Primordial Nucleosynthesis *
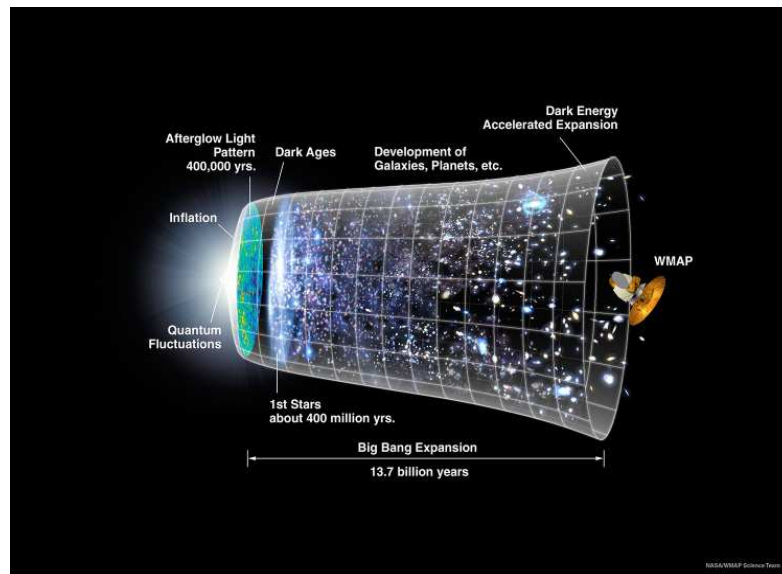
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Abstract

In cosmological terms, *Primordial Nucleosythesis* refers to the production of nuclei other than ^{1}H in the very early phases of the universe during the period from 1 second to about 300 seconds just after the Big Bang. This period somewhat changes according to the models that the cosmologists use. Due to many observational evidences, the theory offers the most reliable explanation of the early universe according to the Standard Model of Cosmology. The predictions of the creation and the abundances of the light elements, D, ^{3}He, ^{4}He and ^{7}Li are in good overall agreement with the observational data. In this review I present a brief history, then the characteristics of primordial nucleosythesis and then mention the reaction network that produced the first light elements just after the Big Bang.

Contents

1 Introduction

The Standard Model of Cosmology proposes that there were some special moments at the very early Universe that the very light nuclei were formed. Especially the first neutron and proton, then some proper atoms which are located at the first lines in the periodic table such as Hydrogen, Helium and traces of Lithium and Beryllium. After the production of primary elements in the first couple of minutes of the Universe, things slowed down and it took some hundred million years in order to form the first stars and galaxies. After the birth of stars, some other heavier elements were produced by stellar nucleosythesis up to ^{56}Fe. Then the supernova explosions are responsible for the formation of the elements heavier than ^{56}Fe which I personally do not believe that this is the only mechanism for the heavier elements, but this is not topic here.

In the article, the nuclides are shown as ^{N}X where X is the standard name of the element and N is the number of nucleons in the nucleus. This theory is also called *Big Bang Nucleosythesis*, hereafter called *BBN*.

2 Milestones of BBN

BBN theory began with Gamow, Alpher and Herman when they predicted that there is a connection between the formation of light elements and the 3 K background radiation in the 1940s. The initial BBN calculations of Gamow and his colleagues assumed that pure neutrons as an initial condition and thus were not particularly accurate, but their inaccuracies had little effect on the group's predictions for a background radiation [Alpher et al., 1948]. While their speculations were not really correct about the details of the nucleosythesis, that led to the prediction of the cosmic microwave background radiation.

Isotope	35 years ago	
	Best Observations	**Presumed Origin**
^{2}D	Sea Water	T-Tauri Stars
^{3}He	Solar Flares	Low Mass Stars
^{4}He	Indirect	BBN
^{7}Li	Pop I stars	T-Tauri Stars
^{6}Li	Meteorites	T-Tauri Stars
Be	Pop I stars	T-Tauri Stars
B	Meteorites	T-Tauri Stars
Isotope	Now	
	Best Observations	**Presumed Origin**
^{2}D	ISM (HST)	BBN
^{3}He	Galactic HII regions	BBN + low mass stars
^{4}He	Extragalactic HII regions	BBN
^{7}Li	Pop II stars	BBN
^{6}Li	Pop II stars	Cosmic Ray Spallation
Be	Pop II stars	Cosmic Ray Spallation
B	Pop II stars	Cosmic Ray Spallation

Table 1: Thirty five years history for the production of light elements [Schramm, 1995].

