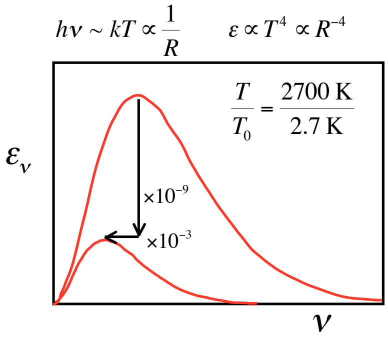
Lecture 2: The First Second
origin of neutrons and protons

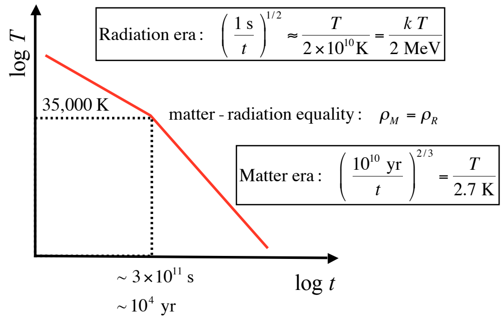
- Hot Big Bang
- Expanding and cooling
- Soup of free particles + anti-particles
- Symmetry breaking
- Soup of free quarks
- Quarks confined into neutrons and protons
- The neutron-proton ratio

Adiabatic Expansion preserves the Blackbody spectrum

$$h\nu \sim kT \propto \frac{1}{R} \qquad \varepsilon \propto T^4 \propto R^{-4}$$



Cooling History: T(t)



$$\text{Radiation era}: \left(\frac{1\ \mathrm{s}}{t}\right)^{1/2} \approx \frac{T}{2\times10^{10}\mathrm{K}} = \frac{k\,T}{2\ \mathrm{MeV}}$$

matter - radiation equality: $\rho_M = \rho_R$

$$\text{Matter era}: \left(\frac{10^{10}\ \mathrm{yr}}{t}\right)^{2/3} = \frac{T}{2.7\ \mathrm{K}}$$

In the early Universe
($kT > E$) photons break up atomic nuclei
binding energies:

Deuterium ~ 2 MeV		$T \sim 10^{9}$ K	$t \sim 100$ s
Iron ~ 7 MeV		$T \sim 10^{10}$ K	$t \sim 1$ s

Earlier still, neutrons and protons break into quarks

mass energies ($E=mc^2$):
neutron ~ 939.6 MeV
proton ~ 938.3 MeV
$T \sim 10^{12}$ K $\quad t \sim 10^{-4}$ s

This takes us back to the quark soup!

Now run the clock forward!

Fundamental Particles

Early Universe: $t < 10^{-4}$ s $\quad T > 10^{12}$ K
Grand Unified Theories (GUTs) predict
all fundamental particles exist in ***roughly*** equal numbers.

quarks
(6 flavours, 3 colours)

mass <---		
	Top …	Bottom …
	Charm …	Strange …
	Up …	Down …

Immune to strong force

mass <---	**leptons**	**neutrinos**
	τ	ν_τ
	μ	ν_μ
	e	ν_e

gluons
(exchanged by quarks)

(others ?)

bosons
Higgs (X)
W$^\pm$, Z^0
Photon γ

Plus antiparticles in equal numbers

Because $kT >> mc^2$,
enough energy to create particle / anti-particle pairs,
pairs annihilate creating photons, collisions / decays create new particles, change one type to another.
(different forms of energy)

Expect: equal numbers of all particles and anti-particles.

net charge = 0
net colour = 0
net spin = 0

The Photon-Baryon ratio

Expect: $N_\gamma \sim N_X \sim N_{\bar{X}} \sim N_q \sim N_{\bar{q}}$

Because: over-abundant species undergo more collisions, transforming to other species, until ***roughly*** equal numbers.

Later, 3 quarks => 1 baryon, expect $N_{photon} \sim N_{baryon}$.

But today, we observe $N_{photon} / N_{baryon} \sim 10^9$. Why?

Why more particles than anti-particles ?

If equal numbers, annihilation when $kT < mc^2$ eliminates all, leaving only photons.

Symmetry breaking: $T \sim 10^{27}$ K $t \sim 10^{-33}$ s.

$X \,\&\, \bar{X}$ bosons decay in two possible ways:

$$X \Rightarrow a\ (q\, q) + (1 - a)\ (\bar{q}\, \bar{l})$$
$$\bar{X} \Rightarrow b\ (\bar{q}\, \bar{q}) + (1 - b)\ (q\, l)$$

If $a > b$, more quarks than anti-quarks.

