PRINT-94-0010 (Northeastern)
Fermilab Library
0 1160 0026465 9

SUPERGRAVITY UNIFICATION, PROTON STABILITY AND COSMOLOGY

*PRAN NATH
Department of Physics, Northeastern University
Boston, MA 02115, USA

and

R. ARNOWITT
†Center for Theoretical Physics, Department of Physics
Texas A & M University, College Station, TX 77843, USA

Physics Research Division
Superconducting Supercollider Laboratory
Dallas, TX 75237 USA

FERMILAB 1993 LIBRARY

ABSTRACT

A review is given of recent developments in supergravity grand unified models. Specifically models with SU(5)-type proton decay are examined under the combined constraints of radiative electro-weak symmetry breaking, proton stability and relic density constraints. Analysis of the full parameter space of the theory is given and predictions at future accelerator and proton decay experiments are made.

I. Introduction

As is now well known the recent high precision LEP data is very encouraging for supersymmetric grand unification[1,2]. The LEP data gives values of the $SU(3)_C \times SU(2)_L \times U(1)$ coupling constants α_3, α_2 and α_1 (where $\alpha_1 = \frac{5}{3}\alpha_y$ and α_y is the hypercharge coupling constant) which when extrapolated to high energy using renormalization group equations meet to within 1 std for the standard supersymmetric SU(5) theory[3]. Currently the only phenomenologically viable supersymmetric grand unified theories where supersymmetry can be broken consistently are the supergravity theories[4,5]. We begin, therefore, with a brief discussion of supergravity unification.

As a starting point, one may begin at the Planck scale. Although it is generally believed that there exists a theory that unifies all interactions at the Planck scale, it is yet uncertain what that theory is. It may be string, membrane or something else. However, although we are not certain what exactly happens at the Planck scale, we shall assume, as a working principle, that the theory below the Planck scale is an applied N=1 supergravity . In an applied N=1 supergravity one couples N=1 supergravity with an N=1 vector

---

* Invited Talk at the XVIth Kazimierz Meeting on Elementary Particle Physics, Kazimierz, Poland, May 24-28, 1993.

† Permanent Address

multiplet belonging to the adjoint representation of a unified gauge group G, and with an arbitrary number of N=1 chiral multiplets. The structure of such a theory is determined completely in terms of three arbitrary functions: (1) a superpotential function $W(z_a)$ which is a holomorphic function of the chiral fields, (2) a Kähler potential $d(z_a, z_a^*)$ which is a function of both the chiral fields and their complex conjugates, and (3) a gauge kinetic energy function $f_{\alpha\beta}$ which enters the gauge kinetic energy as $-\frac{1}{4}\mathrm{Re}\left(f_{\alpha\beta}F_{\mu\nu}{}^{\alpha}F_{\mu\nu}{}^{\beta}\right)$. The supergravity couplings lead to a gaugino term of the form

$$\frac{1}{4}e^{-\frac{G}{2}}\left(G^{-1}\right)^{a}{}_{b}G,^{a}f^{*}{}_{\alpha\beta,b}\bar{\lambda}^{\alpha}\lambda^{\beta} \tag{1.1}$$

where

$$G = -\ell n\left[\kappa^6 WW^*\right] - \kappa^2 d \tag{1.2}$$

and $\kappa = \left(8\pi G_N\right)^{1/2} = 0.41\times10^{-18}$ GeV and G_N is the Newton constant.

In supergravity unification, supersymmetry is broken in the hidden sector using superhiggs effect. Typically the scalar fields $\{z_a\}$ in the theory decompose so that $\{z_a\} = \{z_i, z\}$ where z_i are the matter fields and z, the Polonyi fields which are singlets of the gauge group G. Supersymmetry breaking occurs when the Polonyi fields develop VeVs $O(M_{P\ell})$. In supergravity unification one makes the following basic assumption: there are no direct gauge or Yukawa interactions between matter fields (quarks, leptons, Higgs) and the hidden sector fields. This means that the superpotential and the Kähler potential are block diagonal in the space of matter fields and the hidden sector fields. The only interactions that occur between the matter sector fields and the hidden sector fields are gravitational. One consequence of the above assumption is the natural suppression of flavor changing neutral currents (FCNC).

Next we discuss physics below the grand unification scale M_G. One assumes that as a consequence of VeV formation in the GUT sector, the grand unified group G will break into the standard model gauge group $SU(3)_C \times SU(2)_L \times U(1)$ at the scale $Q = M_G$. After integration over heavy fields and fields of the hidden sector, the effective potential of the theory can be shown to possess the following form below the scale M_G: $V_{eff} = V_0 + V_{SB}$ where $V_o = \Sigma\left|\frac{\partial}{\partial z_i}W_{eff}\right|^2 + V_D$ is the globally supersymmetric part and V_{SB} is the soft SUSY breaking part[4,6,7]

$$V_{SB} = \sum_i m_0^2 z_i z_i^\dagger + \left(A_0 W^{(3)} + B_0 W^{(2)} + h.c.\right) \tag{1.3}$$

