New Constraints on R-Parity-Broken Supersymmetry from Neutrinoless Double Beta Decay

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New constraints on the parameters of the minimal supersymmetric standard model with explicit R-parity violation ($\not{R}_p$MSSM) are obtained from the current experimental lower bound on the half-life of ^{76}Ge $0\nu\beta\beta$ decay. These constraints are shown to be more stringent than those from other low-energy processes and are competitive with or even more stringent than constraints expected from accelerator searches.

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Neutrinoless double beta decay ($0\nu\beta\beta$) has long been recognized as a sensitive tool to put theories beyond the standard model (SM) to the test (for reviews see Refs. [1–3]). A variety of mechanisms which may cause $0\nu\beta\beta$ decay has been studied in the past. The simplest and the most well-known possibilities are via the exchange of a massive Majorana neutrino between the decaying neutrons or due to $(B - L)$-violating right-handed currents. Another mechanism was found within supersymmetric (SUSY) models with $R_p = (-1)^{3B+L+2S}$ violation ($\not{R}_p$) [4]. In Refs. [5] and [6] this SUSY mechanism has been investigated within the minimal supersymmetric standard model (MSSM) with explicit R_p violation in the superpotential ($\not{R}_p$MSSM). In this Letter we extract constraints on the $\not{R}_p$MSSM parameter space from the current experimental lower bound on the ^{76}Ge $0\nu\beta\beta$ decay half-life.

Recently, impressive progress has been achieved in experiments with this isotope, in both the $2\nu\beta\beta$ and the $0\nu\beta\beta$ decay mode [7,8]. We will use, in our analysis, the experimental half-life limit of ^{76}Ge, recently measured by the Heidelberg-Moscow Collaboration [8],

$$T_{1/2}^{0\nu\beta\beta}(^{76}\mathrm{Ge}, 0^+ \to 0^+) > 5.6 \times 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.}). \tag{1}$$

The $\not{R}_p$MSSM has the MSSM field content and is completely specified by the standard SU(3) × SU(2) × U(1) gauge couplings, as well as by the low-energy superpotential and "soft" SUSY breaking terms [9]. The superpotential can be written as $W = W_{R_p} W_{\not{R}_p}$. The R_p-conserving term, W_{R_p}, coincides with the MSSM superpotential [9]. The most general gauge-invariant form of the R_p-violating term is [10]

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k . \tag{2}$$

We use notations L and Q for lepton and quark doublet superfields and use $\overline{E}$, $\overline{U}$, and $\overline{D}$ for lepton and *up* and *down* quark singlet superfields. Indices i, j, k denote generations. The coupling constants λ (λ'') are antisymmetric in the first (last) two indices. The first two terms lead to lepton number violation, while the last one violates baryon number conservation. Proton stability forbids simultaneous presence of lepton- and baryon-number-violating terms in the superpotential [11] (unless the couplings are very small). Therefore, either λ, λ' *or* λ'' Yukawa couplings can be nonzero. Neutrinoless double beta decay, which is the subject of the present paper, requires lepton-number-violating interactions. Therefore we bind ourselves to the $\not{R}_p$MSSM with lepton number violation ($\lambda \neq 0$, $\lambda' \neq 0$) and baryon number conservation ($\lambda'' = 0$). Apparently, $0\nu\beta\beta$ decay can probe only the first-generation lepton-number-violating Yukawa coupling λ'_{111}, because only the first-generation fermions u, d, e are involved in this process.

Let us write down explicitly the $\not{R}_p$ interaction terms of the $\not{R}_p$MSSM Lagrangian relevant for $0\nu\beta\beta$ decay. We use the four-component Dirac bispinor notation for fermion fields. The lepton-number-violating part of the Lagrangian obtained directly from the $W_{\not{R}_p}$ superpotential part [Eq. (2)] has the form

$$\mathcal{L}_{\not{R}_p} = -\lambda'_{111}\Bigg[(\overline{u}_L\ \overline{d}_R)\begin{pmatrix} e_R^c \\ -\nu_R^c \end{pmatrix}\overline{d}_R + (\overline{e}_L\ \overline{\nu}_L)d_R\begin{pmatrix} \tilde{u}_L^* \\ -\tilde{d}_L^* \end{pmatrix} + (\overline{u}_L\ \overline{d}_L)d_R\begin{pmatrix} \tilde{e}_L^* \\ -\tilde{\nu}_L^* \end{pmatrix} + \mathrm{H.c.}\Bigg]. \tag{3}$$

To construct diagrams contributing to $0\nu\beta\beta$ decay one also needs the MSSM R_p-conserving gluino $\tilde{g}$ and neutralino χ_i interactions with quarks, electrons, and their superpartners. The corresponding terms of the MSSM Lagrangian are well known and can be taken from Ref. [9].

