

Astro 406
Lecture 36
Nov. 20, 2013

Announcements:

- **PS 11 due now**
- **PS 12 due Friday after break** last problem set!

Last time:

- finished CMB: the atomic age
big bang working well back to $t = 400,000$ yr
- pressed back to the nuclear age
Q: why don't nuclei fly apart?
Q: characteristic nuclear energy scale?
- ⊢ ● fun nuclear fact:
no nuclei have $A = 5$ or 8 neutrons + protons *Q: why?*

The Cosmic Nuclear Age

in early Universe, strong/nuclear force important

Q: to zeroth order, when is epoch?

Q: what what universe like then? environment, particles?

Q: what transition(s) expected?

Q: what fossils might be left over?

Q: how could we observe them?

Primordial Nucleosynthesis

Big bang nucleosynthesis (BBN): production of lightest elements
H, He, Li in the early Universe

extrapolate expanding U w/ matter, radiation
back to $t \sim 1$ sec \rightarrow Universe is giant nuke reactor!

1950's: George Gamow

since early U. very dense

Q: *what is densest object not a black hole?*

\rightarrow all neutrons

expand: $n \rightarrow p + e^- + \bar{\nu}_e$ decay

$n + p \rightarrow$ *all elements made in first cosmic seconds!*

www: $\alpha\beta\gamma$ paper

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Q: *what flaw(s) in argument?*

Enrico Fermi:

big bang can't make all elements

no stable nuclei with $n + p = 5, 8$ particles

mass "gaps" stop flow

C. Hayashi:

weak interactions (neutrinos) important

initial baryon state *not* just neutrons!

Q: why? what is effect of energetic neutrinos?

Note:

when $kT \sim \text{MeV} \sim \text{nucleon binding}$

Q: are baryons (n, p) relativistic or not?

BBN: Theory

want to predict element “cooking”

Recipe:

follow weak, nuclear reactions
in expanding, cooling U.

The Oven: radiation dominated universe

$a^2 \propto t$, but since $T \propto 1/a$

$t \propto 1/T^2$

$$t = \left(\frac{1 \text{ MeV}}{kT} \right)^2 1 \text{ s} \quad (1)$$

so $kT = 1 \text{ MeV} \rightarrow T \simeq 10^{10} \text{ K}$ at $t \simeq 1 \text{ s}$

Q: *what is central temperature of Sun?*

$kT \gg$ atom binding energy \rightarrow U. ionized

Nucleosynthesis: Ingredients

radiation:

initially, $kT > m_e c^2 = 0.5 \text{ MeV}, m_\nu c^2$

Q: so what does this mean? what is radiation?

→ $\gamma, e^\pm, \nu\bar{\nu}$ (3 species) relativistic

CMB now gamma rays!

matter: $kT \ll m_p c^2, m_n c^2 \simeq 1000 \text{ MeV}$

n, p non-rel; assume DM is too

also: since nuclear binding $\sim \text{MeV}$, nuclei “ionized” too

→ n, p only, no complex nuclei

key parameter: $n_{\text{baryon}}/n_\gamma \equiv \eta$

don't know yet, will solve for it

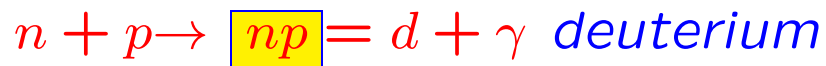
preview: $\eta \sim 10^{-9}$

○ ⇒ billions of photons for every baryon!

Q: which complex nucleus will be the first to form?

BBN: Plot Summary*

to build nuclei, first step is



but $n_\gamma \gg n_B$: $\gamma + d \rightarrow n + p$ can occur

D destroyed as soon as made \rightarrow can't form nuclei
"deuterium bottleneck"

Q: when bottleneck overcome?

then nuclear reactions \rightarrow nuclei

∨ *simplified version

iClicker Poll: Cosmic Nucleosynthesis

Vote your conscience!

At $t = 1 \text{ sec}$ and $T \sim 1 \text{ MeV}$

Cosmic baryons are n and p in the ratio $n/p \approx 1/7$

When nuclear reactions start, what will be the main endproduct?

A hydrogen

B ^4He

C iron

D uranium

The Origin of Species

$kT \sim 0.1 \text{ MeV}$, $t \sim 100 \text{ s}$

now photons too feeble to destroy D
elements build rapidly

www: rxn network

flow \rightarrow most stable (tightest binding) = ${}^4\text{He}$
essentially all $n \rightarrow {}^4\text{He}$

BBN results:

- 24% of baryonic mass into helium-4
- leftover 76%: $p \rightarrow$ hydrogen
- small traces of unburnt D, ${}^3\text{He}$, ${}^7\text{Li}$:
amounts depend strongly on η

www: Schramm plot of BBN predictions

○ Q: why do you think D drops with η , i.e., with more baryons?

Q: why nothing heavier than lithium? why not Fe or U?

Nuclear Freeze

BBN makes nothing heavier than Li

the most abundant species are p and ${}^4\text{He}$

- combining them would make $pp = {}^2\text{He}$,
 $p{}^4\text{He} = {}^5\text{Li}$, or ${}^4\text{He}{}^4\text{He} = {}^8\text{Be}$
- but ${}^2\text{He}$ is *unstable*, as is any *mass 5 or 8* nucleus
 \Rightarrow can't make anything new with 2-body reactions

expanding, cooling U. \rightarrow reactions rarer, less energetic with time

- fewer chances to react at all
- Coulomb repulsion of nuclei \rightarrow shuts off nuke rxns at low T

\Rightarrow "freezeout of strong interactions"

iClicker Poll: The ASTR406 Diaspora

No class next week—Thanksgiving break

How far will you be from this spot one week from now?

- A < 3 miles
- B 3 to 30 miles
- C 30 to 300 miles
- D 300 to 3000 miles
- E > 3000 miles