Fundamental Particles

Standard Model of Particle Physics

There are three different kinds of particles.

**Leptons** - there are charged leptons ($e^-, \mu^-, \tau^-$) and uncharged leptons ($\nu_e, \nu_\mu, \nu_\tau$) and their antiparticles ($e^+, \mu^+, \tau^+$, $\nu_e, \nu_\mu, \nu_\tau$). Leptons are fermions (spin 1/2).

**Quarks** - there are six types (up, down, strange, charm, bottom, and top) and their anti-particles. Each quark has a “color” (RGB; strength of strong force is related to color). No free quark has been found. Particles made of quarks are **Hadrons**. **Baryons** are particles made of 3 quarks (fermions - spin 1/2) and **Mesons** are formed by a quark-antiquark pair (bosons, integer spin).

**Force particles** - the photon (EM force carrier), eight different gluons (strong force carrier), gauge bosons ($W^+, W^-, Z^0$; weak force carriers), and the theoretical “Higgs” boson (which has not yet been found).

Current Collider Physics experiments can reproduce the temperatures, energies and densities that prevailed back to when the Universe was $\sim 10^{-5}$ s, when a plasma of free quarks and glons condensed to form hadrons, including protons and neutrons.
Unification and Symmetry Breaking

At higher temperatures/energies, the relative strength of forces changes. This has been experimentally confirmed for the strong, E&M, and Weak forces.
Fundamental Particles

Current Collider Physics experiments can reproduce the temperatures, energies and densities that prevailed back to when the Universe was $\sim 10^{-11}$ s.

<table>
<thead>
<tr>
<th>Era or Event</th>
<th>Time</th>
<th>Temperature (kT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck Era</td>
<td>$&lt; 5 \times 10^{-44}$ s</td>
<td>$&gt;10^{19}$ GeV</td>
</tr>
<tr>
<td>Planck Transition</td>
<td>$5 \times 10^{-44}$ s</td>
<td>$10^{19}$ GeV</td>
</tr>
<tr>
<td>Grand Unification Era</td>
<td>$5 \times 10^{-44}$ s to $10^{-36}$ s</td>
<td>$10^{19}$ GeV to $10^{15}$ GeV</td>
</tr>
<tr>
<td>Inflation</td>
<td>$10^{-36}$ s to $10^{-34}$ s</td>
<td>$10^{15}$ GeV</td>
</tr>
<tr>
<td>Electroweak Era</td>
<td>$10^{-34}$ s to $10^{-11}$ s</td>
<td>$10^{15}$ GeV to 100 GeV</td>
</tr>
<tr>
<td>Electroweak Transition</td>
<td>$10^{-11}$ s</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Quark Era</td>
<td>$10^{-11}$ s to $10^{-5}$ s</td>
<td>100 GeV to 200 MeV</td>
</tr>
<tr>
<td>Quark-Hadron Transition</td>
<td>$10^{-5}$ s</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Neutrino Decoupling</td>
<td>0.1 s</td>
<td>3 MeV</td>
</tr>
<tr>
<td>Electron-Positron annihilation</td>
<td>1.3 s</td>
<td>1 MeV</td>
</tr>
</tbody>
</table>
Planck Limits

Earliest times and smallest scales in the Universe are set by our fundamental constants. At these points either Quantum mechanics or General Relativity must break down.

Planck Time: \[ t_P \equiv \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44} \text{s} \]

Consider then, from Quantum Mechanics the uncertainty principle. Let \( \Delta x \approx R_s \), which makes the uncertainty on the momentum, \( \Delta p \approx \frac{\hbar}{\Delta x} \approx \frac{\hbar}{R_s} \). The uncertainty on the energy is then \( \Delta E = (\Delta p)c \approx \frac{\hbar c}{R_s} \). Setting this equal to \( GM^2 / R_S \) gives the Planck Mass:

Planck Mass: \[ m_P = \sqrt{\frac{\hbar c}{G}} = 2.18 \times 10^{-8} \text{ kg} \]

Solving for \( R_S \) gives the Planck Length (dropping a factor of 2):

Planck Length: \[ \ell_P \equiv \sqrt{\frac{\hbar G}{c^3}} = 1.62 \times 10^{-35} \text{ m} \]
Matter-Antimatter asymmetry

Why is the majority of matter in the Universe made of Matter? 0.01% of the cosmic rays are antimatter. No evidence of large amounts of antimatter.

