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Experiments to find or exclude a long-lived, light gluino

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Gluinos in the mass range $\sim 1\frac{1}{2} - 3\frac{1}{2}$ GeV are absolutely excluded. Lighter gluinos are allowed, except for certain ranges of lifetime. Only small parts of the mass-lifetime parameter space are excluded for larger masses unless the lifetime is shorter than $\sim 2\times10^{-11}(m_{\tilde{g}}/1\text{GeV})$ sec. Refined mass and lifetime estimates for R hadrons are given, present direct and indirect experimental constraints are reviewed, and experiments to find or definitively exclude these possibilities are suggested.

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I. INTRODUCTION

Short-lived gluinos could be defined to be those which decay before interacting hadronically in a detector or beam dump. Their decay produces the lightest neutralino[1] (LSP) which escapes the detector or dump without interacting, carrying with it much of the gluino's energy and momentum. Short-lived gluinos are excluded for masses $\lesssim 160$ GeV [1] by the absence of characteristic missing energy events in the Fermilab collider. Thus to be lighter than this, gluinos must be long lived.[2] It is natural for gluinos to be much lighter than squarks if their masses are entirely radiative in origin. In that case, if the supersymmetry (SUSY) and electroweak symmetry-breaking scales are less than ~ 10 TeV, gluino and LSP masses will range from order of 100 MeV to order of 30 GeV [4, 5]. This is the mass range explored here.

A gluino in the mass range ~ 1.5–3.5 GeV is excluded, whatever its lifetime, from the absence of a peak in the photon energy spectrum in radiative Υ decay. This is because two gluinos with mass in that range would form a pseudoscalar bound state, $\eta_{\tilde{g}}$, whose branching fraction in $\Upsilon \to \gamma\eta_{\tilde{g}}$ can be reliably computed using perturbative QCD and is predicted [6–8] to be greater than the experimental upper bound[3] [9, 10].

[1] Generally, a superposition of the SUSY partners of the photon, Z^0 and neutral Higgs bosons, not considering effects of a possible light gravitino.

[2] The long-lived gluino window was first pointed out in Ref. [2]. It was subsequently discussed in Ref. [3].

[3] The range excluded by the CUSB experiment is incorrectly claimed to extend to lower gluino masses, by using the perturbative QCD (PQCD) results of Refs. [6–8] out of their range of validity. A detailed analysis of the actual excluded range in given in Ref. [11]. The lower limit for validity of a PQCD, nonrelativistic potential model description of an $\eta_{\tilde{g}}$ was taken to be ~ 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., $\tau \gtrsim \sim 10^{-22}$ sec, will produce the requisite bump in the photon energy spectrum, and thus be excluded by CUSB.

In this paper I address the question of whether long-lived gluinos having mass less than ~ 1.5 or greater than 3.5 GeV are excluded on other grounds. Many experiments which are commonly cited as ruling out gluinos of this mass range actually provide only weak limits when one takes account of the gluino lifetime. These experiments as well as the most powerful indirect constraints, which are also presently unable to exclude this mass range, will be reviewed below. My purpose here is to propose tests which will *unambiguously* demonstrate or exclude the existence of light gluinos.

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 [12]. The lightest of these would be the neutral, flavor singlet $g\tilde{g}$ "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 [2, 13], even lighter than the R nucleons.

The strategy pursued here is to identify production and detection mechanisms for the R^0 for which *reliable* rate estimates can be made, so that searches which are sufficiently sensitive will definitively rule them out or find them. First, we use theoretical arguments to estimate R hadron masses as a function of gluino mass. Then experiments are proposed to settle the question.

II. R HADRON MASS ESTIMATES

If the gluino is heavier than ~ 3.5 GeV, then the R^0 and S^0 will have masses approximately equal to the mass of the gluino. For the window $m_{\tilde{g}} \lesssim 1.6$ GeV, lattice gauge theory (LGT) should be used to determine the hadron spectrum, and hopefully the necessary calculations will be done soon. However, we can get a rough idea without it, as follows. Let us begin by estimating hadron masses if the gluino is as light as possible.

If the gluino were massless, the spectrum would be expected to contain an unacceptably light [14, 15] flavor-singlet Goldstone boson associated with the spontaneous breaking of the nonanomalous linear combination of quark and gluino chiral U(1) symmetries. For three light flavors of quarks the nonanomalous axial current is[4]

$$J^5_\mu = \frac{1}{\sqrt{26}}\left\{\bar{q}^{i,j}_L\gamma_\mu q^{i,j}_L - \bar{q^c}^{i,j}_L\gamma_\mu {q^c}^{i,j}_L - \bar{\lambda}^a\gamma_\mu\lambda^a\right\}. \quad (1)$$

We can obtain a theoretical lower bound on the gluino mass by identifying the η' with this pseudo Goldstone boson.[5] The flavor-singlet pseudoscalar which gets its mass from the anomaly would then be identified with a more massive state, which will be discussed below.

If this were the correct description of the η', 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 η', 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 [16]. 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 η' to decay through strong interactions. This means that rates which could potentially determine whether the η' has a 30% gluino component, in practice cannot be predicted reliably enough to be useful.[6]

Assuming that the η' is the pseudo Goldstone boson connected to the spontaneous breaking of the conserved axial-vector current (1), such as the K^+ for $J^5_K = \frac{1}{\sqrt{6}}\left\{\bar{u}^j_L\gamma_\mu s^j_L - \bar{u^c}^j_L\gamma_\mu {s^c}^j_L\right\}$, standard current algebra manipulations lead to predictions for $m^2_{\eta'}f^2_{\eta'}$ and $m^2_K f^2_K$. Taking their ratio, neglecting m_u and m_d in comparison to m_s, and solving for $m_{\tilde{g}}$ leads to

$$m_{\tilde{g}} \approx \frac{m_s}{4}\frac{\langle\bar{s}s\rangle}{\langle\bar{\lambda}\lambda\rangle}\left[13\left(\frac{m^2_{\eta'}f^2_{\eta'}}{m^2_K f^2_K}\right) - 3\right]. \quad (2)$$

