# PHENOMENOLOGY OF THE PRODUCTION, DECAY, AND DETECTION OF NEW HADRONIC STATES ASSOCIATED WITH SUPERSYMMETRY ☆

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Received 11 April 1978

Supersymmetric theories involve spinorial partners for the gluons of QCD. If the symmetry breaking is such that they are massless or light, they probably combine with quarks to form families of new, relatively low-lying hadronic states, which decay into ordinary hadrons and a new, neutrino-like particle. We discuss how present experiments can put limits on their production.

Supersymmetry [1] is an attractive idea to go beyond the relativistic invariance of gauge theories for the description of particles and their interactions. It turns bosons into fermions and vice versa. If supersymmetry were perfect they would be degenerate in mass, which is clearly not the case in nature. However, supersymmetry could be realized as a spontaneously broken invariance, so that the physical states would not be degenerate, even though the fundamental interaction is supersymmetric. Since we know only part of the spectrum, it is possible that known particles do have partners under supersymmetry which are still to be discovered.

Supersymmetric models have been constructed which appear sufficiently realistic in their description of strong, electromagnetic and weak interactions [2] (together with gravitation [3] when supergravity [4] is included) that supersymmetry can be regarded as a possible invariance of the lagrangian of the world. Therefore it is important to work out its experimental consequences.

Many of the new fields introduced as supersymmetry partners of the ordinary fields are heavy (the most typical mass scale being $m_W$, the mass of the intermediate vector boson $W^{\pm}$); however the existence of several massless (or low-mass) spinorial fields in important classes of supersymmetric theories may lead to phenomena observable in present-day experiments. We show below how available data can place bounds on the production cross section of new hypothetical hadronic states called *R-hadrons*, and we comment on the implication of these bounds for supersymmetric models.

To be definite we shall present our analysis in the framework of a class of supersymmetric theories admitting a conserved quantum number, $R$, carried by the supersymmetry generator, and preserved by the spontaneous symmetry breaking [5]. (The $R$-invariant theories are particularly natural and attractive and have, therefore, received the greatest theoretical attention; however our phenomenological analysis is considerably more general and includes theories without $R$-invariance, as we shall explain in footnote 7.) Bosons (fermions) having $R = 0$ are associated, under supersymmetry, with fermions (bosons) having $R = \pm 1$. The former, $R = 0$, particles will be identified with the familiar particles of ordinary gauge theories; among the latter ($R = \pm 1$) are their partners under supersymmetry. After the spontaneous breaking of weak interaction gauge invariance, the theory involves massless and massive particles in "gauge multiplets" interacting with those in "matter multiplets." The par-

☆ Work supported in part by the U.S. Department of Energy under Contract EY76-C03-0068.
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Table 1
Particle content of the theory with the assignment of $R$-number indicated in parentheses.

| Multiplets | Vectors | Spinors | Scalars |
|---|---|---|---|
| Massless gauge multiplets | photon (0)<br>gluons (0) | photino (1)<br>gluinos (1) | |
| Massive gauge multiplets | intermediate vector bosons (0) | heavy leptons (±1) | Higgs scalars (0) |
| Matter multiplets | | quarks (0)<br>e, $\nu_e$ (0)<br>$\mu$, $\nu_\mu$ (0)<br>... | scalar quarks (±1)<br>scalar leptons (±1)<br>scalar leptons (±1)<br>... |

ticle content is indicated in table 1.

In addition supersymmetry is spontaneously broken, so that the scalar partners of the usual leptons and quarks are heavy. The spontaneous breaking means that a massless Goldstone spinor (*Goldstino*) ‡1 appears [6], which has $R = 1$ like the spin-1/2 particles associated with the photon and the octet of vector gluons (*photino* and *gluinos*, respectively). The first important remark is that $R$-invariance forces the gluinos of the simplest models to be massless [7], although in general gluinos could be massive (see footnotes 7 and 8).

*The R-hadrons.* The gluinos, which are flavor singlets and belong to a color SU(3) octet, interact strongly with the octet of gluons and may combine with quarks, antiquarks and gluons in much the same way as quarks presumably do, giving new hadronic states carrying one unit of $R$, which we call $R$-hadrons. Combined with qqq, $q\bar{q}$ or simply gluons, gluinos lead, respectively, to new bosonic states ($R$-baryons) and new fermionic states ($R$-mesons, $R$-glueballs) which are color-singlets with a flavor multiplet structure similar to ordinary baryons, mesons and glueballs.

