Big-Bang Nucleosynthesis and Lithium abundance

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Introduction

The predictions of the standard big-bang nucleosynthesis (BBN) theory depend on the astrophysical nuclear reaction rates and on additional three parameters, the number of flavours of light neutrinos, the neutron lifetime and the baryon-to-photon ratio in the universe. The effect of the modification of thirty-five reaction rates on light element abundance yields in BBN was investigated earlier by us [1]. In the present work we have replaced the neutron lifetime, baryon-to-photon ratio by the most recent values and further modified ^{3}He(^{4}He,γ)^{7}Be reaction rate which is used directly for estimating the formation of ^{7}Li as a result of β^+ decay by the most recent equation [2]. We find that these modifications reduce the calculated abundance of ^{7}Li by $\sim 12\%$.

BBN, Reaction Rates, 3 Important Inputs

The BBN begin for a time span from around three to about twenty minutes from the beginning of space expansion. After this, the temperature and density of the universe fell below the value which is required for nuclear fusion and thus prevented elements heavier than beryllium to form while at the same time allowed unburned light elements, such as deuterium, to exist. The BBN thus predicts the primordial abundance of light elements such as D, ^{3,4}He and ^{6,7}Li. The most important inputs for the BBN and also for stellar evolution is the astrophysical reaction rate $<\sigma v>$. The other inputs of significance are the number of flavours of light neutrinos, the baryon-to-photon ratio and the neutron lifetime. The relative velocity, v is well described by a Maxwellian velocity distribution for a given temperature T. However, the low energy fusion cross sections σ can only be obtained from laboratory experiments, some of which are not as well known. Several factors influence the measured values of the cross sections and the theoretical estimates of the thermonuclear reaction rates depend on the various approximations used. We need to account for the Maxwellian-averaged thermonuclear reaction rates in the network calculations.

Calculations of abundances in BBN

The present work uses the following rate equation [2] for ^{3}He(^{4}He,γ)^{7}Be reaction :

$$\begin{aligned} &N_A <\sigma v>= \\ &36807.346/T_9^{2/3}\exp(-11.354/T_9^{1/3}) \\ &\times(1.0-15.748\ T_9^{1/3}+56.148\ T_9^{2/3} \\ &+27.650\ T_9-66.643\ T_9^{4/3}+21.709\ T_9^{5/3}) \\ &+44350.648/T_9^{3/2}\exp(-16.383/T_9) \qquad (1) \end{aligned}$$

for temperature ranges up to 5 T_9 (in units of 10^9 K) for the astrophysical ^{7}Be production.

In the standard form the number of light neutrino flavours N_ν is taken as 3.0. The observations by WMAP [3] and Planck [4] space missions enabled precise extraction of the baryon-to-photon ratio of the Universe as $\eta = \eta_{10} \times 10^{-10} = 6.0914 \pm 0.0438 \times 10^{-10}$. The recent experimental value of 880.3 ± 1.1 s [5] is used for the neutron lifetime τ_n.

The twelve most important nuclear reactions which affect the predictions of the abundances of the light elements [^{4}He, D, ^{3}He, ^{7}Li] are n−decay, p(n,γ)d, d(p,γ)^{3}He, d(d,n)^{3}He, d(d,p)t, ^{3}He(n,p)t, t(d,n)^{4}He, ^{3}He(d,p)^{4}He, ^{3}He(α,γ)^{7}Be, t(α,γ)^{7}Li, ^{7}Be(n,p)^{7}Li and ^{7}Li(p,α)^{4}He. The uncertainties for the reactions ^{3}He + ^{4}He $\to$ ^{7}Be + γ, ^{3}H + ^{4}He $\to$ ^{7}Li + γ and p + ^{7}Li $\to$ ^{4}He + ^{4}He directly reflect uncertainty in the predicted yield of ^{7}Li.

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TABLE I: Yields at CMB-WMAP baryonic density ($\eta_{10} = 6.0914 \pm 0.0438$ [3]).

	Ref. [1] (2012)	Ref. [6] (2014)	Ref. [7] (2015)	This work	Observations
^{4}He	0.2479	0.2482±0.0003	0.2484±0.0002	0.2467±0.0003	0.2449±0.0040 [8]
D/H ($\times 10^{-5}$)	2.563	$2.64^{+0.08}_{-0.07}$	2.45±0.05	2.623±0.031	2.53±0.04 [9]
^{3}He/H ($\times 10^{-5}$)	1.058	1.05±0.03	1.07±0.03	1.067±0.005	1.1±0.2 [10]
^{7}Li/H ($\times 10^{-10}$)	5.019	$4.94^{+0.40}_{-0.38}$	5.61±0.26	4.450±0.067	$1.58^{+0.35}_{-0.28}$ [11]

Results and Discussion

Table-I compares the result of the present calculation with our previous one [1] and other recent calculations [6, 7]. The theoretical uncertainties quoted in the table arise out of experimental uncertainties in the magnitudes of τ_n and η_{10}. The present work shows that there has been a marginal decrease in helium mass fraction causing slight improvement compared with the one obtained previously in standard BBN calculations. However, the relative abundances of deuteron and ^{3}He increased marginally, yet remaining within the uncertainties of experimental observations. The most significant change is found in the relative abundance of ^{7}Li, whose value has improved by ∼ 12% compared to previous results [1] of our calculations.

Summary and Conclusion

The modification of ^{3}He(^{4}He,γ)^{7}Be reaction rate by the most recent one as well as the other updated parameters have resulted in improvement of relative abundance of ^{7}Li because the reaction ^{3}He(^{4}He,γ)^{7}Be is used directly for estimating the formation of ^{7}Li. However, if one takes the lower limit of the present theoretical estimate and compares it with the upper limit of the observed value of ^{7}Li relative abundance then these two values appear to be converging but still overestimated by a factor of 2.27. The chances of solving either of the 'lithium problems' by conventional nuclear physics means are unlikely and, if these problems remain up to future observations, we may be forced to consider more exotic scenarios. For instance, if gravity differs from its general relativistic description, the rate of expansion of the universe may be affected and the variation of the fundamental constants may have to be constrained by BBN. The ^{7}Li abundance may be lowered by decay of a massive particle during or after BBN. Similar effect could also be obtained with negatively charged relic particles, like the supersymmetric partner of the τ lepton, that could form bound states with nuclei, lowering the Coulomb barrier and thus leading to the enhancement of nuclear reactions.

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