CPT, STRINGS, AND BARYOGENESIS

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In the context of string field theory, the possibility exists for the spontaneous violation of Lorentz invariance and CPT. In this talk, we review its status and some experimental constraints. We discuss the possibility that stringy CPT violation could give rise to a mechanism in which baryogenesis occurs in the early Universe in thermal equilibrium and show that this can produce, under suitable circumstances, a baryon asymmetry equal to the observed value.

1 Introduction

One of the natural instances where particle physics meets cosmology is in the problem of the generation of baryon asymmetry in the early Universe. Sakharov showed that the simultaneous violation of baryon number and of C and CP symmetries, in the presence of nonequilibrium processes, is sufficient for generating a baryon asymmetry. Many specific mechanisms that implement these constraints have been investigated.

In this talk, we outline an alternative way to generate baryon number in the early Universe, through the spontaneous violation of CPT symmetry. Spontaneous violation of CPT can in principle occur in certain string theories. If CPT and baryon number are violated, baryon asymmetry can arise in thermal equilibrium. This mechanism would have the advantage of being otherwise independent of C- and CP- violating processes, which in a GUT are typically contrived to match the observed baryon asymmetry and

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are unrelated to the experimentally measured CP violation in the standard model.

We describe here how CPT violation might occur spontaneously in string theory, and how it can give rise to baryogenesis along the lines indicated above. We also discuss dilution effects through electroweak sphalerons. Other possible experimental implications of spontaneous CPT violation are considered elsewhere.

2 CPT violation in String Field Theory

2.1 Noncanonical vacua

For definiteness, we use Witten’s version of (type I) string field theory:

\[ L = \int \Phi^* Q \Phi + g \int \Phi * \Phi * \Phi. \]  

(1)

Here, \( \Phi \) is the string field, which can be expanded in particle modes:

\[ |\Phi\rangle = \phi(x_0) + A_\mu(x_0)\alpha_\mu_{-1} + \frac{1}{\sqrt{2}}B_\mu(x_0)\alpha_\mu_{-2} \]

\[ + \frac{1}{\sqrt{2}}B_{\mu\nu}(x_0)\alpha_\mu_{-1}\alpha_\nu_{-1} + \beta_1(x_0)b_{-1}c_{-1} + \ldots | - \frac{1}{2} \rangle. \]  

(2)

First-quantized string theory is obtained as perturbation theory around the solution \( \Phi = 0 \) of the equation of motion \( Q \Phi + \Phi \Phi = 0 \). By no means, however, is this the only solution. Other noncanonical solutions of the equations of motion for \( \Phi \) exist.

Perturbation theory around those backgrounds yields different physics, for instance:

- There are backgrounds with no tachyonic mode, just as in the electroweak standard model the would-be tachyon becomes a massive field as the Higgs field takes a nonzero expectation value.

- Many of the originally (massive) degrees of freedom can become nonpropagating because string field theory is nonlocal on the Planck scale, so derivatives in the cubic term appear in the effective propagator for noncanonical backgrounds.

- Lorentz covariance may be lost due to spontaneous symmetry breaking.

- Other discrete symmetries like CPT may be lost.
2.2 CPT violation

In string field theory, solutions exist in which scalar field components have a nonzero value. This in turn can lead to an effective action for tensor field components that would give a vacuum expectation value to the latter. As an example, consider the bosonic string field theory described above. It contains the coupling $A_\mu A^\mu \phi$. It follows that if $\phi$ gets a negative expectation value, this would contribute in turn to a negative squared mass for $A_\mu$. In that case, $A_\mu$ could get a vacuum expectation value, breaking Lorentz invariance. As $A_\mu$ is odd under CPT, this means that CPT would also be broken.

A numerical investigation based on a level-cutoff scheme\cite{27} has shown that nontrivial solutions of bosonic string field theory do indeed exist. Moreover, among those are solutions that break Lorentz invariance. Evidence for CPT-violating solutions also appears.

