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$SO(10)$ SUSY GUTs, the gravitino problem, non-thermal leptogenesis and axino dark matter

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ABSTRACT

Simple SUSY GUT models based on the gauge group $SO(10)$ require t–b–τ Yukawa coupling unification, in addition to gauge coupling and matter unification. The Yukawa coupling unification places strong constraints on the expected superparticle mass spectrum, with scalar masses ~ 10 TeV while gaugino masses are quite light. A problem generic to all supergravity models comes from overproduction of gravitinos in the early universe: if gravitinos are unstable, then their late decays may destroy the predictions of Big Bang nucleosynthesis. We present a Yukawa-unified $SO(10)$ SUSY GUT scenario which avoids the gravitino problem, gives rise to the correct matter–antimatter asymmetry via non-thermal leptogenesis, and is consistent with the WMAP-measured abundance of cold dark matter due to the presence of an axino LSP. To maintain a consistent cosmology for Yukawa-unified SUSY models, we require a re-heat temperature $T_R \sim 10^6$–10^7 GeV, an axino mass around ~ 0.1–10 MeV, and a PQ breaking scale $f_a \sim 10^{12}$ GeV.

1. *SO*(10) SUSY GUTs and Yukawa unification

Grand unified theories (GUTs) are amongst the most compelling ideas in theoretical physics. Their beauty is only enhanced via a marriage to supersymmetry (SUSY). The $SU(5)$ theory [1] unifies the Standard Model (SM) gauge symmetries into single Lie group, while explaining the ad hoc hypercharge assignments of the SM fermions, and successfully predicting the m_b/m_τ ratio. Adding SUSY to the $SU(5)$ theory stabilizes the hierarchy of interactions, but also receives experimental support from the celebrated unification of gauge couplings at scale $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV.

The $SO(10)$ SUSY GUT theory has even further successes [2]. For one, it explains the ad hoc anomaly cancellation within the SM and $SU(5)$ theories. Further, it unifies all matter of a single generation into the 16-dimensional spinor representation $\hat{\psi}(16)$, provided one adds to the set of supermultiplets a SM gauge singlet superfield $\hat{N}_i^c$ ($i = 1$–3 is a generation index) containing a right-handed neutrino.[1] Upon breaking of $SO(10)$, a superpotential term $\hat{f} \ni \frac{1}{2} M_{N_i} \hat{N}_i^c \hat{N}_i^c$ is induced which allows for a Majorana neutrino mass M_{N_i} which is necessary for implementing the see-saw mechanism for neutrino masses [4]. In addition, the $SO(10)$ theory allows for unification of Yukawa couplings of each generation. This applies calculationally especially to the third generation, where in simple $SO(10)$ SUSY GUTs, we may expect t–b–τ Yukawa coupling unification in addition to gauge coupling unification at scale $Q = M_{\rm GUT}$ [5,6].

In spite of these impressive successes, GUTs and also SUSY GUTs have been beset with a variety of problems, most of them arising from implementing GUT gauge symmetry breaking via large, unwieldy Higgs representations. Happily, in recent years physicists have learned that GUT theories—as formulated in spacetime dimensions greater than four—can use extra-dimension compactification to break the GUT symmetry instead [7]. This is much in the spirit of string theory, where anyway one must pass from a 10- or 11-dimensional theory to a 4-d theory via some sort of compactification.

Regarding Yukawa coupling unification in $SO(10)$, the calculation begins with stipulating the b and τ running masses at scale $Q = M_Z$ (for two-loop running, we adopt the $\overline{DR}$ regularization scheme) and the t-quark running mass at scale $Q = m_t$. The Yukawa couplings are evolved to scale $Q = M_{\rm SUSY}$, where threshold corrections must be implemented [8], as one passes from the SM effective theory to the Minimal Supersymmetric Standard Model (MSSM) effective theory. From $M_{\rm SUSY}$ on to $M_{\rm GUT}$, Yukawa coupling evolution is performed using two-loop MSSM RGEs. Thus, Yukawa coupling unification ends up depending on the complete SUSY mass spectrum via the t, b and τ self-energy corrections.

