RU-96-05
hep-ph/9603271

Detecting Gluino-containing Hadrons

Glennys R. Farrar[1]

Department of Physics and Astronomy
Rutgers University, Piscataway, NJ 08855, USA

Abstract: When SUSY breaking produces only dimension-2 operators, gluino and photino masses are of order 1 GeV or less. The $g\tilde{g}$ bound state has mass 1.3-2.2 GeV and lifetime $\gtrsim 10^{-5} - 10^{-10}$ s. This range of mass and lifetime is largely unconstrained because missing energy and beam dump techniques are ineffective. With only small modifications, upcoming K^0 decay experiments can study most of the interesting range. The lightest gluino-containing baryon ($uds\tilde{g}$) is long-lived or stable; experiments to find it and the $uud\tilde{g}$ are also discussed.

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

I have recently outlined[1] some of the low-energy features of theories in which dimension-3 SUSY breaking operators are highly suppressed. This is the generic situation in several interesting methods of SUSY breaking. Two to four free parameters of the usual minimal supersymmetric standard model (A and the gaugino masses) vanish at tree level. The elimination of these SUSY breaking operators implies that there is no additional CP violation at T=0 beyond what is already present in the standard model[1]. (In contrast, conventional SUSY-breaking generically leads to the embarassing prediction of a neutron electric dipole moment 3-4 orders of magnitude larger than the present experimental upper limit.) The allowed range of the remaining SUSY parameters can be constrained by requiring correct breaking of the SU(2)×U(1) gauge symmetry, consistency with LEP mass limits, and the absence of any new flavor singlet pseudoscalar lighter than the η'[1].

Gauginos are massless at tree level but get calculable masses through radiative corrections from electroweak (gaugino/higgsino-Higgs/gauge boson) and top-stop loops. Evaluating these within the constrained parameter space leads to a gluino mass range $m_{\tilde{g}} \sim \frac{1}{10} - 1$ GeV and photino mass range $m_{\tilde{\gamma}} \sim \frac{1}{10} - 1\frac{1}{2}$ GeV. The lightest chargino has a mass less than m_W. The photino is an attractive dark matter candidate, with a correct abundance for parameters in the predicted ranges[2]. Due to the non-negligible mass of the photino compared to the glueball, prompt photinos are not a useful signature for the light gluinos and the energy they carry[3]. Gluino masses less than about $1\frac{1}{2}$ GeV are largely unconstrained[3]. Experiments to rectify this are proposed here. Consequences for squark and chargino searches are discussed in ref. [**?**].

The gluino forms bound states with gluons and other gluinos, as well as with quarks and antiquarks in a color octet state. The lightest of these states, the spin-1/2 gluon-gluino bound state called R^0, should have a mass $\sim 1.3 - 2.2$ GeV[3, 1]. Since the gluino is light, this state is approximately degenerate with a flavor singlet pseudoscalar comprised mainly of $\tilde{g}\tilde{g}$[3]. Experimental evidence is now quite strong for an "extra" flavor singlet pseudoscalar at ~ 1500 MeV[5], in addition to those which can be accomodated in ordinary QCD[1]. The η' is identified with the pseudogoldstone boson associated with the breaking of the chiral R-symmetry of the nearly massless gluino[3]. The lightest R-baryon is the flavor-singlet spin-0 $uds\tilde{g}$ bound state called S^0, whose mass should lie $0-1$ GeV above that of the R^0. Higher lying R-hadrons decay to the R^0 and S^0 via conventional strong or weak interactions. The rest of this paper is devoted to finding evidence for these R-hadrons.