When Hayashi [1950] revealed the role of neutron-proton equilibration, the framework for BBN calculations has not changed significantly afterwards. The cosmologist predecessors have different arguments regarding the production of the light elements. In the 1960s, the main focus was on ^{4}He, which is very insensitive to the baryon density. The agreement between the BBN prediction and some indirect observations gave strong support to the Big Bang model, but no significant constraint to the baryon density.

Some observations with old techniques presumed that the production of the other light elements had no connection with the Big Bang. Most of the other light elements assumed to have been made during the T-Tauri phase of stellar evolution which is an unstable phase that stars like our Sun go through just before they settle down to the main-sequence (H-burning) phase. But this comprehension has changed gradually in the 1970s and primordial nucleosythesis developed to a more important role in the early Universe. When Ryter et al. [1970] proved that the T-Tauri mechanism for the production of the light elements fail, the knowledge of the Deuterium abundance improved significantly with solar wind, meteoritic and ISM measurements. It was very difficult to understand because most astrophysical processes destroy Deuterium since it is so weakly bounded [Schramm and Turner, 1998].

Table 1 summarizes how attitudes about the various primordial light elements have changed over the past 35 years and 1995, and still is [Schramm, 1995]. Nowadays, from the measurements of the primeval deuterium abundance, the baryon density could be determined to a very precise value. When this hap-

pens, an accurate value of the average density of the ordinary matter can be determined and BBN theory reaches to its completion. This also brings good explanations to the study of the chemical evolution of the galactic and stellar evolution [Schramm and Turner, 1998].

Now the power of homogeneous BBN comes from the fact that essentially all of the physics can be very well determined in the nuclear physics laboratories. The regimes of 0.1 to 1 MeV can be well explored in the labs therefore the behaviour of nuclei under such different conditions is not work of a guess now but can absolutely be known. In fact, it is known for these energy levels far better than it is for the centers of stars like our Sun. The most up to date predictions of the elements are shown in Figure 1. The figure will be explained in the later chapters.
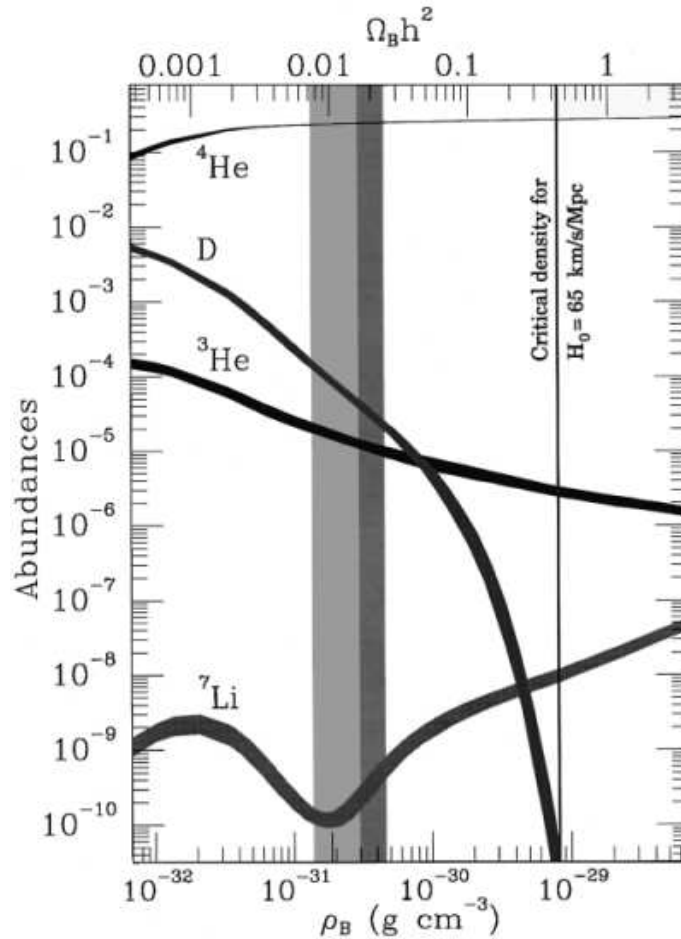

Figure 1: The summary of primordial production of light elements. ^{4}He abundance is mass fraction and others are given as number relative to hydrogen [Schramm and Turner, 1998].

