Neutralino decay rates with explicit R-parity violation

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We compute the neutralino decay rate in the minimal supersymmetric standard model with the addition of explicit R-parity violation. We include the complete squark and slepton mixing matrices, previously neglected, and we improve and correct published formulas. These decays are relevant to accelerator and nonaccelerator searches for R-parity violation, and are especially interesting in light of the reported high Q^2 anomaly at DESY HERA. [S0556-2821(98)04105-8]

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In the minimal supersymmetric standard model [1], a discrete symmetry called R-parity is invoked to forbid gauge invariant lepton and baryon number violating operators. The R-parity of a particle is given by $R_p=(-1)^{L+2S+3B}$, where L and B are the lepton and baryon numbers, and S is the spin. Standard model fermions, Higgs bosons, and gauge bosons have $R_p=+1$, while their superpartners have $R_p=-1$. This symmetry guarantees the stability of the lightest superpartner (LSP).

There is no deep theoretical motivation for imposing R-parity, and it is an interesting exercise to explore the phenomenology of R-parity violation [2]. We introduce explicit R-parity violation by adding

$$W_{\not{R}_p}=\lambda LLE^c+\lambda' LQD^c+\lambda'' U^cD^cD^c \tag{1}$$

to the superpotential. The first two terms violate lepton number, and the third violates baryon number. The LSP can now decay into standard model particles.

In models where supersymmetry is broken by supergravity, the LSP is usually the lightest of the neutralinos, which are superpositions of the superpartners of the neutral electroweak gauge bosons and the superpartners of the neutral Higgs bosons. R-parity violation allows the neutralino, which is a Majorana fermion, to decay into three standard model fermions (see Fig. 1).

Neutralino decays are relevant to accelerator searches for R-parity violation, especially resonant squark production [3,4]. Astrophysical neutralino decays are also of interest, and can put strong constraints on the R-parity violating couplings [5].

It is interesting to note that neutralino decays may be relevant to the reported high Q^2 anomaly at the DESY ep collider HERA [6]. The anomaly is an excess of events with a positron in the final state at high Q^2. One interpretation [7] is resonant production of a squark $\tilde{u}$ in $e^+d\to\tilde{u}$ due to an LQD^c term in the superpotential. The squark may decay back to a positron via the R-parity violating operator or may decay into $\chi^0 u$ and the neutralino χ^0 then decay into a positron by an R-parity violating interaction. This scenario awaits confirmation, such as from related charged current events [8].

The calculations of neutralino decay rates into fermions are subtle because they involve both Majorana fermions and fermion-number violating operators. To our knowledge, only one calculation is available in the literature [4], and it neglects sfermion mixing. We improve this calculation by including the complete sfermion mixings and we find some small but significant differences.

The differential decay rate of the neutralino is given by a standard three-body phase space factor multiplied by a squared amplitude which is averaged over the initial neutralino spin and summed over the final fermion spins. We denote this spin sum by a primed summation symbol:

$$\frac{\partial^2\Gamma}{\partial x_1\partial x_2}=\frac{m_\chi}{256\pi^3}\sum_{\text{spins}}{}' \ |\mathcal{M}|^2. \tag{2}$$

Here $x_{1,2}=2E_{1,2}/m_\chi$ and $E_{1,2}$ are two final state fermion energies.

In the following we present the calculation of the spin averaged squared amplitudes for neutralino decay. We first consider the $U^cD^cD^c$ term in the superpotential, followed by LQD^c and finally LLE^c.

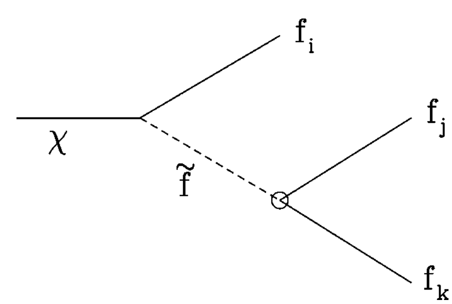

FIG. 1. Typical diagram for neutralino decay into standard model fermions via sfermion exchange. The R-parity violating vertex is circled.

