Lower Limits on *R*-Parity-Violating Couplings in Supersymmetric Models with Light Squarks

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We interpret the results of searches for strongly interacting massive particles to place absolute lower limits on R-parity-violating couplings for squarks with mass ($m_{\tilde{q}}$) below 100 GeV. Recent searches for anomalous isotopes require that there be a baryon-number-violating or lepton-number-violating coupling larger than 10^{-22}–10^{-21} if $m_{\tilde{q}} > 18$ GeV. Using data from searches for stable particles at the CERN Large Electron Positron Collider (LEP) we demonstrate that this lower limit increases by 14 orders of magnitude, to an R-parity-violating coupling larger than 10^{-8}–10^{-7} for any squarks of mass less than 90 GeV. In the presence of an R-parity-violating coupling of this magnitude, neutralinos cannot explain the dark matter density in the Universe.

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In supersymmetric extensions of the standard model of elementary particle physics, particles are typically assigned a new quantum number called R parity (R_p) [1]. Particles of the standard model are defined to have even R_p, and their corresponding superpartners have odd R_p. If R parity is conserved, then superpartners must be produced in pairs, each of which decays to a final state that includes at least one stable lightest supersymmetric particle (LSP). One appealing feature of R-parity conservation is that if the LSP is a neutralino, then it is naturally predicted to exist with the necessary relic density to explain the dark matter density in the Universe [2].

In contrast, if R parity is not conserved, then supersymmetric particles may decay into standard-model particles, and supersymmetry may not provide a explanation of dark matter. Further, many of the postulated signatures of supersymmetry (SUSY), such as missing energy in high energy collider experiments, may not exist. In particular, many of the exclusion limits on squark masses may no longer apply if R parity is violated. On the other hand, if the R-parity-violating couplings are small enough, then superparticles may appear to be stable on a time scale relevant for collider searches. In the search for physics beyond the standard model in cosmological and terrestrial experiments, it is of substantial importance to address explicitly the question of R-parity violation, a possibility that we explore in this Letter.

The present *upper* bounds on possible R-parity-violating couplings are obtained principally from next-to-leading order quantum corrections to the rates for particle decays and neutral meson mixing. These bounds are relatively restrictive for the first generation of quarks and leptons but are much less so for states of the second and third generations [3]. In this Letter, we approach R-parity-violating couplings from the other direction. We demonstrate that there must be strong *lower* bounds on R-parity-violating couplings for a large range of squark masses. Otherwise, squarks with mass in these ranges cannot exist.

We focus on squarks with mass below 100 GeV. Although it is widely held that squarks in this range are ruled out by experiment, this limitation does not apply in general SUSY-breaking scenarios if the states with lowest mass are coupled feebly to the neutral gauge boson Z. One such scenario [4] involving a light bottom squark $\tilde{b}$ and a gluino of moderate mass provides an explanation for the large excess in the b-quark cross section measured at hadron colliders [5,6] and is supported by the recent observation of a large time-averaged $B^0\bar{B}^0$ mixing probability $\bar{\chi}$ [7]. If the lighter of the two bottom squarks is an appropriate mixture of left-handed and right-handed squarks, its tree-level coupling to the Z can be arbitrarily small, permitting good agreement with the precise measurements of Z-peak observables [8], including effects at loop level [9].

In this Letter we go beyond Ref. [4], and examine the decays of all flavors of squarks. We demonstrate that a lower bound on baryon-number or lepton-number violating couplings of 10^{-22}–10^{-21} can be extracted from primordial abundance searches. Then, using data from searches for massive stable particles produced at LEP, we place absolute lower bounds on R-parity-violating couplings as a function of squark mass. For any squarks with mass less than 90 GeV, we show that the lower bounds on baryon-number or lepton-number violating couplings improve to 10^{-8}–10^{-7}.