Having specified all necessary interaction terms, one can construct diagrams describing the $\not{R}_p$MSSM contribution to the $0\nu\beta\beta$ decay. The complete set of these diagrams presented in Fig. 1 has been found in Ref. [6]. The supersymmetric mechanism of $0\nu\beta\beta$ decay was first proposed in Ref. [4] and later studied in more detail in Ref. [5]. However, only a subset

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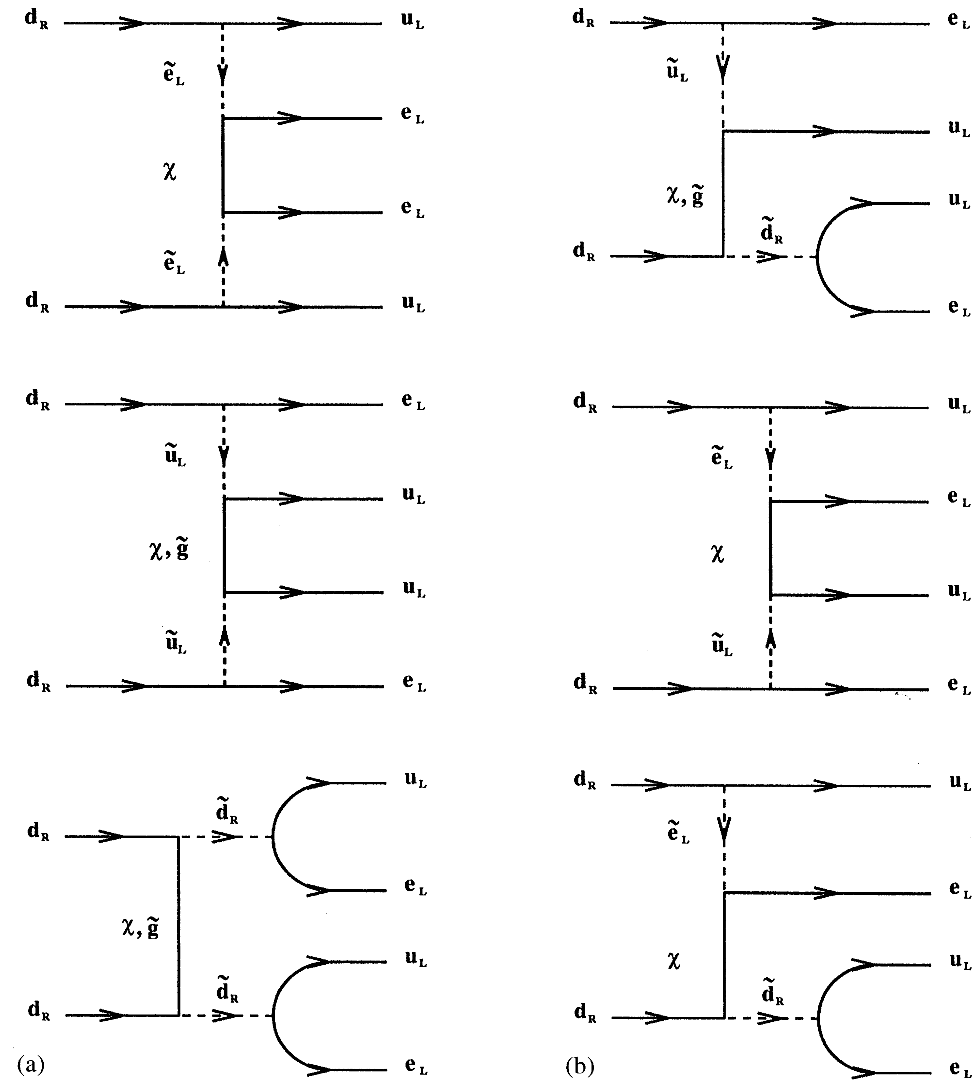

FIG. 1. Feynman graphs for the supersymmetric contributions to $0\nu\beta\beta$ decay.

of the $R\!\!\!/_p$MSSM diagrams relevant to $0\nu\beta\beta$ decay was considered in these papers.

