Cosmological Constraints on the Scale of Supersymmetry Breaking

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(Received 9 March 1982)

The gravitino must be either light enough so that ambient gravitinos would not produce too large a cosmic deceleration, or heavy enough so that almost all gravitinos would have decayed before the time of helium synthesis. The second alternative is shown to allow supersymmetry-breaking scales above a model-dependent lower bound of 10^{11} to 10^{16} GeV.

PACS numbers: 11.30.Pb, 11.30.Qc, 04.60.+n, 98.80.-k

Supergravity theories[1] necessarily involve a massive spin-$\frac{3}{2}$ particle, the gravitino, whose mass m_g is related to the scale F of spontaneous supersymmetry breaking by the formula[2]

$$m_g = (4\pi/3)^{1/2} F/m_{\rm Pl}, \tag{1}$$

where $m_{\rm Pl}$ is the Planck mass, 1.2×10^{19} GeV. A recent Letter by Pagels and Primack[3] makes the interesting point that the upper bound on the cosmological mass density requires that m_g be less than 1 keV, leading to the upper bound $\sqrt{F} < 2\times10^6$ GeV on the scale of spontaneous supersymmetry breaking. This is an important conclusion, because it would mean that supersymmetry, if valid at all, remains unbroken down to energies far below those of order 10^{15} GeV, at which gauge symmetries connecting the strong and electroweak interactions are generally supposed to be broken.[4]

As recognized in Ref. 3, this conclusion applies only if the gravitino is stable enough to survive to the present. It is assumed in Ref. 3 that the gravitino is kept stable by a discrete reflection symmetry,[5] known as "R parity." As conventionally defined, the R parity is even for quarks, leptons, and gauge and Higgs bosons, and odd for their superpartners. The supercurrent is manifestly odd under R parity, so that the gravitino is R odd, and is presumed to be the lightest R-odd particle. In this case, if R parity is conserved, the gravitino may be expected to be absolutely stable.

In this note I wish to examine whether a supersymmetry breakdown at a very high energy such as 10^{15} GeV is really ruled out by the arguments of Ref. 3. First, although R parity is automatically conserved in a wide class of supersymmetric theories, supersymmetric theories do exist in which R parity is not conserved, or at least not with R-parity assignments that would prohibit gravitino decay. Also, even if R parity is an exact symmetry of the Lagrangian, it might be spontaneously broken by whatever mechanism breaks supersymmetry.[6] Further, even if R-parity conservation is exact and not spontaneously broken, how do we know that the gravitino is the lightest R-odd particle? Finally, even if R-parity conservation were exact and not spontaneously broken, and the gravitino were the lightest R-odd particle and consequently absolutely stable, one must still consider whether the annihilation of heavy gravitino pairs might reduce the gravitino mass density to acceptable levels, thus allowing gravitino masses above some lower bound, as is the case for heavy neutrinos.[7]

Let us first dispose of the last issue. Even if R-parity conservation is exact and unbroken, and if the gravitino is the lightest R-odd particle, gravitinos can disappear through annihilation of gravitino pairs, say into $\nu\bar{\nu}$ or $\gamma\gamma$ pairs. Relativistic helicity-($\pm\frac{1}{2}$) gravitinos behave essentially like massless spin-$\frac{1}{2}$ Goldstone fermions,[8] and so these gravitinos annihilate readily at temperatures above m_g, but at these temperatures gravitino pairs are equally readily created in collisions of other particles. Annihilation can only reduce the gravitino population at temperatures below m_g, where the gravitinos are nonrelativistic. At such temperatures the couplings of helicity-($\frac{1}{2}$) as well as -($\pm\frac{3}{2}$) gravitinos are suppressed by powers of $\sqrt{G} = 1/m_{\rm Pl}$. Further, most of the annihilation will take place at temperatures of order m_g, because the thermal average $\langle\sigma v\rangle$ of the product of the gravitino-gravitino annihilation cross section and relative velocity becomes constant for late times, so that the annihilation rate goes like $n_g \propto R^{-3} \propto t^{-2}$, while the cosmic expansion rate $\dot{R}/R$ goes like $(Gm_g n_g)^{1/2} \propto R^{-3/2} \propto t^{-1}$. (This argument can be made more precise by solving the Boltzmann equation for the gravitino number density n_g, as done in Ref. 7.) The dominant contribution to $\langle\sigma v\rangle$ is provided by the conversion of a gravitino pair into a single virtual graviton which then converts into any sufficiently light particle-

