RU-95-26
hep-ph/9508292
July 11, 1995

Phenomenology of Light Gauginos
II. Experimental Signatures

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Abstract: When SUSY breaking produces only dimension-2 terms in the minimal supersymmetric standard model, the parameters of the theory can be rather well constrained. This paper deals with strategies for the detection of the new hadrons predicted in the 1-3 GeV mass range. Some limits are obtained. New signatures for squarks are also given. Squark masses as small as 45 GeV are not yet excluded.

[1]Research supported in part by NSF-PHY-94-23002

In a companion Letter[1][2], I outlined the low-energy features of a particularly economical and attractive form of SUSY-breaking, in which the coefficients of dimension-3 SUSY breaking operators are negligible. The absence of these operators is a consequence of a number of interesting SUSY breaking scenarios and explains the non-observation of new sources of CP violation generally expected with SUSY. Two to four free parameters of the usual minimal supersymmetric standard model "MSSM" (A and the gaugino masses) vanish at tree level. The allowed range of the remaining SUSY parameters can be constrained by requiring correct breaking of the SU(2)$\times$U(1) gauge symmetry and consistency with LEP chargino, neutralino, and Higgs mass limits. As described in (I), a first estimate implies $M_0 \sim 100-300$ GeV, $\mu \lesssim 100$ GeV, and $tan\beta \lesssim 2$. Gauginos are massless at tree level but get calculable masses through radiative corrections from top-stop and electroweak (gaugino/higgsino-Higgs/gauge boson) loops. Evaluating these within the constrained parameter space leads (I) to the predictions: Gluino mass $m_{\tilde{g}}$ is 100-600 MeV; photino mass $m_{\tilde{\gamma}}$ is $\sim 100 - 1000$ MeV; lightest chargino has a mass less than m_W; the lightest Higgs boson may be near its present limit; SUSY-breaking scalar masses can be lighter, and thus electroweak symmetry breaking more natural, than is now possible in the conventional scenario.

The gluino forms bound states with gluons, other gluinos, and quarks and antiquarks in a color octet state. The lightest of these, the spin-1/2 gluon-gluino bound state called R^0 was shown ((I) updating [3]) to have a mass $\sim 1.4 - 2.2$ for gluinos in the 100-300 MeV range. The other lowest lying new hadrons are the pseudoscalar $\tilde{g}\tilde{g}$ bound state (whose mass should be approximately the same as the R^0 mass), and the lightest R-baryon, the flavor-singlet spin-0 $uds\tilde{g}$ bound state called S^0 whose mass is probably in the range $1\frac{1}{2} - 2\frac{1}{2}$ GeV. Higher lying states decay to these via conventional strong or weak interactions. In (I) a method was developed to estimate the

[2]Refered to as (I) below; notation not defined here can be found there. A preliminary discussion of many points developed here and in (I) was given in [2].

lifetime of the R^0, which decays to a photino and hadrons. For most of the parameter space of interest its lifetime is longer than about $\sim 10^{-10}$ sec.

Let us begin with discovery strategies for the R^0. The mass and lifetime estimates given in (I), along with our lack of exact information about squark masses, leave a large enough range of uncertainty that for the present we must consider discovery strategies in two cases: that the R^0 can be discovered via its decay, or it is too long lived for that. While we should consider detection of R-hadrons for all $\tilde{g}$ and $\tilde{\gamma}$ masses in the predicted ranges, and all R^0 lifetimes $\gtrsim 5 \times 10^{-11}$ sec, the most interesting portion of the range is that for which the photinos account for the cold dark matter of the Universe[4]: $1.6 \lesssim r \equiv m(R^0)/m_{\tilde{\gamma}} \lesssim 2.2$. Defining $M_{sq} = \mu_{sq} \cdot 100$ GeV, the discussion in (I) leads to the lifetime range $\sim (10^{-10} - 10^{-7})\ \mu_{sq}^4$ sec for r in the range 1.6 - 2.2 and $1.4 < M(R^0) < 2$ GeV. This is comparable to the the $K_L^0 - K_S^0$ lifetime range if $\mu_{sq} \sim 1$.

In ref. [3] I discussed strategies for detecting or excluding the existance of an R^0 with a lifetime so long that it only rarely decays in the apparatus. Here I discuss several approaches appropriate if the R^0 lifetime is in the $\sim 10^{-6} - 10^{-10}$s range. If R^0's exist, beams for rare K^0 decay and ϵ'/ϵ experiments would contain them, and the detectors designed to observe K^0 decays can be used to study R^0 decays. While R^0 production cross sections can be reliably computed in perturbative QCD when the R^0's are produced with $p_\perp \gtrsim 1$ GeV, high-luminosity neutral kaon beams are produced at low $p_\perp$ so pQCD cannot be used to estimate the R^0 flux in the beam. The most important outstanding phenomenological problem in studying this scenario is to develop reliable methods for estimating the R^0 production cross section in the low $p_\perp$ region; this problem will be left for the future. In the remainder of this paper we will simply paramterize the ratio of R^0 to K_L^0 fluxes in the beam at the production target by $p \cdot 10^{-4}$.

