Light Gluinos\textsuperscript{1}

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Abstract: Gluino and lightest neutralino masses are naturally less than a few GeV if dimension-3 susy-breaking operators are absent from the low energy theory. In this case gaugino masses come from loops and are calculable in terms of known particle masses and two mass parameters, $\mu$ and $\tilde{m}$. The phenomenology of such a scenario is discussed.

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Up to now, theoretical attention has mostly been focused on models in which susy-breaking gives comparable masses to the squarks and gauginos. However in some attractive types of models it happens instead that gauginos are massless at tree-level and thus only get masses on account of their interaction with other particles which are massive. For instance if supersymmetry is broken in a hidden sector and there are no gauge-singlets, dimension-3 operators are suppressed by a factor \( \frac{\tilde{m}}{M_{pl}} \) and thus are negligible.\(^3\) This scenario is particularly appealing from the standpoint of phenomenology since it produces a low-energy theory which has far fewer parameters than the usual MSSM and furthermore is subject to verification or falsification in the next few years. In this talk I will summarize the results of work done in collaboration with Antonio Masiero\(^2\) to compute the masses of the gluino and lightest neutralino and chargino. With this as motivation, I then survey the results obtained in ref. \(^3\) concerning the hadron physics and experimental situation of this scenario. An experimental approach for settling the question is discussed in ref. \(^3\). A few new points are made here but mostly it is a review of refs. \(^2, 3\), which should be consulted for most details.

In the absence of a tree-level susy- and R-symmetry breaking mass term, the gluino gets its mass from top-stop loops and, if all dimension-3 susy-breaking operators are absent, it is completely determined just in terms of the stop and top masses and \( \alpha_{QCD} \). The chargino and neutralino sectors in addition get contributions from loops containing a higgsino or ew gaugino and a Higgs or ew gauge boson. Thus they depend in addition on the characteristic masses of the Higgses and the parameter \( \mu \) which governs the (supersymmetry-respecting) coupling between the two Higgs doublets. Given \( m_t, \mu, \) and \( \tilde{m} \), one could determine the Higgs masses for any particular scheme of ew symmetry breaking. For instance in the particularly attractive scenario in which the Higgs potential develops a negative mass-squared term

\(^3\)See \(^1\) for a discussion of this point.
on account of radiative corrections\textsuperscript{4}\textsuperscript{, 5}, there is only one free parameter in addition to $m_t$, $\mu$, and $\tilde{m}$, namely $B$. However in any case the mass scale of the heavy Higgses should be of the same order as $\tilde{m}$. Thus identifying these scales, one can estimate the gluino, chargino and neutralino masses in terms of the two unknowns $\mu$ and $\tilde{m}$.

To summarize ref. \textsuperscript{[2]}:

1. There are two distinct allowed regions for $\mu$ and $\tilde{m}$ – namely $\mu \lesssim 100$, or $\mu \gtrsim$ several TeV with $\tilde{m} \gtrsim 8$ TeV – which are consistent with the lightest chargino and squark being more massive than the LEP lower bound of $45 \text{ GeV}$\textsuperscript{[4]}\textsuperscript{.} If a chargino is not discovered at LEPII with mass less than $m_W$, the low $\mu$ region will be ruled out.

2. For the low $\mu$ region, the mass of the gluino is $\lesssim 300 \text{ MeV}$. If for some reason the tree-level gaugino masses vanish but not the dimension-3 susy-breaking squark-squark-Higgs coupling, $A$, then the gluino mass can be higher. E.g., if $A = 1$ the gluino mass is of order 1-2 GeV.

3. In the large $\mu$ region the gluino mass vanishes if $A = 0$. However if $A = 1$ and $\tilde{m} = 10$ TeV, $m_{\tilde{g}} \sim 40 \text{ GeV}$, for example.

4. In the low $\mu$ region the lightest neutralino has a mass ranging up to 400-700 MeV if $A = 0$ and up to 700-1000 MeV for $A = 1$. In the low $\mu$ region the lightest neutralino is very nearly a photino.

5. In the large $\mu$ region the lightest neutralino has a mass of at least 10 GeV, independent of $A$, and it is almost a pure bino.

6. Generically, the lightest neutralino is heavier than the gluino if all dimension-3 soft-susy-breaking operators are absent from the low energy theory, i.e., if $A = 0$.