In Eq. (1.3), $W^{(2)}$ and $W^{(3)}$ are the quadratic and the cubic parts of the low energy effective superpotential W_{eff} i.e. $W_{eff} = W^{(2)} + W^{(3)}$. In addition to Eq. (1.3) one has SUSY breaking in the gaugino mass term which can arise from Eq. (1.1). One has

$$L^{mass}_{gaugino} = -m_{\frac{1}{2}} \bar{\lambda}^{\alpha} \lambda^{\alpha} \tag{1.4}$$

Eqs. (1.3) and (1.4) give us four soft SUSY breaking parameters

$$m_o, m_{1/2}, A_o, B_o \tag{1.5}$$

Eq. (1.5) represents an enormous reduction in the number of SUSY breaking parameters relative to the most general set of SUSY breaking parameters one can add in a globally supersymmetric theory[8]. It is interesting to note that the universality of the soft SUSY breaking scalar masses at the GUT scale generates relations such as $m^2_{\tilde{c}_L} - m^2_{\tilde{u}_L} = m_c^{\ 2} - m_u^{\ 2}$ which lead to an automatic suppression of FCNC.

We now turn to the specifics of the GUT sector. There are many possible GUT groups one might consider such as SU(5), SO(10), E (6) etc.[9]. We discuss here the simplest such possibility i.e. SU(5). The superpotential of the GUT sector here is taken to be of the form[8] $W_G = \lambda_1\left(\frac{1}{3}\Sigma^3 + \frac{1}{2}M\Sigma^2\right) + \lambda_2 H_2(\Sigma + 3M')H_1$ where $(H_1, H_2) = (5, \bar{5})$ and Σ is a $\underline{24}$ representation of SU(5). Here SU(5) breaks to $SU(3)_C \times SU(2)_L \times U(1)$ when Σ develops a VeV of the form diag (Σ) = M(2,2,2,-3,-3). An unpleasant feature of this GUT model is that a fine tuning, i.e. $M' = M$, is needed to achieve a pair of light Higgs doublets H_1, H_2 which one needs for the breaking of the electro-weak symmetry. An attractive mechanism for circumventing the finetuning problem has recently been suggested[10]. It utilizes a higher global symmetry such as SU(6) or SO(10) in the GUT sector. Spontaneous breaking of this global symmetry generates pseudo-Goldstones which can be identified with the light Higgs doublets, while the Higgs triplets fields are all superheavy. This model[10] achieves the $M' = M$ condition in a natural fashion.

The outline of the rest of the paper is as follows: In Sec. II we discuss radiative breaking of the electroweak symmetry. In Sec. III we discuss constraints of proton stability, while relic density constraints on the lightest neutralino are discussed in Sec. IV. Conclusions are given in Sec. V.

II. Radiative Breaking Of The Electroweak Symmetry

One of the advantages of supergravity models over the Standard Model is that here the electro-weak symmetry can be broken via radiative effects[11]. We shall describe briefly[12] this phenomenon since it is central to the analysis of Secs. III and IV. In supergravity models the potential that governs electro-weak symmetry breaking, assuming

charge and color conservation, is given by $V = V_o + \Delta V_1$ where V_o is the renormalization group improved semi-classical tree potential at scale Q given by

$$V_o(Q) = m_1^2(t)|H_1|^2 + m_2^2(t)|H_2|^2 - m_3^2(t)(H_1H_2 + h.c.) + \frac{1}{2}(g_2^2 + g_Y^2)\left(|H_1|^2 - |H_2|^2\right)^2 \tag{2.1a}$$

and ΔV_1 is the one loop correction

$$\Delta V_1(Q) = \frac{1}{64\pi^2}\sum_i (-1)^{2j_i+1} n_i \left[M_i^4 \left(\log\frac{M_i^2}{Q^2} - \frac{3}{2} \right) \right] \tag{2.1b}$$

In Eq. (2.1) m_i^2 are given by

$$\begin{aligned} m_i^2(t) &= m_{Hi}^2(t) + \mu^2(t); \quad i = 1,2 \\ m_3^2(t) &= -B(t)\mu(t) \\ t &= \ln\left(M_G^2 / Q^2\right) \end{aligned} \tag{2.2}$$

and satisfy the GUT boundary conditions

$$\begin{aligned} m_i^2(M_G) &= m_0^2 + \mu_0^2; \quad i = 1,2 \\ m_i^2(M_G) &= -B_0\mu_0 \end{aligned} \tag{2.3}$$

The analysis proceeds as follows: One uses renormalization group equations on gauge and Yukawa couplings, and on soft SUSY breaking terms starting at M_G. Spontaneous breakdown of the electro-weak symmetry breaking occurs when below a scale Q_o the symmetric point of the potential is no longer the absolute minimum. One must also guarantee that the effective potential is bounded from below both at the GUT scale as well as at the scale Q where Q minimization of the potential is carried out. Breaking of the electroweak symmetry is characterized by the following relations.

$$\frac{1}{2}M_Z^2 = \frac{\mu_1^2 - \mu_2^2\tan^2\beta}{\tan^2\beta - 1} \quad , \quad \sin^2\beta = \frac{2m_3^2}{\mu_1^2 + \mu_2^2} \tag{2.4}$$

where

$$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle; \;\; \mu_i^2 = m_i^2 + \frac{\partial \Delta V_1}{\partial v_i^2}; \;\; i = 1,2 \tag{2.5}$$

One may quantify the size of one loop corrections to electro-weak breaking by $(\mu_t - \mu_t)/\mu_t$ where $\mu_t(\mu_t)$ are the tree (loop) values of μ at scale Q. A priori, one expects a large correction to μ due to the large number of states contributing in Eq. (2.1b). However, it turns out that over a significant region of the parameter space there are large cancellations[13] reducing the loop correction to a few percent of the tree value. Loop corrections obviously become important when one in close to flat directions in the tree potential[14].

