

Overview of Big Bang Nucleosynthesis and Light Element Abundance Models

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Abstract

This paper serves as a review of Big Bang Nucleosynthesis (BBN) the formation of elements in the first several minutes of the Big Bang. Matter existed in a dense state of quark-gluon plasma (QGP) in the extremely early universe $t < 10^{-6}$, before hadronization. Following the cooling of this substance due to the expansion of the universe, free-neutrons were formed and decayed into protons and neutrons over the first 10 or so minutes following the Big Bang, after which the amount of the neutron to proton ratio in the universe remained effectively fixed. This caused the formation of deuterons and light elements, producing a vast majority of the ^4He present in the universe today. Modern advancements in the theory of BBN are also covered, such as improving the precision of lifetimes and abundances of chemical species in the early universe, results from experimental particle physics such as heavy-ion collision conducted at particle accelerators, and study of the resulting onset of deconfinement using QGP created in collisions.

1 Introduction

Our universe is thought to have expanded from an extreme state of high temperature and density, leading to rapid expansion and the birth of stars, galaxies, and all of the elements we observe today; The Big Bang. The process by which the initial state of the universe gave rise to all of the different forms of matter we see today is described by the model of Big Bang Nucleosynthesis (BBN) [31]. Specifically, BBN is concerned with modeling the synthesis of light elements such as ^2H (also known as deuterium) and helium from the initial state of the universe [21], which happened on the timescale of minutes after the Big Bang. Studying BBN allows us to understand how the state of our current universe, billions of years later, was influenced by the extreme beginnings that charted the course for the creation of ordinary matter as we know it.

1.1 Historical Overview

In the mid 20th century, astronomers were beginning to uncover the evidence which pointed toward the Big Bang. One such astronomer was Richard Tolman of Caltech,

who used thermodynamic arguments to conclude that the universe must have begun a finite time earlier, and its initial state must have been astronomically dense [57]. However, at this time there was much uncertainty about these ideas, and Tolman explored ideas such as “continuous regeneration” in which radiation originating from matter in intergalactic space transforms into ordinary matter which then repeats a perpetual cycle.

George Gamow, a Soviet-American physicist and cosmologist published the earliest theory of BBN in 1948, in which he argued that the formation of matter must have started with the formation of deuterons from the initial neutrons that existed in the universe [5]. Building on the ideas of astronomers like Tolman, he claimed that the matter in the very early universe could be thought of as a “highly compressed neutron gas” which would form the building blocks of the chemical elements we are aware of today after a portion of neutrons decayed into protons and electrons. From this premise, Gamow was able to determine a rough estimate of the temperature during the time of deuteron dormation, which he stated was on the

order of $T_0 \approx 10^9$ K [5].

$$\frac{d}{dt}lg\ell = \left(\frac{8\pi G}{3} \frac{\sigma T^4}{c^2} \right)^{1/2}$$

where ℓ is a distance in space, $\sigma T^4/c^2$ is the density of radiation, and G is the gravitational constant [21].

Following the landmark discovery of the Cosmic Microwave Background (CMB) in 1965 [45], Princeton’s P.J.E Peebles adopted the idea that the spectrum of the CMB was blackbody radiation that originated from the “primordial fireball” of the Big Bang [44]. Using the temperature of the CMB and mean mass density of the universe, Peebles computed the primeval helium density to be 27–30% by mass. By examining the helium abundance in our own Sun and the amount of helium present now, astronomers had been able to determine that hydrogen fusion in galaxies was not able to account for the quantity of helium present in the universe. He further asserted that there would be no viable reactions that would be capable of producing elements heavier than helium [44].

As chemical measurements such as half lives of neutrons, ^3He , ^7Li and other light elements thought to have been found in the early universe became more refined, a more precise picture of BBN began to emerge. Sophisticated techniques such as Monte Carlo analysis were applied to model abundances and compare them to observation such as in Michael Smith’s 1993 work done at Caltech [53].

Smith’s paper utilized the aforementioned chemical data, the most comprehensive error analysis to date in a nucleosynthesis model, as well as fine tuning of their model by allowing temperature-dependent rate uncertainties and a careful examination of the contemporary work in BBN. From this, Smith was able to constrain the baryon density of the early universe as $0.01 \leq \Omega_b \leq 0.09$, with primordial $D+^3\text{He}$ abundance and ^4He abundance setting the lower and upper bounds respectively [53].

This work was instrumental to laying the groundwork for and refining the theory of BBN that we understand today, which astronomers use to explain the formation of elements in our universe and glimpse into the universe was like at its earliest. With an understanding of the history and context behind the study of BBN, this paper will serve as a comprehensive review of the reactions by which light elements, such as ^4He , and the vital deuterium, formed in the early universe.

1.2 Key Events in BBN

A condensed timeline of BBN is as follows. First, the ultra-dense and hot primordial matter of the universe, the Quark-Gluon Plasma (QGP), exists as highly energetic “liquified” matter [50]. As the universe expands and cools, the temperature drops enough for hadronization to occur ($t \approx 10^{-6}$ s) and quarks and gluons are able to join together into neutrons but are annihilated by energetic photons until about 10 s into the universe’s life [63]. Neutrinos decouple from other matter about a second after the Big Bang. 10 s after the Big Bang, when neutrons are no longer photodissociated, the decay over the course of $t \approx 10$ min and their decay products are able to form into deuterium, which opens the floodgates to the formation of ^3He , ^4He , and other light elements such as ^7Li and ^7Be [31]. After this point, the universe keeps expanding, cooling, and obtaining more complex chemical elements through many avenues, eventually leading to how it exists today [51]. A timeline is shown in figure 1

1.3 Experimental BBN

Predictions from BBN incorporate the cosmic microwave background (CMB) to verify results, as well as observations of elemental abundances that are tested against BBN predictions [35] [19]. Using the current CMB temperature of 2.73 K, it is possible to obtain an estimate of n_γ , the number density of photons during the Big Bang [19]. This quantity is important to determining values of baryon mass density today, a direct outcome from our models of BBN. Furthermore, measurements of light elements such as deuterium and ^4He are validations of BBN theory, as predictions that rely on models such as stellar nucleosynthesis do not account for nearly enough of the abundance that we observe [19]. Predictions and validation of BBN are discussed in more detail in section 4.3.

