Electroweak Baryogenesis

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Physics 735

December 4, 2008

The asymmetry between matter and anti-matter is a question that has puzzled particle physicists and cosmologists. We know that the asymmetry exists; we would not exist otherwise. Instead, the universe would simply consist of γ-radiation that results from nucleon-antinucleon annihilations. This asymmetry has been detected through cosmological experiments such as WMAP. In order for successful nucleosynthesis, we require that the baryon asymmetry of the universe (BAU), $n_B/n_\gamma\ 10^{-10}$ where n_B is the baryon number density, and n_γ is the photon number density at temperature T.

Through naturalness arguments, we assume that inflation washes out ay initial baryon asymmetry so that we start with $B = 0$, where B is the baryon number. Therefore, we require some dynamic mechanism called baryogenesis that generates a non-zero B after inflation. Any such mechanism must satisfy Sakharov's requirements:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

All three of these conditions are satisfied in both the Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM). However, the CP-violating processes in the SM only generate an asymmetry of order 10^{-18}, which is too small compared to the known value of 10^{-10}. There are several theories for baryogenesis: GUT-Baryogenesis, Electroweak Baryogenesis, and the Affleck-Dine Mechanism. I will focus on the electroweak model for baryogenesis. Electroweak baryogenesis was introduced by Shaposnikov in the late 1980s, and is of interest because it only uses known physics, or physics that will be testable in the near future.

In the early universe, temperatures were high enough to allow for the unification of the electromagnetic and weak fields in a $SU(2) \times U(1)$ symmetry. At temperatures around 100 GeV, commonly called T_c or the critical temperature, this electroweak symmetry was broken into $U(1)$, the electromagnetic field, and $SU(2)$, the weak field. We call this symmetry-breaking the electroweak phase transition (EWPT).

Electroweak baryogenesis occurs as follows. If the EWPT is strongly first-order, bubbles of broken phase will nucleate within the symmetric phase as the Universe cools beneath T_c. This satisfies condition 3 of Sakharov. We then have CP-violating interactions within the bubble walls that generate chiral charge asymmetries. These asymmetries then diffuse into the symmetric phase outside of the bubbles. Here, we have satisfied condition 2 of Sakharov. In this symmetric phase, sphaleron transitions convert these asymmetries into a net B, which then diffuse back into the broken phase bubbles. This satisfies condition 1.

In general, we call any mechanism for baryogenesis that uses sphaleron transitions to satisfy baryon number violation electroweak baryogenesis. So what are sphalerons transitions? Sphalerons are time-independent solutions to the electroweak field equations in the Standard Model. Sphaleron processes are the transitions between degenerate vacua in the electroweak field, and the sphaleron is the saddle-point on the ridge between vacua. The important thing about these anamolous processes is that they violate $B + L$, baryon + lepton number, but preserve $B - L$. Therefore, we have the Ward-Takahashi identities

$$\partial_\mu j^\mu_{B+L} = \frac{N_f}{16\pi^2}[g_2^2 \mathrm{Tr}(F_{\mu\nu}\widetilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}] \tag{1}$$

$$\partial_\mu j^\mu_{B-L} = 0 \tag{2}$$

where N_f is the number of fermion generations, g_i are coupling constants, and F and B are the field strength tensors of A_μ and B_μ respectively. We can then combine these to get

$$B(t_f) - B(t_i) = N_f[N_{CS}(t_f) - N_{CS}(t_i)] \tag{3}$$

where N_{CS} is the Chern-Simons number defined as

$$N_{CS}(t) = \int d^3\vec{x}\epsilon_{ijk}[g_2^2 \mathrm{Tr}(F_{ij}A_k - \frac{2}{3}g_2 A_i A_j A_k) - g_1^2 B_{ij}B_k]_t \tag{4}$$

N_{CS} is an integer that classifies the unitary transformations in the $SU(2)$ gauge field, and connects two degenerate vacua of the gauge theory. Therefore, for each sphaleron transition between adjacent vacua, $\Delta N_{CS} = 1$, and hence both B and L change by 1 for each generation.

Electroweak baryogenesis relies heavily on the assumption that the EWPT is strongly first-order. What this means is that the vacuum expectation value of the Higgs field at the critical temperature is larger than 1

$$< v_c > /T_c > 1 \tag{5}$$

We require this because we need for sphaleron transitions to be strongly suppressed in the broken phase, like $e^{-E_{sph}/T}$ for $T < T_c$. This is because sphaleron transitions tend to destroy any baryon number generated. With this requirement, we only have sphaleron processes occur in the symmetric phase outside of the bubble walls, thus preserving any baryon number generated.

The requirement that the EWPT be strongly first-order also places limits on the Higgs mass. This is because

$$< v_c > \sim 1/m_H \tag{6}$$

where m_H is the Higgs mass. A first-order phase transition can be induced by loop effects of light bosonic particles for a sufficiently light Higgs boson. However, the only particles in the SM that do this are gauge bosons, and their couplings are not strong enough to induce a first-order phase transition. This problem is solved in the MSSM because there are additional bosonic degrees of freedom which contribute to the strength of the phase-transition.

Electroweak baryogenesis is a deep field, and this paper only serves as a brief introduction to the topic. For more information and details, please refer to the references listed below.

References

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[2] Balazs, et. al., *Overview of Electroweak Baryogenesis*, ALCPG0333

[3] Funakubo, *Status of the Electroweak Baryogenesis*, http://dirac.phys.saga-u.ac.jp/~funakubo