

Astro 596/496 PC

Lecture 23

March 12, 2010

Announcements:

- PF4 was due at noon
- PS4 out, due next Friday in class

Last time: began big bang nuke & particle cosmology

Big Bang Nucleosynthesis (BBN) expectations:

- BBN–CMB analogy: *unbound components* → *bound states*
- BBN epoch set by $T_{\text{BBN}} \sim B_{\text{nuke}} \sim 1 \text{ MeV}$
when $t(1\text{MeV}) \sim 1 \text{ sec}$
- BBN occurs deep into radiation-dominated Universe

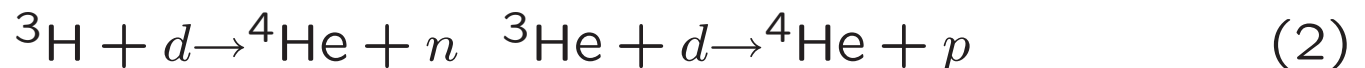
Element Synthesis

first step in building complex nuclei: $n + p \rightarrow d + \gamma$
but $d + \gamma \rightarrow n + p$ until $T \ll B(d)$; see Extras

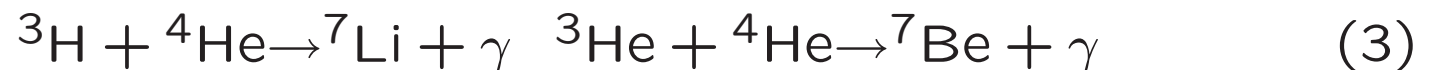
when photodissociation ineffective, $n + p \rightarrow d + \gamma$ fast
rapidly consumes all free n and builds d
which can be further processed to mass-3:



and to ${}^4\text{He}$



some of which can then make mass-7:



² Q: *what limits how long these reactions can occur?*

Q: *which determines which products are most abundant?*

BBN Reaction Flows

Binding Energy

nuclei are bound quantum structures, confined by nuclear forces among the “nucleons” n, p

can quantify degree of stability—i.e., resistance to destruction via binding energy: for nucleus with Z protons, N neutrons, $A = N + Z$ nucleons

$$\begin{aligned} B_A &= \text{energy of individual parts} - \text{energy of bound whole} \\ &= (Zm_p + Nm_n - m_A)c^2 \\ &> 0 \text{ if bound} \end{aligned}$$

ω note: generally B_A increases with A
but that's not the whole story on stability

binding shared among all A nucleons,
so binding **per nucleon** is B_A/A

nuclear stability \leftrightarrow high B_A/A

www: plot of B_A/A vs A

lowest binding/nucleon: $d!$

highest: ^{56}Fe , but among light elements, ^4He highest by far

Q: implications for BBN

Reaction flows: tightest binding favored

→ essentially all pathways flow to ${}^4\text{He}$

www: nuke network

almost all $n \rightarrow {}^4\text{He}$:

$$n({}^4\text{He})_{\text{after}} = 1/2 n(n)_{\text{before}}$$

$$Y_p = \frac{\rho({}^4\text{He})}{\rho_B} \simeq 2(X_n)_{\text{before}} \simeq 0.24 \quad (4)$$

⇒ $\sim 1/4$ of baryons into ${}^4\text{He}$, $3/4$ $p \rightarrow \text{H}$

result weakly (log) dependent on η

Robust prediction: large universal ${}^4\text{He}$ abundance

But $n \rightarrow {}^4\text{He}$ incomplete: as nuke rxns freeze, leave traces of:

- D
- ${}^3\text{He}$ (and ${}^3\text{H} \rightarrow {}^3\text{He}$)
- ${}^7\text{Li}$ (and ${}^7\text{Be} \rightarrow {}^7\text{Li}$)

abundances \leftrightarrow nuke freeze T

trace species D, ${}^3\text{He}$, ${}^7\text{Li}$: strong $n_B \propto \eta$ dependence

BBN theory predictions summarized in **“Schramm Plot”**

Lite Elt Abundances vs η

www: Schramm plot

o Note: no $A > 7$...so no C,O,Fe... Q: *why not?*

Why no elements $A > 7$?