1.4 Overview of Current Research

While many revolutionary ideas have paved the way to our modern understanding of BBN and the rise of the chemical elements, much exciting work is being done today to further this understanding.

Some of the most exciting work is being done at particle accelerators such as A Large Ion Collider Experiment (ALICE) (pictured in figure 7 operated by the European Organization for Nuclear Research (CERN), in

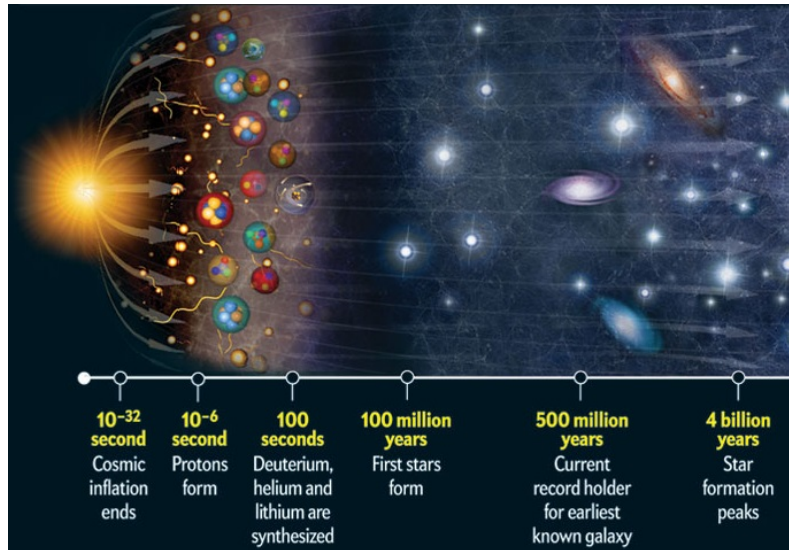


Figure 1: A timeline of events concerning the formation of elements after the Big Bang. The period of BBN chiefly concerns the period of time from 10^6 s to several minutes after the Big Bang. Image taken from Malcolm Godwin of Scientific American [32].

which conditions of the early universe are studied through large ion collision [60]. In this process, heavy isotopes of atoms such as Pb or sometimes Au are accelerated to energies on the order of TeV and then collided together to achieve extreme conditions that emulate the temperatures and properties of the early universe [60]. Other collaborations such as the Brookhaven National Laboratory in conjunction with CERN continue to design novel experiments and obtain fascinating results today, with new landmark results being found as recently as May 2025 [1] [28].

An application of QGP production through heavy ion collision is the study of the onset of deconfinement, the phase transition by which strongly interacting particles (like quarks and gluons) solidify to normal matter [34]. Experiments from CERN's Super Proton Synchrotron (SPS) in 2006 have shown interesting results that verify quantum chromodynamic models of deconfinement, and more studies are being conducted in modern times [22].

The Cosmic Microwave Background Stage 4 Project (CMB-4) is an ambitious global project centered around creating an observational array of detectors on the order of 500,000 strong to address some of the most difficult challenges in modern astrophysics [59]. With high quality data from this project, precisions for BBN calculations and elemental abundance measurements from the early universe that depend on CMB data and other

important observations such as quasars will be greatly enhanced [42]. The project began construction in 2023 and is projected to begin operations in 2029, and some of its missions include mapping hot ionized gas at high redshift, creating a precise map of the CMB, and looking for undiscovered 'light relic' particles which may have formed at initial extreme energies in the universe [42].

2 The Newborn Universe

Following the Big Bang, the universe existed in an extreme early state which was hostile to the lasting existence of ordinary matter. In this section, we will discuss the mechanisms by which this exotic state eventually gave rise to all of the chemistry and structures that we can observe today.

2.1 The Quark-Gluon Plasma

In the currently accepted model of the post-Big Bang universe, matter was in the form of quark-gluon plasma (QGP) [64] up until $\sim 10^{-6}$ [67]. To understand the properties of QGP, it is necessary to study elementary particles and their composition. In 1964, Murray Gell-Mann proposed that there is a subatomic particle, which he named the quark, that is the foundation for normal matter [23][25]. Today, we understand that normal matter, or baryons, are made up of an odd number of (usually three)

quarks [25]. Meanwhile, mesons, unstable subatomic particles usually born out of high energy interactions, are composed of an even number of (usually two each) up and down quarks [7].

Examples of baryons include protons which are made of two up quarks and one down quark, and neutrons which are made of two down quarks and one up quark. Gluons are massless subatomic particles that are responsible for determining the magnitude of the strong nuclear interaction between quarks, and were discovered in 1978 by the PLUTO experiment [55]. Any particle that interacts via the strong interaction is known as a hadron, including both mesons and baryons [39]. Similarly, any subatomic particle with a half-integer spin is a fermion, which includes quarks and leptons [65]. There are 8 different types of gluons and they only exist within hadrons, in which they are exchanged back and forth between quarks [25]. A visualization of the different quarks and leptons is shown in figure 2.