Supersymmetric notation.—There are several popular choices of convention for the squark mixing angles and for the normalization of R-parity-violating couplings. For evaluating the lifetimes of squarks, we use the R-parity-violating superpotential [10]

$$W_{\not{R}_p} = \epsilon^{\sigma\rho}\lambda'_{ijk}L_{i\sigma}Q^{\alpha}_{j\rho}D^c_{k\alpha} + \epsilon^{\alpha\beta\gamma}\lambda''_{ijk}U^c_{i\alpha}D^c_{j\beta}D^c_{k\gamma}, \quad (1)$$

where (σ, ρ) are SU(2) indices, (α, β, γ) are SU(3) color indices, and (i, j, k) are generation indices. L and Q are leptonic and hadronic left-handed superdoublets, respectively. U^c and D^c are right-handed up- and down-type conjugate superfields, respectively. The first term violates lepton number, and the second term violates baryon number. The dimensionless couplings λ'_{ijk} and λ''_{ijk} measure the strengths of lepton-number and baryon-number violation, respectively. In general, the couplings are complex.

The physical squarks are a mixture of the scalar partners of the left- and right-chiral quarks. The mass eigenstates are two complex scalars, $\tilde{q}_1$ and $\tilde{q}_2$, expressed in terms of left-handed (L) and right-handed (R) squarks, $\tilde{q}_{\rm L}$ and $\tilde{q}_{\rm R}$. We choose the squark mixing matrix such that $\tilde{q}_1$ is mostly right-handed when the mixing angle is small. (Note we use a different mixing convention here than presented in Ref. [11].)

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{q}} & \sin\theta_{\tilde{q}} \\ -\sin\theta_{\tilde{q}} & \cos\theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_R \\ \tilde{q}_L \end{pmatrix}. \tag{2}$$

Given the mixing matrix above, the partial widths of a squark decaying into two massless quarks are

$$\begin{aligned} \Gamma(\tilde{q}_1 \to qq) &= \frac{m_{\tilde{q}_1}}{2\pi}\cos^2\theta_{\tilde{q}}|\lambda''_{ijk}|^2, \\ \Gamma(\tilde{q}_2 \to qq) &= \frac{m_{\tilde{q}_2}}{2\pi}\sin^2\theta_{\tilde{q}}|\lambda''_{ijk}|^2, \qquad j < k. \end{aligned} \tag{3}$$

The partial widths of an up-type squark that decays into a massless quark and lepton are

$$\begin{aligned} \Gamma(\tilde{u}_{1j} \to \overline{e}_i d_k) &= \frac{m_{\tilde{u}_{1j}}}{16\pi}\sin^2\theta_{\tilde{u}_j}|\lambda'_{ijk}|^2, \\ \Gamma(\tilde{u}_{2j} \to \overline{e}_i d_k) &= \frac{m_{\tilde{u}_{2j}}}{16\pi}\cos^2\theta_{\tilde{u}_j}|\lambda'_{ijk}|^2, \end{aligned} \tag{4}$$

and for a down-type squark, they are

$$\begin{aligned} \Gamma(\tilde{d}_{1j} \to \overline{\nu}_i d_k) &= \frac{m_{\tilde{d}_{1j}}}{16\pi}\sin^2\theta_{\tilde{d}_j}|\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2j} \to \overline{\nu}_i d_k) &= \frac{m_{\tilde{d}_{2j}}}{16\pi}\cos^2\theta_{\tilde{d}_j}|\lambda'_{ijk}|^2, \end{aligned} \tag{5}$$

$$\begin{aligned} \Gamma(\tilde{d}_{1k} \to \nu_i d_j) &= \frac{m_{\tilde{d}_{1k}}}{16\pi}\cos^2\theta_{\tilde{d}_k}|\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2k} \to \nu_i d_j) &= \frac{m_{\tilde{d}_{2k}}}{16\pi}\sin^2\theta_{\tilde{d}_k}|\lambda'_{ijk}|^2, \end{aligned} \tag{6}$$

$$\begin{aligned} \Gamma(\tilde{d}_{1k} \to e_i u_j) &= \frac{m_{\tilde{d}_{1k}}}{16\pi}\cos^2\theta_{\tilde{d}_k}|\lambda'_{ijk}|^2, \\ \Gamma(\tilde{d}_{2k} \to e_i u_j) &= \frac{m_{\tilde{d}_{2k}}}{16\pi}\sin^2\theta_{\tilde{d}_k}|\lambda'_{ijk}|^2. \end{aligned} \tag{7}$$

If one R-parity-violating coupling is large compared to the others, then only one of these partial widths will be applicable at any given time. For simplicity we present results assuming one significant coupling. Any other combination of couplings may be derived using the widths above.