I shall assume here that photinos are responsible for the cold dark matter of the Universe. This fixes more exactly the mass of the photino and R^0 because in order to obtain the correct density of photinos, the ratio $r \equiv m(R^0)/m_{\tilde{\gamma}}$ must fall between about $\sim 1.6-2$[2], which is in the range predicted on the basis of the gluino and photino mass calcuations[1]. The lifetime of the R^0 is then[1] $\tau_{R^0} \gtrsim (10^{-10}-10^{-7})\left(\frac{M_{sq}}{100\mathrm{GeV}}\right)^4$ sec for $1.4 < M(R^0) < 2$ GeV. This is comparable to the the $K^0_L - K^0_S$ lifetime range if $M_{sq} \sim 100$ GeV, or longer for heavier squarks. In ref. [3] I discussed strategies for detecting or excluding the existance of an R^0 with a lifetime so long it cannot be detected by its decays. Here I discuss several approaches appropriate if the R^0 lifetime is in the $\sim 10^{-5}-10^{-10}$s range.

If R^0's exist, beams for rare K^0 decay and ϵ'/ϵ experiments would contain R^0's. The detectors designed to observe K^0 decays can be used to study R^0 decays. The R^0 production cross section can be estimated in perturbative QCD when the R^0's are produced with $p_\perp \gtrsim 1$ GeV. However high-luminosity beams are produced at low $p_\perp$ so pQCD cannot be used to determine the R^0 flux in the beam. The most important outstanding phenomenological problem in studying light gluinos 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 I simply paramterize the ratio of R^0 to K^0_L fluxes in a given beam at the production point 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 $P_h = \sqrt{m_R^4 + m_{\tilde{\gamma}}^4 + m_h^4 - 2m_R^2 m_{\tilde{\gamma}}^2 - 2m_{\tilde{\gamma}}^2 m_h^2 - 2m_h^2 m_R^2}/(2m_R)$. For the typical case $1.6 < r \lesssim 2$ and $m_{R^0} = 1.7$ GeV, $P_\pi \sim 500 - 600$ MeV. This illustrates that, 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, multi-hadron final states will be significantly suppressed by phase space.

While dominant with respect to phase space, two body decays are suppressed by the approximate C-invariance of SUSY QCD. The R^0 and $\tilde{\gamma}$ have $C = +1$ and $C = -1$ respectively[2], so that the R^0 can decay to a photino plus a single $C = +1$ meson such as a π^0 or η only if charge conjugation is violated. In general C and P are violated, e.g., because the superpartners of left and right chiral quarks are not mass degenerate. The decay matrix element for $R^0 \to \tilde{\gamma} + 0^{-+}$ is proportional to $\frac{m(S_{uL})^2 - m(S_{uR})^2}{m(S_{uL})^2 + m(S_{uR})^2}$ (and similar contributions from the d- and s- squarks, weighted with their charges and projected onto the flavor of the pseudoscalar meson current). Since the squark $L - R$ mass-splittings are a model-dependent aspect of SUSY-breaking, we henceforth take the branching fraction of R^0 into two (three) body final states to be a free parameter, b_2 (b_3). The C-allowed decays such as $R^0 \to \tilde{\gamma}\rho^0$ are treated as three-body decays. Since multibody decays are suppressed by phase space, $b_2 + b_3 \approx 1$; therefore bounding both b_2 and b_3 can rule out R^0's.

The most important three-body decay mode is $R^0 \to \pi^+\pi^-\tilde{\gamma}$. Since the R^0 is a flavor singlet and the $\tilde{\gamma}$ has photon-like couplings, the $\pi^+\pi^- : \pi^0\pi^0$ branching fractions are in the ratio 9:1. Because of phase space suppression, decays involving K's and η's can be neglected compared to the $\pi\pi\tilde{\gamma}$ final state. Thus $R^0 \to \pi^+\pi^-\tilde{\gamma}$ accounts for $\sim 90\%$ of three-body decays. One can require $M(\pi^+\pi^-) > M_K$ to reduce background without a severe loss of

[2]Familiar fermions are not eigenstates of C because they have some non-vanishing conserved quantum number such as charge or lepton number. This is not true of the R^0 and photino. Supersymmetry generators commute with the charge conjugation operator, so the $\tilde{\gamma}$ and R^0 have the same C as their superpartners: the photon and 0^{++} glueball and 0^{-+} "$\eta_{\tilde{g}}$". Because SUSY and C are broken, the mass eigenstates in fact contain a small admixture of states with opposite C.

signal: e.g., for $M_{R^0} = 1.7$ GeV and $r = 2$, 72% of the $R^0 \to \pi^+\pi^-\tilde{\gamma}$ decays would pass this cut. The branching fraction for decays meeting this cut is therefore 0.65 b_3.