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antiparticle pair. This gives $\langle\sigma v\rangle$ proportional to $G^2 = m_{\rm Pl}^{-4}$ and to the number N of species of particles with mass less than m_g; on dimensional grounds, we then expect that for $kT \leq m_g$, $\langle\sigma v\rangle$ is of order $Nm_{\rm Pl}^{-4}m_g^2$. Hence for $kT \approx m_g$, the annihilation rate $n_g\langle\sigma v\rangle$ is of order $Nm_{\rm Pl}^{-4}m_g^5$. But the expansion rate at these temperatures is of order $(Nm_g^4/m_{\rm Pl}^2)^{1/2}$, and so the ratio of annihilation to expansion rates is of order $N^{1/2}(m_g/m_{\rm Pl})^3$. Even for N as large as 1000, gravitino-gravitino annihilation is negligible as long as $m_g < 0.3m_{\rm Pl}$.

What about gravitino decay? For orientation, it is useful to note that in a certain class of theories, R parity is automatically conserved and is not spontaneously broken. These are the models [like SU(5)[9] when extended by supersymmetry] in which the quark and lepton superfields form a set which couples only bilinearly to all other (e.g., gauge and Higgs) superfields, and in which $B-L$ is conserved (or conserved modulo 2). In such theories, the Lagrangian obviously conserves a "quark-lepton parity," which is -1 for quarks and leptons and their superpartners, and $+1$ for everything else; this cannot be spontaneously broken, because any color-neutral operator with $B=L$ contains an even number of quarks and leptons and their superpartners. Quark-lepton parity is equivalent to R parity, because the two are related by a 360° rotation.

In theories of this sort, gravitinos can decay only if there are lighter R-odd particles. This may well be the case. Among the R-odd particles are the fermionic superpartners of gauge bosons, which will be referred to as "gauge fermions." If any of the $SU(3)\otimes SU(2)\otimes U(1)$ gauge fermions along with the corresponding gauge boson are lighter than the gravitino, then the gravitino will decay into the gauge fermion and gauge boson, with a rate of order Gm_g^3. Furthermore, if $\sqrt{F}$ is much greater than the scale of $SU(2)\otimes U(1)$ breaking, the mass of a $SU(3)\otimes SU(2)\otimes U(1)$ gauge fermion is negligible in tree approximation, and is therefore no greater than of order $\alpha\sqrt{F}/2\pi$. The gravitino will therefore be able to decay into an $SU(3)\otimes SU(2)\otimes U(1)$ gauge fermion plus gauge boson if $\alpha\sqrt{F}/2\pi$ is larger than (1), i.e., if $\sqrt{F}$ is greater than about 10^{16} GeV. Even for smaller values of $\sqrt{F}$, it is possible for such decays to occur if the masses of some gauge fermions are especially small. In particular, in many theories there is not only a conserved R parity, but also a conserved additive R quantum number.[5] The gauge fermions all have $R=+1$, and with R conserved could only get masses by pairing with the $R=-1$ fermion components of $R=0$ chiral superfields. The $SU(3)\otimes SU(2)\otimes U(1)$ gauge fermions can therefore not get large masses unless there are $R=0$ chiral superfields in the adjoint representation of $SU(3)\otimes SU(2)\otimes U(1)$. This is not the case in most models.