In the case of $0\nu\beta\beta$ decay where characteristic momenta are much smaller than intermediate particle masses, one can treat the interactions of external particles described by the diagrams in Fig. 1 as pointlike. Then it is straightforward to construct the low-energy effective Lagrangian describing this process. The final result is [6]

$$\mathcal{L}_{\text{eff}}^{\Delta L_e=2}(x) = \frac{G_F^2}{2} m_P^{-1}[(\eta_{\tilde g} + \eta_\chi) \times (J_{PS}J_{PS} - \tfrac{1}{4} J_T^{\mu\nu} J_{T_{\mu\nu}}) + (\eta_{\chi\tilde e} + \eta'_{\tilde g} - \eta_{\chi\tilde f}) J_{PS}J_{PS}][\bar e(1+\gamma_5)e^c]. \quad (4)$$

The lepton-number-violating parameters are defined as follows:

$$\eta_{\tilde g} = \alpha_s \Lambda^2 \frac{m_P}{m_{\tilde g}}\left[1 + \left(\frac{m_{\tilde d_R}}{m_{\tilde u_L}}\right)^4\right], \qquad \eta_{\chi\tilde e} = 9\alpha_2\Lambda^2\left(\frac{m_{\tilde d_R}}{m_{\tilde e_L}}\right)^4 \sum_{i=1}^{4} \epsilon_{Li}^2(e)\frac{m_P}{m_{\chi_i}},$$

$$\eta_\chi = \frac{3\alpha_2}{4}\Lambda^2\sum_{i=1}^{4}\frac{m_P}{m_{\chi_i}}\left[\epsilon_{Ri}^2(d) + \epsilon_{Li}^2(u)\left(\frac{m_{\tilde d_R}}{m_{\tilde u_L}}\right)^4\right], \qquad \eta'_{\tilde g} = 2\alpha_s\Lambda^2\frac{m_P}{m_{\tilde g}}\left(\frac{m_{\tilde d_R}}{m_{\tilde u_L}}\right)^2, \quad (5)$$

$$\eta_{\chi\tilde f} = \frac{3\alpha_2}{2}\Lambda^2\left(\frac{m_{\tilde d_R}}{m_{\tilde e_L}}\right)^2\sum_{i=1}^{4}\frac{m_P}{m_{\chi_i}}\left[\epsilon_{Ri}(d)\epsilon_{Li}(e) + \epsilon_{Li}(u)\epsilon_{Ri}(d)\left(\frac{m_{\tilde e_L}}{m_{\tilde u_L}}\right)^2 + \epsilon_{Li}(u)\epsilon_{Li}(e)\left(\frac{m_{\tilde d_R}}{m_{\tilde u_L}}\right)^2\right].$$

Here $\Lambda = (\sqrt{2\pi}/3)\lambda'_{111}G_F^{-1}m_{\tilde{d}_R}^{-2}$. $\alpha_2 = g_2^2/(4\pi)$ and $\alpha_s = g_3^2/(4\pi)$ are $SU(2)_L$ and $SU(3)_c$ gauge coupling constants; $\lambda^{(a)}$ are 3×3 Gell-Mann matrices ($a = 1, \ldots, 8$). $m_{\tilde{g}}$, $m_{\tilde{u}_L,\tilde{d}_R}$, and $m_{\tilde{e}_L}$ are masses of the gluino $\tilde{g}$, squarks $\tilde{u}_L, \tilde{d}_R$, and selectron $\tilde{e}_L$. In the following, we use the approximation $m_{\tilde{u}_L} \approx m_{\tilde{d}_R} \approx m_{\tilde{q}}$. Neutralino coupling constants are defined as [9] $\epsilon_{Li}(\psi) = -T_3(\psi)\mathcal{N}_{i2} + \tan\theta_W[T_3(\psi) - Q(\psi)]\mathcal{N}_{i1}$, $\epsilon_{Ri}(\psi) = Q(\psi)\tan\theta_W\mathcal{N}_{i1}$. Here Q and T_3 are the electric charge and weak isospin of the field ψ. Coefficients N_{ij} are elements of the orthogonal mixing matrix which diagonalizes the 4×4 neutralino mass matrix [9]. The four neutralino mass eigenstates χ_i with masses m_{χ_i} have the field content $\chi_i = \mathcal{N}_{i1}\tilde{B} + \mathcal{N}_{i2}\tilde{W}^3 + \mathcal{N}_{i3}\tilde{H}_1^0 + \mathcal{N}_{i4}\tilde{H}_2^0$. We use notations $\tilde{W}^3$ and $\tilde{B}$ for neutral $SU(2)_L \times U(1)$ gauginos, and $\tilde{H}_2^0$ and $\tilde{H}_1^0$ for Higgsinos which are the superpartners of the two neutral Higgs boson fields H_1^0 and H_2^0 with a weak hypercharge $Y = -1, +1$, respectively. Color-singlet hadronic currents have the form $J_{PS} = \overline{u}^\alpha(1 + \gamma_5)d_\alpha$, $J_T^{\mu\nu} = \overline{u}^\alpha(1 + \gamma_5)d_\alpha$.