3   Happy Birthday Universe

According to the Standard Model of Cosmology at the instant of Big Bang, all the matter and radiation and etc. in the Universe was condensed in a single point. Just after, there is no information that can be understood, but by making instruments in order to look far out into the Universe and combining this information with the particle physics, scientists can manage to model the first time of 10^{-43} seconds just after the Big Bang.

3.1 10^{-43} seconds

Since the predictions starts after 10^{-43} seconds, it is believed that the events were happening very fast. The Universe's (known!) forces of Gravitational, Strong, Weak, and Electromagnetic forces were indistingusihable. Particles of matter and antimatter existed in equal portions and they were constantly annihilating to produce radiation and being recrated from that radiation.

Figure 2: The Universe is 10^{-43} & 10^{-34} seconds old. Image courtesy: CERN Outreach

3.2 10^{-34} seconds

Around this age of the Universe, a very rapid expansion is necessary to explain today's large scale uniformity and other problems such as flatness problem, horizon problem, and monopole problem. This rapid growth is called the "Cosmic Inflation" which was first proposed by Alan Guth and Andre Linde in 1981 [Guth, 1981]. Since this is also a very long topic, I am not going to mention more on Inflation here. In this time of the Universe, the strong force that binds the quarks together into protons and neutrons also became distinct from the electromagnetic and weak forces which remained indistinguishable. Due to the very high energy radiation that was still spreaded through the Universe any groupings of quarks were rapidly broken up, therefore protons and neutrons did not start to form. Matter was sort of high density cosmic soup so-called "Quark Gluon Plasma", shortly QGP. Moreover, another event that happened in this time was the tiny excess of matter over antimatter, just one matter particle surviving for every 10^9 particles to annihilate with antimatter, began to develop. It is these survivors that make up our Universe today [CERN Outreach].

3.3 10^{-10} seconds

Between 10^{-34} seconds to 10^{-10} seconds the electromagnetic and weak forces separated. According to the unified electroweak theory, this was formulated by Glashow, Weinberg and Abdussalam in 1960s and proven consistent by Gerard 't Hooft and Veltman in 1971. In this time, the energy of the radiation had also fallen sufficiently to allow protons and neutrons to form as well as short-lived particles, called "Mesons", made of a quark and an antiquark. Moreover, antimatter started to disappear because when quarks and antiquarks were annihilated, there was no longer enough energy in the radiation to recreate quarks.
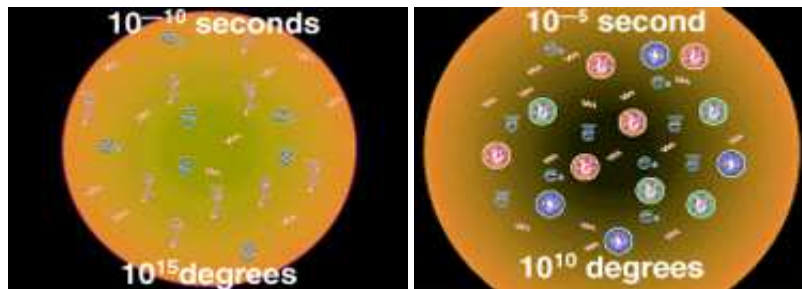

Figure 3: The Universe is 10^{-10} & 10^{-5} seconds old. Image courtesy: CERN Outreach

3.4 10^{-5} seconds

Protons and neutrons continuously builded around and after this time. The remaining antimatter in the form of positrons disappeared significantly as the radiation energy density declined below the necessary level to create electron-positron pairs [CERN Outreach].

3.5 1 second

When the universe was 1 second old, things really started to slow down and the primordial nucleosythesis reactions started to happen.

4 Characteristics of Primordial Nucleosythesis

One of the most essential predictions of the Standard Big Bang Model is the sythesis of light elements in the primordial universe. As stated by Schramm [1995], there are three pillars of Big Bang Cosmology which are the Hubble Expansion, CBR - Cosmic Background Radiation and the Big Bang Nucleosythesis. BBN examines back to earlier times of the Universe than the other two and it also has to deal with nuclear and particle physics along with cosmology. Moreover, while Hubble expansion can also be used by some other alternative cosmological theories (e.g. steady state), the evidences of CBR and BBN observations really lead cosmologists to a universe which was very hot and dense in the very beginning.

