Photoproduction of Very Light Gluinos

C.E. Carlson and Marc Sher
Physics Department, College of William and Mary, Williamsburg, Virginia 23187
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Current experiments allow the possibility of gluino masses below about 600 MeV if the lifetime of the gluino is longer than 100 psec. If the mass and lifetime are in this window, then photoproduction of pairs of gluino-gluon bound states can provide a means to observe them. The cross section is large enough that the window can be fully explored, up to lifetimes exceeding a microsecond, at high luminosity electron accelerators.

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In recent years, an apparent inconsistency between the value of α_s at low energies and that at the mass of the Z has led to a revival of interest in the possibility of very light gluinos [1]. Although the latest data seems to be consistent, within errors, both with and without light gluinos, the possibility that the gluino is extremely light needs to be thoroughly explored.

In 1987, the UA1 Collaboration [2] published a detailed analysis of the experimental searches for gluinos. They found three allowed windows in the gluino-squark mass plane: (i) gluino masses below approximately 600 MeV and squark mass above something like 100 GeV, (ii) a triangular shaped window for gluino masses between 2.5 and 4.0 GeV and squark masses between 100 and 400 GeV, and (iii) a window for gluino masses between 2.0 and 5.0 GeV and squark masses in the TeV range. These windows are all controversial; looking at the long listings in the Particle Data Group table [3] for gluino masses will show the extent of the controversy. In this Letter, we will focus on the most intriguing window—gluino masses below 1 GeV.

Because of R parity, gluinos will always be produced in pairs. Once produced, they will either combine with each other into a $\tilde{g}\tilde{g}$ state, a "gluinoball," and then annihilate quickly into hadrons, or else they will hadronize with gluons or quarks into a "glueballino" ($g\tilde{g}$) or a "gluino hybrid" or "hybridino" ($\tilde{g}q\overline{q}$) state. In the case of the single-gluino hadron, the lightest resulting state will be long-lived, since the gluino will decay into a $q\overline{q}\tilde{\gamma}$ via squark exchange with a lifetime approximately given by [4]

$$\tau \sim (3\times 10^{-12}\ \text{sec})\left(\frac{1\ \text{GeV}}{\widetilde{M}}\right)^5\left(\frac{m_{\text{squark}}}{m_W}\right)^4, \qquad (1)$$

where $\widetilde{M}$ is the mass of the $g\tilde{g}$ or $\tilde{g}q\overline{q}$ state. For squark masses between 50 and 2000 GeV, this gives lifetimes ranging from a picosecond to a microsecond.

Present limits on light gluino masses come from searches for $\tilde{g}\tilde{g}$ gluinoballs in radiative heavy vector meson decays (e.g., $\Upsilon \rightarrow \gamma+$ gluinoballs). Such processes have the advantage of being completely independent of the gluino lifetime, squark masses, etc. The best bound comes from the CUSB Collaboration [5], who exclude gluinos with masses between 600 and 2200 MeV coming from radiative Υ decays. The lower bound comes from the low detection efficiency of low multiplicity final states, and is quite uncertain. (The bound refers to half the gluinoball mass. The gluinos could conceivably be somewhat heavier or lighter, or even massless.) The bound has been criticized [6] since the determination of the expected branching ratio [7] is very strongly dependent on the value of the wave function at the origin of the gluinoball, and is thus quite model dependent, and because decays into more expectable things such as $\gamma+\eta'$ and $\gamma+$ glueball have also not been seen.

Lifetime limits come from searches for $g\tilde{g}$ glueballinos or a $\tilde{g}q\overline{q}$ state in beam dump experiments. Such experiments have conclusively ruled out [8] gluinos with lifetimes less than 10^{-10}–10^{-11} sec. If a $\tilde{g}q\overline{q}$ *charged* state has a lifetime greater than $\sim 10^{-10}$ sec, then it would have been detected [9] in hyperon beam experiments. However, if the mass of the $\tilde{g}q\overline{q}$ state is sufficiently greater than the glueballino then it will decay strongly into the glueballino, and such a bound would not be relevant. (In several models, the $\tilde{g}d\overline{u}$ state will be sufficiently heavy to decay into a glueballino and one or two pions; however, in most of these models, the $\tilde{g}s\overline{u}$ state will not be able to decay strongly into a glueballino and a kaon. In these models, the uncertainties in the masses are sufficiently large that such a decay cannot be excluded; furthermore, the W-mediated decay of the $\tilde{g}s\overline{u}$ into a glueballino and a charged pion will occur with a lifetime of approximately 10^{-10}–10^{-11} sec, and thus might not be detected in the hyperon beam.) We conclude that there may still be a window for gluino masses less than approximately 1000 MeV and lifetimes between 100 psec and a microsecond if the lightest gluino containing hadron is a $g\tilde{g}$ glueballino. In this Letter, we will propose an experiment that could close this window—or find the gluino.

