PARTICULARITIES OF NUCLEOGENESIS AT EARLY STAGE OF THE UNIVERSE EVOLUTION*

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Particularities of nucleogenesis and role of neutrons at early stage of the Universe evolution are considered. It means a period of adiabatic extension of the Universe when photons are no longer able to prevent nucleosynthesis, and the leading part is given to neutron component of the matter. This short moment defines the main primordial abundance of chemical elements. Thermodynamic description of nucleus matter is carried out in the same way as it is made in the well-known problem of "ionization equilibrium" of atomic plasma.

Introduction

Scenario of the Universe evolution after "The Big Bang" is well grounded by modern physical theories. These theories give a good explanation of observation phenomena and are confirmed by vast base of experimental data (see, for example [1-11]). It is remarkable that decrease of density and temperature has been creating conditions for structure alteration of the matter many times for cooling down and expansible Universe.

At the early stage of the Universe life ($t > 1\ min$), when photons are no longer able to prevent nuclei synthesis, the key role is given to neutron component of matter.

Neutron component creates a certain variety of the lightest nuclei and disappears leaving a sufficient portion of Helium isotopes and some tiny portions of *Li* and *Be* isotopes. Free neutrons disappear in energetic flame of these reactions not using even a quarter of their own lifetime. Further, the Universe matter has been evolving smoothly without free neutrons.

However, the synthesis is already cut off at nuclei $A \leq 10$. As it is known the formation of nuclei $Z \geq 4$ is impossible due to Coulomb barrier, which became insuperable at very low energies. Further, substance temperature and density fall down to a degree when nuclear forces are switched off. Synthesis of even the lightest nuclei is impossible [9-11].

Then, structure formation takes its next stage: where neutral objects of matter appear – atoms and molecules. Electromagnetic radiation lost common

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thermodynamic equilibrium – the matter is transparent for photons. Now it is observed as a relic radiation [4,5,10].

At the following stages of the Universe evolution, more interesting processes take their start and most of them continue at the present. For example, the following can be recalled: a gravitational formation of galaxies and stars, strong compression of matter inside stars, which leads again to nuclear reactions creating a middle nuclei, star explosions and production of heavy nuclei, formation of complex objects, pulsars, neutron stars, etc. [1-6].

Abundance of light elements in standard cosmological model is usually calculated on the basis of numerical solution of evolution equations system. These calculations require such common parameters as nuclear reaction data, the number of baryons, photon density, etc. [9-11]. Coordination between the major segment of the data and predictions demonstrates a success of standard model based on "the Big Bang" concept.

However, information on abundance of the lightest nuclei causes a number of questions and requires additional analysis and clarifications.

1. Early stage of the Universe extension – peculiarities of thermodynamic equilibrium

This work is concerned a private question – a role of neutron in nucleogenesis at early stage of the Universe evolution. It is taken a time of minutes since "The Big Bang" that determines the main primordial abundance of nuclei.

It is clear that abundance depends on intensity of nuclear processes, which differ at various stages. For instance, nuclear synthesis at early stage of the Universe under adiabatic extension is quite different from the one taking its process inside the stars under adiabatic compression of matter. The most important factor is availability of neutrons. This component is available and rather essential at the early Universe evolution. In star environment, on the contrary, neutrons appear only as secondary product of nuclear reactions.

Thermodynamic description of nuclear matter is used in the frames of approach of quantum state functions. The key advantage of the description is independence of thermodynamic values from the details of interactions between particles of the matter. These values are defined by integral characteristics (average energy or temperature, pressure etc.) and statistical weights of initial and final states.

1.1. Thermodynamic equilibrium at the first seconds.

Before nuclear synthesis at $T > 10\ MeV$ $(t < 1c)$ nucleons with photons, leptons are in a state of common thermodynamic equilibrium [10,11].

Due to reactions of weak interaction: $p+e^- \leftrightarrow n+\nu_e$; $p+\overline{\nu}_e \leftrightarrow n+e^+$; $n+\nu_e \leftrightarrow p+e^-$, ratio of neutron number N_n to proton number N_p is defined by the factor (considering that $k=1$, $\hbar=1$, $c=1$): $N_n / N_p = \exp(-\Delta m / T)$, where $\Delta m = m_n - m_p \approx 1{,}3 MeV$.

At $T \approx 3MeV$, for example: $N_n / N_p \approx 0{,}65$.