In this Letter, we adopt the Isajet 7.75 program for calculation of the SUSY mass spectrum and mixings [9] and IsaReD [10] for the neutralino relic density. Isajet uses full two-loop RG run-

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[1] Here, we adopt the superfield "hat" notation as presented in Ref. [3].

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ning for all gauge and Yukawa couplings and soft SUSY breaking (SSB) terms. In running from $M_{\rm GUT}$ down to $M_{\rm weak}$, the RG-improved 1-loop effective potential is minimized at an optimized scale choice $Q = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, which accounts for leading two-loop terms. Once a tree-level SUSY/Higgs spectrum is calculated, the complete 1-loop corrections are calculated for all SUSY/Higgs particle masses. Since the SUSY spectrum is not known at the beginning of the calculation, an iterative approach must be implemented, which stops when an appropriate convergence criterion is satisfied.

Yukawa coupling unification has been examined in a number of previous papers [5,6,11–14]. The parameter space to be considered is given by

$$m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ {\rm sign}(\mu) \tag{1}$$

along with the top quark mass, which we take to be $m_t = 171$ GeV. Here, m_{16} is the common mass of all matter scalars at $M_{\rm GUT}$, m_{10} is the common Higgs soft mass at $M_{\rm GUT}$ and M_D^2 parameterizes either D-term splitting (DT) or Higgs-only soft mass splitting (HS). The latter is given by $m_{H_{u,d}}^2 = m_{10}^2 \mp 2M_D^2$. As in the minimal supergravity (mSUGRA) model, $m_{1/2}$ is a common GUT scale gaugino mass, A_0 is a common GUT scale trilinear soft term, and the bilinear SSB term B has been traded for the weak scale value of $\tan\beta$ via the EWSB minimization conditions. The latter also determine the magnitude (but not the sign) of the superpotential Higgs mass term μ.

What has been learned is that t–b–τ Yukawa coupling unification *does* occur in the MSSM for $\mu > 0$ (as preferred by the $(g-2)_\mu$ anomaly), but *only if certain conditions* are satisfied.

- The scalar mass parameter m_{16} should be very heavy: in the range 5–20 TeV.
- The gaugino mass parameter $m_{1/2}$ should be as small as possible.
- The SSB terms should be related as $A_0^2 = 2m_{10}^2 = 4m_{16}^2$, with $A_0 = -2m_{16}$ (in our sign convention). This combination was found to yield a radiatively induced inverted scalar mass hierarchy (IMH) by Bagger et al. [15] for MSSM + right-hand neutrino (RHN) models with Yukawa coupling unification.
- $\tan\beta \sim 50$.
- EWSB can be reconciled with Yukawa unification only if the Higgs SSB masses are split at $M_{\rm GUT}$ such that $m_{H_u}^2 < m_{H_d}^2$. The HS prescription ends up working better than DT splitting [12,13].

In the case where the above conditions are satisfied, then Yukawa coupling unification to within a few percent can be achieved. The resulting sparticle mass spectrum has some notable features.

- First and second generation matter scalars have masses of order $m_{16} \sim 5$–20 TeV.
- Third generation scalars, m_A and μ are suppressed relative to m_{16} by the IMH mechanism: they have masses on the 1–2 TeV scale. This reduces the amount of fine-tuning one might otherwise expect in such models.
- Gaugino masses are quite light, with $m_{\tilde{g}} \sim 350$–500 GeV, $m_{\tilde{Z}_1} \sim 50$–80 GeV and $m_{\tilde{W}_1} \sim 100$–150 GeV.

The sparticle mass spectra from $SO(10)$ SUSY GUTs shares some features with spectra generated in "large cutoff supergravity" or LCSUGRA, investigated in Ref. [16]. LCSUGRA also has high mass scalars—typically with mass around 5 TeV—and low mass gauginos. The $SO(10)$ SUSY GUT models are different from LCSUGRA in that they have a large A_0, with $A_0 \sim -2m_{16}$, and a μ term of around 1–2 TeV. This means $SO(10)$ SUSY GUTs have a dominantly bino-like $\tilde{Z}_1$ state, whereas the LCSUGRA authors adopt the mSUGRA model focus point region, which has a mixed higgsino–bino $\tilde{Z}_1$ state. The latter can easily give the measured abundance of cold dark matter (CDM) in the form of lightest neutralinos.