In order to detect the decays of a neutral particle whose lifetime could be as long as a microsecond, one needs to produce them with very little kinetic energy (i.e., a relatively low energy machine) and with a very high luminosity. We will consider the photoproduction of light gluinos off a proton target at a high luminosity electron accelerator.

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The relevant diagrams are shown in Fig. 1. We will first consider the production rate of light gluinos, and then discuss signatures in the next section.

The square of the matrix element of the diagrams of Fig. 1 is given by

$$|M|^2 = \frac{64 g_s^4 e^2}{-\hat{u}\hat{s} r^4} \{ (r^2 - 2\Delta^2)(\hat{s}^2 + \hat{u}^2 + 2r^2 \hat{t}) + 8r^2 [(p \cdot \Delta)^2 + (p' \cdot \Delta)^2] \}, \quad (2)$$

where r^2 is the invariant mass of the gluino pair, Δ is half the difference between the four-momenta of the gluinos, and p and p' are the four-momenta of the initial and final quarks, respectively. We have omitted a factor e_q^2 for the quark charge which we shall restore before our final calculation. In integrating over phase space, it is convenient to first write the integrals in covariant form, pick the $\mathbf{r} = 0$ frame, do the integrations over gluino momenta, and reexpress the result in covariant form before doing the integral over the outgoing quark directions in the subprocess center of mass. The resulting cross section is given by

$$\frac{d\hat{\sigma}}{d\epsilon} = \frac{64 \alpha \alpha_s^2}{3} \frac{(1 - \epsilon - \tilde{\mu}^2)\sqrt{1 - \frac{4\tilde{\mu}^2}{1-\epsilon+\mu_q^2}}}{(1-\epsilon)^2} \times \left(2\left[(1-\epsilon)^2 + \epsilon^2\right] \ln \frac{1+\beta}{1-\beta} + 4\epsilon - 3\epsilon^2 \right), \quad (3)$$

where $\tilde{\mu}$ and μ_q are the gluino mass and target quark mass scaled by $\sqrt{\hat{s}}$ and ϵ is twice the outgoing quark energy (in the subprocess center of mass) scaled by $\sqrt{\hat{s}}$. Here, $\beta = \sqrt{1 - 4\mu_q^2/\epsilon^2}$ is the final quark velocity. We kept the mass of the final state quark only when necessary to avoid infrared singularities—letting the quark mass vary from 300 to 1000 MeV will give an indication of the sensitivity of the calculation to this mass. The limits of ϵ integration are from $2\mu_q$ to $1 - (4\tilde{\mu}^2 - \mu_q^2)$.

After we obtain the subprocess cross section, we must embed the target quark in a proton and integrate over the allowed range of $\hat{s}$. For various incoming photon energies and various particle masses, we obtain the cross sections shown in Fig. 2. Some details follow.

We fold the subprocess cross section with the distribution functions of the quark in a proton,

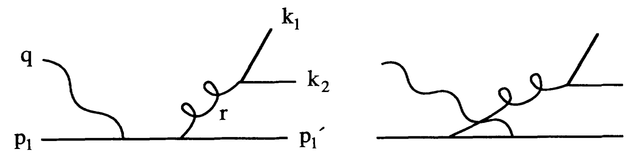

FIG. 1. Feynman diagrams for photoproduction of gluino pairs via photoproduction off a quark. The corkscrew line is a gluon and the lines labeled k_1 and k_2 are the gluinos.

$$\sigma = \int dx \sum_q e_q^2 f_q(x) \hat{\sigma}(\hat{s}) = \int dx\, \hat{\sigma}(\hat{s}) F_{2p}(x)/x, \quad (4)$$

where F_{2p} is the proton electromagnetic structure function and the scale (i.e., Q^2, where Q is some relevant momentum transfer) dependence of f_q is tacit. We used the up-to-date CTEQ distributions [10], specifically CTEQ1L, for Fig. 2. [In addition, some old but simple distribution functions [11] were used for calibration purposes. The results using the Ref. [11] distributions were about 30% below the CTEQ results over most of the plotted range, although they were slightly higher very near threshold. This mirrors the behavior of the distributions functions in x, since the closer we are to threshold in our process the higher the average x must be, and the Ref. [11] distributions are higher (and actually fit the limited amount of nonresonance region data better) at high x, whereas the CTEQ distributions are higher (and fit the data better) at $x < 0.75$. The average x for the top curve in Fig. 2 is unity at threshold, passes 0.75 at $\omega = 6$ GeV, and is 0.39 at the right hand edge.]

