BIG BANG NUCLEOSYNTHESIS AND THE HELIUM ISOTOPE RATIO

RYAN J. COOKE1,2,3

1 Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA; rcooke@ucolick.org
2 UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA

Received 2015 August 3; accepted 2015 September 8; published 2015 October 9

ABSTRACT

The conventional approach to search for departures from the standard model of physics during Big Bang Nucleosynthesis involves a careful, and subtle measurement of the mass fraction of baryons consisting of helium. Recent measurements of this quantity tentatively support new physics beyond the standard model but, historically, this method has suffered from hidden systematic uncertainties. In this letter, I show that a combined measurement of the primordial deuterium abundance and the primordial helium isotope ratio has the potential to provide a complementary and reliable probe of new physics beyond the standard model. Using the recent determination of the primordial deuterium abundance and assuming that the measured pre-solar \(^3\)He/\(^4\)He meteoritic abundance reflects the primordial value, a bound can be placed on the effective number of neutrino species, \(N_{\text{eff}}(\text{BBN}) = 3.01^{+0.95}_{-0.76}\) (with 95% confidence). Although this value of \(N_{\text{eff}}\) supports the standard model, it is presently unclear if the pre-solar \(^3\)He/\(^4\)He ratio reflects the primordial value. New astrophysical measurements of the helium isotope ratio in near-pristine environments, together with updated calculations and experimental values of several important nuclear reactions (some of which are already being attempted), will lead to much improved limits on possible departures from the standard model. To this end, I describe an analysis strategy to measure the \(^3\)He \(\beta\) flux emitted from nearby low metallicity \(\text{H}_\alpha\) regions. The proposed technique can be attempted with the next generation of large telescopes, and will be easier to realize in metal-poor \(\text{H}_\alpha\) regions with quiescent kinematics.

Key words: cosmological parameters – galaxies: abundances – methods: numerical – primordial nucleosynthesis

1. INTRODUCTION

The standard model of cosmology and particle physics provides our current best physical description of the Universe. Two of the most remarkable predictions of this model, now experimentally confirmed, include the production of the lightest chemical elements during the first minutes after the Big Bang (known as Big Bang Nucleosynthesis, or BBN; Alpher et al. 1948), and the existence of a relic cosmic microwave background (CMB) radiation (Penzias & Wilson 1965).

Seconds after the Big Bang, ordinary matter consisted mostly of free neutrons and protons. As the Universe expanded and cooled, some neutrons and protons combined to form deuterium (D); soon after, BBN entered full production. Nearly all of the deuterium nuclei were fused to form the more tightly bound helium-4 (\(^4\)He) nuclide. Other light nuclides were also produced, but in much lower abundance, including the lighter isotope of helium (\(^3\)He) and a very small amount of lithium-7 (\(^7\)Li). After ~20 minutes, the nuclear reactions were quenched by the decaying temperature and density of the Universe, and BBN was complete (for a review, see Steigman 2007; Cyburt et al. 2015).

The relative abundances of the primordial nuclides produced during BBN are sensitive to the universal expansion rate, and the cosmic density of ordinary matter (i.e., the cosmic baryon density, \(\Omega_{\text{B,0}}\)). The expansion rate is set by the total energy density of CMB photons and relativistic particles, which for the standard model includes electrons, positrons and three flavors of neutrino. Typically, the various contributions to the expansion rate are collected and parameterized by an “effective number of neutrino species”, \(N_{\text{eff}}\), where the standard model value corresponds to \(N_{\text{eff}} = 3.046\) (Mangano et al. 2005).
At present, it is unclear if additional, unaccounted for systematic uncertainties are biasing the best measurements of \(Y_p\), and therefore masquerading as non-standard physics (see e.g., Figure 8 from Steigman 2012). To alleviate this concern, a new, sensitive and reliable probe is required to complement the measurement of \(Y_p\) in the search for possible departures from standard BBN. Until now, the power of combining measurements of the primordial \(D/H\) and \(^3\!He/\!He\) ratios has not been fully appreciated.