2.1.1 QGP Energy Density

Now with more background on its constituents, it is possible to better understand the QGP. QGP is an extremely dense state of matter in which the quarks and gluons that comprise baryonic matter are not confined in a proton or neutron, but rather are free to move independently [28]. It was experimentally discovered for the first time at CERN in 2000, after having been theorized to exist for decades [28]. The extremely high temperatures of the early universe ($T > 100 \text{ GeV}$) caused asymptotic freedom within the QGP that allows it to be approximated as a relativistic gas [30]. The number densities of the constituents of such a gas in which particles and antiparticles are constantly being created and annihilated can be described with,

$$n_i = \int \frac{d^3 p_i}{(2\pi)^3} \frac{1}{e^{\beta E_i} \pm 1} \quad (1)$$

where $\beta = 1/k_B T$, the $-$ sign is applied for bosons, and the $+$ sign is applied for fermions [30]. Knowing this, it is simple to calculate the energy density for each unique hadron present in the gas using equation 1 [30],

$$\epsilon_i = E_i n_i = \begin{cases} \frac{\pi^2}{30} T^4 & \text{(boson)} \\ \frac{7}{8} \left(\frac{\pi^2}{30} \right) T^4 & \text{(fermion)} \end{cases}$$

After computing the degeneracy factors, which count the total degrees of freedom summed over the different possible characteristics of each particle, we are able to calculate the energy density of the QGP [30]. At $\sim 1 \text{ GeV}$, we find that:

$$\epsilon_{QGP} \simeq 47.5 \frac{\pi^2}{30} (k_B T)^4$$

Using this model of the QGP, we can now examine how the constituents of the strange substance eventually formed into the building blocks of matter as we know it.

2.2 Expansion of the Universe

The universe is constantly expanding, which is a well accepted fact in modern times, but was a paradigm shift in astronomy in the early 20th century. Einstein's theory of general relativity, published in 1920, predicted the expansion of the universe even though this prediction was not accepted by him until 1931 [18]. His acceptance of the expansion is credited to the work of Edwinn Hubble's work published in 1929, in which observational evidence was found for the expansion of the universe involving measurements of standard candles such as Cepheid variable stars and supernovae [29].

The expansion rate of the universe is determined by its density of energy or mass, which are interchangeable according to the famous $E = mc^2$ relation [17]. But different forms of energy/matter contribute differently to the energy of the universe, and thus change the expansion rate of the universe when they dominate the universe's density. The period of initial inflation notwithstanding, modern cosmology identifies three distinct epochs of expansion: radiation dominated, matter dominated, and dark energy dominated expansion [51].

2.2.1 Expansion of the Newborn Universe

When studying the period of time directly following the big bang, we are concerned with the radiation dominated case, the expansion rate of which is found by considering the Relativistic form of the Friedmann equation [36] [52],

$$\left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho(t) - \frac{\kappa c^2}{R_0^2} \frac{1}{a(t)^2} \quad (2)$$

where ρ is the mass density of the universe in relation to energy density $\epsilon = \rho c^2$, κ/R_0^2 characterizes the current curvature of space, and $a(t)$ is the cosmological scale fac-

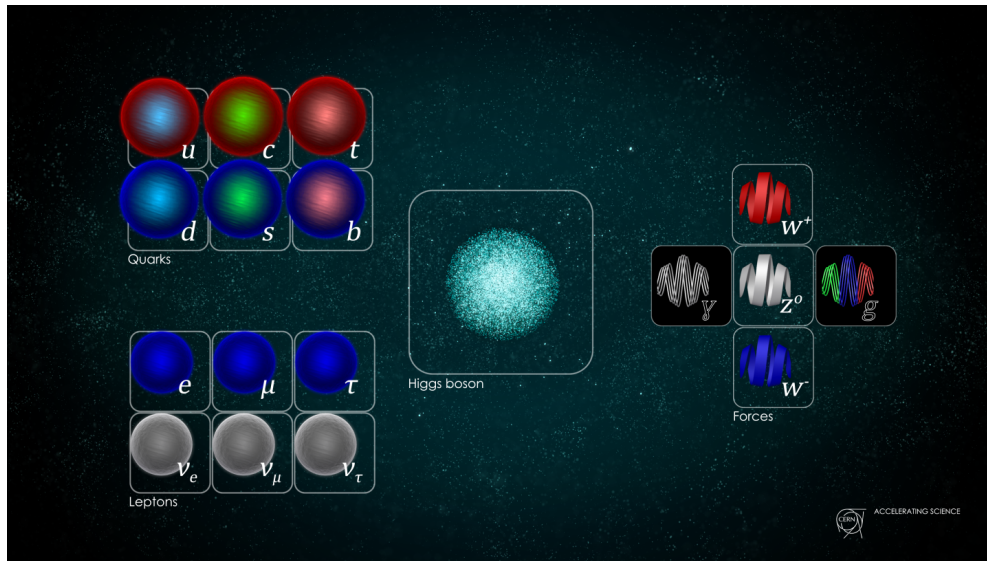


Figure 2: A diagram of elementary particles, which are the building blocks of matter. These consist of quarks (above) and leptons (below). Each different quark has a different set of characteristics and can be “up”, “down”, “charm”, “strange”, “top” or “bottom”. Quarks also have different “colors” which determine how they can mix. Image taken from Daniel Dominguez of CERN [13]

tor [50] [51]. Integration of equation 2 gives us the scale factor,

$$a(t) = a(t_0) \exp \left[\int_{t_0}^t \sqrt{\frac{8\pi G \epsilon(t')}{3c^2}} dt' \right] \quad (3)$$

where a radiation dominated universe gives us $a(t)/a(t_0) = \sqrt{t/t_0}$ [50]. Numerical simulations suggest that this ratio starts to diverge at the quantum chromodynamic phase transition, in which quark and gluon degrees of freedom disappear in favor of hadronic degrees of freedom [24] [33]. This model is valid on the order of μs after the big bang, directly after which we can start to analyze the expansion and cooling as it applies to the QGP. A diagram of the phase changes of the QGP is shown in figure 4.

