Helium Formed When Universe Was 3 Minutes Old—27 Oct

- How & where were the elements made?
  - Carbon, Iron, Calcium in stars
  - Hydrogen is primordial
  - Helium is too abundant to have been made in stars.
  - Helium was made at 3min.
- Evidence: Observations of $^4\text{He}$ (and $^3\text{He}$, $^7\text{Li}$, $^2\text{H}$)

Helium in the Sun

- $^4\text{He}$ mass = 67% Mostly made in BB in 3 min
- $^3\text{He}$ mass = 25% Mostly made in BB

- R1: $p + p \rightarrow ^4\text{He} + e^+ + \nu$ (10 Byr)
- R2: $^3\text{He} + p \rightarrow ^4\text{He}$ (6 Myr)

Key is to follow the neutrons

1. When hydrogen fuses to become helium in the sun, does the ratio $n/p$ change?
   - Yes
   - The reactions in the sun
     - R1: $p + p \rightarrow ^4\text{He} + e^+ + \nu$ (10 Byr)
     - R2: $^3\text{He} + p \rightarrow ^4\text{He}$ (6 Myr)

1. For which reactions does $n/p$ change?
   - A. R1 & R2
   - B. R1 only
   - C. R2 only
   - D. neither R1 nor R2

Helium Abundance is High

- Helium is much more abundant than every element but hydrogen
  - Abundance He = #He/#H
  - Abundance He = 1/12
  - Abundance O = 1/800
  - Abundance Au = 1/trillion
- Abundance of elements born in stars is 1/800 or less. Helium is born in BB.
Key is to follow the neutrons

• The reactions in the sun
  – R1: \( p + p \rightarrow \text{He}^4 + e^+ + \nu \) (10Byr)
  – R2: \( \text{H} + p \rightarrow \text{He}^3 \) (6s)
  – \( \text{He}^3 + \text{He} \rightarrow \text{He}^4 + 2p \) (1Myr)

1. For which reactions does \( \#n/\#p \) change? R1

• Reaction 1 takes a very long time because a neutrino & electron are produced.
• In Big Bang, the only possible reactions are ones that occur quickly.
• In BB, the ratio \( \#n/\#p \) is nearly preserved.

Follow the neutrons

• \( \#n/\#p = 2/14 = 1/7 \) now
• Processing in stars changes \( \#n/\#p \) slightly.
  – \( \#n/\#p \) in H and O
  – \( \#n/(800\#p+8\#p) = 1/101 \)
• \( \#n/\#p \) has been 1/7 from 3 min to now.
• \( \#n/\#p = 1 \) at 1 ms.
• How do neutrons change into protons?

Changing neutrons & protons

• Proton changes into neutron
  – \( p + e^- \rightarrow n + \nu + \text{energy} \)
  – \( E = 2\text{MeV} \)

• Neutron changes into proton
  – \( n + e^- \rightarrow p + \text{energy} + \nu \)
  – \( \text{happens spontaneously in 1000s} \)
  – \( \text{positron must hit neutron} \)
• 1 electron-Volt is the typical energy of a chemical reaction.
• \( 1\text{eV} = 1.6 \times 10^{-19} \text{J} \)
• 1 MeV is the typical energy of a nuclear reaction.
• Radiation in the universe
  – 2.7K
  – \( E = \text{eV}/4000 \)
• At 3 min
  – 1 BK
  – \( E = 0.1\text{MeV} \)
• At 0.001s
  – 400 BK
  – \( E = 40 \text{MeV} \)

Key is to follow the neutrons

• In the outer parts of the sun, the material is nearly primordial.
• \( \text{He} \) is 25% of the mass, \( \text{H} \) is 75%. 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
Changing neutrons & protons

• Proton changes into neutron
  - \( p + e^- + \text{energy} \to n + \nu \)
  - \( E = 2 \text{MeV} \)

• Neutron changes into proton
  - \( n + e^- \to p + e^- + \text{energy} \)
  - \( \nu \) (positron must hit neutron)
  - \( n \to p + e^- + \text{energy} \)
  - (happens spontaneously in 1000s)

- If average \( E = 40 \text{MeV} \)
  - \( p \to n \)
  - \( n \to p \)

- If average \( E = 1 \text{MeV} \)
  - \( p \to n \)
  - \( n \to p \)

- If temperature is too hot
  - \( E > 0.1 \text{MeV} \)
  - Deuterium gets broken apart.
  - \( ^2\text{H} \) combines to form \(^4\text{He} \)

Neutrons/protons when deuterium forms

- \( ^0\text{He} \) forms from \( n \) & \( p \)
  - \( p + n \leftrightarrow \text{deuterium + energy} \)
  - \( E = 0.1 \text{MeV} \)

- When temperature is too hot
  - \( E > 0.1 \text{MeV} \), deuterium gets broken apart.

- As universe cools
  - \( n \neq p \)
  - \#n/\#p drops.

- Neutrons in deuterium are safe; they no longer change into protons.

- \#n/\#p is a fossil from the universe at 3 min.