Title
DOES THE PHOTINO DECAY?

Author
Hall, L.J.

Publication Date
1986-08-01

LBL-22074 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

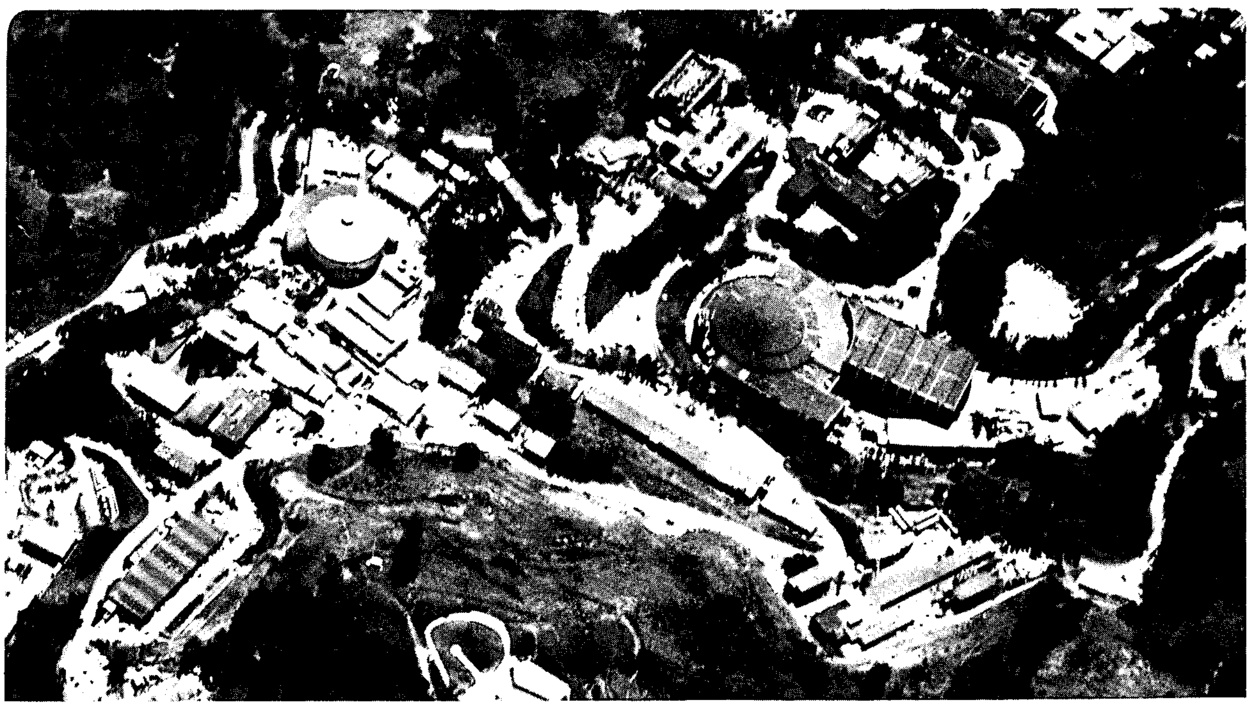
Physics Division

Presented at the Quarks and Galaxies Workshop
Lawrence Berkeley Laboratory, Berkeley, CA,
July 28 - August 15, 1986

DOES THE PHOTINO DECAY?

L.J. Hall

August 1986



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

August 29, 1986 LBL-22074

DOES THE PHOTINO DECAY? [*] [†]

Lawrence J. Hall

Lawrence Berkeley Laboratory
and
Department of Physics
University of California
Berkeley, California 94720

Abstract

The stability of the lightest superpartner is a crucial aspect of many experimental searches for supersymmetry and of supersymmetric dark matter candidates. It is shown that R parity may occur in operators of dimension four or less as an accidental consequence of an exact Z_N symmetry. In this case the lightest superpartner can decay via higher dimension operators. The lifetime depends on the scale of the new physics responsible for the non-renormalizable operators; it could be anywhere in the region 10^{-20} seconds to 10^{+20} seconds. Explicit examples are given.

[*]This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

[†]Talk given at the *Quarks and Galaxies* Workshop held at Lawrence Berkeley Laboratory, July 28 – August 15, 1986

Particle physicists believe that the standard model must be incorporated in a more unified framework because there is so much which the standard model cannot explain. This is an oft-quoted motivation for studying extensions of the standard model, such as supersymmetric theories. However, in the standard model there are some things that we really do understand: the proton is stable and the neutrino is massless because there are no gauge invariant, renormalizable operators which violate baryon (B) and lepton (L) number. The large number of searches for proton decay and for neutrino masses are due to the widespread belief that the standard model cannot be the whole story. The negative results to date are an indication that the standard model, at least in some areas, is a fantastically good approximation to the ultimate theory.