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To calculate the $U^cD^cD^c$ decay, we first obtain the Feynman rule for the R-parity violating vertex. Writing all indices explicitly the superpotential reads

$$W_{UDD}=\epsilon^{\alpha\beta\gamma}[\lambda''_{ijk}U^c_{i\alpha}D^c_{j\beta}D^c_{k\gamma}], \tag{3}$$

where $U^c_{i\alpha}$, $D^c_{j\beta}$ and $D^c_{k\gamma}$ are the superfields of the right-handed quarks (and squarks) respectively, the superscript c denotes charge conjugation, i, j, and k are generation indices and α, β, and γ are $SU(3)_c$ triplet indices. It follows from the antisymmetry of $\epsilon^{\alpha\beta\gamma}$ that λ''_{ijk} is antisymmetric in the last two indices, thus there are 9 couplings for three generations. The superpotential can be written as

$$W_{UDD}=2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}U^c_{i\alpha}D^c_{j\beta}D^c_{k\gamma}, \tag{4}$$

with $k>j$. The Lagrangian that follows from the above superpotential contains

$$\mathcal{L}_{UDD}\ni -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}[\tilde{u}_{Ri\alpha}\bar{\eta}^D_{j\beta}\bar{\eta}^D_{k\gamma}+\tilde{d}_{Rj\beta}\bar{\eta}^U_{i\alpha}\bar{\eta}^D_{k\gamma} + \tilde{d}_{Rk\gamma}\bar{\eta}^U_{i\alpha}\bar{\eta}^D_{j\beta}]+\text{H.c.}, \tag{5}$$

where $\bar{\eta}^D_{i\alpha}$ is the right-handed component of the down-quark with generation index i and color index α, and $\tilde{d}_{Ri\alpha}$ is the squark associated to it. To pass to four-component notation we use the relation $\bar{\eta}_1\bar{\eta}_2=\overline{\psi^c_1}P_R\psi_2$, with $P_R=(1+\gamma_5)/2$. We obtain

$$\mathcal{L}_{UDD}\ni -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}[\tilde{u}_{Ri\alpha}\overline{d^c_{j\beta}}P_Rd_{k\gamma}+\tilde{d}_{Rj\beta}\overline{u^c_{i\alpha}}P_Rd_{k\gamma} + \tilde{d}_{Rk\gamma}\overline{u^c_{i\alpha}}P_Rd_{j\beta}]+\text{H.c.} \tag{6}$$

The sfermion mass eigenstates $\tilde{f}_\kappa$, with $\kappa=1,\ldots,6$, are related to left- and right-handed sfermions through the 6×3 mixing matrices $\Gamma^f_{R\kappa i}$ and $\Gamma^f_{L\kappa i}$, where $i=1,2,3$ is a generation index. Without mixing, $\kappa=i$ is a left-handed sfermion with generation i and $\kappa=i+3$ is a right handed sfermion with generation i. In general, the sfermion mixings are given by

$$\tilde{f}_\kappa=\Gamma^f_{R\kappa i}\tilde{f}_{Ri}+\Gamma^f_{L\kappa i}\tilde{f}_{Li}, \tag{7}$$

with inverse

$$\tilde{f}_{Ri}=\Gamma^{f*}_{R\kappa i}\tilde{f}_\kappa, \quad \tilde{f}_{Li}=\Gamma^{f*}_{L\kappa i}\tilde{f}_\kappa. \tag{8}$$

Note that there is only a left-handed sneutrino, so there is only a left handed mixing matrix and $\kappa=1,2,3$. In the simple case of no flavor mixing but with left-right mixing, the only nonzero elements are

$$\Gamma^f_{Lii}=\Gamma^f_{R(i+3)i}=\cos\theta_f,$$

$$\Gamma^f_{Rii}=-\Gamma^f_{L(i+3)i}=\sin\theta_f, \tag{9}$$

where θ_f is the left-right mixing angle for sfermion $\tilde{f}$.