With $f_{\eta'} \approx f_K$, this gives $m_{\tilde{g}} \sim 11\frac{\langle\bar{s}s\rangle}{\langle\bar{\lambda}\lambda\rangle}m_s$. Since the QCD attractive force between color octets is greater than that between triplet and antitriplet, $\langle\bar{\lambda}\lambda\rangle$ is presumably larger than $\langle\bar{s}s\rangle$. Most-attractive-channel arguments [17] suggest that the condensates depend exponentially on the Casimirs of the condensing fermions so that since $C_8/C_3 = 9/4$, $\langle\bar{\lambda}\lambda\rangle$ could be an order of magnitude or more larger than $\langle\bar{s}s\rangle$. Thus pending lattice calculations of $\langle\bar{\lambda}\lambda\rangle$ 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.

If the gluino were massless, the mass of the R^0 should be 1440 ± 375 MeV, i.e., about $1\frac{1}{2}$ GeV, as follows. Consider supersymmetric SU(3) Yang-Mills theory. Since supersymmetry in this theory does not break dynamically [18], hadrons must fall into degenerate supermultiplets. The massive chiral supermultiplet containing the 0^{++} glueball also contains a 0^{-+} (the lowest $\tilde{g}\tilde{g}$ bound state) and two spin-$\frac{1}{2}$ states, namely, the two helicities of the R^0 (the $g\tilde{g}$ bound state). At the classical level this theory has a chiral U(1) phase invariance since the gluinos are massless, like the chiral U(1) of ordinary QCD with massless quarks. This symmetry is clearly not realized in the hadron spectrum, since the R^0 is degenerate with the massive glueball. Nor is there a Goldstone boson associated with the breaking of this U(1) symmetry since the pseudoscalar $\tilde{g}\tilde{g}$ bound state is also degenerate with the glueball. This is not paradoxical for the same reason that in ordinary QCD we can accommodate the η' mass. Namely, the axial U(1) current has an anomaly so that nonperturbative effects give the pseudoscalar $\tilde{g}\tilde{g}$ bound state a mass. The chiral U(1) symmetry is explicitly broken by quantum effects so that Goldstone's theorem is circumvented.[7]

Now consider hadron masses in QCD with three light quarks and a massless gluino. The mass of the 0^{++} glueball is predicted [19] using lattice QCD in quenched approximation (i.e., QCD with only gluons and no quarks or gluinos) to be 1440 ± 110 MeV. In ordinary lattice QCD, with three light quarks but no gluinos, the quenched approximation is commonly taken to be valid at the 10–15 % level for hadron masses.[8] Since the one-loop β function for QCD with no light quarks but an octet of gluinos is the same as for QCD with three light quarks, one can expect that the error for quenched approximation in the supersymmetric Yang-Mills theory is also 10–15 %, and that the quenching error with both quarks and gluinos is $\sim$15–25 %. If this is so, then a full lattice calculation in QCD with three light quarks and a massless octet of gluinos would give a mass for the R^0 of $\sim 1440 \pm 375$ MeV, where the lattice error of Ref. [19] on the glueball mass was combined in quadrature with the estimated error from the quenched approximation, taken to be 25% of 1440 MeV to be conservative. As we shall see below, it is much more difficult to detect an R^0 with mass $\sim$ 1065 GeV than one with mass $\sim$ 1800 GeV. Thus a LGT calculation which reduced the range of uncertainty on the mass of the R^0 would be very helpful, especially if it showed we could ignore the region close to 1 GeV.

In QCD extended by gluinos, the flavor-singlet pseudoscalar which gets mass from the anomaly is orthogonal to the anomaly-free current (1), thus it is 70% $\tilde{g}\tilde{g}$ and

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[4]The fields appearing in this expression are left-handed Weyl spinors and a sum over indices is understood. i labels the three light quark flavors and j and a label the 3 quark and 8 gluino color degrees of freedom.

[5]This possibility was suggested in Ref. [2] but not developed in quantitative detail as is done here.

[6]A possible way to discriminate is to study the production of the various pseudoscalars in J/ψ decay. [G. Farrar and G. Gabadadze (in preparation).]

[7]It is interesting that supersymmetry relates the mass produced by nonperturbative effects through the anomaly to the mass gap for the glueball coming from confinement, suggesting that confinement is essential to the understanding of the mass of the η' even in ordinary non-SUSY QCD.

[8]See Ref. [20] for a critical discussion of quenched approximation.

30% $u\bar{u} + d\bar{d} + s\bar{s}$. In the supersymmetric Yang-Mills theory discussed above, the pseudoscalar $\tilde{g}\tilde{g}$ state which gets mass from the anomaly and is degenerate with the 0^{++} glueball would have a mass of 1440 ± 240, adding the error in Ref. [19] in quadrature with a 15% error for unquenching. There is evidence for an "extra" flavor-singlet pseudoscalar present in the meson spectrum in the 1410–1490 region [21–23], which has a large coupling to gluons [11]. If confirmed, it is an excellent candidate to be the pseudoscalar whose mass comes from the anomaly, in the very light gluino scenario.

To recapitulate, we have seen above that from purely theoretical considerations we can at present only rule out R^0 and S^0 masses below about 1100 MeV. Having the lightest possible masses requires both the η' and extra pseudoscalar meson in the 1410–1490 MeV region to have large gluino components, but increasing the gluino mass to $\sim$ 700 MeV allows one to return to the conventional phenomenology for the η' and interpret the extra state as a simple $\eta_{\tilde{g}}$, the lowest-lying $\tilde{g}\tilde{g}$ bound state. If gluinos are much heavier than this, one needs another explanation for the extra state in the 1410–1490 region.