It is astonishing that supersymmetric theories are so popular, given that in the supersymmetric version of the standard model it is no longer possible to understand the conservation of B and L as a result of gauge invariance and renormalizability. These symmetries could be broken by

$$(\ell h_1, \ell\ell e^c, q\ell d^c, u^c d^c d^c]_F, \tag{1}$$

where q, ℓ are SU(2) doublet quark and lepton superfields, u^c, d^c, e^c are singlet antiquark and antilepton superfields, and h_1, h_2 are Higgs doublet superfields.

Why should the coefficients of the operators be zero, or at least small? One possibility is for reasons of chiral symmetry: they are small, perhaps $\sim 10^{-5}$, for the same reason that the electron Yukawa coupling is small. This is fine for the lepton number violating operators, but not for the operators $u^c d^c d^c$.

Another possibility is that the theory possesses a Z_2 symmetry under which all quark and lepton superfields change sign. This matter parity, M_2, forbids the operators (1). In fact, we can define matter and Higgs fields by whether they are $-$ or $+$ under M_2. Even if we introduce exotic fields with M_2 $+$ or $-$, providing M_2 is conserved, then baryon number is necessarily conserved by renormalizable operators. Indeed M_2 is just

$$M_2 = (-)^{Q+L}, \tag{2}$$

where Q is quark number and L is lepton number.

Higher dimension operators can violate B and L, even if they conserve M_2, for example

$$[qqq\ell, u^c u^c d^c e^c]_F. \tag{3}$$

As long as M_2 is conserved, so is R-parity

$$R_2 = M_2(-1)^F, \tag{4}$$

$$h_1(\beta^*), \quad h_2(\beta).$$

Z_{N_B} has group element α, with $\alpha^{N_B} = 1$, and is a discrete subgroup of B. Z_{N_L} has group element γ, with $\gamma^{N_L} = 1$, and is a discrete subgroup of L. Z_{N_R} has group element β, with $\beta^{N_R} = 1$, and is a discrete subgroup of T_{3R}. In the rest of this talk I will consider the case of just a single Z_N. I take $N_B = N_L = N_R = N$ and the Z_N is taken as the product of the above three Z_N.

To avoid renormalizable L violation

$$\beta^*\gamma \neq 1, \tag{7}$$

and to avoid renormalizable B violation

$$\beta\alpha^3 \neq 1. \tag{8}$$

At the outset it is important to point out that the electroweak breaking vevs, $\langle h_1 \rangle$ and $\langle h_2 \rangle$, do not lead to a problem with domain walls, even if $\beta \neq 1$. This is because the vacua labelled by $1, \beta, \beta^2, \ldots$ are related by a hypercharge gauge transformation: the wall between domains does not contain any energy.

The operators of dimension 5 allowed by (7) and (8) are:

$$[qq q\ell, u^c u^c d^c e^c]_F \sim \alpha^3\gamma, \tag{9a}$$

$$[qu^c e^c \ell]_F, \quad [h_1^+ \ell e^c]_D \sim 1, \tag{9b}$$

$$[\ell\ell h_1 h_1]_F \sim \gamma^2\beta^{*2}. \tag{9c}$$

Those of (9b) cannot be forbidden. However they conserve B and L and therefore M_2 and are harmless. The most important point is that all the M_2 violating operators at dimension 5 are ruled out by (7) and (8). These include $[qqqh_2, qu^c e^c h_2]_F$ and $[d^{c+} qq, d^{c+} u^c e^c, e^{c+} h_1 h_1, h_1^+ h_2 e^c]_D$. At this order the LSP is still stable. However, the physics of this model can differ from the Z_2 case. If

$$\alpha^3\gamma \neq 1, \tag{10}$$

then B is conserved to this order, and the scale of the physics responsible for these operators can be quite low. This allows the neutrino masses of (9c) to be large enough to be interesting. This is unlike the Z_2 case where (9a) cannot be forbidden.

I now introduce a simple way of treating operators of high dimension which break B, L, or R_2. This does not require the additional freedom of β, which I now take to be unity. An operator of baryon number (b, ℓ) can be forbidden by

$$(\alpha^3)^b(\gamma)^\ell \neq 1. \tag{11}$$

An operator which allows proton decay has $b+\ell$ even, while one which allows LSP decay has $b+\ell$ odd. Conditions (7) and (8) are now

$$\gamma \neq 1, \quad \alpha^3 \neq 1, \tag{12}$$

which forbid (0,1) and (1,0) operators. The operators (2,0), (1,1), and (0,2) conserve R parity and in order to discuss LSP decay we must examine (3,0), (2,1), (1,2) and (0,3). Of these the lowest dimension operators are:

$$(0,3) : [\ell^3 h_1^3]_F \tag{13a}$$

$$(1,2) : [qqq\ell\ell h_1]_F, [d^c d^c d^c \ell\ell]_F. \tag{13b}$$

In the former case $\tilde{\gamma} \to \nu\nu\nu$, which is an invisible decay, while in the latter case the $\tilde{\gamma}$ decays visibly to quarks and leptons.