In the state of equilibrium an abundance of protons and neutrons is given by the following [10]:

$$X_{n,p} = N_{n,p} /(N_n + N_p) = 1/\left[\exp(\pm \Delta m / T) + 1\right] \tag{1}$$

and X_A - abundance of certain nucleus (for element of number Z and mass A) is defined by the Boltsmann's distribution:

$$X_A = \frac{g_A}{2} A^{5/2} \left[\sqrt{\frac{8}{\pi}} \zeta(3) \; (T / m_N)^{3/2} \eta \right]^{A-1} X_p^Z X_n^{A-Z} \exp(E_A / T) \tag{2}$$

where $\eta = N_B / N_\gamma$ is ratio of baryon number to photon number, E_A - bound energy of nucleus [10].

If temperature is below $T_f \approx 0{,}8$ MeV, the speed of weak processes is less than the one of the Universe extension, and weak interaction passes to the category of slow one – "it freezes". So, neutrons leave the state of equilibrium with protons. That is why neutron and proton number' ratio "freezes" at temperature T_f .

Mass fractions of neutron X_n and proton X_p are no longer described by equilibrium expressions and become almost constant. Characteristic abundance of light elements is defined by the following values [10]:

$$X_n \approx 1/7,\; X_D \approx 10^{-12},\; X_{^3He} \approx 10^{-23},\; X_{^4He} \approx 10^{-28},\; X_{^{12}C} \approx 10^{-108}, \ldots \tag{3}$$

1.2. Thermodynamic equilibrium at the first minutes

At this period of the early Universe the lightest nuclei generation is especially effective at temperatures T ~ 0.3 ÷ 0.1 MeV.

Considering thermodynamic description of the substance the following physical principle is taken as a basis: interactions of the fastest component in speed are considered as main and taken into account first. Substance component that meets this requirement provides a thermodynamic equilibrium in the system.

It is obvious that the fast component of the substance is the neutrons. Other components cause slow change as compared with actions of the main one.

It is more convenient to divide nuclei into isotope groups: H group - *(p, d, t)*, He group *(^3He, ^4He)*, Li group *($^{6\text{-}9}Li$)*, etc. Groups differ in the value Z – the number of chemical element.

It is known that reaction product can be defined by $J(E) = f\sigma$, where $f = E\exp(-E/T)$ is the Maxwell curve of particles flow, $\overline{E} = kT = T$ is an average energy, $\sigma(E) = \pi ƛ^2 D$ - a cross section of reaction, *D(E)* - Coulomb barrier transparency.

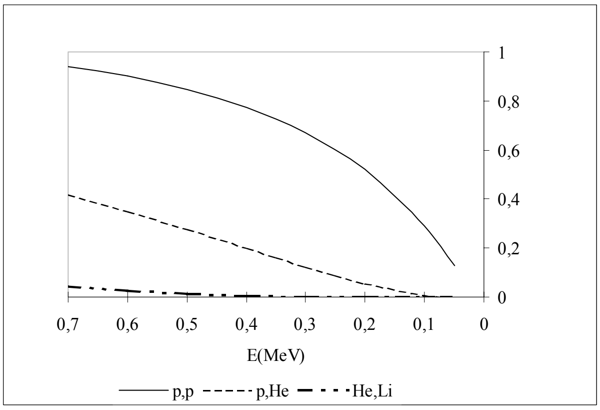

Figure 1. *D(E)* – function of Coulomb barrier transparency.

In case of nucleon-nucleus reactions the value D shows ratio of speeds of *p,A* reaction to *n,A* one, if only their nuclear interactions are almost equal.

At about *T ~ 0.3 ÷ 0.1 MeV* speeds the neutron reactions with nuclei are rather exceeding those of protons. This is the reason why the neutrons with all-penetrating character and quick interaction cause thermodynamic equilibrium in the matter faster than others.

2. “Ionization equilibrium” in the lightest nuclei synthesis

Thermodynamic description of nuclear matter at period $t \approx 1 \div 3\,\text{min}$, when the lightest nuclei synthesis occurs, can be carried out in the same way as it is made in the well-known method of atomic plasma “ionization equilibrium” description. This method comes to the following [12].

A gas at low temperatures is considered to consist of neutral atoms. With temperature increase atoms get ionized:

$$A_0 \to A_1 + e,\;\; A_1 \to A_2 + e,\;\; A_2 \to A_3 + e, \ldots \qquad (4)$$

where A_0 - neutral atom, A_1 - once ionized, A_2 - twice ionized and so on.

