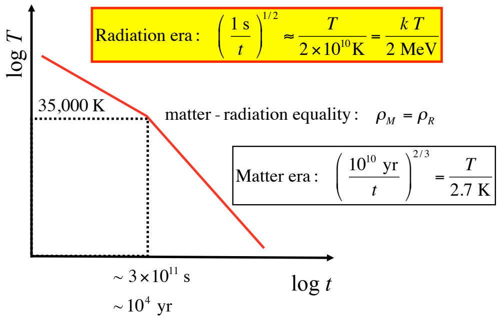
Lecture 2: The First Second
Baryogenisis: origin of neutrons and protons

- Hot Big Bang
- Expanding and cooling
- "Pair Soup" free particle + anti-particle pairs
- Matter-Antimatter symmetry breaking
- Annihilation => 1 quark per 10^9 photons
- "Quark Soup" => Ups and Downs
- Quarks confined into neutrons and protons
- Proton/Neutron ratio when deuterium ^{2}D forms

Cooling History: T(t)



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

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

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

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.

Rest mass ($E = m\,c^2$):
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!

Presently Known 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":

mass ⇒

Top …	Bottom …
Charm …	Strange …
Up …	Down …

3 "colours": (RGB)

gluons
(exchanged by quarks
causing exchange of
"flavour" and "colour")

Immune to strong force

mass ⇒

leptons	**neutrinos**
τ	ν_τ
μ	ν_μ
e	ν_e

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

18 quarks, 3 leptons, 3 neutrinos, 18x17 gluons, 5 bosons
+ anti-particles in equal numbers

"Pair Soup": When $k\,T >> m\,c^2$,
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 **~ 10^9**

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

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 $k\,T < mc^2$ eliminates all, leaving only photons. ☹

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

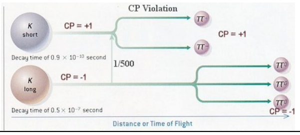
$$\begin{array}{lll} \text{quarks} & 10^9+1 & \qquad 1 \ \ \text{quark} \\ \text{anti-quarks} & 10^9 \quad \xrightarrow{\qquad} & \sim 10^9 \ \ \text{photons} \end{array}$$

Why a tiny excess of particles? Requires a violation of CP (charge conjugation and parity) and this is observed in weak interactions (K^0 meson decays).

$$K^0 = (d\,\bar{s}) \quad \bar{K}^0 = (\bar{d}\,s)$$

$$K_S = \tfrac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$$

$$K_L = \tfrac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$$

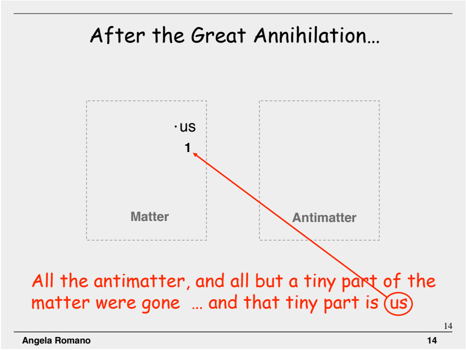


Why is there something, rather than nothing ?


We are lucky because…

Immediately after the Big Bang,
the matter and antimatter… were NOT exactly equal

The Great Annihilation followed !!!


After the Great Annihilation…

All the antimatter, and all but a tiny part of the matter were gone … and that tiny part is us

Pairs => Quark Soup => Ups and Downs

When $k\,T < m\,c^2$, particle/antiparticle pairs of this mass can no longer be created – they “freeze out”.

Massive particles then decay to lower-mass particles plus photons.

quark flavour:	S	C	B	T
$m\,c^2$ (GeV)	0.10	1.27	4.20	171.2

X, W, Z bosons also “freeze out”, decay to quarks.

Heavy quarks (S, C, T, B) “freeze out”, transmute into lightest quarks, U and D (2.4 and 4.8 MeV).