The dominant two-body decay channel is $R^0 \to \pi^0\tilde{\gamma}$. Searching for this decay is much like searching for the decay $K_L^0 \to \pi^0\nu\bar{\nu}$. Fortunately, the two final states are readily distinguishable because a typical π^0 from R^0 decay has much larger $p_\perp$ than one from $K_L^0 \to \pi^0\nu\bar{\nu}$, for which $p_\perp^{max} = 231$ MeV. Furthermore, the $p_\perp$ spectrum of the pion in a two body decay exhibits the striking Jacobean peak at $p_\perp = P_\pi$. The existing limit on $br(K_L^0 \to \pi^0\nu\bar{\nu})$ will be used below to obtain some weak constraints on the R^0 lifetime and production cross section. Future experiments with a good acceptance in the large $p_\perp$ region can place a much better limit.

Another interesting two-body decay is $R^0 \to \eta\tilde{\gamma}$. Since $m(\eta) = 547$ MeV $>$ $m(K^0) = 498$ MeV, there would be very little background mimicking η's in a high-resolution, precision K^0-decay experiment. Detecting η's in the decay region of one of these experiments, e.g., via their $\pi^+\pi^-\pi^0$ or $\pi^0\pi^0\pi^0$ final states whose branching fraction are 0.23 and 0.32, would be strong circumstantial evidence for an R^0. The relative strength of the $R^0 \to \pi^0\tilde{\gamma}$ and $R^0 \to \eta\tilde{\gamma}$ matrix elements is determined by squark masses and the $\eta\eta'$ mixing angle. With the prefered mixing angle and equal-mass u and d squarks the branching ratio would be 0.23, if phase space suppression for the η final state could be neglected. However since two body phase space $\sim P_h$, in the r region of interest the $R^0 \to \tilde{\gamma}\eta$ decay is suppressed kinematically compared to $R^0 \to \tilde{\gamma}\pi^0$. For $r = 1.6$ (2.0) and $M_{R^0} = 1.7$ GeV, the branching fraction for $R^0 \to \tilde{\gamma}\eta$ is reduced to about 0.12 b_2 (0.17 b_2) and drops rapidly for smaller M_{R^0}.

Although the rate for $R^0 \to (\eta \to \pi^+\pi^-\pi^0)\ \tilde{\gamma}$ may be only a few percent that of $R^0 \to \pi^0\tilde{\gamma}$, both final states are comparably accessible because experiments to study the single π^0 require a Dalitz conversion to reduce background. With full $p_\perp$ acceptance, $m_{\tilde{\gamma}}$ and M_{R^0} can be determined with only and a handful of events in both channels even though the momenta of the R^0 and $\tilde{\gamma}$ are unknown. The $p_\perp$ spectrum of a two body decay is strongly peaked at $p_\perp^{max} = P_h$. Thus determining P_π and P_η, gives two conditions fixing the two unknowns, $m(R^0)$ and $m_{\tilde{\gamma}}$. Determination of the ratio $m(R^0)/m_{\tilde{\gamma}}$ is important to confirm or refute the proposal[2] that relic photinos are responsible for the bulk of the missing matter of the Universe.