3 Experimental constraints

Consider the cubic coupling

$$T_{\mu_1...\mu_n} \bar{\psi} \Gamma^{\mu_1...\mu_r} \partial^{\mu_{r+1}}...\partial^{\mu_n} \psi$$

in which $T_{\mu_1...\mu_n}$ acquires a vacuum expectation value. If $T$ is odd under CPT, this yields a CPT-violating chemical potential $\mu$ for the fermion (quark) $\psi$.

The chemical potential can, for instance, create an effective mass (or energy) difference between particles and antiparticles, thus violating CPT. The tightest experimental bounds on CPT violation involve the neutral $K-K$ system\cite{28}

$$\frac{\Delta m}{m} < 2 \times 10^{-18}. \quad (4)$$

For this reason, we expect CPT violation, if present, to be highly suppressed. The natural suppression factor is the energy scale over the Planck mass.

An analysis\cite{15,14} shows that, for the case $k = 0$, any expectation value of the tensor field should be suppressed by two powers of $m_t/M_{pl}$, and for the case $k = 1$ at least by one. For $k \geq 2$ the required suppression factors are automatically provided by the derivatives.

4 Baryogenesis

4.1 Baryogenesis in thermal equilibrium

As indicated above, the presence of CPT violation gives rise to the possibility of baryogenesis in the early Universe. In the presence of processes violating baryon number (for instance, at the GUT scale) in thermal equilibrium,
a nonzero baryon number is attained that is controlled by the value of the chemical potential.

In this case, a calculation shows that the contribution to the baryon-number asymmetry per comoving volume for \( k = 0 \) is given by

\[
\frac{n_q - n_{\bar{q}}}{3s} \sim \frac{15g_s}{2\pi^4g^*(T)} \frac{\mu}{T} I_0(m_q/T) ,
\]

where \( \mu \) is the chemical potential generated by the CPT-violating term, and

\[
I_0(r) = \int_r^\infty dx x \sqrt{x^2 - r^2} e^x (1 + e^x)^{-2}.
\]

The integral obeys the condition \( I_0(r) < I_0(0) = \pi^2/6 \). If we take \( \mu \) to be suppressed by two orders of \( m_l/M_{Pl} \), or \( \mu \sim m_l^2/M_{Pl} \), we find \( n_B/s \sim (10^{-16}m_l/T)I_0(m_q/T) \), far too small to reproduce the observed value \( n_B/s \simeq 10^{-10} \).

A similar analysis shows that the case \( k = 1 \) also generates too small a contribution to reproduce the observed baryon asymmetry.

However, \( k = 2 \) generates a baryon asymmetry

\[
\frac{n_B}{s} \sim \frac{3}{5} \frac{T}{M_{Pl}}.
\]

which, for appropriate decoupling temperature \( T_{D} \), can reproduce the observed value. Note, however, that possible dilution mechanisms that might occur subsequently must be taken into account.

### 4.2 Dilution through sphaleron transitions

It has been pointed out that baryon asymmetry can be diluted by the occurrence of sphaleron transitions, which violate baryon number. These processes are expected to be unsuppressed above the electroweak scale, and exceed the expansion rate of the Universe below \( 10^{12} \) GeV.

If the initial value of \( B - L \) is zero, an analysis shows that the original asymmetry is diluted by a factor of about \( 10^{-6} \). If initially \( B - L \neq 0 \), the dilution by the \( (B - L \text{ conserving}) \) sphalerons is by a factor of order one. In the former case, this means that the observed asymmetry is generated if the initial baryon asymmetry takes place at a temperature of \( 10^{-4}M_{Pl} \), a value close to the GUT scale and the leptoquark mass \( M_X \), which is consistent with the requirement the rate of baryon number violation exceeds the expansion rate of the Universe during that period.
5 Summary

We have explored the possibility that baryogenesis occurs through spontaneous CPT breaking from string theory. We have found that the CPT-breaking terms with $k = 2$, accompanied by interactions violating baryon number, generate a large baryon asymmetry at the GUT scale. If the interactions preserve $B - L$, the subsequent dilution through sphaleron transition will then reproduce the observed baryon asymmetry.