We use electro-weak symmetry breaking to determine μ and the soft SUSY breaking parameter B_0 in terms of $\tan\beta$ using Eq. (2.4). The low energy theory can then be described by the following four parameters:

$$m_o, \; m\tfrac{1}{2}, \; A_o, \; \tan\beta \tag{2.6}$$

Masses of 32 supersymmetric particles can be computed in terms of these four parameters. Thus there are 28 predictions one can make in theory[13,15-21]. Some of these predictions can be conveniently described in the form of sum rules[22].

III. Proton Stability Constraints

We begin by recalling that in the non-SUSY SU(5) theory, proton decays much more rapidly than the experimental bounds allow which eliminates the non-SUSY SU(5)[23] as a viable grand unified model. Specifically in non-SUSY SU(5) the $e^+\pi^o$ mode, which is generated via the exchange of lepto-quarks, has a partial lifetime $\tau(p \to e^+\pi^o) \approx 4 \times 10^{29\pm2}\, yr$, while the Kamiokande/IMB experimental limit on this mode is $\rangle 5.5 \times 10^{32}\, yr (90\% CL)$[24]. In supergravity SU(5) the scale of unification is larger than in the standard SU(5), which gives a $\tau(p \to e^+\pi^o)$ lifetime much larger $(\approx 3 \times 10^{37\pm2}\, yr)$ than the experimental value[25]. Thus it appears unlikely that the $e^+\pi^o$ mode would be observable even in the next generation of proton decay experiments which can reach a sensitivity of $1 \times 10^{34}\, yr$ for this model[26].

As is well known[27,28] in supergravity SU(5) the dominant proton decay arises via the baryon number violating Higgs triplet exchange which generates a set of dimension five operators with chiral structure LLLL and RRRR. These dimension five operators when dressed by exchange of chargino, neutralino and gluino exchanges generate dimension six operators of the form LLLL, LLRR, RRLL and RRRR, which are responsible for proton decay. A large number of decay modes result. The decay modes for the proton are

$$\begin{aligned}&\overline{\nu}_i K^+, \overline{\nu}_i \pi^+, e^+ K^o, \mu^+ K^o, e^+ \pi^o \mu^+ \pi^o, \\ &e^+ \eta, \mu^+ \eta; \;\; i = e, \mu, \tau\end{aligned} \tag{3.1}$$

Of the decay modes in Eq. (3.1), the most dominant are the $\overline{\nu}_i K^+$. Using the chiral Lagrangian approach one obtains the following decay width for this mode:

$$\begin{aligned}&\Gamma\left(p \to \overline{\nu}_i K^+\right) = \frac{\beta_p^2}{M_{H_3}^2} \frac{m_N}{32\pi f_\pi^2}\left(1 - \frac{m_K^2}{m_N^2}\right) \\ &\left|1 + \frac{m_N(D+3F)}{3m_B} - \frac{2}{3}\frac{M_N}{m_B} D\right|^2 \\ &\left|\alpha_2^2 \left(2M_W^2\right)^{-1} m_{di} m_c V_{i1}^\dagger V_{21} V_{22}\right|^2 A_L^2 \left(A_S^L\right)^2 \\ &\left|\sum_{A=1,2,3} B_{Ai}\right|^2\end{aligned} \tag{3.2}$$

where β_p is the 3-quark matrix element of the proton[27,28], for which we use the lattice gauge (quenched approximation) result of[29] $\beta_p = (5.6 \pm 0.8) \times 10^{-3} GeV^3$. In Eq. (3.2) V_{ij} are the K-M matrix elements, $A_L\left(A_S^L\right)$ are the long (short) distance suppression factors, D, F, f_π etc. are the chiral Lagrangian factors and B_{Ai} are the dressing loop functions defined in Ref. (28).

