MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Physics Department

Physics 8.286: The Early Universe — December 1, 2009

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Lecture Notes 9

BIG BANG NUCLEOSYNTHESIS

STATUS:

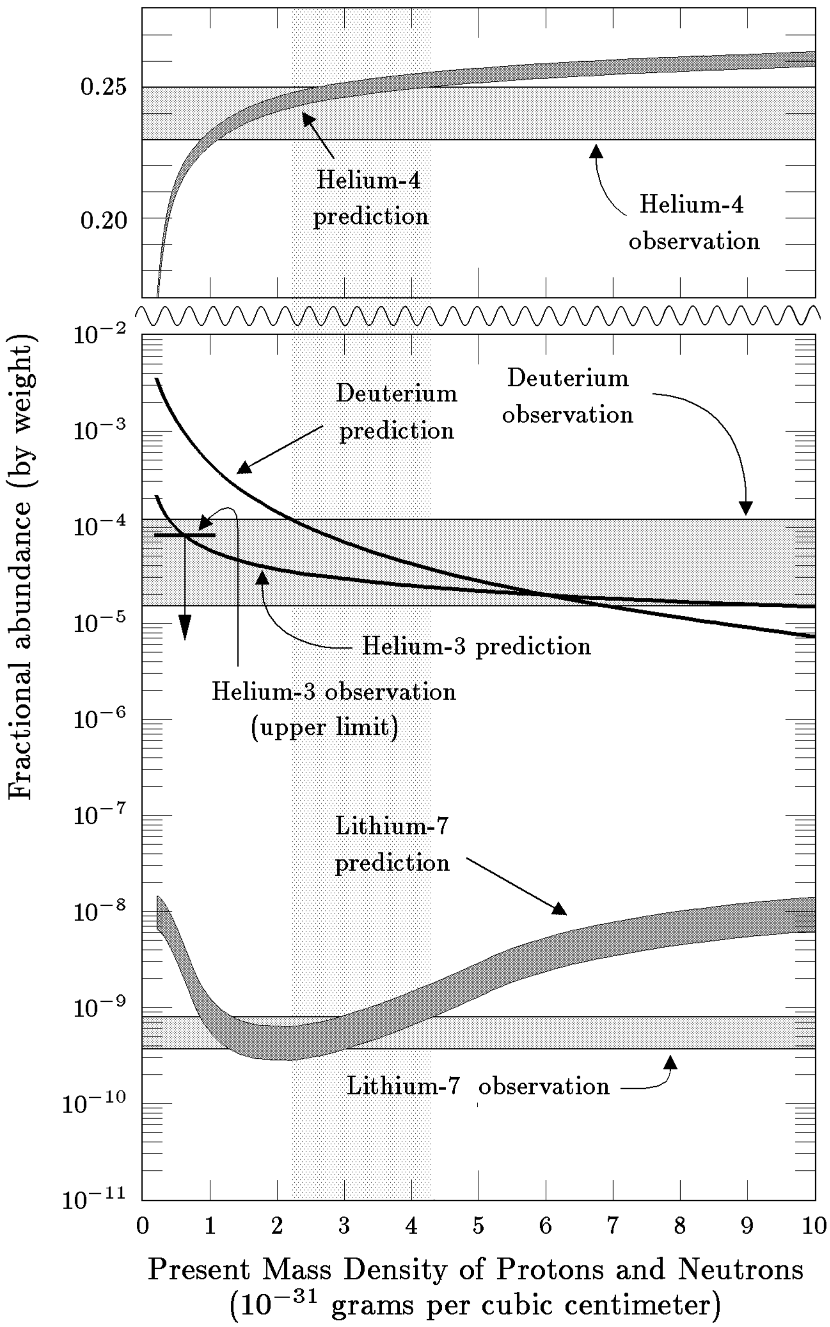
This set of lecture notes is being made available for your personal curiousity only. I have decided that for this year I will not try to cover big bang nucleosynthesis beyond the level of Weinberg's *The First Three Minutes* and Ryden's Chapter 10, both of which you are expected to have read. In previous years these notes on served as an addendum to the other readings, but they were never intended to be self-contained.

INTRODUCTION:

There will not be any detailed lecture notes on big-bang nucleosynthesis, but in class we will go over the subject, following the outline of Chapter 5, "The First Three Minutes," of Weinberg's book, also called *The First Three Minutes*. In lecture I will try to give some of the equations that Weinberg is using. These notes will be restricted to some relevant graphs.

The numbers that Weinberg gives come originally from a 1966 calculation of P.J.E. Peebles, published in the *Astrophysical Journal*, vol. **146**, p. 542 (1966). Shown below are some more recent results. One significant difference is that the Peebles calculation assumes two species of neutrinos (the ν_e and ν_μ), while we now believe that there are at least three species (with the addition of the ν_τ).

