Threshold temperatures

- If a particle encounters its corresponding antiparticle, the two will annihilate:

  \[ \text{particle} + \text{antiparticle} \rightarrow \text{radiation} \]

* Correspondingly, radiation can transform into a particle - antiparticle pair if the radiation carries sufficient energy:

  \[ \text{radiation} \rightarrow \text{particle} + \text{antiparticle} \]

* For radiation to transform into particles, the energy in radiation must exceed the equivalent of the combined rest masses of the particles:

  \[ E = mc^2 \]

where energy, \( E \), has a temperature equivalency, \( E = kT \)

* Equating these concepts defines the threshold temperature

  \[ T_{th} = mc^2/k \]

  \( (m = \text{mass}, \ T = \text{temperature}, \ c = \text{velocity of light}, \ k = \text{Boltzmann constant}) \)
Threshold temperatures (continued)

- At temperatures above the threshold, there are lots of photons of radiation with enough energy for creation of particle-antiparticle pairs.
- Below the threshold temperature, photons with enough energy for pair production are rare.
- These constraints can be summarized with the following expressions:

\[ p + \overline{p} \iff \gamma \quad \text{if } T > T_{\text{th}} \]
\[ p + \overline{p} \implies \gamma \quad \text{if } T < T_{\text{th}} \]

(\(p = \text{particle, } \overline{p} = \text{antiparticle, } \gamma = \text{radiation}\))

We live in a matter-dominated Universe

# We live in a world with matter, not antimatter. Why?

# The simple answer is that we would not exist if there were a perfect balance between matter and antimatter because there would have been almost complete annihilation. One of these forms must have been predominant. But why?
Threshold temperatures (continued)

We have quantitative knowledge of the amount of imbalance between matter and antimatter in the early Universe, as follows:

# When the Universe was so hot that it was above the threshold temperatures for common particles then there would have been roughly equal numbers of all particle species and radiation. The process $p + \overline{p} \leftrightarrow \gamma$ would have been in equilibrium.

# But today, there are far more photons from the Big Bang (in the cosmic microwave background [CMB] radiation) than there are nuclear particles.

# CMB photons / # nuclear particles $\sim 10^9$

(the number of CMB photons is precisely known from the temperature of the cosmic microwave background radiation of 2.7 K. The number of nuclear particles is given by the density of visible matter today and from an understanding of the process of nucleosynthesis in the Big Bang [still to be discussed])

# This observation tells us that for every $1,000,000,001$ particles that existed at temperatures above threshold, there were $1,000,000,000$ antiparticles. As the temperature of the Universe dropped below threshold, the billion antiparticles annihilated against a billion of the particles, leaving a tiny residue of particles.

# Dilemma: for all practical purposes today, nuclear reactions conserve the number of nuclear particles. Particles and antiparticles are created or destroyed in pairs, so the total number of particles - antiparticles is constant. If this is a strict conservation law then the slight imbalance of particles and antiparticles would have always been the same. But then, what could have been the reason for this imbalance?
proton decay

Possible departures from conservation of nuclear particle number: proton decay?
* The figure provides a schematic of a speculated event. A proton consists of 2 up quarks and a down quark. By rare chance, one of the up quarks and the down quark exchange an X particle which can change all of the charge, spin, and nuclear color properties of the particles. Here, the down quark released the X and the residual is a positron. The up quark accepted the X and became an anti-up quark. The residual up and anti-up quarks proceed to annihilate and the positron annihilates against a free electron. Hence we started with a proton and are left with nothing but radiation.

* If a proton decays into radiation, then particle number is NOT conserved. The key to this non-conservation was the exchange of the X particle. The X particle, though, is EXTREMELY MASSIVE. It's rest mass of $10^{27}$ eV corresponds to a threshold temperature of $10^{31}$ K, which was the condition of the Universe at time $10^{-35}$ seconds.

* In today's Universe, virtual X and $\bar{X}$ particles could be created but from the Heisenberg uncertainty principle such a huge mass-energy could only persist for an infinitesimal time and traverse an infinitesimal domain of space ($10^{-29}$ cm).