From the analysis of LEP data (see e.g. Amaldi et. al. in Ref. (3)), one obtains in the minimal supersymmetric standard model (MSSM), under the assumption of a common GUT scale M_G and a common SUSY scale M_S, the following values for the GUT parameters α_G M_G and the SUSY scale Ms:

$$\alpha_G^{-1} = 25.4 \pm 1.7 \tag{3.3a}$$

$$M_G \equiv 10^{16.2 + 5.7(\alpha_3/0.118 - 1)} \tag{3.3b}$$

$$M_s \equiv 10.^{2.4 + 17.4(1 - \alpha_3/0.118)} \tag{3.4}$$

A convenient description of proton stability is in terms of the quantity B define by

$$B \equiv \left[|B_2|^2 + |B_3|^2\right]^{\frac{1}{2}} \left[M_s / 10^{2.4} GeV\right]^{0.33} \times 10^6 GeV^{-1} \tag{3.5}$$

where B_i are loop integrals given by

$$B_i = \frac{m_i^d V_{i1}^\dagger}{m_s V_{21}^\dagger}\left[P_2 B_{2i} + \frac{m_t V_{31} V_{32}}{m_c V_{21} V_{22}} P_3 B_{3i}\right]\frac{1}{\sin 2\beta} \tag{3.6}$$

Using the current experimental bound of $\tau(p \to \bar{\nu}K) \rangle 1.0 \times 10^{32} yr$, one then finds a bound on B of[13,15],

$$B \leq 100\left(\frac{M_{H_3}}{M_G}\right) GeV^{-1} \tag{3.7}$$

A reasonable range for M_{H_3} is given by $M_{H_3} \leq 10 M_G$ which is consistent with the condition that Yukawa couplings be perturbative at the GUT scale. Since B depends on the SUSY particle spectrum, Eq. (3.7) becomes a constraint on the SUSY masses. In addition the SUSY particle spectrum generated by renormalization group radiative breaking analysis is subjected to the LEP and CDF constraints as follows[1,2,30]:

LEP Constraints of

Sleptons:	$m_{\tilde{e}}, m_{\tilde{\mu}}, m_{\tilde{\tau}} > 45 GeV$	[LEP]
	$m_{\tilde{\nu}} > 32 GeV$	[LEP]
Stop:	$m_{\tilde{t}_i} \geq 45 GeV$	[LEP]
Charginos:	$m_{\tilde{W}_1} > 45 GeV;\ \tan\beta > 3$	[LEP]
Neutralinos:	$m_{\tilde{Z}_1} > 20 GeV;\ \tan\beta > 3$	[LEP]
	$m_{\tilde{Z}_2} > 51 GeV;\ \tan\beta > 3$	
Higgs (SUSY):	$m_h > 43 GeV$	[LEP]
	$m_A > 20 - 44 GeV$	
	$m_{H^\pm} > 42 GeV$	(3.8a)

CDF constraints of

Top:	$m_t \geq 115 GeV$	[CDF]

Gluino:	$m_{\tilde{g}} \geq 130 GeV$	[CDF;BTW[31]]	
Squark:	$m_{\tilde{g}} \geq 150 GeV$	[CDF;BTW]	(3.8b)

One of the important consequences of proton stability constraint is that one finds that over much of the parameter space one has $\mu^2 >> M_Z^2$. This generates the following approximate relations for the neutralino and chargino masses[13,15]:

$$
\begin{aligned}
& m_{\tilde{W}_1} \cong m_{\tilde{Z}_2} \\
& m_{\tilde{Z}_1} / m_{\tilde{Z}_2} \cong \tilde{m}_1 / \tilde{m}_2 = 0.508 \\
& m_{\tilde{W}_2} \cong m_{\tilde{Z}_3} \cong m_{\tilde{Z}_4}
\end{aligned}
\tag{3.9}
$$

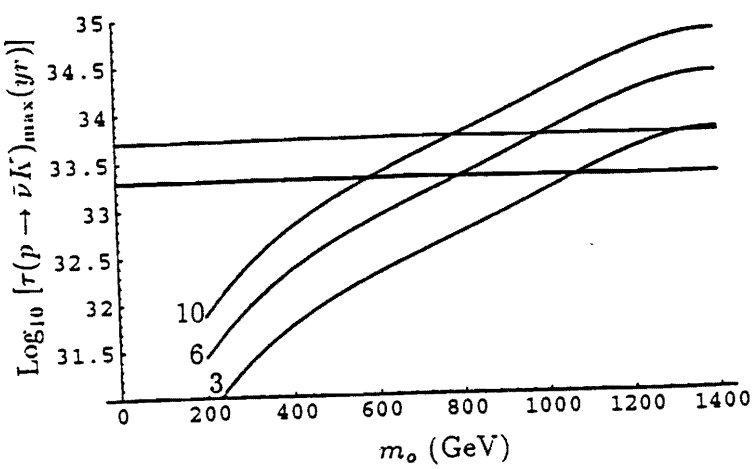

Fig. 1. The maximum partial lifetime $\tau(p \to \overline{\nu}K^+)$ as a function of m_0 for $m_\tau = 150 GeV, \mu > o$ and for three values of $M_{H_3} / M_G = 3,6,10$ (bottom to top).

