BARYOGENESIS AND PROTON DECAY

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SUMMARY

We analyze the constraints that proton decay experiments and cosmologically sound unification models impose on each other. An intermediate scale of around 10^{10} GeV arises from considerations on baryogenesis, inflation and supersymmetry breaking. An upper bound to the gravitino mass of about 50 TeV follows from current proton lifetime limits.

INTRODUCTION

One of the most astounding successes of the grand unification program [1], initiated about ten years ago, was the understanding of the origin of the baryon asymmetry of the universe [2]. The program suffered an early setback when minimal SU(5) failed to explain quantitatively this baryon asymmetry and predicted too fast a proton decay rate. Nowadays, the experimental limits on the proton's lifetime [3] and the requirements of efficient baryogenesis tightly constrain the parameters in the lagrangian of candidate unification models. An excellent theoretical laboratory arises from the locally supersymmetric grand unified model below [4-8], which is consistent

(a) internally below the Planck scale (anomaly-free),

(b) with the SU(3)xSU(2)xU(1) standard model at "low" energies,

(c) with Big Bang inflationary cosmology at "high" energies, and

(d) with underground detector limits on proton decay.

The general traits of this SUPERSYMMETRIC INFLATIONARY COSMOLOGY (SIC) are reviewed, with a particular emphasis on the intriguing relationship between supersymmetry breaking [6], proton decay [7] and baryogenesis [8], the last two being the baryon-number-violating processes about which we have the most experimental information.

Within four-dimensional N=1 supergravity with minimal kinetic terms, the superpotential can be taken of the form [5]

$$P = I + G + S$$

with I the inflation sector, S the (O'Raifeartaigh) supersymmetry breaking sector, and G the visible grand unified sector which includes higgs and matter fields. These sectors interact with each other only gravitationally, that is with couplings suppressed by powers of $M=(8\pi G)^{-1/2} \simeq 2.4 \times 10^{18}$ GeV.

GRAND UNIFICATION

Good old SU(5) seems to work well enough as a generic grand unified gauge group, as long as minimality is not imposed. Condition (b) basically restricts the particle spectrum of the model: three matter families of $(\bar{5} + 10 + 1)$ coupling to a rather large Higgs sector $(\bar{5} + \overline{45} + 5 + 5 + 5)$ to reproduce (1) the observed mass ratios between charge -1/3 quarks and charge -1 leptons, and (2) the Kobayashi-Maskawa matrix, including the large (c,b) entry inferred from the long B-meson's lifetime.

The judicious use of condition (a) enlarges the Higgs sector to cancel gauge anomalies, and to break the Peccei-Quinn symmetry at an intermediate ($\simeq 10^{11}$ GeV) scale. The right-handed neutrino develops a large Majorana mass m_R, the strong CP problem is solved, and the electroweak higgs doublets (1,2) remain light while a large mass is given to their grand unified partners, the higgs color triplets (3,1).

These triplet fields appear in any unification scheme and mediate proton decay. Their own decay, which occurs out of equilibrium and violates CP, can produce a net baryon number from an initially matter-antimatter symmetric universe. Conditions (c) and (d) above, hence, translate into stringent upper and lower bounds, respectively, on the masses and couplings of the color triplets.

One of the global U(1) symmetries of the superpotential is the anomalous Peccei-Quinn symmetry, which forbids the higgses coupling to the 10.10 sector from mixing with those coupling to the $\bar{5}.10$ sector, and thus prevents the appearance of "dimension-five" proton decay operators. This symmetry is crucial: were it not there, proton decay would proceed through helicity- flipping higgsinos at a very fast rate $\approx m_3^{-2}$ instead of $\approx m_3^{-4}$, due to the difference between fermionic and bosonic propagators. To obtain reasonable proton decay rates, the mass of the color triplets m_3 would have to be larger than about 10^{15} GeV. Such heavy triplets could never be produced after inflation and could not account for the observed baryon asymmetry of the universe.