Limits on squark masses and R-parity-conserving couplings.—To place R-parity-*violating* couplings into context, we begin with a brief summary of the current limits on R-parity-*conserving* decays of squarks. In R-parity-conserving SUSY, squarks are either completely stable or undergo R-parity-conserving decays into final states containing a stable sparticle. If the daughter sparticle is neutral, then there will be missing energy in the event. Many limits on squark masses are based on searches for jets plus missing energy, and some are predicated on the assumption that couplings to the Z boson are not suppressed. In our work, by contrast, we place the most conservative lower limits on R-parity-violating couplings, and we therefore include cases in which the squarks decouple from the Z boson.

In the absence of strong coupling to the Z boson, direct limits on the existence of up-type and down-type squarks differ significantly. Because of their larger coupling to photons, the R-parity-conserving decay of up-type squarks to any LSP is ruled out for $m_{\tilde{q}} < 63$ GeV [12–15] as long as the lifetime of the squark is less than 1–10 ns [12]. This limit increases to 83–89 GeV in any case where $\Delta m = m_{\tilde{q}} - m_{\rm LSP} > 5$ GeV [15,16]. Down-type squarks with masses of 40–89 GeV, R-parity-conserving decays, and $\Delta m > 5$ GeV are also excluded. However, below 40 GeV the only limits on R-parity-conserving decays for down-type squarks come from exclusions of possible decay products. All sleptons, charginos, and neutralinos are excluded below 37 GeV [13], and stable gluinos are excluded below 27 GeV [12]. Unless there is a stable gluino of mass 27–35 GeV, or finely tuned LSP mass, all squarks less than 83–89 GeV will either appear to be stable on the time scale of accelerator experiments, or decay via R-parity-violating interactions. For the rest of this Letter, we consider the R-parity-conserving decays to be excluded.

R-parity-violating couplings.—Limits on the relic abundances of stable primordial particles may be used to set an initial lower bound on R-parity-violating couplings. For hadron masses less than 100 GeV, Fermi motion in nuclei is expected to prevent the capture of exotic states in the nuclei of light elements, such as sodium or oxygen. Heavy elements, such as gold and iron, are believed to be capable of capturing strongly interacting massive particles (SIMPs) [17]. Recently, a search for anomalous gold and iron isotopes was used to set limits on the cosmological density parameter Ω_S, the ratio of the density of relic primordial SIMPs to the critical density. Upper limits of $\Omega_S \approx 6\times 10^{-8}(m_{\tilde{q}}[\text{GeV}])^{1.7}$ were extracted for the mass range 2.8 to 100 GeV [18]. Following Ref. [19], we calculate that the relic abundance of squarks, including all QCD and supersymmetric annihilations, contributes approximately $10^{-8}(m_{\tilde{q}}[\text{GeV}])^{2.29}$ to Ω_S. We find a freeze-out temperature that varies between $T_F = m_{\tilde{q}}/36$ and $m_{\tilde{q}}/30$. The QCD annihilation into two gluons completely dominates the annihilation rate. Hence, the abundance of stable squarks depends solely on the mass of the squarks, and no other supersymmetric parameters. If the assumptions regarding exposure times for the samples and capture cross sections are correct, then completely stable primordial squarks may be excluded between 18–100 GeV.

