Lecture 22 Origin of the Elements

MODEL: Origin of the Elements or Nucleosynthesis

Fundamental Particles
- quarks, gluons, leptons, photons, neutrinos

Basic Forces
- gravity, electromagnetic, nuclear

Interactions
- gravity, electromagnetic, nuclear

OUTLINE:

Primary Sources of the Elements
1. Big Bang – Creation
2. Stellar Nucleosynthesis
3. Cosmic-Ray Interactions

I. Cosmological Nucleosynthesis: The Big Bang (Gamow)

A. Evidence

1. Red Shift: Doppler Effect
   Light from all distant galaxies is shifted to the RED
   \( \Delta \lambda \) is proportional to distance (Hubble)
   Implication: Everything is moving away from us \( \therefore \)
   a. Universe is EXPANDING
   b. Matter has a COMMON ORIGIN
      Age \( = 13 \pm 2 \times 10^9 \) years

2. Universal Black-Body Radiation – Remnant of primordial Explosion
   \( T_{\text{present}} = 2.7 \, ^\circ \text{K} \Rightarrow \rho \approx 10^{-31} \, \text{g/cm}^2 \) (Penzias & Wilson)
   This radiation is isotropic in space \( \therefore \) it's not from our galaxy
3. **Abundances of the Light Elements** – esp. in old halo stars

\(^1\text{H}\) dominates the universe; \(^2\text{H}, ^3\text{He}, ^4\text{He}\) (little variation); \(^7\text{Li}\)

**Conclusion:** Universe must have formed from the simplest particles.

4. **STANDARD MODEL:** Universe originated in a hot, dense explosion involving the simplest particles:

THE BIG BANG

**B. Basic Assumptions of Standard Model (small subset)**

1. **Only the known particles and forces are allowed**

GUTS = Grand Unification Theories – Origin of Forces

2. **Matter vs. Energy Dominance:**

\[ E = Mc^2 \]

Energy drives expansion; gravity (mass) constrains expansion

3. **\( T = f \) (density)\**

Universe cools as it expands: \(<E> = (3/2) kT; k = 0.86 \times 10^{-10} \text{ MeV/K}\)

**C. Chronology of the Big Bang**

1. **Elementary Particle Phase:** [time < \(10^{-6} \text{ s}\); \(T > 10^{13} \text{ K} > M_n\)]

   a. Most of mass-energy of the Universe in the form of ENERGY.
   b. Only fundamental particles present; complex particles dissolved in heat bath (including nucleons).

2. **Hadron Phase:** [\(10^{-6} \text{ s} \lesssim \) time \(\lesssim 1 \text{ sec}\); \(10^{13} \text{ K} > T > 10^{10} \text{ K}\)]

   a. Quarks and gluons condense to form hadrons (p, n, π, …)
   b. No complex nuclei exist; \(^2\text{H}\) is simplest and binding energy is 2.2 MeV

   \(~2 \times 10^{10} \text{ K}\); \(\therefore\) Universe is too hot for \(^2\text{H}\) to form.
   c. Equilibria:

   \[
   \begin{align*}
   \text{p + e} & \rightarrow \text{n + v} \\
   \text{n + e}^+ & \rightarrow \text{p + v}
   \end{align*}
   \]

   reaction rates determine p/n

   ratio: needs to be \(~1:1\) for \(^2\text{H}\)
3. **Nucleosynthesis Phase**: [time ~ 3 minutes ; T ~ 10^{9} K, p ~0.1 g/cm^{3}]
   a. First step in nucleosynthesis now possible
   \[ \begin{align*}
   ^{1}\text{H} + ^{0}\text{H} & \rightarrow ^{2}\text{H} + \gamma \\
   ^{2}\text{H} + ^{0}\text{H} & \rightarrow ^{3}\text{H} \\
   ^{3}\text{H} + ^{1}\text{H} & \rightarrow ^{4}\text{He} \\
   ^{3}\text{He} + ^{4}\text{He} & \rightarrow ^{7}\text{Li}
   \end{align*} \]
   b. Chain stops at ^{4}\text{He}, although a little ^{7}\text{Li} sneaks through (−10^{-11})
   Synthesis of heavier elements is inhibited due to nuclear shell structure and very short lifetimes for nuclei just beyond doubly-magic ^{4}\text{He}
   c. Theory predicts abundances of ^{1}\text{H}, ^{2}\text{H}, ^{3}\text{He}, ^{4}\text{He} and ^{7}\text{Li} well.