The momentum in the R^0 rest frame of a hadron h, produced in the two body decay $R^0 \to \tilde{\gamma} + h$, is:

$$P_h = \frac{\sqrt{m_R^4 + m_{\tilde{\gamma}}^4 + m_h^4 - 2m_R^2 m_{\tilde{\gamma}}^2 - 2m_{\tilde{\gamma}}^2 m_h^2 - 2m_h^2 m_R^2}}{2m_R}. \quad (1)$$

This falls in the range 350-800 MeV when $h = \pi^0$, for the mass ranges of greatest interest: 1.2 GeV $< m_{R^0} <$ 2 GeV and $1.6 < r \lesssim 2.2$. Therefore, unless the R^0 is in the extreme high end of its mass range and the photino is in the low end of its estimated mass range, final states with more than one hadron will be significantly suppressed by phase space[3].

A particularly interesting decay to consider is $R^0 \to \eta\tilde{\gamma}$.[4] Since $m(\eta) =$ 547 MeV $> m(K^0) =$ 498 MeV, there would be very little background mimicking η's in a precision K^0-decay experiment, so that detecting η's in the decay region of one of these experiments (e.g., via their $\pi^+\pi^-\pi^0$ final state whose branching fraction is 0.23) would be strong circumstantial evidence for an R^0. Since the R^0 is a flavor singlet and the $\tilde{\gamma}$ is a definite superposition of isosinglet and isovector, the relative strength of the $R^0 \to \pi^0\tilde{\gamma}$ and $R^0 \to \eta\tilde{\gamma}$ matrix elements is determined by Clebsches and is $3:1$. Thus the branching fraction of the $\eta\tilde{\gamma}$ decay mode is about 10%, in the most favorable case that multibody decay modes and phase space suppression of the η relative to the π^0 are unimportant. If η's are detected, the Jacobian peak in the η transverse momentum, which occurs at $p_\perp \approx P_\eta$ defined in eq. (1) above, gives both a confirming signature of its origin, and provides information on the allowed regions of R^0 and $\tilde{\gamma}$ masses.

We can estimate the sensitivity of the next generation of neutral kaon experiments to R^0's as follows. The number of decays of a particle with decay length $\lambda \equiv <\gamma\beta c\tau>$, in a fiducial region extending from L to $L+l$, is

$$N = N_0 \left(e^{-\frac{L}{\lambda}} - e^{-\frac{L+l}{\lambda}} \right), \quad (2)$$

[3] For instance the final state $\pi^+\pi^-\pi^+\pi^-\tilde{\gamma}$ suggested by Carlson and Sher, while certainly distinctive, has a very small branching ratio for practically all the masses under consideration.

[4] I thank W. Willis for this suggestion.

where N_0 is the total number of particles leaving the production point. In the $\frac{\epsilon'}{\epsilon}$ experiments which will begin running during 1996 at FNAL and CERN (KTeV and NA48), $L \sim 120$ m, $l \sim 12 - 30$ m, and $\lambda_{K_L^0} \sim 4.5$ km, so $e^{-\frac{L}{\lambda}} - e^{-\frac{(L+l)}{\lambda}} \approx \frac{l}{\lambda} e^{-\frac{L}{\lambda}}$. Denote by $N_{R^{+-0}}$ the number of reconstructed $R^0 \to \pi^+\pi^-\pi^0\tilde{\gamma}$ events, in which the $\pi^+\pi^-\pi^0$ invariant mass is that of an η, and by $N_{K_L^{00}}$ the number of reconstructed $K_L \to \pi^0\pi^0$ events. Then defining $br(R^0 \to \eta\tilde{\gamma}) \times br(\eta \to \pi^+\pi^-\pi^0) \equiv b\ 10^{-2}$, using $br(K_L \to \pi^0\pi^0) = 9\ 10^{-4}$, and idealizing the particles as having a narrow energy spread, eq. (2) leads to:

$$N_{R^{+-0}} \approx N_{K_L^{00}}(\ p\ 10^{-4}) \left(\frac{b\ 10^{-2}}{9\ 10^{-4}}\right) \left(\frac{\epsilon^{+-0}}{\epsilon^{00}}\right) \frac{< \gamma\beta\tau >_{K_L^0}}{< \gamma\beta\tau >_{R^0}} exp[-L/ < \gamma\beta c\tau >_{R^0}], \tag{3}$$

where ϵ^{+-0} and ϵ^{00} are the efficiencies for reconstructing the $\pi^+\pi^-\pi^0$ final state of the η and the $\pi^0\pi^0$ final state of the K_L^0 respectively, $\gamma = \frac{E}{m}$ is the relativistic time dilation factor, and $\beta = \frac{P}{E}$ will be taken to be 1 below. Introducing $x \equiv \frac{<E_{K_L^0}> m_{R^0} \tau_{K_L^0}}{<E_{R^0}> m_{K_L^0} \tau_{R^0}}$, we have

$$x\ exp[-\frac{L}{\lambda_{K_L^0}} x] = \frac{0.9\ 10^3}{pb} \frac{N_{R^{+-0}}}{N_{K_L^{00}}} \frac{\epsilon^{00}}{\epsilon^{+-0}} \equiv x^{lim}_{\eta(L)}. \tag{4}$$