The relation between x and $\hat{s}$ at high energy, where one can neglect masses, is clear. One has $x = \hat{s}/s$. We have used a modification of this just to ensure that the threshold points of $\hat{s}$ and s are maintained, namely,

$$x = \left(\frac{\sqrt{\hat{s}} - m_q}{\sqrt{s} - m_N} \right)^2, \quad (5)$$

where m_N is the nucleon mass. This has little effect except near threshold where the cross section is small anyway.

We envision each gluino within a glueballino (a bound state of gluinos with gluons) so that the mass necessarily

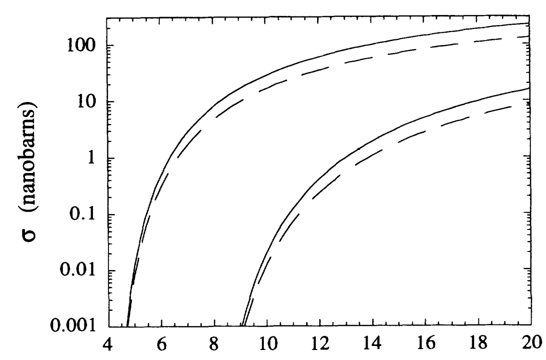

FIG. 2. The total cross section for photoproduction of glueballino pairs. The upper curves are both for glueballino mass (inserted for $\tilde{m}$ in our formulas) of 1.0 GeV and the lower curves have glueballino mass 1.5 GeV. The solid curves are for quark mass m_q of 0.3 GeV and the dashed curves use m_q = 1.0 GeV. The CTEQ1L quark distributions at their benchmark of $Q^2 = 4$ GeV^2 were used for this figure. As seen, the results are sensitive to gluino mass but not to quark mass.

produced is at least that of the glueballino, and in evaluating our formulas we have interpreted $\tilde{m}$ as the glueballino mass. Regular glueballs are not massless even though the gluon is, and we anticipate that the glueballino will be in the same mass range, namely a mass of about 1.5 GeV for the lightest example (see, e.g., the lattice gauge results reported in [12]). Our cross section is sensitive to this mass, as may be seen from the figures, where we present results for $\tilde{m}$ being both 1.0 and 1.5 GeV. The cross section is in contrast insensitive to changes in the quark mass.

A signature of a gluino in the mass and lifetime range we are considering is that it appears in certain aspects as a long lived particle and in other aspects as a short lived particle. The particle is in fact long lived so that there should be a noticeable gap between its production point and decay point. The gluino decay will be into a photino plus nonsupersymmetric particles and the photino will exit undetected and with its energy undetermined. The ordinary matter from the glueballino decay will therefore have a variable energy and will appear like a strongly unstable particle with a wide width. The apparent width of the decay will of course not have a Lorentzian shape, but this may not be apparent if the statistics are limited in a first experiment.

The cross section scale, a couple of GeV above threshold, is of the order of nanobarns. At the large acceptance spectrometer at CEBAF, a photon tagger will be able to produce a high luminosity monochromatic photon beam impinging directly on the target. The expected luminosity is 10^{34} cm^{-2}sec^{-1}, resulting in approximately ten events per second. At electron accelerators without a photon tagger, of course, one would have to convolute the photoproduction cross section with the distribution of real photons in the electron beam, and also calculate the rate for virtual photons.

With lifetimes in the 10^{-10} to 10^{-6} sec range, the glueballinos will travel between 3 cm and 300 m. Even for the longer lifetimes, 1% of the glueballinos will decay within a typical detector (roughly 3 m in size), corresponding to one every 10 sec at CEBAF. At higher energy machines, the luminosity is generally considerably lower, and the glueballinos will travel farther due to the time dilation factor, resulting in many fewer decays in the detector. Nonetheless, the number of events is sufficiently large that experimenters at these machines should consider searching for gluino signatures.

As noted above, the glueballino will decay into an undetected photino and a quark-antiquark-gluon hybrid, which will immediately decay into strongly interacting hadrons. An interesting final state such as four charged pions, would, to judge from the decays of other particles in this mass range [3], have a branching ratio not less than a part in a thousand. Thus, one expects at worst an event every few hours in which four pions emerge from a point which is at least a few centimeters from the target. We know of no background to this signature, and thus, even including detector efficiencies in detecting four charged particles, CEBAF should be easily able to explore the window, up to its kinematic limit. (One could also look for two- and three-body final states, which may also appear with significant apparent width noticeably far from the interaction region, although the backgrounds would be larger.)

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