Astro2020 Science White Paper

Big Bang Nucleosynthesis and Neutrino Cosmology

Thematic Areas
Cosmology and Fundamental Physics

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Abstract

There exist a range of exciting scientific opportunities for Big Bang Nucleosynthesis (BBN) in the coming decade. BBN, a key particle astrophysics "tool" for decades, is poised to take on new capabilities to probe beyond standard model (BSM) physics. This development is being driven by experimental determination of neutrino properties, new nuclear reaction experiments, advancing supercomputing/simulation capabilities, the prospect of high-precision next-generation cosmic microwave background (CMB) observations, and the advent of 30m class telescopes.

1 Introduction

Big Bang Nucleosynthesis (BBN) studies in the coming decade can give us a unique “fossil” record of the thermal history and evolution of the early universe, and thereby provide new insights into beyond standard model (BSM), neutrino, particle, and dark sector physics. BBN, coupled with the primordial deuterium abundance determined via QSO absorption lines, gave the first determination of the baryon content of the universe. This was later verified by the Cosmic Microwave Background (CMB) anisotropy-determined baryon-to-photon ratio. This represents a crowning achievement of the marriage of nuclear and particle (neutrino) physics with astronomy. Though the BBN enterprise is 50+ years old [1], it is poised to undergo a revolution driven by high precision CMB observations [2, 3, 4], the advent of 30m class optical/near-infrared telescopes [5], laboratory determination of neutrino properties and nuclear cross sections, and by the capabilities of high performance computing. As we will discuss below, these developments are transforming BBN into a high precision tool for vetting BSM and dark sector physics operating in the early universe. This tool will leverage the results of accelerator-based experiments and CMB studies. Moreover, it will also give constraints on light element chemical evolution which, in turn, may give insights into the history of cosmic ray acceleration, and so into star and galaxy formation as well.

BBN has been understood in broad-brush, and used as means to explore and constrain particle physics possibilities, for over half a century. So what is new and how will these observational, experimental, and computational advances transform this enterprise? The answer lies in the anticipated precision of the observations *and* the calculations. For example, upcoming CMB observations will enable high precision (order 1% uncertainty) measurements of the relativistic energy density at photon decoupling, N_{eff}, and the primordial helium abundance with comparable uncertainty. Likewise, 30m class telescopes will achieve sub-percent precision in measurements of primordial deuterium. In turn, these high precision observations could be leveraged into high precision constraints via advanced simulations of the weak decoupling and nucleosynthesis processes. These calculations could also achieve order 1% uncertainty, setting up a situation where any BSM physics that alters the time/temperature/scale factor relationship at $\mathcal{O}(1\%)$ during the extended weak decoupling regime may be constrained by the observations.

2 Weak Decoupling, BBN, and the Computational Challenge

The thermal and chemical decoupling of the neutrinos and the weak interaction, and the closely associated freeze out of the strong and electromagnetic nuclear reactions, together comprise a relatively lengthy process. This process plays out over some thousands of Hubble times, H^{-1}, occurring roughly between temperatures $30\,\text{MeV} > T > 1\,\text{keV}$. Putative wisdom parses this protracted process into three sequential events: (1) Weak decoupling, wherein the rates of neutrino scattering fall below the Hubble expansion rate H, implying that the exchange of energy between the neutrino and the photon/$e^{\pm}$-pair plasma becomes inefficient and thermal equilibrium can no longer be maintained; (2) Weak freeze out, where the charged current neutrino and lepton capture rates fall below H, and nucleon isopsin, equivalently the neutron-to-proton ratio n/p, drops out of equilibrium with the neutrino component; and (3) Nuclear statistical equilibrium (NSE) freeze-out, where strong and electromagnetic nuclear reaction rates fall below H and light element abundances are frozen in. In fact, only recently with the advent of modern precision ”kinetic” early universe

