Time of primordial ^{7}Be conversion into ^{7}Li, energy release and doublet of narrow cosmological neutrino lines

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ABSTRACT

One of the important light elements created during the big bang nucleosynthesis is ^{7}Be which then decays to ^{7}Li by electron capture when recombination becomes effective but well before the Saha equilibrium recombination is reached. This means that ^{7}Be should wait until its recombination epoch even though the half-life of the hydrogenic beryllium atom is only 106.4 days. We calculate when the conversion from primordial ^{7}Be to ^{7}Li occurs taking into account the population of the hyperfine structure sublevels and solving the kinetic equations for recombination, photoionization and conversion rate. We also calculate the energies and the spectrum of narrow neutrino doublet lines resulting from ^{7}Be decay.

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Key words: *cosmic microwave background, cosmic neutrino background, big bang nucleosynthesis, early Universe*

1. Introduction

The first major event in the Universe after the big bang and the inflation stage is the creation of light elements (Wagoner, Fowler, and Hoyle 1967) including D, He-3 and Li, which are of importance for our everyday life or considered as energy source on the Earth in the future. The combination of neutron and proton to form deuterium is the first step in the nuclear reaction chain. The big bang nucleosynthesis (BBN) starts when the temperature of the Universe is about $T \sim 0.1$MeV (redshift $z \sim 4 \times 10^8$) and the deuterium destroying high energy photons have become rare. BBN proceeds swiftly after this deuterium bottleneck is overcome and is over by $T \sim 0.01$MeV. The next major event in the Universe is that of the recombination of primordial plasma (Zeldovich, Kurt, and Syunyaev (1968);Peebles (1968)) to form neutral atoms starting with helium recombination at $z \sim 8000$ and ending with hydrogen recombination at $z \sim 1000$. In this paper we will explore a unique connection between these two major events, the recombination of beryllium ^{7}Be and its decay to lithium ^{7}Li and in the process also mention a doublet of narrow lines in the cosmic neutrino background. This unique event brings together the MeV scale nuclear physics of nucleosynthesis and eV scale atomic physics of recombination. We will also find that the very low energy atomic physics of hyperfine transitions in ^{7}Be has a surprisingly strong influence on the decay properties of ^{7}Be usually associated with MeV scale physics. This problem of beryllium to lithium conversion is one of the last problems not investigated in detail so far connected with the primordial nucleosynthesis and the process of recombination of ions and electrons in the radiation field of the cosmic microwave background (CMB). This problem is very attractive because it demonstrates a very rare case in astrophysics when the atomic processed and even the populations of the hyperfine structure influences nuclear processes.

The cosmological parameters used for numerical calculations are Hubble constant $H_0 = 73$km/s/Mpc, matter fraction $\Omega_m = 0.24$, CMB temperature $T_{CMB} = 2.726K$, baryon fraction $\Omega_b = 0.043$, cosmological constant $\Omega_\Lambda = 0.76$.

2. Decay of ^{7}Be

At the end of BBN the abundances of light elements relative to hydrogen are (Serpico *et al.* 2004): $X_{^4\mathrm{He}} = 6\times10^{-2}$, $X_{^2\mathrm{H}} = 2.5\times10^{-5}$, $X_{^3\mathrm{He}} = 10^{-5}$, $X_{^3\mathrm{H}} \sim 10^{-7}$, $X_{^7\mathrm{Be}} \sim 10^{-10}$, $X_{^7\mathrm{Li}} \sim 10^{-11}$, $X_{^6\mathrm{Li}} \sim 10^{-14}$ and $X_{\mathrm{M}} \lesssim 10^{-15}$, where X_{M} is the abundance of all heavier elements, $X_i = n_i/n_{\mathrm{H}}$, n_i is the abundance of species i and n_{H} is the number density of hydrogen nuclei. Note that about $\sim 90\%$ of the primordial ^{7}Li comes from ^{7}Be and only $\sim 10\%$ of ^{7}Li is produced directly in BBN, this division is however sensitive to the baryon to photon ratio η (Iocco *et al.* 2009).

^{7}Be in its fully ionized state in the early Universe is stable. Fully ionized beryllium can capture electrons from the plasma at the high densities in the stellar interiors (Bahcall 1989). However the electron capture rate for the fully ionized beryllium from the plasma is completely negligible in the early Universe due to the low electron density. Once recombined with an electron beryllium decays by electron capture through the following reactions

$$^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \nu_{\mathrm{e}} \tag{1}$$

$$^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li}^* + \nu_{\mathrm{e}},\ {}^7\mathrm{Li}^* \rightarrow {}^7\mathrm{Li} + \gamma, \tag{2}$$

where $^7\mathrm{Li}^*$ is the excited state of lithium nucleus with energy 477.6KeV above the ground state. The Q-value of the reaction is 861.8KeV (Tilley *et al.* 2002). The laboratory value for the half life of ^{7}Be is 53.2 days. The branching ratio is 10.44% for reaction 2. These laboratory values have been calculated and measured for neutral ^{7}Be with four electrons.