We can estimate the sensitivity 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

$$N = N_0 \left(e^{-\frac{L}{\lambda}} - e^{-\frac{L+l}{\lambda}} \right), \tag{1}$$

where N_0 is the total number of particles leaving the production point. In typical K_L^0 experiments[3], $L \sim 120$ m, $l \sim 12-30$ m, and $L/\lambda_{K_L^0} \sim 0.08$, so $e^{-\frac{L}{\lambda}} - e^{-\frac{(L+l)}{\lambda}} \approx \frac{l}{\lambda} e^{-\frac{L}{\lambda}}$. Denote the number of reconstructed $R^0 \to \tilde{\gamma} X$ events by N_X^R and denote the number of reconstructed $K_L \to Y$ events by N_Y^K. Then defining $br(R^0 \to \tilde{\gamma} X) \equiv b_X^R \; 10^{-2}$ and $br(K_L \to Y) = b_Y^K 10^{-4}$, and idealizing the particles as having a narrow energy spread, eq. (1) leads to:

$$N_X^R \approx N_Y^K(\; p \; 10^{-4}) \left(\frac{b_X^R \; 10^{-2}}{b_Y^X \; 10^{-4}} \right) \left(\frac{\epsilon_X}{\epsilon_Y} \right) \frac{< \gamma\beta\tau >_{K_L^0}}{< \gamma\beta\tau >_{R^0}} exp[-L/ < \gamma\beta c\tau >_{R^0}], \tag{2}$$

where ϵ_X and ϵ_Y are the efficiencies for reconstructing the final state particles X and Y, $\gamma = \frac{E}{m}$ is the relativistic time dilation factor, and $\beta = \frac{P}{E}$ will be taken to be 1 below. Letting $x \equiv \frac{\lambda_K}{\lambda_{R^0}} = \frac{<E_{K_L^0}> m_{R^0} \tau_{K_L^0}}{<E_{R^0}> m_{K_L^0} \tau_{R^0}}$, and introducing the "sensitivity function" $\mathcal{S}(x) \equiv x \; exp[-Lx/\lambda_{K_L^0}]$, eqn (2) implies that an experiment with

$$\mathcal{S}^{lim} \equiv \frac{100 \; b_Y^K}{p \; b_X^R} \frac{N_X^R}{N_Y^K} \frac{\epsilon_Y}{\epsilon_X} \tag{3}$$

[3]E.g., Fermilab's E799 and the $\frac{\epsilon'}{\epsilon}$ experiments KTeV and NA48 which are scheduled to begin running during 1996 at FNAL and CERN.

will restrict x to be such that $\mathcal{S}(x) \leq \mathcal{S}^{lim}$. Thus the sensitivity of various experiments with the same $L/\lambda_{K_L^0}$ can be directly compared by comparing their $\mathcal{S}^{lim}$ values. Fig. 1 shows $\mathcal{S}(x)$ for $L/\lambda_{K_L^0} \sim 0.08$. The qualitative features are as expected: an experiment with a large K_L flux $(\frac{N_Y^K}{b_Y^K \epsilon_Y})$ has a low $\mathcal{S}^{lim}$ and thus is sensitive to a large range of $x \approx 4\frac{\tau_{K_L^0}}{\tau_{R^0}}$. For shorter lifetimes (large x), the R^0's decay before reaching the fiducial region, while for longer lifetimes (small x) the probability of decay in the fiducial volume is too low for enough events to be seen.

Consider first the Fermilab E799 experiment, which obtained[6] a 90% cl limit $br(K_L^0 \to \pi^0 \nu \bar{\nu}) \lesssim 5.8\ 10^{-5}$. In this case the R^0 final state X and the K_L final state Y both consist of a single π^0 and missing energy. Therefore $\frac{\epsilon_Y}{\epsilon_X}$ is just the ratio of probabilities (which we will denote respectively f_K and f_R) for the π^0 to have P_t in the allowed range, $160 < P_t < 231$ GeV, in the two cases. Taking $br(R^0 \to \tilde{\gamma}\pi^0) \approx b_2$ and $br(K_L^0 \to \pi^0 \nu\bar{\nu}) \leq\ 5.8\ 10^{-5}$[6] means $b_Y^R = b_2\ 10^2$ and $b_Y^K < 0.58$, so that we have

