V. Big Bang Nucleosynthesis (BBN)

To test/constrain the big bang theory at $z > 10^7$, we must turn to nucleosynthesis, "archeology" based on element abundances

The Basic Physics

After electron-positron annihilation at $t \sim 1$ second, the constituents of the universe are photons, neutrinos, and (at an abundance smaller by a factor $\sim 10^9$) protons, neutrons, and electrons.

The energy density is dominated by the photons and neutrinos. The relation between the age of the universe and the photon temperature is determined by the radiation-dominated Friedmann equation, which yields:

$$t(T) \approx 1.32 \left(\frac{kT}{1\text{ MeV}}\right)^{-2} \text{ s.}$$

(as shown in PS 3 and PS 4).

While interconversion between neutrons and protons (by weak interactions involving neutrinos) is fast compared to the expansion time, the neutron-to-proton ratio is pinned to its thermal equilibrium value

$$\frac{n}{p} = e^{-Q/kT}, \quad Q \equiv (m_n - m_p)c^2 = 1.2934\,\text{MeV}.$$

The conversion reactions become slow compared to the expansion at $t \sim 3$ seconds, $kT \sim 0.7$ MeV.

The neutron-to-proton ratio "freezes in" at $n/p \sim 1/6$.

Synthesis of elements heavier than hydrogen has to start with deuterium formation ($n+p \rightarrow D + \gamma$).

The binding energy of deuterium is $B_D = 2.22$MeV.

Naively one expects deuterium synthesis to begin when the temperature falls to $kT \sim B_D$. However, the baryon-to-photon ratio is $\eta \sim 5 \times 10^{-10}$, so the exponential tail of the blackbody distribution can still dissociate deuterium even when kT is significantly below B_D.

Synthesis of deuterium actually begins when $kT \sim B_D / -\ln\eta \sim 0.1$ MeV, at time $t \sim$2 minutes.

The decay time for free neutrons is ~ 900 sec, so in two minutes a small but non-negligible fraction of the neutrons left over from "freeze-out" have decayed.

The neutron-to-proton ratio at the time of deuterium synthesis is $n/p \sim 1/7$.

The reaction rate for $n + p \to D + \gamma$ is fast, so when the temperature falls below 0.1 MeV, all neutrons are quickly processed into deuterium.

The reactions that process D into ^{4}He are also fast, and to first order all neutrons go into ^{4}He .

A small fraction ($\sim 10^{-5}$) of D "escapes" and is never processed into heavier nuclei.

A comparable fraction is processed into ^{3}He but not into ^{4}He .

A small amount ($\sim 10^{-10}$) of ^{7}Li is produced.

There are no stable elements of atomic number 5 or 8.

Starting with protons and neutrons, there is no way to bridge the gap at atomic number 8 to build heavier nuclei.

Stars do it by the "triple-α" reaction: ^{4}He + ^{4}He + ^{4}He $\longrightarrow ^{12}$C*, but this requires high temperature *and* density.

Consequence: only light elements are made in the early universe. All elements heavier than ^{7}Li are made in stars.

The "standard" nucleosynthesis calculation

Assume particle content of the standard particle physics model.

Assume GR, homogeneity, use measured interaction rates.

Integrate reaction network in cosmological background, predict abundances.

Primary free parameter is baryon-to-photon ratio η, which is proportional to $\Omega_B h^2$.

Number of neutrino species N_ν can be treated as a second free parameter.

$N_\nu > 3$ can represent actual additional neutrino species or some other form of energy density that affects the cosmic expansion rate at early times.

^{4}He production depends mainly on weak interaction cross sections vs. expansion rate.

Weakly sensitive to η, thus a robust prediction of the standard model (at the 10% level).

Some dependence on η because of free neutron decay.

Quite sensitive to N_ν (Steigman, Schramm, & Gunn 1977), thus a probe of the relativistic degrees of freedom present at $t \sim 1$ sec.

Other light element abundances depend on fusion rates rates vs. expansion rate, hence sensitive to density.