The ^{7}Be in the primordial plasma will however decay as soon as it acquires a single electron. Therefore we are interested in hydrogen-like $^7\mathrm{Be}^{3+}$. The electrons in the $2s$ shell of neutral ^{7}Be have a $\sim 1\%$ effect on the decay rate as shown by experiments involving $\mathrm{Be}^{2+}(\mathrm{OH}_2)_4$ as well as other chemical compositions (Huh 1999) and we will ignore the influence of 2s shell electrons in the discussions below. Helium-like $^7\mathrm{Be}^{2+}$ has practically the same lifetime and branching ratio as the neutral ^{7}Be. The change in the decay rate and the branching ratio from helium-like $^7\mathrm{Be}^{2+}$ to hydrogen-like $^7\mathrm{Be}^{3+}$ depends strongly on the spin temperature of the hyperfine structure of hydrogen-like $^7\mathrm{Be}^{3+}$ ions.

This statement is easy to understand. We will make simple estimates of decay rates based on the calculations by Patyk *et al.* (2008). ^{7}Li* has a nuclear spin of $I = 1/2$ which is different from the nuclear spin of $I = 3/2$ of ^{7}Li and ^{7}Be. The two initial states available for ^{7}Be^{3+} are with total angular momentum $F^+ = 2$ and $F^- = 1$. The two final states available to ^{7}Li$^* + \nu_e$ are $F = 0, 1$. Thus the angular momentum can only be conserved for the reaction 2 from the initial state $F^- = 1$ of ^{7}Be^{3+} to the final state $F = 1$ of ^{7}Li*. The reaction is suppressed for the other initial hyperfine state with total angular momentum $F^+ = 2$. Correspondingly for reaction 1, where the nuclear spin does not change in the reaction, the two available final states have the same total angular momentum as the initial state, $F = 1, 2$, and the reactions from both the initial hyperfine states are possible. Millielectronvolt hyperfine splitting dictates the branching ratio for these two nuclear reactions. In hydrogen-like ^{7}Be^{3+} ion the population levels of the two hyperfine states (or equivalently the spin temperature) are determined by the rates of radiative decay and pumping due to well known physical processes.

Our calculation is simplified because pumping by the CMB radiation field and due to electron collisions is much faster than the decay rate and cosmological time, i.e. the spin temperature should be close to the CMB temperature T equal at that time to the electron temperature. The energy of the hyperfine splitting is much smaller than the temperature at that time. This means that the spin temperature is very high compared to the hyperfine splitting and the hyperfine structure sublevels are populated according to their statistical weights.

The Lyman-α resonant scattering (Field 1958; Varshalovich 1967) with rate $P_\alpha \sim 4\pi \int d\nu \sigma_\nu I_\nu/(h\nu) \sim 100\mathrm{s}^{-1}$ at $z \sim 30000$, spin changing collisions with electrons with rate $\sim n_e \kappa_{10} \sim 10^{-4}\mathrm{s}^{-1}$ (Furlanetto and Furlanetto 2007) and stimulated emission and absorption of CMB at hyperfine transition with rate $\sim B_{21} I_\nu \sim 4 \times 10^{-6}\mathrm{s}^{-1}$ are all faster than the decay rate $\lambda \sim 7 \times 10^{-8}\mathrm{s}^{-1}$ and would make the spin temperature equal to the matter/radiation temperature T. Above σ_ν is the absorption cross section for Lyman$-\alpha$ photons including the line profile from Doppler broadening. I_ν is the background CMB intensity. It corresponds to

Wien region of the black body spectrum for the Lyman-α photons and Rayleigh-Jeans region for the hyperfine transition radiation. B_{21} is the Einstein B coefficient for stimulated emission. n_e is the electron number density and κ_{10} is the spin change cross section. $\kappa_{10} \propto Z^{-2}$ for hydrogenic ions (Augustin, Müller, and Greiner 1989), where Z is the nuclear charge. There is also a mild energy dependence of the cross section at temperatures of interest of $\sim 1/T^{1/2}$. The spin change cross section for hydrogen-electron collisions is of the order $\sim 10^{-9}\mathrm{cm}^3\mathrm{s}^{-1}$ at $T \sim 10^5$K (Smith (1966);Furlanetto and Furlanetto (2007)) and thus for $^7\mathrm{Be}^{3+}$ it will be $\sim 10^{-10}\mathrm{cm}^3\mathrm{s}^{-1}$. Thus Lyman-$\alpha$ scattering, Ionization and recombination, Collisions with electrons and stimulated emission and radiation of CMB and maintains $T_{spin} = T$. These rates are plotted in Figure 1 along with the expansion rate defined by the Hubble parameter $H(z)$. It is interesting to note that a typical hydrogenic beryllium atom would have flipped its electron spin a billion times due to Lyman-α scattering and recombined and ionized 100 times before finally being able to decay. The energy difference between the two hyperfine states is 10^{-4}eV $<<$ T. Thus the hyperfine states would always be distributed according to their statistical weights.