Of course, it does not help for the gravitinos to decay into lighter R-odd particles if these particles have masses above 1 keV and survive to the present. This need not be a problem because the gauge fermions, unlike the gravitinos, can readily annihilate by ordinary $SU(3)\otimes SU(2)\otimes U(1)$ gauge interactions, at least if they are sufficiently heavy.[10]

It is also possible for the gravitino to decay into ordinary R-even particles if R parity is intrinsically or spontaneously broken. For instance, suppose that in addition to the quark and lepton superfields, the theory involves some $SU(3)\otimes SU(2)\otimes U(1)$-neutral left chiral superfields N_i, as in the supersymmetric extensions of models in which lepton number is the fourth color,[11] as well as in models based on SO(10).[12] Here there may be interactions

$$g_{N_i}(L_L H_L' N_i)_F + [f(N)]_F + \text{H.c.}, \tag{2}$$

where L_L and H_L' are the left chiral lepton and Higgs SU(2)-doublet superfields, and F denotes the $\theta_L\theta_L$ term. If H' is the same Higgs superfield that also gives mass to the "up" quarks then the N_i in the first interaction must be assigned an odd R parity, but then any term in $f(N)$ which is trilinear in such N_i would break R parity. This would produce Yukawa coupling terms $g_N' nn\mathcal{N}$ (where n and $\mathcal{N}$ are the spinor and scalar components of N) so that the gravitino could decay in two-loop order into $\nu + \mathcal{H}'^0$, with a rate of order $Gm_g^3 g_N'^2 g_N^6/(8\pi^2)^4$. If g_N and g_N' were as large as e, this decay rate would be of the order of $2\times 10^{-12} Gm_g^3$.

Even if R parity is conserved in the Lagrangian, it may be spontaneously broken. For instance, a vacuum expectation value of $\mathcal{N}$ would lead to a neutrino-$\mathcal{H}'^0$ (where $\mathcal{H}'^0$ is a neutral spin-$\frac{1}{2}$ Higgs fermion) off-diagonal mass term $g_N\langle\mathcal{N}\rangle$, so that gravitinos could decay into $\nu + \mathcal{H}'^0$ with a rate of order $Gm_g^3 g_N^2\langle\mathcal{N}\rangle^2/m_{\mathcal{H}'^0}^2$. If $\langle\mathcal{N}\rangle$ and the $\mathcal{H}'^0$ mass are of order $\sqrt{F}$, and g_N is of order e, the gravitino decay rate is about $0.1Gm_g^3$.

Now we must ask whether the decay of the gravitino is fast enough to avoid conflict with current cosmological ideas. The fastest possible decay mode would be into lighter R-odd particles, with rate $\Gamma_g \approx m_g^3/m_{\rm Pl}^2$. At the temperature $kT \approx m_g$, the expansion rate of the universe is $H_g \approx m_g{}^2/m_{\rm Pl}$, which is faster by a factor $m_{\rm Pl}/m_g$. Hence in all cases the gravitino will not decay until the temperature has dropped far below the gravitino mass.[13]

At these low temperatures the cosmic energy density will be dominated until gravitinos decay by the gravitino mass density, which is of order $m_g(kT)^3N(T)/N(T_e)$, where $N(T)$ is the number of species of particles with mass below kT, and T_e is the temperature ($>m_g$) at which the gravitinos went out of thermal equilibrium with other particles. Hence the expansion rate during this period will be of order $m_g{}^{1/2}(kT)^{3/2}N(T)^{1/2}/m_{\rm Pl}N(T_e)^{1/2}$. We will write the gravitino decay rate as $\alpha_g m_g{}^3/m_{\rm Pl}{}^2$, with α_g a dimensionless number that as we have seen is never greater than of order unity, and may be very much less. Most of the gravitinos will decay when these two rates become equal, i.e., at

$$kT_d \approx m_g{}^{5/3}m_{\rm Pl}{}^{-2/3}\alpha_g{}^{2/3}N(T_e)^{1/3}N(T_d)^{-1/3}. \qquad (3)$$

After the gravitinos decay and their decay energy is thermalized, the temperature will have risen to a value

$$kT_d{}' \approx [m_g(kT_d)^3/N(T_d)]^{1/4} = m_g{}^{3/2}m_{\rm Pl}{}^{-1/2}\xi^{1/2}, \qquad (4)$$

where $\xi \equiv \alpha_g N(T_e)^{1/2}/N(T_d)$. The factor $N(T_e)^{1/2}/N(T_d)$ is not likely to be very large, so ξ like α_g is at most of order unity. We see that gravitinos will have survived to the present if $T_d{}' < 3$ K, i.e., if $m_g < \xi^{-1/3}\times 10$ MeV. In all models, then, the range of gravitino mass from 10 MeV down to 1 keV appears to be ruled out.