Inserting the mixing matrices into the previous Lagrangian, we have

$$\mathcal{L}_{UDD}\ni -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}[\Gamma^{u*}_{R\kappa i}\tilde{u}_{\kappa\alpha}\overline{d^c_{j\beta}}P_Rd_{k\gamma}+\Gamma^{d*}_{R\kappa j}\tilde{d}_{\kappa\beta}\overline{u^c_{i\alpha}}P_Rd_{k\gamma} + \Gamma^{d*}_{R\kappa k}\tilde{d}_{\kappa\gamma}\overline{u^c_{i\alpha}}P_Rd_{j\beta}]+\text{H.c.} \tag{10}$$

The R-parity violating vertices are read directly from this Lagrangian.

We also need the neutralino-sfermion-fermion vertex. It comes from the interaction term

$$\mathcal{L}_{\chi f\tilde{f}}\ni \bar{\chi}(g^L_{\chi f_i\kappa}P_L+g^R_{\chi f_i\kappa}P_R)f_{i\alpha}\tilde{f}^*_{\kappa\alpha}+\text{H.c.}, \tag{11}$$

where i is a fermion generation index, κ specifies the sfermion mass eigenstate, and α is a color index. The couplings are

$$g^A_{\chi f_i\kappa}=\Gamma^f_{R\kappa i}g^{RA}_{\chi f_i}+\Gamma^f_{L\kappa i}g^{LA}_{\chi f_i}, \tag{12}$$

where A can be L or R and

$$g^{LL}_{\chi f_i}=-\sqrt{2}[(q_f-T_3)g'N_{\chi1}+T_3gN_{\chi2}], \tag{13}$$

$$g^{LR}_{\chi u_i}=g^{RL}_{\chi u_i}=-\frac{gm_{u_i}N_{\chi4}}{\sqrt{2}m_W\sin\beta}, \tag{14}$$

$$g^{LR}_{\chi d_i}=g^{RL}_{\chi d_i}=-\frac{gm_{d_i}N_{\chi3}}{\sqrt{2}m_W\cos\beta}, \tag{15}$$

$$g^{RR}_{\chi f_i}=+\sqrt{2}q_fg'N_{\chi1}. \tag{16}$$

Here T_3 is the third component of the weak isospin, N_{ij} is the 4×4 neutralino mixing matrix in the convention in which all neutralino masses are positive, u is an up-type quark or neutrino ($T_3=+1/2$), and d is a down-type quark or charged lepton ($T_3=-1/2$). The charges are $q_u=2/3$, $q_d=-1/3$, $q_\nu=0$, and $q_e=-1$. Notice that the only surviving neutrino couplings are $g^{LL}_{\chi\nu_i}$.

We can now obtain the full expression for the decay amplitude. In order to get correct signs for the interference terms we use Wick's theorem. The effective operator for neutralino decay is

$$\mathcal{T}(\chi\to\bar{u}_i\bar{d}_j\bar{d}_k)=-2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk} \times[\bar{\chi}(G^{RL}_{u_i}P_L+G^{RR}_{u_i}P_R)u_{i\alpha}\overline{d^c_{j\beta}}P_Rd_{k\gamma} + \bar{\chi}(G^{RL}_{d_j}P_L+G^{RR}_{d_j}P_R)d_{j\beta}\overline{u^c_{i\alpha}}P_Rd_{k\gamma} + \bar{\chi}(G^{RL}_{d_k}P_L+G^{RR}_{d_k}P_R)d_{k\gamma}\overline{u^c_{i\alpha}}P_Rd_{j\beta}], \tag{17}$$

where

$$G^{AB}_{f_i}=\sum_{\kappa}\Gamma^{f*}_{A\kappa i}\Delta^*_{\tilde f_\kappa}g^B_{\chi f_i\kappa}, \tag{18}$$

A and B are either R or L and $\Delta_{\tilde f_\kappa}=(p^2-m^2_{\tilde f_\kappa}+im_{\tilde f_\kappa}\Gamma_{\tilde f_\kappa})^{-1}$ is the sfermion propagator. In the case of no sfermion mixing, $\theta_f=0$, we find

$$G^{AB}_{f_i}=\Delta^*_{\tilde f_{Ai}}g^{AB}_{\chi f_i}. \tag{19}$$

In all cases G^* corresponds to a fermion and G corresponds to an antifermion in the decay amplitudes. The rates for the charge conjugated decays are found by complex conjugating G and G^* everywhere in our expressions for the spin summed squared amplitudes and thus are identical.

