Nuclear Physics and Astrophysics

PHY-302

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Lecture 21
Nucleosynthesis

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Primordial Particle and Nucleosynthesis

Many details of cosmology rely heavily on models of particle production in early universe
Based on knowledge of particle physics & nuclear physics
Additional observations of universe

Current universe is photon dominated - ratio nucleon:photon ~ 1:10^9
Universe appears completely matter dominated - no antimatter in universe!

If there is no CP violation what would universe look like?

In very early universe production of elementary particles & photons in equilibrium

$$\gamma + \gamma \leftrightarrow e^+ + e^-$$
$$\gamma + \gamma \leftrightarrow p + \bar{p}$$
$$\gamma + \gamma \leftrightarrow n + \bar{n}$$

expect equal amount of matter/antimatter

Some unknown interaction is responsible for matter-antimatter asymmetry
Particles from Grand Unified Theories (GUTs) with masses ~10^{18} MeV <u>could</u> be responsible
Only small imbalance is needed 1×10^{-9} matter:antimatter
Once temp of universe drops below ~10^{18} MeV (t=10^{-36} s) asymmetry is frozen
After 10^{-6} s (E, kT <1000 MeV) matter-antimatter nucleons annihillate to photons
Only small asymmetry of matter nucleons remains

photons at too low energy to create ~1000 MeV nucleons

Similar annihilation happens for $2\gamma \leftrightarrow e^{+} + e^{-}$

At t=1s photon energy E=0.511 MeV (electron mass) only annihilation process occurs

Only asymmetric matter remained - rest annihilated to photons

Universe now composed of only of photons, n, p^{+} , e^{-} and neutrinos

Through charge conservation number electrons & protons is same

Through CP violation only matter remains, all antimatter annihilated with matter to photons

This ends period of particle synthesis 1s after big bang

Period of big bang nuclear synthesis begins t~225s

Universe must be cool enough to stop photon dissociation of deuterium

Universe must be hot enough for fusion to occur

Lasted for only ~3 mins!

$$n + p \rightarrow d + \gamma$$

At high energy photodissociation occurs when photon energy = binding energy of deuterons

i.e. below energy threshold deuteron formation wins

Note: different to stellar fusion process - here neutrons are free particles

Once deuterium forms then other reactions are possible:

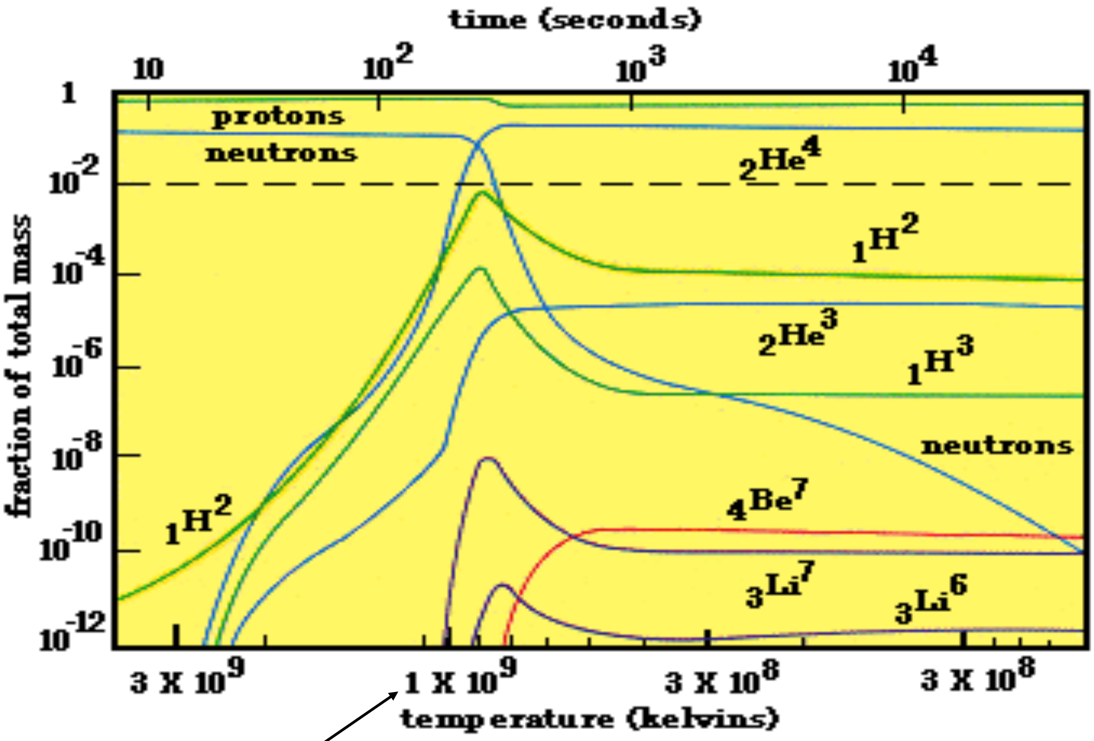
$$d + n \rightarrow {}^{3}H + \gamma$$
$$d + p \rightarrow {}^{3}He + \gamma$$