Future proton decay experiments will be able to place much more stringent constraints on the model. One expects that super Kamiokande will reach a sensitivity of 2×10^{33}yr for the $\overline{\nu}K^+$ mode[26], while ICARUS is expected to reach a sensitivity of 5×10^{33}yr for this mode[32]. These limits, if realized, come close to exhausting the full parameter space of the SU(5) supergravity model if $m_{\tilde{q}} \leq 1$TeV. In Fig. 1 we exhibit the maximum partial $\tau(p \to \overline{\nu}K)$ lifetime by exhausting the full parameter space of the theory[33] at fixed m_0. Here for the case m_t=150GeV and three characteristic values of M_{H_3} one finds that super

Kamiokande will see proton decay if $m_o < 600GeV$ and ICARUS will see proton decay if $m_o < 800GeV$. One can get even more stringent constraints if the chargino spectrum is restricted by $m_{\tilde{W}_1} > 100GeV$[33].

IV. Relic Density Constraints

A remarkable aspect of supergravity SU(5) model is that under the constraints discussed in Sec. III, the lightest neutralino turns out to be the LSP[13,15]. Thus it is reasonable to subject this neutralino to the constraint that its relic density not overclose the universe i.e. $\Omega_{\tilde{Z}_1} h^2 < 1$ where $\Omega_{\tilde{Z}_1} = \rho_{\tilde{Z}_1} / \rho_c$ where $\rho_{\tilde{Z}_1}$ is the matter density due to the lightest neutralino and ρ_c is the critical density, while h is Hubble parameter in units of $100km/s.Mpc$. Experimentally h lies in the domain $\frac{1}{2} \le h \le 1$. We follow standard procedure and write the matter density of $\tilde{Z}_1$ as given by the following approximate relation[34,35]

$$\rho_{\tilde{Z}_1} = 4.75 \times 10^{-40} \left(\frac{T_{\tilde{Z}1}}{T_\gamma} \right)^3 \left(\frac{T_\gamma}{2.75^o{}_{\mathrm{K}}} \right)^3 N_F^{\frac{1}{2}} \left(\frac{GeV^{-2}}{J(x_f)} \right) \frac{g}{cm^3} \tag{4.1}$$

In Eq. (4.1), N_F is the number of degrees of freedom at the freeze out temperature, $\left(T_{\tilde{Z}_1}/T_\gamma\right)^3$ is the reheating factor, T_γ is the current background temperature and $J_f(x_f) = \int_o^{x_f} dx \langle \sigma \mathrm{v} \rangle$ where $x_f = kT_f / m_{\tilde{Z}_1}$ and T_f is the freezeout temperature, which is determined by the following approximate relation

$$x_f^{-1} = \ell n \left[x_f^{\frac{1}{2}} \langle \sigma \mathrm{v} \rangle \sqrt{45 m_{\tilde{Z}_1}} \Big/ \left(4\pi^3 N_F^{\frac{1}{2}} G_N^{\frac{1}{2}} \right) \right] \tag{4.2}$$

where $\langle \sigma \mathrm{v} \rangle$ is the thermally averaged cross-section evaluated at x_f.

An interesting consequence of the supergravity SU(5) analysis is that over much of the physically interesting domain of the parameter apace, the neutralino annihilation is dominated by the Higgs and Z-poles[36]. Thus analyses where integration over these poles is replaced by the approximate relation $\langle \sigma \mathrm{v} \rangle = a + b\mathrm{v}^2$, where v is the relative velocity of the annihilating neutralinos, can give enormously inaccurate results[37,36]. This is essentially true for all previous GUT analyses of the relic density. Recently a correct analysis of this problem was given where a careful integration over the Higgs poles and the

Z-pole was carried out[36,38]. Similar results have subsequently been obtained by other authors[12,39].

In the analyses of Refs. (36) and (38) a single integral formula for J in Eq. (4.1) was obtained for the Higgs and the Z-pole contributions. This single integral formulation enormously facilitates the numerical analysis of the relic density. We exhibit this integral formula for the Higgs pole. Under the finetuning restriction of $m_{\tilde{q},\tilde{g}} \leq 1TeV$, the Higgs pole that enters in the neutralino annihilation is that for the lightest Higgs. The annihilation cross-section for $\tilde{z}_1$ neutralinos near this pole in the non-relativistic approximation, is given by

$$(\sigma v)_h = \frac{A_h}{m_{\tilde{z}_1}^2} \frac{v^2}{\left(\left(v^2 - \varepsilon_h\right)^2 + \gamma_h^2\right)} \tag{4.3}$$

where

$$\varepsilon_h = \left(m_h^2 - 4m_{\tilde{z}_1}^2\right) / m_{\tilde{z}_1}^2, \quad \gamma_h = m_h \, \Gamma_h \, / m_{\tilde{z}_1}^2 \tag{4.4}$$

and m_h is the Higgs mass and Γ_h is the Higgs decay width. Using Eq. (4.3) we can carry out the explicit integration on x in $J(x_f)$ and obtain

$$J_h(x_f) = \frac{A_h}{2\sqrt{2m_{\tilde{z}_1}^2}} \left[I_{1h} + \frac{\varepsilon_h}{\gamma_h} I_{2h} \right] \tag{4.5}$$

where

$$I_{1h} = \frac{1}{2} \int_0^\infty d\xi \xi^{-\frac{1}{2}} e^{-\xi} \ell n \left[\frac{\left(4\xi x_f - \varepsilon_h\right)^2 + \gamma_h^2}{\varepsilon_h^2 + \gamma_h^2} \right] \tag{4.6}$$

and

$$I_{2h} = \int_o^\infty d\xi \xi^{-\frac{1}{2}} e^{-\xi} \left[\tan^{-1}\left(\frac{4\xi x_f - \varepsilon_h}{\gamma_h} \right) + \tan^{-1}\left(\frac{\varepsilon_h}{\gamma_h} \right) \right] \tag{4.7}$$

A similar analysis holds for integration over the Z-pole.