Let us write down the formula for the inverse $0\nu\beta\beta$ decay half-life corresponding to the effective Lagrangian equation (4):

$$[T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)]^{-1} = G_{01} \parallel (\eta_{\tilde{g}} + \eta_\chi)\langle F|\Omega_{\tilde{q}}|I\rangle + (\eta_{\chi\tilde{e}} + \eta'_{\tilde{g}} - \eta_{\chi\tilde{f}})\langle F|\Omega_{\tilde{f}}|I\rangle \parallel^2, \quad (6)$$

where G_{01} is the leptonic phase space integral, calculated according to the prescription of Ref. [2]. The transition operators $\Omega_{\tilde{q},\tilde{f}}$ were calculated in Ref. [6]. In this Letter we calculate their nuclear matrix elements appearing in Eq. (6) within the proton-neutron quasiparticle random phase approximation (*pn* QRPA). Following the description of Ref. [12] we have found the numerical values of these matrix elements for ^{76}Ge:

$$\mathcal{M}_{\tilde{q}} \equiv \langle F|\Omega_{\tilde{q}}|I\rangle = 283, \qquad \mathcal{M}_{\tilde{f}} \equiv \langle F|\Omega_{\tilde{f}}|I\rangle = 13.2. \quad (7)$$

The theoretical precision in determination of these matrix elements within *pn* QRPA is estimated to be 20% for $\mathcal{M}_{\tilde{q}}$ and a factor of 2 for $\mathcal{M}_{\tilde{f}}$. Thus the former value is quite reliably calculated, while the latter one is more uncertain. Fortunately, the last term in Eq. (6), depending on the matrix element $\mathcal{M}_{\tilde{f}}$, can be safely neglected in the numerical analysis. In order to show this, let us estimate the relative size of the five lepton-number-violating parameters η defined in Eqs. (5). Basically, they have very different magnitudes. In fact, one can see from Eqs. (5) that $\eta_{\tilde{g}}, \eta'_{\tilde{g}} \gg \eta_\chi, \eta_{\chi\tilde{e}}, \eta_{\chi\tilde{f}}$ if $m_{\tilde{q}} \sim m_{\tilde{e}}$, $m_{\chi_i} \gtrsim 0.02 m_{\tilde{g}}$ with the actual values of the gauge coupling constants $\alpha_s = 0.127, \alpha_2 = 0.0337$ [13] and for any field composition of the neutralino states χ_i. The last mass inequality is well satisfied even for a gluino mass $m_{\tilde{g}}$ as large as 1 TeV if the neutralino mass obeys the inequality $m_{\chi_i} \gtrsim 20$GeV. The latter is guaranteed by the present experimental lower bound on the mass of the lightest neutralino $\chi \equiv \chi_1$ [14].