III. EXISTING EXPERIMENTAL LIMITS

From the CUSB experiment, we infer[9] 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

$$m(R^0) = 0.72(1 + e^{-\frac{m_{\tilde{g}}}{2}}) + m_{\tilde{g}}(1 - e^{-m_{\tilde{g}}}), \qquad (3)$$

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.

In another quarkonium decay experiment, the ARGUS group [24] looked for events in which $\Upsilon' \to \gamma + \chi_b(1\,^3P_1)$, followed by $\chi_b(1\,^3P_1) \to g\tilde{g}\tilde{g}$, with one of the final R hadrons decaying in a distance of 1–60 cm from the e^+e^- interaction point. From the absence of such events at a level predicted by PQCD they concluded that gluinos in the mass range 1–4.5 GeV do not exist in the lifetime range to which they were sensitive. However, perturbative QCD overestimates the branching fraction $\chi_b(1\ ^3P_1) \to g\tilde{g}\tilde{g}$ for very light gluinos, since it fails to include the effect of the substantial reduction in phase space arising from the minimum invariant mass of a pair of R^0's being about 3 GeV, even when the gluino is massless (see Sec. II). To determine whether the experimental sensitivity extends to a gluino mass as low as 1 GeV as stated in Ref. [24], the experiment should be reanalyzed using a more realistic model of the branching fraction for $\chi_b(1\ ^3P_1) \to g\tilde{g}\tilde{g}$ in the nonperturbative portion of phase space. The ARGUS results, taken from Fig. 4(a) of Ref. [24], are plotted on Fig. 1 using the above function to convert from their quoted gluino masses to a common R^0 mass. For the largest masses no conversion is used, in order not to make the nonsensical claim that they can exclude R^0's which cannot be kinematically produced.

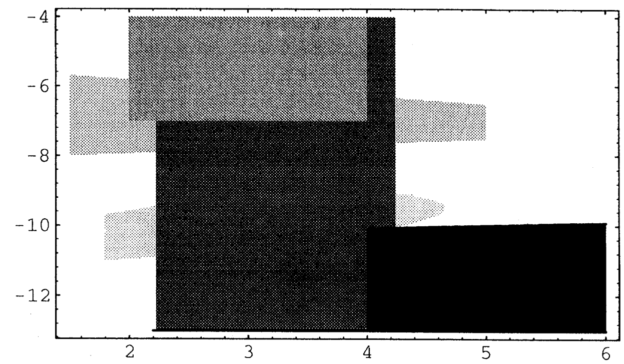

FIG. 1. Experimentally excluded regions of $m(R^0)$ and $\tau_{\tilde{g}}$. Horizontal axis is $m(R^0)$ in GeV; vertical axis is $\log_{10}$ of the lifetime in sec. ARGUS and Bernstein *et al.* give the lightest and next-to-lightest regions (lower and upper elongated shapes), respectively. CUSB gives the next-to-darkest block; its excluded region extends over all lifetimes. Gustafson *et al.* give 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 in the figure.

The best constraints beyond CUSB and ARGUS for long-lived gluinos in the radiatively generated range of up to $\sim$30 GeV come from searches for new neutral particles. Gustafson *et al.* [25] searched for new hadrons with lifetimes greater than 10^{-7} sec, using time of flight in a 590 m long neutral beam at Fermilab. On account of timing and energy resolution limitations, they were capable of distinguishing a particle from a neutron only if its mass was greater than 2 GeV. From the limits of Gustafson *et al.*, Dawson, Eichten, and Quigg (DEQ) [3] concluded that gluino masses in the 2–4 GeV range could be excluded. This experiment is therefore consistent with CUSB and Bernstein *et al.* (see below), and for $\tau_{\tilde{g}} > 10^{-7}$ sec extends the lower end of the excluded mass range to 2 GeV as shown in Fig. 1.

The experiment of Bernstein *et al.* [26] places an upper bound on the production cross section of a neutral hadron produced in 400 GeV proton collisions, with mass in the range 1.5–7.5 GeV, which decays with a lifetime $(10^{-8} - 2 \times 10^{-6})$ sec to a two- or three-body final state containing a charged hadron. They find $E\frac{d\sigma}{d^3p}|_{90^\circ} \lesssim 5 \times 10^{-35} \frac{\mathrm{cm}^2}{(\mathrm{GeV}^2/c^3)}$ for mass of 1.5 GeV, and $\lesssim 3 \times 10^{-32} \frac{\mathrm{cm}^2}{(\mathrm{GeV}^2/c^3)}$ for 7.5 GeV, taking the most sensitive lifetime value of 3×10^{-8} sec. Typical decays would be $R^0 \to$ LSP + π('s) and $S^0 \to$ LSP + Λ^0 + π('s) or $S^0 \to$ LSP + N + K + π('s). Since the S^0 has baryon number +1, it would be expected to be produced mainly in the forward direction rather than at 90° where the ex-

[9] See footnote 3.

