Lectures 17-18

Ignoring equivalence epoch.

Early Universe (continued) and the synthesis of light elements
Liddle Chapter 11 continued, and chapter 12.
At the start of lecture 15, we had the thermal history of the universe back to 1 second (calculation). Now covering the physics in the period from $10^{-10} \rightarrow 10^3 s$, including the nucleosynthesis era $1 \rightarrow 10^3 s$.

A useful "signpost" is that at time $t = 1s$, the temperature was around $T \approx 10^{10} k$, and the scale factor was around $a \approx 2 \times 10^{-10}$. Remember that $T(t) \propto T^{-1/2}$, and $a(t) \propto t^{1/2}$. This was the start of the radiation dominated era.

Period before $1s$: particle era.
Very high temperatures: proton energies high → pair production if $E_{photon} > mc^2$, where m is for a particular particle species: quarks, leptons, …
If T is high enough, then get equilibrium between creation and annihilation.
Some of the physics has been explored back to $\sim 100GeV$ in particle accelerators, e.g. CERN, Fermilab. Soon $> 1TeV$ as these accelerators are upgraded.
$\sim 100GeV \equiv T \approx 10^{15} k$ $(k_B T = E)$. Since $T(t = 1s) = 1.5 \times 10^{10} k$, and $T(t) \propto t^{-1/2}$, then $t(T = 10^{15} k) \sim 10^{-10} s$. At this point there is a "soup" of quarks, gluons, neutrinos, photons, electrons, etc. all interacting very strongly.

Ignoring factors of 2 for simplicity…

$t(s)$	$T(k)$	$E(MeV)$	Comments ("what's happening")
$< 10^{-10}$	$> 10^{15}$	$\sim 10^5$	Quark+++ "soup": at earlier times need new physics. Some physics known at $t > 10^{-11} s$. … Then not much new for a period.
10^{-4}	$\sim 10^{12} k$	~ 100	Quark → hadron phase transition. Quarks combine to form protons and neutrons, etc. Complicated physics, just starting to be explored via colliding heavy nuclei.
10^{-3}	$\sim 3 \times 10^{11}$	~ 30	Even the photon tail is below the threshold for baryon pair production. → baryon-antibaryon annihilation dominates. Why are there any baryons left? Why not equal numbers? Photon-baryon ratio $\sim 1:10^9$ represents the slight excess of baryons over antibaryons. $10^9 + 1 : 10^9$.

1	$\sim 10^{10}$	~ 1	Starting to drop below the e^-, e^+ pair production threshold. But the same proportion of $e^- : e^+$, i.e. $10^9+1:10^9$, must exist to make the universe electrically neutral.

Photon-baryon ratio is a direct diagnostic of a fundamental asymmetry in particle physics.

Now after 1 second → nucleosynthesis area.
[The First 3 Minutes: Steven Weinberg]

Arguments will be similar to production of atoms at decoupling era (350,000 years later), but at higher energies. Note that if $\langle E_{photon}\rangle \geq 1MeV$ → nuclei will be disassociated. Just like at decoupling get disassociation for $\langle E_{photon}\rangle \geq 0.8eV$ (photons in tail dominate the process).
There are three other main points to note at start:

- Neutrons are heavier than protons. $\left(939.6MeV/c^2\right)$ vs. $\left(938.3MeV/c^2\right)$
- Free neutrons decay spontaneously. $n \rightarrow p + e^- + \nu_e$.
  $t_{1/2} = 615s$.
  $\tau = 887s$ ($e^{-t/\tau}$).
- When neutrons are bound into stable nuclei they stop decaying.