2.2.2 Photodissociation

Photodissociation occurs when photons absorbed by molecules cause a chemical bond to be broken. The energies of the absorbed photon determine what manner of bond can be broken. For example, covalent chemical bonds require photons from the visible or ultraviolet regions to be broken [63]. As we will discuss in depth during the following section, a deuteron is the product of the fusion of a proton and neutron, where it is produced

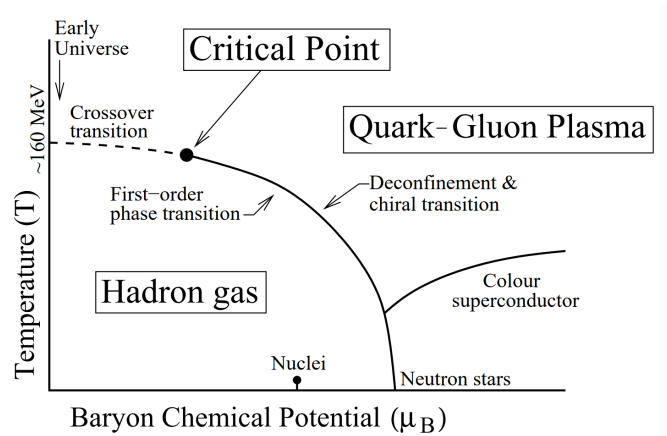


Figure 3: A quantum chromodynamic phase diagram of the Quark-Gluon Plasma. The different phases of the QGP are shown across temperature and baryon chemical potential, which shows the transition of QGP to matter in the early universe. Taken from [9].

alongside an energetic photon as [51]

$$p + n \leftrightarrow D + \gamma \quad (4)$$

The energy that is released in the form of this energetic photon is also known as the binding energy of the deuteron. When a photon with energy higher than the binding energy interacts with the deuteron, it will cause photodissociation, in which the reaction 4 will run in reverse. The binding energy is [51]

$$B_D = (m_n + m_p - m_D)c^2 = 2.22 \text{ MeV} \quad (5)$$

The ultra-dense and high-temperature conditions of the early universe contained photons that were above B_D , effectively meaning deuterons could not exist stably without being bombarded and dissociated by photons. This continued until about 10 s after the big bang, until the temperature was low enough for deuterons to exist stably, and gives us a reasonable lower limit of time to consider [38].

2.3 Hadronization

From the QGP, early expansion of the universe, and photodissociation, we can see a picture emerge of the early universe. It was a dense, hot place that was rapidly expanding, filled with a sea of ‘liquified’ subatomic particles which could not combine with each other, lest they get broken apart by powerful radiation. But the expansion, and thus cooling, of the universe meant that eventually, conditions would become more amenable to the formation of hadrons out of quarks and gluons. This process is known as hadronization [48].

2.3.1 Hadron Thermodynamics

In the 1960s, particle physicists were faced with a dilemma in which it seemed that the number of species of elementary particles that appeared to exist kept growing to explain the resonant hadronic states at increasing masses [10]. Rolf Hagedorn, a German theoretical physicist, utilized statistical mechanics to argue that there must be a maximum temperature at which hadrons can exist [10] [26]. We can use a ‘bootstrap’ thermodynamics model to describe this situation, beginning with the

partition function for a resonance gas [10]

$$\ln \mathcal{Z}(T, V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2\left(\frac{m_i}{T}\right) \quad (6)$$

where we are considering a box with volume V , particles of temperature T , and we can write an equation for the number of states of mass m_i , given by the function ρ_m with

$$\rho(m, V_0) = \delta(m - m_0) + \sum_N \frac{1}{N!} \left[\frac{V_0}{(2\pi)^3} \right]^{N-1} \int \prod_{i=1}^N [dm_i \rho(m_i) d^3p_i] \delta^4(\sigma_i p_i - p)$$

where V_0 is the composition volume of the particle. This complicated expression was solved analytically by Werner Nahm [37] [10] and we can obtain an expression in which it is possible to see that

$$\rho(m, V_0) = \text{const. } m^{-3} \exp m/T_H$$

$$T_H = [\pi^2(2 \ln 2 - 1)]^{1/3} V_0^{-1/3} \simeq 1/r_h$$

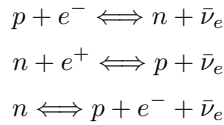
The composition volume can be written $V_0 = (4\pi/3)r_h^3$ and r_h is the range of strong interactions between particles. Finally, by assuming a range for the strong interaction, which is commonly given as $r_h \simeq 1 \text{ fm}$, we obtain $T_h \simeq 200 \text{ MeV}$. This is the largest temperature at which strongly interacting matter, like hadrons, can possibly exist and is known as the Hagedorn temperature [10]. Examining the time it takes for the universe to reach the Hagedorn temperature, we obtain an estimate of $\sim 10^{-6} \mu s$, which is consistent with the stated time in section 2.1 [67].

This statistical hadronization model was the same model applied to the CERN experiments which led to the first observations of QGP in a laboratory on Earth [49].