Suppressing color wave functions, we obtain the following amplitude for the decay $\chi\to\bar u_i\bar d_j\bar d_k$:

$$\begin{aligned}\mathcal{M}(\chi\to\bar u_i\bar d_j\bar d_k)&=\langle\bar u_i\bar d_j\bar d_k|\mathcal{T}|\chi\rangle=-2\lambda''_{ijk}\\&\times[\bar v_\chi(G^{RL}_{u_i}P_L+G^{RR}_{u_i}P_R)v_{u_i}\bar u_{d_j}P_Rv_{d_k}\\&-\bar v_\chi(G^{RL}_{d_j}P_L+G^{RR}_{d_j}P_R)v_{d_j}\bar u_{u_i}P_Rv_{d_k}\\&+\bar v_\chi(G^{RL}_{d_k}P_L+G^{RR}_{d_k}P_R)v_{d_k}\bar u_{u_i}P_Rv_{d_j}],\end{aligned} \tag{20}$$

where u_f and v_f are the usual particle and antiparticle Dirac spinors associated with quark f. Notice the minus sign in the second term in brackets, which comes from Dirac statistics. It is comforting that the same relative sign is obtained from the familiar Feynman rule of the sign of the fermion permutations: the first term has the fermions in the order (χ,u_i,d_j,d_k), the second in the order (χ,d_j,u_i,d_k), and the third in the order (χ,d_k,u_i,d_j). The second and the third are odd and even permutations of the first. This confirms the relative minus sign for the second term.

Squaring the amplitude, averaging over the two spin states of the neutralino, and summing over the final antiquark spin states, we obtain

$$\begin{aligned}\sum_{\text{spins}}{}'|\mathcal{M}(\chi\to\bar u_i\bar d_j\bar d_k)|^2&=8c_f|\lambda''_{ijk}|^2\\&\times\mathrm{Re}\{d_j\cdot d_k[(|G^{RL}_u|^2+|G^{RR}_u|^2)\chi\cdot u+2G^{RL}_uG^{RR*}_um_\chi m_u]\\&+u\cdot d_k[(|G^{RL}_{d_j}|^2+|G^{RR}_{d_j}|^2)\chi\cdot d_j+2G^{RL}_{d_j}G^{RR*}_{d_j}m_\chi m_{d_j}]\\&+u\cdot d_j[(|G^{RL}_{d_k}|^2+|G^{RR}_{d_k}|^2)\chi\cdot d_k+2G^{RL}_{d_k}G^{RR*}_{d_k}m_\chi m_{d_k}]\\&-G^{RR}_uG^{RR*}_{d_j}g(u,d_k,d_j,\chi)-G^{RL}_uG^{RR*}_{d_j}(d_k\cdot d_j)m_\chi m_u-G^{RR}_uG^{RL*}_{d_j}(d_k\cdot u)m_\chi m_{d_j}-G^{RL}_uG^{RL*}_{d_j}(\chi\cdot d_k)m_um_{d_j}\\&-G^{RR}_uG^{RR*}_{d_k}g(u,d_j,d_k,\chi)-G^{RL}_uG^{RR*}_{d_k}(d_k\cdot d_j)m_\chi m_u-G^{RR}_uG^{RL*}_{d_k}(u\cdot d_j)m_\chi m_{d_k}-G^{RL}_uG^{RL*}_{d_k}(\chi\cdot d_j)m_um_{d_k}\\&-G^{RR}_{d_j}G^{RR*}_{d_k}g(d_j,u,d_k,\chi)-G^{RL}_{d_j}G^{RR*}_{d_k}(d_k\cdot u)m_\chi m_{d_j}-G^{RR}_{d_j}G^{RL*}_{d_k}(d_j\cdot u)m_\chi m_{d_k}-G^{RL}_{d_j}G^{RL*}_{d_k}(\chi\cdot u)m_{d_j}m_{d_k}\},\end{aligned} \tag{21}$$

with the color factor $c_f=6$, and $g(a,b,c,d)=(a\cdot b)(c\cdot d)-(a\cdot c)(b\cdot d)+(a\cdot d)(b\cdot c)$. Particle four-momenta have been denoted by the particle letter and unambiguous indices have been suppressed.