periment was done, so is not directly constrained by this experiment. However, this experiment does constrain the possibility of R^0's. For the light end of the mass range, a reasonably good analog process which should be even more Okubo-Zweig-Iizuka (OZI) suppressed, is $pp \to \bar{p}X$ whose invariant cross section is $\sim 10^{-27} \frac{\mathrm{cm}^2}{(\mathrm{GeV}^2/c^3)}$ [27], for similar kinematics. For a gluino mass of 3.5 GeV or larger, it is legitimate to use perturbative QCD (PQCD) to compute the expected rate, as a function of gluino mass. This was done in tree approximation by DEQ [3] for $m_{\tilde{g}} = 3$ GeV. They predicted an invariant cross section of $\sim 10^{-28} \frac{\mathrm{cm}^2}{(\mathrm{GeV}^2/c^3)}$ for $p_\perp = 0$. We can very crudely estimate the cross section for the production of a gluino of higher mass but $p_\perp = 0$ by noting that the cross section is mainly dependent on the combination $m^2 + p_\perp^2$. The DEQ prediction for $m = 3$ GeV and $p_\perp = 4$ GeV is $\sim 3 \times 10^{-34} \frac{\mathrm{cm}^2}{(\mathrm{GeV}^2/c^3)}$ (see Fig. 44), which is the same as the limit of Bernstein *et al.* for $m = 5$ GeV and $p_\perp = 0$. Thus the limit of Bernstein *et al.* very roughly rules out R^0's with mass less than 5 GeV. The range of lifetime sensitivity corresponding to the cross-section limits of Fig. 4(a) is shown in 4(b), for $m = 3$ GeV where it is $\sim 2 \times 10^{-8}$–2×10^{-7} sec. Since for a fixed production rate the detector sensitivity depends mainly on $\gamma\beta\tau$, and $\gamma \sim m^{-1}$, the range of maximal sensitivity will shift upward, roughly in proportion to m, for $m > 3$ GeV. The range excluded by Bernstein *et al.* is shown in the figure. It is upper elongated region ending at 5 GeV.

The limits could in principle be somewhat tightened if there are charged R hadrons which decay only weakly to the R^0 or S^0, e.g., $R_{K^+} \to R^0 + \pi^+$. This will be the case if the mass gap between charged R pions and R kaons and the R^0, and between charged R baryons and the S^0, is greater than the mass of the corresponding kaon or pion. Lattice calculations of the R-hadron mass splittings as a function of gluino mass are badly needed here. Bag-model predictions for R hadrons cannot be trusted since parameters fixed to fit the ordinary hadrons may not be applicable to R hadrons, and furthermore bag-model estimates have not been been reliable for the glueball spectrum. Nonetheless old bag-model estimates [28, 2, 13] suggest that for some parameters there may not be enough phase space for $R_K \to K + R^0$ or $R_N \to K + S^0$. Thus a search for charged R hadrons is worthwhile even though a null result would not exclude gluinos. Note that there is no relation between the lifetimes of the R^0 and S^0 and lifetimes of charged R hadrons, since the latter decay to the R^0 and S^0 through conventional weak interactions and would be expected to have a lifetime comparable to weakly decaying hadrons of a similar mass, i.e., 10^{-10}–10^{-13} sec for masses in the range 1–5 GeV. Briefly, the experimental constraints would be the following.

(i) Cutts *et al.* [29] use time of flight to exclude lifetimes greater than $\sim$ (2–5) $\times 10^{-8}$ sec, for charged particles with masses in the 4–10 GeV range.

(ii) Bourquin *et al.* [30] search for decaying particles in the CERN hyperon beam, extending the excluded range for new charged particles to cover the 2–4 GeV mass range, for lifetimes of order 10^{-9}–10^{-8} sec.

(iii) Charged R hadrons having mass of the same order of magnitude as the D or B mesons must have a lifetime too short or too long to decay in vertex detectors used to measure D and B lifetimes.

(iv) There is a Collider Detector at Fermilab (CDF) limit on the existence of charged hadrons having $\gamma\tau \gtrsim 10^{-7}$ sec [31], but it only addresses masses greater than 50 GeV because the present detector has time resolution at the nanosecond level.

Otherwise the constraints on charged R hadrons are poor and the coverage is surprisingly spotty. It must be reemphasized, however, that even if strong-interaction-stable R hadrons exist, one cannot immediately apply these experimental constraints on the allowed regions for their mass and lifetime to the limits in Fig. 1, because there is no direct relation between the lifetime of a charged R hadron and that of the R^0.

If the gluino lifetime is long because the squark mass is much larger than m_W, then beam-dump experiments [12, 32–35], which look for the reinteraction of the LSP in a neutrino detector, become ineffective because the LSP cross section falls as $\left(\frac{m_W}{M_{\mathrm{sq}}}\right)^4$. Even if the LSP cross section is not too small, the gluino must decay before losing energy in the dump, e.g., in 10 cm in the Ball *et al.* Fermilab beam-dump experiment [33, 36], i.e., requiring a lifetime $\lesssim 5 \frac{m_{\tilde{g}}}{1\ \mathrm{GeV}} 10^{-11}$ sec. Likewise, the Big European Bubble Chamber (BEBC) experiment [34] observes that if $\tau_{\tilde{g}} \gtrsim 5 \times 10^{-11}$ sec, the gluino decay does not occur before interaction, "severely degrading the photino flux reaching our detector." For massless photino they model this effect, but in general, beam-dump experiments need to be analyzed in terms of the three parameters $m_{\tilde{g}}$, σ_{LSP}, and $\tau_{\tilde{g}}$. Beam-dump experiments cannot be used to exclude regions of the gluino mass-lifetime plane without further assumptions which are not in general appropriate to our case, except for gluinos with lifetimes shorter than about 5×10^{-11} sec. The HELIOS experiment [35] explicitly addresses direct production of weakly interacting massive particles (WIMP's), and not long-lived gluinos, since it requires that no energy degradation occurs in the dump.

The possibility of large gluino mass is at present only addressed by collider missing energy searches that detect the existence of a gluino which decays inside the apparatus with a substantial portion of its energy going to the LSP which is very weakly interacting and escapes. Indeed, this is the classic gluino signal [37]. The CDF missing energy search [1] is sensitive to gluinos which decay within about 1 m of their production, i.e., having $\frac{E_{\tilde{g}}}{m_{\tilde{g}}} \tau_{\tilde{g}} \lesssim 3 \times 10^{-9}$ sec. They require the missing transverse energy to be greater than 40 GeV. To get a very rough idea of their regime of sensitivity (which could be determined more accurately by modeling the energy spectrum of the produced gluinos), we can take as a typical event the case in which the gluino is emitted at 45° and assume it decays giving 1/3 its energy and momentum to the LSP which escapes with the minimal transverse energy to satisfy their cuts. In this case, the actual energy of the decaying gluino would be $3 \times \sqrt{2} \times 40 = 170$ GeV, ignoring gluino, quark, and LSP masses. Thus gluinos with lifetimes longer than about $2 \times 10^{-11} \left(\frac{m_{\tilde{g}}}{1\ \mathrm{GeV}}\right)$ sec would not be efficiently detected in the CDF search. They do not investigate masses lower than 20 GeV, where they lose efficiency on account of the acoplanarity and missing E_T cuts.