These states should be produced in pairs in hadronic reactions. Naively, since the gluino–gluon interaction is like the quark–gluon interaction except for Clebsch–Gordan coefficients, one can expect $R$-hadron pair production comparable to the pair production of corresponding hadrons of comparable mass. In particular the $R = \pm 1$ fermionic partners of the glueballs should be relatively easy to produce if they are not too massive. The lowest glueball mass is predicted in the bag model to be 960 MeV/$c^2$ [8] and in any event should be less than 1.5 GeV/$c^2$ [9]. If the gluinos are indeed massless, 1–1.5 GeV/$c^2$ is a reasonable estimate of the mass of the $R$-glueball, and the production of $R$-hadrons should naively be at the millibarn level in high-energy interactions ‡2.

*Decays of R-hadrons.* Depending on the mass spacing of the $R$-baryons, $R$-kaons, $R$-pions, $R$-glueballs, etc., all or some of the $R$-hadrons may have strong and/or electromagnetic decays to an $R$-glueball (presumably the lowest mass $R$-hadron). Thus there may be one or several $R$-hadrons which are stable to strong and electromagnetic decays.

However, even these $R$-hadrons are unstable and decay to ordinary hadrons by emitting a Goldstino or a photino, which we collectively denote as *nuinos* ‡3. We will return to the behaviour of the nuinos after estimating the typical lifetime of these $R$-hadrons.

The elementary tree diagrams responsible for the decays are shown in fig. 1. a gluino is absorbed, turning a quark into a heavy spin-0 quark, which gives back the original quark (whose color has been changed)

‡1 When gravitation is included the Goldstino is in fact eliminated and the *gravitino* (spin 3/2 partner of the graviton) acquires a mass. However a very light massive gravitino has much the same behavior as a Goldstino [3], so that including explicitly the effects of gravitation does not affect our analysis here.

‡2 The importance of the possible production of these states has been emphasized by M. Gell-Mann.

‡3 "Nuinos" were called "$R$-neutrinos" in the preprint (CALT 68-648) of this letter.

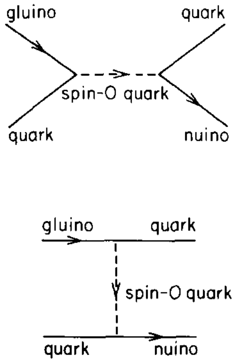


Fig. 1. Diagrams responsible for the decay of $R$-hadrons. The spin-0 quarks exchanged are those denoted by s and t in ref. [2], with $R = +1$ and $R = -1$ respectively. The arrows show $R$-number = +1 flow.

and a nuino. Altogether, the $R$-hadron has lost its gluino by emitting a nuino, with charge, color, $R$, etc., all conserved.

The diagrams of fig. 1 lead, in the local limit, to effective four-fermion interactions with Fermi-type coupling constants

$$G_{\text{decay}} \sim g_1 g_c/m_s^2 \quad \text{and} \quad g_2 g_c/m_t^2, \tag{1}$$

in which $g_1$ or $g_2$ (coupling constants depending on the quark, the spin-0 quark, and the nuino considered) and $g_c$ (the QCD "strong" coupling constant) come from the nuino and gluino vertices, respectively, and $m_s$ and $m_t$ are the spin-0 quark masses. Although various hypotheses on the masses and coupling constants are possible we shall examine here only the simplest one [2]: the mass$^2$-gap between scalar and spinor quarks, due to spontaneous supersymmetry breaking, is of the same order of magnitude as the mass$^2$-gaps due to the spontaneous breaking of weak interaction gauge invariance (i.e., $m_s^2$ and $m_t^2 \sim m_W^2$); and the nuino couplings are of the order of the semi-weak coupling constant $g$ (where $G_F \sim g^2/m_W^2$), as is the case for the photino couplings, which are fixed by the electrical charge. Then

$$G_{\text{decay}} \sim g g_c/m_W^2 \sim (g_c/g)\, G_F, \tag{2}$$

so that, when we compare with ordinary weak decays, we have an extra factor $\sim g^2/g_c^2$ in the lifetimes of $R$-hadrons.

