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Light Gluinos

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A light gluino is not presently excluded experimentally if the lightest of the gluino-containing (R-)hadrons are long lived. In this case the properties of R-hadrons are very different than has been previously assumed. Strategies for their detection are suggested.

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The properties of gluinos and hadrons containing them were originally examined[1] under the assumption that the supersymmetric partners of the u and d quarks have masses comparable to the W and Z masses, and that the photino is lighter than the gluino. In this case gluino-containing (R-)hadrons decay with weak-interaction-like lifetimes to ordinary hadrons plus a photino, so that the characteristic signature of R-hadron production is the escaping photino. Failure to detect the missing energy or reinteractions associated with the photinos leads to a limit on the R-hadron masses $\gtrsim 2$ GeV.[1,2] The purpose of this Letter is to point out that the possibility of a light gluino (say < 100 MeV) is not ruled out if the lightest R-hadrons are long lived, as they would be if they are lighter than the photino or the s-quarks (spin-zero quarks) are heavier than $\sim O(100\text{ GeV})$. Since cosmological bounds on the gravitino mass may indicate that s-quarks must be heavier than 10 TeV,[3] this possibility needs to be taken seriously. A light gluino is not only intrinsically interesting in itself,[4] but may prove to be necessary for consistency with the stringent limits on the electric dipole moment of the neutron.[5]

A gluino, being a color octet, must bind with quarks, gluons, or other gluinos to form color-singlet hadrons. Hadrons containing a single gluino and consequently anomalous quantum numbers from the standpoint of the ordinary quark-gluon model of hadrons have been called R-hadrons.[1] They carry a conserved quantum number (called R-parity[1,6,7]) and are therefore pair produced in ordinary hadron collisions. The lightest of the R-hadrons is likely to be an "R-glueball," a gluino-gluon bound state. Guided by glueball mass estimates (which unfortunately vary over a wide range), we can plausibly guess that the lightest R-glueball has mass 0.7–1.2 GeV if the gluino mass $m_{\tilde g}=0$. R-mesons, made of a $q\bar q$ pair in a color-octet state, bound to a gluino to make a color-singlet hadron, will form spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ flavor nonets. These almost surely will decay via strong interactions [e.g., as shown in Fig. 1(a)] to one or more pseudoscalar mesons and an R, since the pseudoscalar mesons are "anomalously" light because of their role as Goldstone bosons for chiral symmetry breaking.[8]

The R-baryons are more interesting. The three quarks must be in a color-octet state and they can have spin $\frac{1}{2}$ or $\frac{3}{2}$. (We can ignore excited states with $L \neq 0$ because they are surely heavy enough to decay strongly.) A spin-$\frac{1}{2}$ state can be a flavor singlet, octet, or decuplet, while the spin-$\frac{3}{2}$ state must be a flavor octet, in order that the three-quark state has the overall antisymmetry required by Fermi statistics. If we use the bag model with hyperfine splitting, and take the gluino mass to be ap-

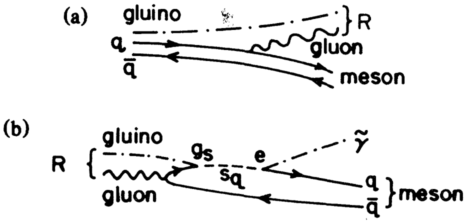

FIG. 1. (a) R-meson decaying strongly to R-glueball + meson. (b) R-glueball decay to photino + meson. The R-glueball is denoted by R, g_s is the QCD coupling constant, and s_q signifies the spin-zero quark.

proximately equal to the up- and down-quark masses, the lightest R-baryons have $J=0$ and are the flavor singlet (strangeness $=-1$!) at 0.6–1 GeV, flavor octet with R-nucleons at 0.9–1.2 GeV, and flavor decuplet with R-Δ's at 1.3–1.6 GeV. (Surprisingly, the lighter $J=1$ flavor octet has a slightly lower mass in the bag model than the $J=0$ octet.[9]) The flavor singlet will be very long lived or stable (see below). The R-nucleons probably decay to the strangeness -1 flavor-singlet R-baryon and a pion, in analogy with $\Lambda \rightarrow N\pi$, with lifetimes $\lesssim 10^{-10}$ sec. All heavier R-baryons can almost surely decay strongly into lower-mass R-hadrons, and thus are not detectable directly.