D and ^{3}He result from "incomplete" processing to ^{4}He $\Longrightarrow$abundances decrease as η increases.

^{7}Li vs. η has minimum at $\eta \sim 2.5 \times 10^{-10}$ because of competition between production and destruction mechanisms.

BBN in practice

Goals:

- test the standard model — is there a value of η consistent with all of the inferred abundances?
- constrain the model's free parameters: η and N_ν
- test alternatives, e.g., decaying particles, time-varying gravitational constant, inhomogeneities present at nucleosynthesis, extra energy components

While the calculation itself is improved as inputs become better known, most of the art (and controversy) has to do with inferring primordial abundances from observations.

Deuterium

Cleanest case, because seems impossible to make anywhere other than the big bang (because so weakly bound).

Destroyed in stars $\Longrightarrow$observed abundance is lower limit to primordial abundance $\longrightarrow$upper limit on η

Solar system and ISM estimates give D/H$\sim 1 - 2 \times 10^{-5}$.

Estimates from high-redshift QSO absorbers give D/H$= 2 - 4 \times 10^{-5}$. A weighted average of these is generally taken as the best current estimate of primordial D/H.

Yields $\Omega_b h^2 = 0.022 \pm 0.002$, $\eta = 6.1^{+0.7}_{-0.5} \times 10^{-10}$.

CMB anisotropies now allow an independent estimate of $\Omega_b h^2$ based on completely different physics.

BBN and CMB results are consistent, an important piece of evidence for the validity of the standard model (of both BBN and CMB anisotropy).

The estimated value is substantially below the estimated value of Ω_m (by a factor $\sim 6 - 8$) $\longrightarrow$dark matter is not made of baryons.

Helium-4

Can be measured accurately.

The big question: how accurately? Need to extrapolate to zero metal abundance, correct for an assortment of systematics.

Estimates of primordial mass fraction range from $Y_P \sim 0.23 - 0.25$, though quoted error bars have traditionally been much smaller.

^{4}He /H is a weakly increasing function of η, and values of Y_P at low end of above range conflict with η implied by D/H.

A compelling argument for low Y_P would produce an interesting conflict with the standard model.

The most obvious changes to the physics (e.g., adding extra degrees of freedom that increase the expansion rate in the early universe) increase rather than decrease the predicted Y_P.

Some current estimates of the primordial ^{4}He abundance agree well with the standard BBN prediction (given the value of η implied by deuterium), and the general attitude today seems to be that the systematic uncertainties are at least large enough to encompass this value.

Helium-3 and Lithium-7

Agree with standard model at order-of-magnitude level, providing additional low precision evidence for it.

But ^{3}He and ^{7}Li can both be produced and destroyed in stars.

Inferred primordial ^{3}He abundance depends on chemical evolution modeling, stellar yields.

Inferred primordial ^{7}Li abundance depends on stellar astrophysics, especially rotational mixing mechanisms that might allow destruction in metal poor stars (work by Pinsonneault, Deliyannis, and others).

Probably can't use factor of few discrepancies as cosmological tests, because of uncertainties in chemical evolution and stellar astrophysics.

Similarly, can't use ^{3}He and ^{7}Li to confirm standard model at high precision.

BBN Bottom Line

$\sim 25\%$ ^{4}He is a key piece of evidence for the Big Bang model, at $\sim 10\%$ precision.

D is the "baryometer"; best estimates of D/H imply $\Omega_b h^2 \approx 0.02$.

Consistency with CMB measurements of $\Omega_b h^2 \Longrightarrow$important consistency check of standard model via independent methods.

^{3}He and ^{7}Li give two additional, low precision (factor ~ 10) tests.

Departures from GR, standard particle content at $t \sim 1$ sec – 3 mins are tightly constrained.

Improved understanding of "astrophysical" systematics on primordial abundance measurements could yet yield interesting conflicts, but necessary improvements difficult to achieve.

Can instead use "known" primordial abundances and measurements to test astrophysical creation/destruction mechanisms, chemical evolution models.