References

1. A.D. Sakharov, JETP Lett. 5 (1967) 24.
2. M. Yoshimura, Phys. Rev. Lett. 41 (1978) 281; Phys. Lett. B 88 (1979) 294.
3. A.Yu. Ignatiev, N.V. Krasnikov, V.A. Kuzmin and A.N. Tavkhelidze, Phys. Lett. B 76 (1978) 436.
4. S. Weinberg, Phys. Rev. Lett. 42 (1979) 850.
5. A.D. Linde, Phys. Lett. B 70 (1977) 306.
6. S. Dimopoulos and L. Susskind, Phys. Rev. D 18 (1978) 4500.
7. M. Claudson, L.J. Hall and I. Hinchliffe, Nucl. Phys. B 241 (1984) 309.
8. K. Yamamoto, Phys. Lett. B 168 (1986) 341.
9. O. Bertolami and G.G. Ross, Phys. Lett. B 183 (1987) 163.
10. A. Cline and S. Raby, Phys. Rev. D 43 (1991) 1781.
11. S. Mollerach and S. Roulet, Phys. Lett. B 281 (1992) 303.
12. I. Affleck and M. Dine, Nucl. Phys. B 249 (1985) 361.
13. V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, Phys. Lett. B 155 (1985) 36.
14. O. Bertolami, D. Colladay, V.A. Kostelecký and R. Potting, Phys. Lett. B 395 (1997) 178.
15. V.A. Kostelecký and R. Potting, Nucl. Phys. B 359 (1991) 545.
16. A.D. Dolgov and Ya.B. Zeldovich, Rev. Mod. Phys. 53 (1981) 1.
17. A.G. Cohen and D.B. Kaplan, Phys. Lett. B 199 (1987) 251; Nucl. Phys. B 308 (1988) 913.
18. V.A. Kostelecký, R. Potting, and S. Samuel, in S. Hegarty et al., eds., Proceedings of the 1991 Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics, World Scientific, Singapore, 1992;
   V.A. Kostelecký and R. Potting, in D.B. Cline, ed., Gamma Ray–Neutrino Cosmology and Planck Scale Physics (World Scientific, Singapore, 1993) [hep-th/9211116].
19. V.A. Kostelecký and R. Potting, Phys. Rev. D 51 (1995) 3923; D.
Colladay and V.A. Kostelecký, Phys. Rev. D 55 (1997) 6760.
20. D. Colladay and V.A. Kostelecký, Phys. Lett. B 344 (1995) 259; V.A. Kostelecký and R. Van Kooten, Phys. Rev. D 54 (1996) 5585.
21. D. Colladay and V.A. Kostelecký, Phys. Rev. D 52 (1995) 6224.
22. E. Witten, Nucl. Phys. B 268 (1986) 253.
23. S. Giddings, E. Martinec and E. Witten, Phys. Lett. B 176 (1986) 362.
24. S. Giddings and E. Martinec, Nucl. Phys. B 278 (1986) 91.
25. V.A. Kostelecký and S. Samuel, Nucl. Phys. B 336 (1990) 263; Phys. Rev. Lett. 64 (1990) 2238; Phys. Rev. D 42 (1990) 1289.
26. V.A. Kostelecký and S. Samuel, Phys. Rev. D 39 (1989) 683; *ibid.*, 40 (1989) 1886; Phys. Rev. Lett. 63 (1989) 224; *ibid.*, 66 (1991) 1811.
27. V.A. Kostelecký and R. Potting, Phys. Lett. B 381 (1996) 89.
28. L.K. Gibbons et al., Phys. Rev. D 55 (1997) 6625.
29. J. Ambjørn and A. Krasnitz, Phys. Lett. B 362 (1995) 97.