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R-parity violating decays of the gluino

L. Clavelli [a], H. Stremnitzer [b]

[a] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
[b] Institut für Theoretische Physik, Universität Wien, A-1090 Vienna, Austria

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Abstract

Assuming the lightest supersymmetric particle is the gluino, we treat the decays $\tilde{g} \to q\bar{q}\nu$ and $\tilde{g} \to g\nu$. Such couplings can be induced by the R-parity violating quark–squark–lepton interaction which can also be responsible for neutrino masses and mixings. These R-parity violating gluino decays have the same final state structure (jets plus missing energy) as previously considered decays into quark–antiquark–photino and gluon–gravitino but with significantly different gluino lifetimes.

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1. Introduction

The possibility of the lightest supersymmetric particle (LSP) decaying through R-parity violation has been discussed since the early days of supersymmetry [1], many studies have been made (e.g. [2]), and many experimental searches have been undertaken (e.g. [3]). There seem, however, to have been no investigations up to now of the possibility considered here of R-parity violating decays of the gluino. Although these would be most relevant if the recent theme of a light or relatively light gluino were to be experimentally confirmed they could also be important in the case of a heavy gluino LSP. In some cases [4,5] the phenomenological advantages of a light gluino have as much to do with a large hierarchy between gluino and squark masses as with a light gluino mass per se. Most recent light gluino investigations have concentrated on the mass region around 12 GeV possibly accompanied by a b squark near 4 GeV [6,7]. Alternative possibilities have also been noted [8]. In the minimal supersymmetric standard model (MSSM), a light gluino is typically accompanied by an even lighter photino allowing the decay $\tilde{g} \to q\bar{q}\tilde{\gamma}$. In gauge mediated SUSY breaking models, there is often an ultra-light gravitino below the gluino in mass leading to the decay $\tilde{g} \to g\tilde{G}$. In some models these channels are closed leading to an absolutely stable gluino or to one decaying through R-parity violating processes. In this article we assume the gluino is the lightest supersymmetric particle and we consider lepton number violating gluino decays. In Section 2 we treat the decays $\tilde{g} \to q\bar{q}\nu$. The fact that the third generation seems, in some respects, special compared to the first two suggests models in which the R-parity violation is tied to the third generation.

If the R-parity violation is entirely in the third generation and the gluino lies below the $b\bar{b}$ threshold,

E-mail addresses: lclavell@bama.ua.edu (L. Clavelli), hanns.stremnitzer@univie.ac.at (H. Stremnitzer).

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there will be the loop induced decay $\tilde{g} \to g\nu$. This is treated in Section 3 neglecting the possibility of a right-handed neutrino.

Finally, in the presence of a light right-handed neutrino, there is the possibility, treated in Section 4, that the dominant decay could be a two loop process coupling the gluino to gluon plus ν_R. It might be expected that such a dominant decay mechanism would lead to an ultra-long-lived gluino.

2. The gluino decay to quark–antiquark–neutrino

We assume an R-parity violating and lepton number violating term in the superpotential of the form

$$W = \lambda'_{ijk} L_i Q_j D_k, \tag{2.1}$$

where i, j, k are family indices. Then, if the gluino is above a quark–antiquark threshold one will have the gluino decay to $q\bar{q}\nu$ corresponding to the graph of Fig. 1.

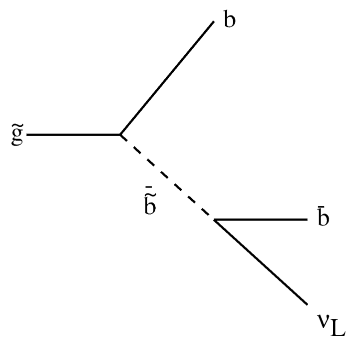

Fig. 1. Gluino decay into quark–antiquark–neutrino.

The fact that the third generation seems, in some respects, special compared to the first two suggests models in which the R-parity violation involves third generation quarks and squarks only. We, therefore, take as a working assumption that the non-zero quark flavor indices in (2.1) are third generation only. In any case, the experimental limits on R-parity violating couplings are much less restrictive [2,9] in the third generation so these could well be dominant. A λ' involving only third generation quarks could be as great as 0.1. Then the gluino decay would be into $b\bar{b}\nu$ assuming the gluino mass is above the $2b$ threshold. In this case a light gluino pair production could explain the excess b production seen at Fermilab without requiring the light b squarks of [6].