PROTON DECAY

Proton decay does proceed, however, through the interchange of the scalar color triplets, via "dimension-six" operators. Integrating away the triplets, one can write the low-energy Lagrangian for nucleon decay ($qqq\bar{\ell}$) in terms of the electroweak current eigenstates as follows, with the family indices a,b,c,d running from one to three:

$$\mathcal{L}_p = \Sigma\{L_{abcd}\langle abcd\rangle_\nu - L_{abcd}\langle abcd\rangle_e + R_{abcd}\{abcd\}\} \qquad (1)$$

The coefficients L and R follow from the superpotential G and are of the form

$$(\text{mixing factor})\times \frac{(\text{Yukawa})^2}{m_3^2}$$

up to a numerical factor which is 1/2 for L and 16 for R. The mixing factor, between zero and one, reflects our ignorance about the equivalent of the Kobayashi-Maskawa matrix for the higgs sector. Note that the operators $\langle abcd\rangle$ come from $(\bar{5}.10)^+(\bar{5}.10)$ and produce a right-handed anti-lepton from nucleon decay, whereas $\{abcd\}$ operators arise from $(10.10)^+(10.10)$ and produce an outgoing left-handed anti-lepton. Explicitly, in two-component notation,

$$\langle abcd\rangle_\nu = -(u^T_{bR}d_{aR})(\nu^T_{cL}d_{dL})$$

$$\langle abcd\rangle_e = -(u^T_{bR}d_{aR})(e^T_{cL}u_{dL})$$

$$\{abcd\} = -(d^T_{bR} u_{aR})(e^T_{cL} u_{dL})$$

To rewrite (1) in terms of the mass eigenstates one must insert the appropriate left and right rotation matrices for the charged leptons and for the quarks, which can be readily obtained [4] from the detailed form of the superpotential G. We sum over all neutrino flavors, experimentally indistinguishable:

$$\mathcal{L}_p = \Sigma \{LN_{abd}\langle abd\rangle + LE_{abcd}\langle abcd\rangle + RE_{abcd}\{abcd\}\} \quad (2)$$

$$LN_{abd} = E \sum_{efgh} L_{efgh}(V^+_{-1/3R})_a{}^e\ (V^+_{2/3R})_b{}^f\ (V_{-1/3L})^h{}_d$$

$$LE_{abcd} = -E \sum_{efgh} L_{efgh}(V^+_{-1/3R})_a{}^e(V^+_{2/3R})_b{}^f(V_{\ell L})^g{}_c(V_{-1/3L})^h{}_d$$

$$RE_{abcd} = E \sum_{efgh} R_{efgh}(V_{2/3R})^e{}_a(V_{-1/3R})^f{}_b(V^+_{\ell L})_c{}^g(V^+_{2/3L})_d{}^h$$

where E = 2.89±.2 is an enhancement factor due to the non-abelian renormalization of the four-fermion operators, down to very low energies from the unification scale (5.6×10^{16} GeV, with $\alpha = 19.6^{-1}$ and $\sin^2\theta_\omega(M_W) = .237$, all with a 5% uncertainty).

Expressions for the proton decay rates into various channels can be calculated [4] from (2), with the usual uncertainty in relating quark operators to nucleon and meson operators. The favored decay modes, which constrain m_3 most, are $p \to \mu^+K^0$ and $p \to \nu K^+$. Using the latest limits [3] to normalize the lifetimes,

$$\frac{m_3}{10^{10}\text{GeV}} = \left[(4\text{-}10)\ \frac{\tau_{\mu K}}{4\times10^{31}\text{years}}\right]^{1/4}$$

$$\frac{m_3}{10^{10}\text{GeV}} = \left[(5\text{-}18)\ \frac{\tau_{\nu K}}{5\times10^{31}\text{years}}\right]^{1/4}$$

where the quoted uncertainty arises from higgs mixings. It follows that $m_3 > 2 \times 10^{10}$ GeV, a rather low value which greatly facilitates baryogenesis.