If the photino mass is greater than the mass of the R-glueball m_R, and no extra light superparticles are introduced in the theory, the R-glueball will be the lightest particle with negative R-parity and consequently will be absolutely stable, as will be the lightest R-baryon (probably the flavor singlet), on the assumption that its mass is less than the sum of the proton and R-glueball masses,[10] as seems plausible. On the other hand if the photino is light the R-glueball can decay, e.g., by the graph shown in Fig. 1(b). The lifetime of an R-meson of mass 1.2 GeV, decaying to mesons and a photino via the mechanism of Fig. 1(b), was estimated in Ref. 1 to be 10^{-12}–10^{-15} sec by analogy with known weak decays, assuming the s-quark mass $m_{\tilde{q}} \sim \sin\theta_W m_W$. If, instead, we use the gravitino mass $m_{3/2} > 10^4$ GeV to put a lower bound on $m_{\tilde{q}}$, we obtain as a rough estimate for the lifetime of a ~ 1.2-GeV R-glueball

$$\tau_R = (10^{-12}\text{–}10^{-15}\ \text{sec}) \left(\frac{m_{\tilde{q}}^2}{m_W^2 \sin^2\theta_W} \right)^2 > 10^{-3}\text{–}10^{-6}\ \text{sec} . \tag{1}$$

For an R-glueball of mass 0.7 GeV, a better analogy is with $K \rightarrow \mu\nu$. In this case we roughly expect that $\tau_R \sim (m_{\tilde{q}}/m_W)^4 \sin^2\theta_C \times 10^{-8}$ sec for a massless photino. Thus an s-quark mass as low as $2m_W$ would give $\tau_R \sim 10^{-6}$ sec which is difficult to exclude experimentally, as will become evident below. The flavor-singlet R-baryon decays to nucleon plus photino, requiring both an intermediate s-quark and a strangeness-changing weak interaction, so that even for an s-quark mass of m_W, the singlet R-baryon is essentially stable as far as accelerator experiments are concerned.

The crucial observation at this point is that the problem of detecting these "new" R-hadrons is totally different than if they are thought to decay rapidly to photinos. Missing energy is no longer a good signature for them: Because of their strong interactions and long lifetimes they will deposit their energy in a calorimeter and be absorbed in a beam dump like any ordinary hadron.

It is nontrivial to detect pair-produced, long-lived neutral particles such as the R-glueball and the singlet R-baryon, even if they are copiously produced. The best present limit on new neutral long-lived particles is for masses > 2 GeV,[11] well above the interesting mass range of $\lesssim 1$ GeV. With a lifetime $\lesssim 10^{-10}$ sec, the R-proton and R-neutron are too short lived to have been detected, even in the super proton synchrotron hyperon beam.[12]

The strangeness -1 of the flavor-singlet R-baryon (denoted by S below for brevity) may be useful in providing a signature: A reaction such as $pp \rightarrow K^+K^+ + SS$ could occur below threshold if the S mass is $\lesssim 1.1$ GeV, but in any case is distinguishable from $K^+K^+\Lambda\Lambda$ since the Λ's decay and the S's do not. However, particularly near threshold, S pair production may be strongly suppressed (e.g., by a factor of 100 or more) relative to Λ pair production, because of the difficulty of incorporating more than the minimal three degrees of freedom of the quarks. The cross section for a reaction such as $K^-p \rightarrow R$-glueball$+S$ may be less radically suppressed.

Given the uncertainty in estimating masses and production rates for the R-baryons, as well as the possibility that they, too, decay rapidly to R glueballs plus a baryon, it is desirable to search for R-glueball production.[13] Although the production cross section in hadron collisions may be as large as a few millibarns, and the background from ordinary hadrons might be reduced in ψ and Υ decays, establishing definitive evidence for this phenomenon and measuring the R-glueball mass is very demanding experimentally. In a scattering experiment, relatively low energy is desirable, say $p_{\text{lab}} \sim 30$ GeV, to keep the final multiplicity small. At this energy, threshold effects should not be important unless $m_R \gtrsim 1$ GeV. Very high detection efficiency for ordinary neutrals is essential, as is good momentum resolution. A sample of events is to be produced in which there are missing neutrals, which cannot be identified with known particles or pairs of known particles. A missing-mass plot for these events should display a continuum with a threshold at $2m_R$. Decreasing the beam energy and observing the disappearance of the signal as threshold is approached is important for establishing the authenticity of the signal. There should be occasional events in which one (or both) of the R-glueballs scatters, establishing its direction and a lower bound on its energy, thus providing two more constraints for the event reconstruction. With a large enough sample, the method of observing the secondary scattering can also yield m_R.

By virtue of containing only two constituents, the R-glueball + nucleon total cross section is likely to be comparable to $\sigma_{\pi N}$. Likewise the R-baryon probably has a total cross section $\sim \frac{4}{3}\sigma_{NN}$. These differences may be helpful in distinguishing the R-glueball and S from neutrons.

Theoretically, light gluinos seem to be acceptable. They affect the β function as much as three additional light quarks, so that asymptotic freedom is not lost. In principle deep-inelastic scattering experiments can measure β and thus infer the gluino contribution[14]; however, in actual experiments the q^2 range is too small to discriminate between nonstandard logarithmic variations and higher twist effects.

