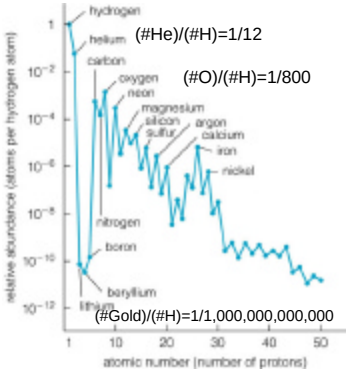
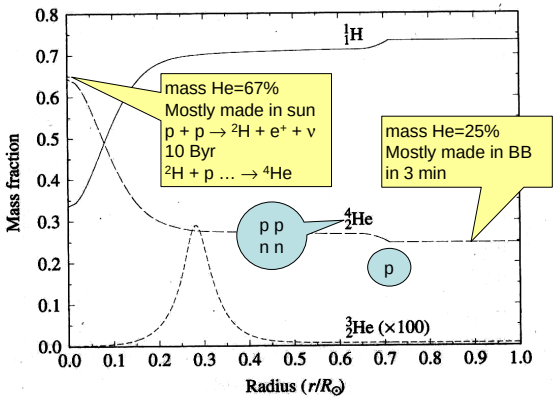
Helium Formed When the Universe was 3 Minutes Old—15 Apr

- Most of the helium is primordial
  - It formed when the universe was 3 minutes old
- Follow the neutrons
  - (Number of neutrons):(No. protons) = 1/7 now
  - 1:1 at 1 ms
- Observations of ^{4}He (and ^{3}He, ^{7}Li, ^{2}H) agree with calculations using Big Bang & nuclear physics



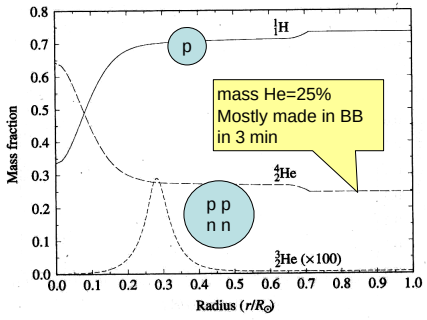
Helium in the Sun



Neutrons:Protons

- From mass He = 25%, find #n/#p at present
- 12 H atoms for every He atom
  - Mass He = 4
  - Mass H = 12
  - Total mass = 16

1. #n / #p =
   a. 1:1
   b. 1:12
   c. 2:14
   d. 4:12
   e. 2:3



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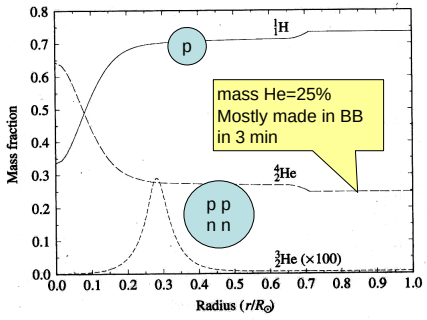

Changing neutrons & protons

- Proton changes into neutron
  - $p + e^- + \text{energy} \rightarrow n + \nu$
  - E = 2MeV
- Neutron changes into proton
  - $n + e^+ \rightarrow p + \text{energy} + \nu$ (positron must hit neutron)
  - $n \rightarrow p + e^- + \text{energy} + \nu$ (happens spontaneously in 1000s)

p 2 MeV ↔ n

- Now
  - 2.7K
  - E=eV/4000
- 3 min
  - 1 BK
  - E=0.1MeV
- 0.001s
  - 400 BK
  - E=40 MeV

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p 2 MeV ↔ n

- If average E=40MeV

p 2 MeV often→ n

p 2 MeV often← n

- 1000p → 900p+100n
  - 1 in 10 changes
- 1000n → 900n+100p
  - 1 in 10 changes
- #p and #n are balanced
  - Before & after: 1000p+1000n
- #p = #n

Changing neutrons & protons

2. When the energy of the universe drops to 1 MeV, the reaction p → n
   a. becomes rarer than n → p
   b. becomes more common than n → p
   c. stays the same.

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p 2 MeV often→ n

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Changing neutrons & protons

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- If average E=1 MeV

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  - 1000p → 990p+10n
    - 1 in 100 changes
  - 100n → 90n+10p
    - 1 in 10 changes
- #p and #n are balanced
  - Before & after: 1000p+100n
- #p > #n

Look at neutrons

- 0.001s
  - Temperature = 400 BK
  - E=40 MeV is much greater than cost to be a neutron
  - n:p = 1:1
- 3 min
  - Temperature = 1 BK
  - E=0.1MeV is much less than cost to be a neutron
  - n:p = 1:7
- Deuterium forms
  - p + n $\rightarrow$ deuterium + energy
  - E=0.1MeV (Deuterium is fragile)
- 4 min
  - Temperature < 1 BK
  - E<0.1 MeV
  - n:p = 1:7
  - Neutrons are safe inside ^{4}He
- 13 Byr
  - Temperature = 2.7K
  - E=0.00025 eV
  - n:p slightly bigger than 1:7
  - Neutrons are safe inside ^{4}He
  - Some neutrons are made in stars

Forming Helium

3. When U was 0.001s old, was the average energy enough to destroy deuterium? To change a proton into a neutron?
   a. YY
   b. YN
   c. NY
   d. NN