In this letter, I investigate the sensitivity and observational prospects for uncovering new physics beyond the standard model using the \(D/H\) and \(^3\!He/\!He\) abundance ratios set by BBN. In Section 2, I derive the dependence of these ratios on \(\Omega_{B,0} h^2\) and \(N_{\text{eff}}\), and summarize the current best observational determinations. In Section 3, I discuss the importance of obtaining new experimental values of several important reaction cross sections. I also discuss the future potential of measuring the He isotope ratio in near-primordial environments, before highlighting the main conclusions of this work in Section 4.

### 2. THE BBN ISOTOPES

The relationships between \(\Omega_{B,0} h^2\), \(N_{\text{eff}}\), and the primordial abundances of \(D/H\) and \(^3\!He/\!He\) are derived from calculations (Iocco et al. 2009) that use the PARThENOPE code (Pisanti et al. 2008). These results are in good agreement with recent calculations (Cyburt et al. 2015) using the latest determinations of the neutron lifetime (Olive et al. 2014) and the reaction rate cross-sections (Xu et al. 2013). The primordial hydrogen and helium isotope number abundance ratios are given by

\[
y_{\text{H,He}} = \sum \sum a_{nm} \omega_B^n \Delta N_{\text{eff}}^m
\]

where \(y_{\text{H}} = 10^5 \times D/H\), \(y_{\text{He}} = 10^4 \times ^3\!He/^4\!He\), \(\omega_B = \Omega_{B,0} h^2\), and \(\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046\). The coefficients \(a_{nm}\) are provided in Tables 1 and 2. I adopt a conservative 5% standard error in \(y_{\text{H}}\) (Cyburt et al. 2015) and a 3% standard error in \(y_{\text{He}}\) (Steigman 2007) due to uncertainties in the nuclear reaction rates relevant for the BBN calculations. As discussed further below, this uncertainty dominates the current error budget on \(\Omega_{B,0} h^2\) (BBN) and \(N_{\text{eff}}\) (BBN).

The \(D/H\) number abundance ratio can be determined in near-primordial environments to high precision. The employed technique (Adams 1976) requires a rare, chance alignment between a near-pristine “cloud” of neutral gas and a bright, usually unrelated, background source (typically a quasar). The foreground gas cloud imprints the Lyman series absorption lines of neutral D and H on the light from the unrelated background quasar, allowing the relative column density of D I and H I to be measured. In this work, I adopt the latest determination \(D/H = (2.53 \pm 0.04) \times 10^{-5}\) by Cooke et al. (2014), derived from the highest precision measurements currently available.

The helium isotope ratio \(^3\!He/^4\!He\), on the other hand, has received relatively little attention from both the theoretical and observational BBN community. The current best estimate of the He isotope ratio is measured from the so-called “quintessential” phase (He-Q) from solar system meteorite samples (Lewis et al. 1975). The isotope ratios of the noble gases that are incorporated into “phase Q” are believed to represent the values that preceded the formation of the solar system, when the Universe was less than 67% of its current age (i.e., less than \(~9\) billion years after the Big Bang). Although He-Q may not represent the primordial \(^3\!He/^4\!He\) ratio (see Section 3.2), this estimate provides an illustrative value that can be used in the present work.

Extracting the noble gases contained in phase Q requires a two stage process (Busemann et al. 2000). In the first step, a meteorite is exposed to hydrochloric and hydrofluoric acid (i.e., demineralization), which leaves a resistant carbonaceous residue. This residue is subsequently exposed to nitric acid, which oxidizes the (presently unknown) carrier “Q”, thereby releasing the noble gases, including both He isotopes. The ideal meteorites for determining the phase Q isotopic abundances are those that have the lowest cosmic ray exposure age, since the isotope ratio will be less affected by cosmogenic He production. The best current determination of the He-Q isotope ratio comes from the Isna meteorite (Busemann et al. 2000, 2001), which has a remarkably short cosmic ray exposure age, \(T_{21} = 150,000\) years (Scherer & Schultz 2000). The Isna He-Q isotope ratio is \(^3\!He/^4\!He = (1.23 \pm 0.02) \times 10^{-4}\).