Actually the ionization equilibrium is a private case of chemical equilibrium. As it is applied to these reactions the law of Acting Mass gives a set of equations

$$\frac{c_{n-1}}{c_n c} = PK^n(T), \quad n = 1,2,\ldots \tag{5}$$

where c_0 means neutral atom concentration, $c_1, c_2, \ldots$ - different ion concentrations, but c is electron concentration. The equation $c = c_1 + 2c_2 + \ldots$ reflects electrical neutrality of gas in general.

As it is known, equilibrium constants can be described as follows:

$$K^n = \frac{g_{n-1}}{2g_n}\left(\frac{2\pi}{m_e}\right)^{3/2} T^{-5/2}\exp(I_n / T) \tag{6}$$

where $g = (2L+1)(2S+1)$ is statistical weight of atom (or ion), L - orbital moment and S – spin of atom, m_e - mass of electron, but $I_n = \varepsilon_{0,n} - \varepsilon_{0,n-1}$ - energy of n - ionization. This set of equations defines a concentration of different ions and gives their functional dependence on temperature change.

In our issue the substance components’ correlation changes not due to atom ionization but because of the nuclear reactions with neutrons, and the temperature falls not rises.

Neutrons play the role of electrons. At the final stage all neutrons are caught by nuclei. Ionization reaction chain can be recorded as follows for each isotope-group:

$$A \to (A-1) + n,\ (A-1) \to (A-2) + n,\ (A-2) \to (A-3) + n, \ldots \tag{7}$$

It is obvious that the most accurate solution of the problem requires taking into account the nuclear reactions with proton participation and nuclei-nuclei reactions.

However, at the first step one can omit reactions between charged particles because of the stated role of neutrons – as main component, which quickly creates thermodynamic equilibrium in the system. Role of superfluous protons can be considered as a substance – solvent.

In case of chemical equilibrium, solvent is passive in reactions between chemical reagents. Under these circumstances another peculiarity of the problem appears that deals with an issue concluded in each isotope group, which can be considered separately. It means that within one isotope group neutrons can provide a thermodynamic equilibrium very fast.

At the same time, the reactions between nuclei of different isotope groups are as “slow” processes connected with overcoming of the Coulomb barrier.

2.1 H group

Reaction chain in hydrogen isotope group is: $p+n \to d+\gamma$, $d+n \to t+\gamma$, . . If it is taken other way (i.e. from right to left), it gives an equation for equilibrium constants:

$$\frac{c_t}{c_d\, c_n} = PK^1(T), \quad \frac{c_d}{c_{\tilde{p}}\, c_n} = PK^2(T) \tag{8}$$

Here c_t is triton concentration, c_d means that of deutrons, c_n - neutrons, but $c_{\tilde{p}} = (c_n - c_d)/2$.

Equilibrium constants are as follows:

$$\begin{aligned} PK^1(T) &= \frac{1}{3} M(T)\exp(I_1/T), \quad I_1 = \varepsilon_t - \varepsilon_d \approx 6{,}25 MeV \\ PK^2(T) &= \frac{3}{4} M(T)\exp(I_2/T), \quad I_2 = \varepsilon_d \approx 2{,}23 MeV \end{aligned} \tag{9}$$

where for the adiabatic process:

$$\begin{aligned} M(T) &= \frac{P}{T}\left(\frac{2\pi}{m_n T}\right)^{3/2} \approx C_M\, T^{-0{,}01} \approx 10^{-6}, \\ \frac{P}{T} &= Const\, T^{-\frac{1}{1-\gamma}}, \quad \gamma \approx 1.67. \end{aligned} \tag{10}$$

As an initial quantity c_n is taken in accordance with (3). Then, coordinated values of concentrations can be gained according to Eqs. (8), (9).

Table 1. Concentrations of H-group isotopes at different temperature.

T (MeV)	0.3	0.25	0.2	0.1
C_n	0.13	$0.5\cdot10^{-1}$	$0.7\cdot10^{-2}$	$\sim10^{-8}$
C_d	$0.63\cdot10^{-5}$	$0.3\cdot10^{-4}$	$1.3\cdot10^{-6}$	$\sim10^{-13}$
C_t	$2.7\cdot10^{-4}$	$0.8\cdot10^{-1}$	0.12	0.13

It should be noted that c_t rapidly grows from a negligible quantity to a high value comparable with initial concentration of free neutrons.

Then, in the nearest future triton will decay and reform into nuclei ^3He . It may be the reason of rather high abundance of ^3He at the Universe.
It is important that at $T < 0{,}25\ MeV$ neutron component is rapidly degenerating.