For these experiments $\frac{L}{\lambda_{K_L^0}} \approx 0.08$, so if $\frac{\epsilon^{00}}{\epsilon^{+-0} pb} \sim 10$ and we demand three reconstructed η's so $N_{R^{+-0}} = 3$, a sensitivity $x^{lim}_{\eta(L)} = 5.4\ 10^{-3}$ is reached after collecting $5\ 10^6$ reconstructed $K_L \to \pi^0\pi^0$ events, typical of the next generation of $\frac{\epsilon'}{\epsilon}$ experiments. Such a sensitivity allows the range $0.0054 < x < 103$ to be probed. This translates to an ability to discover R^0's with a lifetime in the range $\sim 2\ 10^{-9} - 4\ 10^{-5}$ sec, using $x = 4 \frac{\tau_{K_L^0}}{\tau_{R^0}}$. For shorter lifetimes, the R^0's decay before reaching the fiducial region, while for longer lifetimes not even one reconstructed R^0 decay is expected during the experiment. The dependence of the lifetime reach on the efficiency and production rates, whose combined effect is contained in $x^{lim}_{\eta(L)}$, is illustrated in Fig. 2a showing the left and right hand sides of eq. (4) for $x^{lim}_{\eta(L)} = 4.8$, of interest below. As one would expect, the reach to longer lifetimes (small x) is extremely sensitive to the event rate while the short lifetime cutoff has a relatively small variation as $x^{lim}_{\eta(L)}$ varies. Note that in a rare K^0_L-decay experiment the flux of K^0_L's is much greater than for the $\frac{\epsilon'}{\epsilon}$ experiments, so a greater sensitivity can be achieved for a comparable acceptance. Unfortunately, the E799 trigger did not accept such events.

Use of an intense K^0_S beam would allow shorter lifetimes to be probed. The FNAL E661 experiment designed to search for the CP violating $K^0_S \to \pi^+\pi^-\pi^0$ decay had a high K^0_S flux and a decay region close to the production target. However its 20 MeV invariant mass resolution may be insufficient to adequately distinguish η's from K^0's. Unfortunately, the K^0_S flux planned for upcoming experiments is inadequate to improve upon the limits which will be obtained from the K^0_L beams. We can repeat the analysis above for the NA48 $\frac{\epsilon'}{\epsilon}$ experiment, taking into account that for their K^0_S beam $\lambda_{K^0_S} \approx L \approx l/2$. In this case x must satisfy

$$\left(e^{-\frac{Lx}{\lambda_{K^0_S}}} - e^{-\frac{(L+l)x}{\lambda_{K^0_S}}}\right) < \left(e^{-\frac{L}{\lambda_{K^0_S}}} - e^{-\frac{(L+l)x-}{\lambda_{K^0_S}}}\right) \frac{br(K^0_S \to \pi^0\pi^0)}{b\ 10^{-2} p\ 10^{-4}} \frac{N_{R+-0}}{N_{K^{00}_L}} \frac{\epsilon^{00}}{\epsilon^{+-0}} \equiv x^{lim}_{\eta(S)}. \tag{5}$$

Taking the same production rate and efficiencies as before and assuming $\sim 10^7$ reconstructed $K^0_S \to \pi^0\pi^0$ decays gives $x^{lim}_{\eta(S)} = 0.3$. The left and right hand sides of this equation is shown in Fig. 2b for this value of $x^{lim}_{\eta(S)}$. The sensitivity range $0.24 < x < 1.1$ is much less than in the K^0_L beams, simply because their K^0_S beam is roughly three orders of magnitude lower in intensity than their K^0_L beam.

The possibility that photinos account for the cold dark matter of the universe leads us to be particularly interested in masses for which $r = \frac{m_R}{m_{\tilde\gamma}} \lesssim 2.2$[1]. Since the phase space volume $\sim P_h^2$, we see from Fig. 1 which shows how P_h depends on r, that in the r region of interest the $R^0 \to \tilde\gamma\eta$ decay may be considerably kinematically suppressed compared to $R^0 \to \tilde{\gamma}\pi^0$. For instance for $r = 1.6$ and $M_{R^0} = 1.7$ GeV, the branching fraction for $R^0 \to \tilde{\gamma}\pi^0$ should be about 97%, while the branching fraction for $R^0 \to \tilde{\gamma}\eta$ is about 3% and drops rapidly for smaller M_{R^0}. Therefore it would be very attractive to be able to identify the π^0 plus missing photino final state in the K^0 beam experiments. This is demanding technically, but justifies the effort. Even though the overall kinematics of individual decays is unknown, both $m_{\tilde{\gamma}}$ and M_{R^0} can be determined if $p_\perp^{max}$ is measured for *both* π and η final states, because eq. (1) gives two conditions fixing the two unknowns, $m(R^0)$ and $m_{\tilde{\gamma}}$, in terms of the observables, P_π and P_η. When the photino mass, the R^0 mass and lifetime, and the cross section for $R^0\ N \to \tilde{\gamma}\ X$ have been measured[5] it will be possible to refine the estimate of the critical value of r. This will permit confirmation or refutation of the proposal[4] that relic photinos are responsible for the bulk of the missing matter of the Universe.