In helium-like $^7\mathrm{Be}^{2+}$ (or Li-like and neutral ^{7}Be) spin directions of two 1s shell electrons is always opposite and the problem radically differs from the problem in the hydrogen-like ion. Thus there is no hyperfine splitting in the case of helium-like ions, but the relative direction of the spins of the captured electron and nucleus is of great importance. We can write the probabilities of the two reactions in helium-like ions in terms of the corresponding probabilities of the hydrogen-like ions in the two hyperfine states using the recent theoretical calculations of Patyk *et al.* (2008) which have the support of experiments involving hydrogen-like and helium-like ^{142}Pm ions (Winckler *et al.* 2009). Then we can use these relations and the relative populations of the hyperfine structure sub-levels in the hydrogen-like ions to find the formula for the probabilities of both channels of interest. The reactions for hydrogen-like $^7\mathrm{Be}^{3+}$ and helium-like *best* are summarized in Figures 2 and 3.

For reaction 1 the initial and final spin of the nuclei are same, $I = 3/2$ and the electron

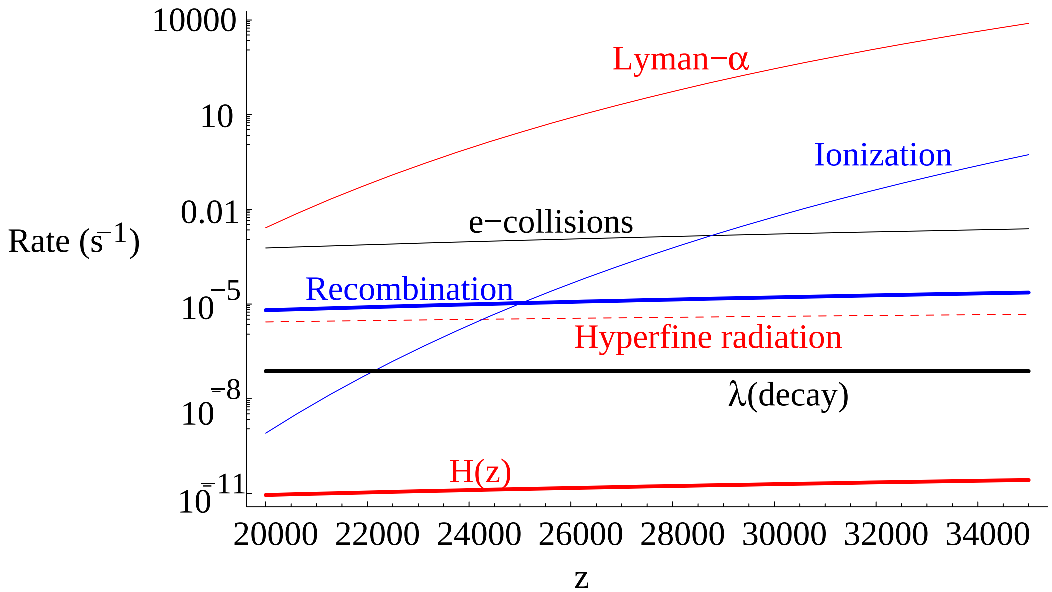

Fig. 1.— Comparison of different processes influencing beryllium to lithium decay. It is interesting to note that a typical hydrogenic beryllium atom would have flipped its electron spin a billion times due to Lyman-α scattering and recombined and ionized 100 times before finally being able to decay.

capture rates of $^7Be^{2+}$ and $^7Be^{3+}$ are related by (Patyk *et al.* 2008)

$$\lambda_{^7Be^{2+}} = \left(\frac{2F^+ + 1}{2I+1}\right)\lambda^+ + \left(\frac{2F^- + 1}{2I+1}\right)\lambda^-, \tag{3}$$

where $\lambda^\pm$ are the decay rates from two hyperfine states of $^7Be^{3+}$. If $f^\pm$ are the fraction of atoms in the two hyperfine states, the net decay rate is given by

$$\begin{aligned} \lambda_{^7Be^{3+}} &= f^+\lambda^+ + f^-\lambda^- \\ &= \left(\frac{2F^+ + 1}{2(2I+1)}\right)\lambda^+ + \left(\frac{2F^- + 1}{2(2I+1)}\right)\lambda^- \\ &= \lambda_{^7Be^{2+}}/2, \end{aligned} \tag{4}$$

where we used the fact that $(2F^+ + 1) + (2F^- + 1) = 2(2I+1)$. The factor of two can be understood as follows. In the helium-like atom both channels corresponding to λ^+ and λ^- are available simultaneously which are added according to the statistical weights. For the hydrogen-like atom also for high spin temperature we add the probabilities of two channels according to the statistical weights. But for the helium-like atom the capture rate gets

