Photoproduction of very light gluinos

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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 picoseconds. 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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1 Introduction

In recent years, an apparent inconsistency between the value of $\alpha_s$ 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” ($\tilde{g}q\bar{q}$) state. In the case of the single gluino hadron, the lightest resulting state will be long-lived, since the gluino will decay into a $g\tilde{q}\gamma$ via squark exchange with a lifetime approximately given by \[4\]

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

where $\tilde{M}$ is the mass of the $g\tilde{g}$ or $\tilde{g}q\bar{q}$ 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., $\Upsilon \rightarrow \gamma + \text{gluinoballs}$). Such processes have the advantage of being completely independent of the gluino lifetime, squark masses, etc. The best bound comes from CUSB \cite{5}, who exclude gluinos with masses between 600 and 2200 MeV coming from radiative $\Upsilon$ decays. The lower bound comes from the low detection efficiency of low multiplicity final states, and is quite uncertain.\footnote{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 \cite{6} since the determination of the expected branching ratio \cite{7} is very strongly dependent on the value of the wave function at the origin of the gluino-ball, 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 $\tilde{g}g\bar{q}$ states in beam dump experiments. Such experiments have conclusively ruled out \cite{8} gluinos with lifetimes less than $10^{-10} - 10^{-11}$ seconds. If a $\tilde{g}g\bar{q}$ charged state has a lifetime greater than $\sim 10^{-10}$ seconds, then it would have been detected \cite{9} in hyperon beam experiments. However, if the mass of the $\tilde{g}g\bar{q}$ state is sufficiently greater than the glueballino then it will decay strongly into the glueballino, and such a bound would not be relevant.\footnote{In several models, the $\tilde{g}d\bar{u}$ state will be sufficiently heavy to decay into a glueballino and one or two pions; however, in most of these models, the $\tilde{g}s\bar{d}$ 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 $\tilde{g}s\bar{d}$ into a glueballino and a charged pion will occur with a lifetime of approximately $10^{-10} - 10^{-11}$ seconds, 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 picoseconds 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.

## 2 Photoproduction of light gluinos

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

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

where \(r^2\) is the invariant mass of the gluino pair, \(\Delta\) 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 \(\vec{r} = 0\) frame, do the integrations over gluino momenta, and re-express 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

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

where \(\tilde{\mu}\) and \(\mu_q\) are the gluino mass and target quark mass scaled by \(\sqrt{s}\) and and \(\epsilon\) is twice the outgoing quark energy (in the subprocess center of mass) scaled by \(\sqrt{s}\). 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 $\epsilon$ 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 Figure 2. Some details follow.

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

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

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. 3.

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

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

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

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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 non-resonance 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. 3 is unity at threshold, passes 0.75 at $\omega = 6$ GeV, and is 0.39 at the right hand edge.
that the mass necessarily 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.

3 Signatures of gluino production

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. For lifetimes near the low end of the $10^{-10}$ to $10^{-6}$ second range and a roughly 10 GeV incoming photon beam, many of the gluinos produced will have a measurable gap before decay, while for lifetimes near the high end of the range, some gluinos (at least 1%) will decay in the detector.

The gluino will decay into a photino plus non-supersymmetric 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 is of the order of nanobarns. For a photon luminosity of $10^{34}$ cm$^{-2}$sec$^{-1}$, a number pertinent to the large acceptance spectrometer at CEBAF, a nanobarn gives ten events per second. Higher energy machines will be less suitable for
detecting gluinos with long lifetimes due to both the time dilation factor as well as lower luminosity.

A final state such as four charged pions, would, to judge from the decays of other particles in this mass range \[3\], have a sufficient branching ratio to give several gluino counts per hour if they are there. This final state would be easily detectable and there seems to be no other particle that could produce it with a significant apparent width, and yet have its decay point significantly separated from its production location. \[4\]

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\[4\] 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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Figure 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.

Figure 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.
This figure "fig1-1.png" is available in "png" format from:

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