The signature of such a decay, hadrons plus missing energy, would be identical to the conventional $q\bar{q}\tilde{\gamma}$ decay. The inverse width for this latter decay is

$$\tau(\tilde{g} \to q\bar{q}\tilde{\gamma}) \approx \tilde{m}^4 / \left(m_{\tilde{g}}^5 \alpha_s \alpha\right). \tag{2.2}$$

With a light gluino and a squark mass in the 100 GeV range, this typically results in a gluino lifetime in the nanosecond range which is counter-indicated by the KTEV search [10]. If, however, the gluino is the LSP and decays through the R-parity violating graph of Fig. 1, the lifetime could easily be much longer so that the lightest supersymmetric hadron, presumably the gluino–gluon bound state, would not decay in the sensitive region of a KTEV type experiment.

$$\tau(\tilde{g} \to q\bar{q}\nu) \approx \tilde{m}^4 / \left(m_{\tilde{g}}^5 \alpha_s \lambda'^2\right). \tag{2.3}$$

The neutrino mass matrix corresponding to the R-parity violation of (2.1) is [11]

$$M^{\nu}_{ii'} \approx \frac{3}{8\pi^2} \sum_{jk} \lambda'_{ijk} \lambda'_{ikj} m_d(j) m_d(k) / \tilde{m}, \tag{2.4}$$

where $\tilde{m}$ is the assumed degenerate squark mass and $m_d(k)$ is the down-type quark mass in the kth family. We have also made the simplification of neglecting the CKM quark mixing angles and have assumed that $A_d - \mu \tan\beta$ is of order $\tilde{m}$. If the dominant k, j are third generation, [11] notes that a 4.5 eV ν_e mass would correspond to

$$\lambda'_{133} \approx 7 \times 10^{-4} \left(\frac{\tilde{m}}{100\ \text{GeV}}\right)^{1/2} \tag{2.5}$$

although the present indications of a sub-eV neutrino mass would lead to a λ' an order of magnitude below (2.5). Such a relation substituted into (2.3) would lead to a gluino lifetime depending only on the ratio of gluino mass to squark mass.

$$\tau(\tilde{g}) = 0.013s \left(\frac{\tilde{m}}{1000 m_{\tilde{g}}}\right)^5 \left(\frac{0.1}{\alpha_s}\right) \left(\frac{7 \times 10^{-5}}{\lambda'_{i33}}\right)^2. \tag{2.6}$$

A gluino–gluon bound state with a lifetime of order 0.013 s might have evaded the current searches since it would appear as a quasi-stable particle whose ultimate decay with a missing neutrino could be confused with a neutron knock-on event.

3. The gluino decay to gluon plus neutrino

If the gluino mass is less than twice the mass of the quarks appearing in the R-parity violating couplings, one has the hitherto uninvestigated decay

$$\tilde{g} \to g\nu. \tag{3.1}$$

A recent analyses of constraints from Z decay suggests at 95% confidence level [12,13]

$$m_{\tilde{g}} > 6.3\ \mathrm{GeV}/c^2. \tag{3.2}$$

This limit still allows the possibility that the gluino mass is below the b quark pair threshold. The matrix element corresponding to the graph of Fig. 2 plus the analogous graph where the gluon is emitted from the squark line is

$$\begin{aligned}\mathcal{M} = {}& \epsilon_\mu \frac{\lambda' {g_3}^2 m_b}{4} \bar{u}(p') \\ & \times \int \frac{d^4k}{(2\pi)^4} \left(\frac{(\not{p}' + \not{k})\gamma^\mu + \gamma^\mu(\not{p} + \not{k})}{(p+k)^2 - m_b^2} \right. \\ & \left. + \frac{(2k-q)^\mu}{(k-q)^2 - \tilde{m}^2} \right) \\ & \times (1-\gamma_5) u(p) \frac{1}{(p'+k)^2 - m_b^2} \frac{1}{k^2 - \tilde{m}^2},\end{aligned} \tag{3.3}$$

where $p' = p - q$ is the final state neutrino momentum.

This amplitude is equivalent to that induced by an effective magnetic moment coupling

$$\mathcal{L} = i\mu_a \bar{u}_L(\nu)\sigma^{\mu\nu} q_\nu u(\tilde{g})\epsilon_\mu(g) \tag{3.4}$$

with

$$\mu_a \approx \frac{m_b \alpha_s \lambda'}{\tilde{m}^2}. \tag{3.5}$$

The corresponding decay rate is

$$\Gamma(\tilde{g} \to g\nu) = |\mu_a|^2 m_{\tilde{g}}^3 \approx \frac{m_b^2 m_{\tilde{g}}^3 \alpha_s^2 \lambda'^2}{\tilde{m}^4}. \tag{3.6}$$

Nominal values of 10 GeV, 10 TeV, 0.1, and 7×10^{-5} for $m_{\tilde{g}}$, $\tilde{m}$, α_s, and λ', would correspond to a gluino lifetime of 5.2×10^{-3} s.

A two loop graph that would lead to a gluino decay to gluon plus right-handed neutrino is shown in Fig. 3. To investigate such two loop effects we consider an extended superpotential containing a right-handed singlet superfield N.