The UA1 missing energy search [38] claims to be sensitive enough to exclude masses as low as 4 GeV. Although a gluino lifetime is not included in their efficiency Monte Carlo, they state that they believe they are fully sensitive to gluinos whose lifetime is shorter than 10^{-10} sec. This agrees with the crude estimate given above for the CDF experiment, for $m_{\tilde{g}} = 5$ GeV. Nonetheless, especially for the high mass end of the UA1 experiment, a Monte Carlo is needed to know the lifetime sensitivity as a function of mass. For simplicity, and to be conservative, we will use the estimate $2\times10^{-11}\,(\frac{m_{\tilde{g}}}{1\text{ GeV}})$ sec for both CDF and UA1.

To summarize this section, gluinos in the mass range ~ 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 2×10^{-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 have a lifetime longer than about $\sim 2\times10^{-11}\,(\frac{m_{\tilde{g}}}{1\text{ GeV}})$ sec (UA1,CDF), with the ranges $> 10^{-7}$ sec (Gustafson *et al.*), 2×10^{-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 Eq. (3). Given the primitive nature of Eq. (3) and the ±375 MeV uncertainty on the R^0 mass when the gluino is massless (Sec. II), as well as the very rough methods used to extract the ranges of mass and lifetime sensitivity for the various experiments, a $\gtrsim 20\%$ uncertainty should be attached to all the boundaries shown in this figure.

IV. THEORETICAL COMMENTS: GLUINO LIFETIME AND PRODUCTION ESTIMATES

How natural is it from a theoretical point of view for an R^0 in the mass range 1.5–2.5 GeV to have a lifetime longer than 2×10^{-6} sec, or for an R^0 with mass $\gtrsim 5$ GeV to have a lifetime longer than $\sim 2\times10^{-11}\,(\frac{m_{\tilde{g}}}{1\text{ GeV}})$ sec? For the higher mass range the R^0 and gluino lifetimes can be taken to be approximately the same, since for a relatively massive state one can ignore the effects of confinement on the overlap of the initial and final states, and the modifications to phase space from the hadron masses. For the low end of the range, if the LSP mass is low compared to the gluino mass, one could either argue by analogy to known hadron decays [12] or, following Franco [39], take the R^0 lifetime to be that of a gluino of $\sim \frac{3}{4}$ of its mass. For the interesting case that the LSP mass is a significant fraction of $m(R^0)$, tools have not yet been developed which allow us to reliably estimate the resultant suppression in the decay rate.

The decay rate for an unconfined gluino to decay to the LSP and a $\bar{q}q$ pair can be obtained as follows. In general, the LSP is a superposition of the fermionic partners of the neutral SU(3) and U(1) gauge (W-ino and b-ino) and Higgs bosons (Higgsinos). However, it is shown in Ref. [5] that when gaugino masses are all radiatively generated the Higgsino component of the LSP is in fact less than 1% in amplitude. Thus we can approximate the LSP wave function as $\cos\theta|\tilde{b}\rangle + \sin\theta|\tilde{w}_3\rangle$. The decay rate of the gluino assuming the LSP to be a photino was given in Ref. [40], so we need only replace e_q^2 appearing in their expression by $(\frac{\sin\theta}{\sin\theta_W})[I_z + z\frac{Y}{2}]^2$, where $z = \frac{\tan\theta_W}{\tan\theta}$, and average over left- and right-handed contributions. Thus the total rate for gluino to decay to the LSP and a $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$ pair, ignoring the quark masses is

$$\Gamma_{\tilde{g}} = \frac{\alpha_s\alpha_{\rm em}(1-\frac{2}{9}z+z^2)m_{\tilde{g}}^5}{128\pi M_{\rm sq}^4}\left(\frac{\sin\theta}{\sin\theta_W}\right)^2[(1-y^2)(1+2y-7y^2+20y^3-7y^4+2y^5+y^6)+24y^3(1-y+y^2)\ln(y)], \tag{4}$$

where $y = \frac{m_{\rm LSP}}{m_{\tilde{g}}}$. We have taken $M_L^{\rm sq} = M_R^{\rm sq} = M_{\rm sq}$ for simplicity. The θ dependent factor ranges from 1, for a light neutralino in the low-μ region where $\theta \approx \theta_W$, to $(\cos\theta_W)^{-2}$ for a heavy neutralino in the high-μ region where $\cos\theta \approx 1$. Thus for a rough estimate we take this factor to be 1. We also take $\alpha_s \sim 0.1$ and $\alpha_{\rm em} = 1/128$, since the relevant scale is the squark mass. Then, for instance with a massless LSP, the squark mass must be greater than ~ 2 TeV for a gluino with effective mass in the 1–1.5 GeV mass range to have $\tau_{\tilde{g}} \geq 2\times10^{-6}$ sec. If instead the LSP mass is 90% of the gluino effective mass, the squark mass must only be greater than about 200 GeV. For a gluino of mass 5 GeV, the UA1 bound is most relevant. For LSP mass of zero or $0.9m_{\tilde{g}}$ one finds that the squark mass must be greater than 1 TeV or ~ 130 GeV, respectively. These squark masses increase to 6 TeV or 670 GeV for a 15 GeV gluino. As shown in Ref. [5], when gaugino masses arise radiatively, these conditions are naturally accommodated in much of parameter space.