To evade the primordial abundance bounds the squarks must have decayed with a lifetime less than the age of the Universe. For reasons discussed above we assume that R-parity-conserving decays are excluded for squarks of mass less than 100 GeV. Using our complete relic density calculation, Eqs. (3)–(7), and exact limits on Ω_S from Ref. [18], we conclude that there must be at least one R-parity-violating coupling $\lambda'' > (2\text{–}3) \times 10^{-22}$ or $\lambda' > (6\text{–}9) \times 10^{-22}$ if $20 < m_{\tilde{q}} < 100$ GeV. In the case of mixing, this limit is larger by $|1/\sin\theta_{\tilde{q}}|$ or $|1/\cos\theta_{\tilde{q}}|$.

While a few combinations of masses and R-parity-violating couplings have been excluded [20], we now show that there is a strong lower limit on at least one baryon-number or lepton-number violating coupling for all squarks of mass less than 85–90 GeV by using the results of a new ALEPH study [12,21]. From the absence of heavy hadron tracks and unexplained missing energy, the ALEPH study concludes that squarks, if produced, decay before leaving a discernible signature. That investigation rules out squarks that live more than a few nanoseconds between the electroweak precision lower limit of 1.3 and 92 (95) GeV for down-type (up-type) squarks [12,21]. Working from the results of that paper, we use our Eqs. (3)–(7) to derive the minimal necessary R-parity-violating couplings under the assumption of only one nonzero coupling.

We present our results in Figs. 1 and 2. The curves in Fig. 1 show that there must be a baryon-number-violating coupling $\lambda'' \gtrsim 5 \times 10^{-9}\text{–}10^{-7}$ for squark masses less than 90 GeV. If there are no large baryon-number-violating couplings, then the curves in Fig. 2 show that there must be a lepton-number-violating coupling $\lambda' \gtrsim 10^{-8}\text{–}5 \times 10^{-7}$ for squark masses less than 90 GeV. In these figures, we distinguish the minimal couplings obtained in the cases where the lightest squarks ($\tilde{d}_1$ or $\tilde{u}_1$) decouple from the Z boson ($\sin\theta_{\tilde{d}} \approx 0.39$ or $\sin\theta_{\tilde{u}} \approx 0.56$). The decrease with mass of the lower limits in part reflects the fact that partial widths in Eqs. (3)–(7) are proportional to the squark mass.

There are two distinct regions in Figs. 1 and 2. In the region of small squark masses, the assumed production process is $e^+e^- \to q\bar{q}g$, with $g \to \tilde{q}\tilde{q}^*$. Beyond a squark mass of roughly 10 GeV, there are not enough events to provide a competitive limit. In the higher mass region the assumed production process is $\tilde{q}\tilde{q}^*$ pair production, and a lifetime limit of about 1 ns can be set up to 92 GeV. Below a squark mass of 10 GeV the relevant production process is independent of mixing angle. Therefore, the lower bound for a given squark mixing angle is $|1/\sin\theta_{\tilde{q}}|$ or $|1/\cos\theta_{\tilde{q}}|$ larger than the absolute bound. Above 10 GeV the cross section for pair production is measured under the assumption that the squarks are decoupled from the Z boson. If the mixing angle changes, then the squarks couple to the Z boson and the cross section used to estimate the lifetime increases dramatically. The mixing-angle dependence will temper or enhance the large increase in the lower bound in an experiment-dependent manner that we do not attempt to estimate.

In conclusion, if there are squarks with mass less than about 90 GeV, both exotic isotope searches and data from LEP require that they are not stable. Since R-parity-conserving decay modes are explicitly excluded, exotic isotope searches imply that R-parity-violating

