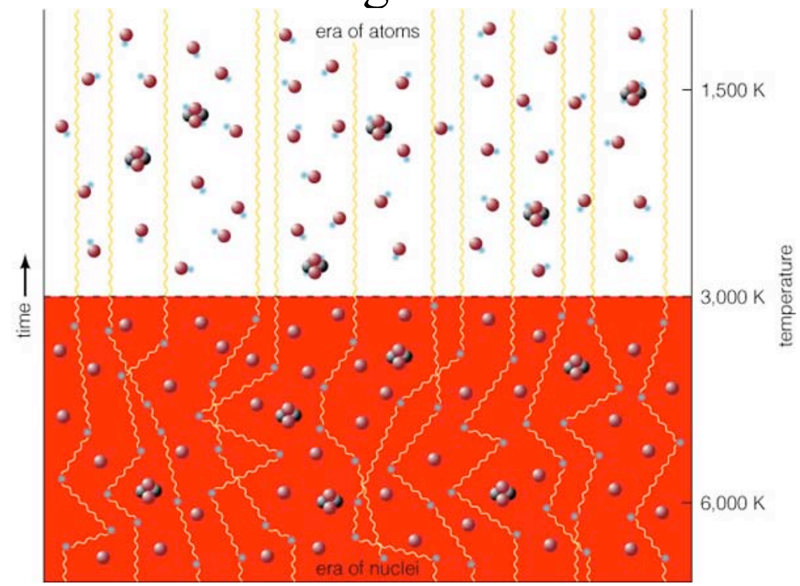
Disappearance of Atoms

- As we go back in time, temperature goes up.
  - T=2.73(1+z) K
- At z~1100, T~3000 K
  - About the same temperature as M-dwarfs
- Ionization of hydrogen atoms
  - H + photon → p + e^-
    - Inverse process: recombination p + e^- → H + photon
- Electrons scatter photons in all directions
  - Similar to the interior of the Sun
  - Photons cannot travel freely
  - The universe becomes "opaque"
- Therefore, z~1100 is the edge of the "visible universe"
  - We cannot look back beyond this epoch using light
  - The epoch called the ***decoupling epoch***.

The origin of CMB



Radiation Era

- In the present universe, radiation energy/matter energy is about 1/3200.
- At the decoupling epoch, this ratio is about 1/3.
- At z~3200, the radiation energy equals the matter energy – the matter-radiation equality
  - z>3200: Radiation Era
  - z<3200: Matter Era
- In the radiation era,
  - $\rho t^2 \sim 10^6$
  - $tT^2 \sim 10^{20}$
    - ρ in g/cm^3, t in seconds, and T in Kelvin.
- The radiation era ends at age about 30,000 years.
  - The decoupling epoch is ~380,000 years.

Nucleosynthesis

- The origin of helium
  - About 25% of the mass of atoms in the universe is helium.
    - 85% is hydrogen
  - Where did helium come from?
  - Stars fuse hydrogen into helium
    - This was incredibly inefficient process
    - Stars could fuse **only 2%** of all hydrogen in the universe into helium – not enough!!
- The first three minutes
  - T~1 billion K
  - The universe was a very efficient nuclear reactor
  - "Big-bang nucleosynthesis"

Synthesize Helium

- n + p → D + photon
  - When T>1 billion K, photo-dissociation process
    - D + photon → n + p

    also occurs frequently and destroys the formed deuterium
  - One has to wait until temperature drops below 1 billion K: t~100 seconds

- D + D → T + p
  - T is tritium (^{3}H; one proton and two neutrons)
- T + D → ^{4}**He** + n

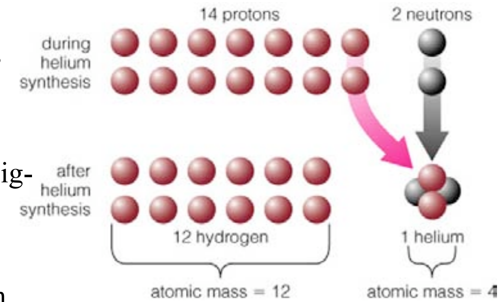
Consumption of Neutrons

- To form D, both n and p are required
  - However, n slowly decays via β-decay:
    - n → p + e^- + ν_e
  - Therefore, n is outnumbered by p, and the amount of helium synthesized is essentially determined by the amount of neutrons
    - **n:p = 1:7**
- This n/p ratio explains

  He:H=1:3

•This is one of the most important predictions of the Big-bang model

•The prediction is robust – it does not depend very much on cosmological parameters



Deuterium

- The amount of deuterium depends on density of nuclei, or Ω_{atoms}. How?
- Low Ω_{atoms}
  - Collision of deuterium, **D + D → T + p**, does not occur frequently
  - A larger fraction of D survives
- High Ω_{atoms}
  - More collision → A smaller fraction survives

…yet we need stars…

- The Big-bang nucleosynthesis cannot synthesize any elements heavier than Lithium.
  - Density of nuclei was too low
- The initial proposal of the BBN was abandoned because of this "failure"
- Later it was realized that heavier elements must be synthesized by fusion in stars
  - Although temperature is low (10 million K vs 1 billion K), density is high (100 g/cm^3 vs 20 μg/cm^3)