The Fermilab E799 experiment obtained[5] a 90% cl limit $br(K_L^0 \to \pi^0\nu\bar{\nu}) \lesssim 5.8\ 10^{-5}$, which can already be used to limit the R^0 lifetime if the R^0 flux is $\gtrsim 10^{-4}$ of the K_L^0 flux. In that experiment, pions were required to have transverse momentum in the range $160 < P_t < 231$ MeV/c. For a given flux of K_L^0's, the ratio of the number of π^0's in this P_t range coming from $R^0 \to \pi^0\tilde{\gamma}$ compared to those coming from $K_L^0 \to \pi^0\nu\bar{\nu}$ is

$$p\ 10^{-4}\frac{br(R^0 \to \pi^0\tilde{\gamma})}{br(K_L^0 \to \pi^0\nu\bar{\nu})}\frac{\epsilon^0}{\epsilon^{0\nu\bar{\nu}}}\frac{<\gamma\beta\tau>_{K_L^0}}{<\gamma\beta\tau>_{R^0}}exp[-L/<\gamma\beta c\tau>_{R^0}], \tag{6}$$

where ϵ^0 is the fraction of π^0's in $R^0 \to \pi^0\tilde{\gamma}$ having $160 < P_t < 231$ MeV/c times the π^0 detection efficiency, $\epsilon^{0\nu\bar{\nu}}$ is the same thing for π^0's coming from $K_L^0 \to \pi^0\nu\bar{\nu}$, and we neglect depletion of the K_L^0 beam by decays before the fiducial region. Since the π^0 detection efficiency is the same in the two cases, $\frac{\epsilon^0}{\epsilon^{0\nu\bar{\nu}}}$ is just the ratio of probabilities (which we will denote respectively f_K

[5] For cosmology one actually needs $\sigma(R^0\pi \to \tilde{\gamma}\pi)$ but that can be far better estimated when $\sigma(R^0 N \to \tilde{\gamma}N)$ is known.

and f_R) for the π^0 to have $160 < P_t < 231$ GeV in the two cases. Thus in terms of the variable x used previously, this excludes the region for which

$$xExp[-\frac{L}{\lambda_{K_L^0}}x] \geq \frac{5.8\ 10^{-5}\ f_K}{p\ 10^{-4}\ f_R} \equiv x^{lim}_{\pi(L)}. \tag{7}$$

With the spectrum $\frac{d\Gamma}{dE_{\pi^0}}$ used in ref. [5], $f_K = 0.5$. For $R^0 \to \pi^0\tilde{\gamma}$, $f_R = \frac{(231)^2-(160)^2}{P_\pi^2} \sim (0.06 - 0.11)$, when $M_{R^0} = 1.7$ GeV and r is in the range $2.2 - 1.6$. Taking the smallest of these values ($f_R = 0.06$) to be conservative gives $x^{lim}_{\pi(L)} = 4.8/p$ so that for $p = 1$ no limit is obtained, as can be seen from Fig. 2a. If all pions with $P_t > 160$ MeV/c are retained in the analysis, 6 rather than 0 events pass the cuts[6]. With this larger P_t acceptance, f_R increases to 0.94, so the sensitivity improves to $x^{lim}_{\pi(L)} = 1.4/p$. I have used the fact that seeing no events, a 90 % cl limit is calculated as if there are 2.3 events, while with 6 events it is calculated as if there are 10.5 events[6]. Now the range $1.6 < x < 42$ is excluded for $p = 1$. Again assuming $x \sim 4\frac{\tau_{K_L^0}}{\tau_{R^0}}$, this excludes the lifetime range $\sim (5\ 10^{-9} - 10^{-7})$ sec. However, the entire lifetime range is allowed if $p \lesssim 0.3$. Thus it is clear that a good understanding of the expected production cross sections is necessary before one can set limits on the allowed R^0 lifetime. In conclusion, this discussion shows that the decay $R^0 \to \pi^0\tilde{\gamma}$ is feasible to study experimentally. The increase in branching ratio in comparison to the $\eta\tilde{\gamma}$ final state is capable of offsetting the cuts needed to reduce background to the solitary π^0 final state. Even though the existing limit[5] is inadequate to definitively exclude any part of the R^0 lifetime range, on account of the present theoretical uncertainty about the R^0 production parameter p, the space of allowed lifetime vs production cross section has been restricted, which will be useful for planning future experiments.

