Cosmology Notes for L. Susskind's Lecture Series (2013), Lecture 8

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Abstract

This paper contains my notes on Lecture Eight of Leonard Susskind's 2013 presentation on Cosmology for his Stanford Lecture Series. These notes are meant to aid the viewer in following Susskind's presentation, without having to take copious notes. The fault for any inaccuracies in these notes is strictly mine.

1 Baryogenesis

Our fundamental question to answer is Why is there so much more matter than antimatter in the universe? That is, assuming that the universe didn't just start off with more matter than anti-matter. Or, stated another way, why is the photon to proton ratio so large, being about 10^8?

In 1967, Andrei Sakharov wrote a paper in which he described the three conditions in which the universe could produce more matter than anti-matter: (1) there is some process in which baryon number is not conserved; (2) CP violation occurs; (3) the early Universe is not in a state of thermal equilibrium.

For a blackbody spectrum the entropy goes as the number of photons.

$$\frac{N_{\mathrm{p}^+} - N_{\mathrm{p}^-}}{N_\gamma} \approx \frac{N_{\mathrm{p}^+} - N_{\mathrm{p}^-}}{N_{\mathrm{p}^+} + N_{\mathrm{p}^-}} \approx 10^{-8} \,. \tag{1}$$

Let N_{q} and $N_{\overline{\mathrm{q}}}$ be, respectively, the quark and antiquark numbers. The

$$\text{Baryon } \# = \tfrac{1}{3}\big(N_{\mathrm{q}} - N_{\overline{\mathrm{q}}}\big) \,. \tag{2}$$

Now, suppose that the baryon number is conserved. Hence, if there were an excess of baryon number in the early universe, then that excess would persist. Now, consider the following proton decay possibility.

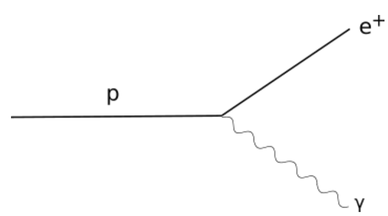


Figure 1. A particular proton decay mode which violates the conservation of baryon number.

Electrons do not have particle-antiparticle symmetry. Let's investigate CPT symmetry.

$$\begin{aligned}
&\text{C} = \text{Charge conjugation symmetry}\\
&\text{P} = \text{Parity or mirror reflection symmetry}\\
&\text{T} = \text{Time reversal symmetry (for simple experiments)}\,.
\end{aligned}$$

We know from quantum field theory that that application of all three of these actions at the same time will be a symmetry.

If we assume that the universe started with an equal number of particles and antiparticles, then what happened to all the antiparticles?

The Sakharov conditions that the universe could produce more matter than anti-matter are:

1. It's possible that baryon number is not conserved.
2. Both C and CP asymmetry occurs in the laws of physics.
3. The universe is expanding out of equilibrium.

If the proton has extra energy, it can have a transistion mode that uses a very heavy particle of mass M. In fact, baryon number conservation is allowed to be violated in most modern theories. If the proton has extra energy from some place then its transition frequency will go as

$$\text{transition freq} \sim \frac{1}{(M-E)^2}\,. \tag{3}$$

However, we don't know if this hypothetical decay mode is doable.

So, we also have

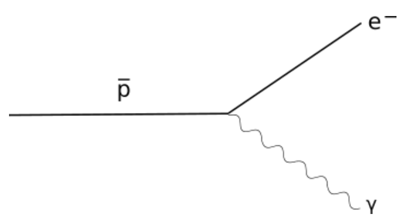


Figure 2. A particular antiproton decay mode which violates the conservation of baryon number. This is the charge conjugate process seen in Fig. 1.

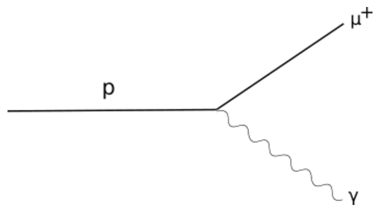
If this is so, then the proton and antiproton decays should, on average, be the same. We need an explanation of how to justify an asymmetry between proton and antiproton decays. This would have to break charge-conservation symmetry.

Definition: A baryon is a particle having an odd number of quarks in it.

We wish to have an example of charged-particle antisymmetry. A 'B particle' is a meson having a b quark and an anti-down quark $\overline{\text{d}}$. Of course, the anti-B meson, $\overline{\text{B}}$, would be an $\overline{\text{b}}$ quark and a down quark d. Some decay possibilities are

$$\begin{aligned}
\text{B} &\longrightarrow \text{K}^+ + \pi^-\,,\\
\overline{\text{B}} &\longrightarrow \text{K}^- + \pi^+\,.
\end{aligned}$$

What we know is that the decay rates for the B and anti-B particles are the same at low temperatures. However, the decay rates are not strictly the same:



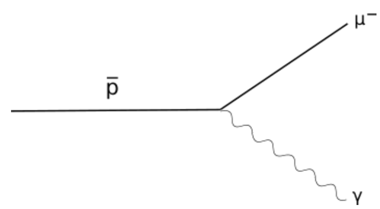


Figure 3a. A proton-to-muon decay mode. Figure 3b. An antiproton-to-muon decay mode.