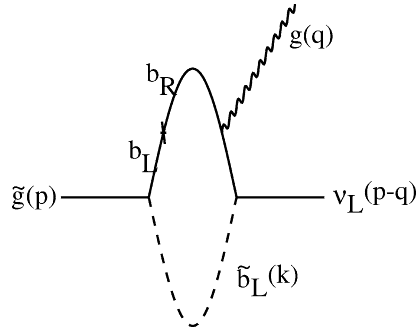

Fig. 2. Gluino decay to gluon plus left-handed neutrino.

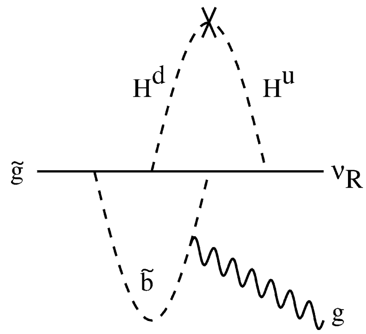

Fig. 3. Typical Feynman graph for gluino decay to gluon plus right-handed neutrino.

$$W = W_{\mathrm{MSSM}} + \lambda' QDL + \epsilon H^u H^d N + h_\nu LNH^u. \tag{3.7}$$

Here, lepton number and R-parity violation comes through a new $H^u H^d N$ interaction governed by the coupling constant ϵ in addition to the conventional λ' coupling. W_{MSSM} contains the usual Higgs mixing term $\mu H^u H^d$. The small Yukawa coupling h_ν is proportional to the neutrino Dirac mass:

$$h_\nu = \frac{m_\nu^{\mathrm{Dirac}}}{\langle H^u \rangle}. \tag{3.8}$$

The effective transition magnetic moment from Fig. 3 is

$$\mu_a \approx \frac{1}{(4\pi)^3} \frac{\lambda' h_\nu h_b \alpha_s \mu B m_b}{\tilde{m}^2 m_H^2}. \tag{3.9}$$

Here, μB is the off-diagonal entry in the Higgs mass squared matrix. In the MSSM with electroweak symmetry breaking [14], it is given by $\mu B = \frac{1}{2} M_A^2 \sin(2\beta)$ where M_A is the mass of the CP-odd Higgs scalar.

This μ_a, however, would be proportional to the neutrino mass and would be negligible compared to the transition magnetic moment of (3.5).

4. A dominant gluino decay to gluon plus right-handed neutrino

Even in the absence of the R-parity violating quark–squark–lepton coupling of (2.1), the R-parity and lepton number violating Higgs–Higgsino–Lepton coupling in (3.7) could lead to a gluino decay into gluon plus right-handed neutrino.

The lowest order graph contributing to gluino decay would be that of Fig. 4 as well as those graphs related by attaching the gluon to other colored lines or by changing the flavor of the internal quark (squark) lines. These amplitudes are proportional to the trilinear boson coupling parameters A, which are induced in the softly broken MSSM thru supergravity. We can entertain the possibility that the λ' parameters are negligible and that the dominant trilinear coupling is that of the top quark. Then the two loop gluino decays of Fig. 4 could be dominant for a gluino LSP of mass up to the minimum of twice the top mass or twice the stop mass:

$$\mu_a \approx \frac{1}{(4\pi)^3}\frac{\mu\cos(2\beta)m_{\chi^0}A\epsilon\alpha_s h_t}{\tilde{m}^2 m_H^2}, \tag{4.1}$$

where m_{χ^0} is the mass of the neutralino. However, if the top quark is heavier than the neutralino, then m_{χ^0} should be replaced by m_t in the estimate here.

Depending on the flavor structure, the ϵ coupling might be limited only by neutrino mass measurements and might, therefore, be expected to be extremely small. It is clear that the corresponding gluino lifetime could easily be long enough to have cosmological significance. There is, for instance, the possibility that the gluino–gluon bound state could traverse cosmological distance scales before decaying and, if sufficiently energetic, could contribute through its decay products to the ultra-high-energy cosmic rays. We leave delayed calculation of some of the possible effects discussed here to future investigations.

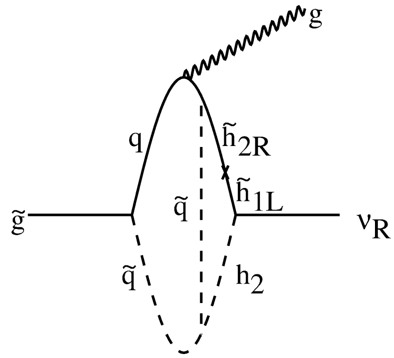

Fig. 4. Alternative mechanism for gluino decay into gluon plus right-handed neutrino.

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