To deal with heavier gravitinos, we note that when the gravitinos decay the entropy density of the universe will rise by the large factor $(T_d{}'/T_d)^3 \propto (m_{\rm Pl}/\xi m_g)^{1/2}$. If cosmic nucleosynthesis were over by the time this occurred, then the baryon-entropy ratio at the time of helium synthesis would have been much greater than at present,[14] leading to the production of too much helium (and too little deuterium). It seems necessary therefore to require that the gravitinos with $m_g > 1$ keV are heavy enough so that after they decay the temperature will rise to a value $kT_g{}' > 0.4$ MeV which is high enough to break up any previously formed helium nuclei and restore the neutron-proton ratio to its equilibrium value, thus giving nucleosynthesis a fresh start. This requires that $m_g > \xi^{-1/3}\times 10^4$ GeV, corresponding to $\sqrt{F} > \xi^{-1/6}\times 10^{11}$ GeV.

The conclusion is that in all models there is a finite range of excluded supersymmetry-breaking scales, extending from the 2×10^6 GeV of Ref. 3 up to a model-dependent bound between 10^{11} and 10^{16} GeV. Cosmological constraints do not rule out symmetry-breaking scales above this bound. In particular, it is still quite possible that supersymmetry is broken at a scale of about 10^{15} GeV.

I am grateful to John Preskill for a conversation last year on the possibility of the decay of cosmic gravitinos. I also wish to thank Savas Dimopoulos, Glennys Farrar, and Edward Witten for valuable recent discussions.

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[14]This may raise the early baryon-entropy ratio above levels which can be accounted for by baryon-nonconserving processes in the very early universe. For instance, if $\sqrt{F} = 10^{15}$ GeV so that $m_g = 10^{11}$ GeV, then (4) gives an entropy increase by a factor $> 10^4$; a present value of 10^{-10} for the baryon-entropy ratio would thus correspond to an early value of $> 10^{-6}$, which seems rather high. Of course, those would be no problem here if one were to suppose that baryon number is conserved, and that a large baryon-entropy ratio was put in at the beginning, or that $\sqrt{F} > 10^{18}$ GeV, in which case baryon production could occur after the gravitinos decay.

Determination of the Fundamental Parameters of the K^0-$\bar{K}^0$ System in the Energy Range 30–110 GeV

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K^0 regeneration data in the energy range 30–110 GeV have been analyzed to determine the values of the K_L-K_S mass difference, Δm, K_S lifetime, τ_S, and CP-nonconservation parameter η_{+-}. We find $\Delta m = 0.482(14)\times 10^{10}\hbar\ \mathrm{s}^{-1}$, $\tau_S = 0.905(7)\times 10^{-10}$ s, $|\eta_{+-}| = 2.09(2)\times 10^{-3}$, and $\tan\varphi_{+-} = 0.709(102)$, corresponding to $\varphi_{+-} = 35(4)°$. The data suggest that these parameters may have an anomalous energy dependence.

PACS numbers: 14.40.Aq, 13.25.+m, 13.20.Eb

In this Letter we describe an analysis of data from three K^0 regeneration experiments[1-3] to determine for the first time the fundamental parameters of the K^0-$\bar{K}^0$ system at Fermilab energies. The details of the work summarized here are to be published elsewhere.[4]

In the experiments analyzed here, a K_L beam impinged on a material target (hydrogen,[1] carbon,[2] or lead[3]) and the $K^0\to\pi^+\pi^-$ decay distribution in the forward direction behind the targets was studied. The proper time distribution of the decays is given by[5]

$$N_{+-}(t) = N_L\{|\rho|^2\exp(-t/\tau_S) + |\eta_{+-}|^2\exp(-t/\tau_L) + 2|\rho||\eta_{+-}|\exp(-t/2\tau_S - t/2\tau_L)\cos(\Delta m t + \Phi)\}, \tag{1}$$

where N_L is the flux of K_L's, $t=0$ at the exit face of the target, and $\Phi = \arg\rho - \arg\eta_{+-} \equiv \varphi_\rho - \varphi_{+-}$. The

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