$$\mathcal{S}^{lim}_{E799} = \frac{0.58 f_K}{p\ b_2\ f_R}. \tag{4}$$

With the spectrum $\frac{d\Gamma}{dE_{\pi^0}}$ used in ref. [6], $f_K = 0.5$. For $R^0 \to \pi^0\tilde{\gamma}$, $f_R = \frac{\sqrt{1-(160)^2} - \sqrt{1-(231)^2}}{P_\pi} \approx (0.02 - 0.03)$, when $M_{R^0} = 1.4 - 2$ GeV and r is in the range $2.2 - 1.6$. Taking $f_R = 0.025$ gives $\mathcal{S}^{lim}_{E799} = 11.6/(pb_2)$. The peak of the function on the lhs of eq. (4) (see Fig. 1a) occurs for $x = \frac{L}{\lambda_{K_L^0}}$, which is ≈ 12.5. Using $x \approx 4\frac{\tau_{K_L^0}}{\tau_{R^0}}$, the peak sensitivity is for an R^0 lifetime of $2\ 10^{-8}$s, for which the existing experimental bound on $K_L^0 \to \pi^0\nu\bar{\nu}$ yields a limit $pb_2 \leq 2.4$. Whether or not this is a significant restriction on R^0's can only be decided when reliable predictions for (or at least reliable lower limits on) b_2 and the R^0 production cross section are in hand.

The next generation of K_L^0 experiments, KTeV and NA48, expect to collect $\sim N_Y^K = 5\ 10^6$ reconstructed $K_L \to \pi^0\pi^0$ events. What sensitivity does this allow in searching for $R^0 \rightarrow \eta\tilde{\gamma}$, reconstructing the η from its $\pi^+\pi^-\pi^0$ decay? With a ~ 5 MeV resolution in the $\pi^+\pi^-\pi^0$ invariant mass and negligible background between the K^0 and η, three reconstructed η's would be sufficient to be convincing, so let us take $N_X^R = 3$. We know $br(K_L^0 \rightarrow \pi^0\pi^0) = 9\ 10^{-4}$ and $br(\eta \rightarrow \pi^+\pi^-\pi^0) = 0.23$, and take $br(R^0 \rightarrow \eta\tilde{\gamma}) \approx 0.1\ b_2$, so we have $b_Y^K = 9$ and $b_X^R \sim 2.3\ b_2 10^{-2}$. Thus $\mathcal{S}^{lim} = 2\ 10^{-2}\frac{\epsilon_Y}{pb_2\epsilon_X}$ where ϵ_Y is the efficiency of reconstructing the $\pi^0\pi^0$ final state of a K_L^0 decay and ϵ_X is the efficiency for reconstructing the $\pi^+\pi^-\pi^0$ final state of an η. ϵ_X needs to be determined by Monte Carlo simulation. If $pb_2 \sim 1$ and ϵ_X is good enough that, say, $\mathcal{S}^{lim} = 3\ 10^{-2}/(pb_2)$, such a sensitivity allows the range $0.03 < x < 102$ to be probed. This corresponds to an ability to discover R^0's with a lifetime in the range $\sim 2\ 10^{-9} - 0.7\ 10^{-5}$ sec. Note that in a rare K_L^0-decay experiment the flux of K_L^0's is much greater than for the $\frac{\epsilon'}{\epsilon}$ experiments, so other things being equal a greater sensitivity can be achieved for a comparable acceptance. Unfortunately, E799 rejected the $\eta\tilde{\gamma}$ final state.

Use of an intense K_S^0 beam would allow shorter lifetimes to be probed. The FNAL E621 experiment designed to search for the CP violating $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ decay had a high K_S^0 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. To estimate the sensitivity of, e.g., the NA48 detector we must return to eq. (1), since for the planned K_S^0 beam $\lambda_{K_S^0} \approx L \approx l/2$. In this case $x_S \equiv \frac{<E_{K_S^0}> m_{R^0}\tau_{K_S^0}}{<E_{R^0}> m_{K_S^0}\tau_{R^0}} \approx \frac{4\ \tau_{K_S^0}}{\tau_{R^0}}$, must satisfy