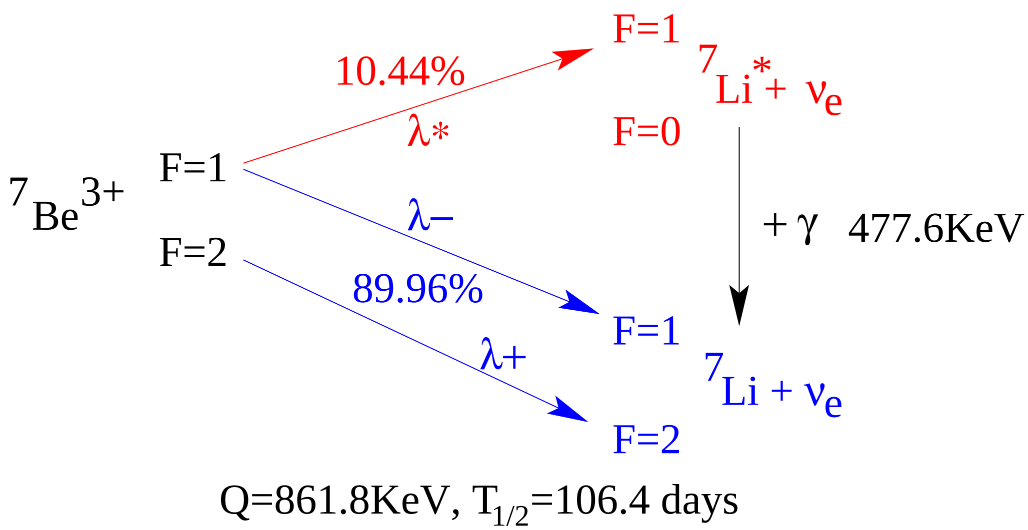

Fig. 2.— Effect of hyperfine splitting of $^7Be^{3+}$ on the nuclear reactions. The half-life given above corresponds to the high redshift universe when the spin temperature is maintained at a high value by collisions with electrons. The half-life would be different if the populations of hyperfine levels of hydrogenic $^7Be^{3+}$ are not distributed according to their statistical weights.

multiplied by a factor of two corresponding to the fact that any of the available electrons can be captured through any of the available channels. Thus the factor of two is the result of the fact that there are two electrons available for helium-like atom and that for high spin temperature for the hydrogen-like atom we add the capture rates according to their statistical weights. This factor would, in general, be different from two if the atoms in the hyperfine state were not distributed according to their statistical weights, for example at low temperatures comparable to the energy difference between the two states. Since the statistically averaged rate coefficients relevant for our calculation for the helium-like and hydrogen-like atoms differ by a just factor of two, we do not need the individual rates for λ^+ and λ^- and can use the experimental result for the helium-like/neutral ^{7}Be.

For reaction 2 however the $^7Li^*$ has a spin of $1/2$ and only capture from F^- state is allowed. The above formula is valid with $\lambda^+ = 0$ and for the net decay rate we have the same result, $\lambda^*_{^7Be^{3+}} = \lambda^*_{^7Be^{2+}}/2$. We are using * for the reaction rates of reaction 2 while no * indicates the reaction rates for reaction 1. Using the laboratory value of $\lambda_{\rm lab} = \ln 2/53.2$days for the total decay rate of $^7Be^{2+}$, we get net decay rate $\lambda_{\rm bbn} = 0.5\lambda_{\rm lab}$ with the same branching

