

Astro 350
Lecture 34
Nov. 26, 2012

Announcements:

- **Homework 10** due Friday at start of class
- **Discussion 10** Wednesday

Before break: special topic—antimatter

Today: getting back in the flow

“running the movie backward” into the cosmic past

Q: ordinary matter behavior—cold to hot?

Q: implications for cosmic evolution?

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Q: how's this working for us?

Cold

Hot

atoms \rightarrow ions= $e +$ nuclei $\rightarrow n + p + e \rightarrow$ quarks \rightarrow ???

As matter gets *hotter*
collisions *more violent*
ground to smaller bits

Universe should follow reverse trend: *cooling matter*:

Hot

Cold

??? \rightarrow quarks $\rightarrow n + p + e \rightarrow$ nuclei, $e =$ plasma \rightarrow atoms

the story so far:

ionized \rightarrow *neutral* transition

also *opaque* \rightarrow *transparent*

releases “fossil” radiation: CMB

\rightarrow observed! has thermal spectrum! cosmic success story!

The Nuclear Force and Nuclear Structure

In nucleus:

Electrical repulsion between protons (like charges)
but stable: repulsion overcome by attractive force
nuclear force between p, n

nuclei are **quantum objects** governed by **nuclear force**
i.e., like “juiced” atoms, with stronger force

- still energy levels: ground, excited states
- stronger force \rightarrow much much larger binding energy BE
i.e., “sticking strength” = energy input to rip apart
- still unbound if given energy $> BE$

The Ties that Bind

Nuclear force + quantum levels
→ determines binding of each nucleus

www: chart of nuclides

weakest binding: deuterium $d = n + p$

strongest binding in a light nucleus (below carbon):



${}^4\text{He} = \alpha$ “alpha particle” tightly bound = *very stable*

consequently, *no stable nuclei at mass 5, 8*

“would rather be alphas!”

mass 5 decays → $\alpha + n$ or p

mass 8 decays → 2α

Cosmic Lingo: Fancy Name for Ordinary

neutrons and protons are not elementary

→ both made of 3 quarks

other 3-quark particles exist, but are unstable

→ decay to n or p

any particle made of 3 quarks: **baryon**

www: lists of known baryons

in practice: under most conditions, baryons = n or p

or things made of n and p : atoms, people, stars, galaxies

so: to cosmologists

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baryons = “made of atoms” “ordinary” matter \neq dark matter

Primordial Nucleosynthesis

Primordial nucleosynthesis, a.k.a. Big bang nucleosynthesis (BBN): production of lightest elements H, He, Li in the early U.

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

basic story:

transition from “ionized” free n and p to “neutral” bound nuclei, largely ${}^4\text{He}$

- o *Q: at high (but not ultrahigh) T , what are cosmic ingredients?*

Primordial Nucleosynthesis Initial Conditions

time $t < 1$ sec, temperature $T > 10^{10}$ K = 10 billion degrees

radiation

- “CMB” photons now gamma rays!
- also a sea of cosmic neutrinos!

radiation density huge!

→ $\rho_{\text{radiation}} \gg \rho_{\text{matter}}$ opposite of situation today
“radiation-dominated era”

matter

- ordinary (known) matter: only n , p , and e
collisions too violent for complex nuclei
and certainly much too violent for atoms
- dark matter: must be around, but weakly interacting

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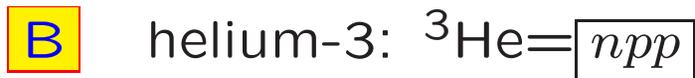
dark energy

must also be around, but if Λ -like, unimportant

iClicker Poll: Cosmic Fusion

primordial nuke: transition from free n , p
to bound nuclei, through a series (chain) of reactions

Starting from p and n only, which nucleus is made first?



Primordial Nucleosynthesis: Element Production

as the universe expands and cools,

n and p collisions weaker than $d = \boxed{np}$ binding

→ at last d can survive: $n + p \rightarrow d$

then can combine d with n , p , and d to make heavier things

www: reaction network

flow → most stable (tightest binding) = $\boxed{{}^4\text{He}}$

essentially all $n \rightarrow {}^4\text{He}$

BBN result: 25% of baryons in He, leftover $p \rightarrow \text{H}$ (75%)

small traces of unburnt D, ${}^3\text{He}$, ${}^7\text{Li}$:

amounts depend strongly on density of nuclei (“*baryons*”)

www: Schramm plot

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Nothing heavier than lithium made—why?

Nuclear Freeze

nothing heavier than Li:

- no stable nuclei with masses 5, 8
⇒ don't make anything from $p + {}^4\text{He}$ or ${}^4\text{He} + {}^4\text{He}$
- cooling universe → weaker collisions
but combining nuclei with large charge
requires large energy to overcome electrical repulsion

result: nuclear reactions shut down after lithium production
...and not even much of that!

“freezeout of strong interactions”

BBN Predictions: Executive Summary

Q: what are main predictions? qualitatively, quantitatively?

Q: where, when do they apply?

Q: what predictions “robust” /unavoidable?

Q: what would be involved in testing the predictions?

Q: what would it mean if BBN predictions confirmed? if not?

Q: what assumptions went into the calculation? (“Standard BBN”)

II Q: i.e., regarding dark matter? dark energy? neutrinos? additional elementary particles?