$$\begin{aligned}
\mathcal{S}^S(x) &= \left(e^{-\frac{Lx_S}{\lambda_{K_S^0}}} - e^{-\frac{(L+l)x_S}{\lambda_{K_S^0}}}\right) < \\
\mathcal{S}^S_{lim} &\equiv \left(e^{-\frac{L}{\lambda_{K_S^0}}} - e^{-\frac{(L+l)}{\lambda_{K_S^0}}}\right) \frac{br(K_S^0 \rightarrow \pi^0\pi^0)}{b_X^R\ 10^{-2}\ p\ 10^{-4}} \frac{N_{R^{+-0}}}{N_{K_S^{00}}} \frac{\epsilon^{00}}{\epsilon^{+-0}}. \qquad (5)
\end{aligned}$$

Taking the same production rate and efficiencies as before, and assuming $\sim 10^7$ reconstructed $K_S^0 \rightarrow \pi^0\pi^0$ decays, gives $\mathcal{S}_S^{lim} = 0.26$. $\mathcal{S}_S(x)$ is shown in Fig. 1b. The sensitivity range is $0.19 < x_S < 1.3$ for $pb_2 = 1$; this corresponds to the lifetime range $3\ 10^{-10} - 2\ 10^{-9}$s.

Thus for $pb_2 \approx 1$ the next generation of ϵ'/ϵ experiments will be able to see R^0's in the lifetime range $3\ 10^{-10} - 0.7\ 10^{-5}$ sec. The greatest sensitivity is for $\tau_{R^0} = 2\ 10^{-8}$ sec; for this lifetime, values of pb_2 as small as $\sim 6\ 10^{-3}$ should be accessible. For a given p, even better sensitivity is possible, using the final state $\pi^+\pi^-\tilde{\gamma}$ with $m(\pi^+\pi^-) > m_K$, if $b_3 \geq b_2/8$. If we assume the background to this mode is low enough that observing ~ 10 events with $m(\pi^+\pi^-) > m_K$ is sufficient for detection, the factor $\frac{N_X^R}{b_X^R \epsilon_X}$ appearing in eq. (3) is reduced by the factor $\frac{10/3}{(0.65b_3)/(0.023b_2)}$. Thus $\mathcal{S}^{lim}$ is reduced by the factor $0.12b_2/b_3$ compared to the $R^0 \rightarrow \eta\tilde{\gamma}$ search. Hence, unless $p << 1$, the planned ϵ'/ϵ experiments will be sensitive to nearly the entire lifetime range of interest below $\sim 10^{-5}$ sec independently of the relative importance of 2- and 3-body decays of the R^0.

Turning now to other R-hadrons, the ground-state R-baryon is the flavor singlet scalar $uds\tilde{g}$ bound state denoted S^0. On account of the very strong hyperfine attraction among the quarks in the flavor-singlet channel[7], its mass is about 210 ± 20 MeV lower than that of the lowest R-nucleons. The mass of the S^0 is almost surely less than $m(\Lambda) + m(R^0)$, so it cannot decay through strong interactions. As long as $m(S^0)$ is less than $m(p) + m(R^0)$, the S^0 must decay to a photino rather than R^0 and would have an extremely long lifetime since its decay requires a flavor-changing-neutral-weak transition. The S^0 could even be stable, if $m(S^0) - m(p) - m(e^-) < m_{\tilde{\gamma}}$ and R-parity is a good quantum number[4]. This is not experimentally excluded[8, 3] because the S^0 probably does not bind to nuclei. The two-pion-exchange force, which is attractive between nucleons, is repulsive between S^0 and nucleons because

[4]If the baryon resonance known as the $\Lambda(1405)$ is a "cryptoexotic" flavor singlet bound state of $udsg$, one would expect the corresponding state with gluon replaced by a light gluino to be similar in mass. In this case the S^0 mass would be $\sim 1\frac{1}{2}$ GeV and the S^0 would be stable as long as the photino is heavier than ~ 600 MeV, as it would be expected to be if photinos account for the relic dark matter.

the mass of the intermediate R_Λ or R_Σ is much larger than that of the S^0.