\textsuperscript{4}It is not appropriate to use the CDF bound\textsuperscript{[6]} without further analysis because that relies on model-dependent assumptions about the gluino.
Turning now to the hadron phenomenology of the above situation, I am summarizing results of ref. [3]. If gluinos have properties such that they decay to a photino before hadronization degrades their energy, they can be ruled out for a very large range of masses: up to 126 GeV in a simple SUSY scenario[6]. This largely rules out gluinos having a lifetime less than $\sim 2 \times 10^{-11} \left( \frac{m_{\tilde{g}}}{1 \text{GeV}} \right)$ sec. However in the scenario at hand the lifetime of the gluino is typically longer than this because of phase space suppression.

An inevitable consequence of the existence of a long-lived gluino is the existence of neutral hadrons containing them. Generically, hadrons containing a single gluino are called $R$-hadrons[7]. The lightest of these would be the neutral, flavor singlet $g\bar{g}$ "glueballino", called $R^0$. There would also be $R$-mesons, $\bar{q}q\tilde{g}$, and $R$-baryons, $qqq\tilde{g}$, with the $\bar{q}q$ or $qqq$ in a color octet. Unlike ordinary baryons which are unable on account of fermi statistics to be in a flavor singlet state, there is a neutral flavor-singlet $R$-baryon, $uds\tilde{g}$, called $S^0$ below. It should be particularly strongly bound by QCD hyperfine interactions, and probably is the lightest of the $R$-baryons[8, 9], even lighter than the $R$-nucleons.

By considering the multiplet structure of supersymmetric pure glue QCD, and using the lattice gauge theory estimate of the mass of the $0^{++}$ glueball in quenched approximation, the mass of the $R^0$ is estimated in ref. [3] to be $1440 \pm 375$ MeV when the gluino is massless. However if the gluino were massless, the spectrum would be expected to contain an unacceptably light[10, 11] flavor-singlet goldstone boson associated with the spontaneous breaking of the non-anomalous linear combination of quark and gluino chiral $U(1)$ symmetries. For three light flavors of quarks the non-anomalous axial current is:

$$ J_5^\mu = \frac{1}{\sqrt{26}} \left\{ q_{i,j}^L \gamma_\mu q_{i,j}^L - q_{i,j}^i \gamma_\mu q_{i,j}^j - \tilde{\lambda}_a \gamma_\mu \lambda_a \right\}. $$

Thus the minimum mass of the gluino can be found by requiring it to be heavy enough to make a sufficient contribution to the mass of the $\eta'$. Using
standard current algebra arguments\[3\] this requires

\[m_{\tilde{g}} < \bar{\lambda} \lambda > \sim 11 m_s < \bar{s} s > .\] (2)

Since the QCD attractive force between color octets is greater than that between triplet and antitriplet, \(< \bar{\lambda} \lambda >\) is presumably larger than \(< \bar{s} s >\).

Most-attractive-channel arguments\[12\] suggest that the condensates depend exponentially on the Casimirs of the condensing fermions so that since \(C_8/C_3 = 9/4\), \(< \bar{\lambda} \lambda >\) could be an order of magnitude or more larger than \(< \bar{s} s >\).

Thus pending lattice calculations of \(< \bar{\lambda} \lambda >\) or \(m(\eta')\) as a function of gluino mass and without gluinos, the phenomenological analysis should be general enough to include a gluino as light as \(\sim 100\) MeV or less. In this case the \(R\)-hadron properties are about the same as they would be for a massless gluino.

The flavor singlet pseudoscalar orthogonal to the \(\eta'\) which gets its mass from the anomaly would be identified with a more massive state. Neglecting its quark component it is the SUSY partner of the \(R^0\) so its mass should be comparable to that of the \(R^0\), i.e., \(1440\) MeV for a massless gluino. Let us call this particle the \(\tilde{\eta}\). There is evidence for an “extra” flavor singlet pseudoscalar present in the meson spectrum in the 1410-1490 region\[13, 14, 15\], which has a large coupling to gluons\[16\]. It is an excellent candidate for this state if it is confirmed.

The scenario in which the \(\eta'\) is a pseudogoldstone boson and a heavier particle, the \(\tilde{\eta}\), is the particle which gets its mass from the anomaly, is attractive from the large \(N_c\) point of view. While no-one would insist that \(N_C = 3\) is large enough that all leading large-\(N_c\) predictions should be valid, it has nonetheless been astonishing to what extent the large \(N_c\) limit seems to be “precociously” attained in hadron properties, apart from the \(\eta'\) mass.