In the quark era, there should have been equal numbers of particles and antiparticles.

\[ X \iff q + q \]
\[ \bar{X} \iff \bar{q} + \bar{q} \]

For matter to win out the top reaction must be a little faster than the bottom one. This exact matter-antimatter asymmetry has been seen in the reaction rates experimentally in Kaon particles, which decay to pions.

\[ K \rightarrow \pi^- + e^+ + \nu_e \]
\[ K \rightarrow \pi^+ + e^- + \bar{\nu}_e \]

The first reaction occurs slightly more often. This is called “CP” violation in particle physics, but meant that out of 1,000,000,000 protons+antiprotons at the end of the quark epoch, one proton was left after everything else annihilated.
Problems with the Big Bang

Why is the cosmic background radiation so smooth? The Universe is Homogeneous even though much of the Universe is not casually connected. This is the Horizon Problem.

Why is the Universe so flat ($\Omega_0 \approx 1$)? The Universe is Homogeneous even though much of the Universe is not casually connected. This is the Flatness problem.

Why are there no (or very, very few) magnetic monopoles? These should be left over as topological defects from symmetry breaking. This is the monopole problem.
Problems with the Big Bang

**Inflation**: theory that solves these problems. It was proposed in 1980 by Alan Guth. The basic concept is that when $t \approx 0$ (just after the big bang) the Universe was very small and everywhere was casually connected.

During inflation, the size of the Universe increased exponentially. This solves both the Horizon and Flatness problems.

In practice, there are many variants of inflation, but the theory seems to have the most promise.

Alan Guth
b. 1947
Virtual Particles

These are particles that spring into and out of existence without violating energy conservation. Quantum Mechanics and the uncertainty principle make this possible.

\[ \Delta E \Delta t \approx \hbar \]

You can create any amount of energy you want so long as it negates with \( \Delta t < \frac{\hbar}{\Delta E} \).

Virtual particles are when a particle and its anti-particle appear at random with \( m = \frac{\Delta E}{c^2} \) and then annihilate with \( \Delta t < \frac{\hbar}{\Delta E} \).

This effect was experimental confirmed by Hendrick Casimir, who measured an attractive force between two uncharged parallel, conducting plates.

Virtual particles mean that the **Vacuum** is never a perfect Vacuum (there are always virtual particles present).
The False Vacuum and Inflation

At the end of the GUT epoch, $t \sim 10^{-36}$ s, when $T \sim 10^{28}$ K. The Universe was in a **false vacuum**. The universe was supercooled, which happens when the cooling rate is much faster than the phase-transition rate.

This is very similar to supercooled water, which can be supercooled to 20 K.

This false vacuum is like a phase transition. Physics works differently in different phases (consider gaseous, liquid, and solid H$_2$O).

When $t < 10^{-36}$ s, inflation likely began when quantum fluctuations governed by the Uncertainty Principle allowed a small region of space to enter a true vacuum state (at lower energy), where the rest of the Universe was in the false vacuum. The pressure within the true vacuum was zero, but it expanded exponentially into a Universe filled with negative pressure from the false vacuum.

During this time ($10^{-35}$ to $10^{-34}$ s) your book works out that Universe grew in size by a factor of $e^{100} = 3 \times 10^{43}$. 

Wednesday, April 25, 2012
Problems with the Big Bang

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The overall geometry of the Universe is closely related to the total density of matter (and energy).