4.1 The Physics of the BBN

At first assumption, the Friedmann-Robertson-Walker cosmological model is the standard scenario underlying the BBN theory. Moreover, the solution of the Einstein equations lead to an isotropic and homogeneous universe; so the uniformity of the CBR temperature, which is $T = 2.7277 \pm 0.002K$ across the sky, as well as the success of the standard BBN theory serve to validate this approximation [Schramm and Turner, 1998]. The primordial harvest of light elements is determined by the time during the expansion of the Universe. It is possible to characterize the BBN in general; that the paradigm most frequently uses the Friedmann equation to relate the BBN expansion rate, H, to the thermal properties of the particles present at that epoch. By expansion, the rates of the weak interactions that transform neutrons and protons, and the rates of the nuclear reactions that build up the complex nuclei. The general Friedmann equation which describes the Universe, is defined as;

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

where κ is the curvature term, $a(t)$ is the scale factor, R_0^2 is the radius of curvature and the $\epsilon(t)$ is the total energy density. Since the contributions of the curvature term and the cosmological constant are very small in the very early Universe, the Friedmann equation turns to be as

$$H^2 = \left(\frac{\dot{a}}{a}\right) = \frac{8\pi G}{3c^2}\epsilon(t). \tag{2}$$

The Standard Model of Particle Physics suggests that the candidate particles' energy density contribute to $\epsilon(t)$, but it should be nice to keep in mind that this may fall short of the actual particle content at that time. Even so, after blueshifting the currently observed CMB energy density back to the epoch of BBN, it emerges that the energy density of the Universe was dominated by the relativistic particles during the BBN [Kneller and Steigman, 2004].

The Standard Model of Cosmology, under the assumptions that the universe is isotropic and homogeneous, is the best description of the particle content of the universe at temperatures in the order of a few MeV, the predicted primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li depends on the baryon density as well as the expansion rate. The baryon-to-photon ratio $\eta \equiv n_B/n_\gamma$ is the most important parameter that determines the standard predictions of BBN. It is formulated as

$$\eta_{10} = 273\Omega_B h^2, \tag{3}$$

where Ω_B is the baryon density ratio to the critical density and the Hubble parameter $H_0 = 100h$ km/s/Mpc; $\eta_{10} = \eta/10^{10}$ [Schramm, 1995].

For the standard BBN, the energy density, $\epsilon(t)$, at the time of nucleosythesis, is described by the standard model of particle physics.

$$\epsilon = \epsilon_\gamma + \epsilon_e + N_\nu \epsilon_\nu \tag{4}$$

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[1]The notation used, is from *Introduction to Cosmology*, Ryden [2003].

	Reactions		Reactions
1	$n \leftrightarrow p + e^- + \bar{\nu}$	7	$^3He + \alpha \to ^7 Li + \gamma$
2	$^1H + n \to ^2 H + \gamma$	8	$^3He + n \to ^3 H + p$
3	$^2H + p \to ^3 He + \gamma$	9	$^3He + D \to ^4 He + p$
4	$^2H + D \to ^3 He + n$	10	$^3He + \alpha \to ^7 Be + \gamma$
5	$^2H + D \to ^3 He + p$	11	$^7Li + p \to ^4 He + \alpha$
6	$^3H + D \to ^4 He + n$	12	$^7Be + n \to ^7 Li + p$

Table 2: Twelve crucial reactions in the time of BBN

where ϵ_γ, ϵ_e, and ϵ_ν are the density of cosmic background radiation; photons, electrons and positrons and massless neutrinos and anti-neutrinos, respectively and N_ν is the equivalent number of massless neutrino species which in standard BBN is precisely 3 (electron neutrino, muon neutrino, tau neutrino) [Olive et al., 2000].

$$\epsilon = \epsilon_\gamma + \epsilon_e + 3\epsilon_\nu = \frac{43}{8}\epsilon_\gamma \tag{5}$$

4.2 Theory

The reactions which happened at the duration of BBN can be organised into two groups: a) the reactions that interconvert neutrons and protons which are $n + e^+ \Longleftrightarrow p + \bar{\nu}$, $n + e^+ \Longleftrightarrow p + \bar{\nu}$ and $n \Longleftrightarrow p + e^- + \bar{\nu}$, and b) the rest reactions. The first group can be expressed in terms of the mean neutron lifetime τ_n, and the second group are determined by many different nuclear cross-section measurements. There are twelve crucial reactions presented in Table 2 and are shown as reaction network in Figure 4.

