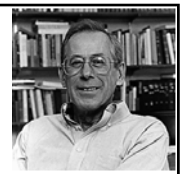
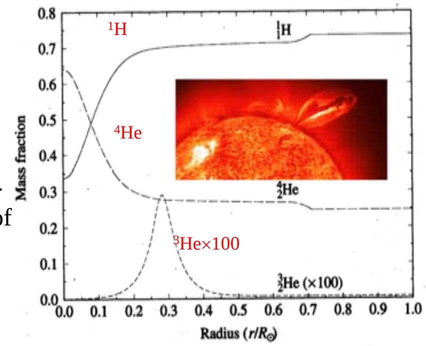
# Helium Formed When Universe Was 3 Minutes Old—27 Oct

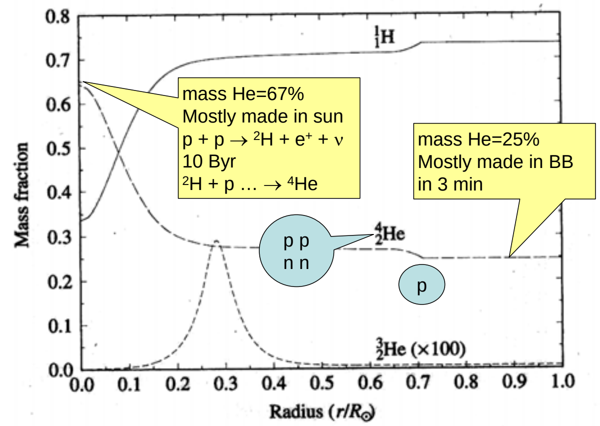


Jim Peebles

- 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 $^4$He (and $^3$He, $^7$Li, $^2$H)

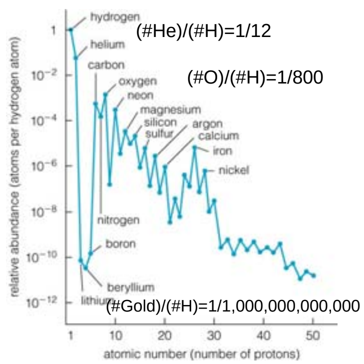



# Helium in the Sun




# 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

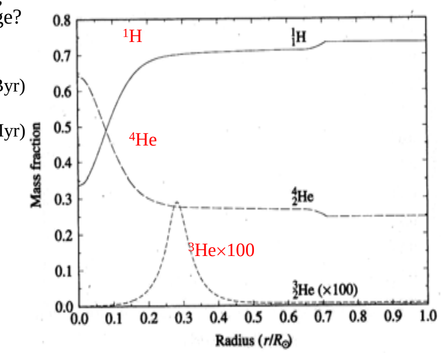
1. When hydrogen fuses to become helium in the sun, does the ratio #n/#p change? Yes

- The reactions in the sun
  - R1: p+p→$^2$H+e$^+$+υ (10Byr)
  - R2: $^2$H+p →$^3$He (6s)
  - $^3$He+ $^3$He →$^4$He+2p (1Myr)

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

p p
n n

p



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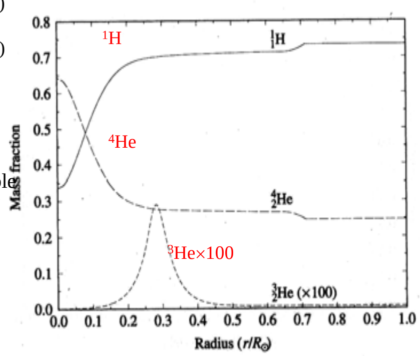
1. For which reactions does #n/#p change? R1

- 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.



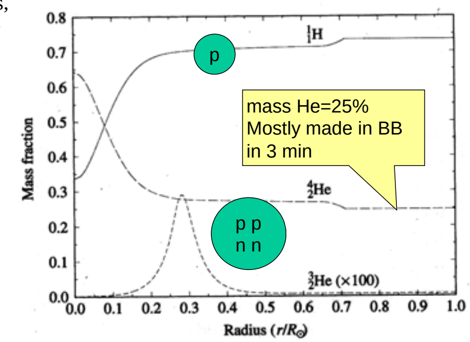

p p
n n

p

## Key is to follow the neutrons

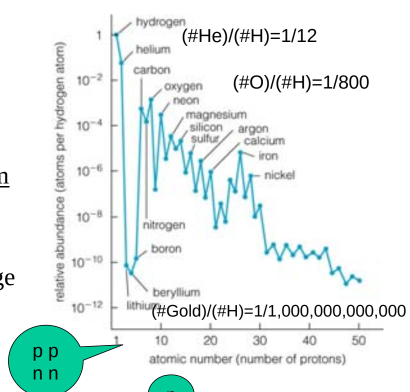
- In the outer parts of the sun, the material is nearly primordial.
- He is 25% of the mass, H is 75%. 12 H atoms for every He atom
  - Mass He = 4
  - Mass H = 12
  - Total mass = 16

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




## Follow the neutrons

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




p

## Changing neutrons & protons

- Proton changes into neutron
  - p + e$^-$ + energy → n + ν
  - E = 2MeV
- Neutron changes into proton
  - n + e$^+$ → p + energy + ν (positron must hit neutron)
  - n → p + e$^-$ + energy + ν (happens spontaneously in 1000s)

- 1electron-Volt is the typical energy of a chemical reaction.
- 1eV = 1.6×10$^{-19}$J
- 1MeV is the typical energy of a nuclear reaction.
- Radiation in the universe
  - 2.7K
  - E=eV/4000
- At 3 min
  - 1 BK
  - E=0.1MeV
- At 0.001s
  - 400 BK
  - E=40 MeV

p 2 MeV ↔ n

## Changing neutrons & protons

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- Neutron changes into proton
  - n + $e^+$ → p + energy + ν (positron must hit neutron)
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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.

- If average E=40MeV
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  - p 2 MeV often← n
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## Changing neutrons & protons

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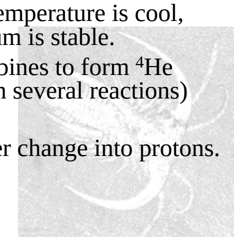
- If average E=1 MeV
  - p 2 MeV rare→ n
  - p 2 MeV often← n
  - 1000p → 990p+10n
    - 1 in 100 changes
  - 100n → 90n+10p
    - 1 in 10 changes
- #p and #n are balanced
  - Before & after: 1000p+100n
- #p > #n

## Neutrons/protons when deuterium forms

- 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
- As universe cools, #n/#p drops.

- Deuterium forms from n & p
  - p + n ↔ deuterium + energy
  - E=0.1MeV
  - Deuterium is fragile
- If temperature is too hot (E>0.1MeV), deuterium gets broken apart.
- When temperature is cool, deuterium is stable.
- $^2$H combines to form $^4$He (through several reactions)



- Neutrons in deuterium are safe; they no longer change into protons.
- #n/#p is a fossil from the universe at 3 min.