2.4 Neutron Decay

Once the QGP solidifies into elementary particles such as neutrons and protons, interactions that are closer to the chemistry that we are familiar with today start taking place. In this high temperature regime where photons are very energetic, the following interconversions taking

place



where p is the proton, e^- the electron, n the neutron, $\bar{\nu}_e$ the electron neutrino, and e^+ the positron [54]. Many of these can also run in reverse as discussed during section 4. The final reaction, concerning free neutrons decaying into protons, is especially important to understand big bang nucleosynthesis, because it allows us to analyze the creation of deuterons [16]. Free neutrons that are not part of an atomic nucleus are known to decay most commonly via beta decay into a proton, electron, and an electron neutrino. Free neutron half life has been measured to have a mean lifetime of $879.7 \pm 0.8s$ [3], placing their half life on the order of 10 minutes.

2.5 Decoupling and Freezeout

An important cosmological principle used to characterize different epochs of the universe is decoupling. When particles are no longer in thermal equilibrium with each other due to temperature changes caused by the expansion of the universe, they are decoupled [51]. Another way to understand decoupling is that it is when the interaction rate of particular species of particles fall below the Hubble parameter, H_0 , so the universe is expanding faster than these particles are able to interact with each other [51]. Neutrinos are elementary particles that are Leptons, so they interact via the weak nuclear force and are created by processes described in section 2.4 [13] [43]. At the very beginning of the universe, these neutrinos were in thermal equilibrium with the highly energetic photons that existed, but they quickly decoupled. We can calculate the temperature at which neutrinos decouple from photons in the very early universe by using $\Gamma \approx G_F^2 T^2$, $H^2 = \frac{8\pi\rho}{3}G$ where Γ is the weak interaction rate, G_F is the Fermi constant, and ρ is the energy density of the universe at the time [8] [61]. Using the radiation dominated approximation of $\rho \propto T^4$, we can solve this for temperature [66]

$$\begin{aligned}
 G_F^2 T^5 &\approx \sqrt{GT^4} \\
 T &\approx \left(\frac{\sqrt{G}}{G_F^2} \right) \approx 1 \text{ MeV}
 \end{aligned}$$

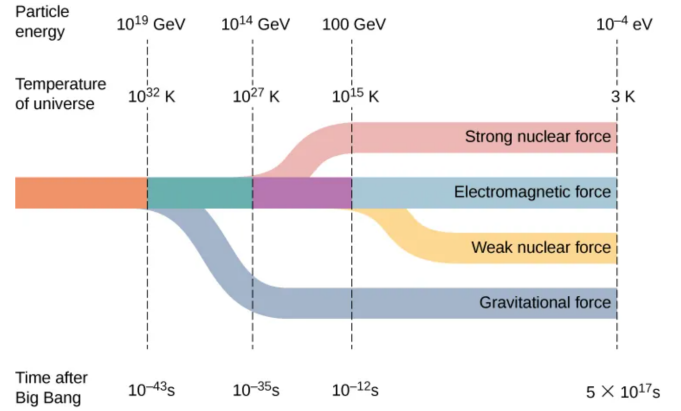


Figure 4: A diagram of the freezeout times and temperatures between the fundamental forces. Taken from [40].

Which coincides with about 1 second after the Big Bang. The interpretation of this is that the weak force interaction between neutrinos and other matter is inactive lower than this temperature, and it explains why neutrinos interact so scarcely with other matter today [43]. A diagram of the freezeout between the fundamental forces is shown in figure

2.5.1 Neutron to Proton Ratio

As neutrons decayed over the first several minutes of the Big Bang following hadronization, we can quantify the relative amounts of free-neutrons to protons that existed in the universe. This data is shown in table 1, where a nucleon is a particle that is either a proton or neutron [58]. There is a clear decrease in the n_n/n_p as time progresses, as neutrons decay into protons. Knowing the decay, half life, and types of reactions that protons and neutrons undergo, we can find the freezeout temperature of protons and neutrons. For a given process Γ and expansion rate of the universe H , when $\Gamma \gg H$, particle interactions have a much smaller timescale than expansion [46].

$$t_c = \frac{1}{\Gamma} \ll t_H = \frac{1}{H} \quad (7)$$

where t_c is the interaction timescale and t_H is the expansion timescale. Particles ‘decouple,’ or end their reactions with each others when $t_c \approx t_H$. For neutrons and protons, this freezeout time comes out to about 340 s with a freezeout temperature of $T_f \approx 0.8 \text{ MeV}$ [31]. With this information, we can find the neutron-proton ratio for the universe after this quantity becomes essentially fixed after the freezeout time. Considering this is when the chemical

potentials would be equal, we can write [47]

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{(m_n - m_p)c^2}{kT_f}\right)$$

where n_n is the number of neutrons, n_p is the number of protons, m_n, m_p are their respective masses, c is the speed of light, and k is Boltzmann's constant [31]. Plugging in these values,

$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{1.38\text{MeV}}{0.8\text{MeV}}\right) \approx \frac{1}{5}$$

Accounting for the half life of the neutron throughout the time taken to reach the freezeout temperature

$$\frac{n_n}{n_p} \simeq \frac{1}{5} \exp\left(-\frac{340\text{ s} \times \ln 2}{n_{hl}}\right) \simeq \frac{1}{7} \quad (8)$$

Finally, the ratio of neutrons to protons in our universe before it stopped changing is found to be about 1/7. This quantity is important to understand in order to examine the synthesis chains that form vital chemical elements like deuterium and helium [58].

3 Post-Deuteron Formation

Now we have a comprehensive picture of matter at the very beginning of the universe. It existed in a dense state of quark-gluon plasma, which contained the building blocks of neutrons, which was necessary for the formation of protons and electrons as well. This QGP was able to cool down due to the expansion of the universe until after $t \approx 10^{-6}\text{s}$ [38] it drops below the Hagedorn temperature, $T_H \approx 200\text{ MeV}$, the upper limit for hadron formation [26] [10]. After this time, hadronization took place, but the vast majority of deuterons that formed were blasted apart by energetic photons via photodissociation until $t \approx 10\text{ s}$ after the Big Bang [63]. In this section, we will discuss the lasting formation of deuterons and light elements in the universe after the universe's initial turmoil.

