NEUTRINO PHYSICS AND THE PRIMORDIAL ELEMENTAL ABUNDANCES

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Limits can be placed on nonstandard neutrino physics when big bang nucleosynthesis (BBN) calculations employing standard neutrino physics agree with the observationally inferred primordial abundances of deuterium (D), $^3$He, $^4$He, and $^7$Li. These constraints depend most sensitively on the abundances of D and $^4$He. New observational determinations of the primordial D and/or $^4$He abundances could force revisions in BBN constraints on nonstandard neutrino physics.

1 Big Bang Nucleosynthesis and Neutrino Physics

The primordial elemental abundances depend on $\langle n/p \rangle_{\text{WFO}}$, the ratio of neutrons to protons at “weak freeze-out.” Weak freeze-out occurs when the expansion rate of the universe exceeds the rates of the reactions that interconvert neutrons and protons. The $^4$He abundance depends strongly on $\langle n/p \rangle_{\text{WFO}}$, while the abundances of D, $^3$He, and $^7$Li have a weaker dependence on this quantity.

The expansion rate can be parametrized by an “effective number of neutrinos,” $N_\nu$, which represents the relativistic degrees of freedom in addition to those contributed by photons and electron-positron pairs. $N_\nu$ also indirectly parametrizes any phenomenon that affects the $^4$He abundance by altering $\langle n/p \rangle_{\text{WFO}}$ (even though the effect may be on the $n \leftrightarrow p$ interconversion rates rather than through the expansion rate).

The primordial elemental abundances also depend on the baryon-to-photon ratio $\eta$. The $^4$He yield depends somewhat weakly on $\eta$, while the yields of the other light elements have a strong dependence on $\eta$. The strength of the dependence of the primordial elemental abundance yields on $N_\nu$ and $\eta$ can be visualized from the figures in Refs. 11, 12.

Many investigators over the years have studied the effects of nonstandard neutrino physics on BBN. These have included, for example, the number of neutrinos; neutrino mixing with sterile neutrinos; adding a mass, lifetime, and various decay products to the tau neutrino; and net cosmic lepton number, i.e. endowing the neutrino seas with chemical potentials.

Standard big bang nucleosynthesis calculations assume three massless neutrinos with zero net cosmic lepton number and no other relativistic degrees of freedom. When a range of baryon-to-photon ratio $\eta$ is obtained for which the
calculated primordial elemental abundances agree with those inferred from observations. Nonstandard neutrino physics can be constrained. In the absence of a concordant range of $\eta$, one can either reassess the observational errors or claim nonstandard neutrino physics (or some other physics) as a solution to bring the calculated abundances into line with the primordial abundances inferred from observations. It should be noted that nonstandard neutrino physics primarily affects $(n/p)_{\text{WFO}}$, and could therefore change $^4\text{He}$ rather easily. But more extreme neutrino physics would have to be introduced to significantly adjust the D, $^3\text{He}$, and $^7\text{Li}$ abundances, and then fine tuning would be required to avoid unacceptable changes in the calculated $^4\text{He}$ abundance yield.

2 The Observational Situation

The observationally inferred abundances of the light elements produced in BBN have continued to be the subject of discussion and observational effort. Of particular interest are deuterium (D), which provides the most sensitive measure of the baryon density; and $^4\text{He}$, which constrains $N_\nu$. Also of interest is the primordial abundance of $^7\text{Li}$, which provides a cross-check to the range of $\eta$ determined by D and $^4\text{He}$. The primordial abundance of $^3\text{He}$ is less useful for the purpose of determining $\eta$ due to its complicated history of chemical and galactic evolution.

While inferences of the primordial D/H ratio formerly were based on “local” measurements in the solar system and interstellar medium, observations of quasar absorption systems (QAS) have recently provided determinations of D/H in a much more pristine environment. Initially there was a strong dichotomy in inferences of D/H, with claimed values differing by an order of magnitude. However, at this conference the situation appears to be coming to a resolution, with the low value of D/H now favored. It is also worth pointing out that the higher baryon density implied by low D/H is advantageous from other cosmological/astrophysical considerations.

The inferred primordial abundance of $^4\text{He}$ has also been the subject of recent action. A commonly accepted range of the $^4\text{He}$ abundance does not provide a value of a concordant with that inferred from the low values of D/H inferred from QAS, for $N_\nu=3$. (As it turns out, the primordial abundance of $^7\text{Li}$ inferred from the “Spite plateau” does not agree with low D/H for $N_\nu=3$ either.) One group of observers has claimed a higher range of $^4\text{He}$ abundance, but this analysis may have some difficulties. It is not unreasonable, however, that systematic errors in the determinations of $^4\text{He}$ and $^7\text{Li}$ could allow for concordance at low D/H for $N_\nu=3$. 

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3 An Example: Mixing with Sterile Neutrinos

Neutrino mixing with “sterile” (SU(2) singlet) neutrinos during the epoch of BBN, which has been studied by many authors, provides an example of how constraints on nonstandard neutrino physics depend on the primordial abundances of D and $^4$He. Two kinds of mixing with sterile neutrinos have been suggested to solve neutrino puzzles: $\nu_e \leftrightarrow \nu_s$ for the solar neutrino problem, and $\nu_\mu \leftrightarrow \nu_s$ for the atmospheric neutrino problem.

Neutrino mixing with steriles does two things to increase primordial $^4$He: first, it effectively brings another degree of freedom into thermal contact; and second, it depletes the $\nu_e$ population, reducing the $n \leftrightarrow p$ interconversion rates. The demand that $^4$He not be overproduced places limits on mixing with steriles. The constraint comes from upper bounds on D/H and the $^4$He mass fraction. This is because the largest D/H (and hence the minimum allowed $\eta$) allows the largest $N_\nu$ for a given $^4$He abundance.

In constraining mixing with steriles, previous studies assumed, for example, $\eta > 2.8 \times 10^{-10}$ based on estimates of primordial (D+$^3$He)/H derived from “local” measurements. Until this conference, it appeared that discordant deuterium determinations could be indicating a minimum value of $\eta$ that was either lower or higher than this. As an example of the consequences of a possible change in the minimum value of $\eta$, Cardall and Fuller published a calculation in which the $\nu_\mu \leftrightarrow \nu_s$ solution to the atmospheric neutrino problem was assumed, and the resultant $^4$He mass fraction was plotted as a function of D/H. For the purported “high” values of D/H, it appeared that the $\nu_\mu \leftrightarrow \nu_s$ solution to the atmospheric neutrino problem might be allowed. For low D/H, this mixing is even more strongly ruled out.

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