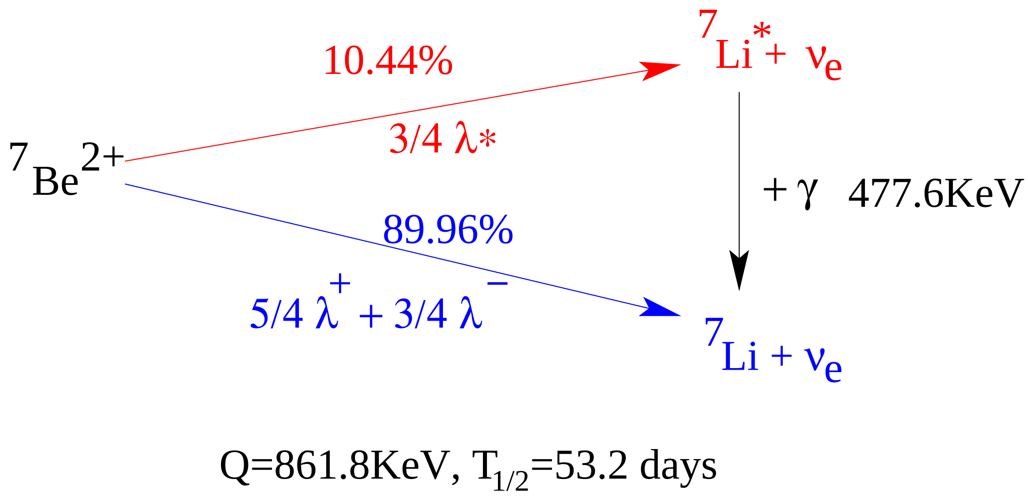

Fig. 3.— Decay of helium-like ^{7}Be^{2+}.

ratio, 10.4% of the decays following reaction 2. The half life of hydrogen-like ^{7}Be^{3+} with the hyperfine states distributed according to their statistical weights is thus equal to 106.4 days. Coincidently this is the same result we would have got from the simple considerations of the electron density at the nucleus. We must emphasize here that the exact life time of ^{7}Be^{3+} is not very important for us as long as it is much shorter than the cosmological time at the epoch of beryllium to lithium conversion and the duration of ^{7}Be^{3+} recombination. All the width of the two neutrino lines comes from the kinetics of recombination.

3. Recombination of ^{7}Be

Now we can write down the kinetic equations for recombination of ^{7}Be^{4+}.

$$\frac{dX_{^7\mathrm{Be}^{4+}}}{dz} = \frac{1}{H(z)(1+z)}\left[n_e(z)X_{^7\mathrm{Be}^{4+}}\alpha_{^7\mathrm{Be}^{4+}} - \beta_{^7\mathrm{Be}^{3+}}X_{^7\mathrm{Be}^{3+}}\right] \quad (5)$$

$$\frac{dX_{^7\mathrm{Be}^{3+}}}{dz} = \frac{1}{H(z)(1+z)}\left[-n_e(z)X_{^7\mathrm{Be}^{4+}}\alpha_{^7\mathrm{Be}^{4+}} + \beta_{^7\mathrm{Be}^{3+}}X_{^7\mathrm{Be}^{3+}} + \lambda_{\mathrm{bbn}}X_{^7\mathrm{Be}^{3+}}\right] \quad (6)$$

$$X_{^7\mathrm{Be}} = X^{decay}_{^7\mathrm{Li}} + X_{^7\mathrm{Be}^{4+}} + X_{^7\mathrm{Be}^{3+}}, \quad (7)$$

where $n_e(z)$ is the number density of electrons at redshift z, $H(z)$ is the Hubble parameter, $\alpha_{^7\mathrm{Be}^{4+}}$ is the total recombination coefficient including recombination to the ground state.

$X^{decay}_{^7\mathrm{Li}}$ is the lithium fraction coming from decay of beryllium and excludes the lithium produced during BBN. Because of the extremely low number density of beryllium, the number of ionizing photons released during direct recombination to the ground state is negligible (about 10 orders of magnitude less) compared to the ionizing photons already present in the background radiation and can be neglected. $\beta_{^7\mathrm{Be}^{3+}}$ is the total ionization coefficient which is related to $\alpha_{^7\mathrm{Be}^{4+}}$ by the condition that Saha equation must be satisfied in equilibrium. Thus

$$\beta_{^7\mathrm{Be}^{3+}} = \alpha_{^7\mathrm{Be}^{4+}} \frac{(2\pi m_e k_B T)^{3/2}}{(2\pi\hbar)^3} e^{\frac{-\chi_{Be}}{k_B T}} . \tag{8}$$

Note that the 2-photon decay rate from $2s$ state of $^7\mathrm{Be}^{3+}$ is $3.4\times10^4\mathrm{s}^{-1}$ (Goldman 1989). This is much faster than the same rate for hydrogen $\sim 8\mathrm{s}^{-1}$ due to the higher charge of the nucleus. More importantly it is much faster than the ionization rate $\beta \sim 6 \times 10^{-3}\mathrm{s}^{-1}$ at $z \sim 30000$ and the electron capture rate $\lambda_{bbn} = 7.5 \times 10^{-8}\mathrm{s}^{-1}$, $t_{1/2} = 106.4$days. Thus $2s$ level must be included in the total recombination coefficient. The number of Lyα photons produced would be of order $X_{^7\mathrm{Be}}$ and can be neglected. Thus equations for beryllium recombination are much simpler than that of hydrogen and helium recombination. $\alpha_{^7\mathrm{Be}^{4+}}$ is the total recombination coefficient including direct recombinations to the ground state and is given by (Pequignot, Petitjean, and Boisson 1991)