In principal, the nuclear harvest of BBN depends upon the baryon density, the mean neutron lifetime τ_n, the quantity that counts the total number of spin degrees of freedom of the relativistic particles g_*, the number of neutrino species N_ν, and twelve key nuclear cross sections. In the beginning of the theory, the uncertainties of these parameters make the cosmologists to think that BBN depend on many parameters. But with the current technology, and achieving more advanced instruments; the CBR temperature was measured very precisely by WMAP, the number of neutrino species found to be $N_\nu = 3$ by measurements of the decay width of the Z^0 boson made at CERN and at SLAC, and the mean neutrino lifetime at $\tau_n = 887 \pm 2$ seconds by experiments using trapped, ultracold neutrons), along with improved determinations of some nuclear cross sections have reduced the standard BBN scenario to one parameter, the baryon density. For the standard scenario, $N_\nu = 3$, $g_* = 10.75$ and $\tau_n = 887$ sec, the only uncertainties are for the reactions $^3He + ^4 He \to ^7 Be + \gamma$, $^3H + ^4 He \to ^7 Li + \gamma$ and $p + ^7 Li \to ^4 He + ^4 He$, and these lead to about 50% uncertainty in the predicted yield of ^7Li [Schramm and Turner, 1998].
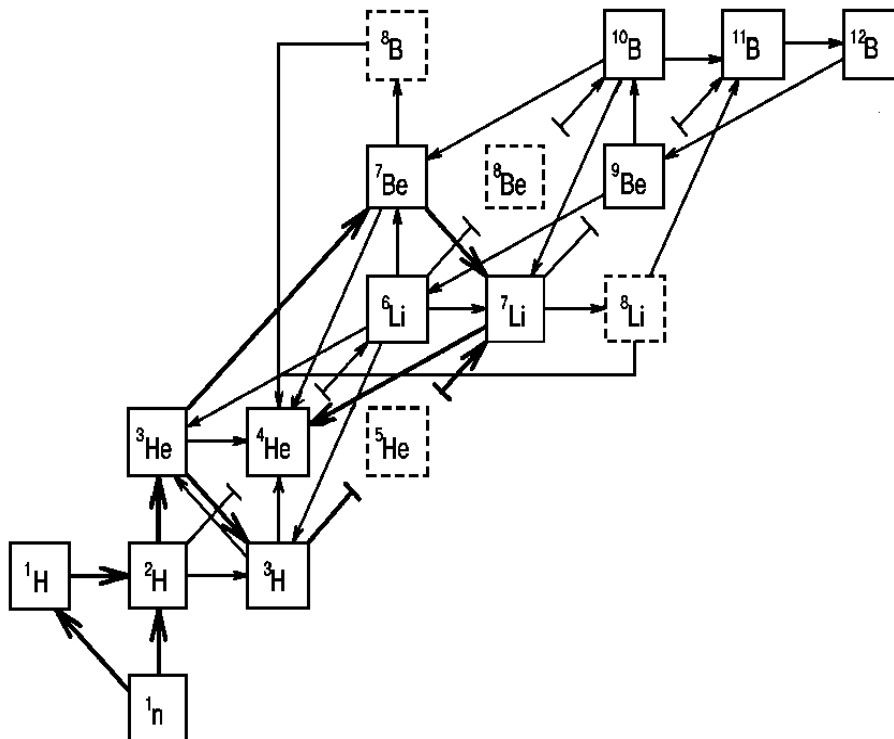
Figure 4: The reaction network used for BBN by Copi et al. [1995]. The figure covers the standard BBN elements while the original paper has the figure which includes the network until the production of some later atoms (Carbon, Nitrogen and Oxygen).

4.3   Reactions at the BBN

At the high temperatures, neutrons and protons can interconvert via weak interactions. Less than 1 second after the Big Bang, the reactions of,

$$p + e^- \iff n + \nu \tag{6}$$

$$n + e^+ \iff p + \bar{\nu} \tag{7}$$

maintain the neutron-to-proton ratio in thermal equilibrium. About 1 second after the Big Bang, the temperature is slightly less than the neutron-to-proton mass difference, these weak interactions become slower than the expansion rate of the Universe.