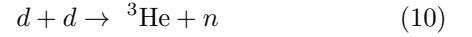
3.1 Light Element Formation

After photodissociation is no longer a threat, deuterons created by neutrons and protons that result from neutron decay can exist stably, and the process is at this point usually one-way, $n + p \rightarrow D + \gamma$ [58]. This allows more complex chemistry to form, because now neutrons,

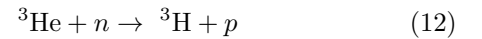
protons, and deuterons can interact with each other [16].

3.1.1 ^3He and ^3H Synthesis

The next nuclide of importance is ^3He , which was formed in the early universe by one of the following reactions

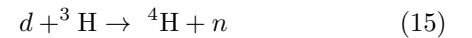


These two forms of ^3He are stable nuclides that include two protons and one neutron [16]. An unstable isotope of hydrogen containing one proton and 2 neutrons, called triton, was also formed by the following reactions



3.1.2 ^4He Synthesis

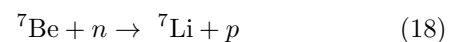
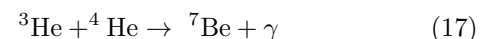
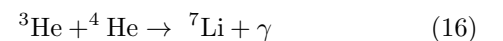
These ingredients are all that's needed to begin the synthesis of ^4He through the following reactions [16]



This stable nuclide is extremely important further into the life of the universe, and we will return to ^4He in future sections, to discuss the relative mass ratio of ^4He to other elements, and what its abundance can tell us about BBN.

3.1.3 ^7Be and ^7Li Synthesis

The final elements produced that are considered 'light' during BBN are ^7Be and ^7Li . After the creation of these nuclides, the chemical complexity of the universe grows substantially as more interactions become possible [16]. The mechanisms by which ^7Be and ^7Li are made are shown below



A reduced formation diagram of these light elements is shown along with some heavier elements in figure 5.

Table 1: Neutron to Proton Ratio in the Early Universe, taken from [58]. As neutrons decay, the relative ratio of protons to neutrons increases significantly across the first several minutes after the Big Bang. Notable, pre-hadronization would have a relative ratio of 1 of n_n/n_p due to quarks and gluons not solidifying yet.

Time (s)	T (K)	n_n/n_p	p per 1000 Nucleons	n per 1000 Nucleons
2.3×10^{-4}	1×10^{12}	0.985	504	496
2.3×10^{-2}	1×10^{11}	0.861	537	463
2.3	1×10^{10}	0.223	818	182
6.9	5×10^9	0.221	819	181
37	2.5×10^9	0.212	825	175
231	1×10^9	0.164	859	141

3.2 Light Element Abundances

With an understanding of the pathways by which light elements formed after the first $\sim 10s$ of the universe passed, we can now analyze the abundances of these elements and the amounts that were present.

3.2.1 Nuclear Statistical Equilibrium

Nuclear Statistical Equilibrium (NSE) is a concept that applies when there are multiple, sufficiently-rapid reactions that can change the number of nuclide species [31]. Boltzmann statistics can be applied to find the mass fractions of different chemical species X_i , given the atomic number A , charge Z , temperature T , mass density ρ , temperature-dependent partition function $\omega(T)$, mass function for the nucleus $M(A, Z)$, binding energy function for the nucleus $B(A, Z)$, and the chemical potential of the isotope $\mu(A, Z)$ [56]

$$X_i(A_i, Z_i, T, \rho) = \frac{A}{N_A \rho} \omega(T) \left(\frac{2\pi k T M(A_i, Z_i)}{h^2} \right) \times \exp \left[\frac{\mu(A_i, Z_i) + B(A_i, Z_i)}{kT} \right]$$

where we are considering the i_{th} chemical species, h is Planck's constant, and N_A is Avogadro's number. The reason this complicated function is useful is because it can allow us to find the chemical potentials of protons and neutrons given inputs of temperature, mass density, and charge [56]. By applying conservation of mass (baryon number) and charge, this allows us to determine the relative abundances of different chemical species by examining their potentials [56]. Practically, we can use a mass, temperature, and baryon-to-photon ratio of energy in the universe as arguments of this function to find out abundances. Because the temperature of the universe is re-

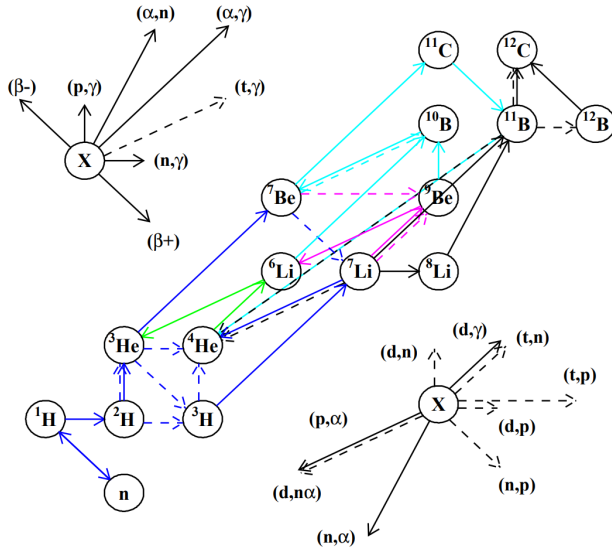


Figure 5: A reduced primordial nucleosynthesis network that displays the important reactions for light elements such as ^4He , D, ^3He , ^7Li , and ^7Be among other heavier elements. Taken from [15].

lated to the species that exist, these sets of three values encode the same information [31].