Before leaving the topic of detecting R^0's decaying in a K_L^0 beam, we estimate the branching fraction for the reaction $br(R^0 \to \pi^+\pi^-\tilde{\gamma})$. While not as dramatic as detecting η's, a $\pi^+\pi^-$ pair with several hundred MeV of

[6] E799, private communication.

transverse momentum and invariant mass greater than m_K would nonetheless be a rather background-free signal. For some experimental setups, this is a more tractable final state to reconstruct than one including a π^0. As noted above, the coupling of R^0 to photino plus isotriplet is three times the coupling to the same particles in an isosinglet state. Thus the 2 pions in $R^0 \to \pi\pi\tilde{\gamma}$ are 90% of the time in an $I=1,\ I_z=0$ state which is necessarily $\pi^+\pi^-$, and 10% of the time in an $I=0$ state which is 2/3 of the time $\pi^+\pi^-$. Therefore 97% of the $\pi\pi\tilde{\gamma}$ final state will be in the favorable $\pi^+\pi^-\tilde{\gamma}$ channel. Since the $\pi^0\tilde{\gamma}$ final state completely dominates the decay rate, we have $br(R^0 \to \pi^+\pi^-\tilde{\gamma}) \sim \Phi_3/\Phi_2/\Lambda^2$, where Φ_n is the phase space for the n-particle final state and Λ is some characteristic mass scale of the problem. For $M_{R^0} = 1.7$ (1.4) GeV and r=2, taking $\Lambda = m_\rho$ gives $br(R^0 \to \pi^+\pi^-\tilde{\gamma}) \sim 6\ 10^{-3}$ ($3\ 10^{-3}$). It seems unlikely that the characteristic mass scale of the problem would be as low as 200 MeV, but if it were, the branching fraction estimate should be increased by a factor of ~ 15. The loss due to requiring $M(\pi^+\pi^-) > M_K$ is not severe: e.g., for $M_{R^0} = 1.7$ GeV and $r=2$, 72% of the events would pass this cut.

Given $br(R^0 \to \pi^+\pi^-\tilde{\gamma})$ we can evaluate the sensitivity of Bernstein et al[7] to R^0's. This experiment placed limits on the production cross section times branching ratio of a neutral hadron decaying into charged particles, with lifetimes in the range $10^{-8} - 2\times 10^{-6}$ sec and masses between 1.5 and 7.5 GeV, by looking for a deviation from a smooth decrease in the transverse momentum distribution. The analysis assumed that the final state particles were all pions[7], so that the Jacobian peak in their transverse momentum falls at approximately half the mass of the decaying particle. When $m_{\tilde{\gamma}} \sim \frac{1}{2}m(R^0)$ however, the peak in the transverse momentum of the pions falls at a much lower value: about 350 MeV for an R^0 mass of 1.5 GeV, where their cross section limit is most stringent. Since the background in that transverse momentum bin is a factor of ~ 100 larger than at 750 MeV, the

[7]G. Thomson, private communication.

sensitivity is reduced by at least a factor of ~ 10. Combining our estimate for $br(R^0 \to \pi^+\pi^-\tilde{\gamma}) \sim 3\ 10^{-3}$ with this reduction in sensitivity and the 1.5 reduction in sensitivity due to having a 3-body final state leads to a limit on the R^0 production cross section in 400 GeV $p + Be$ collisions at $x_f = 0.2$ and $p_\perp = 0$ of $\frac{Ed\sigma}{d^3p} \lesssim 2.510^{-30} cm^2/GeV^2$ or higher, in their most sensitive lifetime region of $\tau = 3\ 10^{-8}$ sec. This is about a factor of 16 lower than the production cross section for $\bar{\Xi}^0$. For comparison, the $\bar{\Xi}^0$ invariant cross section is a factor of 25 smaller than that of the $\bar{\Lambda}^0$ in the same kinematic region, while $m(\bar{\Xi}^0)/m(\bar{\Lambda}^0) \approx 1.5\mathrm{GeV}/m(\bar{\Xi}^0)$. The experiment does not give limits for lower R^0 mass while for larger mass the limits are worse than this. Thus I conclude that the Bernstein et al experiment would not be expected to have seen R^0's.

There is another interesting ground-state R-hadron besides the R^0, namely the flavor singlet scalar baryon $uds\tilde{g}$ denoted S^0. On account of the very strong hyperfine attraction among the quarks in the flavor-singlet channel[8], its mass is about 210 ± 20 MeV lower than that of the lowest R-nucleons. It is even possible that the S^0 might be close in mass to the R^0. If the baryon resonance known as the $\Lambda(1405)$, whose properties have not been easy to understand within conventional QCD, is a "cryptoexotic" flavor singlet bound state of $udsg$ as suggested in [2], one would expect the corresponding state with gluon replaced by a light gluino to be similar in mass. In any case, the mass of the S^0 is surely less than $m(\Lambda) + m(R^0)$, so it does not decay through strong interactions. Its mass is also expected to be less than $m(p) + m(R^0)$, so there must be a photino rather than R^0 in the final state of its decay. Therefore the S^0 has an extremely long lifetime since its decay requires a flavor-changing-neutral weak transition as well as an electromagnetic coupling, and is suppressed by M_{sq}^{-4}. It could even be stable, if $m(S^0) - m(p) - m(e^-) < m_{\tilde{\gamma}}$ and R-parity is a good quantum number. This is not experimentally excluded[9, 3] as long as the S^0 does not bind to nuclei[8]. There is not a first-principles understanding of the intermediate-range nuclear force, so that it is not possible to decide with certainty whether the S^0 will bind to nuclei. However the two-pion-exchange force, which is attractive between nucleons, is repulsive in this case[3] because the mass of the intermediate R_Λ or R_Σ is much larger than that of the S^0. For further discussion of the S^0 and other R-hadrons see refs. [9], [3], and (II).