* It would be extraordinarily rare for 2 quarks to get so close that there would be time for them to exchange an X particle. It is thought that it would happen in an atom every $10^{35}$ years or so (the Universe is only $10^{10}$ years old).

* In fact, proton decay has NOT yet been detected, though it is expected that it happens.
The GUT Era and Baryogenesis
(Grand Unified Theory: GUT)

# We are focusing on the question of why there is a slight excess of matter over anti-matter in the early Universe.

# The exchange of the $X$ particle results in events where there is non-conservation of particle number. For example, a particle could be destroyed (converted into energy) without affecting the anti-particle count. There would be similar processes that involve anti-particles at the exclusion of particles. However, the events are decoupled and the rates do not have to be the same.

# The threshold temperature for the $X$ particle ($10^{31}$ K) corresponds to the GUT era, when the electromagnetic, strong, and weak forces become of equal strength.

# At temperatures above the threshold of $10^{31}$ K, copious quantities of $X, \bar{X}$ particles existed and the sort of reaction illustrated by proton decay could have been commonplace.

# If event rates were slightly different for some interactions in comparison with the anti-particle equivalent, then the particle-antiparticle imbalance could have arisen.

# Once the temperature of the Universe dropped below the GUT threshold, the inequality between matter and antimatter would be frozen in.

# It is understood that the interaction rates could be different as required to create the observed imbalance but there is not a good theoretical prediction of why the amount should be what it is.
As the Universe cools, it crosses the thresholds for the various particles in the high-energy zoo. Below each threshold there is annihilation of the particle-antiparticle pairs with release of photon energy.

For example, when the Universe was a micro-second ($10^{-6}$ sec) old the temperature had dropped to $10^{13}$K corresponding to the rest mass of neutrons (939.8 MeV) and protons (938.5 MeV).

Below this threshold, $p + \bar{p} \rightarrow \gamma$ and $n + \bar{n} \rightarrow \gamma$ All the $\bar{p}$ and $\bar{n}$ (the antiparticles) are destroyed. A small residue of one part in a billion of $p$ and $n$ (the particles) remain, the legacy of the small 'baryon' imbalance created during the GUT era.

The next interesting threshold occurs when the Universe is about 3 seconds old, when the temperature is down to $5 \times 10^9$ K. We reach the threshold temperature for electrons ($e^+, e^-$) with 0.5 MeV rest mass. At lower temperatures, $e^- + e^+ \rightarrow \gamma$ The residue thereafter reflects the 1 part per billion excess of $e^-$ over $e^+$ (electrons over positrons).

But before we reached the electron threshold something else was happening that we should know about. It has to do with the balance between neutrons and protons.
Some important thresholds:

<table>
<thead>
<tr>
<th>species</th>
<th>rest mass</th>
<th>equivalent temperature</th>
<th>associated age of universe</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrinos $(\nu, \bar{\nu})$</td>
<td>~1 ev</td>
<td>$10^4$ K</td>
<td>$10^9$ yrs</td>
</tr>
<tr>
<td>electrons $(e^-, e^+$)</td>
<td>0.5 Mev</td>
<td>$5 \times 10^9$ K</td>
<td>3 sec</td>
</tr>
<tr>
<td>W$^-$ mesons</td>
<td>$\sim 100$ Mev</td>
<td>$1.5 \times 10^{10}$ K</td>
<td>$10^4$ sec</td>
</tr>
<tr>
<td>protons</td>
<td>938 Mev</td>
<td>$1 \times 10^{13}$ K</td>
<td>$10^{-6}$ sec</td>
</tr>
<tr>
<td>neutrons</td>
<td>940 Mev</td>
<td></td>
<td></td>
</tr>
<tr>
<td>weak interactions (spin)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W$^-$, $W^+$</td>
<td>100 GeV</td>
<td>$10^{14}$ ev</td>
<td>$10^{15}$ K</td>
</tr>
<tr>
<td>'electroweak' (spin + charge)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X'</td>
<td>$10^{-24}$ ev</td>
<td>$10^{31}$ K</td>
<td>$10^{35}$ sec</td>
</tr>
<tr>
<td>'GUT' (spin, charge, color)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Neutrons slightly heavier than protons
Proton - Neutron Equilibrium

With these conversion processes, the neutron $n$ is slightly heavier than the proton $p$, by about 1 MeV (or 1 part in 1000).