$$\alpha_{^7\mathrm{Be}^{4+}} = 10^{-13} Z \frac{at^b}{1+ct^d}\ \mathrm{cm}^3\mathrm{s}^{-1}, \tag{9}$$

where $t = (T/10^4K)/Z^2$, $a = 5.596$, $b = -0.6038$, $c = 0.3436$ and $d = 0.4479$ and Z is the nuclear charge.. Figure 4 shows the result of integrating the recombination equations for beryllium. For comparison the Saha equilibrium solution for beryllium recombination is also shown. The beryllium to lithium conversion occurs significantly earlier at $z = 30000$ than the $z = 25000$ value predicted by the Saha solution. The reason of the difference is connected with the short decay time of recombined $^7\mathrm{Be}^{3+}$. In the Saha equation we follow the balance between the recombination and photoioinization but a typical atom has recombined and ionized many times even though the net recombination in equilibrium may be small. In reality due to the decay of beryllium on a time scale much shorter than the cosmological time the equilibrium is never established.

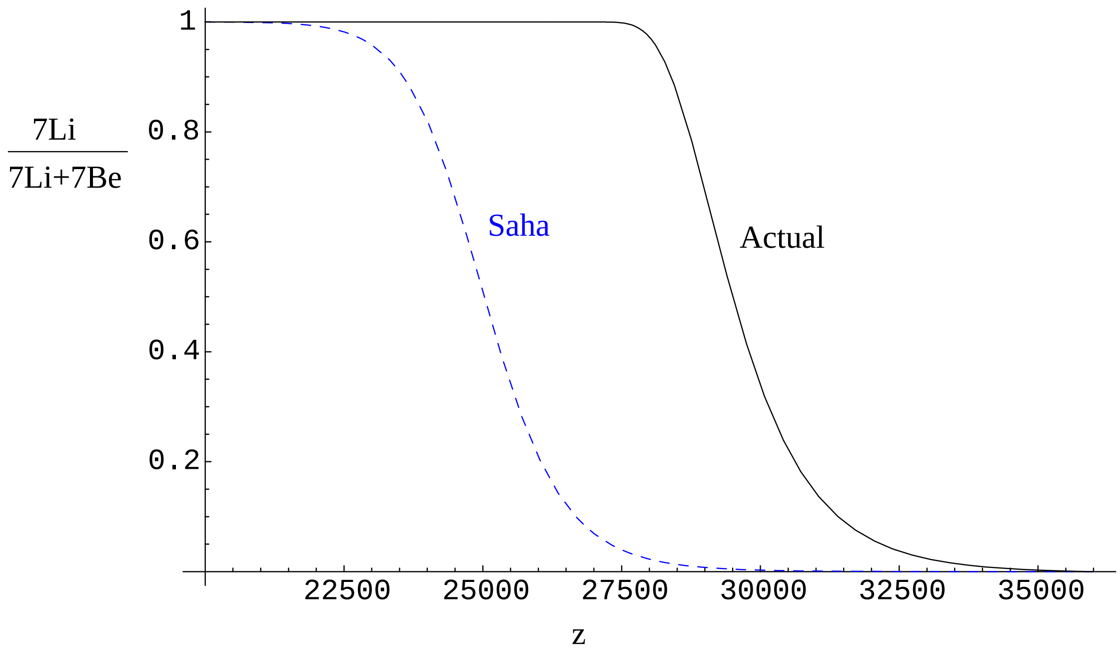

Fig. 4.— Lithium number density as a fraction of total beryllium and lithium number density from decay of beryllium. For comparison thermal equilibrium results using Saha equation are also plotted.

4. Energy release and narrow doublet of neutrino lines

Every decay of beryllium to lithium is accompanied by emission of an electron neutrino with 89.6% of them having energy of 861.8KeV and nuclear recoil energy of 56.5eV. 10.4% of the decays go to excited state of lithium, electron neutrino gets 384.2KeV and nuclear recoil has energy of only 11.2eV which is slightly larger than the thermal energy $T = 7eV$ of the plasma at redshift $z = 30000$. The recoil velocity of $v/c = 5.85 \times 10^{-5}$ will result in a natural line width of 56eV due to Doppler shift for the 477.6KeV photon emitted when lithium relaxes to ground state almost instantaneously ($T_{1/2} = 73$fs). These photons will down scatter by Compton scattering with electrons giving most of their energy to the plasma due to recoil effect (Zeldovich and Sunyaev 1969). The energy transfer by Compton scattering will become inefficient when the photons reach the critical energy of $m_e H(z)/n_e \sigma_T|_{z=30000} \sim 80$eV when the energy transfer rate becomes less than the expansion rate (Bernstein and Dodelson (1990)). This will leave a small distortion in the high energy part of CMB. The energy transfered to plasma will additionally cause a $y-$type distortion of $\sim (0.104E_\gamma/T)X_{^7\mathrm{Be}}\eta \sim 10^{-16}$. The neutrinos however will free stream to us and we can calculate the neutrino spectrum today. This is plotted in Figure 5 including both 861.8KeV neutrinos and 384.2KeV neutrinos,