The S^0 can be produced via a reaction such as $K\ p \rightarrow R^0\ S^0 + X$, or can be produced via decay of a higher mass R-baryon such as an R-proton produced in $p\ p \rightarrow R_p\ R_p + X$. In an intense proton beam at relatively low energy, the latter reaction is likely to be the most efficient mechanism for producing S^0's, as it minimizes the production of "extra" mass. One strategy for finding evidence for the S^0 would be to perform an experiment like that of Gustafson et al[12], in which a neutral particle's velocity is measured by time of flight and its kinetic energy is measured in a calorimeter. This allows its mass to be determined via the relation $KE = m(\frac{1}{\sqrt{1-\beta^2}} - 1)$. On account of limitations in time of flight resolution and kinetic energy measurement, ref. [12] was only able to study masses > 2 GeV, below which the background from neutrons became too large. An interesting aspect of using a primary proton beam at the Brookhaven AGS, where the available cm energy is limited ($p_{beam} \sim$ 20 GeV), is that production of pairs of S^0's probably dominates associated

[8]Even if R-parity is violated so the photino decays (e.g.,$\tilde{\gamma} \rightarrow \nu\gamma$) the S^0 could nevertheless be stable if R-parity is only violated in conjunction with lepton number violation and not baryon number violation[10]. Stable relic S^0's could make up part of the missing mass in our galaxy, but might be too dissipative to make up the bulk of the cold dark matter and still be consistent with the observed spectrum of density perturbations. Since they are neutral and cannot form nuclei (I), they would not form atoms. Thus their energy dissipation would be entirely through the much lower cross section strong interaction leading them to clump less than ordinary matter, but still much more than conventional WIMPS. It is not evident that the relic density of S^0's would give the correct amount of dark matter, for plausible values of the S^0 mass, as the photino does[4]. Since the S^0 is not charged, its scattering from photons in the cosmic microwave background radiation is much smaller than for protons. Therefore S^0's could be responsible for the very high energy cosmic ray events recently observed without being required to originate uncomfortably close to our galaxy as required for protons[11].

production of S^0-R^0 or production of R^0 pairs, due to the efficiency from an energy standpoint of packaging baryon number and R-parity together in an S^0 or R_p whose mass is probably much less than the combined mass of a nucleon and an R^0. This should give an extra constraint which can help discriminate against the neutron background in such a search. Likewise, a low energy S^0 will typically remain an S^0 while scattering in matter, rather than convert to an R^0 via, e.g., $S^0\ N \rightarrow R^0\ \Lambda\ N' + X$, because the mass of the $R^0\ \Lambda$ system is of order 1 GeV larger than that of the S^0. This assures that for sufficiently low energy S^0's, the calorimetric determination of the S^0 kinetic energy is not smeared by conversion to R^0. Although the S^0 has approximately neutron-like interaction with matter, its cross section could easily differ by a factor of two or more, so that the systematic effects on the calorimetry of the unknown S^0 cross section must be studied. Fortunately the behavior of a neutron in a calorimeter can be independently determined by virtue of its similarity to a proton for which there can be no issue of contamination by S^0's in a test beam.

If the R^0 is too long-lived to be found via anomalous decays in kaon beams and the S^0 cannot be discriminated from a neutron, a dedicated experiment studying two-body reactions of the type $R^0 + N \rightarrow K^{+,0} + S^0$ could be done. Depending on the distance from the primary target and the nature of the detector, the backgrounds would be processes such as $K^0_L + N \rightarrow K^{+,0} + n$, etc. If the final state neutral baryon is required to rescatter, and the momentum of the kaon is determined, and time of flight is used to determine β for the incident particle, all with sufficient accuracy, one would have enough constraints to establish that one was dealing with a two-body scattering and to determine the S^0 and R^0 masses. Measuring the final neutral baryon's kinetic energy would give an over-constrained fit which would be helpful.