As stated earlier the power expansion on $\langle \sigma v \rangle$ of the type $a+bv^2$ is a poor approximation when one is close to a threshold or a pole. In Fig. (2) we exhibit the ratio of

Ω approx / Ω. One finds from Fig. (2) that the result of the approximate analysis can be in error up to three orders of magnitude.

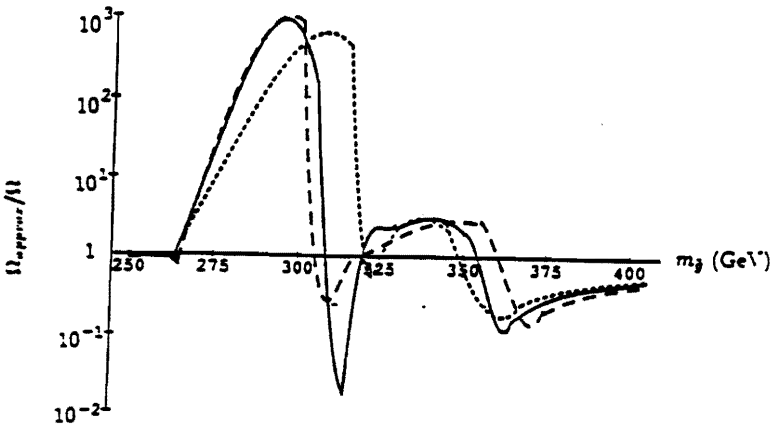

Fig. 2. Plot of Ω approx / Ω as a function of the gluino mass for three values of the top mass: 110 GeV (dashed curve), 125 GeV (solid curve) and 140 GeV (dotted curve). The plot exhibits the large breakdown of the approximate analysis near the Higgs pole and the Z-pole.

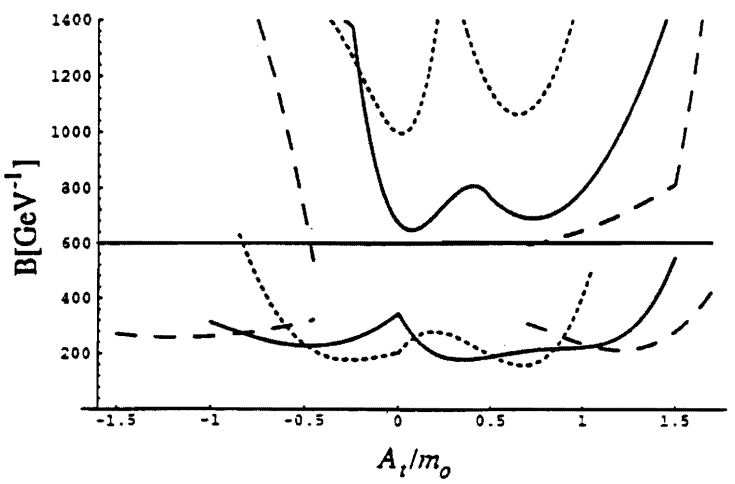

Fig. 3. The domain allowed by relic density and proton stability constraints in the B Vs At/m_0 plot. -The domains consistent with relic density constraint lie between similar upper and lower curves for top mass of 110 GeV (dashed curve), 125 GeV (solid curve) and 140 GeV (dotted curve) when m_0=700 GeV. The domain allowed by proton stability when $M_{H_3} < 6M_G$ lies below the solid horizontal line.

We discuss now the results of the relic density analysis. Using the accurate method for the analysis of relic density described above, the full parameter space of SU(5)

supergravity model was investigated. One finds that the domain of the parameter space where the relic density and proton stability constraints are simultaneously satisfied is quite large. Some typical results are exhibited in Fig. 3[38].

V. Conclusion

Supergravity is an attractive framework for the unification of interactions beyond the Standard Model. The supergravity unified models depend only on a small number of parameters and have a great deal of predictive power. Specifically the low energy theory depends on only four arbitrary parameters, which one may choose to be m_o, $m_{1/2}$, A and $\tan\beta$. One can predict masses of 32 supersymmetric particles in terms of these 4 parameters. Thus the theory is indeed very predictive.

There are a number of predictions of supergravity unified models which can be tested at the current, and future accelerators (Tevatron, LEP2, SSC, LHC). The model predicts $m_t \leq 180$ GeV and thus this prediction can be tested at the Tevatron if an optimal integrated luminosity can be achieved. The lightest Higgs mass is predicted to lie below 110 GeV when $M_{H_3}/M_V \leq 3$. There is an interesting complimentary one finds between the lightest Higgs and the light chargino, which is as follows: either the Higgs mass is less than 95 GeV and is thus most likely observable at LEP2 with an integrated luminosity of 500 pb^{-1} and efficient b-tagging or the Higgs mass is larger than 95 GeV in which case one finds the light chargino mass to lie lower than 100 GeV (and is thus observable at LEP2)[15]. Another remarkable aspect of the analysis is that one finds scaling laws on chargino and neutralino masses over much of the physically interesting parameter space of the theory.