After 1 second, the only reaction that appreciably changes the number of neutrons is neutron decay,

$$n \iff p + e^- + \bar{\nu}. \tag{8}$$

The half-life of the neutron is 615 seconds. Without further reactions to preserve neutrons within stable nuclei, the Universe would be pure hydrogen [Wright].
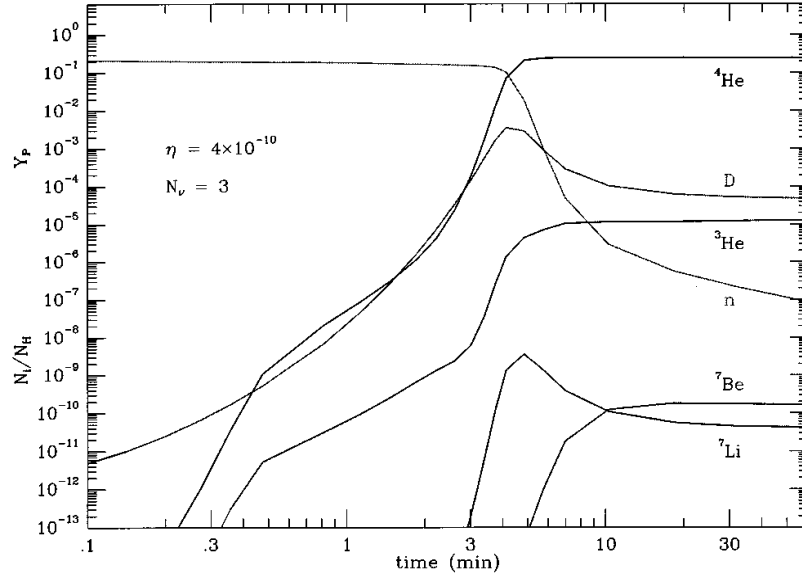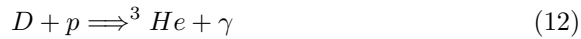
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Figure 5: The time evolution of light element abundances during BBN. In the figure, ^{4}He is given as mass fraction and the other numbers are relative to hydrogen. Image Courtesy Schramm and Turner [1998]

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The formation of Deuterium begins in the process of

$$p + n \Longleftrightarrow D + \gamma. \tag{9}$$

The deuteron is the nucleus of deuterium, which is the heavy form of hydrogen ^{2}H. This reaction is exothermic with an energy difference of 2.23 MeV, but since photons are 10^9 times more numerous than protons, the reaction does not proceed until the temperature of the Universe falls to 10^9K or $kT = 0.1$ MeV. This because, photo-dissociation by the high number density of photons delays production of deuterium and other complex nuclei after T drops well below the binding energy of deuterium, $\Delta_D = 2.23$ MeV.

When the Deuteron formation has happened some further reactions proceed to make ^{4}He nuclei.

$$D + n \Longrightarrow^3 H + \gamma \tag{10}$$

$$^3H + p \Longrightarrow^4 He + \gamma \tag{11}$$

$$D + p \Longrightarrow^3 He + \gamma \tag{12}$$

$$^3He + n \Longrightarrow^4 He + \gamma \tag{13}$$

Both light helium ^{3}He and normal helium ^{4}He are formed along with the ^3H. Fractions are shown in figure 5. Since helium nucleus is 28 MeV more

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bound than the deuterons and the temperature has already fallen to 0.1 MeV, these reactions can be photoreactions and only go one way.

The following four reactions also produce ^{3}He and ^{4}He and they usually go faster since they do not involve the relatively slow process of photon emission.

$$D + D \Longrightarrow^3 He + n \tag{14}$$

$$D + D \Longrightarrow^3 He + p \tag{15}$$

$$^3He + D \Longrightarrow^4 He + n \tag{16}$$

$$^3He + p \Longrightarrow^4 He + p \tag{17}$$

Eventually the temperature gets so low that the electrostatic repulsion of the deuterons causes the reaction to stop. Almost all the neutrons in the Universe end up in ^4He nuclei. at the time of deuteron formation, 25% of the mass ends up in helium [Wright].

$$D + D \Longrightarrow^4 He + \gamma \tag{18}$$

5 Conclusions

This article has been devoted to an explanation of the formation of light elements in the beginning of the Universe just after the Big Bang. There are still many unanswered questions regarding the formation of elements. All our current knowledge about the universe say that only up to 4% is baryonic matter and only 1% is in the form of known objects such as stars, galaxies etc. and 26% is non-baryonic dark matter. Morover the rest of 70% is the dark energy and together with the dark matter that makes around 99% of the Universe, is still a big quaestion. BBN theory opened a door to study the earliest moments and helped to forge the relationship between particle physics and cosmology.

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