Assuming that the universe as very hot in its early stages, then there could be enough energy to allow for the decay of the proton through a very heavy particle, called the 'M' particle.

In all QFT's, CPT is a symmetry.

In a universe of complete thermal equilibrium, there is no sense of time. However, such a universe would have CP symmetry. Hence,

$$\frac{[\mathrm{CPT}]_{\mathrm{symm}}}{[\mathrm{T}]_{\mathrm{symm}}} = [\mathrm{CP}]_{\mathrm{symm}} \,. \tag{4}$$

In such a universe one cannot have a particle-antiparticle discrepancy. But in the early times, our universe was not in thermal equilibrium, but rather was expanding so fast that it allowed for particle-antiparticle production to proceed asymmetrically.

Sakharov third condition is that the universe is expanding out of equilibrium and with cooling. Nevertheless, the current state of our knowledge of high-energy physics does not allow us to calculate the 10^{-8} factor.

2 Inflation

The CMB shows that the universe is isotropuic to high precision. The implication being that the early univrese was also highly isotropic. Also, the homogeneity of the early universe must have aso been highly isotropic, but not prefectly so. Small region of either less or greater mass densities must have occurred. In the regions of greater mass densities, we expect also greater gravitational attraction.

At the time of decoupling, let ρ be the local density. Then $\delta\rho$ is the mean excess density in a lump relative to the background. taking their ratio we get a unitless number:

$$\frac{\delta\rho}{\rho} \approx 10^{-5} \,. \tag{5}$$

To account for this level of homogeneity, Allan Guth proposed his Inflation Hypothesis, which is that the early universe experienced a period of great inflation that occurred to the cosmic egg shortly after is was in thermal equilibrium. One result of this inflation was to 'flatten out' space.

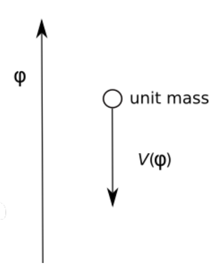


Figure 4. A unit mass falling through a viscous fluid under the influence of an external force $\ddot{\varphi} = -\nabla_\varphi V(\varphi) = -dV/d\varphi$.

Imagine an object of unit mass falling through a viscous fluid under the influence of an external force F as in the figure above. From $F = ma$ and $F = -\nabla_\varphi V(\varphi) = -dV/d\varphi$, we get

$$\ddot{\varphi} = -\frac{dV}{d\varphi}\,, \tag{6}$$

which describes the force without viscosity. Now, we include it.

$$\ddot{\varphi} = -\gamma\dot{\varphi} - \frac{dV}{d\varphi}\,. \tag{7}$$

At terminal velocity (speed): if $\ddot{\varphi} = 0$ then $\dot{\varphi} = F/\gamma$. If $v(\varphi)$ has a shallow slope, then it takes a long time to go down the slope.

Next, we propose the existence of a scalar field called the *inflaton field*.

Assume that φ is initially uniform in space. What is the energy of the field?

$$E = \frac{\dot{\varphi}^2}{2}\,, \tag{8}$$

which describes this energy as all 'kinetic'. We have ignored the spacial derivative of the field because it varies too slowly. But if we do include the potential energy, the equation for energy (density) takes to form of

$$E = \frac{\dot{\varphi}^2}{2} + V(\varphi)\,. \tag{9}$$

We can think of our energy as being contained in a box. Then we can scale the volume of the box in time by the scalar factor a^3, to get

$$E = a^3(t)[\,\frac{\dot{\varphi}^2}{2} + V(\varphi)\,]\,. \tag{10}$$

from this we can setup the Lagrangian:

$$\mathscr{L} = a^3(t)[\,\frac{\dot{\varphi}^2}{2} - V(\varphi)\,]\,. \tag{11}$$

The Euler-Lagrange equation

$$\frac{d}{dt}\frac{\partial\mathscr{L}}{\partial\dot{\varphi}} = \frac{\partial\mathscr{L}}{\partial\varphi} \tag{12}$$

gives us

$$\frac{d}{dt}\big(\dot{\varphi}a^3(t)\big) = -a^3(t)\frac{dV}{d\varphi}\,. \tag{13}$$

After a little computation, we have that

$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} = F\,. \tag{14}$$

And we finally stop at

$$\ddot{\varphi} + 3H\dot{\varphi} = F\,, \tag{15}$$

where that factor $3H$ is referred to as the *viscosity coefficient*, and $3H\dot{\varphi}$ is referred to as the *cosmic friction term.*