A full analysis of the parameter space of the SU(5) type supergravity model points to strong tests of SU(5)-type proton decay in future proton decay experiments. Specifically one finds that the $\bar{\nu}K^+$ mode should be seen at super Kamiokande (m_0<800 GeV) and at ICARUS (for m_0<600 GeV) for GUT models with $M_{H_3}/M_3 < 6$. One also finds that for $M_{H_3}/M_3 < 10$ and $m_{\tilde{q}}, m_{\tilde{g}} < 1TeV$, either $m_h < 95GeV$ or $m_{\tilde{w}_1} < 100GeV$ if $\tau(p \to \tilde{\nu}K^+) > 1.5x10^{33}yr$. In the above situation either the light Higgs or the light chargino (and possibly both) would be accessible at LEP2.

Previously signals for supersymmetry have been pursued in the context of generic SUSY models. However, at the present stage one has progressed to a point where supergravity unification appears to be the most likely next level of unification beyond the Standard Model. It is thus imperative that one pursue analyses of SUSY signals in the context of specific supergravity GUT models using the mass spectra specific to these models. A signal which continues to be of interest is the trileptonic signal which arises from the decay of an off-shell W[40]: $W^* \to \tilde{W}_1 + \tilde{Z}_2 \to \ell_1\ell_2\bar{\ell}_2 + P_T$. This signal can act as a probe of $\tilde{W}_1$ mass even beyond the reach of LEP2.

In summary in this review we have examined the SU(5) supergravity model under the combined proton stability and relic density constraints. One finds that there exist significant domains of the parameter space where both of these constraints are simultaneously satisfied.

Acknowledgments:

This research was supported in part by NSF Grant Nos. PHY-19306906 and PHY-916593.

References:

1. M. Davier, Proc. Lepton-Photon High Energy Physics Conference, Geneva, 1991, Eds. S. Hegarty et. al. *(World Scientific, Singapore 1991).*
2. H. Bethke, XXVI Proc. Conference on High Energy Physics, Dallas 1992. Ed. J. Sanford, AIP Proc. **No. 272** (1993); G. Altarelli, talk at *Europhysics Conference, on High Energy Physics, Marseille,* August 1993.
3. P. Langacker, Proc. *PASCOS90-Symposium,* Eds. P Nath and S. Reucroft (World Scientific, Singapore 1990); J. Ellis, S. Kelley and D. V. Nanopoulos, *Phys. Lett.* **249B** (1990) 441; **B260** (1991) 131; U. Amaldi, W. deBoer and H. Fürstenau, Phys. Lett. **260B** (1991) 447: F. Anselmo, L. Cifarelli, A. Peterman and A. Zichichi, *Nuov. Cim.* **104A** (1991) 1817; **115A** (1992) 581; M. Carena, S. Pokorski and C. E. M. Wagner, MPI_Ph/93-10.
4. A. H. Chamseddine, R. Arnowitt and P. Nath, *Phys. Rev. Lett.* **29** (1982) 970.
5. For a review see P. Nath, R. Arnowitt and A. H. Chamseddine, "Applied N=1 Supergravity", (*World Scientific, Singapore* (1984); H. P. Nilles, *Phys. Rep.* **110** (1984)1, H. Haber and G. Kane, *Phys. Rep.* A. B. Lahanas and D. V. Nanopoulos, *Phys. Rep.* **145** (1987) 1.
6. R. Barbieri, S. Ferrara and C.A. Savoy, *Phys. Lett.* **B119** (1982) 343.
7. L. Hall, J. Lykken and S. Weinberg *Phys. Rev.* **D27** (1983) 2359; P. Nath R. Arnowtt and A. H. Chamseddine, *Nucl. Phys.* **B227** (1983) 121; S. Soni and A. Weldon, *Phys. Lett.* **B126** (1983) 215.
8. S. Dimopoulos and H. Georgi, *Nucl. Phys.* **B193** (1981) 150; N. Sakai, *Zeit. F. Phys.* **C11**(1981) .
9. See e.g. R. Slansky, *Phys. Rep.* 79 (1981) 1;
10. K. Inoue, A. Kakuto and T. Tankano, *Prog. Theor. Phys.* **75** (1986) 664; A. Anselm and A. Johansen, *Phys. Lett.* **B200** (1988) 331; A. Anselm, *Sov. Phys. JETP* **67** (1988) 663; R. Barbieri, G. Dvali and A. Strumia, *Nucl. Phys.* **B391** (1993) 487.
11. K. Inoue et al., *Prog. Theor. Phys.* **68** (1982)927 ; L. Ibañez and G. G. Ross, *Phys. Lett.* **B110** (1982)227 ; L. Avarez-Gaume', J. Polchinski and M. B. Wise, *Nucl. Phys.* **B250** (1983)495 ; J. Ellis, J. Hagelin, D. V. Nanopoulos and K. Tamvakis, *Phys. Lett.* **125B** (1983) 275 ; L. E. Ibañez and C. Lopez, and C. Muños, *Nucl. Phys.* **B256**(1985)218 .
12. See also S. Pokorski, talk at this conference.
13. R. Arnowitt and P. Nath, *Phys. Rev. lett.* **69** (1992)725.