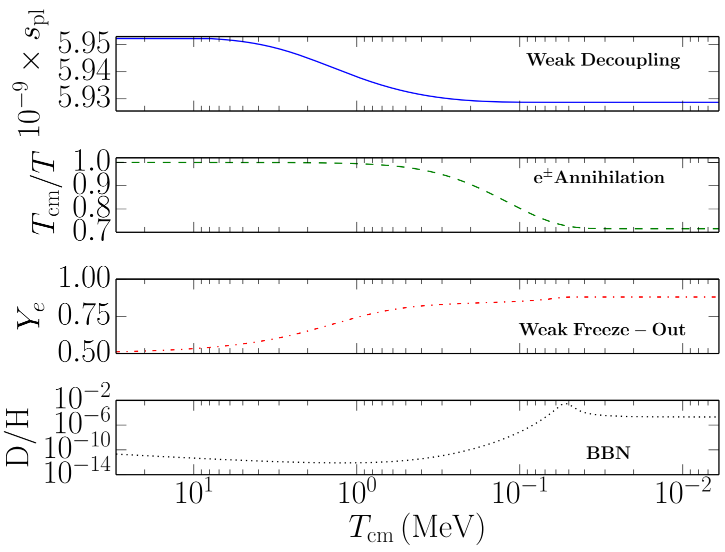

Figure 1: Entropy is transferred out of equilibrium via $\nu - e^{\pm}$ scattering from the photon-electron-positron plasma into the decoupling neutrinos. Shown here are the entropy per baryon in the plasma $s_{\rm pl}$ (upper panel); temperature T relative to $T_{\rm cm}$ (second from top panel), where $T_{\rm cm}$ is a proxy for scale factor; $Y_e = 1/(n/p + 1)$ (third panel from top); and the deuterium abundance (bottom) as functions of co-moving temperature $T_{\rm cm}$. (Figure from Ref. [6])

large-scale parallel simulation codes has it become apparent that these three processes are not distinct, overlap for significant periods of time, and they are coupled.

With Standard Model physics, the evolution of the early universe through the weak decoupling/BBN epoch is set largely by two salient features: (1) Symmetry, in particular homogeneity and isotropy of the distribution of mass-energy; and (2) High entropy-per-baryon. Symmetry implies a gravitation-driven expansion which in the radiation-dominated conditions – a consequence of high entropy – proceeds at rate $H \approx (8\,\pi^3/90)^{1/2}\, g^{1/2}\, T^2/m_{\rm pl}$, where $m_{\rm pl}$ is the Planck mass, and g is the statistical weight in relativistic particles, i.e., the photons, neutrinos, and $e^{\pm}$-pairs (at high temperature) of the standard model. From the deuterium abundance and the CMB anisotropies, we know that the baryon-to-photon ratio is $n_{\rm b}/n_{\gamma} = \eta \approx 6.1 \times 10^{-10}$ [7], implying an entropy-per-baryon $s \approx 5.9 \times 10^{9}$ in units of Boltzmann's constant $k_{\rm b}$.

As a homogeneous and isotropic spacetime precludes spacelike heat flows, the co-moving entropy will be conserved when all components and processes in the primordial plasma remain in thermal and chemical equilibrium. An interesting feature of the weak decoupling/BBN epoch, however, is that they *do not* remain in equilibrium. The symmetry does allow for overall homogeneous *timelike* entropy sources. Out of equilibrium processes, like neutrino-electron scattering in the partially decoupled neutrino seas, provide just such an entropy source. The net result is that a small amount of entropy is transferred from the photon-electron-positron plasma into the decoupling neutrinos (Fig. 1 top panel). An even smaller amount of entropy is actually *generated* in this process. Note that the number of $e^{\pm}$-pairs remains significant even at temperatures well below the electron rest mass $0.511\,\mathrm{MeV}$ because of high entropy (Fig. 1 second panel).

Alongside this neutrino decoupling process there is a parallel competition between: the six (forward and reverse) isospin-changing charged current weak interaction lepton capture/decay reactions $\nu_e + n \rightleftharpoons p + e^-$, $\bar{\nu}_e + p \rightleftharpoons n + e^+$, $n \rightleftharpoons p + e^- + \bar{\nu}_e$; and the expansion rate H. This competition, an extended freeze out process in its own right, determines the neutron-to-proton ratio n/p. The history of the baryon isospin, as expressed by the electron fraction $Y_e = 1/(n/p + 1)$, is shown as a function of co-moving temperature in the third panel of Figure 1.