4. **Cooling Phase**: [t > 3 min, T < 10^{9} K]
   Expansion continues
   a. Neutron Decay: ^{0}\text{n} \rightarrow ^{1}\text{H} + ^{0}\beta^{-} + \bar{\nu} ; t_{1/2} = 10.8 \text{ min}
   b. Nuclear reactions cease ; T too low to exceed Coulomb barrier for charged particles and neutrons are gone.
   c. Matter now dominates the Universe

5. **Chemistry Phase**: [t ~ 10^{5} y ; T \lesssim 10^{5} °K]
   Electrons now attach to H, He and Li ions to form neutral atoms
   **FLASH !** photon burst → microwave background
   \[ ^{1}\text{H}^{+} + e^{-} \rightarrow ^{1}\text{H} + \gamma \]
II. Stellar Nucleosynthesis

Neutral gas expands
Local inhomogeneities develop (consequence of Inflation at $\sim 10^{-30}$ s)

Once matter is inhomogeneous, localized gravitational fields are created that set the stage for galaxy formation

Result: \[
\begin{cases}
(1) \text{ Density increases and reheats matter; esp. in core of field.} \\
(2) \text{ Stars form}
\end{cases}
\]

A. Main Sequence Stars ($\sim 90\%$ of stars)

Sun: $M_\odot = 2 \times 10^{33}$ g

1. Primordial Proton (+ He & Li) Gas: conditions
   a. Gravitational pressure heats core; ionizes medium.
   b. Electrostatic repulsion inhibits nuclear reactions and contraction
   c. IF $M_{\text{star}} \gtrsim 0.5 M_\odot$, gravity dominates and $T$ increases
   d. At $T_{\text{core}} \sim 10^7$ K, proton burning begins to occur in high energy tail of Maxwell-Boltzmann distribution:

2. Hydrogen Burning

   a. Core conditions \( T \approx 1-2 \times 10^7 \text{ K} \)

      \[
      \begin{align*}
      &\text{Universe: } \rho \sim 10^{-31} \text{ g/cm}^3 \\
      &\text{Nucleus: } \rho \sim 10^{14} \text{ g/cm}^3 \\
      &\rho \approx 100 \text{ g/cm}^3 \\
      &\text{H}_2 @ \text{ STP: } \rho \sim 1 \times 10^{-4} \text{ g/cm}^3
      \end{align*}
      \]
b. **Fundamental Reaction**

\[
^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + ^0_{-1}\beta^+ + \nu \quad \text{WEAK INTERACTION SLOW}
\]

\[
\text{rate-determining step}^* \]

c. **Solar Neutrino Experiment**

![Graph of solar neutrino spectrum](image)

**Spectrum of solar neutrinos**

- **Homestake, SD**: \( ^{37}_{17}\text{Cl} + \nu \rightarrow ^{37}_{18}\text{Ar} + ^0_{-1}\text{e}^- \) ; \( ^{37}_{18}\text{Ar} + \text{e}^- \rightarrow ^{37}_{17}\text{Cl} + \nu \)
- **GALLEX (Italy)** \( ^{71}_{31}\text{Ga} + \nu \rightarrow ^{71}_{32}\text{Ge} + \text{e}^- \)
- **SAGE (Russia)** \( ^{71}_{32}\text{Ge} + \text{e}^- \rightarrow ^{71}_{32}\text{Ge} + \text{e}^- \)
- **Kamiokande (Japan)** \( \nu + \text{e}^- \rightarrow \nu' + \text{e}' \)
- **SNO (Canada/US)** \( \nu + ^1_1\text{H} \rightarrow \text{n} + \text{p} + \nu' \) (10³ tons of D₂O)

See also: [http://www.hep.anl.gov/ndk/hypertext/solar_experiments.html](http://www.hep.anl.gov/ndk/hypertext/solar_experiments.html)


The experimental procedure for GALLEX is as follows: 30.3 tons of gallium in form of a concentrated GaCl₃-HCl solution are exposed to solar neutrinos. In GaCl₃-HCl solution, the neutrino induced \(^{71}_{31}\text{Ge}\) atoms (as well as the inactive Ge carrier atoms added to the solution at the beginning of a run) form the volatile compound GeCl₄, which at the end of an exposure is swept out of the solution by means of a gas stream (nitrogen). The nitrogen is then passed through a gas scrubber where the GeCl₄ is absorbed in water (see figure 1). The GeCl₄ is finally converted to GeH₄, which together with xenon is introduced...
into a proportional counter in order to determine the number of $^{71}$Ge atoms by observing their radioactive decay.

