgsino can be the lightest superparticle. However, if we require that radiative corrections to the tree-level effective potential give the correct electroweak vacuum then it is possible to determine numerically the higgsino mass in terms of m_0 and $m_{1/2}$. We have checked that for the gaugino-dominated scenario a right-handed slepton really is the lightest superparticle. It should be noted that the gaugino-dominated scenario allows one to solve [19] the problem with flavor-changing neutral currents arising due to a nonuniversal squark mass matrix. For the case $m_0 \geq 0.17 m_{1/2}$ we recover the standard and for us not very interesting case in which the gaugino (its mixture with another neutralino) is the lightest superparticle. We shall assume in this paper that the lightest superparticle is the charged right-handed τ-slepton. For the model with exact R-parity the existence of a stable electrically charged particle contradicts to the experimental data on the abundances of anomalous superheavy isotopes [20]–[21], but for models with explicitly broken R-parity the existence of a long-lived charged superparticle is not contradicted by arguments based on abundances of heavy isotopes. In the model considered here the right-handed τ-slepton $\tilde{\tau}$ will decay into a left-handed τ-lepton and τ-neutrino. Using the superpotential (1), one can find after the integration over right-handed sneutrino and higgsino that the effective superpotential with R_p-parity violation has the form

$$W_R = \frac{\lambda h_\tau h_\nu}{\mu M_\nu} \bar{\tau} L H_1 L H_2 \quad (7)$$

The scale of the R-violation in our model is determined by the Majorana τ-neutrino mass. After electroweak symmetry breaking ($\langle H_1 \rangle \neq 0$, $\langle H_2 \rangle \neq 0$) we find that the effective Lagrangian describing the decay of the right-handded τ-slepton into a neutrino and τ-lepton has the form

$$L_{\tilde{\tau} \to \tau \nu_\tau} = h \tilde{\tau}_R^+ \tau_L \nu_L + \text{h.c.}, \quad (8)$$

where

$$h = \frac{\lambda h_\tau h_\nu \langle H_1 \rangle \langle H_2 \rangle}{\mu M_\nu} \quad (9)$$

In our model the smallness of the neutrino mass is due to see-saw mechanism [23], namely

$$m_{\nu_\tau} = \frac{(\langle H_1 \rangle h_\nu)^2}{M_\nu} \tag{10}$$

Thus the coupling constant h can be rewritten in the form

$$h = \frac{\lambda m_\tau m_\nu}{\mu m_{D\nu}}, \tag{11}$$

where $m_\tau = h_\tau \langle H_2 \rangle$ and $m_{D\nu} = h_\nu \langle H_1 \rangle$. For the Lagrangian (8) the decay width of the right-handed τ-slepton into τ-lepton and ν_τ-neutrino is determined by the formula

$$\Gamma(\tilde{\tau}_R \to \tau \nu_\tau) = \frac{h^2 M_{\tilde{\tau}_R}}{16\pi}. \tag{12}$$

From the cosmological upper bound on the neutrino mass, $m_\nu \leq 10$ eV, on the assumption that $m_{D\nu} \sim m_\tau$ and $\mu \sim 100$ GeV, we find that the lifetime of the right-handed τ-slepton is

$$T_{\tilde{\tau}_R} \sim O(10^{-4}(\lambda)^{-2})\,\mathrm{sec} \tag{13}$$

As a consequence of the small neutrino mass (large Majorana mass) we find that in our model the lightest superparticle is long-lived (it does not decay within detector), and that leads to a different strategy in the search for supersymmetry at supercolliders. Such long-lived charged particles can form bound states with nuclei and electrons — quasistable supermatter (analogs of mu-atoms and muonium). If the lightest superparticle is a neutralino, then it is also long-lived and decays outside the detector, so the supercollider phenomenology coincides with the standard one and is not very interesting. Let us discuss briefly the phenomenology of such long-lived particles. At LEP2 the cross section of the reaction

$$e^+ e^- \to \tilde{\tau}_R^+ \tilde{\tau}_R^- \tag{14}$$

is well known [24, 25] and it is equal to 0.064 pb for $M_{\tilde{\tau}} = 85$ GeV and 0.033 pb for $M_{\tilde{\tau}} = 90$ GeV). For the luminosity $L = 500$ pb^{-1} we expect 32 events for $M_{\tilde{\tau}} = 85$ GeV and 16 events for $M_{\tilde{\tau}} = 90$ GeV. It is not difficult to distinguish the reaction (14) from the standard reaction $e^+e^- \to \mu^+\mu^-$. By measuring the momentum p of the charged particle in a magnetic field one can determine its mass using the standard formula $M = \sqrt{\frac{s}{4} - \mathrm{p}^2}$. We thus conclude that LEP2 will be able to discover long-lived right-handed τ-sleptons with masses up to 90 GeV. At TEVATRON and LHC, because of the smallness of the R-parity violating interaction (7), SUSY particles will be produced in pairs as in the standard scenario. In the final states (after the squarks, qluino, wino, sleptons and neutralino have decayed into ordinary particles and the right-handed τ-slepton) we shall have two long-lived charged particles. Again it is possible to distinguish such particles from muons by measurement of their momentum: as a consequence of the nonzero mass of right-handed slepton we shall have missing E_T if we misidentify the right-handed slepton as a muon[1]. In our model (1) with explicit R-violation we manually set to zero the possible renormalizable R-violating terms in the superpotential:

[1]A detailed discussion of the possibility of detecting charged long-lived particles at LEP2, TEVATRON and LHC will be given elsewhere.

$$\delta W = \lambda_{ijk} L_i L_j \bar{l}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k \,. \tag{15}$$

Here L_i, $\bar{l}_k$, Q_j, $\bar{u}_i$, $\bar{d}_j$ are lepton doublets, lepton charged singlets, quark doublets, up quark singlets, and down quark singlets, respectively. In general it is not clear why such terms are absent and the R-violation is small.