References [8, 9, 10] gave the first calculations of BBN with out-of-equilibrium neutrino spectra, whereas Ref. [11] details the most recent calculation with flavor oscillations. Figure 2 shows the interplay between weak decoupling and BBN. A new generation of early-universe simulation calculations [6, 11, 12, 13, 14] take into account both the non-equilibrium energy-transport effects, charged current weak interactions, and neutrino flavor oscillation effects by solving the neutrino quantum kinetic equations (QKEs) [15, 16, 17, 18]. Only then is the objective of achieving the requisite sub-percent accuracy needed for BSM signal determination possible. This effort in precision theoretical modeling of the early universe during BBN is then clearly essential. But it is of little use if the nuclear reaction cross sections can not be determined with sufficient accuracy.

Sub-percent level precision in theoretically- and experimentally-determined nuclear reaction cross sections at low energies (a few keV) are required to obtain sub-percent level determination of the light-element abundances generated in BBN [19, 20]. Examples of nuclear reaction rate precision determinations are given in Refs. [21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. *Ab initio* theoretical approaches [31] are typically in the 5-10% range of precision for light-element capture reactions. Phenomenological R-matrix approaches [32, 33, 34], which incorporate unitarity constraints at the reaction amplitude level, can achieve descriptions of the cross section precise to within a few percent of the world data with χ^2 per degree of freedom in the range from about 1.3 to 2.0. Currently, the applied theoretical and experimental nuclear physics communities verify and validate evaluated nuclear cross sections via a suite of *integral benchmarks* [35] that incorporate cross section from large ranges of nuclides, from light-elements (H, He, Li, Be, etc.) to the transition metals, and through the actinides. The nuclear cross section evaluations, which are extracted from various accelerator and activation-type experiments, are sometimes inconsistent with each other in light of the integral benchmark constraints. For the light elements, however, the early universe provides an excellent opportunity to constrain their interaction cross sections given the highly pure, low-A environment that obtains during BBN.

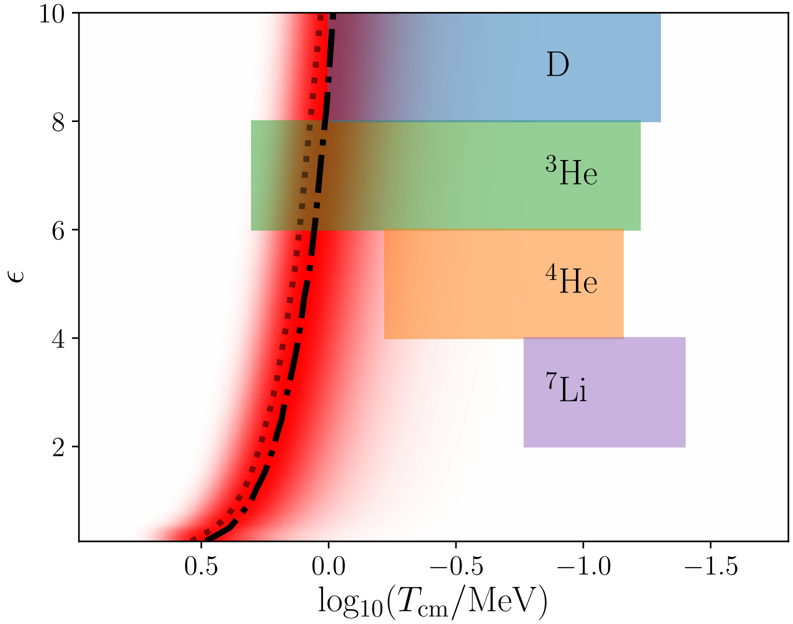

Figure 2: Simultaneous epochs of weak decoupling and BBN. The rectangles show when in $T_{\rm cm}$ the evolving abundances of D, ^{3}He, ^{4}He, and ^{7}Li experience rapid change either in or out of NSE. The shaded red region shows where out-of-equilibrium electron-neutrino scattering occurs as a function of $\epsilon = E_\nu/T_{\rm cm}$ for neutrino energy E_ν. The dot-dash line shows the peak kinetic transport of electron neutrinos. The dotted line is the peak kinetic transport of either μ or τ neutrinos.