The BBN contours for the above observations and calculations are presented in the left panel of Figure 1. This figure highlights some of the benefits of using the He isotope ratio to test the standard model; the \(D/H\) and \(^3\!He/^4\!He\) abundance ratios offer almost orthogonal bounds on \(\Omega_{B,0} h^2\) and \(N_{\text{eff}}\). The determination of \(N_{\text{eff}}\) therefore depends almost equally on \(D/H\) and \(^3\!He/^4\!He\), unlike the combination of \(D/H+Y_p\), where \(Y_p\) drives the determination of \(N_{\text{eff}}\). Moreover, \(D/H, Y_p,\) and \(^3\!He/^4\!He\) all exhibiting a very different dependence on \(\Omega_{B,0} h^2\) and \(N_{\text{eff}}\), and their combined measurement will provide a highly complementary approach to identify physics beyond the standard model.

Assuming that the pre-solar \(^3\!He/^4\!He\) ratio reflects the primordial value, and adopting a conservative uncertainty in the BBN calculations (5% for \(y_{\text{H}}\), 3% for \(y_{\text{He}}\)), the following limits are placed on the baryon density and the effective number of neutrino species: \(\Omega_{B,0} h^2\) (BBN) = \(0.0227_{-0.0013}^{+0.0016}\) and

### Table 1

| \(m\) | \(n\) | \(a_{nm}\) |
|------|------|-----------|
| 2    | 1    | 3.7763    |
| 3    | 1    | 0.18882   |
| 4    | 1    | 0.045346  |

### Table 2

| \(m\) | \(n\) | \(a_{nm}\) |
|------|------|-----------|
| 2    | 1    | 2.6670    |
| 3    | 1    | 0.11296   |
| 4    | 1    | 0.11005   |

Cooke
$N_{\text{eff}}(\text{BBN}) = 3.01^{+0.95}_{-0.76}$ (95% confidence limits). These results agree remarkably well with the standard model of cosmology and particle physics, and the Planck CMB analysis (gray contours in Figure 1).

3. FUTURE PROSPECTS

3.1. Improving the BBN Reaction Rates

By improving a few key BBN nuclear reaction rates (discussed further below), significantly tighter bounds on $\Omega_{B,0}h^2(\text{BBN})$ and $N_{\text{eff}}(\text{BBN})$ will be possible using observational measures of comparable precision. For example, assuming the same central values for the BBN reaction rates, a 1% standard error in these rates would reduce the uncertainty on $N_{\text{eff}}(\text{BBN})$ by a factor of 2. The BBN contours for this level of uncertainty in the reaction rates are illustrated in the right panel of Figure 1, and are competitive with that of the Planck CMB experiment.

In order for this level of precision to be realized, several BBN reaction rates must be revisited and measured using modern facilities. The three most uncertain reaction rates that determine the $\text{D}/\text{H}$ abundance are $d(p,\gamma)^3\text{He}$, $d(d,n)^3\text{He}$, and $d(d,p)^3\text{H}$ (Fiorentini et al. 1998; Nollett & Burles 2000; Cyburt 2004; Serpico et al. 2004). For the He isotope ratio, the most important reactions are $d(p,\gamma)^3\text{He}$ and $^3\text{He}(d,p)^4\text{He}$. New experimental data for the crucial $d(p,\gamma)^3\text{He}$ reaction, which contributes the dominant uncertainty for both the $\text{D}/\text{H}$ and $^3\text{He}/^4\text{He}$ abundance ratios, are currently being acquired by the Laboratory for Underground Nuclear Astrophysics (LUNA; Broggin et al. 2010; Di Valentino et al. 2014). New data for the remaining reaction rates are now needed.