As shown by Witten\[17\], in a theory in which the anomaly only gets contributions from fermions in the fundamental representation of the color group, the mass of the pseudoscalar which is \emph{not} a pseudogoldstone boson and gets
its mass via the anomaly must vanish as $N_c \to \infty$, while the pseudogoldstone bosons have finite masses in this limit. When specialized to $N_c = 3$, it leads for instance to Georgi’s inequality\cite{18} $\frac{m_\eta}{m_{\eta'}} < 0.540$, in disagreement with the experimental value 0.572. However in the present scenario the large $N_c$ mass hierarchy is not violated by the pseudoscalars because neither the $\eta'$ which is a pseudogoldstone boson, nor the $\tilde{\eta}$ which gets its mass from the anomaly, are predicted to have vanishing masses in the $N_c \to \infty$ limit, since gluino loops have the same large $N_c$ behavior as gluon loops.

If the $\eta'$ were indeed the pseudogoldstone boson related to the current in eqn\ (4), its quark content would be reduced by a factor of $\frac{18}{26} \approx 0.7$ in comparison to the usual picture. Interestingly, this seems not to be ruled out by existing constraints. Sound predictions for the $\eta'$, avoiding model dependent assumptions such as the relation between $F_1$ and $F_8$, are for ratios of branching fractions to final states which couple to the quark component\cite{19}. These ratios are insensitive to the presence of a gluino or gluonic component. Absolute predictions are highly sensitive to theoretically incalculable hadronic effects, due to the very restricted phase space for the $\eta'$ to decay through strong interactions. This means that rates which could potentially determine whether the $\eta'$ has a 30% gluino component, in practice cannot be predicted reliably enough to be useful.\footnote{A possible way to discriminate is to study the production of the various pseudoscalars in $J/\Psi$ decay.} However it would be a worthwhile project to reanalyze the experimental and theoretical constraints on the $\eta,\eta',\tilde{\eta}$ system to see if it can be described as well in the light-gluino interpretation as in the usual one.\footnote{Actually, the $\tilde{\eta}$ is completely mysterious in the usual picture, so the real question is whether in the light-gluino picture there is any problem with finding a consistent choice of mixing angles, as was done in ref.\cite{20} for the conventional description.}

Let us turn now to experimental constraints on this scenario. A gluino in the mass range $\sim 1.5 - 3.5$ GeV is excluded, whatever its lifetime, from the absence of a peak in the photon energy spectrum in radiative Upsilon

\[ \text{radiative Upsilon} \]
decay. This is because two gluinos with mass in that range would form a pseudoscalar bound state, the $\eta_\tilde{g}$, whose branching fraction in $\Upsilon \rightarrow \gamma \eta_\tilde{g}$ can be reliably computed using perturbative QCD and is predicted\cite{21, 22, 23} to be greater than the experimental upper bound\cite{24, 25}.

From the CUSB experiment, we infer that the $\eta_\tilde{g}$ does not lie in the 3-7 GeV range, so that the gluino would not be in the $\sim 1.5 - 3.5$ GeV range. In order to compare to limits from other experiments searching for $R^0$'s, we shall convert this limit to an effective gluino mass using the relation

$$m(R^0) = 0.72(1 + e^{-m_\tilde{g}^2}) + m_\tilde{g}(1 - e^{-m_\tilde{g}}),$$

with all masses in GeV. This is actually just a convention for making the figure, but is physically reasonable in that it yields the $m_\tilde{g} = 0$ result of the previous section and in analogy with mesons made of one light and one heavy quark associates an additive confinement energy of about half the mass of a light-quark-meson (here, of the $0^{++}$ glueball whose mass is $\sim 1.44$ GeV) to the light constituent (here, the gluon) of a light-heavy composite.