2.2. He group

In this group one reaction is enough to be considered: $^3He + n \to {}^4He + \gamma$.
Then, the relation for equilibrium constant is as follows:

$$\frac{c_4}{c_3^2} = P\,K(T) \approx \frac{C_M}{4}\exp(20{,}57\,/\,T) \qquad (11)$$

where $c_{3,4}$ are concentrations of corresponding isotopes. From Ed. (11) follows that with temperature decrease the concentration c_3 tends to zero as compared with c_4.

The fact of rapid growth of c_4 is to be marked as tritons in previous case. It means that free neutrons are immediately caught by nuclei ^3He. As a result ^3He turns to ^4He.

Table 2. Ratio of concentrations of He-group isotopes at different temperature.

T (MeV)	0.3	0.25	0.2	0.1
C_4/C_3	10^{-12}	10^{-15}	10^{-19}	10^{-41}

It can be said that when temperature falls, the number of free neutrons at $T < 0.25MeV$ decreases very fast; thus, it becomes negligibly small. That is why, reactions with free neutron participation are subject to be off very soon.

Further, a synthesis of nuclei is carried out between protons and the lightest nuclei or between the lightest nuclei.

2.3. Li group

Li isotope group processes are considered to be significantly more complicated than in the previous groups. It is attributed the importance to issues of generation and decay of Li group nuclei.

Nucleus generation is due to these reactions: $\alpha + d \to {}^6Li + \gamma$, $\alpha + t \to {}^7Li + \gamma$, ${}^3He + t \to {}^6Li + \gamma$, ... , while there is a decay of : ${}^6Li + n \to \alpha + t$, ${}^7Li + p \to \alpha + \alpha$, ...

However, it should be noted that a distinguishing feature of thermodynamic description of the matter is an independence from the details of specific reactions. The only thing important is that a speed of setting thermodynamic and chemical balances has to be much greater than a speed of change of total concentrations of Li-group isotopes increasing or falling due to external influence, for instance.

As in previous cases the consideration is held in the frames of "ionization equilibrium" approach. The chain of transformations: ${}^6Li + n \to {}^7Li + \gamma$, ${}^7Li + n \to {}^8Li + \gamma$, ${}^8Li + n \to {}^9Li + \gamma$, results in the set of equations.

$$\frac{c_9}{c_8 c_n} = \frac{2}{5}\widetilde{C}_M \exp(4{,}06/T), \quad \frac{c_8}{c_7 c_n} = \frac{5}{8}\widetilde{C}_M \exp(2{,}03/T),$$
$$\frac{c_7}{c_6 c_n} = \frac{2}{3}\widetilde{C}_M \exp(7{,}25/T), \quad and \quad c_n = c_8 + 2c_7 + 3c_6, \tag{12}$$

It is impossible to link directly the constant $\widetilde{C}_M$ with the value $M(T)$ due to the suggestions concerning the flow of generation and disintegration of Li-group isotopes. In order to achieve values that meet requirements of equilibrium, constant ratio is possible.

Table 3. Concentrations of Li-group isotopes at different temperature.

T (MeV)	0.3	0.25	0.2	0.1
C_6	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-14}$	$\sim 10^{-28}$
C_7	$\sim 10^{-12}$	$\sim 10^{-10}$	$\sim 10^{-10}$	$\sim 10^{-11}$
C_8	$\sim 10^{-21}$	$\sim 10^{-17}$	$\sim 10^{-16}$	$\sim 10^{-15}$
C_9	$\sim 10^{-27}$	$\sim 10^{-22}$	$\sim 10^{-18}$	$\sim 10^{-10}$

This data proves that even though the senior isotopes c_8 and c_9 grow rather fast when temperature decreases, their concentrations fail to get appreciable values and thereof contribution can be neglected.

At the same time concentrations of ^6Li and ^7Li manage to change in contribution. It is due to significantly strong exponential dependence of corresponding equilibrium constant on the temperature.

It should be noted that if neutron validity exist till temperature $T \approx 0,1\ MeV$, the situation may could have been changed completely. Concentration of senior (unstable) isotope can be comparable with concentration of ^7Li in this case.

Conclusion

This research is aimed on a study of neutron play in nucleogenesis at the early stage of the Universe evolution. Calculations and analysis carried out lead to the following conclusions:

1. Free neutrons are very quickly caught by the lightest nuclei. This process leads to a drastic increase of senior isotope concentrations in every isotope group.
2. In H isotope group a number of tritons abruptly increases with $t \geq 3\,\text{min}$.
3. In He isotope group ^3He becomes ^4He with a moment. A great number of tritons may be a reason of ^3He abundance in nature at the present.
4. An increase of *Li* senior isotope's concentration can contribute in solving the issue of Be primordial abundance.

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