3.2. Measuring $^3\text{He}/^4\text{He}$ in Near-pristine Environments

The Isna He-Q measurement currently provides our best indication of the primordial He isotope ratio. However, it remains unclear if He-Q is a true reflection of the primordial BBN value. A measurement of the He isotope ratio in a near-pristine environment, where the post-BBN chemical evolution of $^3\text{He}$ is expected to be negligible, will provide a more reliable determination of the truly primordial $^3\text{He}/^4\text{He}$ ratio. In principle, such a measurement should be possible in known metal-poor H II regions by comparing the profiles of two He I emission lines, since the isotope shift is different for all He I transitions (a relative shift of up to 40 km s$^{-1}$ for the optical and near-infrared emission lines; Morton et al. 2006). For example, the $^4\text{He}$ 3D $\rightarrow$ 2P singlet transition (He I $\lambda$6679) has an isotope shift of $\approx$ +22.5 km s$^{-1}$, and the $^3\text{He}$ 2P $\rightarrow$ 2S triplet transition (He I $\lambda$10833) has an isotope shift of $\approx$ +35.2 km s$^{-1}$.

The above combination of emission lines is perhaps the best suited to obtain a direct measurement of the $^3\text{He}/^4\text{He}$ ratio from a metal-poor H II region. Assuming a flux ratio of $\mathcal{F}(^3\text{He}/^4\text{He}) = 10^{-4}$, the centroid of the $^3\text{He}$ line would need to be ideally $\geq 5\sigma$ from the centroid of the $^4\text{He}$ line to ensure that the He I emission dominates the signal. For the 1.0833 $\mu$m He I line, this $\geq 5\sigma$ shift corresponds to a $^3\text{He}$ profile with a full width at half maximum of FWHM $\lesssim$ 18 km s$^{-1}$. For comparison, thermal broadening of the $^4\text{He}$ line at a temperature of 15,000 K, which is typical of H II regions (Izotov et al. 2014; Aver et al. 2015), would produce a profile with an FWHM $\approx$ 13 km s$^{-1}$. To detect the $^3\text{He}$ feature at $5\sigma$ confidence, the signal-to-noise ratio (S/N) of the $^4\text{He}$ feature must exceed $5 \times \sqrt{\mathcal{F}(^3\text{He}/^4\text{He})}$, or S/N $\gtrsim$ 500. This S/N requirement would need to be increased if the stellar continuum of the target galaxy is bright, or if the red wing of the $^4\text{He}$ emission line extends over the $^3\text{He}$ emission line. In any case, the primary requirement is that the $^4\text{He}$ profile is smooth and narrow. To confirm that an observed feature is due to $^3\text{He}$ emission, and not a coincident weak $^4\text{He}$ emission feature, another He I emission line with a different isotope shift (e.g., He I $\lambda$6679) can be inspected. An example comparison of two He I emission lines is presented in Figure 2 for a Gaussian profile with an FWHM = 13 km s$^{-1}$. Measuring the $^3\text{He}$ flux from a nearby metal-poor H II region might be possible with the next generation of 30+ m telescopes. The current instrument concepts of the HIRES and HROS echelle spectrographs, to be mounted on the European Extremely Large Telescope and the Thirty Meter
The Astrophysical Journal Letters, 812:L12 (5pp), 2015 October 10

Cooke

4. SUMMARY AND CONCLUSIONS

The primordial abundance of helium-3 ($^3$He/H), is generally considered to provide very little constraining power on the physics of BBN, since it is less sensitive to the baryon density than the primordial deuterium abundance, is less affected by the expansion rate than the $^4$He mass fraction, and a reliable estimate of the primordial value has not been measured. This paper highlights the possibility of combining the deuterium abundance and the helium isotope ratio ($^3$He/$^4$He) to simultaneously estimate $\Omega_{B,0} h^2$ and $N_{\text{eff}}$ at the time of BBN. The following conclusions are drawn.

(i) The D/H and $^3$He/$^4$He isotope ratios set by BBN offer almost orthogonal bounds on $\Omega_{B,0} h^2$ and $N_{\text{eff}}$, unlike $\gamma_{P}$ which is essentially independent of $\Omega_{B,0} h^2$. Therefore, by combining D/H and $^3$He/$^4$He, evidence for physics beyond the standard model is less influenced by a single measurement.