As $T$ drops below $10^{10}$ K = 1 MeV, then it becomes more difficult to do $p \rightarrow n$ than the converse.

# freezing the $n/p$ ratio:
1. At densities below $10^6$ gm/cm$^3$ ($t=1$ sec, $T=10^{10}$ K) neutrinos decouple from the rest of matter because they interact so weakly.
2. At $T < 10^{10}$ K, then $e^- e^+$ annihilate.

Between 1 and 2, the environment for the sustenance of the $(p,n)$ conversion process is removed. $\Rightarrow$ $n/p$ ratio is frozen.

# minor effect: free neutrons spontaneously decay into protons on a timescale of 15 minutes

(though, neutrons in nuclei are NOT unstable)
Consequence of the frozen p/n ratio

Given the constraints presented on the previous slide on the conversions n <-> p, we can predict the p/n ratio once it is frozen.

- depends on temperature T at moment when e^-,e^+ densities fall so low that interactions can no longer occur.
- minor dependence on density of Universe:
  > higher densities -> e^-,e^+ collision rates higher -> e^-,e^+ exhaustion at higher T -> “freeze-out” at higher T -> fewer p’s per n
  > also, higher density -> expansion rate faster -> neutrinos ν, ν decouple at higher T since (see the quality ‘Q’ term below)
  a smaller time interval Δt requires the product of density x velocity, ρ x ν, to be higher.

> predict p/n = 7 (bit lower in closed universe; higher in open universe)

Conditions for interactions between nuclear particles depends on the product:

\[ Q = (\text{density}) \times (\text{interaction cross-section}) \times (\text{velocity}) \times (\text{time}) \approx \rho \cdot T \cdot t \]

where velocity is directly proportional to temperature.

>>>> need densities and temperatures normally only found in cores of stars or in the early Universe.
p/n \sim 7 \text{ freeze-out review}

\[ p^+ + \overline{\nu} \leftrightarrow n + e^+ \quad \text{requires energy input} \]
\[ n + \nu \leftrightarrow p^+ + e^- \quad \text{releases energy (n more massive than p)} \]
\[ \Rightarrow \text{n convert to p as universe cools} \]

At a time of a few seconds, two things happen:

1. Cross \( T_{th} \) for annihilation of \( e^+ \), \( e^- \) so essentially all \( e^+ \) disappear and only 1 part in a billion \( e^- \) survive
2. Density becomes too low for \( \nu, \overline{\nu} \) to collide with other particles

\[ \Rightarrow \text{the reactions given above can no longer occur because there no longer is a bath of} \ e^+, e^- \ \text{and} \ \nu, \overline{\nu} \]

So the process with \( n \leftrightarrow p \)
with \( n \Rightarrow p \) favored because of energetics
comes to an end with \( p/n \) about 7
Nucleosynthesis

* production of deuterium ($^2\text{H}$)

\[ p + n \rightarrow ^2\text{H} + \gamma \]

problem: reaction occurs in only a very narrow range of temperature \( T=10^9 \text{ K} \) \( t = 100 \text{ sec} \)

- at higher \( T \), $^2\text{H}$ destroyed as fast as it is produced

- at lower \( T \), the interaction time-scale becomes too long (ie, \( Q \) is small unless time \( t \) is long)
  [recall: \( Q \) proportional to density \( \rho \), cross-section \( \chi \), temperature \( T \), and time \( t \)]

* production of Helium ($^4\text{He}$)

- each of the products in these reactions are more stable than $^2\text{H}$, so these reactions occur very quickly once deuterium $^2\text{H}$ has been formed. -> within a few minutes, when \( T=10^9 \text{ K} \) and \( Q \) was large for the reaction $p+n\rightarrow^2\text{H}$, essentially all free neutrons became incorporated into Helium nuclei
Given p/n ~ 7/1
⇒ of 16 free nucleons, 2 are n and 14 are p
⇒ the 2 n unite with 2 p to form $^4\text{He}$ and 12 p are left over

