

# Introductory Astronomy

Week 8: Cosmology

Clip 7: Big Bang Nucleosynthesis

# Alpher, Gamow 1948

- For a brief time universe was **hot** and **dense** as stellar interiors:  
**Fusion everywhere**
- Can **Big Bang Nucleosynthesis** explain abundances of the elements?
- **Partially.** Triple-alpha process not **effective**.
- Predict **Helium** abundance
- **Assume:** Thermal **equilibrium** in expanding flat universe
- **High T:** number densities of **relativistic** particles similar (**Stefan-Boltzmann**)  $n_A \sim (k_B T)^3$
- **Low T:** number densities of **nonrelativistic** particles  $n_A \sim e^{-m_A c^2/k_B T}$

# Who's Radiation?

Particle	Q	$N_e$	$N_\mu$	$N_\tau$	Mass	$Mc^2/k_B$	g
$p$	1	0	0	0	935	$10^{13}$	2
$n$	0	0	0	0	938	$T_p + 1.5 \times 10^{10}$	2
$e$	-1	1	0	0	0.511	$5.93 \times 10^9$	2
$\nu_e$	0	1	0	0	?	0?	1
$\mu$	-1	0	1	0	106	$1.22 \times 10^{12}$	2
$\nu_\mu$	0	0	1	0	?	0?	1
$\pi$	1,0,-1	0	0	1	1777	$1.6 \times 10^{12}$	1
$\gamma$	0	0	0	0	0	0	2

# Cosmic Neutrinos

- At  $T > 10^{12}$  K;  $t \leq 10^{-4}$  s all species in thermal equilibrium with antiparticles present.

$$\frac{N_n}{N_p} = e^{-(m_n - m_p)c^2/k_B T} = e^{-1.5 \times 10^{10} \text{ K}/T} \sim 1$$

- By  $T \sim 10^{11}$  K;  $t \sim 10^{-3}$  s muons annihilate  $N_n/N_p \sim 0.86$
- By  $T \sim 3 \times 10^{10}$  K;  $t \sim 0.1$  s neutrinos decouple  $N_n/N_p \sim 0.6$
- By  $T \sim 5 \times 10^9$  K;  $t \sim 10$  s electrons annihilate producing photons  $T_\gamma/T_\nu = 1.4$

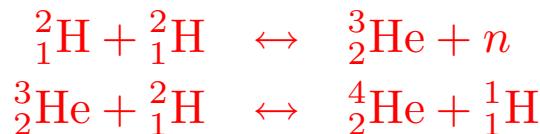
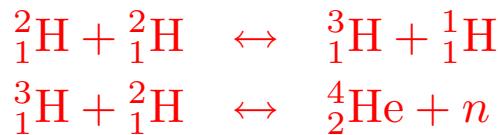
# Alpher, Bethe, Gamow 1948

- In a hot  $10^{12}$  K dense early  $10^{-4}$  s universe, protons and neutrons in chemical equilibrium under
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
- Below  $10^{10}$  K these slow as neutrinos decouple and soon thereafter most electrons gone

$$N_n/N_p \sim 0.223$$

# Nuclei

- Deuterium stable after  $T \sim 10^9 \text{ K}$ ;  $t \sim 180 \text{ s}$
- Neutrons have decayed ( $t_{1/2} = 614 \text{ s}$ )  $N_n/N_p = 0.122$
- Essentially all remaining neutrons bind to form deuterium and then Helium



# Helium Fraction

- Helium fraction is  $\frac{0.122/2}{1 - (3/2) \times 0.122} = 0.0747$
- Helium mass fraction is  $4 \times 0.0747 = 0.299$
- Close to 0.24 observed. More refined calculation produces agreement
- Insensitive to details

# Other Nuclei

- Fusion **beyond** Helium inefficient
- Trace abundances of **deuterium** that failed to fuse sensitive to
$$\eta = \Omega_{Db,0} / \Omega_{R,0}$$
- BBN constrains **cosmology** and **particle physics**