SUPERSYMMETRY AND INFLATION

The superpotential S contains [5,6] two parameters μ and λ, after tuning a third one to make the cosmological constant vanish at the minimum of the full potential. S contains a superfield whose F-term acquires a vev and thus breaks supersymmetry at the intermediate scale μ. The fermionic component of this superfield provides the gravitino with the helicity 1/2 states it needs to become massive, $m_{3/2} = \mu^2/M$. Its scalar component (O'Raifearton) develops a one-loop mass $m_{O'R} = \lambda\mu$, stores potential energy, and releases it after inflation into gravitino pairs with rate $(16\pi^2)^{-1}\ \lambda^4\ \mu$.

I contains [5] only one parameter, Λ, and a single complex superfield whose real scalar part (with mass $m_I \approx 3.2\ \Lambda^2/M$) is called the inflaton because it drives inflation while its potential energy dominates the energy density of the universe. The quantum fluctuations of the inflaton leave the horizon during inflation and reenter it afterwards, generating [2] a primordial adiabatic spectrum of scale-free density fluctuations of magnitude $\frac{\delta\rho}{\rho} \simeq 10^4\ (\frac{\Lambda}{M})^2$ (up to logarithms).

The inflaton wiggles into the minimum of its effective potential and without achieving thermal equilibrium decays preferentially into the heaviest possible fields around, the higgs color triplets. The universe is ultimately reheated to a temperature $T_R \simeq \frac{\Lambda^3}{M^2}$, lower than the mass of the inflaton.

BARYOGENESIS

Recall that one can understand the current amount of baryonic matter per unit entropy (equivalently, the number of baryons per photon, $\frac{n_{B-\bar{B}}}{n_\gamma} \simeq 10^{-10}$) as originating from a baryon-antibaryon symmetric universe which developed a net asymmetry through (decay) processes fulfilling the three requirements of baryon-number (B) violation, time reversal (T) violation, and lack of equilibrium.

The triplet fields may have masses much greater than T_R, need never be in thermal equilibrium, and hence are not Boltzmann-suppressed in abundance. We may follow the analysis in [9] to write the asymmetry for this out-of-equilibrium decay case as

$$\frac{n_{B-\bar{B}}}{n_\gamma} = \frac{T_R}{m_I}\ \delta B$$

where m_I is the mass of the inflaton whose decay reheats the universe after inflation, $\frac{T_R}{m_I} = \frac{\Lambda}{M}$ and δB is the baryon asymmetry produced per decay of an $I - \bar{I}$ pair, which is roughly the same as that produced per decay of triplet-antitriplet pair. Realistic baryon to photon ratios are possible if δB is sufficiently large.

To estimate δB one must evaluate the total decay width of the triplets and the one-loop interferences in all the decay channels. The analysis of the possible CP-violating interferences is greatly facilitated by the use of supergraphs, which exhibit the chiral structure transparently. Having forbidden mixings among higgs triplets, the required helicity flips must appear in the decay fields. Since ordinary quarks and leptons are massless at the intermediate scale, all the baryon asymmetry is generated in the decays of triplets into quarks and heavy ($m_R \lesssim 10^{10}$ GeV) right-handed neutrinos. Assuming the relative phases of the various Yukawa couplings to be of order one, the result is [8]

$$\delta B \approx \frac{1}{32\pi^2}\ (\text{Yukawa})^2\ (\frac{m_R}{m_3})^2.$$

Pushing the Yukawa couplings to the limits of perturbation theory, one can stretch δB as high as 10^{-5}, although a somewhat lower value is more likely. Neutrino oscillations are completely unobservable and no SO(10) relations hold among the various Yukawas.