To overcome this shortcoming let us consider the $SU(3)\otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$ generalization of our $SU(3) \otimes SU(2)_L \otimes U(1)$ model. Superquark multiplets and superlepton multiplets have the following transformation rules under the $SU(2)_L \otimes SU(2)_R \otimes U(1)$ gauge group:

$$Q_L \equiv (2,1,1/3);\ \bar{Q}_R \equiv (1,2,-1/3)\,, \tag{16}$$

$$\Psi_L \equiv (2,1,-1);\ \bar{\Psi}_R \equiv (1,2,1) \tag{17}$$

The superhiggs sector of the model consists of a superhiggs bidoublet $\Phi(2,2,0)$ which corresponds to two superhiggs doublets H_1 and H_2 of the standard $SU(3) \otimes SU(2) \otimes U(1)$ model. In the minimal left-right model [26, 27] the superhiggs sector also includes superhiggs triplets: $\Delta_L(3,1,2) \oplus \bar{\Delta}_L(3,1,-2)$ and $\Delta_R(1,3,2) \oplus \bar{\Delta}_R(1,3,-2)$. Nonzero vacuum expectation values of supermultiplets $\Delta_R(1,3,2) \oplus \bar{\Delta}_R(1,3,-2)$ lead to $SU(2)_L \otimes SU(2)_R \otimes U(1) \to SU(2)_L \otimes U(1)$ breaking, whereas nonzero vacuum expectation values of the superhiggs bidoublet $\Phi(2,2,0)$ are responsible for $SU(2) \otimes U(1)$ breaking and nonzero fermion masses. However for such superhiggs structure it is impossible to write down gauge invariant R-violating terms in the superpotential containing an odd number of supermatter, so the R-parity for such a Higgs structure is conserved automatically and this case is not of interest to us. To break the $SU(2)_R$ gauge group we shall use superhiggs doublets $H_R \equiv (2,1,-1) \oplus \bar{H}_R \equiv (2,1,1)$ and $H_L \equiv (1,2,-1) \oplus \bar{H}_L \equiv (2,1,1)$. A nonzero vacuum expectation value of the superhiggs $H_R \oplus \bar{H}_R$ leads to $SU(2)_R \otimes SU(2)_L \otimes U(1) \to SU(2)_L \otimes U(1)$ breaking. The terms in the superpotential responsible for nonzero neutrino Majorana mass and R-violation read

$$W_1 = \lambda_1 \bar{\Psi}_R H_R \varphi + \lambda_2 \Phi\Phi\varphi + \frac{M_1 \varphi^2}{2} \tag{18}$$

Here φ is $SU(2)_R \otimes SU(2)_L \otimes U(1)$ singlet superfield. The superpotential (18) and supermatter terms $M\varphi M$ ($M \equiv (Q_L, \bar{Q}_R, \Psi_L, \bar{\Psi}_R)$) are invariant under the discrete transformations

$$\Phi \to \exp(i\frac{\pi}{2})\Phi\,, \tag{19}$$

$$\varphi \to -\varphi\,, \tag{20}$$

$$(H_R, \bar{H}_R) \to \exp(-i\frac{3\pi}{4})(H_R, \bar{H}_R) \tag{21}$$

$$M \to \exp(-i\frac{\pi}{4})M\,, \tag{22}$$

After integration over the heavy superfield φ we find the effective superpotential

$$W'_1 = \frac{(\lambda_1 \bar{\Psi}_R H_R + \lambda_2 \Phi\Phi)^2}{M_1} \tag{23}$$

After $SU(2)_R$ gauge symmetry breaking the neutrino acquires a nonzero Majorana mass $M_\nu = \frac{2\lambda_1^2 \langle H_R \rangle^2}{M}$. The term $\bar{\nu} H_1 H_2$ in the superpotential (3) originates from the superpotential (23) with the coefficient $\lambda = \frac{2\lambda_1\lambda_2 \langle H_R \rangle}{M_1}$. Thus we see that the $SU(2)_L \otimes SU(2)_R \otimes U(1)$ generalization of the standard $SU(2)_L \otimes U(1)$ electroweak gauge group allows one to obtain the smallness of the R-violation in a natural way as a consequence of the large neutrino Majorana mass.

To conclude, we have proposed a model with small R-violation. In the gaugino-dominated scenario the lightest superparticle is the charged right-handed τ-slepton and its lifetime is $\geq O(10^{-4})$ sec. This means that such a long-lived charged particle can form bound states with ordinary nuclei and electrons — quasistable supermatter (the analog of mu-atoms and muonium). The supercollider phenomenology for this model differs from the standard one in a drastic way, namely, in the final states there are two right-handed τ-sleptons coming from squark, gluino, chargino, neutralino and slepton decays. The $SU(2)_R \otimes SU(2)_L \otimes U(1)$ generalization of the standard $SU(2)_L \otimes U(1)$ electroweak gauge group allows one to obtain a very small R-violation in a natural way as a consequence of the large neutrino Majorana mass.

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