Other experimental constraints are reviewed in ref.\cite{3}. To summarize that discussion: Gluinos in the mass range $\sim 1.5 - 3.5$ GeV are absolutely excluded (CUSB). Lighter gluinos are allowed, as long as the $R^0$ lifetime is not in the range $2 \times 10^{-6} - 10^{-8}$ sec if the $R^0$ mass is greater than 1.5 GeV (Bernstein et al), or the range $> 10^{-7}$ sec if its mass is greater than 2 GeV (Gustafson et al). Gluinos with mass around 4 GeV or above, must

\footnote{The range excluded by the CUSB experiment is incorrectly claimed to extend to lower gluino masses, by using the pQCD results of refs.\cite{21, 22, 23} out of their range of validity. A detailed analysis of the actual excluded range in given in ref.\cite{16}. The lower limit for validity of a pQCD, non-relativistic potential model description of an $\eta_\tilde{g}$ was taken to be $\sim 3$ GeV, mainly by analogy with the success of the same description of charmonium. However since the effective value of the coupling is so much stronger due to the larger color charge of the gluino in comparison to a quark, even a 3 GeV $\eta_\tilde{g}$ may not be in the perturbative regime, in which case the range of validity of the CUSB procedure may not be even this large. Note that any gluino whose lifetime is longer than the strong interaction disintegration time of the $\eta_\tilde{g}$, i.e., $\tau \gtrsim 10^{-22}$ sec, will produce the requisite bump in the photon energy spectrum, and thus be excluded by CUSB.}

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have a lifetime longer than about $\sim 2 \times 10^{-11} \left( \frac{m_\tilde{g}}{m_{1\text{GeV}}} \right)$ sec (UA1,CDF), with the ranges $> 10^{-7}$ sec (Gustafson), $2 \times 10^{-6} - 10^{-8}$ sec (Bernstein et al) and $\sim 10^{-10}$ sec (ARGUS) ruled out for masses in the vicinity of 4-5 GeV. The figure is an attempt to summarize these results, combining experiments which report results directly in terms of $m(R^0)$ with those characterized by limits on $m_\tilde{g}$ by use of eqn. (3). Given the primitive nature of eqn. (3) and the $\pm 375$ MeV uncertainty on the $R^0$ mass when the gluino is massless, as well as the very rough methods used to extract the ranges of mass and lifetime sensitivity for the various experiments, a $\sim 20\%$ uncertainty should be attached to all the boundaries shown in this figure.

Some discussion of $R^0$ lifetimes which can be expected for given gluino and lightest neutralino masses can found in ref. [3]. The general conclusion is that existing experimental constraints are insufficient to exclude the particularly interesting range $1.1 < m(R^0) < 2.2$ GeV. Unfortunately, much more theoretical work is needed to obtain a reliable estimate of the lifetime of the $R^0$ when the gluino mass is $< 300$ MeV but the lightest neutralino mass is $\sim 1$ GeV (possibly the most interesting range). Experiments which can find or exclude such a possibility must be sensitive to long-lived $R^0$'s, and therefore should look for its reinteraction rather than its decay in order to be insensitive to its lifetime. Some experimental possibilities are discussed in ref. [3]. Experiments to definitively rule out or discover them are possible but very challenging.

In the $A = 0$ large $\mu$ scenario the lightest neutralino has a mass $\gtrsim 10$ GeV but the gluino mass vanishes. In this case the $R^0$ and $S^0$ would be absolutely stable unless the gravitino mass is low enough that it provides a decay channel. Absolute stability is a real possibility for the $S^0$ even in the low $\mu$ region, since the mass difference between it and the lightest neutralino must be greater than 938.8 MeV for it to decay. If either the $R^0$ or $S^0$ bind to nuclei, then their absolute stability could be ruled out experimentally by
the sensitive searches for exotic isotopes, at least for some mass regions\cite{26}. However one would expect a repulsive, not attractive, interaction between the flavor-singlet $S^0$ or $R^0$ and a nucleus\cite{3}. Anomalous signals in extensive air showers and underground muons seemingly coming from Cygnus X-3 are consistent with the intermediate particle being a neutron, except that the neutron decays too quickly to make the long trip\cite{8}. Long-lived $R^0$'s were investigated\cite{28}, but discarded\cite{29} on account of the mistaken belief that they would imply a long lived charged $R$-proton which is ruled out by, e.g., ref. \cite{26}. If the present quiet of Cygnus X-3 is only a cyclical phenomenon and such events are observed again in the future, an $R^0$ or $S^0$ interpretation should be seriously considered.