⇒ 25% of mass in $^4\text{He}$
75% ““ “ 1H

The Big Bang theory predicts that 20-30% of the mass of baryons in the universe will be in Helium nuclei and essentially all the rest will be in Hydrogen nuclei

Trace amounts of $^2\text{H}$, $^3\text{He}$, $^7\text{Li}$, $^9\text{Be}$, $^{11}\text{B}$

$^2\text{H}$ is deuterium with 1 p and 1 n
**Bottleneck that prevents nucleosynthesis of heavier elements**

Why doesn’t the process of nucleosynthesis continue to form heavier elements in the early universe?

- Reactions like
  - \( ^4\text{He} + n \rightarrow ^5\text{He} + \gamma \)
  - \( ^4\text{He} + p \rightarrow ^5\text{Li} + \gamma \)
  - \( ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} + \gamma \)

  **cannot** occur because the nuclei on the right side are all **unstable**
  
  **===> bottleneck that cannot be breached**

- **In stars**, there is the reaction \( ^4\text{He} + ^4\text{He} + ^4\text{He} \rightarrow ^{12}\text{C} + \gamma \)
  
  But this reaction requires densities and temperatures much higher than existed in the evolving universe after the formation of Helium.

- **Conclusion:** Cannot explain the origin of elements heavier than Helium in the Big Bang.
- However heavier elements can be built in stars.
- The abundance of He of about 25% is a predicted consequence of BB. By contrast, such a high fraction of Helium could not have been produced in stars (since most Helium is not returned to interstellar space).

- The abundances of heavy elements varies wildly with location, being low in relatively pristine environments and high in places with a lot of star formation.
  
  - By contrast, the abundance of Helium is almost the same everywhere, compatible with the proposition that it is primordial.

- **The difference between the early universe and stars:**
  
  - early universe progresses from **hot** to **cool**
  - cores of stars progress from **cool** to **hot**
Constraints on the Density of Normal Matter in the Universe

“Standard Model” assumes homogeneous, isotropic expanding universe with 3 kinds of neutrinos

Detailed nucleosynthesis calculations lead to predictions concerning the abundances of $^4$He, $^3$He, $^2$H, $^7$Li that can be compared with observations.

1. $^4$He enhanced in higher density universe because of freeze-out at higher Temperature (because of enhanced $e^+/-$ reactions with higher densities and earlier $\nu$ decoupling in a more rapidly expanding universe).

2. $^2$H (= D deuterium) and $^3$He depleted in high density universe because the rate that these elements are converted to $^4$He depends on density. In a low density universe, the conversion of $^2$H and $^3$He to $^4$He is less complete in the limited time available for nucleosynthesis to proceed.

3. With $^7$Li, there are two prominent production reactions and one important destruction reaction. The 3 reactions have different density dependencies which accounts for the complicated dependency on density.
Summary of events when the universe was seconds to minutes old

Before $t \sim 1$ microsecond, the universe was a caldron of elementary particles, their anti-particles, and radiation.

As the universe cooled below the threshold temperatures for the various species of particles, annihilation ceased to be balanced by creation, so anti-particles were lost, a tiny (1 part in a billion) residue of particles remained, and most of the mass-energy in particles was converted into radiation.

Freeze-out of conversions between protons and neutrons lead to a ratio of 7 protons for every neutron (because p are 0.1% less massive than n).

Through nucleosynthesis, the neutrons found their way into Helium atoms, resulting in the observed condition that 25% of matter in `baryons' is Helium and almost all the rest is Hydrogen.

Heavier elements could not be produced in the Big Bang. They are produced later in stars.

Detailed calculations of Big Bang nucleosynthesis constrained by the observed abundances of trace elements leads to the conclusion that 4% of the mass-energy density needed to give a topologically flat universe is in `baryonic' matter (ie, matter made up of protons and neutrons).

According to the current `standard model', 20% of the mass-energy density is in the form of dark matter and 76% is dark energy.