The chiral symmetry associated with massless gluinos is broken explicitly by their mass, dynamically by the gluino-gluino condensate $\langle \bar{\lambda}\lambda \rangle$, and by the QCD triangle anomaly of the gluinos. There is an anomaly-free linear combination of the gluino axial current with the quark U(1) axial current, which for three flavors is $2^{-1/2}(\bar{q}\gamma_\mu\gamma_5 q - \bar{\lambda}\gamma_\mu\gamma_5\lambda)$. Identifying the pseudo-Goldstone boson associated with the spontaneous breakdown of this symmetry with the η', standard current-algebra arguments[15] give $F_{\eta'}^2 m_{\eta'}^2 = 2m_{\tilde{g}}\langle \bar{\lambda}\lambda \rangle$, neglecting the negligible contribution of the quarks. To account for the observed mass of the η' requires that $m_{\tilde{g}}\langle \bar{\lambda}\lambda \rangle / F_{\eta'}^2 \sim 14 m_s \langle \bar{s}s \rangle / F_\eta^2$, where $\langle \bar{s}s \rangle$ is the strange-quark condensate and m_s the strange-quark mass. Tumbling arguments, which have had confirmation from lattice gauge calculations,[16] indicate that this is quite plausible, especially with $m_{\tilde{g}} \sim m_s$. Current-algebra predictions for processes involving the η' can be used to test the hypothesis that it is a pseudo-Goldstone boson.[17] This picture, that the η' is "half the time" a $q\bar{q}$ pair and "half the time" a gluino pair, has some encouragement from recent experiments which have found the $\eta' \to \gamma\gamma$ width to be significantly smaller than expected in the quark model.[18]

Recapitulating, I have argued that the possibility of a very light gluino is both theoretically acceptable and not ruled out by present experiments. More generally, long-lived neutral R-hadrons and long-lived gluinos, be they light or heavy, are not ruled out by experiments relying on a missing-energy signature. (Gluino jets produced in the $p\bar{p}$ collider would resemble quark and gluon jets if they did not decay to a photino before hadronization.) This means that limits on gluino production and masses are not independent of the masses of the photino and s-quarks.

I have benefitted greatly from the generosity of many colleagues in offering suggestions for detection possibilities, in teaching me what they know of relevant calculational techniques, and generally in being skeptical that such things as new stable baryons could have escaped our notice. I especially want to thank G. Baym, T. Devlin, P. Fayet, A. Guth, R. Jaffe, K. Johnson, M. Kalelkar, J. Lach, L. Littenberg, M. Ross, H. Steiner, J. Weiss, S. Weinberg, E. Witten, and T. Yamagouchi.

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[1] G. R. Farrar and P. Fayet, Phys. Lett. **76B**, 442, 575 (1978).

[2] See also G. Kane and J. Leveille, Phys. Lett. **112B**, 227 (1982), for the case $m_{\tilde{g}} \gtrsim 1.5$ GeV in the "old" scenario, and T. Goldman, Phys. Lett. **78B**, 110 (1978), for the case of charged R-mesons with $\tau \sim 10^{-10}$ sec.

[3] In models in which supergravity induces supersymmetry breaking, the s-quarks and s-leptons characteristically have masses comparable to the gravitino mass $m_{3/2}$. Thus $m_{3/2} \gtrsim 20$ GeV is necessary for compatibility with mass limits on scalar leptons [G. R. Farrar and P. Fayet, Phys. Lett. **89B**, 191 (1980); S. Yamada, in Proceedings of the 1983 International Symposium on Lepton and Photon Interactions, Cornell University, 1983 (to be published)]. As long as the gravitino is this heavy it must be massive enough that when the big-bang gravitinos decay the temperature of the universe increases enough to give nucleosynthesis a fresh start, which requires $m_{3/2} > 10^4$ GeV. [S. Weinberg, Phys. Rev. Lett. **48**, 1303 (1982); see also P. Fayet, in *Proceedings of the Seventeenth Rencontre de Moriond, Moriond, 1982,* edited

by J. Trân Thanh Vân (Editions Frontières, Gif-sur-Yvette, 1982); L. Krauss, Nucl. Phys. **B227**, 556 (1983), shows that, contrary to the conclusion of J. Ellis, A. D. Linde, and D. V. Nanopoulos, Phys. Lett. **118B**, 59 (1982), and D. V. Nanopoulos, K. A. Olive, and M. Srednicki, Phys. Lett. **127B**, 30 (1983), reasonable inflationary models do not evade the bound. It may not prove possible to build a satisfactory supersymmetric grand-unified theory model with $m_{3/2} > 10$ TeV but I do not address that question here.]