(ii) If the pre-solar meteoritic value of $^3$He/$^4$He reflects the primordial value, the following bounds can be placed on the baryon density, $\Omega_{B,0} h^2(\text{BBN}) = 0.0227^{+0.0010}_{-0.0013}$, and the effective number of neutrino species, $N_{\text{eff}}(\text{BBN}) = 3.01^{+0.59}_{-0.76}$ with 95% confidence, assuming a conservative uncertainty for the measured BBN reaction rates (5% for $\gamma_{H}$ and 3% for $\gamma_{He}$).

(iii) In order to achieve bounds on $\Omega_{B,0} h^2$ and $N_{\text{eff}}$ that are competitive with the latest results from the Planck satellite, several important BBN reaction rates must be redetermined, including $d(p,\gamma)^3$He, $d(d,n)^3$He, $d(d,p)^3$He, and $^3$He($d,p)^4$He.

(iv) It is presently unclear to what degree the He-Q isotope ratio is affected by post-BBN nucleosynthesis. It is therefore necessary to obtain a measurement of the He isotope ratio in a near-pristine environment. Nearby metal-poor H II regions could be the most promising systems to estimate the primordial $^3$He/$^4$He ratio. The He I optical and near-infrared emission lines typically seen in H II regions exhibit a variety of isotope shifts (up to $\sim40$ km s$^{-1}$), allowing the $^3$He emission to be unambiguously identified. With a view to this goal, I present a possible strategy to measure the $^3$He flux from nearby metal-poor H II regions.

Although such a delicate measurement will have to wait for the next generation of 30+ m telescope facilities, it is critical that the relevant BBN reaction rates are now measured with high precision. Once this goal is achieved, the combined information provided by the primordial D/H abundance and the $^3$He/$^4$He isotope ratio has the potential to deliver a reliable probe of possible departures from the standard model of physics during the early Universe.

I thank M. Pettini and J. X. Prochaska for useful discussions about the work described in this paper, and for suggesting comments on an earlier draft. I am grateful to the anonymous referee who provided constructive comments that improved the presentation and clarity of this work. R.J.C. is currently supported by NASA through Hubble Fellowship grant HST-HF-51338.001-A, awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. The majority of the analysis and figures presented in this paper were prepared using publicly available PYTHON packages, including Astropy, NumPy, SciPy, Cython, and Matplotlib (Hunter 2007; Behnel et al. 2011; van der Walt et al. 2011; Astropy Collaboration et al. 2013).

REFERENCES

Adams, T. F. 1976, A&A, 50, 461
Alpher, R. A., Bethe, H., & Gamow, G. 1948, PhRv, 73, 803
Astropy Collaboration et al. 2013, A&A, 558, A33
Aver, E., Olive, K. A., & Skillman, E. D. 2015, JCAP, 7, 011
Behnel, S., Bradshaw, R., Citro, C., et al. 2011, CSE, 13, 31
Broggini, C., Benemer, D., Guglielmetti, A., & Menegazzo, R. 2010, ARNPS, 60, 53
Busemann, H., Baur, H., & Wieler, R. 2001, L&PS, 32, 1598
Busemann, H., Baur, H., & Wieler, R. 2000, M&PS, 35, 949
Busemann, H., Baur, H., & Wieler, R. 2000, M&PS, 35, 949

Figure 2. Synthetic line profiles for the He I triplet ($\lambda\lambda10833$; left panel) and singlet ($\lambda6679$; right panel) emission. Both profiles are normalized to the peak flux of the profile. The vertical red dashed lines at a velocity of $+35.2$ km s$^{-1}$ in both panels indicate the He isotope shift of the $\lambda\lambda10833$ line. Note that the He isotope shift of the $\lambda6679$ line is $+22.5$ km s$^{-1}$. Therefore, the detection of an emission feature at $+35.2$ km s$^{-1}$ in the $\lambda\lambda10833$ profile, together with the absence of a feature at the same velocity in the $\lambda6679$ profile, can be used to confirm the identification as $^3$He I emission.