3.2.2 Stability of ${}^4\text{He}$

The strong nuclear force binds the protons and neutrons within a nucleus through a short-range yet very powerful attractive force [11]. The number of neutrons and protons needed for a nucleus to have a stable due to the balancing of the nuclear force and the electrostatic repulsion of protons within the nucleus sits at a 1 : 1 ratio for most atoms. Some exceptions include ${}^1\text{H}$ and ${}^3\text{He}$, which have a ratio under 1. Out of all of the earlier discussed nuclides, ${}^1\text{H}$, ${}^3\text{He}$, and ${}^4\text{He}$ are therefore the most stable because they either obey this ratio or are the exceptions[14]. The half life of the other light elements is much less than these atoms, and we can predict that the stable elements will therefore be much more populous than the other light elements after the initial period of synthesis [11]. Furthermore, because ${}^3\text{He}$ has several avenues to become ${}^4\text{He}$, and both are stable, we expect that there will be a relatively large amount of ${}^4\text{He}$ and Hydrogen remaining when the reaction rate decreases with expansion.

3.3 Relative Abundances

We now have a clear understanding of the pathways by which the early chemical elements in the universe formed, when they could have started forming, how quickly they formed, and how they interacted with each other. Calculations of these abundances across different baryon-to-photon ratios have been numerically computed by the Particle Data Group and are displayed in figure 6 [20].

This result shows just how relatively low the formation of the light elements discussed earlier actually are. Nearly all of the neutrons that are available actually go into creating ${}^4\text{He}$. The fraction of baryons that are ${}^4\text{He}$ is then

$$\frac{{}^4\text{He}}{b} = \frac{0.5 \times 4m_n n_n}{m_n(n_n + n_p)} \simeq 25\% \quad (20)$$

where b is the total number of baryons [31].

3.3.1 Observational Evidence

The most simple way to observationally test the model of BBN is to observe ${}^4\text{He}$ abundances across different regions in the universe, and compare it to prediction [62]. More

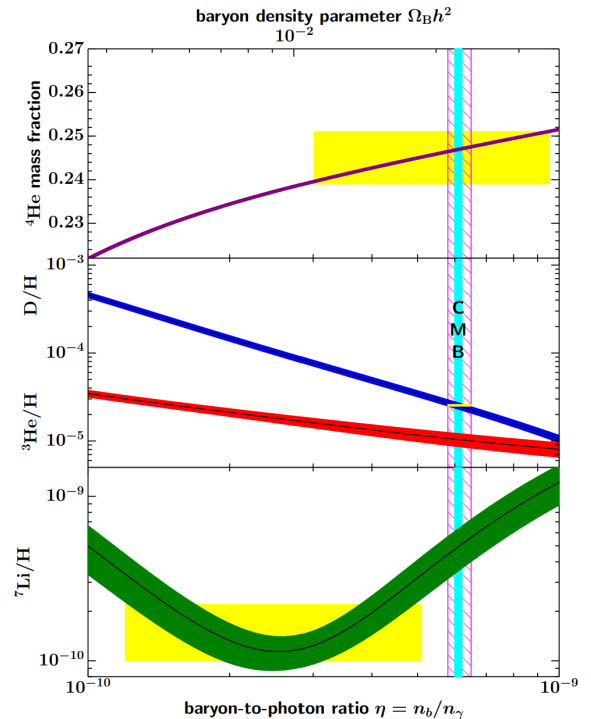


Figure 6: Primordial abundances of light elements given by the model of BBN with a 95% confidence interval. Taken from [20].

specifically, the ratio of the mass fraction, γ , of ${}^4\text{He}$ and heavier elements like Oxygen is measured to test BBN vs the other methods of helium production like stellar nucleosynthesis. Given that both elements are created through fusion in the cores of stars, the correlation between their abundances, if significant, can tell us whether or not BBN correctly accounts for ${}^4\text{He}$ abundance [62]. Then by simple regression on observational data over many regions, it is possible to find the primordial helium mass fraction [41]. A 1991 study conducted by Pagel et al found that the primordial helium mass fraction using this method is $\gamma_P = 0.228 \pm 0.005$, which supports the earlier theoretical estimate of $\approx 25\%$ extremely well [41].

4 Modern BBN

So far, we have covered the onset of matter formation in the universe through BBN. Despite the study of BBN dealing with such extreme conditions as the first several minutes of the universe, it is possible to study many of the relevant hypotheses and models experimentally on Earth. Through large particle accelerators, we can study the properties and formation of QGP, and readings of the

Cosmic Microwave Background (CMB) allow us to test our light element abundances against observation.

4.1 Heavy Ion Collision

An active area of research that is extremely closely related to the physics of the QGP and the early universe. Heavy ion collisions, which are relativistic collisions between heavy isotopes (usually ^{208}Pb) that create extreme temperatures and conditions similar to that of the early universe, have been performed to try and create QGP and study its properties here in laboratories on Earth. Experimental procedures originally by CERN and later the Brookhaven National Laboratory [28] [27]. CERN's Large Hadron Collider (LHC) is a particle accelerator that is capable of accelerating Pb nuclei to extreme speeds, with their 2017 experiment having beam energies of 2.67 TeV and total collision energies of $\sqrt{s} = 5.74 \text{ TeV}$ [60] [4]. This collision of heavy nuclei causes the strong nuclear interaction between the constituent quarks and gluons to form QGP that has been observed in several experiments. Today, experiments at colliders have been creating more extreme conditions and giving us better insight than ever into the conditions of the early universe. A Large Ion Collider Experiment (ALICE) is one of the facilities at the LHC, and is mainly tasked with creating and observing QGP [4]. ALICE consists of a massive 3km loop in which particles are accelerated through the use of electromagnetic fields to relativistic speeds, and then collided together and studied using sophisticated particle detectors [60]. Recent results in May of 2025 from ALICE show that the field of heavy ion collision and the study of QGP are more active than ever, with beam energies of $\sqrt{s} = 5.02 \text{ TeV}$ being achieved, and emissions of free neutrons and protons being detected [1]. Measurements due to these experiments continue to inform and refine our current models of QGP, as it was found that cross sections described by previous models by up to 25% [1] [2].