If the S^0 is stable, it provides a possible explanation for the several very high energy cosmic ray events which have been recently observed[9]. Greisen-Zatsepin-Kuzmin (GZK) pointed out[10] that the cross section for proton scattering from the cosmic microwave background radiation is very large for energies above $\sim 10^{20}$ eV, because at such energies the $\Delta(1230)$ resonance is excited. If cosmic ray protons are observed with larger energies than the GZK bound they must have originated within about 30 Mpc of our galaxy. Since there are no good candidates for ultra-high energy cosmic ray sources that close, the observed events with $E \sim 3\ 10^{20}$ eV[9] have produced a puzzle for astrophysics. However the threshold for producing a resonance of mass M^* in $\gamma(3^o\mathrm{K}) + S^0$ collisions is a factor $\frac{m_{S^0}}{m_p}\frac{(M^*-M_{S^0})}{(1230-940)\mathrm{MeV}}$ larger than the threshold in $\gamma(3^o\mathrm{K}) + p$ collisions. Taking $m(R^0) = 1.7$ GeV, $m_{\tilde\gamma}$ must lie in the range $0.8 \sim 1.1$ GeV to account for the relic dark matter. If $m_{S^0} \approx m_p + m_{\tilde\gamma}$ we have $m(S^0) \sim 1.8 - 2.1$ GeV. Since the photon couples as a flavor octet, the resonances excited in $S^0\gamma$ collisions are flavor octets. Since the S^0 has spin-0, only a spin-1 R_Λ or R_Σ can be produced without an angular momentum barrier. There are two R-baryon flavor octets with $J = 1$, one with total quark spin 3/2 and the other with total quark spin 1/2, like the S^0. Neglecting the mixing between these states which is small, their masses are about 385-460 and 815-890 MeV heavier than the S^0, respectively[7]. Thus the GZK bound is increased by a factor of 2.4 - 6.5, depending on which R-hyperons are strongly coupled to the γS^0 system. Therefore, if S^0's are stable they naturally increase the GZK bound enough to be compatible with the extremely high energy cosmic rays reported in [9] and references therein.

The S^0 can be produced via a reaction such as $K\ p \to R^0\ S^0 + X$, or can be produced via decay of a higher mass R-baryon such as an R-proton produced in $p\ p \to R_p\ R_p + X$. 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[11], 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. [11] 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 pair production of S^0's probably dominates associated production of S^0-R^0 and 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. The expectation that S^0's are produced in pairs gives an extra constraint which can help discriminate against the neutron background in such a search. It is also helpful that, for low energy S^0's, the calorimetric determination of the S^0 kinetic energy is not smeared by conversion to R^0 because of the t_{min} required for a reaction like $S^0\ N \rightarrow R^0 + \Lambda + N' + X$. Although the S^0 has approximately neutron-like interaction with matter, its cross section could easily differ from that of a neutron by a factor of two or more, so that systematic effects on the calorimetry of the unknown S^0 cross section should be considered.

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 $S^0\pi$. The R-nucleon lifetimes should be of order $2\ 10^{-11} - 2\ 10^{-10}$ sec, by scaling the rates for the analog weak decays $\Sigma^- \rightarrow n\ \pi^-$, $\Lambda^- \rightarrow p\ \pi^-$ and $\Xi^- \rightarrow \Lambda\ \pi^-$ by phase space. Existing experimental limits[3] do not apply to the lifetime region and kinematics of interest. Silicon microstrip detectors developed for charm studies are optimized for the lifetime range $(0.2 - 1.0)\ 10^{-12}$ sec. Moreover unlike ordinary hyperon decay, there is at most one charged particle in the final state, 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 $R_p \rightarrow S^0\pi^+$ from the much more abundant background such as $\Sigma^+ \rightarrow n\ \pi^+$, which has a 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. Even without the ability to reconstruct the events, with sufficiently good momentum resolution for the initial and final charged particles, one could search for events which are not consistent with the kinematics of known processes such as $\Sigma^+ \rightarrow \pi^+ n$, and then see if they are consistent with the two body decay expected here. 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, it decays weakly to $R_\Xi + \pi$ or $R_\Sigma + K$, with the R_Ξ or R_Σ decaying strongly to S^0K 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.