d. **Result:** Solar Neutrino Problem  
   Observed Rate only 30-50% of expected rate

3. **ppI chain**

   **FUNDAMENTAL ENERGY SOURCE FOR THE SOLAR SYSTEM**

   \[
   \begin{align*}
   _1^1\text{H} + _1^1\text{H} & \rightarrow _1^2\text{H} + _0^0\beta^+ + \nu \\
   _1^3\text{H} + _1^1\text{H} & \rightarrow _1^1\text{He} + \gamma \\
   2^3\text{He} & \rightarrow _1^4\text{He} + 2^1\text{H}
   \end{align*}
   \]

   \[
   \text{NET: } 4^1\text{H} \rightarrow ^4\text{He} + 2\beta^+ + 2\nu + 26.7\text{ MeV}
   \]

   nuclear fusion power

   Reactions hard to measure:
   \[
   kT \sim 1\text{ keV} \text{ compared to Big Bang } kT \sim 0.1 - 1\text{ MeV}
   \]
4. **Other Chains**

   ppII: $^7\text{Li}$ catalyst
   ppIII: $^7\text{Be}$ catalyst
   CNO: $^{12}\text{C}$ catalyst

   All produce same net reaction, but each is important at different temperatures and elemental compositions

5. **Stellar Structure:** Star in Quasi Equilibrium

   a. **Hydrogen burning** adds a small amount of additional $^4\text{He}$ to Universe.
   b. **Nuclear burning** (mass $\Rightarrow$ energy) counterbalances gravitational attraction.
   c. $\tau_{\text{sun}} \sim 10^{10}$ y; heavier stars burn faster (HR diagram) – more abundant in early Universe.
   d. $^4\text{He}$ in core cannot burn easily at $2 \times 10^7$ K due to Coulomb repulsion
   e. H envelope continues to burn as $^4\text{He}$ accumulates in core.

6. **Subsequent Evolution**

   a. $M \lesssim 10^{33}$ g $\Rightarrow$ White Dwarf (stellar graveyard – calibration candle)
   b. $M \gtrsim 10^{33}$ g $\Rightarrow$ Red Giant (evolution continues)

   **B. Helium Burning:** Red Giant Stars (~10%)

   1. **Gravitation compresses** $^4\text{He}$ in core:
      \[
      \begin{cases}
        \rho \approx 10^5 \text{g/cm}^3 \\
        T \approx 10^8 \text{K}
      \end{cases}
      \]

   2. **Nuclear Reactions**

      a. LiBeB are highly unstable thermally; burn up as soon as they are formed; Accounts for inhibition of heavy element synthesis in Big Bang.
b. **Hoyle**: 3α Reaction  
\[
\begin{align*}
\frac{4}{2}\text{He} + \frac{4}{2}\text{He} & \rightarrow \left[ \frac{8}{4}\text{Be}^* \right] ; \quad \tau \sim 10^{-16} \text{ s} \\
\text{EXOTHERMIC} & \left[ \frac{8}{4}\text{Be}^* \right]^2 + \frac{4}{2}\text{He} \rightarrow \frac{12}{6}\text{C} + \gamma ; \quad E_\gamma = 7.65 \text{ MeV (0+)}
\end{align*}
\]

c. **Three-body nature** of reaction results in low rate  
\[\tau_{\text{RedGiant}} \approx 10^7 - 10^8 \text{ y} ; \text{ still SLOW, like Main Sequence}\]

d. **Sun** will become a Red Giant in \(~ 5 \times 10^9 \text{ y} \) and then become a White Dwarf.

3. **Subsequent Reactions – Richer Chemistry**

\[
\begin{align*}
\frac{12}{6}\text{C} + \frac{4}{2}\text{He} & \rightarrow \frac{16}{8}\text{O} + \gamma \\
\frac{16}{8}\text{O} + \frac{4}{2}\text{He} & \rightarrow \frac{20}{10}\text{Ne} + \gamma
\end{align*}
\]

\[Q = +\]

4. **Composition of the Universe at this stage**: H, He, (Li), C, O and (Ne)

5. **Synthesis of heavier elements in core inhibited by higher Coulomb barriers of O and Ne** ; e.g., \( \frac{12}{6}\text{C} + \frac{12}{6}\text{C} \)

Star in quasi-equilibrium again.