The calculation of the LQD^c decays is very similar. The superpotential is

$$W_{LQD}=\epsilon^{\sigma\rho}[\lambda'_{ijk}L_{i\sigma}Q_{j\rho\alpha}D^c_{k\alpha}], \tag{22}$$

where σ and ρ are $SU(2)_L$ indices and α is an $SU(3)_c$ index. Suppressing color wave functions, we obtain the Lagrangian

$$\mathcal{L}_{LQD}\ni\lambda'_{ijk}[\tilde e_{Li}\bar d_kP_Lu_j+\tilde u_{Lj}\bar d_kP_Le_i+\tilde d^*_{Rk}\bar e^c_iP_Lu_j-\tilde\nu_{Li}\bar d_kP_Ld_j-\tilde d_{Lj}\bar d_kP_L\nu_i-\tilde d^*_{Rk}\bar\nu^c_iP_Ld_j]+\text{H.c.} \tag{23}$$

We have used the identities $\xi_1\eta_2=\bar\psi_2P_L\psi_1$ and $\xi_1\xi_2=\bar\psi^c_1P_L\psi_2$ to pass to four-component notation. Here there are 27 couplings for three generations as the coupling matrix is unconstrained by symmetry arguments.

After introducing sfermion mass eigenstates through Eq. (8), multiplying by Eq. (11), and using Wick's theorem, we obtain the following amplitudes for the decays $\chi\to e^+_i\bar u_jd_k$ and $\chi\to\bar\nu_i\bar d_jd_k$:

$$\begin{aligned}\mathcal{M}(\chi\to e^+_i\bar u_jd_k)=&-\lambda'_{ijk}[\bar v_\chi(G^{LL}_{e_i}P_L+G^{LR}_{e_i}P_R)v_{e_i}\bar u_{d_k}P_Lv_{u_j}-\bar v_\chi(G^{LL}_{u_j}P_L+G^{LR}_{u_j}P_R)v_{u_j}\bar u_{d_k}P_Lv_{e_i}\\&+\bar u_{d_k}(G^{RR*}_{d_k}P_L+G^{RL*}_{d_k}P_R)u_\chi\bar u_{e_i}P_Lv_{u_j}],\end{aligned} \tag{24}$$

$$\mathcal{M}(\chi\to\bar{\nu}_i\bar{d}_j d_k)=\lambda'_{ijk}[\bar{v}_\chi G^{LL}_{\nu_i}P_L v_{\nu_i}\bar{u}_d P_L v_{\bar{d}}-\bar{v}_\chi(G^{LL}_{d_j}P_L+G^{LR}_{d_j}P_R)v_{d_j}\bar{u}_{d_k}P_L v_{\nu_i}+\bar{u}_{d_k}(G^{RR*}_{d_k}P_L+G^{RL*}_{d_k}P_R)u_\chi\bar{u}_{\nu_i}P_L v_{d_j}]. \tag{25}$$

The matrix elements squared then follow as

$$\begin{aligned}\sum_{\text{spins}}{}' |\mathcal{M}(\chi\to e_i^+\bar{u}_j d_k)|^2 &= 2c_f|\lambda'_{ijk}|^2\\
&\times\mathrm{Re}\{e\cdot d[(|G^{LL}_u|^2+|G^{LR}_u|^2)\chi\cdot u+2G^{LL}_u G^{LR*}_u m_\chi m_u]\\
&+u\cdot e[(|G^{RL*}_d|^2+|G^{RR*}_d|^2)\chi\cdot d+2G^{RL*}_d G^{RR}_d m_\chi m_d]\\
&+u\cdot d[(|G^{LL}_e|^2+|G^{LR}_e|^2)\chi\cdot e+2G^{LL}_e G^{LR*}_e m_\chi m_e]\\
&-G^{LL}_u G^{RR}_d g(u,e,d,\chi)-G^{LR}_u G^{RR}_d(e\cdot d)m_\chi m_u-G^{LL}_u G^{RL}_d(e\cdot u)m_\chi m_d-G^{LR}_u G^{RL}_d(\chi\cdot e)m_u m_d\\
&-G^{LL}_u G^{LL*}_e g(e,d,u,\chi)-G^{LR}_u G^{LL*}_e(e\cdot d)m_\chi m_u-G^{LL}_u G^{LR*}_e(u\cdot d)m_\chi m_e-G^{LR}_u G^{LR*}_e(\chi\cdot d)m_u m_e\\
&-G^{RR*}_d G^{LL*}_e g(e,u,d,\chi)-G^{RL*}_d G^{LL*}_e(e\cdot u)m_\chi m_d-G^{RR*}_d G^{LR*}_e(d\cdot u)m_\chi m_e-G^{RL*}_d G^{LR*}_e(\chi\cdot u)m_d m_e\},\end{aligned} \tag{26}$$

