

Astro 507
Lecture 24
March 17, 2014

Announcements:

- **PS4: due Friday or upload by next Monday**
- Office Hours: Thurs. 3:10-4pm or by appt

Today is a great day for Cosmology...

story: MST and COBE

BICEP2 Announcement

$$r = 0.20^{+0.07}_{-0.05}$$

$r > 0$ at 7σ

Detection of Cosmic Gravity Wave Background

CMB polarization experiment BICEP2

finds “*B*-mode” (curl-type) primordial polarization
consistent with gravity wave (tensor) perturbations
laid down during cosmic inflation

along with ordinary mass-energy (scalar) perturbations
tensor-to-scalar ratio

$$r = \frac{\text{tensor}}{\text{scalar}} = 0.20^{+0.07}_{-0.05}$$

probes energy scale of cosmic inflation $r = \varepsilon_{\text{inf}} / (3.3 \times 10^{16} \text{ GeV})^4$

$$P(\text{Nobel} \mid \text{no unplugged cables}) = 1$$

ω A landmark result! Much more after spring break!

Last time: big bang nuke – theory

initial condition for element synthesis: n/p **ratio**

Q: what sets n/p at $T \gtrsim 1$ MeV?

Q: what sets cosmic expansion rate?

Q: what if there were “extra” neutrino species in equilibrium?

Q: how does n/p evolve vs T ?

Weak Freezeout Temperature

Weak interactions freeze when $H = \Gamma_{\text{weak}}$, i.e.,

$$\sqrt{G_N} T^2 \sim \sigma_0 m_e^{-2} T^5 \quad (1)$$

$$\Rightarrow T_{\text{weak freeze}} \sim \frac{(G_N)^{1/6}}{(\sigma_0/m_e^2)^{1/3}} \sim \mathbf{1 \text{ MeV}} \quad (2)$$

gravity & weak interactions conspire to give $T_f \sim m_e \sim B_{\text{nuke}}$!

for experts: note that $G_N = 1/M_{\text{Planck}}^2$, so

$$\frac{T^2}{M_{\text{Pl}}} \sim \alpha_{\text{weak}} \frac{T^5}{M_W^2} \quad (3)$$

$$\Rightarrow T_{\text{freeze}} \sim \left(\frac{M_W}{M_{\text{Pl}}} \right)^{1/3} M_W \sim 1 \text{ MeV} \quad (4)$$

σ freeze at nuclear scale, but by accident!

Q: what happens to n, p then? what else is going on?

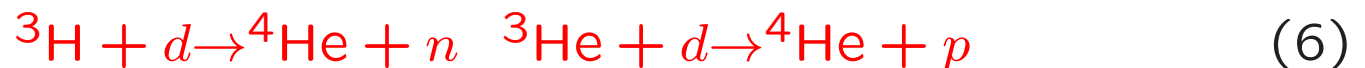
Element Synthesis

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:



° 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

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

∨ 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 $n \rightarrow {}^4\text{He}$:

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

$$Y_p = \frac{\rho({}^4\text{He})}{\rho_B} \simeq 2(X_n)_{\text{before}} \simeq 0.24 \quad (8)$$

⇒ $\sim 1/4$ 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

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