1. Coulomb barrier

2. nuclear physics: “mass gaps”

no stable nuclei have masses $A = 5, 8$

→ with just p & ${}^4\text{He}$, can't overcome via 2-body rxns

need 3-body rxns (e.g., $3\alpha \rightarrow {}^{12}\text{C}$) to jump gaps

but ρ, T too low

Stars *do* jump this gap, but only because have higher density a long time compared to BBN

Testing BBN: Warmup

BBN Predictions: Lite Elements vs η

To test: measure abundances

Where and when do BBN abundances (Schramm plot) apply?

Look around the room—not 76% H, 24% He.

Is this a problem? Why not?

Solar system has metals not predicted by BBN

Is this a problem? Why not?

So how test BBN? What is the key issue?

∞

When does first non-BBN processing start?

Testing BBN: Lite Elements Observed

Prediction:

BBN Theory \rightarrow lite elements at $t \sim 3$ min, $z \sim 10^9$

Problem:

observe lite elements in astrophysical settings

typically $t \gtrsim 1$ Gyr, $z \lesssim \text{few}$

stellar processing alters abundances

Q: If measure abundances in a real astrophysical system, can you unambiguously tell that stars have polluted?

◦ *Q: How can we minimize (and measure) pollution level?*

stars not only alter light elements
but also make heavy element = “metals”
stellar cycling: metals \leftrightarrow time

Solution:

→ measure lite elts and **metals**
low metallicity → more primitive
in limit of metals → 0: primordial abundances!

look for regions with low metallicity → less processing

Deuterium

Two methods:

(1) use D/H_{\odot} , model $D - Z$ evolution:
model dependent **X** (old school)

(2) measure D/H at high z **YES**
“quasar absorption line systems”

QSO: for our purposes

high- z continuum source (lightbulb)

www: QSO spectrum

consider cloud, mostly H

- at $z < z_{\text{qso}}$, but still high z
e.g., $z_{\text{qso}} = 3.4$, $z_{\text{cloud}} = 3$
- H absorbs γ if energy tuned to levels
lowest: $n = 1 \rightarrow 2$, Ly α
- but Ly α in QSO frame
redshifted in cloud frame

What happens?

What about a cloud at yet lower z ?

intervening material seen via absorption

H: “Lyman- α forest”

Deuterium in High- z Absorption Systems

D energy levels \neq H: for Hydrogen-like atoms

$$E_n = -\frac{1}{n^2} \frac{1}{2} \alpha^2 \mu c^2 \quad (5)$$

where $\mu = \text{reduced mass} = m_e m_A / (m_e + m_A) \simeq m_e (1 - m_e / A m_p)$

$$\Rightarrow \Delta E = E_{n,D} - E_{n,H} \approx +1/2 m_e / m_p E_{n,H}$$

$$\Rightarrow \Delta z_D = \Delta \lambda / \lambda = -1/2 m_e / m_p$$

$c \Delta z_D = -82 \text{ km/s}$ (blueward) \rightarrow look for “thumbprint”

www: O’Meara D spectrum

What about stellar processing?

★ stars *destroy* D *before* H-burning! (pre-MS)

★ nonstellar astrophysical (Galactic) sources negligible

Epstein, Lattimer & Schramm 1977; updated in Prodanović & BDF 03)

\Rightarrow **BBN is only important D nucleosynthesis source**

\rightarrow *D(t) only decreases*

ω chem evol models: versus Z metallicity: $D \sim e^{-Z/Z_\odot} D_p$

Quasar absorbers: $Z \sim 10^{-2} Z_\odot \rightarrow$ expect $D_{\text{QSOALS}} \approx D_p$

Deuterium Results

For the 5 best systems
(clean D, well-determined H)

$$\left(\frac{\text{D}}{\text{H}}\right)_{\text{QSOALS}} = \left(\frac{\text{D}}{\text{H}}\right)_p = (2.78 \pm 0.29) \times 10^{-5} \quad (6)$$

For the top 2 (multiple transitions)

$$\left(\frac{\text{D}}{\text{H}}\right)_{\text{QSOALS}} = \left(\frac{\text{D}}{\text{H}}\right)_p = (2.49 \pm 0.18) \times 10^{-5} \quad (7)$$

significant scatter in high- z D/H:

unknown **systematics?**

Sloan Survey \rightarrow many QSO's \rightarrow tighter D/H

very promising cosmological probe!