$$\begin{aligned}\sum_{\text{spins}}{}' |\mathcal{M}(\chi\to\bar{\nu}_i\bar{d}_j d_k)|^2 &= 2c_f|\lambda'_{ijk}|^2\\
&\times\mathrm{Re}\{\nu\cdot d[(|G^{LL}_{d_j}|^2+|G^{LR}_{d_j}|^2)\chi\cdot\bar{d}+2G^{LL}_{d_j}G^{LR*}_{d_j}m_\chi m_{d_j}]\\
&+\bar{d}\cdot\nu[(|G^{RL*}_{d_k}|^2+|G^{RR*}_{d_k}|^2)\chi\cdot d+2G^{RL*}_{d_k}G^{RR}_{d_k}m_\chi m_{d_k}]+\bar{d}\cdot d|G^{LL}_\nu|^2\chi\cdot\nu\\
&-G^{LL}_{d_j}G^{RR}_{d_k}g(\bar{d},\nu,d,\chi)-G^{LR}_{d_j}G^{RR}_{d_k}(\nu\cdot d)m_\chi m_{d_j}-G^{LL}_{d_j}G^{RL}_{d_k}(\nu\cdot\bar{d})m_\chi m_{d_k}-G^{LR}_{d_j}G^{RL}_{d_k}(\chi\cdot\nu)m_{d_j}m_{d_k}\\
&-G^{LL}_{d_j}G^{LL*}_\nu g(\nu,d,\bar{d},\chi)-G^{LR}_{d_j}G^{LL*}_\nu(\nu\cdot d)m_\chi m_{d_j}-G^{RR*}_{d_k}G^{LL*}_\nu g(\nu,\bar{d},d,\chi)-G^{RL*}_{d_k}G^{LL*}_\nu(\nu\cdot\bar{d})m_\chi m_{d_k}\},\end{aligned} \tag{27}$$

where now the color factor is given by $c_f=3$ in both. Note that in Eqs. (26) and (27) for the LQD^c processes the factor in front is 2, not 8 as in Eq. (21) for the $U^cD^cD^c$ processes. This is because the $U^cD^cD^c$ process is identical for λ''_{ijk} and λ''_{ikj}, whereas each element of the LQD^c matrix λ'_{ijk} gives a unique channel.

The calculation of the LLE^c decay is very similar to the LQD^c case. From the superpotential

$$W_{LLE}=\epsilon^{\sigma\rho}[\lambda_{ijk}L_{i\sigma}L_{j\rho}E^c_k], \tag{28}$$

we obtain the Lagrangian

$$\mathcal{L}_{LLE}\ni 2\lambda_{ijk}[\tilde{e}_{Li}\bar{e}_k P_L\nu_j+\tilde{\nu}_{Lj}\bar{e}_k P_L e_i+\tilde{e}^*_{Rk}\bar{e}^c_i P_L\nu_j-\tilde{\nu}_{Li}\bar{e}_k P_L e_j-\tilde{e}_{Lj}\bar{e}_k P_L\nu_i-\tilde{e}^*_{Rk}\bar{e}^c_j P_L\nu_i]+\text{H.c.}, \tag{29}$$

where $j>i$ by the same antisymmetry argument as in the $U^cD^cD^c$ case. Again there are 9 couplings for three generations.