Combining the above estimation of η parameters and the QRPA values of the nuclear matrix elements in Eq. (7), for which numerically $\mathcal{M}_{\tilde{q}} \gg \mathcal{M}_{\tilde{f}}$, we conclude that the dominant contribution to Eq. (6) from the SUSY mechanism is $[T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)]^{-1} \sim \eta_{\tilde{g}}\mathcal{M}_{\tilde{q}}$. (The relation $\mathcal{M}_{\tilde{q}} \gg \mathcal{M}_{\tilde{f}}$ will be satisfied for any nuclear model wave functions. It derives from the fact that there is no contribution from the tensor currents to $\mathcal{M}_{\tilde{f}}$.) Thus we expect the gluino exchange contribution to dominate in $0\nu\beta\beta$ decay. As a result, it is sufficient to survey only the three-dimensional $R\!\!\!/_p$MSSM parameter subspace $\{\lambda_{111}, m_{\tilde{q}}, m_{\tilde{g}}\}$ in analyzing $0\nu\beta\beta$ decay.

Now we are ready to extract the constraints on these parameters from the current experimental lower bound on the ^{76}Ge $0\nu\beta\beta$ decay half-life given by Eq. (1). This bound leads to the inequality

$$\lambda'_{111} \leq 3.9 \times 10^{-4}\left(\frac{m_{\tilde{q}}}{100\ \text{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\ \text{GeV}}\right)^{1/2}. \quad (8)$$

It is interesting to compare this constraint on the $R\!\!\!/_p$MSSM parameters with those derived from other existing experimental data as well as with those expected from future experiments. We discuss only the most stringent limits; weaker constraints can be found in the literature cited below.

In Fig. 2 we show bounds in the λ'_{111}-$m_{\tilde{q}}$ plane, from $0\nu\beta\beta$ decay as given by Eq. (8), from charged current universality [15]; Tevatron searches for the like-sign dileptons [16] as well as recently discussed [17] bounds which can be reached with one year data from the ZEUS detector at HERA. In the case of $0\nu\beta\beta$ decay, limits for two different values of the gluino mass are shown.

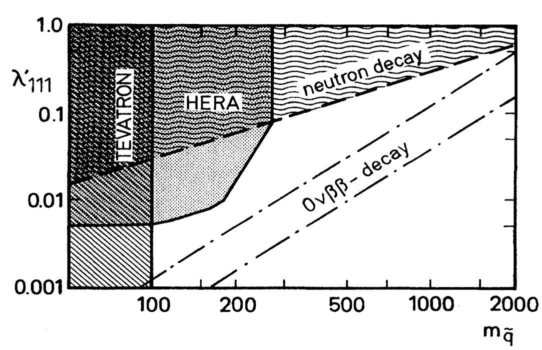

FIG. 2. Comparison of limits on the $R\!\!\!/_p$MSSM parameters from different experiments in the λ'_{111}-$m_{\tilde{q}}$ plane. The dashed line is the limit from charged-current universality according to [15]. The vertical line is the limit from the data of the Tevatron [16]. The thick full line is the region which might be explored by HERA [17]. The two dash-dotted lines to the right are the limits obtained from nonobservation of the $0\nu\beta\beta$ decay of ^{76}Ge for gluino masses of (from left to right) $m_{\tilde{g}} = 1$ TeV, 100 GeV, respectively. The regions to the upper left of the lines are forbidden.

It can be seen that even for a gluino mass as large as 1 TeV, which is marginal from the point of view of SUSY naturalness, the $0\nu\beta\beta$ decay bound [Eq. (8)] from the present ^{76}Ge half-life limit (1) yields the most restrictive bounds.

It is worthwhile noticing that the $0\nu\beta\beta$ decay bounds only very weakly depend on the theoretical uncertainties in the determination of the nuclear matrix elements (7). For instance, a change of $\mathcal{M}_{\tilde{q}}$ by even a factor of 2 leads to a less then 20% shift of the $0\nu\beta\beta$ decay constraint lines along the $m_{\tilde{q}}$ axis in Fig. 2. The shift is small because, as seen from Eqs. (5) and (6), the $m_{\tilde{q}}$ coordinates of these lines depend on the value of the nuclear matrix element as $\sim\mathcal{M}_{\tilde{q}}^{1/4}$.

To summarize this discussion, $0\nu\beta\beta$ decay allows one to stringently restrict R_p violating supersymmetric theories. We have shown that the $0\nu\beta\beta$ decay limits on the $\not{R}_p$MSSM parameter subspace $\{\lambda_{111}, m_{\tilde{q}}, m_{\tilde{g}}\}$ are more stringent than other known limits, as well as those which can be derived from future HERA experiments.

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