The graph on the next page shows the predictions and observations for the quantities of the light chemical elements that were produced in the big bang. The predictions (but not the observations) depend on the present mass density of protons and neutrons in the universe. Included on the graph are those nuclei believed to have been produced primarily in the big bang: helium-4 (^{4}He, 2 protons and 2 neutrons), deuterium (D or ^{2}H, 1 proton and 1 neutron), helium-3 (^{3}He, 2 protons and 1 neutron), and lithium-7 (^{7}Li, 3 protons and 4 neutrons). The abundances are expressed as a fraction of the weight of all known baryonic matter in the universe. By "baryonic matter," we mean matter whose mass is dominated by protons and neutrons (baryons), as is the case for all ordinary atoms. The fractions do not add to one, because hydrogen is not shown; the big bang production of elements heavier than lithium is believed to be totally negligible. The predictions for helium-4 and lithium-7 are shown as thick lines, indicating the uncertainty caused by the estimated error in the measured reactions rates that are used in the calculation. The


0.25
0.20
Helium-4 prediction
Helium-4 observation
Fractional abundance (by weight)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Deuterium prediction
Deuterium observation
Helium-3 prediction
Helium-3 observation (upper limit)
Lithium-7 prediction
Lithium-7 observation
0 1 2 3 4 5 6 7 8 9 10
Present Mass Density of Protons and Neutrons
(10^{-31} grams per cubic centimeter)

uncertainties in the deuterium and helium-3 predictions are not shown, since they are negligible compared to the uncertainty in the observations. The observed abundances of helium-4, deuterium, and lithium-7 are shown as horizontal shaded bars, with a thickness that indicates the uncertainty in these observations. Observations of helium-3 produce only an upper limit on the abundance produced by the big bang, as indicated by the short horizontal line, with a downward arrow extending from it. For the range of densities indicated by the lightly shaded vertical bar, every prediction is in agreement with the corresponding observation.

This agreement is taken to be a significant piece of evidence in favor of the big bang picture. It also provides a strong bound on the density of baryons in the universe, which must be much less than the critical density. Recall from Lecture Notes 4 that for $H^{-1} = 2 \times 10^{10}$ yr (essentially the lowest value of the Hubble constant consistent with observation), the critical density is $\rho_c = 3H^2/(8\pi G) = 4.5 \times 10^{-30}\ \mathrm{gm/cm^3}$. Since the nucleosynthesis graph implies that $\rho_{\mathrm{Baryon}} < 4.5 \times 10^{-31}\ \mathrm{gm/cm^3}$, one concludes that $\Omega_{\mathrm{Baryon}} \equiv \rho_{\mathrm{Baryon}}/\rho_c < 0.1$.

The helium-4 data on this graph were taken from Terry P. Walker, "BBN predictions for ^{4}He," in *Relativistic Astrophysics and Particle Cosmology*, Proceedings of the Texas/PASCOS 1992 Meeting (Carl W. Akerlof and Mark A. Srednicki, eds., Annals of the New York Academy of Sciences, Vol. 688, The New York Academy of Sciences, NY, 1993). The other data were adapted from *The Early Universe*, by Edward W. Kolb and Michael S. Turner (Addison-Wesley, Redwood City, California, 1990, pp. 87-113). The graph itself appears in my own popular-level book, *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins.*

The graph shown here is analogous to Fig. 5.5 on p. 88 of Rowan-Robinson's book, *Cosmology* (Third Edition). Note, however, that the ^{4}He box on Rowan-Robinson's graph was intended to refer to a separate vertical scale that was to be shown at the right of the graph, but which was somehow omitted. The abundance of ^{4}He by weight is about 25%, so it has to be shown on a separate scale from the other constituents. Rowan-Robinson states the inferred density of baryonic matter as

$$\Omega_{b,0} = 0.05 \pm 0.01(H_0/50\ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}})^{-2}\ ,$$

which corresponds to the statement that

$$\rho_b = (2.3 \pm 0.2) \times 10^{-31}\ \mathrm{g/cm^3}\ .$$

It is largely the nucleosynthesis limit on Ω that has fueled the hypothesis of non-baryonic dark matter. Neutrinos, for example, could easily have enough mass to give $\Omega = 1$, since it is only necessary for a single species to have a mass of about 30 eV. The limits on the masses of the neutrinos, according to the 1998