14. G. Gamberini, G. Ridolfi and F. Zwirner, *Nucl. Phys.* **B331** (1990) 331.
15. P. Nath and R. Arnowitt, *Phys. Lett.* **B289** (1992)368 .
16. S. Kelley, J. Lopez, D. V. Nanopoulos, H. Pois and K. Yuan, *Phys. Lett.* **B273** (1991)423 .
17. P. Nath and R. Arnowitt, *Phys. Lett.* **B287** (1992)3282 .
18. G. G. Ross and R. G. Roberts, *Nucl. Phys.* **B377** (1992)971
19. M. Drees and M. M. Nojiri, *Nucl. Phys.* **B369** (1992)54
20. K. Inoue, M. Kawasaki, M. Yamaguchi and T. Yanagida, *Phys. Rev.* **D45** (1992) 387
21. M. Olechowski and S. Pokorski, MPI-PH/92-118.
22. S. P. Martin and P. Ramond, NUB-3067-93TH/SSCL-439(93).
23. H. Georgi and S. L. Glashow, *Phys. Rev. Lett.* **32** (1974) 448.
24. R. Becker-Szendy et. al., *Phys. Rev.* **D42** (1990)2974 .
25. P. Langacker and Polonsky, *Phys. Rev.* **D47** (1993) 4028.
26. Y. Totsuka, Proc. of XXIV Conf. on High Energy Physics, Munich, 1988, Eds. R. Kotthaus and J. H. Kuhn (Springer Verlag, Berlin, Heidelberg, 1989).
27. S. Weinberg, *Phys. Rev.* **d26** (1982)287 ; N. Sakai and T. Yanagida, *Nucl. Phys.* **B197** (1982)533 ; S. Dimopoulos, S. Raby and F. Wilczek, *Phys. Lett.* **112B** (1982)133 ; J. Ellis, D. V. Nanopoulos and S. Rudaz, *Nucl. Phys.* **B202** (1982)43 ; B. A. Campbell, J. Ellis and D. V. Nanopoulos, *Physl Lett.* **141B**, (1984)229 ; S. Chadha, G. D. Coughlan, M. Daniel and G. G. Ross, *Phys. Lett.* **149B** (1984)47 .
28. R. Arnowitt, A. H. Chamseddine and P. Nath, *Phys. Lett.* **156B** (1985)215 ; P. Nath, R. Arnowitt and A. H. Chamseddine, *Phys. Rev.* **32D** (1985)2348 .
29. M. B. Gavela, et.al. *Nucl. Phys.* **B312**(1989) 269.
30. Particle Data Group, *Phys. Rev.* **D45** (92).
31. H. Baer, X. Tata and J. Woodside, *Phys. Rev. Lett.* **63** (1989) 352; FSU-HEP-910211/UH-511-721-91/IS-J4185
32. ICARUS Detector Group, Int. Symposium on Neutrino Astrophysics, Takayama, 1992.
33. R. Arnowitt and P. Nath, CTP_TAMU-32/93-NUB-TH-3066/93-SSCL-Preprint-440 (1993).
34. B. W. Lee and S. Weinberg, *Phys. Rev. Lett.* **39** (1977)165 ; H. Goldberg, *Phys. Rev. Lett.* **50** (1983)1419 ; J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive and M. Srednicki, *Nucl. Phys.* **B238**(1984)453; J. Ellis L. Roszkowski and Z. Lalak, *Phys. Lett.* **B245** (1990) 545
35. L. Lopez, D. V. Nanopoulos and K. Yuan, *Nucl. Phys.* **B370** (1992)445 ; M. Drees and M. M. Nojiri, *Phys. Rev.* **D47** (1993) 376.
36. R. Arnowitt and P. Nath, *Phys. Lett.* **B299** (1993) 58 and Erratum ibid **B303** (1993) 403.
37. K. Griest and D. Seckel, *Phys. Rev.* **D43** (1991)3191 , P. Gondolo and G. Gelmini *Nucl. Phys.* **B360** (1991)145
38. P. Nath and R. Arnowitt, *Phys. Rev. Lett.* **70** (1993)3696 .
39. J. Lopez, D. V. Nanopoulos and K. Yuan, CTP-TAMU-14/93-ACT-4/93

40. P. Nath and R. Arnowitt, *Mod. Phys. Lett.* A, **Vol. 2** No. 5 (1987) 331; R. Barbieri, F. Caravaglio, M. Frigeni and M. Mangano, *Nucl. Phys.* **B367** (1991) 28; H. Baer and X. Tata, FSU-HEP-920907/UH-511-749-92 (1992).