Roughly, $g^2/4\pi \sim \alpha$ and $g_c^2/4\pi$ is between $\sim 0.1$ and 1 depending on whether the QCD coupling strength is fixed by the large spin-0 quark mass scale or the lower, hadronic, mass scale. Crudely, this introduces in the lifetimes of $R$-hadrons an extra factor $10^{-1}$–$10^{-2}$ relative to ordinary weak decay, and there is no factor $\sin^2\theta_c$ as in strangeness-changing weak decays, so that an $R$-hadron lifetime should be $10^{-2}$–$10^{-3}$ times that of an ordinary strangeness-changing decay with comparable kinematics. We have used several estimation methods and conclude that, e.g., an $R$-pion or $R$-glueball of mass 1.2 GeV/$c^2$ (which are expected to decay predominantly to $\pi$–$\pi$–nuino) should have a lifetime $\sim 10^{-12}$–$10^{-15}$ s ‡4. In fact, the lifetime range in which $R$-hadrons might be found is even larger than $10^{-12}$ to $10^{-15}$ s, due to its sensitivity to the $R$-hadron mass. For instance, reducing or increasing the mass from 1.2 GeV/$c^2$ by 0.5 GeV/$c^2$ increases or decreases the lifetime by roughly an order of magnitude.

*Detection of R-hadrons.* A striking feature of $R$-hadrons is their rapid decay into hadrons plus a massless, neutral nuino, with no accompanying lepton. Thus their hadronic pair production could be inferred from a careful study of apparent energy–momentum nonconservation in hadron collisions, in events with no final charged lepton. While this method is the best since it is the least sensitive to theoretical uncertainty in the behavior of $R$-hadrons and nuinos, we discuss below two other methods which rely on published experimental results.

First, experiments searching for tracks due to charmed particles (which are expected to have lifetimes in the $10^{-12}$–$10^{-14}$ s range) could be sensitive to observation of $R$-hadrons if their lifetimes are in this range, as long as a lepton is not required in a trigger. In particular 300 GeV proton–nucleus interactions have been examined for evidence of decaying short-lived particles; the results were interpreted to indicate that the pair production cross section for particles with

‡4 The large uncertainty in this estimate reflects:
(a) the uncertainty in $g_c^2$ mentioned above;
(b) the uncertainty in the coupling constants $g_1, g_2$, and the mass of the spin-0 quarks, due to model-dependent parameters such as mixing angles;
(c) the uncertainty in the hadronic dynamics involved in the pion, kaon and hyperon decays which we used for comparison.

lifetimes in the $10^{-12}$–$10^{-14}$ s range is less than 1.5 $\mu$b [10].

Fortunately there is a method of obtaining a limit on, or measure of, the $R\bar{R}$ production cross section which does not require $R$-hadron lifetimes in such a restricted range. Namely, observe the emitted nuinos. In agreement with $R$-conservation, nuinos interact with matter in two ways:

$$\text{nuino} + \text{hadron} \to R\text{-hadron} + \text{hadron(s)}, \tag{3}$$

$$\text{nuino} + \text{hadron} \to \text{nuino} + \text{hadron(s)}. \tag{4}$$

Process (3) is due to the diagrams of fig. 1 in reverse. The cross section of process (3) is, naively, enhanced by a factor $g_c^2/g^2$ compared to the cross section of process (4) (for the same reason that we had this extra factor in the $R$-hadron decay rates); the latter, again with the same set of hypotheses (i.e., $m_s$ and $m_t \sim m_W$, and nuino coupling constants of the order of the semi-weak coupling constant $g$), is expected to be of the same order of magnitude as ordinary neutrino cross sections[‡5]. Both nuino scattering and $R$-excitation events resemble neutrino neutral current interactions and thus any apparatus capable of detecting neutral current interactions can be used as a nuino detector.

"Beam dump" experiments recently performed at the CERN SPS [11,12], designed for charm detection, are ideal for our purpose. 400 GeV protons interact with nucleons, producing ordinary hadrons which are absorbed in the dump, and possibly short-lived charmed or $R$-hadrons. Thus a "beam" of $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$ and possibly nuinos enters the neutrino detectors downstream. Observation of charged current events with an $e^-$, $e^+$, $\mu^-$ or $\mu^+$ gives the flux of $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$ and $\bar{\nu}_\mu$ and hence the expected rate of neutral current events. If there is an excess of neutral-current-like events they might be attributed to nuinos. Conversely, if no excess is observed that places a limit on the product of the production cross section of $R$-hadrons, $\sigma_{pN\to R\bar{R}+X}$, with the nuino interaction cross section, $\sigma_i$.