$$-\frac{dn_\nu}{dE}(E) = n_{H0}\left[\frac{0.896(1+z)^2}{861.8\mathrm{KeV}}\frac{dX^{decay}_{^7\mathrm{Li}}}{dz}|_{1+z=\frac{861.8\mathrm{KeV}}{E}} + \frac{0.104(1+z)^2}{384.2\mathrm{KeV}}\frac{dX^{decay}_{^7\mathrm{Li}}}{dz}|_{1+z=\frac{384.2\mathrm{KeV}}{E}}\right], \tag{10}$$

where n_{H0} is the density of hydrogen nuclei at $z = 0$. The full width at half maximum (FWHM) for the first line is 2.3eV and the central energy is 29.5eV. For the second line the FWHM is 1eV with a central energy of 13.1eV. The line width at half maximum is $\delta E/E = 7.8\%$. The width and asymmetric line profile of these lines is defined by the kinetcis of recombination.

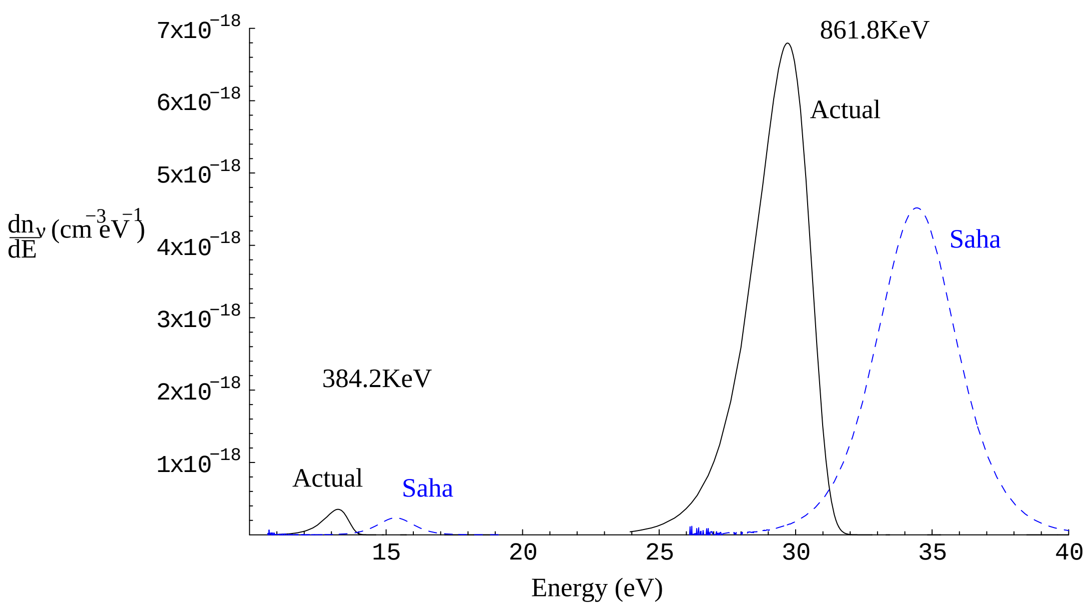

Fig. 5.— Neutrino spectrum from beryllium decay in the early Universe. There are two lines corresponding to two electron capture decay branches. For comparison equilibrium results (marked Saha) are also plotted. The FWHM for high energy line is 2.3eV with a central frequency of 29.5eV. For second line FWHM is 1eV central frequency is 13.1eV. The line width at half maximum is $\delta E/E = 7.8\%$. The width and asymmetric line profile of these lines is defined by the kinetcis of recombination.