It is also worth noting that absolute stability is a real possibility for the S^0, since the mass difference between it and the LSP must be greater than the sum of proton and electron masses for it to decay. If it binds to nuclei, this would be ruled out experimentally by the sensitive searches for exotic isotopes, at least for some mass regions [41]. However, one would expect a repulsive, not attractive, interaction between a nucleus and the flavor-singlet R^0 or S^0 , since the intermediate state created when they exchange mesons with a nucleon has a much higher energy.[10]

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.[11] Long-lived R^0's were investigated [43], but discarded [44] on account of the mistaken belief that they would imply a long-lived charged R proton which is ruled out by, e.g., Ref. [41]. If the present quiet of Cygnus X-3 is only a cyclical phenomenon and such events are observed again in the future, an S^0 interpretation should be seriously considered.

Turning now to cross-section calculations, I am not aware of any recent PQCD calculations of gluino production at a hadron collider, except for very massive gluinos. The old analyses [3, 45] should be updated, making an attempt to estimate the uncertainty in the gluino distribution, as well as including one-loop corrections which have proved very important for ordinary PQCD predictions. From deep inelastic and Drell-Yan experiments, the quark and antiquark distributions are reasonably well fixed. Direct photon production gives information on the gluon distribution function, so the momentum sum rule then provides some constraint on the gluino distribution. The naive argument [46] which leads to behavior $(1-x)^7$ for the sea-quark distribution functions at large x, leads to the same behavior for the gluino distribution function. Since the R^0, η', and $\eta_{\tilde{g}}$ masses are so much larger than pion masses, one would expect that the low-Q^2 gluino distribution functions are smaller than those of the sea quarks. However, since the one-loop β function for gluinos is the same as for three flavors of light quarks, the gluino distribution function evolves as rapidly as all three quarks together, so a light gluino would become an important component of the nucleon at larger Q^2.

Although the gluon and gluino distribution functions are individually difficult to determine well, without assumptions as to their functional form for the entire x range, their sum is much better determined.[12] Since both gluons and gluinos give rise to gluino jets, the actual prediction for R^0 production is relatively stable. If the existence of gluinos were established, the ratio of events with 1 and 2 R^0's would allow the ratio of gluino and gluon distributions to be constrained. Demanding consistency of PQCD predictions with observed jet production may also allow the gluino distribution function to be further constrained, since the amplitudes for gluinos to produce jets differs from those for quarks or gluons to produce jets.

[10]Unlike the binding of a nucleus where exchange of mesons between pairs of nucleons, each of which can absorb or emit an $I = 1$ meson and remain a nucleon, leads to intermediate states close in energy to the original state.

[11]See, e.g., Ref. [42] for a summary.

[12]Comparably to the determination of the gluon distribution function, when the gluino possibility is ignored.

V. INDIRECT EVIDENCE REGARDING LIGHT GLUINOS

For years it has been recognized that in principle the running of α_s is sensitive to the presence of gluinos.[13] In deep inelastic scattering experiments the ambiguity introduced by higher twist contributions is too large to allow one to decide between QCD with and without gluinos.[14] Gluinos modify the e^+e^- annihilation cross sections only in order α_s^2, by providing an additional source of four-jet events and making virtual corrections to two-jet events. The possibility of inferring or excluding gluinos directly from CERN e^+e^- collider LEP event characteristics was discussed in Ref. [49], where the sensitivity to the as-yet-uncalculated one-loop corrections was shown to be too great to allow one to decide between ordinary QCD and QCD with massless gluinos.[15]

The reason that it is generally difficult to discriminate between QCD with and without gluinos is because adding gluinos to the theory modifies it in competing ways which tend to cancel. For instance, the value of α_s at LEP is obtained by fitting QCD predictions for various aspects of event shapes and extracting the value of α_s which gives the best fit. Gluinos are an additional source of four-jet events, but at the same time α_s runs more slowly when there are gluinos. This means that, for a given value of $\alpha_s(M_Z)$, the typical value of $\alpha_s(Q_{\rm eff})$ in multijet events is lower than it would be for QCD without gluinos, which tends to reduce the number of multijet events.[16]

Just as the effects of gluinos tend to cancel at LEP, one cannot simply say that the number of jets predicted at the Fermilab Tevatron will be increased by such-and-such amount, since if there are light gluinos they will be present in the hadron structure functions and will use some of the "room" for gluons, reducing the production of conventional jets to some extent.[17] To address the

[13]For the first discussion of this, see Ref. [47].

[14]Thus comparison of the values of α_s from deep-inelastic scattering and Z^0 decay are inconclusive, although suggestive. G.R.F. remarks given at XXVIIth Rencontre de Moriond, Les Arcs, France, 15–22 March 1992 (unpublished) and [48].

[15]More recent articles on this subject have come to the same conclusion [50, 51].

[16]Reference [52] correctly emphasized the need to extract α_s from data with and without gluinos before evaluating the consistency of the running between different energy scales, with and without gluinos. However, that analysis only includes the virtual corrections to the running of α_s in LEP events and not the effect of real gluino jet production which is of the same order, so is incomplete. Bryan Webber and I (unpublished) tried to see if we could find some systematic preference of the LEP data for QCD with and without gluinos by looking at the entire menagerie of quantities from which α_s is extracted. We found that the only region in which there was a significant difference in predictions with and without gluinos is precisely the region in which hadronization is most important, and for which the one-loop corrections to the four-jet cross section (which are not yet available) are crucial.

[17]See Ref. [49] for a discussion of the difficulty of using hadron collider jet cross-section characteristics to infer or exclude the existence of long-lived gluinos given the present level of theoretical precision.

possibility of light gluinos by their effects on jets or the running of α_s, one must (a) compare predictions for actual experimental observables with and without gluinos and not try to compare derived quantities such as α_s and (b) *fully* incorporate gluinos into the analysis, including their effects on distribution functions.