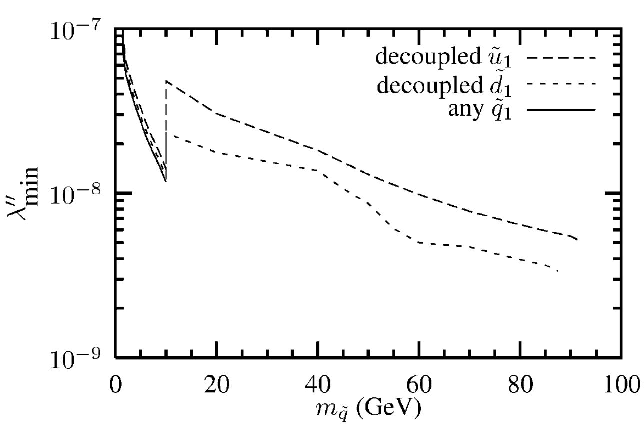

FIG. 1. Lower limits on the baryon-number-violating couplings λ'' as a function of squark $\tilde{q}_1$ mass. The solid line ($m_{\tilde{q}} <$ 10 GeV) indicates an absolute lower limit on the couplings. The dashed lines indicate the limits where $\tilde{d}_1$ or $\tilde{u}_1$ decouple from the Z boson ($\sin\theta_{\tilde{d}} \approx 0.39$ or $\sin\theta_{\tilde{u}} \approx 0.56$). For $m_{\tilde{q}} > 10$ GeV the dashed lines are also absolute lower limits.

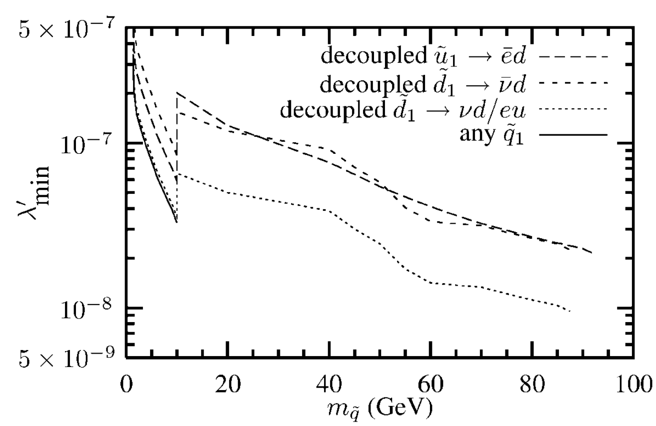

FIG. 2. Lower limits on the lepton-number-violating couplings λ' as a function of squark mass. The solid line ($m_{\tilde{q}} <$ 10 GeV) indicates an absolute lower limit on the couplings. The dashed lines indicate the limits where $\tilde{d}_1$ or $\tilde{u}_1$ decouple from the Z boson ($\sin\theta_{\tilde{d}} \approx 0.39$ or $\sin\theta_{\tilde{u}} \approx 0.56$) and are listed by decay. For $m_{\tilde{q}} > 10$ GeV the dashed lines are also absolute lower limits.

couplings greater than 10^{-22}–10^{-21} must be present if there are squarks of mass 18–100 GeV. The data from LEP improve this lower bound by 14 orders of magnitude and require there to be a baryon-number or lepton-number violating coupling greater than 10^{-8}–10^{-7} for squarks of mass less than 90 GeV. These lower limits can be significantly larger if there is large mixing in the squark sector or nonvanishing coupling to the Z boson.

In the class of supersymmetric models we consider, the LSP can be a neutralino as long as the partial width for the decay of the lightest squark into a neutralino is smaller than the partial width for the R-parity-violating decay of the squark. However, the existence of R-parity-violating couplings means that a neutralino LSP will decay through an off-shell squark to standard-model particles. A minimal R-parity-violating coupling of 10^{-22}, as allowed by exotic isotope searches, is not large enough to significantly reduce the number density of relic neutralinos. However, the data from LEP imply a lifetime of neutralinos that is 10^{28} times shorter, meaning that the neutralinos will have a negligible relic density. Hence, neutralinos cannot explain the excess of dark matter in the Universe in the presence of squarks with mass less than 90 GeV.