or

$$d + d \rightarrow {}^{3}H + p$$
$$d + d \rightarrow {}^{3}He + n$$

finally He can be formed:

$${}^{3}H + p \rightarrow {}^{4}He + \gamma$$
$${}^{3}He + d \rightarrow {}^{4}He + p$$



Moment of primordial nucleosynthesis

Further primordial nucleosynthesis is no longer possible:

no stable nuclei with A=5 exist i.e. ^{4}He + p → ^{5}Li is unstable

no stable nuclei with A=8 exist i.e. ^{4}He + ^{4}He → ^{8}Be is unstable

trace amounts of Li and Be formed via:

$$^4He + \ ^3H \rightarrow \ ^7Li + \ \gamma$$
$$^4He + \ ^3He \rightarrow \ ^7Be + \ \gamma$$

These reactions have Coulomb barrier ~ 1MeV

At this stage average kT~0.1 MeV

All fusion stops!

When kT is less than Coulomb barrier ...

At t= 30 mins universe is:

- 24% ^{4}He
- 76% protons
- trace amount of d & ^{3}He
- trace amount of Li / Be
- electrons / neutrinos
- factor 10^{9} more photons than electrons/nucleons

It is not for another 300,000 years before universe is cool enough for recombination

- formation of neutral atoms by combination of electrons & nuclei

Recombination is important moment: universe becomes transparent to photons

- little interaction of photons with H and He atoms (energy levels are quantised!)
- thus CMB observed today tells us about mass-energy distribution at this moment in time

Only now can gravity start to play a real role in star/galaxy formation

Mass abundance of H and He (76% & 24%) remains unchanged

Changes in abundance due to stellar nucleosynthesis are small

Model predictions agree with observed abundance

Big success for model of big bang nucleosynthesis

Lends weight to interpretation of WMAP data on cosmological parameters

Stellar Nucleosynthesis (A < 60)

At $t=10^9$ years galaxy / star formation occurred

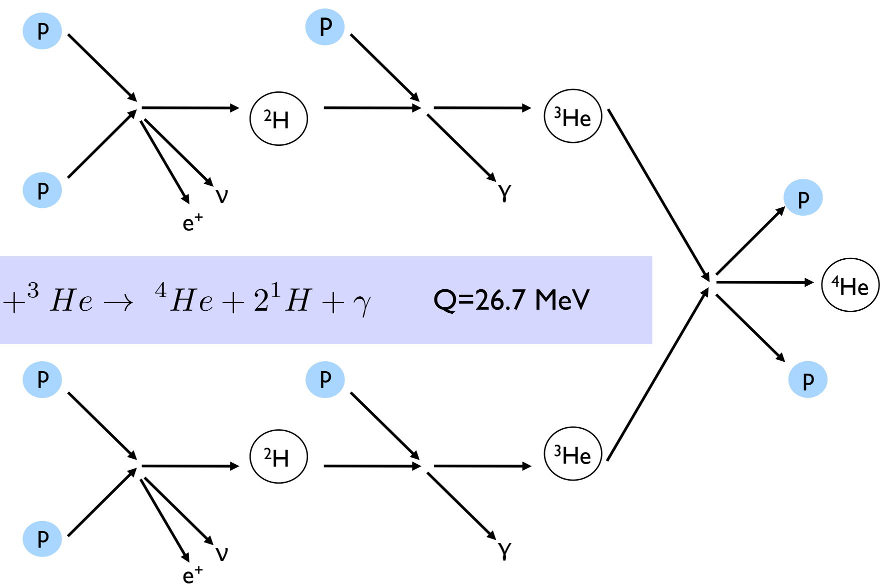
gas clouds of He and H collapsed under gravitational attraction