This state of affairs – that high-energy BSM physics studies and the applied theoretical nuclear physics evaluations of cross sections are inextricably connected – suggests a way forward that allows the solution of both fundamental and applied questions. The evaluation of the light-element cross section data must be optimized not just to the two-body accelerator scattering and reaction data, but also to the early universe BBN abundances as calculated by kinetic transport codes [6].

3 Terrestrial Experiments and Astronomical Observations

What is *presently* known about neutrino properties is adequate, in principle, for the high fidelity weak decoupling and neutrino oscillation calculations described above. Experiments and observations have given us the neutrino mass-squared differences and three of the parameters in the unitary transformation between the neutrino energy (mass) states and the weak interaction (flavor) states. The measured parameters are the vacuum mixing angles, θ_{12}, θ_{23}, θ_{13}, while the one (three) CP-violating phase for Dirac (Majorana) neutrinos are unknown. Moreover, current experiments favor a normal neutrino mass hierarchy [36] and future long baseline neutrino oscillations experiments will resolve any lingering doubt. The absolute neutrino masses remain unknown, but those quantities do not affect the BBN enterprise described here.

The primordial helium and deuterium abundances are key inputs to the BBN tool for studying BSM physics. The deuterium abundance relative to hydrogen, $(\mathrm{D/H})_{\mathrm{P}}$, is derived from gas clouds that are seen in silhouette against an unrelated, background quasar. The Lyman series lines (rest frame [911–1215]Å) of neutral deuterium and hydrogen atoms in the gas cloud absorb the quasar's light, thereby allowing us to count the number of D I and H I atoms along the line-of-sight. This measurement is both accurate and precise, however it is difficult to identify the rare, quiescent, near-pristine gas clouds that permit the best measures (i.e. metal-poor damped Lyman-α systems; DLAs). The latest sample of near-pristine DLAs has allowed $(\mathrm{D/H})_{\mathrm{P}}$ to be measured to 1% precision (see Fig. 3 and Ref. [37]). However, despite two decades of research, this determination is based on only seven systems! This meagre sample is due to: (1) The brightness of the quasars; and (2) the accessible DLAs are limited in redshift to $2.6 \lesssim z \lesssim 3.5$ (by Earth's atmosphere, and the density of high redshift absorption lines).

The forthcoming generation of 30 m telescope facilities are expected to increase the number of D/H measurements by over an order of magnitude [38]. The larger collecting area of these telescopes will allow data to be collected for much fainter quasars, which are considerably more numerous than the quasars that are accessible to current telescope facilities. Furthermore, the high resolution POLLUX spectrograph onboard LUVOIR will permit new D/H measurements of DLAs at redshifts $0.0 < z < 2.6$ towards known $m \sim 18$ quasars, in just a few hours observing time. There are two advantages of measuring D/H at low redshift: (1) There is an increased redshift range over which DLAs can be discovered; and (2) The Lyman-α forest is less dense at low redshift, which greatly facilitates clean, reliable measurements.

The measurements of primordial helium with the lowest uncertainty [$\mathcal{O}(1\%)$] come from H II regions in metal-poor dwarf galaxies [39, 40]. CMB measurements of Y_P will reach a similar precision with small-scale temperature and E-mode polarization power spectra. Although both power spectra contain degeneracies between Y_P and N_{eff}, other characteristics of cosmological spectra (in particular acoustic phase shifts in CMB [41, 42, 43] and BAO [44, 45]) can break the degeneracy to provide meaningful measurements on Y_P and N_{eff}. These two parameters are independent and provide unique signatures for BSM scenarios. Any tension between CMB and galactic-inferred Y_P could motivate and inform further study of dwarf galaxy astrophysics.