In addition to the new hadrons expected when there are light gluinos in the theory, there are many other consequences of light gluinos. 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 and the magnitude of the expected change is smaller than the uncertainty in the theoretical prediction[12]. Calculation of the 1-loop corrections to the 4-jet amplitudes is needed. In $p\bar{p}$ collisions, there is a difference between QCD with and without gluinos 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. Less model dependent might be to search for differences in the expected *relative* n-jets cross sections[12]. Other indirect consequences of light gluinos are not presently capable of settling the question as to whether light gluinos exist, since they all rely on detailed understanding of non-perturbative aspects of QCD. Length restrictions prevent reviewing them here.

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

References

[1] G. R. Farrar. Technical Reports RU-95-17 (hep-ph/9504295), RU-95-25 (hep-ph/9508291), RU-95-26 (hep-ph/9508292), RU-95-73 (SUSY95, Paris, May 1995), Rutgers Univ., 1995.

[2] G. R. Farrar and E. W. Kolb. Technical Report RU-95-18 and astro-ph/9504081, Rutgers Univ., 1995; Phys. Rev. D, to be published.

[3] G. R. Farrar. *Phys. Rev.*, D51:3904, 1994.

[4] G. R. Farrar. Technical Report RU-96-06 (hep-ph/9602324) , Rutgers Univ., 1996.

[5] Z.Bai et al, *Phys. Rev. Lett.*, 65:2507, 1990; J. E. Augustin et al, Technical Report 90-53, LAL, 1990; Crystal Barrel Collaboration, Technical Report submitted to Phys. Lett. B, CERN, 1995.

[6] M. Weaver et al. *Phys. Rev. Lett.*, 72:3758, 1994.

[7] F. Bucella, G. R. Farrar, and A. Pugliese. *Phys. Lett.*, B153:311–314, 1985.

[8] G. R. Farrar. *Phys. Rev. Lett.*, 53:1029–1033, 1984.

[9] N. Hayashida, *Phys. Rev. Lett.*, 73:3491, 1994; D. J. Bird et al, *Ap. J.*, 441:144, 1995.

[10] K. Greisen, *Phys. Rev. Lett.*, 16:748, 1966; G. T. Zatsepin and V. A. Kuzmin, *Sov. Phys.-JETP Lett.*, 4:78, 1966.

[11] H. R. Gustafson et al. *Phys. Rev. Lett.*, 37:474, 1976.

[12] G. R. Farrar. *Phys. Lett.*, 265B:395, 1991.

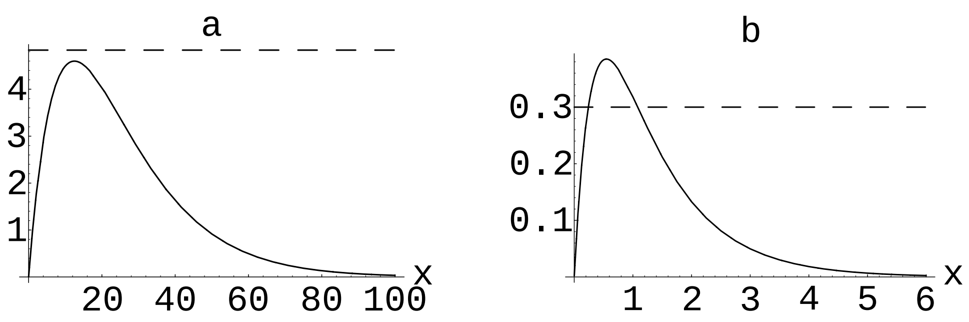

Figure 1: Sensitivity function of (a) a typical K_L^0 beam and (b) an NA48-like K_S^0 beam, with $\mathcal{S}^{lim} = 0.26$ indicated.