Light R-hadrons other than the R^0 and S^0 will decay, most via the strong interactions, into one of these. However since the lightest R-nucleons are only about 210 ± 20 MeV heavier than the S^0, they would decay weakly, mainly to $S^0\pi$. Any model which correctly accounts for the regularities of hyperon lifetimes and branching fractions should be able to give a reliable estimate for the R-nucleon lifetimes. We can expect them to be in the range $\sim 2\,10^{-10} - 10^{-11}$ sec, since the Q value of the decay is comparable to those of the hyperons, whose lifetimes are around 10^{-10} sec, while simply scaling down the average $\Sigma^{\pm}$ lifetime by the fifth power of the mass of the decaying particle[9] gives $\tau(R_N) \sim 1.2\times 10^{-11}\mathrm{sec}[(m(R_N)/(1.8 \text{ GeV})]^{-5}$. As can be seen from [3], existing experimental limits do not apply to the lifetime region of interest. Silicon microstrip detectors for charm studies are unlikely to be very useful since they are optimized for the lifetime range $(0.2 - 1.0)\ 10^{-12}$ sec. Unlike ordinary hyperon decay, no more than one final state particle is charged, except for very low branching fraction reactions such as $R_n \rightarrow S^0\ \pi^-\ e^+\ \nu_e$, or $R_n \rightarrow S^0\ \pi^0$ followed by $\pi^0 \rightarrow \gamma\ e^+\ e^-$. In order to distinguish the decay from the much more abundant background such as $\Sigma^+ \rightarrow n\ \pi^+$, which has a very similar energy release, one could rescatter the final neutral in order to get its direction. Then with sufficiently accurate knowledge of the momentum of the initial charged beam and the momentum (and identity) of the final pion, one has enough constraints to determine the masses of the initial and final baryons. The feasibility of such an experiment is worth investigating. One other charged R-baryon could be strong-interaction stable, the R_{Ω^-}. Assuming its mass is 940 MeV ($= m(\Omega^-) - m(N) + 210$ MeV) greater than the S^0 mass, one would expect it to decay weakly to $R_\Xi + \pi$ or $R_\Sigma + K$, with the R_Ξ or R_Σ decaying strongly to $S^0 K$ or $S^0\pi$ respectively. This would produce a more distinctive signature than the R-nucleon decays, but at the expense of the lower production cross section for R_{Ω^-}'s than for R-nucleons.

In addition to the new hadrons expected when there are light gluinos in the theory, there are also many other consequences of light gluinos. None of them are presently capable of settling the question as to whether light

[9]Dimensionally $\tau \sim M_{sq}^4/M^5$, so this would be the correct procedure if the Q-value scaled as well.

gluinos exist, since they all rely on understanding non-perturbative aspects of QCD. Existing models of non-perturbative behavior are *tuned* to agree with data assuming the validity of standard QCD without gluinos. Adding gluinos to the theory is practically certain to cause a deterioration of the fits. Nonetheless it is interesting to recall that jet production at LEP and FNAL should be different with and without light gluinos[13]. Since gluinos in this scenario live long enough that they hadronize before decaying to a photino, they produce jets similar to those produced by the other light, colored quanta: gluons and quarks. In Z^0 decay, only 4- and more- jet events are modified; the magnitude of the expected change is smaller than the uncertainty in the theoretical prediction[13]. Calculation of the 1-loop corrections to the 4-jet amplitudes would allow the theoretical uncertainty to be reduced sufficiently that data might be able to discriminate between QCD with and without gluinos[13]. In $p\bar{p}$ collisions, there is a difference already in 1-jet cross sections. However absolute predictions are more difficult than for Z^0 decay since they rely on structure functions which have so far been determined assuming QCD without gluinos. More promising might be to search for differences in the expected *relative* n-jets cross sections[13].

Now let us move on to means of detecting evidence of new particles other than gluinos. Conventional squark limits do not apply when the gluino is light and long-enough-lived to hadronize, as in this scenario. Squarks will be produced in pairs at colliders such as the Tevatron, and decay immediately, generally to a gluino and a quark. The gluino and quark produce jets, so that squark pairs will lead to events with at least four jets in which TWO pairs of jets reconstruct to an invariant mass peak. To the extent that splitting between mass eigenstates of each flavor of squark can be neglected, both pairs of jets should reconstruct to the same mass. Furthermore, it is reasonable to expect that the squarks associated with the u, d, s, c and b quarks will be approximately degenerate, while the stop will be significantly heavier. If these approximations are better than the experimental resolution, 5/6 of the signal (all but the stop pairs) will contribute at the same value of invariant mass. The cross section for producing squark pairs is the same as in the conventional picture, and roughly speaking is about half that of producing a $t\bar{t}$ pair of the same mass, for each flavor, so there should be a substantial number of events containing squark pairs at FNAL, up to quite high squark mass. A search for events in which *two* pairs of jets reconstruct to the same invariant mass should be made. Hopefully the experimental dijet-invariant-mass resolution is good enough that the QCD background will not overwhelm the signal. For large enough squark mass the best channel to study is associated production of squark and gluino, either at $O(\alpha_s^2)$ via quark-gluon fusion or at $O(\alpha_s^3)$ via gluon fusion. Squark+gluino final states have three jets, two of which reconstruct to a definite invariant mass. Since this signal is less distinctive than that of squark pairs, QCD background is likely to be a greater problem.

Squarks generally decay to gluino and quark, but a squark also decays to a photino and quark with a branching fraction $Q_{sq}^2 \alpha_{em}/(4/3\alpha_s)$. For a charge $+2/3$ squark this occurs about 2% of the time. To find these events, a trigger on missing energy accompanied by three or more jets can be used. Then a peak should appear in the invariant mass of one pair of the jets. Missing energy alone is a much less efficient tool for finding squarks than in the conventional scenario. Furthermore the search reported in ref. [14] required that the leading jet have NO other jet opposite in ϕ which roughly speaking, would reject 2/3 of the real events. Averaging over the u, d, s, c and b quarks, and taking into account the ϕ cut, leads to a factor ~ 200 reduction in the number of events with missing energy compared to the case that both squarks always decay to a photino and quark jet. The missing E_T spectrum is softer as well.