WMAP shows us the geometry is nearly exactly flat.
Inflation solves the “flatness problem”.

During inflation, any non-flat regions would “inflate” like a balloon.

This causes the universe to become very close to having a flat geometry with matter and density very close to the critical density.
Problems with the Big Bang

**Why is the cosmic background radiation so smooth?** The Universe is Homogeneous even though much of the Universe is not casually connected. This is the **Horizon Problem**.

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Why is the CMB so similar?
Cosmological Distances

Recall that proper distance is just the integral of metric, $[-(ds)]^{1/2}$. Along a radial line from the Earth to a distant object, $d\theta = d\phi = 0$, so:

$$d_p(t) = R(t) \int_0^\infty \frac{d\varpi'}{\sqrt{1 - k\varpi'^2}} = R(t) \int_{t_e}^{t_0} \frac{c \, dt'}{R(t')}$$

Note that $d_{p,0} = d_p(t_0)$ is the proper distance, which is the distance to an object today. It is not the same as the distance between the Earth and the object when the photon was emitted.

The distance at other times is $d_p(t) = R(t) \, d_{p,0}$.

$$d_{p,0} = \varpi \quad \text{(for } k = 0)$$
$$d_{p,0} = \frac{1}{\sqrt{k}} \sin^{-1}(\varpi \sqrt{k}) \quad \text{(for } k > 0)$$
$$d_{p,0} = \frac{1}{\sqrt{|k|}} \sinh^{-1}(\varpi \sqrt{|k|}) \quad \text{(for } k < 0)$$
Cosmological Distances

The distance to the horizon needs the expression of \( R(t) \) for \( \Lambda \) model:

\[
R(t) = \left( \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} \right)^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t \sqrt{\Omega_{\Lambda,0}} \right)
\]

Inserting this into our previous equation gives:

\[
d(t) = \left( \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} \right)^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t \sqrt{\Omega_{\Lambda,0}} \right) \times \int_0^t \frac{c \, dt'}{(\Omega_{m,0}/\Omega_{\Lambda,0})^{1/3} \sinh^{2/3} \left( \frac{3}{2} H_0 t' \sqrt{\Omega_{\Lambda,0}} \right)}
\]

Sadly, this must be solved numerically.... for our WMAP values we find that the distance from \( t=0 \) to \( t=t_0 \) is

\[
d_0 = 4.50 \times 10^{26} \text{ m} = 14,600 \text{ Mpc} = 14.6 \text{ Gpc}
\]

This is the Horizon Distance.
Example: He-4 nuclei were formed when the temperature of the Universe was $10^9$ K at $t=178$ s. This early we can assume the Universe was mass +radiation dominated (no $\Lambda$) so the scale factor was $R(178s) = 2.73 \times 10^{-9}$. This sets the “horizon” distance at

$$d(t) = 2ct = 1.07 \times 10^{11} \text{ m} = 0.7 \text{ AU}.$$  

At this point the whole “visible” Universe would fit into the size of the Earth’s orbit.

The “visible” Universe is the “casually connected” Universe. At a time 178s only 0.7 AU regions were casually connected.

At a time $t=13.7$ Gyr later, this same 0.7 AU region has a present size of $d(t) / R(t) = 3.92 \times 10^{19} \text{ m} = 1.3 \text{ kpc}.$

We can currently see to 14.6 Gpc. The amount of the Universe that is casually connected today is much, much larger than it was at early times.
How is it that the microwave temperature can be nearly identical on opposite sides of the sky?!!
**Inflation** predicts that regions now on opposites sides of the sky were together (communicating) before inflation pushed them out of contact.
Inflation solves Origin of Structure

WMAP gives us detailed pictures of the seeds of structure in the universe.
Origin of Structure

WMAP image

All components removed but background fluctuations
Distribution of galaxies in 2MASS survey

This is directly related to the CMB fluctuations!