Recently, there have been a number of attempts to make the kind of careful analysis which would be necessary to obtain reliable indirect information of the possibilty of light gluinos. Reference [53] used theoretical predictions for the hadronic branching fractions R_τ and R_Z with and without gluinos, to extract $\alpha_s(m_\tau)$ and $\alpha_s(m_Z)$ with and without gluinos, then checked whether the running of α_s between these values was consistent with what QCD predicts, with and without gluinos. The main difficulty with this approach is the issue of how to treat the effect of a light or massless gluino on τ decay, and also the question of the validity of neglecting nonperturbative contributions of order $\frac{1}{m^2}$ as is done in Ref. [54]. The latter issue is discussed in Ref. [55], where it is argued that unless the validity of neglecting $\frac{1}{m^2}$ corrections is established, the error should be taken to be twice that assigned in the "nominal" case of Ref. [53], i.e., that $R_{TH} = 2$ is appropriate for the Ref. [53] analysis. With respect to the former issue, since the invariant mass of an R^0 pair and of the $\eta_{\tilde{g}}$ is too large to contribute significantly to τ decay, independent of the gluino mass, the gluino contribution should be neglected when determining $\alpha_s(m_\tau)$, as is done for the charm quark. This can be implemented[18] by using an "effective" gluino mass $\gtrsim m_\tau/2$ when using their Fig. 2. One then finds that even at 90% confidence level there is no excluded region of gluino mass from this analysis when $R_{TH} = 2$.

For other attempts to study indirect evidence for light gluinos see, e.g., Refs. [56, 57].

VI. PROPOSALS FOR EXPERIMENTS

Now let us turn to the question of how to establish or rule out the existence of new light hadrons, R^0 or S^0. One method, proposed years ago [2], is to look for exclusive reactions, such as $K^-p \to R^0S^0$, followed by elastic scattering of the R^0 and S^0 off protons. With accurate measurements of the R^0 and S^0 production angles, and measurement of the recoil proton momenta in the secondary $R^0p \to R^0p$ and $S^0p \to S^0p$ scatterings, there is in principle one more equation than unknowns and the masses of the R^0 and S^0 can both be determined. Using a hydrogen bubble chamber would seem to work nicely for observing the initial and secondary scatterings, but a high efficiency for identifying K_L^0's and neutrons would be desirable to reduce background, so this may not be the optimal approach. The interaction lengths of the R^0 and S^0 are probably somewhat shorter than for ordinary mesons and baryons, on account of the greater color charge of the gluinos as compared to quarks and on account of the S^0 having four constituents rather than three for a normal baryon. The candidate events should show a threshold behavior consistent with the measured R^0 and S^0 masses, which would corroborate the validity of the overall picture. Note that this experiment is sensitive to gluinos with any lifetime long enough that the R^0 and S^0 rescatter before decaying, so that it is complementary to the experiment of Bernstein *et al.* and sensitive to lower masses than Gustafson *et al.* However, this method has two important weaknesses. First, the cross section may be very small, since one is asking for a very exotic final state to be produced in an exclusive mode. Second, it is not possible to reliably calculate the cross section so that one cannot establish a level of sensitivity adequate to definitively exclude the phenomenon. Unfortunately it is also a demanding, single-purpose experiment and theoretical prejudice has favored heavy gluinos, so that experimenters have not looked just to see if something might be there.[19]

Here I propose other experiments which also do not rely on observing the decay of the R^0 or S^0 and are thus able to rule out or observe long-lived gluinos, but which do not have the difficulties of the one discussed above. Except in the forward direction, we expect that S^0 production is much smaller than R^0 production, so let us ignore S^0's for simplicity. By working at high energy, exotics can be produced relatively easily and inclusive cross sections can be reliably computed from perturbative QCD in appropriate kinematical regions. The cross section for producing R^0's is essentially just the gluino jet cross section, since all gluino jets end in an R^0 (or, rarely S^0) because other R hadrons eventually decay to these.[20] The gluino-jet cross section is approximately 10% [49] of the total jet cross section, so that it is actually quite common for a Tevatron collider or fixed target event to contain an R^0 pair. p_t cuts can be imposed to ensure that perturbative QCD event generators can

[18] M. Schmelling and R. St. Denis (private communication).

[19] Recently, Carlson and Sher [58] proposed searching for the decays of gluinos following their photoproduction at CEBAF. This is an excellent experiment, since something may be found. However, it does not satisfy the present criterion of being useful for excluding a light gluino, since the relatively low invariant mass range which can be probed at CEBAF means that the nonperturbative effects of R^0 and $\eta_{\tilde{g}}$ masses will suppress the signal and the calculations of the production rates are therefore not sufficiently reliable to allow exclusion. They report results for the effective gluino mass being taken to be 1 and 1.5 GeV, and the dramatic rate of decrease with effective gluino mass reflects the sensitivity to this effect. To obtain reliable inclusive cross sections for production of light particles from PQCD, one must impose a $p_\perp^{\min}$ cut. The event rates they quote are so large that this may be possible, but as long as their signal is the decay of the gluino, the proposed experiment can only be used to examine a limited lifetime region.