From particle accelerators: $a - b \sim 10^{-9}\, a$

quarks $10^9 + 1 \longrightarrow 1$ quark

anti-quarks 10^9 $\sim 10^9$ photons

Quark soup

When $kT < mc^2$, high-mass particles no longer created, decay to low-mass particles plus photons.

quark	U D	S	C	T	B
m (GeV)	0.35	0.53	1.8	4.5	40

X, W, Z bosons "freeze out", decay to quarks.

Heavy quarks (S, C, T, B) "freeze out", transmute into U and D.

Leaves a soup of free U and D quarks, leptons, photons, gluons and some residual heavy quarks and bosons.

Quark confinement -> Hadron Era

$t \sim 10^{-2}$ s $T \sim 10^{13}$ K (1 GeV)

U and D quarks confined to form colourless hadrons.

Baryons (3 quarks) :

UUD → proton (938.3 MeV)

DDU → neutron (939.6 MeV)

Mesons (quark + anti-quark)

pions: ($U\bar{U}$, $U\bar{D}$, $D\bar{U}$, $D\bar{D}$)

Others, e.g. UDS, are rare.

Produced in labs but rapidly decay.

Only protons and neutrons are relatively stable.

Hadron Formation

The neutron-proton ratio

Quark charges U: +2/3 D: -1/3

Neutron decay: (DDU) --> (UUD)

$$n \rightarrow p + e^- + \bar{\nu}_e + 0.8\,\text{MeV}$$

When $kT >> 0.8$ MeV, the reaction is reversible and $N_n \sim N_p$.

Thermal equilibrium

Maxwell-Boltzmann distribution:

$$N \propto m^{3/2} e^{(-m c^2 / kT)}$$

$$\boxed{\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{\frac{3}{2}} e^{\left[-\frac{(m_n - m_p)c^2}{kT}\right]}}$$

At $kT \sim 0.8$ MeV, $n \rightarrow p + e^- + \bar{\nu}_e$ no longer reversible.

$$\frac{N_n}{N_p} = \left(\frac{939.6}{938.3}\right)^{\frac{3}{2}} e^{\left[-\frac{(939.6-938.3)}{0.8}\right]} \cong \frac{1}{5}$$

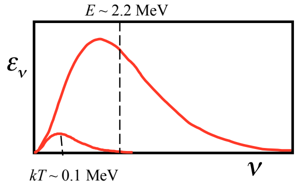
5 protons per neutron

At $t \sim 100$ s and $T \sim 10^9$ K (0.1 MeV),
protons and neutrons confined into nuclei
→ NUCLEOSYNTHESIS

First step: Deuterium p + n → ^{2}D

Nucleosynthesis starts at $kT \sim 0.1$ MeV.
But, ^{2}D binding energy $E \sim 2.2$ MeV.
Shouldn't nucleosynthesis start at 2.2 MeV?

No! Because $N_{photon} / N_{baryon} \sim 10^9$.
Photons in the high-energy tail of the blackbody break up ^{2}D until $kT \sim 0.1$ MeV.



Photons in the blackbody tail:

$$N_\gamma(h\nu > E) = \int_{E/h}^{\infty} \frac{\varepsilon_\nu \, d\nu}{h\,\nu} \approx N_\gamma \exp(-E/k\,T)$$

Set T to get 1 photon with $h\nu > E = 2.2$ MeV per baryon:

$$N_\gamma \exp(-E/kT) \approx N_b$$

$$\frac{E}{kT} \approx \ln\left(\frac{N_\gamma}{N_b}\right) \approx \ln\left(10^9\right) \approx 20$$

With $E = 2.2$ MeV need $kT \sim 0.1$ MeV.

Neutron decay

Free neutron decay time $\tau \sim 940$ s
Cooling time 0.8 MeV to 0.1 MeV: $t \sim 300$ s.
From radioactive decay:

$$N_n(t) = N_n(0)\, e^{-t/\tau} = 0.73\, N_n(0)$$
$$N_p(t) = N_p(0) + 0.27\, N_n(0)$$

$$\frac{N_p(t)}{N_n(t)} = \frac{N_p(0) + 0.27\, N_n(0)}{0.73\, N_n(0)} \approx \frac{5 + 0.27}{0.73} \approx 7$$

7 protons per neutron

Summary

The universe expands and cools
from a sea of particles and anti-particles ($kT > mc^2$),
to a soup of quarks
(symmetry breaking ->10^9 photons per quark)
to a soup of neutrons and protons
(quarks confined).
At $T \sim 0.1$ MeV, there are 7 protons per neutron,
n + p --> D,
leaving 6 protons per Deuterium nucleus.

Next time: ***Nucleosynthesis***