In the usual scenario with $A \sim 1$ and tree level gaugino masses, cosmological considerations rule out the existence of stable neutralinos having mass less than a few GeV\cite{9}, since in that case they would overclose the universe. The question needs to be revisited making assumptions appropriate to the present scenario. One important difference from the usual situation in which gluinos are assumed to be much heavier than the lightest neutralino is that in addition to the usual reactions $\chi\chi \to f\bar{f}$ considered when computing the annihilation of neutralinos, in this scenario one should also include $\tilde{g}\chi \to q\bar{q}$. Not only is the cross section parametrically larger by a factor $\sim \frac{\alpha_3}{\alpha_2}$ but the reaction can go through an s-wave because the gluino and neutralino are not identical fermions. When only $\chi\chi$ annihilation is relevant, the following argument applies: a pair of self-conjugate fermions such as $\chi\chi$ or $\chi\bar{g}$ state has $CP = (-1)^{L+1}$. Meanwhile, a $\chi\chi$ state by fermi statistics must have $(-1)^{S+1}(-1)^L = -1$ so that $L + S$ must be even. Hence the s-wave $\chi\chi$ state must have $S = 0$ and therefore has $J = 0$. However the $J = 0$ states of $f\bar{f}$ have either $L = S = 0$ or $L = S = 1$ and are therefore $CP$ even, since for an identical $f\bar{f}$ pair $CP = (-1)^{L+S}$. Thus $CP$ conservation does not

\begin{footnotesize}
\begin{enumerate}
\item See, e.g., ref.\cite{27} for a summary.
\item See, e.g., ref.\cite{30,31}.
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allow a $\chi \chi$ pair to annihilate to an $f \bar{f}$ pair through the s-wave. This means that the leading term in velocity expansion of the annihilation cross section $\sim v^2 \frac{1}{2}$, leading to a significant reduction in the annihilation rate. However for a $\chi \tilde{g}$ initial state one does not have the requirement from fermi statistics that $L + S$ be even, so that they can be in an $L = 0, S = 1$ state whose $J = 1$ is compatible with the $f \bar{f}$ being CP odd. Thus the reaction $\chi \tilde{g} \rightarrow q \bar{q}$ is not suppressed as $v \rightarrow 0$ and one can expect that the annihilation of neutralinos will be much more efficient in this scenario, reducing the cosmological limit on neutralino mass substantially.

If the overclosure bound on the mass of a stable neutralino still turns out to be significantly greater than 1 GeV, it could be satisfied in the large $\mu$ region. However this would not imply that the large $\mu$ solution is favored, because as long as the lightest neutralino is heavier than the $R^0$, it will decay to $R^0$'s so their relic density will be the issue. Another amusing possibility which arises naturally in the low-$\mu$ region is that the $\chi^0_1$ is heavier than the gluino, but not heavier than the $R^0$, so that above the QCD phase transition $\chi^0_1$'s decay into gluinos, but after the QCD phase transition the relic $R^0$'s decay into $\chi^0_1$'s, leaving a relic density which could account for dark matter with photino masses characteristic of the low-$\mu$ region, i.e., $\lesssim 1$ GeV. Detailed analysis is required to assess the quantitative viability of this suggestion. Thermal effects above the QCD transition would contribute to an effective mass for the gluino, but not significantly for the lightest neutralino, so that they must be included in the calculation to draw reliable conclusions.

In summary, the possibility of gluinos having masses less than a few hundred Mev with the lightest neutralino mass being $\lesssim 1$ GeV emerges naturally in low energy theories without dimension-3 susy-breaking operators. We have seen that such a scenario is not ruled out by laboratory experiments, except for limited regions of parameter space. It probably is capable of accounting

\begin{footnote}
Gluinos annihilate efficiently due to their strong interactions, like the antiquarks which were present in the early universe before they annihilated with quarks.
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for the dark matter of the universe, for values of the mass scale \( \mu \) which would imply a chargino light enough to be found at LEPII.
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Figure 1: Experimentally excluded regions of $m(R^0)$ and $\tau_{\tilde{g}}$. Horizontal axis is $m(R^0)$ in GeV beginning at 1.5 GeV; vertical axis is $\log_{10}$ of the lifetime in sec. A massless gluino would lead to $m(R^0) \sim 1.4 \pm 0.4$ GeV. ARGUS and Bernstein et al give the lightest and next-to-lightest regions (lower and upper elongated shapes), respectively. CUSB gives the next-to-darkest block; its excluded region extends over all lifetimes. Gustafson et al gives the smaller (mid-darkness) block in the upper portion of the figure; it extends to infinite lifetime. UA1 gives the darkest block in the lower right corner; it extends to higher masses and shorter lifetimes not shown on the figure.