Passing to sfermion mass eigenstates and using Wick's theorem, we obtain the following amplitude for the decay $\chi\to e_i^+\bar{\nu}_j e_k^-$:

$$\begin{aligned}\mathcal{M}(\chi\to e_i^+\bar{\nu}_j e_k^-)=&-2\lambda_{ijk}[\bar{v}_\chi(G^{LL}_{e_i}P_L+G^{LR}_{e_i}P_R)v_{e_i}\bar{u}_{e_k}P_L v_{\nu_j}-\bar{v}_\chi G^{LL}_{\nu_j}P_L v_{\nu_j}\bar{u}_{e_k}P_L v_{e_i}\\
&+\bar{u}_{e_k}(G^{RR*}_{e_k}P_L+G^{RL*}_{e_k}P_R)u_\chi\bar{u}_{e_i}P_L v_{\nu_j}].\end{aligned} \tag{30}$$

The matrix element squared is

$$\sum_{\text{spins}}' |\mathcal{M}(\chi\to e_i^+ \bar{\nu}_j e_k^-)|^2 = 8|\lambda_{ijk}|^2$$

$$\times \mathrm{Re}\{ e\cdot\nu[(|G_{e_i}^{LL}|^2+|G_{e_i}^{LR}|^2)\chi\cdot\bar{e}+2G_{e_i}^{LL}G_{e_i}^{LR*}m_\chi m_{e_i}]$$

$$+e\cdot\bar{e}|G_\nu^{LL}|^2\chi\cdot\nu+\bar{e}\cdot\nu[(|G_{e_k}^{RL*}|^2+|G_{e_k}^{RR*}|^2)\chi\cdot e+2G_{e_k}^{RL*}G_{e_k}^{RR}m_\chi m_{e_k}]$$

$$-G_{e_i}^{LL}G_\nu^{LL*}g(\bar{e},e,\nu,\chi)-G_{e_i}^{LR}G_\nu^{LL*}(e\cdot\nu)m_\chi m_{e_i}-G_{e_i}^{LL}G_{e_k}^{RR}g(\bar{e},\nu,e,\chi)-G_{e_i}^{LR}G_{e_k}^{RL}(\chi\cdot\nu)m_{e_k}m_{e_i}$$

$$-G_{e_i}^{LR}G_{e_k}^{RR}(e\cdot\nu)m_\chi m_{e_i}-G_{e_i}^{LL}G_{e_k}^{RL}(\bar{e}\cdot\nu)m_\chi m_{e_k}-G_\nu^{LL}G_{e_k}^{RR}g(\nu,\bar{e},e,\chi)-G_\nu^{LL}G_{e_k}^{RL}(\nu\cdot\bar{e})m_\chi m_{e_k}\}. \tag{31}$$

Again, there is a factor of 8 instead of 2 due to the fact that λ_{ijk} and λ_{jik} allow the same process. Note that if $i>j$, the amplitude gains an overall minus sign, but the squared amplitude is identical.

In the limit of no sfermion mixing, we can compare our results with those of Butterworth, Dreiner, and Morawitz [4]. We differ in several respects. In all three types of decays we keep complex conjugations in the couplings, which are crucial when the neutralino mass eigenvalue is negative, and we do not have the global phase space factor of $2(1-m_1^2/E_1^2)^{-1/2}$ which appears in their rates. Our LLE^c and $U^cD^cD^c$ decay rates are a factor of four larger than theirs, due to the fact that each channel is duplicated in the coupling matrix which doubles the decay amplitude. Finally, we find that in the $U^cD^cD^c$ decay their couplings a and b are exchanged, in other words gauginos and Higgsinos are exchanged, and that in some instances, particles and antiparticles have been confused (because the a's are the same for particles and antiparticles but the b's differ).

Together with Dreiner [9], we have agreed that the formulas in this paper are the correct ones. An erratum to [4] will be published elsewhere [9].

In conclusion, we have computed the neutralino decay rate in R-parity violating extensions to the minimal supersymmetric standard model. For the first time we include complete mixing among sfermions. Our results supersede previously published calculations [4].

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