Cosmological Time-Dependent Quark Masses and Big Bang Nucleosynthesis

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There has been considerable interest [1] in the use of big bang nucleosynthesis (BBN) to constrain any possible time variation of fundamental physical constants in the early universe. A time dependence of fundamental constants in an expanding universe can be a generic result [2] of theories unifying gravity and other interactions. It can be argued [3] that BBN is much more sensitive to variations in the averaged quark mass, i.e., $m_q \equiv (m_u + m_d)/2$, than other physical parameters such as variations in the fine structure constant. Hence, m_q may be the best parameter to search for evidence of time variation of fundamental constants.

We reinvestigate the constraints from BBN on a possible time-dependent quark mass [4]. The limits on such quark-mass variations are particularly sensitive to the adopted observational abundance constraints. Hence, we have adopted updated light-element abundances and uncertainties deduced from observations.

Changing m_q affects nuclear reaction rates through the dependence of the rates on nuclear binding energies and the reaction Q values. Resonant reactions of BBN were treated slightly differently than those in the previous study [1]. There are two important resonant reactions: ^{3}He(d, p)^{4}He and ^{3}H(d, n)^{4}He. We adopt an analytic reaction rate for variable nuclear binding energy [5].

For the ^{3}He(d, p)^{4}He reaction, the resonance is an excited state of the compound nucleus ^{5}Li*. For the ^{3}H(d, n)^{4}He reaction the compound nucleus is ^{5}He*. The resonance energies are related to the excitation energy in the compound nucleus and the net binding energies of the reactants. We point out that there is a consistency check on the δm_q sensitivity of the forward ^{3}He(d, p)^{4}He reaction from the reverse ^{4}He(p, d)^{3}He reaction [4]. As a test on the robustness of the constraint on $\delta m_q/m_q$ we include the variations in the resonance energy based on the parameters in this reverse channel.

In Fig. 1 we show primordial abundances as a function of variations in the quark mass $\delta m_q/m_q$ for a fixed value of baryon-to-photon ratio $\eta = 6.23 \times 10^{-10}$ from WMAP 7 data for model ΛCDM+SZ+lens. The revised constraints on ^{7}Li and ^{4}He do not confirm a concordance best fit for a positive value of $\delta m_q/m_q = 0.016 \pm 0.005$ [1]. Rather, the optimum concordance level is for much smaller values consistent with $\delta m_q/m_q = 0$. Combining limits from all nuclides (except ^{3}He), we deduce conservative concordance limits of $-0.005 \lesssim \delta m_q/m_q \lesssim 0.007$.

Since ^{4}He and D abundances mainly determine the concordance region, we present analytic formulas for the dependence of the ^{4}He and D abundances with quark mass [4]. ^{6}Li production in standard BBN occurs via the ^{4}He(d, γ)^{6}Li reaction, and some consequence of a varying quark mass on its abundance exists. Nevertheless, we show that effects of a varying quark mass on the resonant ^{4}He(d, γ)^{6}Li reaction can be safely neglected [4].

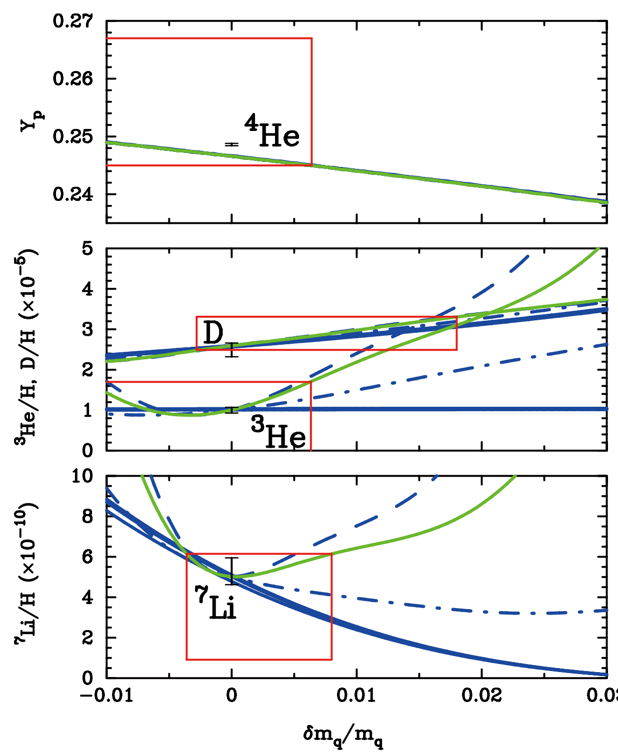

Figure 1: Calculated light-element abundances as a function of variations in the quark mass $\delta m_q/m_q$. The blue solid lines are for the case of no shifts in the resonance energies [1]. The dashed line corresponds to the resonances being shifted the same energy as the ground state. The dot-dashed line corresponds to an averaged value of the resonance sensitivity in the forward direction. The solid green curve is new to the present study. It derives from considering the reverse reaction for the determining the variation of the resonance energy. The red boxes show the allowed parameter regions for the case of the reverse reaction determined using our adopted observational constraints. Error bars at $\delta m_q/m_q = 0$ show theoretical uncertainties in standard BBN [6]. This is reprinted from [4].

References

[1] Berengut, J. C., et al.: 2010, *Phys. Lett. B*, **683**, 114.
[2] Flambaum, V. V.: 2008, *Eur. Phys. JST*, **163**, 159.
[3] Flambaum, V. V., et al.: 2007, *Phys. Rev. C*, **76**, 054002.
[4] Cheoun, M. K., et al.: 2011, *Phys. Rev. D*, **84**, 043001.
[5] Cyburt, R. H.: 2004, *Phys. Rev. D*, **70**, 023505.
[6] Cyburt, R. H., et al.: 2004, *Phys. Rev. C*, **78**, 064614.