[20] Or *very* rarely, gluinos from independent jets can annihilate, but at this order one must also consider jet evolution which produces gluinos.

be reliably used to compute the expected rate, even for light gluinos. Showing that there are no such events at a level of 4σ below the prediction, would then convincingly rule out the existence of these gluinos.[21]

Basically the idea is an outgrowth of the suggestion of Ref. [2], but sacrificing the additional constraints of exclusive production in favor of the higher rate and reliable calculability of high energy inclusive production. A high energy beam from an accelerator is incident on the primary target. This produces a neutral beam containing neutrons, kaons, hyperons, and possibly R^0's and S^0's. This beam illuminates a secondary target in which an elastic scattering $R^0 p \to R^0 p$ may occur. Measuring the momentum of the recoil proton and the angle of the produced R^0 (by observing *its* interaction, which need not be elastic) gives enough constraints to solve for m_R, if indeed the reaction is elastic. Knowing the visible energy of the final particles in the secondary scattering of the produced R^0 can help choose between multiple solutions and help discard events in which the primary scattering is not elastic.[22] Of course the background due to other reactions, especially $n\,p \to n\,p$ or $K_L^0 p \to K_L^0 p$, or inelastic scattering, will be quite severe even after vetoing on extra charged particles and π^0's, so excellent resolution is crucial.

Timing could be used to measure p/E of the incident neutral. With this information, one would have an overconstrained system of equations without relying on the secondary scattering being elastic and one could verify that the initial reaction was indeed $R^0 p \to R^0 p$ as well as determine the R^0 mass. If the R^0 is sufficiently heavy, one can get adequate resolution with nsec accuracy using the beam buckets without being forced to put the secondary target so far away that the loss of solid angle would be intolerable.[23] Modern $\sim$10 psec timing could allow the lower mass regions to be investigated, except that it requires tagging the initial R^0 production event, so entails a reduction in rate. Detailed Monte Carlo simulation is needed to determine whether it is possible to cover the very light gluino regime, where the R^0 may be difficult to distinguish from a neutron. With many events, a discrepancy between the observed and expected event characteristics such as angular distribution and rates would be a useful diagnostic. Another handle for some range of R^0 lifetimes would be a distance dependence of the anomalous events.

In the above discussion I focused on the process $R^0 p \to R^0 p$ for identifying the R^0. It is the most attractive option from a theoretical point of view since its cross section is easiest to estimate.[24] If one's goal is to try to unambiguously exclude light gluinos, then one must use reactions which can be estimated with some confidence both to produce and to detect them. However, if one wants the most effective way to discover light gluinos if they exist, one can consider other detection reactions such as $R^0 p \to R_p \eta'$ or $R^0 p \to K^+ S^0$, whose signature may be much more distinctive.[25] In the resonance region, such cross sections can be very large. Further work is needed to try to estimate them.

A setup, such as kTeV, where the distance between primary and secondary targets (the regenerator) is 120 m and the typical energy of the long-lived neutrals is about 100 GeV, would be mainly sensitive to lifetimes longer than $\sim 4 \times 10^{-9}$ sec. Thus if it can be used for this purpose, it will be able to probe a large part of the interesting lifetime range.

In a collider experiment, pair-produced heavy gluinos would radiate gluons and light quarks to produce jets containing ordinary hadrons and an R^0. For sufficiently heavy R^0 and good timing capabilities, one could in principle detect the time delay p/E for the late-arriving neutral particles to deposit energy in the calorimeter. Assuming each of them to be an R^0 which stopped in the calorimeter, producing very light particles, the energy it deposited in the calorimeter would be roughly of the same magnitude as p of the R^0. Knowing p and p/E, one could solve for m_R. A detailed study of the conversion of an R^0's momentum to the energy deposition in the calorimeter (in particular the extent of the fluctuations to be expected) is needed to see if this method is feasible in practice. Another way that the production of a pair of heavy long-lived gluinos might be inferred in principle, would be to search for events in collider experiments in which fitting energy and momentum conservation at the jet level requires two of the jets to be given a large mass.

VII. SUMMARY

As is shown in [5], if gaugino masses are generated by loop effects, the gluino and LSP masses will be in the range from $\sim$ 100 MeV to $\lesssim 30$ GeV if the SUSY and electroweak symmetry-breaking scales are $\lesssim 10$ TeV. Furthermore, in a substantial part of parameter space the LSP is near in mass or heavier than the gluino, so that

[21] Care must be taken to realistically estimate the theoretical uncertainty, including that from the distribution functions and neglect of higher order corrections to the partonic scattering amplitudes, which in ordinary QCD have proven to be larger than originally estimated.

[22] I am grateful to T. Devlin for making these points.

[23] Keeping the distance between the two targets as small as possible is also desirable from the standpoint of being sensitive to relatively short-lived R^0's as well.

[24] The optical theorem relates the forward elastic cross section to the total cross section. Above the resonance region one would expect $\sigma(R^0 p) \sim \sigma(\pi p) \sim \sigma(pp)$ since the confinement scale rather than the color charge of the valence constituents seems most important in determining the size of a system of light, relativistic quarks or gluons or gluinos. Using lattice gauge theory, it might be possible to measure the color charge radius of the R^0 or at least its ratio to that of the pion or nucleon, to improve upon this crudest possible estimate. Or one could use information from LGT on glueball masses to try to constrain a bag model for color octet constituents and then determine their radius.

[25] I am indebted to W. Willis for emphasizing this point.

long gluino lifetimes are natural. The phenomenology of such light, long-lived gluinos is the subject of the present paper. Some aspects of the phenomenology of the associated LSP are discussed in Ref. [5]. A very light gluino (mass of order a few hundred MeV or less) is particularly attractive since it emerges naturally when dimension-3 SUSY breaking operators are absent from the low-energy theory, as is the case in hidden sector dynamical SUSY breaking with no gauge singlets [59]. Consideration of the pseudoscalar spectrum is shown to imply that the gluino mass must be greater than $\sim$ 100 MeV. A very light gluino would lead to new hadrons, the R^0 $(g\tilde{g})$, and S^0 $(uds\tilde{g})$, with masses around $1\frac{1}{2}$ GeV. Experiments to definitively rule out or discover them are possible but very challenging. Existing direct and indirect experimental constraints are reviewed and found not to address the most interesting scenarios. Experiments directed at the higher mass range are also mentioned.

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