Assessing BBN: Theory vs Observations

(Standard) BBN theory has a free parameter: $n_B/n_\gamma = \eta$
different lite element predictions for different η

*Q: so how to compare with observations?
is it even possible to test the theory?*

*What uncertainties are there in the **standard** theory?*

What uncertainties are there in the obs?

How can we account for these uncertainties when comparing theory and observations?

*If theory & obs **agree**, what would this mean:
qualitatively? quantitatively?*

*If they **disagree**, what would this mean?*

Assessing BBN: Theory vs Observations

BBN Theory:

all elements dependent on η

the only free parameter in standard (“vanilla”) calculation

⇒ for each η value, 4 lite elements: “overconstrained”

a priori η is unknown, but homogeneous U → one value today

www: Schramm plot

Lite Elt Observations:

1. measure *one* element: find η

2. measure *more* elements: each picks an η

⇒ do they agree? test of BBN & of cosmology!

Assessing BBN: Procedure

Combine observations (+ errors!)

statistical errors only:

- ^4He and D agree
- ^7Li likes lower η

include systematics:

Concordance!

www: Schramm plot w/ data boxes

lite elts fit if η in range

$$3.4 \times 10^{-10} \leq \eta \leq 6.9 \times 10^{-10} \quad (8)$$

Have extrapolated hot big bang to $t \sim 1$ s

predict lite elts \rightarrow agrees w/ theory

big bang model works back to $t \sim 1$ s, $z \sim 10^{10}$!

lends confidence to extrapolation $t < 1$ s

Directors' Cut Extras

The Short but Interesting Life of a Neutron

(1) at $T > T_f$, $t \sim 1$ s

$n \leftrightarrow p$ rapid

maintain $n/p = e^{-\Delta m/T}$

(2) at $T = T_f$,

fix $n/p = e^{-\Delta m/T_f} \simeq 1/6$

so n “mass fraction” is

$$X_n = \frac{\rho_n}{\rho_B} = \frac{m_n n}{m_n n + m_p p} \approx \frac{n}{n + p} \approx 1/7 \quad (9)$$

(3) until nuclei form,

free n decay: $\dot{n} = -n/\tau_n$, with $\tau_n = 885.7 \pm 0.8$ s

then mass fraction drops as

$$X_n = X_{n,i} e^{-\Delta t/\tau} \quad (10)$$

Q: why take this simple form?

Nuclear Astrophysics: Overcoming the Coulomb Barrier

to go from n, p to ${}^4\text{He}$ requires
at least one nuclear reactions between charged nuclei
so must contend with Coulomb repulsion

$$V_C(r) = \frac{Z_1 Z_2 e^2}{r} \sim 1 Z_1 Z_2 \text{ MeV} \left(\frac{1 \text{ fm}}{r} \right) \quad (11)$$

but nuclear force, while strong, is short-ranged: $r_{\text{nuke}} \sim 1 \text{ fm}$
→ particles apparently need $mv^2/2 \sim |V_C| \sim 1 \text{ MeV}$ to fuse
but $mv^2/2 \sim T \ll 1 \text{ MeV}$, and higher energies exponentially
suppressed

Q: how can we overcome this barrier?

Quantum Mechanics to the Rescue

Quantum mechanics → tunneling

Penetration probability

$$P \propto e^{-2\pi Z_1 Z_2 e^2 / \hbar v} = e^{-bE^{-1/2}} \quad (12)$$

so $P \neq 0$ even when $E \ll |V_C|$

→ tunnel under barrier, then react

note: not as serious an issue in BBN as it is in most stars

e.g., the sun