CONSTRAINTS FROM THE INTERMEDIATE SCALE

Big bang cosmology [2] imposes strong limits on the masses and lifetimes of unstable particles, particularly on the gravitino or any other field with couplings of only gravitational strength. Its very long lifetime $\sim \frac{M^2}{m_{3/2}^3}$ would in principle force it to decay after primordial nucleosynthesis and thereby destroy the succesfully predicted relative abundances of light elements (Polonyi problem or supersymmetric entropy crisis). If the gravitino mass is around a TeV (to solve the hierarchy problem, common to all realistic gauge field theories), then a period of inflation before baryogenesis is definitely needed to dilute the initial gravitino abundance, as well as to explain the flatness of the universe, its spectrum of density fluctuations, the absence of monopoles, and all the other inflationary goodies.

After inflation, excessive production of gravitinos through scattering processes can only be avoided if the reheat temperature is bounded above [10],

$$T_R < 2.5 \times 10^7 \text{ GeV } \left(\frac{1 \text{ TeV}}{m_{3/2}}\right) \qquad (3)$$

where we have assumed that photinos are lighter than gravitinos and hence gravitinos are unstable. To prevent gravitino regeneration from direct inflaton decay into O'Raifeartons, we can simply forbid it kinematically, $\lambda\mu > \Lambda^2/M$.

From the discussion above, a fascinating hierarchy of masses is established, $m_R < m_3 < m_I < m_{O'R}$ at the <u>intermediate scale</u>, $10^9 \sim 10^{12}$ GeV, associated with the physical phenomena of Peccei-Quinn symmetry breaking, baryon-number violation, inflation, and hidden-sector supersymmetry breaking. Several limits relevant for the experimental quest after supersymmetry and proton decay follow.

The bound $m_3 > 2\times10^{10}$ GeV from proton decay experiments implies the limit $\Lambda > 10^{-4.25}$ in Planck (2.4×10^{18} GeV) units. The relationship (3) can be rewritten in our framework as $\Lambda^3\mu^2 < 4.2\times10^{-27}$. These two inequalities result in $\mu < 1.54\times10^{-7} = 3.7\times10^{11}$ GeV, or $m_{3/2} < 57$ TeV. <u>Proton decay experiments have thus obtained an upper bound on the gravitino mass</u>, the scale of supersymmetry breaking in the observable sector.

On the other hand, the lack of experimental confirmation for supersymmetry in accelerator experiments allows us to expect $m_{3/2} > 100$ GeV , from which it follows that $\Lambda < 10^{-3.3}$, hence $m_3 < 1.9\times10^{12}$ GeV, hence $\tau_{\mu K} < 1.3\times10^{40}$ years, not a very useful bound. Assuming supersymmetry is not found at the SSC then the gravitino mass will be narrowly constrained between lower bounds from the SSC and upper bounds from upgraded proton decay experiments. If the largest conceivable Earth-based detectors [3] improve the proton lifetime limit to $\tau_{\mu K} > 5\times10^{34}$ years, then $\Lambda \gtrsim 10^{-3.9}$ and $m_{3/2} \lesssim 7$ TeV. A more likely and happier possibility, of course, is that some positive signal is found.

From (the remoteness of) supersymmetry and (the absence of) proton decay, we have thus argued that $10^{-3.3} > \Lambda > 10^{-4.25}$. Now, the preferred value for adiabatic cold dark matter density fluctuations [2] is $\frac{\delta\rho}{\rho} \simeq 10^{-4\pm.5}$, which implies $\Lambda \simeq 10^{-4\pm.25}$, in sharp agreement with the result above. The magnitude of the density fluctuations appears, as a matter of fact, as a prediction of the model. The best values for Λ, around 10^{-4}, fulfill also the requirement for baryogenesis, $10^{-10} \simeq \Lambda\cdot\delta B$, for we argued above that $\delta B \sim 10^{-6}$ is a reasonable number.

Further investigation of the intermediate scale through the interplay between particle physics (both accelerator and non-accelerator) and cosmology is under way. The examination of similar phenomenological issues in the context of models derived from the heterotic string will be reported elsewhere.

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