[4] Radiative corrections to gaugino masses have been calculated to one loop by R. Barbieri, L. Girardello, and A. Masiero, Phys. Lett. **127B**, 429 (1983), and to two loops by R. Barbieri and L. Maiani, Istituto di Fisica, Università di Pisa Report No. TH 7/84 (to be published), in $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)$ models in which supersymmetry is broken by supergravity. Depending on parameters, the gluino is lighter or heavier than the photino; both can have a large range of possible masses.

[5] W. Buchmüller and D. Wyler, Phys. Lett. **121B**, 321 (1983), and J. Polchinski and M. Wise, Harvard University and California Institute of Technology Report No. HUTP-83/A016-CALT-68-1011 (unpublished), find a neutron electric dipole moment about three orders of magnitude larger than the experimental bound, for $m_{\tilde q}$ and $m_{\tilde g} \sim 100$ GeV, assuming mixing angles are $O(1)$. Since the gluino contribution $\sim m_{\tilde g}/m_{\tilde q}^2$, a gluino mass of 100 MeV provides adequate suppression, even without assuming that the s-quarks are heavier than 100 GeV, or that mixing angles are extremely small.

[6] P. Fayet, in *Unification of the Fundamental Particle Interactions,* edited by S. Ferrara, J. Ellis, and P. van Nieuwenhuizen (Plenum, New York, 1980).

[7] G. R. Farrar and S. Weinberg, Phys. Rev. D **27**, 2732 (1982).

[8] M. Chanowitz and S. Sharpe, Phys. Lett. **B126**, 225 (1983), have estimated the R-meson masses; although they focus mainly on the case of a heavy gluino, they find that the mass of the R-glueball is less than the mass of the R-meson for the light gluino of interest here.

[9] For a complete calculation of the $L=0$ masses see G. Farrar, F. Buccella, and A. Pugliese, to be published. I am also indebted to R. Jaffe and K. Johnson for their help in evaluating the hyperfine splitting in the $J=0$ R-baryon sector. The existence of nuclei implies that the lightest R-baryon is heavier (or only very slightly lighter) than the nucleon, since otherwise the doubly weak reaction $NN \rightarrow R$-baryon pair would cause nuclei to disintegrate. I am grateful to E. Witten for this observation, which argues for the upper end of the quoted bag-model mass ranges.

[10] Effects which could conceivably break R-parity conservation are likely to be extremely small, like baryon-number nonconservation, and so we ignore them here. An absolutely stable singlet R-baryon is unacceptable if it binds to a proton because it would have been detected in the high-sensitivity experiment of R. Muller *et al.*, Science **196**, 521 (1977), unless its mass were $\gtrsim 1.4$ GeV to sufficiently dilute its expected abundance.

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

[12] M. Bourquin *et al.*, Nucl. Phys. **B153**, 13 (1979). See also W. Bartel *et al.*, Z. Phys. C **6**, 295 (1980); J. Weiss *et al.*, Phys. Lett. **101B**, 439 (1981); B. Alper *et al.*, Phys. Lett. **46B**, 265 (1973); J. Badier *et al.*, Phys. Lett. **39B**, 414 (1972); J. A. Appel *et al.*, Phys. Rev. Lett. **32**, 428 (1974).

[13] In the same spirit of skepticism regarding theoretical calculations, it would be worthwhile to explore experimentally the possibility that the lightest R-baryons are R-Δ's. In this case there should be long-lived charge-2 baryons. For a discussion of this possibility see, G. R. Farrar, Rutgers University Report No. RU-83-49 (unpublished).

[14] G. R. Farrar and E. Monsay, unpublished; G. R. Farrar, in Proceedings of the Cornell Workshop on *Z* Physics, 6–8 February 1981 (unpublished), and Rutgers University Report No. RU-81-07 (to be published); I. Antoniadis, C. Kounnas, and R. Lacaze, Nucl. Phys. **B211**, 216 (1983).

[15] Such as used by S. Weinberg, Phys. Rev. D **11**, 3583 (1975), to derive his famous relation $m_{\eta'} < \sqrt{3}\, m_\pi$ when only quarks contribute to the chiral U(1) current.

[16] S. Raby, S. Dimopoulos, and L. Susskind, Nucl. Phys. **B169**, 373 (1980); J. Kogut, J. Shigemitsu, and D. K. Sinclair, "The Scale of Chiral Symmetry Breaking with $I=1$ Quarks in SU(2) Gauge Theory" (to be published).

[17] Unfortunately, light gluinos in this description do not provide a solution to the strong *CP* problem, because the requirement that the vacuum be stable against η' emission fixes the relative phases in the quark and gluino mass matrices, so that *CP*-nonconserving phases cannot be rotated at will from the quarks into the harmless gluino sector.

[18] Ch. Berger, in Proceedings of the 1983 International Symposium on Lepton and Photon Interactions, Cornell University, 1983 (to be published).