Particle Properties Data Booklet,* are $m(\nu_e) < 10$–15 eV, $m(\nu_\mu) < 0.17$ MeV (90% confidence), and $m(\nu_\tau) < 18.2$ MeV (95% confidence). (The Data Booklet, however, contains the following remark concerning the limit on $m(\nu_e)$: "Unexplained effects have resulted in significantly negative m^2 in the new, precise tritium beta decay experiments. It is felt that a real netutrino mass as large as 10–15 eV would cause observable spectral distortions even in the presence of the end-point count excesses.") Nonetheless, people who worry about galaxy formation rule out the possibility of a universe dominated by neutrinos. The problem is that the neutrinos, being very light, "free stream" over large distances during the early history of the universe. This free-streaming erases most nonuniformities, up to the scale of galactic superclusters. It is then impossible for the universe to develop the rich structure that we see on smaller scales. Better candidates are the axion, the photino, or the gravitino. The axion is a hypothetical particle that was introduced to resolve a fine-tuning problem involving the symmetries of the strong interactions. Without the axion, there is a dimensionless parameter, in the form of an angle, that must have a value less than 10^{-9} radians to be consistent with the observation that the strong interactions possess a symmetry called CP (charge conjugation times parity). (Specifically, this bound is required to explain the observational limit on the electric dipole moment of the neutron.) Many particle physicists find it implausible that such fine-tuning should occur without explanation, so the need for such fine-tuning is regarded as a suggestion that the theory is incomplete. With the addition of the hypothetical axion, the fine-tuning is no longer necessary. The photino is a hypothetical particle that would be related to the photon by a proposed symmetry called supersymmetry. Similarly, the gravitino is a hypothetical particle that would be related to the graviton, the carrier of the gravitational field.

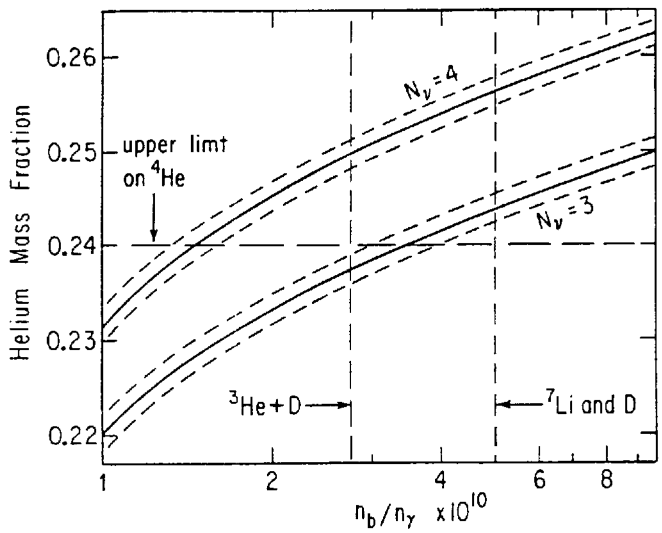
Once bounds are set on the baryon density, one can look again at the helium production to see how much one can determine about the number of neutrinos. The graph on the next page shows how the predicted abundance of helium depends on the number of neutrino species and on the density baryons.

This graph was taken from "Big Bang Nucleosynthesis: The Standard Model and Alternatives," by David N. Schramm, published in the proceedings of Nobel Symposium No. 79, *The Birth and Evolution of Our Universe*, Gräftåvallen, Sweden, June 11-16, 1990 (*Physica Scripta,* vol. **T36**, pp. 22-29 (1991)).

Clearly $N_\nu = 3$ (N_ν = number of neutrino species) is the best fit, and it is precisely in accord with particle physics expectations. From this data Schramm concludes that the cosmological data imply that $N_\nu < 3.4$. For comparison, recent

* C. Caso et al. (Particle Data Group), *European Physical Journal* **C3,** 1 (1998), http://pdg.lbl.gov/1998/contents_tables.html.

experimental data on the decay of the Z^0 particle from LEP (the Large Electron-Positron collider at CERN) and SLC (the Stanford Linear Collider), as summarized in the 1998 Particle Properties Data Booklet, indicate that $N_\nu = 2.994 \pm 0.012$. To be fair, however, we should remember that LEP and cosmology are sensitive to different things. Cosmology counts all relativistic particles with masses less than about 10 MeV, while LEP and SLC count any weakly interacting neutral particle with mass less than about 45 GeV, provided that the Z^0 particle can decay into it.



Helium mass fraction versus the cosmological baryon-to-photon ratio. The left vertical line is the lower bound on this ratio from considerations of ^{3}He and D (see Yang, Schramm, Steigman, and Rood, *Astrophysical Journal* **227**, 697 (1979)). (Using ^{7}Li as a constraint would move the line only slightly to the left.) The horizontal line is the current upper bound of 0.24. The width of the lines for $N_\nu = 3$ and 4 is due to $t_n = 890 \pm 4$ sec (where t_n = mean neutron lifetime). Note that $N_\nu = 4$ appears to be excluded barring a systematic error upward in Y_p (the primordial helium abundance), which would be contrary to current systematic trends.