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Big-Bang Nucleosynthesis (Cont'd):

Having predictions for primordial abundance of light elements, we have to compare them with observations. This will allows us to check the consistency of the big-bang model. The three important parameters that enter calculations of light element abundances are: τ_n (neutron lifetime), η (baryon to photon ratio), and N_ν^{eff} (the effective number of neutrinos). τ_n is very precisely measured by laboratory experiments, and hence can be used as an input parameter. N_ν^{eff} is predicted to be 3.04 in the SM, but its value can be different from this in the case of new physics beyond the SM. The main free parameter is η. Therefore, observations can be used to infer η and see whether all measured abundances conform with the predictions for some value of η.

A difficulty that arises is that measured value of the light element abundances are made "here" and "now," while the primordial abundances are a result of physics happened "there" and "then". Astrophysical processes can affect the abundance of light elements. For example, D is destroyed by stellar evolution processes, while ^4He is made by stars. As a result, we do not really measure the primordial abundances by using observations, but we rather derive them. The point is how to make this derivation as accurate as possible. It is clear that observations should be made by using systems that have been affected least by processes like star formation. Since elements heavier than ^4He (called "metals" in astrophysics) are made in stars, we should use observations of systems that have very low metallicities. This ensures that these systems are affected least by star formation, and hence measurements of the light element abundances are good representative of their primordial values.

Here we briefly discuss observation to derive the primordial abundance of D, ^4He, ^3He, ^7Li:

(1) D: The primordial abundance of D is inferred from Lyman-α absorption (in the UV part of the spectrum) in high-redshift low-metallicity quasar absorption systems. The Lyman-α transition is between the ground state ($n=1$) and the first excited level ($n=2$), which occurs by absorbing a photon with the following wavelength:

$$\frac{1}{\lambda} = R_M \left(\frac{1}{1^2} - \frac{1}{2^2}\right) \qquad R_M = \frac{R_\infty}{1 + \frac{m_e}{M}}$$

Here R_∞ is the Rydberg's constant, and M is the nucleus mass. R_∞ is given by:

$$R_\infty = \frac{m_e c^4}{8 \varepsilon_0^2 h^3 c} = 1.0973 \times 10^7 \ m^{-1}$$

The absorption line for D is isotopically shifted relative to that for H:

$$R_D - R_H \simeq R_\infty \frac{m_e}{2m_p}$$

Averaging over 7 most precise observations of quazar systems (having a redshift $z \sim 3$) gives the following derived value (when both statistical and systematic errors are included):

$$\frac{D}{H} = (2.82 \pm 0.21) \times 10^{-5} \qquad (\mathrm{I})$$

(2) ^4He: The primordial abundance of ^4He is inferred from emission lines in the extragalactic HII regions. The HII regions are hot enough to ionize the neutral (Hydrogen) atoms. The most metal poor of these regions are found in dwarf galaxies. By extrapolating the measured value of ^4He in these systems to zero metallicity, one finds:

$$Y_p = 0.249 \pm 0.009 \qquad (\mathrm{II})$$

The error in Y_p is mostly systematics. There are other extrapolations, giving different values of Y_p, that depend on which set of emissivities for ionized ^4He are used. They are, however, in agreement with that in Eq. (II) within the margin of error.

(3): ^3He; The primordial abundance of ^3He could be inferred from emission line (in the radio part of the spectrum) via the hyperfine emission of singly ionized ^3He. However, the availabe data are from the solar system and high-metallicity HII regions in our galaxy. Moreover, it is not clear at this time whether low mass stars are net producers or net destroyers of ^3He. Consequently, it is no longer appropriate to use ^3He as a cosmological probe of η. Instead, one might hope to turn the problem around and try to constrain stellar nucleosynthesis models of ^3He by using the predicted primordial abundance of ^3He.

(4) ^7Li: The primordial abundance of ^7Li is inferred from the absorption line of neutral lithium (which is in the optical part of the spectrum). The systems best suited for observation of ^7Li are metal poor Pop II stars in our galaxy. These are old and cold stars in the spheroid of our galaxy, some of which have metallicities as low as 10^{-4} times of the solar value. Including systematic effects, the derived value for ^7Li primordial abundance is given by:

$$\frac{^7Li}{H} = (1.70 \pm \overset{\text{statistical}}{0.06} \pm \underset{\text{systematics}}{0.44}) \times 10^{-10} \qquad (\mathrm{III})$$

The question is now whether the derived values of the primordial abundances of D, ^4He, ^7Li in Eqs (I, II, III) respectively consistently point to a given range of η. As it turns out, once systematics are included, D and ^4He abundances give rise to,

$$5.1\times10^{-10} < \eta < 6.5\times10^{-10} \quad (95\% \text{ CL}) \quad (\text{IV})$$

However, the predicted value of $\frac{^7Li}{H}$ by using this range is low by a factor of few and for η lies a few standard deviations away from the derived value in Eq. (III). The question is how one may address this discrepancy called the "Lithium problem". Possible solutions fall in three classes:

(a) Astrophysical solutions. The measured ^7Li primordial abundances may be revised. The revision may push the ^7Li abundance up to the predicted value. For example, once a correction factor is included to take the ionized ^7Li in the atmosphere of Pop II stars into account. Or, when destruction of ^7Li in the atmosphere due to convection is properly accounted for.

A purely astrophysical solution to the "Lithium problem" remains as a possibility. On the other hand, the observed ^7Li trends, including the presence of the more fragile isotope ^6Li, strongly constrain solutions of this type. Therefore, it is entirely possible that the "Lithium problem" cannot be explained through astrophysical solutions.

(b) Nuclear physics solutions. Nuclear physics processes that are unaccounted for may alter the reaction flow into and out of ^7Li. For example, ^7Li production from ^7Be may be suppressed if some strong resonance in ^7Be reactions exist. One possible resonance that is poorly constrained by experiment is $^7Be + d \rightarrow {}^9B^*$. Since these resonant states are accessible, one can identify or exclude game and draw a conclusion for a nuclear physics solution to the "Lithium problem".

(c) Solutions from beyond the SM. Invoking new particle physics or non-standard cosmologies can change the predicted value of ^7Li abundance and bring it close to the derived value from measurements. This area is ripe for further theoretical, observational, and experimental developments. We do not wish, however, to discuss it further.

We note that even with the "Lithium problem", the Big-Bang Nucleosynthesis is a remarkable success of the big-bang cosmology and one of its observational pillars. The fact that primordial abondance of light elements, spanning over 10 orders of magnitude, can be predicted based on microphysical reactions that occured in the first second after the big bang is very impressive. Moreover, there is very good agreement (in general) between the predicted and measured values.

For the past decade, the increasingly more precise of CMB measurements have allowed use to determine η independently from the measurements of light element abundances. This, more precise, probe has resulted in:

$\eta = (6.19 \pm 0.15) \times 10^{-10}$ (95% CL) (V) [WMAP 7 year data]

This is in very good agrement with that from Eq. (IV).

Now, one can use the value of η inferred from CMB as an input parameter for BBN calculations, and then compare the predicted abundances from the derived ones.

It can also be used to constrain N_ν^{eff}:

$N_\nu^{eff} < 4.2$ (95% CL) (VI)

This allows roughly one additional neutrino species.

This is in very good agreement with the bound from CMB only:

$N_\nu^{eff} = 3.36^{+0.68}_{-0.64}$ (95% CL) (VII) [Planck]