Notice that proton decay can occur only via operators which are $b+\ell$ even, hence it is the R_2 conserving operators which must be forbidden by the discrete symmetries. The operators (13) do not allow proton decay, neutron oscillations or neutrino masses, so that the mass scale M responsible for these operators could be quite low.

The LSP decay rate is $\Gamma_{LSP} \sim m^5/M^4$ where m is the LSP mass:

$$\tau_{LSP} \sim 10^{-18}\,\text{sec}\,.\left(\frac{M}{10^4\text{GeV}}\right)^4 \left(\frac{100\text{GeV}}{m}\right)^5 \tag{14}$$

Decay on a cosmological time scale would require a scale $M \leq 10^{11} m$. If the LSP is the photino with mass less than 10 GeV, further astrophysical constraints require $\tau < 10^5$ sec.[12], requiring a scale $M \lesssim 10^8 m$. If $M \lesssim$ 100 TeV there will be no missing energy signatures in particle physical experiments even if the LSP is neutral.

I have shown that if a supersymmetric SU(3) $\times$ SU(2) $\times$ U(1) $\times$ Z_N model persists up to an energy scale above $10^{11} m$, without the addition of any extra fields, then the higher dimension operators do not give any significant LSP decay. This may reinforce one's belief in a stable LSP. However, first it is necessary to examine the effects of extending the theory at the TeV scale.

A model in which baryon and lepton number violation first appear via a (1,2) operator is usually considered to be artificial. In models where discrete symmetries Z_N arise naturally, such as in those inspired by superstrings, this is to be expected. Condition (12) implies that $\alpha, \gamma \neq 1$. Suppose $N = 5$ and $\alpha = \gamma = a, a^5 = 1$. The first baryon and lepton number violation is then (13b) with $\alpha^3\gamma^2 = 1$. For $N = 6$ and $\alpha = \gamma = a, a^6 = 1$, two types of operators occur at dimension 8:

$$(2,0) : [qqqqd^{c+} d^{c+}]_D \tag{15}$$

$$(1,3) : [u^c u^c u^c e^c \ell^+ \ell^+]_D.$$

The first allows neutron oscillation, while the second allows proton decay to three leptons. Our inability to observe B and L violating processes is often attributed to M being enormous; perhaps it is because N is not small.

Next we consider adding extra fields to the minimal set. There are a great many possibilities, and a completely general analysis is not possible. We show how the previous results are modified in a few particular cases. The power of the method should be clear.

Suppose the extra fields do not couple to quarks, leptons or Higgs. For a collection of Majorana fields X there will be mass terms $[XX]_F$, while for a Dirac pair the mass terms are $[XX^c]_F$. In either case, there is a parity, X-parity, which ensures that the lightest X particle is stable.

More interesting is the case when X couples to quarks and leptons. In many situations X can be assigned a lepton and baryon number such that B and L are conserved at dimension four. Higher dimension operators carrying (b,ℓ) allowed by Z_N can then be listed as before.

Consider the case of a quark which has charge -1/3 but is SU(2) neutral: $D(3,1,-1/3)$ and $D^c(\bar{3},1,1/3)$. If D^c has the same Z_N quantum number as d^c, then we have $[DD^c + qD^c h_2]_F$. To forbid renormalizable B and L violation: $\gamma \neq 1, \alpha^3 \neq 1$. This automatically forbids the new dangerous operators $[qqD + Du^c e^c]_F$. As before the (0,2), (1,1), and (2.0) operators conserve M_2 and so the LSP will decay at quite high dimension. In addition to (13b) there are dimension 7 (1,2) operators involving the exotic quark: $[DDD\ell^+\ell^+]_D$.

Another possibility is to introduce a pair of color neutral weak doublets: $L(1,2,-1/2)$ and $L^c(1,2,1/2)$. If they couple with $[\ell e^c L]_F$ then they are just like a pair of Higgs doublets. On the other hand if they couple with $[Le^c h_2]_F$, they are exotic leptons with Z_N quantum numbers $L(\gamma)$, $L^c(\gamma^*)$. There will be new operators involving L^c, but the counting is as before.