4.2 Onset of Deconfinement

Closely related to heavy ion collision is the study of the onset of deconfinement [22]. While we have very good models for the way phase transitions for normal matter occur, the phase transitions and properties of strongly interacting matter like quarks and gluons have been a mystery. Now that it is possible to experimentally cre-

ate and study QGP, the deconfined and confined phases of quarks and gluons can now be studied [22]. CERN's Super Proton Synchrotron (SPS) is the machine that accelerates protons to use as beams at the LHC, was used to conduct the NA49 experiment, a landmark experiment for onset of deconfinement [34] [12]. The experiment measured energy and size dependence of particle production in heavy ion collisions, and found a change at low energies, which could require the onset of deconfinement [34]. Specifically, the pion yield per collided nucleon in $Pb + Pb$ collisions and $p + p$ interactions were studied as functions of detected energy and mass, and was found to indicate the onset of deconfinement at low energies [34]. Studying the onset of deconfinement in strongly interacting particles continues to be an active area of research, with follow-up experiments being planned and conducted even now [22].

4.3 Baryon Density and Abundance Estimate Refinement

The Cosmic Microwave Background (CMB) is the thermal imprint of the very early universe, and planned observations have the potential to provide us with more precise observational information about the baryon density of the early universe than we are able to achieve using BBN models [16]. Given that the BBN model relies on the baryon-to-photon ratio at a time in the universe to generate abundance predictions, obtaining better estimates for this quantity is of the utmost importance to make BBN predictions more accurate. Observations of quasars and the CMB are able to pinpoint finer estimates for the ratio of baryonic matter in the universe, pointing to $\eta = 6.104 \pm 0.058 \times 10^{-10}$ where η is the ratio of baryons to photons [6]. This improvement in precision that is a result of high quality data from the Planck data on the CMB actually allows for the existence of a dark baryonic component in the early universe within experimental error, a major potential discovery [6]. The CMB Stage 4 project (CMB-S4) is a next generation ground based program designed to work on some of the most prevalent topics in modern astrophysics, including dark energy, inflation, and of course the early universe's properties through the CMB by conducting a deep survey of 70% of the sky [59] [42]. In this project, it is expected that there will be on the order of 500,000 detectors with a large range of detection wavelengths, and spread across

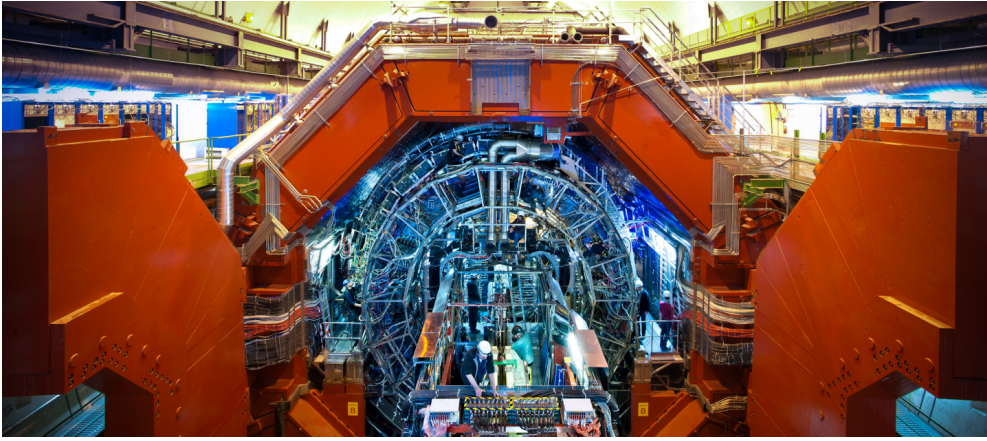


Figure 7: A photo of the ALICE experiment at CERN in Geneva, Switzerland. ALICE is one of the detector experiments at the Large Hadron Collider (LHC), tasked with studying QGP. Image taken from [62]

many geographical locations with the support of a large amount of the High Energy Physics community and many national labs [59]. Operation of the CMB-S4 project are projected to begin in 2029, and [42]. Given the refinements that modern observations have caused in error and the amount of new possibilities for the study of the early universe this opens, the CMB-S4 project is a highly anticipated development in the field of observational BBN.

5 Conclusion

In conclusion, Big Bang Nucleosynthesis is the event in which many of the light elements present in our universe today, including a vast majority of the ${}^4\text{He}$ we observe today. The early universe, which existed in a state of Quark-Gluon Plasma, cooled with the expansion of the universe to allow subatomic particles to form neutrons, which decay into protons and electrons and begin the formation of chemical elements. Light elements that formed during this time have most of their abundances accounted for through BBN and not through other channels such as stellar nucleosynthesis. Modern advances in the study of BBN continue to make measurements and predictions more precise by using observational CMB data, as well as give us a better understanding of the exotic substances such as QGP through heavy ion collision experiments in particle accelerators.

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