gravitational potential energy transferred to kinetic energy via collisions

temperature of gas cloud increases

when temperature high enough He and H overcome Coulomb barriers: fusion process begins

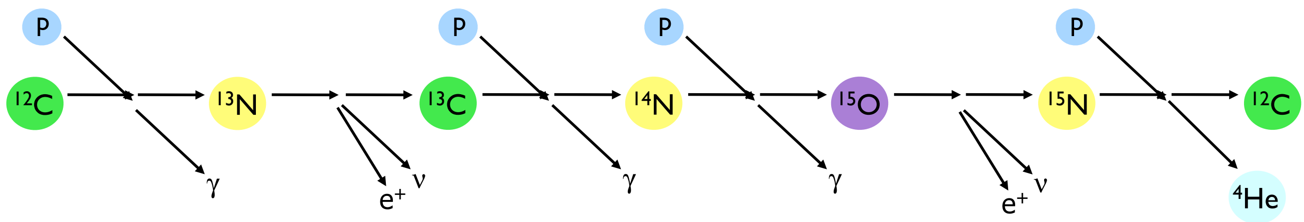
Proton-proton Cycle



$$^3He + ^3He \rightarrow \; ^4He + 2^1H + \gamma \qquad Q=26.7 \text{ MeV}$$

- Why is formation of ^{2}H known as the "bottleneck" ?
- Which other reaction burns hydrogen?

CNO Cycle



Once heavier elements are present other reactions can occur

Important example: Carbon, or CNO cycle

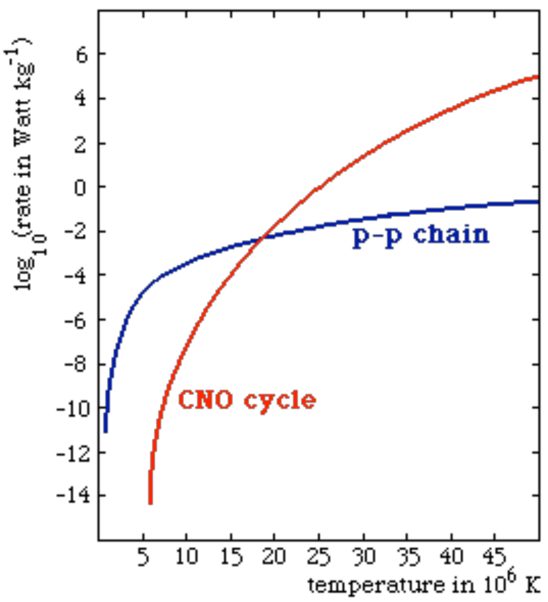
Net process is:

$$4^1H \rightarrow \ ^4He + 2e^+ + 2\nu_e + 2\gamma \qquad Q=26.7\ \text{MeV}$$

Same Q and products as before!

Note: ^{12}C is used as a catalyst - facilitates, but is not used up in reaction

CNO Cycle



- Difference between pp and CNO cycles:
  - CNO cycle requires no deuterium - no bottleneck
  - ^{12}C has larger Coulomb repulsion - thus CNO cycle occurs at higher temperatures

- pp and CNO cycles all burn hydrogen
  - Sun radiates 1.4 x 10^3 W/m^2 at surface of earth
  - Total power output of sun = 4x10^{26} W
  - Assuming 25 MeV release per cycle consuming 4 hydrogen nuclei, then sun will continue to burn hydrogen for ~10^{10} years

What happens then?