Another possibility is that D and D^c are leptoquarks rather than exotic quarks. This occurs if the renormalizable interactions are

$$[DD^c + Du^c e^c]_F. \tag{16}$$

In this case the Z_N transformations are $D(\alpha\gamma)$ and $D^c(\alpha^*\gamma^*)$ showing that they carry unit quark number (α) and unit lepton number (γ). $\gamma \neq 1$ rules out the usual (0,1) operator together with $[qD^c h_2]_F$, while $\alpha^3 \neq 1$ rules out the usual (1,0) operators. However there are other dimension 4 operators

$$[qqD, u^c d^c D^c]_F \sim (1,1) \qquad \gamma\alpha^3 \neq 1$$

$$[u^c D^c D^c]_F \sim (1,2) \qquad \gamma^2\alpha^3 \neq 1.$$

Thus the operators (13*b*) are immediately ruled out in this model, and the LSP can first decay via (0,3) operators.

An alternative possibility is to take $\gamma = 1$, $\alpha^3 \neq 1$, with $D(\alpha)$. This allows:

$$[DD^c, Du^c e^c, qD^c h_2, \ell h_1, \ell\ell e^c, qd^c\ell, qD^c\ell, \ell\ell h_1 h_1]_F. \tag{17}$$

All $(0,\ell)$ operators are allowed, while (b,ℓ) may easily be forbidden to quite high b (4 for $N = 4$, 5 for $N = 5$). The renormalizable lepton number violation leads to $\mu \rightarrow e\gamma$, neutrino masses, etc. but gives only fairly mild constraints on the coefficients of the (0,1) operators. Of course the $(0,\ell)$ terms could also be allowed in the minimal supersymmetric model.[2] The LSP lifetime depends greatly on what the LSP is. The photino decays at one loop and would probably travel a measurable distance. On the other hand, if the LSP was a slepton it would decay to two leptons very rapidly.

All the examples given so far for X could occur in superstring inspired models. Each X had quantum numbers of a member of a 27 of E_6. However, the real superstring motivation for this work is that discrete symmetries Z_N, $N > 2$, occur very readily in these models.[9–11]

As a last example consider X to have charge 2: $X(1,1,2)$ and $X^c(1,1,-2)$. If $\gamma^2\alpha^3 = 1$, a (1,2) operator can occur at dimension 5:

$$[XX^c, e^c e^c X^c, u^c u^c u^c X]_F. \tag{18}$$

The photino can decay into 3 up quarks and two electrons with a rate $\Gamma_{LSP} \sim m^3/M^2$, which can be very rapid.

There has been a theoretical bias that the LSP is stable. This has led to many supersymmetry searches based on missing energy, and has led to considerable work on the LSP as dark matter. It is certainly true that a simple way of building acceptable supersymmetric models is to make the LSP stable. However, I have argued that low energy supersymmetric theories with a discrete Z_N symmetry, $N > 2$, are also perfectly acceptable. These theories naturally account for our inability to uncover B and L violation. Indeed they often predict that the proton is stable, or that it has very unusual decay modes. A wide variety of LSP lifetimes is possible. Experimental searches for supersymmetry should bear in mind the new possibilities: that the LSP may decay before travelling a measurable distance, that it may travel an observable distance before decay, or that it may escape the apparatus having left a track. The last possibility appears very likely, and would correspond to the LSP being a long-lived charged slepton or squark (R meson).

R parity breaking remains a very important question for supersymmetry. I have shown that R parity may just be a low energy accident due to the presence of a Z_N symmetry.

Acknowledgments

I thank the organizers of the *Quarks and Galaxies* workshop held at LBL for a very stimulating meeting. The idea of generalizing R parity to Z_N was invented at this workshop in discussions with Graham Ross.

This work was supported in part by NSF Grant PHY82-15249, by a Sloan Fellowship and also in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

1. That R parity is sufficient to yield a stable particle was realized by G. Farrar and P. Fayet, Phys. Lett. 76B (1978) 575. The necessity for a matter parity in modern supersymmetric models was realized by S. Dimopoulos and H. Georgi, Nucl. Phys. B193 (1981) 150.
2. L.J. Hall and M. Suzuki, Nucl. Phys. B231 (1984) 419.
3. I-Hsiu Lee, Nucl. Phys. B246 (1985) 120.
4. F. Zwirner, Phys. Lett. 132B (1983) 103.
5. R. Barbieri and A. Masiero, Nucl. Phys. B267 (1986) 679.
6. G.G. Ross and J.W.F. Valle, Phys. Lett. 151B (1985) 375.
7. J. Ellis, G. Gelmini, C. Jarlskog, G.G. Ross, and J.W.F. Valle, Phys. Lett. 150B (1985) 142.
8. I thank B. Grinstein for pointing this out to me, and G. Gelmini for conversations.
9. L.J. Hall and G.G. Ross, preprint in preparation.

10. E. Witten, Nucl. Phys. B258 (1985) 75.

11. B. Greene, K. Kirklin, P. Miron, and G. Ross, Oxford preprint, May 1986.

12. A. Bouquet and P. Salati, preprint (1986) LAPP-TH-157.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720