Leaves a “quark soup” of free U and D quarks (+ leptons, photons, gluons, residual heavy quarks and bosons).

Quark confinement => Hadron Era

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

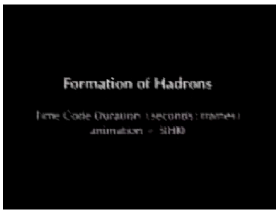
Strong (colour) force confines U and D quarks to form “colourless” hadrons.

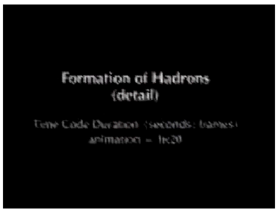
Baryons (3 quarks each of different “colour”) :
DDU → neutron (939.6 MeV)
UUD → proton (938.3 MeV)

Mesons (quark + anti-quark of same “colour ”)
pions: ($\mathrm{U\bar{U}}$, $\mathrm{U\bar{D}}$, $\mathrm{D\bar{U}}$, $\mathrm{D\bar{D}}$)

Others, e.g. UDS, are rare.
Produced in accelerators but rapidly decay.
Only protons and neutrons are relatively stable.

Hadron Formation





Strong (colour) force binds 3 quarks to form “colourless” baryons.
UUD = proton DDU = neutron

The neutron-proton ratio

Quark charges   U: +2/3   D: -1/3
Neutron decay: (DDU) --> (UUD)   (weak interaction D->U)

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

Energy conservation: 939.6 = 938.3 + 0.5 + 0 + 0.8
When $kT >> 0.8$ MeV, the reaction is reversible and $N_n \sim N_p$.

Thermal equilibrium gives a Maxwell-Boltzmann distribution:

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

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

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

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

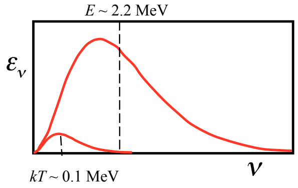
5 protons per neutron

At $t \sim 400$ s and $T \sim 10^9$ K (0.1 MeV),
protons and neutrons confined into nuclei
→ NUCLEOSYNTHESIS   (generating atomic nuclei)

First step: Deuterium   p + n → ^{2}D + 2.2 MeV

Nucleosynthesis starts at $k\,T \sim 0.1$ MeV.
But, ^{2}D binding energy $E = 2.2$ MeV, so
why does nucleosynthesis not start at 2.2 MeV?

Because $N_{photon} / N_{baryon} \sim 10^9$.
Photons in the high-energy tail of the blackbody break up ^{2}D until $k\,T \sim 0.1$ 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 $k\,T \sim 0.1$ MeV.

Neutron decay

Free neutron decay time $\tau \sim 940$ s
Cooling time from 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

Neutron decay

Free neutron decay time $\tau \sim 940$ s
Cooling time from 0.8 MeV to 0.1 MeV: $t \sim 300$ s.
From radioactive decay (weak force changing D->U):

neutrons: $n(t) = n(0)\, e^{-t/\tau} = 0.73\, n(0)$

protons: $p(t) = p(0) + n(0)\,(1 - e^{-t/\tau}) = p(0) + 0.27\, n(0)$

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

7 protons per neutron

Summary

The Universe expands and cools, changing
from a “soup” of <u>particles</u> and <u>anti-particles</u> ($kT > mc^2$),
to a “soup” of <u>quarks</u>
(small 10^{-9} particle / anti-particle asymmetry
=>10^9 photons per quark)
to a “soup” of <u>neutrons</u> and <u>protons</u>
(quarks => U,D, confined as UUD and UDD).
At $T \sim 0.8$ MeV, thermal equilibrium gives p/n = 5.
At $T \sim 0.1$ MeV, neutron decay gives p/n = 7.
n + p => D + 2.2 MeV
leaving 6 protons per Deuterium nucleus.

Next time: ***Nucleosynthesis***