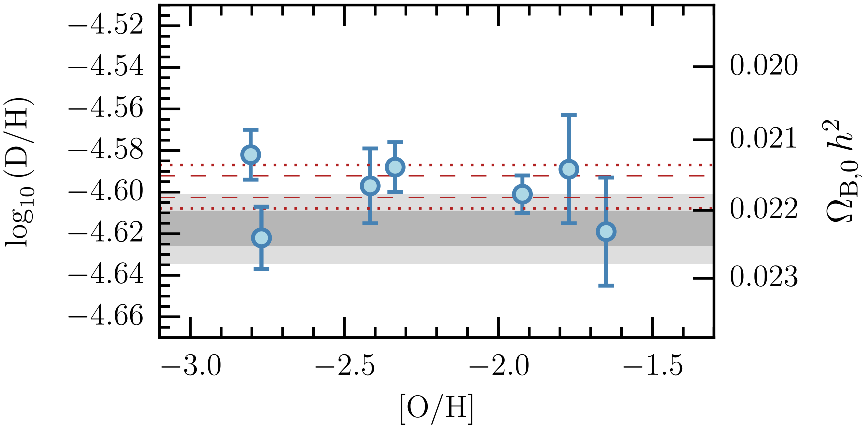

Figure 3: Measurements of D/H (blue symbols; red dashed lines show the standard error of the weighted mean) versus [O/H] from Ref. [37]. The gray band indicates the CMB value of $\Omega_{\mathrm{B},0}\,h^2$, assuming the Standard Model (dark/light bands represent 68% and 95% bounds).

4 Future Challenges and Conclusions

Deuterium and helium measurements agree with predictions but lithium (more specifically ^{7}Li) does not at the $> 3\sigma$ level [1]. If observations come into agreement with predictions, then the utility of BBN for constraining BSM physics is enhanced. If they do not, then the discrepancy could signal new physics or involve issues in stellar-evolution physics.

Solutions to the lithium problem include a class of models with a yet-to-be-determined particle. If the sea of unknown particles decays into out-of-equilibrium standard-model particles during BBN, they can modify the nuclear photo-dissociation rates and alter the primordial abundances [46]. Such models can solve the lithium problem but create a new tension in deuterium [47]. Other solutions may not require the decay of an unknown particle, but still rely on the electromagnetic plasma having distortions from thermal equilibrium [48].

Other issues in cosmology and BBN exist besides lithium. Firstly, light sterile neutrinos as suggested by short-baseline oscillation experiments [49] present a tension with current values of N_{eff} if produced solely through oscillations with active neutrinos. To resolve the problem, other physics would need to suppress the production, e.g., an asymmetry between neutrinos and antineutrinos or hidden interactions within the neutrino seas [50]. Either solution could alter the abundances away from their standard BBN values and require precise codes to characterize the deviations. Secondly, the identity of dark matter remains elusive and its production mechanism even more nebulous. The Hubble expansion rate during BBN is not sensitive to the energy density of dark matter, but the abundances (especially deuterium) are sensitive to the entropy in the electromagnetic sector. If dark matter production in any way modifies the entropy history of the early universe, the abundances could provide a signature which would be absent in neutrino observables like N_{eff}. Lastly, dark matter and light dark fermions could be representatives of a much richer dark sector. Dark electromagnetism [51, 52] and dark nuclear physics [53, 54, 55] would have couplings to their standard model cousins which BBN would put tight constraints on.

There exist publicly-available codes for BBN calculations, including but not limited to PRIMAT [29], PArthENoPE [56], and AlterBBN [57]. These codes contain procedures to model some of the BSM physics described here. Other codes, such as BURST [6], remain in development and will provide the community with additional tools to model neutrino physics in BBN. We conclude that the BBN tool, already well used in particle astrophysics, is on the threshold of becoming a precision BSM probe.

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