When combined with upper limits on R-parity-violating couplings, our study leads to the conclusion that there may be very interesting signals of R-parity-violating supersymmetry at high energy colliders. In particular, squarks may be produced with lifetimes that are long enough to produce displaced vertices when they decay. In addition, R-parity-violation offers the possibility that superpartners may be produced singly, rather than in pairs, a subprocess that has significant advantages especially at collider energies that are not substantially higher than the masses of the produced states [11]. We urge additional attention in current and anticipated experiments to searches for explicit R-parity-violating decay modes.

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[1] P. Fayet, Nucl. Phys. **B90**, 104 (1975); A. Salam and J. Strathdee, Nucl. Phys. **B87**, 85 (1975); G. R. Farrar and P. Fayet, Phys. Lett. B **79**, 442 (1978).

[2] For a review, see G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996); H. Baer and M. Brhlik, Phys. Rev. D **53**, 597 (1996).

[3] R-parity Working Group, B. Allanach *et al.*, in *Proceedings of the Physics at Run II: the Supersymmetry/Higgs Workshop, Fermilab, 1998*, edited by M. Carena and J. Lykken (Fermilab, Batavia, 2002), p. 299; B. C. Allanach, A. Dedes, and H. K. Dreiner, Phys. Rev. D **60**, 075014 (1999); hep-ph/0309196.

[4] E. L. Berger, B.W. Harris, D. E. Kaplan, Z. Sullivan, T. M. P. Tait, and C. E. M. Wagner, Phys. Rev. Lett. **86**, 4231 (2001), and references therein.

[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **71**, 500 (1993); **75**, 1451 (1995); **79**, 572 (1997); D0 Collaboration, B. Abbott *et al.*, Phys. Lett. B **487**, 264 (2000); Phys. Rev. Lett. **85**, 5068 (2000).

[6] A combination of higher-order effects in b-quark production and/or fragmentation may reduce the discrepancy with experiment; cf. M. Cacciari and P. Nason, Phys. Rev. Lett. **89**, 122003 (2002). However, explanations within the context of QCD do not predict an increase of the time-averaged mixing probability $\bar{\chi}$.

[7] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. D **69**, 012002 (2004).

[8] M. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, Phys. Rev. Lett. **86**, 4463 (2001).

[9] E. L. Berger, J. Lee, and T. M. P. Tait, Phys. Rev. D **69**, 055003 (2004).

[10] S. Weinberg, Phys. Rev. D **26**, 287 (1982); N. Sakai and T. Yanagida, Nucl. Phys. **B197**, 533 (1982).

[11] E. L. Berger, B.W. Harris, and Z. Sullivan, Phys. Rev. D **63**, 115001 (2001).

[12] ALEPH Collaboration, A. Heister *et al.*, Eur. Phys. J. C **31**, 327 (2003).

[13] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[14] B. Naroska, Phys. Rep. **148**, 67 (1987); UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B **198**, 261 (1987); CELLO Collaboration, H. J. Behrend *et al.*, Z. Phys. C **35**, 181 (1987); Topaz Collaboration, I. Adachi *et al.*, Phys. Lett. B **218**, 105 (1989); VENUS Collaboration, J. Shirai *et al.*, Phys. Rev. Lett. **72**, 3313 (1994); OPAL Collaboration, R. Akers *et al.*, Phys. Lett. B **337**, 207 (1994); ALEPH Collaboration, A. Heister *et al.*, Phys. Lett. B **537**, 5 (2002).

[15] ALEPH Collaboration, R. Barate *et al.*, Phys. Lett. B **499**, 67 (2001).

[16] OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. B **456**, 95 (1999).

[17] R. N. Mohapatra, F. I. Olness, R. Stroynowski, and V. L. Teplitz, Phys. Rev. D **60**, 115013 (1999).

[18] D. Javorsek, E. Fischbach, and V. Teplitz, Astrophys. J. **568**, 1 (2002).

[19] E.W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Redwood City, 1990), Chap. 5.

[20] Bottom squarks of mass between 3.5 and 4.5 GeV decaying through λ'_{i23} are ruled out by the CLEO Collaboration, V. Savinov *et al.*, Phys. Rev. D **63**, 051101 (2001).

[21] P. Janot, CERN (private communication).