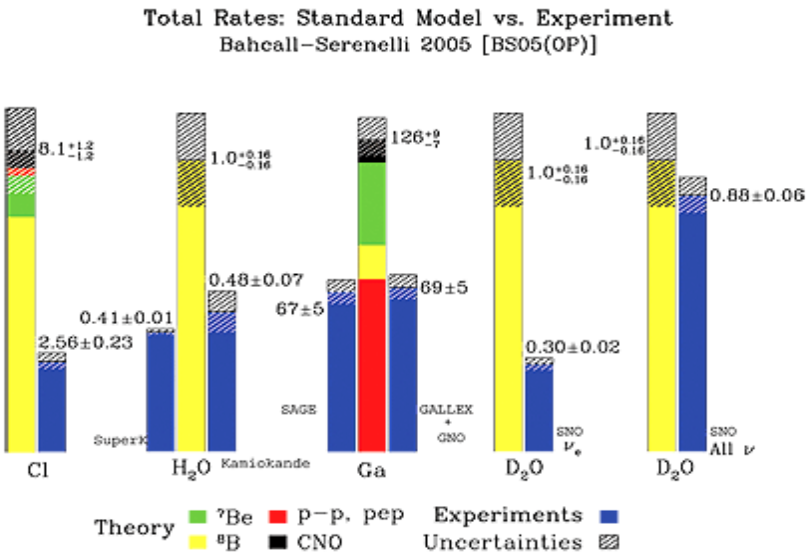
Stars start to burn He and successively higher A elements up to A=56

Due to larger Coulomb repulsion stars need to burn hotter to overcome this

This model explains main category of stars observed & atomic relative abundances

Solar Neutrinos

Can test model of solar fusion from measured solar neutrino energy spectrum



Measure fewer neutrinos compared to theory!

Expts measure one ν_e type

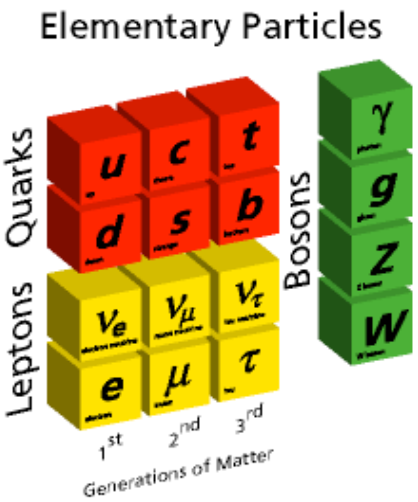
SNO expt. can also measure all ν types (ν_e ν_μ ν_τ)

Solar Neutrino Problem

Results imply:

- solar electron neutrinos are missing
- solar fusion calculations are wrong
- a new theory of neutrino interactions is required

One of the most exciting developments in particle physics in last few years!



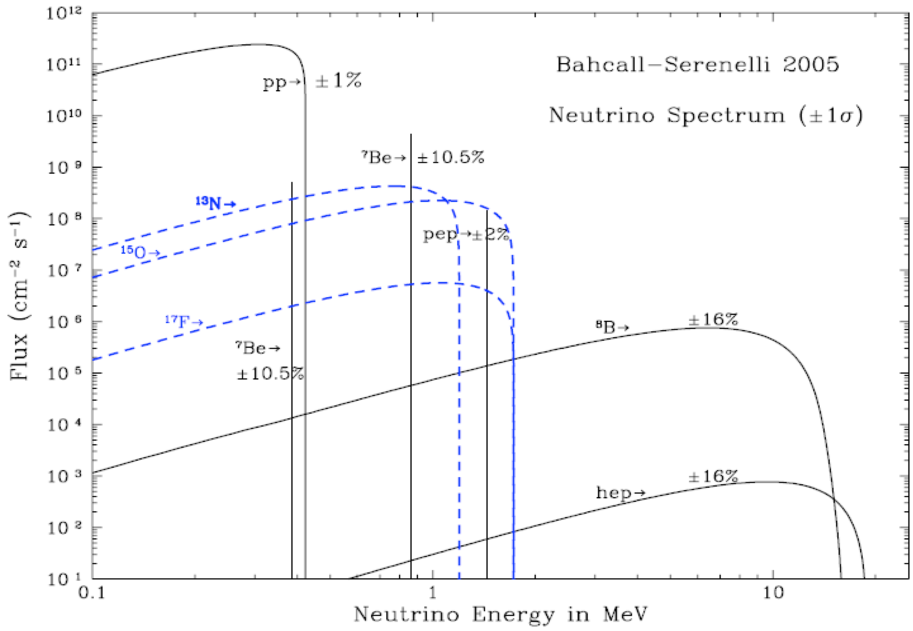
Standard Model: quarks and leptons come in 3 generations:

electron muon & tau neutrinos exist

Standard Model assumes neutrinos are massless

β decay end-point measurements showed ν have very low mass

Solar Neutrino Problem



Beta decay neutrino spectrum endpoint is sensitive to neutrino mass:
Masses are <u>small</u> < 1eV for ν_e

Neutrino Masses

If neutrino masses allowed:

- neutrino generations mix
- neutrino interactions via $W^{\pm}$ exchange produce ν of definite weak flavour (ν_e ν_μ or ν_τ)
- but these do not have a definite mass!
- weak eigenstates are not mass eigenstates (ν_1, ν_2, ν_3)
- when particle propagate - they propagate as mass eigenstates (definite energy)
- as neutrinos propagate QM interference allows weak eigenstates to mix
- means flavour is not conserved
- we expect flavour conservation from charged lepton sector

As an example just take 2 neutrino generations:

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta \qquad \nu_2 = \nu_e \sin\theta + \nu_\mu \cos\theta$$

mixing angle is dependent on mass difference

Means ν_e produced in sun oscillate into ν_μ and ν_τ and back again

But How is Carbon Formed?

^{12}C is relatively plentiful - how is it formed?

$^{4}He + {}^{4}He \rightarrow {}^{8}Be$ is highly unstable ($\tau \sim 10^{-16}$ s)

Small equilibrium quantity of ^{8}Be too small for large abundance of ^{12}C ...?

If temp is high enough and enough ^{4}He exists then

$$^{4}He + {}^{8}Be \rightarrow {}^{12}C$$

A 'resonance' is needed to explain abundance of ^{12}C
cross section has peaks for ^{8}Be and ^{12}C production

This is the net triple alpha process
Net reaction is simply:

$$3\,^{4}He \rightarrow {}^{12}C$$

Helium Burning

After production of ^{12}C further reaction chains are available:

$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma \qquad E_B\text{=3.57 MeV}$$
$$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma \qquad E_B\text{=4.47 MeV}$$
$$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma \qquad E_B\text{=5.36 MeV}$$

Note: each step consumes helium

E_B is Coulomb barrier - each step in chain increases Coulomb barrier

Larger nuclei are less likely to form

Carbon / Oxygen Burning

Once helium supply is exhausted fusion pressure unable to halt gravitational collapse

Star begins to heat up till ^{12}C can ignite:

$$^{12}C + \ ^{12}C \rightarrow \ ^{20}Ne + \ ^{4}He$$
$$^{16}O + \ ^{16}O \rightarrow \ ^{28}Si + \ ^{4}He$$

Carbon burning produces nuclei in range A~20-24: Ne, Na, Mg

Oxygen burning produces nuclei in range A~24-32: Mg, Si, P, S

These have Z ~ 10-16 Coulomb barrier is larger and temperature is insufficient for direct fusion reaction: $^{28}Si + ^{28}Si \rightarrow ^{56}Fe$

Odd Z nuclei are formed by two routes:

- chains of ^{4}He fusion starting from $^{13,14,15}N$ remnants of CNO cycle
- proton fusion with N or other nuclei

Silicon Burning

At this stage photodissociation reaction becomes important

$$^{28}Si + \ \gamma \rightarrow \ ^{24}Mg + \ ^{4}He$$
$$^{28}Si + \ ^{4}He \rightarrow \ ^{32}S + \ \gamma$$

Many similar reactions also occur

Note: He is produced by photodissociation (none left in star) fragments then undergo fusion

Chains of these reactions produce elements A~56 (Ni, Co, Fe)

At this stage no more energy can be released from fusion processes