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Matter-antimatter Asymmetry of The Universe:

As far as we can see, the universe is made of matter. The amount of antimatter is very small in the observable part of the universe. In the early universe, however, matter and antimatter both existed at comparable amounts. In fact, any particle coexisted with its antiparticle at temperatures above the particle mass.

A major question is how this asymmetry has arisen. Not only the origin of matter-antimatter asymmetry is a question, but also its size. We know from BBN and CMB that:

$$\eta = \frac{\overset{\text{present}}{n_B}}{n_\gamma} = \frac{\overset{\text{all/early times}}{n_B - n_{\bar{B}}}}{n_\gamma} \sim 6\times 10^{-10}$$

There are various possibilities for having $\eta \neq 0$:

(1) $\eta \sim 6\times10^{-10}$ comes as an initial condition. We are not worried about its origin, and accept it as an initial condition.

However, such an initial value will not survive inflation. According to inflationary theory, which is the dominant paradigm of the early universe cosmology, any number density is exponentially diluted during inflation. In the content of inflationary cosmology, we therefore need to have $\eta \sim 6\times10^{-10}$ created after inflation. Recall that all particles (and antiparticles) must be produced after inflation in order to restore the hot big-bang universe.

(2) The universe is baryon symmetric after the transition from inflation to hot big bang. Baryons and antibaryons annihilate

– to lighter particles until the annihilation drops out of equilibrium.

This yield a value for $\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma}$, and at some point baryons and antibaryons get separated such that the observable part of the universe contains baryons only.

Within this scenario we must address two issues,

(a) $\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$ must be obtained.

(b) a causal separation mechanism must be found.

Lets consider the first issue. At $T \ll 1\,GeV$ the baryons are mainly protons and neutrons. The relevant annihilation processes will be $p\bar{p} \to 2\pi$ and $n\bar{n} \to 2\pi$. For $p\bar{p} \to 2\pi$, we have,

$$\boxed{\Gamma_{p\bar{p}} = n_p \langle \sigma_{p\bar{p}}\, v \rangle \simeq n_p \sigma_0 \qquad \sigma_0 \simeq 2 \times 10^{-26}\,cm^2}$$

The annihilation rate drops below the expansion rate when $\Gamma_{p\bar{p}} \lesssim H$. Until then, we have,

$$n_p = n_{\bar{p}} = \left(\frac{m_p T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_p}{T}\right)$$

We can find the freeze-out time for $p\bar{p} \to 2\pi$ by equating $\Gamma_{p\bar{p}}$ and H:

$$\Gamma_{p\bar{p}} \sim H \Rightarrow \left(\frac{m_p T_{f,o.}}{2\pi}\right)^{3/2} \exp\left(-\frac{m_p}{T_{f,o.}}\right) \sigma_0 \sim \frac{T_{f,o.}^2}{M_p} \Rightarrow \frac{m_p}{T_{f,o.}} \sim \frac{1}{2}\ln\left(\frac{m_p}{T_{f,o.}}\right)$$

$$-2.76 + \ln(\sigma_0 m_p M_p) \Rightarrow \boxed{\frac{m_p}{T_{f,o.}} \sim 44}$$

This results in (up to logarithmic corrections) $T_{f,o.} \sim 20\,MeV$.

After the freeze out $\frac{n_p}{s} = \frac{n_{\bar{p}}}{s}$ will remain constant. We can find its value:

$$\frac{n_p}{s} = \left(\frac{n_p}{s}\right)_{f,o.} \sim \frac{\frac{T_{f,o.}^2}{M_p} \frac{1}{\sigma_0}}{\frac{2\pi^2}{45} g_* T_{f,o.}^3} \Rightarrow \boxed{\frac{n_p}{s} \sim 5\times 10^{-18}}$$

$g_* = 10.75$ at $T \sim 20\,MeV$

This is several orders of magnitude below the value inferred from BBN and CMB $\frac{n_B}{s} \sim 9\times 10^{-11}$. Therefore the correct value of η will not be yielded.

Another issue is that we will not get enough baryons

- to form even a galaxy through a causal separation mechanism. At $T \sim 20$ MeV, the total mass (in baryons) inside the horizon radius is 10^{-5} solar mass. While, the mass in the milky way is $\sim 10^{12}$ solar masses. To collect the latter at the time freeze out requires a separation mechanism that acts at distances far outside the horizon radius.

(3) The universe starts in a baryon symmetric state (after transition to hot big bang), but an asymmetry is generated by microphysics.

The general conditions to create baryon asymmetry from a symmetric initial condition are outlined by Sakharov, and are known as "Sakharov's conditions."

- To elucidate, consider the situation where a decay process $I \to F$ is responsible for producing the observed baryon asymmetry, where I and F denote the initial and final states including seme particles respectively. The Sakharov's Conditions are:

(a) Baryon number violation. It is obvious that there will be no asymmetry in F if we start with zero baryon number in I, unless baryon number is violated in the process I→F.

(b) C and CP violation. C stands for charge conjugation (essentially multiplying all quantum charges by -1) and P stands for parity (left↔right). Let assume the process I→F give rise to a change ΔB in the baryon number. Then the charge conjugated process $\bar{I} \to \bar{F}$ gives rise to a change $-\Delta B$ in the baryon number (note that baryon number is a quantum charge). If C is conserved, both processes happen at the same rate, thus,

$$\left.\begin{array}{ll} I \rightarrow F & ; \Delta B \\ \bar{I} \rightarrow \bar{F} & ; -\Delta B \end{array}\right\} \Rightarrow \Delta B_{net} = \Delta B + (-\Delta B) = 0$$

We therefore need C violation. A similar argument can be used to show the requirement for CP violation.

(c) Out-of-equilibrium condition. Even if baryon number, C, and CP are violated, no net baryon number will be generated in thermal equilibrium. The key point is that the process $I \rightarrow F$ and its inverse process $F \rightarrow I$ happen at the same rate in a thermal equilibrium situation. With the charge-conjugated processes taken into account, we have:

$I \rightarrow F$; ΔB $\qquad\qquad$ $F \rightarrow I$; $-\Delta B$

$\bar{I} \rightarrow \bar{F}$; $\Delta B'$ $\qquad\qquad$ $\bar{F} \rightarrow \bar{I}$; $-\Delta B'$

$$\Delta B_{net} = \Delta B + \Delta B' + (-\Delta B) + (-\Delta B') = 0$$

This can be understood another way too. The distribution function of a particle in thermal equilibrium is $f = A \exp\left(-\frac{E+\mu}{T}\right)$, while that of an antiparticle is $\bar{f} = A \exp\left(-\frac{E+\bar{\mu}}{T}\right)$. The mass, hence energy, of a particle and its antiparticle are equal. Starting from a baryon symmetric initial condition, we have $\mu = \bar{\mu}$. As a result $f = \bar{f}$ if thermal equilibrium is maintained at all times.

The interesting point is that an acceptable baryogenesis, which results in $\eta \sim 6\times 10^{-10}$, is not achievable in the standard model of particle physics. All perturbative processes in the standard model respect baryon number conservation. There are non-perturbative processes, related to electroweak interactions, that violate baryon number.

In principle, they could lead to generation of baryon asymmetry at the electroweak phase transitio ($T \sim 100$ GeV). However, we now know that an acceptabl baryon asymmetry cannot be obtained within the standard model.

Matter-antimatter asymmetry, like dark matter, requires physics beyond the standard model. There are many proposed scenarios for baryogenesis, all of which implement Sakharov's conditions in some new physic beyond the standard model. "Leptogenesis" is a particularly interesting and attractive scenario, whic connects generation of baryon asymmetry to neutrinos