In fact the BEBC collaboration [11] quotes a 90% confidence level upper limit for the product:

$$2\sigma_{pN\to R\bar{R}+X} \cdot \sigma_i < 2 \times 10^{-66}\ \text{cm}^4 \tag{5}$$

(however without specifying the $p_\perp$ and $x_F$ spectrum assumed for the production of the new "neutrino" in the p–N collision). The factor of two on the left-hand side comes from the fact that each $R\bar{R}$ pair gives both nuino and an anti-nuino. The average energy of their "neutral-current" events is about 30 GeV. In order to obtain an upper limit on $\sigma_{pN\to R\bar{R}+X}$ we must rely on theoretical estimates of $\sigma_i$ which are model-dependent, as discussed above. With the estimate $\sigma_i > 10\,\sigma_{\nu_\mu}^{NC}$, we conclude that this experiment implies that either the $R$-pair production cross section is less than 2 $\mu$b, or that the value of $\sigma_i$ is lower than the one we used. If the hadron physics of gluinos is as expected, it is hard to imagine how the models relying primarily on two simple hypotheses, namely a single scale for heavy particle masses (i.e., $m_s$ and $m_t \sim m_W$), and massless gluinos, can be compatible with these results, since in such models neither nuino scattering nor $R$-pair production is small[‡6].

Since the implications for supersymmetry of small nuino scattering or small hadronic $R$-pair production are quite different, it is important to determine which of them is small. For this, an energy–momentum "conservation" experiment is needed.

Can an $R$-pair production cross section much smaller than, e.g., the $p\bar{p}$ production cross section, be tolerated in a supersymmetric theory? Probably not in a model with massless gluinos, unless the $R$-hadrons are more massive than naively expected or there is some unforeseen dynamical mechanism inhibiting their production. However massless gluinos are not an essential feature of supersymmetry, and are not essential to the phenomenological analysis we have presented here[‡7]. Thus a small $R$-pair production cross section cannot be interpreted as evidence against supersymmetry, but rather as evidence that constraints requiring massless gluinos

[‡5] It is difficult to give here a precise estimate of these cross sections, since they depend heavily on model-dependent parameters such as mixing angles and mass ratios.

[‡6] However in gauge theories with a larger gauge group and heavier vector bosons, the natural mass scale for the spin-0 quarks ($m_s$ and $m_t$) may be the mass of the heavier vector bosons instead of the $W^\pm$ mass. If, for instance, the spin-0 masses are increased by a factor 6 (with nuino coupling constants still $\sim g$ or $e$) the nuino cross sections are decreased by $\sim 10^3$, and the upper limit determined for the production cross section would be ~2 mb. (But decreasing the nuino–$R$-hadron coupling without increasing the $R$-hadron masses may not be phenomenologically acceptable as $R$-hadron lifetimes $\gtrsim 10^{-11}$ s would lead to observable tracks in bubble chambers.)

[‡7] For footnote see next page.

cannot be present in the theory. For example the gluinos could be massive if associated with another octet of spinorial particles, or if the theory were not invariant under continuous $R$-transformations [‡8]. Massive gluinos could give $R$-hadron masses in the several GeV/$c^2$ range, so that they would still be detectable.

In any event, the prospect of learning from present-day experiments about the possible existence of a new, geometrical, spacetime symmetry of nature is enormously exciting. As we have seen above, even upper limits on production cross sections give important information on the nature of the theory.

We have benefited from discussions with M. Gell-Mann, F. Sciulli, J. Steinberger and W. Willis.

[‡7] Our analysis does not apply only to models having a continuous $R$-invariance and massless gluinos, but also to any ordinary to extended supersymmetric theory embedding QCD, provided (i) one can define at least a conserved multiplicative quantum number

$$\epsilon = (-1)^{3B+N_e+N_\mu+\ldots}$$

($B, N_e, N_\mu$, ... standing for baryonic, electronic, muonic, ... numbers), and therefore a conserved "$R$-parity" $(-1)^R = (-1)^{2\,\mathrm{spin}} \cdot \epsilon$, and (ii) that one of the supersymmetry generators is colorless and has $\epsilon = +1$ so that it is odd under $R$-parity. Therefore the usual gluinos and photino (massless at zeroth order) and Goldstino (massless, as long as gravitation is not introduced) exist as before, with odd $R$-parity. This is enough to apply our phenomenological analysis as long as the masses of $R$-particles are not too high.

[‡8] In any case $R$ will be broken by the introduction of gravitation, owing to the super-Higgs mechanism which makes the gravitino massive [3]. To have a spontaneous breaking of $R$-invariance in a theory of weak, electromagnetic and strong interactions only, we may give a vacuum expectation value to scalar bosons carrying $|R| = 2$, already existing in such theories [2,5] and simply denoted by ... in table 1. This still preserves a discrete symmetry, $R$-parity, as discussed in footnote 7. Although the spontaneous breaking of $R$-invariance generates a massless Goldstone boson, it does not couple directly to leptons and quarks. Alternately, the strong interaction between gluinos could itself lead to a dynamical breakdown of $R$-invariance, through an $R = 2$ color singlet formed from a pair of gluinos.

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