Since the lightest neutralino of $SO(10)$ SUSY GUTs is nearly a pure bino state, it turns out the neutralino relic density $\Omega_{\tilde{Z}_1}h^2$ is calculated to be extremely high, of order 10^2–10^4. This conflicts with the WMAP-measured value [17], which gives

$$\Omega_{\rm CDM}h^2 \equiv \rho_{\rm CDM}/\rho_c = 0.111^{+0.011}_{-0.015}(2\sigma) \tag{2}$$

where $h = 0.74 \pm 0.03$ is the scaled Hubble constant.

Several solutions to the $SO(10)$ SUSY GUT dark matter problem have been proposed in Refs. [14,18]. Here, we will concentrate on the most attractive one: that the dark matter particle is in fact not the neutralino, but the *axino* $\tilde{a}$. Axino dark matter occurs in models where the MSSM is extended via the Peccei–Quinn (PQ) solution to the strong *CP* problem [19]. The PQ solution introduces a spin-0 axion field into the model; if the model is supersymmetric, then a spin-$\frac{1}{2}$ axino is also required. It has been shown that the $\tilde{a}$ state can be an excellent candidate for cold dark matter in the universe [20]. In this Letter, we will find that $SO(10)$ SUSY GUT models with an axino DM candidate can (1) yield the correct abundance of CDM in the universe, (2) avoid the gravitino/BBN problem and (3) have an compelling mechanism for generating the matter–antimatter asymmetry of the universe via non-thermal leptogenesis.

2. The gravitino problem

An affliction common to all models with gravity mediated SUSY breaking (supergravity or SUGRA) models is known as the gravitino problem. In realistic SUGRA models (those that include the SM as their sub-weak-scale effective theory), SUGRA is broken in a hidden sector by the super-Higgs mechanism, which induces a mass for the gravitino $\tilde{G}$, which is commonly taken to be of order the weak scale. The gravitino mass $m_{\tilde{G}}$ ends up setting the mass scale for all the soft breaking terms, so then all SSB terms end up also being of order the weak scale.

The coupling of the gravitino to matter is strongly suppressed by the Planck mass, so the $\tilde{G}$ in the mass range considered here ($m_{\tilde{G}} \sim 5$–20 TeV) is never in thermal equilibrium with the thermal bath in the early universe. Nonetheless, it does get produced by scatterings of particles that do partake of thermal equilibrium. Thermal production of gravitinos in the early universe has been calculated in Ref. [21], where the abundance is found to depend naturally on $m_{\tilde{G}}$ and on the re-heat temperature T_R at the end of inflation. Once produced, the $\tilde{G}$s decay into all varieties of particle–sparticle pairs, but with a lifetime that can exceed ~ 1 s, the time scale where Big Bang nucleosynthesis (BBN) begins. The energy injection from $\tilde{G}$ decays is a threat to dis-associate the light element nuclei which are created in BBN. Thus, the long-lived $\tilde{G}$s can destroy the successful predictions of the light element abundances as calculated by nuclear thermodynamics.

The BBN constraints on gravitino production in the early universe have been calculated by several groups [22]. The recent results from Ref. [23] give an upper limit on the re-heat temperature as a function of $m_{\tilde{G}}$. The results depend on how long-lived the $\tilde{G}$ is (at what stage of BBN the energy is injected), and what its dominant decay modes are. Qualitatively, for $m_{\tilde{G}} \lesssim 5$ TeV, $T_R \lesssim 10^6$ GeV is required; if this is violated, then too many $\tilde{G}$ are produced in the early universe, which destroy the ^{3}He, ^{6}Li and D abundance calculations. For $m_{\tilde{G}} \sim 5$–50 TeV, the re-heat upper bound is much less: $T_R \lesssim 5 \times 10^7$–$10^9$ GeV (depending on the ^{4}He abundance) due to overproduction of ^{4}He arising from $n \leftrightarrow p$ conversions. For