5. Comparison with other sources of neutrinos and energy release before recombination

At $T \sim 0.1$MeV annihilation of electrons and positrons makes the biggest contribution to cosmic neutrinos, however these neutrinos have a much broader thermal spectrum and form part of the low energy cosmic neutrino background (CNB). Decay of neutrons and other nuclear reactions during BBN also contribute neutrinos, but due to high redshift $z \sim 10^8$ these neutrinos are also today redshifted to the sub-eV energies, $\sim 1\text{MeV}/10^8 \sim 0.01$eV. The spectrum of these neutrinos would be broad since they are emitted over a period when redshift changes by a factor of ~ 2. Energy released during BBN is also quickly thermalized and does not lead to spectral distortions. Decay of tritium created during BBN occurs at $z \sim 2.5 \times 10^5$ corresponding to half life of 12.32 years. Decay of tritium to helium-3 results in an electron with average energy of $Q_e = 5.7$KeV and an antineutrino with average energy ~ 12.9KeV. The antineutrino spectrum would be broad as they decay over a period corresponding to the age of the Universe at that time and these antineutrinos would have an average energy of $\sim 0.05eV$ today assuming they have zero mass. About 10% of tritium has decayed by $z = 6.35 \times 10^5$ and 90% by z=1.35×10^5 leading to the width of the neutrino spectrum of $\delta E/E \sim 1.4$. This broadening is comparable to the intrinsic width of the neutrino spectrum $\delta E/E \sim E_{max}/E_{avg} \sim 18.6/12.9 = 1.4$. Thus non-thermal neutrinos from all sources before recombination other than ^{7}Be decay would have a spectrum much broader than those from ^{7}Be decay and would have much lower energy. These low energy neutrinos would be non-relativistic today in one or more mass eigenstates (Nakamura and Particle Data Group 2010) compared to relativistic neutrinos from ^{7}Be decay. The energy released into the plasma from tritium decay in the form of energetic electrons would result in a chemical potential of $\mu \sim (Q_e/T)(n_{^3H}/n_\gamma) \sim 10^{-15}$ in the CMB. This is about the same amount of entropy generated in the beryllium decay much later.

6. Conclusions

Lithium-7 observed today was originally produced as beryllium-7 during primordial nucleosynthesis (Wagoner, Fowler, and Hoyle 1967). Although half life of beryllium atoms is very short, it has to wait until the beginning of recombination epoch to decay. We have calculated the exact redshift when this happens. We have also estimated the effect of energy release during the decay on the cosmic microwave background. In addition the neutrinos produced during the decay give rise to unique narrow lines in the cosmic neutrino background. These lines are too weak to be observable today. We should mention that the detection of the much more numerous but lower energy CNB neutrinos is currently being discussed (Ringwald 2009). The recombination and decay of beryllium has nevertheless theoretical significance. It marks the end of primordial nucleosynthesis and the beginning of recombination.

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REFERENCES

J. Augustin, B. Müller, W. Greiner, Zeitschrift fur Physik D Atoms Molecules Clusters **14**, 317 (1989)

J. N. Bahcall, Neutrino astrophysics, (1989)

J. Bernstein, S. Dodelson, Phys. Rev. D **41**, 354 (1990)

G. B. Field, Proc. IRE **46**, 240 (1958)

S. R. Furlanetto, M. R. Furlanetto, MNRAS **374**, 547 (2007)

S. P. Goldman, Phys. Rev. A **40**, 1185 (1989)

C. Huh, Earth and Planetary Science Letters **171**, 325 (1999)

F. Iocco, G. Mangano, G. Miele, O. Pisanti, P. D. Serpico, Physics Reports **472**, 1 (2009)

K. Nakamura, Particle Data Group, Journal of Physics G Nuclear Physics **37**, 075021 (2010)

Z. Patyk, J. Kurcewicz, F. Bosch, H. Geissel, Y. A. Litvinov, M. Pfützner, Phys. Rev. C **77**(1), 014306 (2008)

P. J. E. Peebles, ApJ **153**, 1 (1968)

D. Pequignot, P. Petitjean, C. Boisson, A&A **251**, 680 (1991)

A. Ringwald, Nuclear Physics A **827**, 501 (2009)

P. D. Serpico, S. Esposito, F. Iocco, G. Mangano, G. Miele, O. Pisanti, JCAP **12**, 10 (2004)

F. J. Smith, Planetary and Space Science **14**, 929 (1966)

D. R. Tilley, C. M. Cheves, J. L. Godwin, G. M. Hale, H. M. Hofmann, J. H. Kelley, C. G. Sheu, H. R. Weller, Nuclear Physics A **708**, 3 (2002)

D. A. Varshalovich, Soviet Journal of Experimental and Theoretical Physics **25**, 157 (1967)

R. V. Wagoner, W. A. Fowler, F. Hoyle, ApJ **148**, 3 (1967)

N. Winckler, H. Geissel, Litvinov, et al., Physics Letters B **679**, 36 (2009)

Y. B. Zeldovich, R. A. Sunyaev, Ap&SS **4**, 301 (1969)

Y. B. Zeldovich, V. G. Kurt, R. A. Syunyaev, Zh. Eksp. Teor. Fiz. **55**, 278 (1968)