While awaiting a reanalysis of the Tevatron collider data, our best limit on squark masses is obtained by requiring the squarks not add too much to the Z^0 hadronic width. The expected change in the hadronic width of the

Z^0 is 21.3 times the contribution to the width of the Z^0 from a selectron of the same mass, assuming the u, d, s, c and b squarks are degenergate and using width ratios given in [15]. Thus the limit on "extra" hadronic width of the Z^0, $\Gamma_X < 46$ MeV[16], requires the squarks to be heavy enough that $\frac{21.3}{4}\beta^3 < 0.27$. This implies that if there are five degenerate "light" squarks, their mass must be greater than 42 GeV. If only one parity eigenstate of a single flavor of squark is light, this limit is reduced to 27.5 GeV. Note than any excess width would be entirely in 4 jet events, which might allow the limit from LEP to be improved, but clearly only slightly in the case where it is already 42 GeV.

In summary, we have seen that the phenomenology of SUSY breaking without dimension-3 operators is very rich and accessible. Present limits are shockingly weak in comparison to the usual scenario.

Acknowledgements: I am indebted to many people for information and helpful discussions and suggestions including M. Calvetti, J. Conway, T. Devlin, J. Kane, L. Littenberg, I. Mannelli, M. Schwartz, S. Somalwar, G. Thomson, W. Willis, B. Winstein, and M. Witherell.

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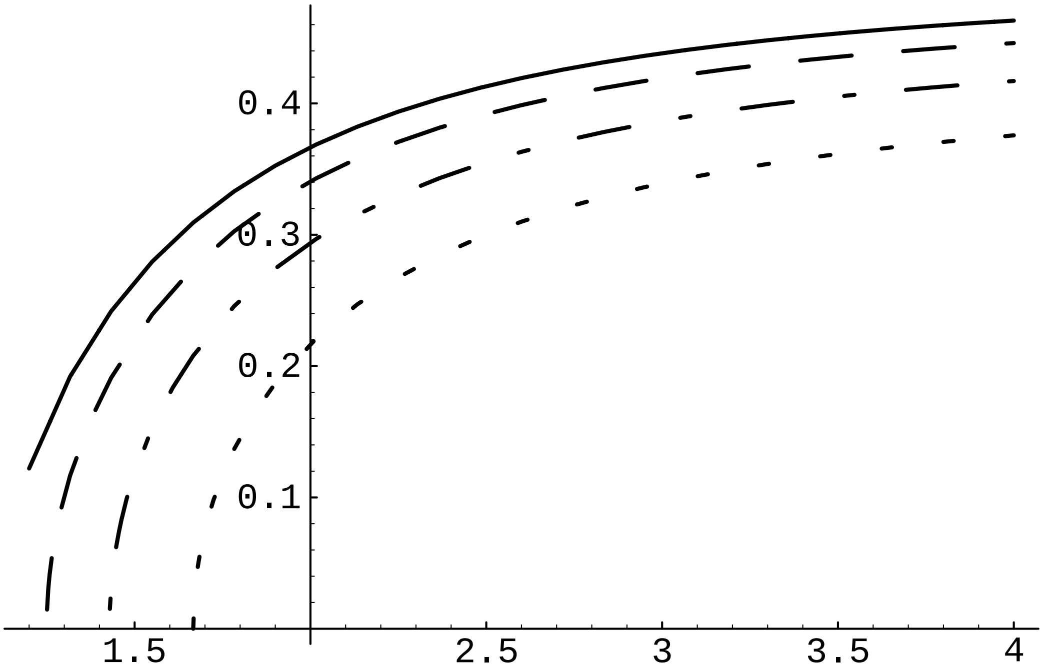

Figure 1: P_h in units of $m(R^0)$ as function of $r \equiv \frac{m(R^0)}{m_{\tilde{\gamma}}}$, for $\frac{m_h}{m(R^0)} = 0.1$ (solid), 0.2 (dashed), 0.3 (dot-dashed), and 0.4 (dotted).

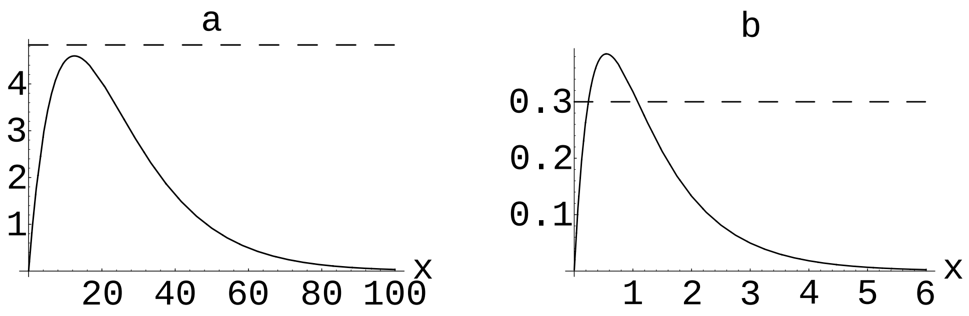

Figure 2: Sensitivity of (a) K_L^0 beam with $x^{lim} = 4.8$ and (b) an NA48-like K_S^0 beam, with $x^{lim} = 0.3$.