Start at time $\leq 1s$ when p, n (& e^-) are in thermal equilibrium with photons. As the universe expands and cools the p and n bind together to form nuclei. During this phase of thermal equibrium, the numbers of particles is governed by Boltzman factor $\propto e^{-mc^2/kT}$, so the relative numbers of protons and neutrons $\propto e^{-[m_n-m_p]c^2/kT}$. Some factors of unity mixed in, which can be ignored here.
So it is just a little bit harder to form neutrons than protons. So when $kT \sim 1.3MeV/c^2$, i.e. $\left(M_n - M_p\right)$, there are significantly fewer neutrons than protons.

$t(s)$	$T(k)$	$E(MeV)$	Comments ("what's happening")
~ 2	$\sim 10^{10}$	~ 0.8	Thermal equilibrium photons / protons / neutrons ceases as kT falls and the relative number of protons and neutrons is frozen. "baryon decoupling" from photons. $\frac{N_N}{N_P} \sim e^{-1.3MeV/0.8MeV} \sim 0.2$ At decoupling of baryons, there are 5 protons for every neutron. At this point, neutron decay starts

			becoming a factor. All processes of synthesis have to be finished before the neutrons have disappeared.
~ 10	$\sim 5\times 10^{9}$	~ 0.4	Various reaction chains now possible, but can "only" proceed via two-body collisions – all routes must start with deuterium production. $p+n \leftrightarrow D+\gamma$. Fusion, plus photodissociation, is happening. Initially balanced. Called the "Deuterium bottleneck".
~ 250	$\sim 10^{9}$	~ 0.08	D becomes stable against photodissociation (binding energy is $2.2 MeV / c^2$). NB: 400 seconds in Liddle. How many neutrons left? $\frac{N_N}{N_P} = \frac{1}{5} e^{-250s/887s} \approx 0.15$

At this point there are around 7 protons for every neutron (cf 5 at $t = 2s$). Synthesis of heavier elements can now proceed. There is a huge network of reactions which have to be modeled on a computer. Some of them are:

$D + D \rightarrow {}^4He + \gamma$

$D + {}^3He \rightarrow {}^4He + p$

$2\,{}^3He \rightarrow {}^4He + 2p$

${}^3He + n \rightarrow {}^4He + \gamma$

These are all forming ${}^4He$, which is the most stable light nuclei. Really only H, He^4 are formed in significant amounts. Heavier elements are hard to form since there are no stable nuclei with atomic weight $A = 5$ or 8 - another bottleneck. Heavier nuclei are formed in stars when the reactions have longer time available to them. The universe didn't have time for low probability reactions.

How much ${}^4He$?

A good assumption is that all the neutrons end up in ${}^4He$. $7:1$ proton-neutron ratio at 200 seconds. So in 16 nucleons, 2 are neutrons, and 14 are protons. Therefore since one ${}^4He$ consists of 2 neutrons and 2 protons, there are 12 protons, e.g. 12 hydrogen nuclei, left over. So the mass fraction ${}^4He$ / total = $4/(4+12)$.

→ Big Bang Nucleosynthesis (BBN) calculations predict ~ 25% of the baryons should be in The form of ${}^4He$, and ~75% in H.

The full calculation suggests 23 – 24%, cf. $D \sim 10^{-4}$, ${}^3He \sim 10^{-5}$, ${}^7Li \sim 10^{-10}$.

Notes:

i. This amount of helium is observed all over the universe (e.g. intergalactic clouds) → BBN must be approximately right.

ii. Amount of D (and the exact amount of ${}^4He$) is sensitive to the density of baryons. Higher density will imply a greater probability of D combining with a proton or neutron and vice versa.

iii. The current amounts of hydrogen, deuterium, ^3He, ^4He and ^7Li can be made to agree with a single value of the baryon density Ω_{baryon} (cf. the critical density).

$0.016 \le \Omega_{baryon} h^2 \le 0.024$

Taking $h = 0.7$, i.e. $H_0 = 70 kms^{-1} Mpc^{-1}$, baryons contribute 3.2% to 4.8% of ρ_{crit} for a flat universe.

BBN predicts that it is impossible for baryons to make up ρ_{crit}. See picture 44.