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Neutrons and features of primordial nucleosynthesis

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The analysis based on the special feature of the primordial nucleosynthesis which is a considerable quantity of free neutrons is presented. It is the early stage of the Universe evolution, when photons and neutrinos are no longer able to prevent a nuclear fusion. Penetrating interaction of neutron with any nuclei determines the key role of the neutrons as a component leading to chemical equilibrium in the nuclear matter. On the contrary, nuclear interactions between protons and nuclei are blocked by Coulomb barrier at low temperatures.

A neutron enrichment of nuclei of the lightest chemical elements is considered within the framework of the Saha equations. This method is known in physics of atomic plasma as the method of ionization equilibrium.

The Saha equations define concentrations of different ions and give their functional dependences on temperature. In our issue the substance components are changed not due to the atom ionization but because of the nuclear reactions.

This method gives simple and quick results which can be used as the first approximation for more complicated theories.

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We consider nuclear reactions at the early stage of Universe evolution ($t \sim 1 \div 3\, min$) using the method of thermodynamic description of matter states. Thermodynamic description of nuclear matter gives easy evaluations for component transformations as functions of energy, i.e. temperature.

1. Thermodynamic equilibrium in the first minutes

At this period of the early Universe the generation of nuclei of light elements is effective at temperatures $\sim 0.3 \div 0.1 MeV$ (see, for example, [1] - [4]).

The rates of neutron reactions with nuclei exceed those of protons. This is the reason why the neutrons with all-penetrating character cause the "chemical" thermodynamic equilibrium in the matter faster than other components. The main advantage of thermodynamic description is an independence of thermodynamic values on the details of the 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 [5].

The well-known method of the atomic plasma “ionization equilibrium” description is the following. A gas is considered to consist of neutral atoms at low temperatures. When the temperature increases the atoms are ionized:

$$A_0 \to A_1 + e, \;\; A_1 \to A_2 + e, \;\; A_2 \to A_3 + e, \;\; \cdots \tag{1.1}$$

where A_0 - a neutral atom, A_1 - once ionized, A_2 - twice ionized and so on. These reactions are described by the law of Acting Mass that gives a set of well-known Saha's equations

$$\frac{c_{n-1}}{c_n c} = PK_n(T), \;\; n = 1, 2, \ldots \tag{1.2}$$

where c_0 means a neutral atom concentration, $c_1, c_2, \ldots$ - different ion concentrations, c is an electron concentration. The equation $c = c_1 + 2c_2 + 3c_3 + \cdots$ in general reflects the electrical neutrality of gas.

The equilibrium constants K_n can be described as follows:

$$K_n = \frac{g_{n-1}}{2g_n} \left(\frac{2\pi}{m_e}\right)^{3/2} T^{5/2} \exp(I_n/T) \tag{1.3}$$

where g is statistical weight of atom (or ion), m_e - mass of electron, $I_n = \varepsilon_{0,n} - \varepsilon_{0,n-1}$ - energy of n - ionization. This set of equations defines concentrations of different ions and gives their functional dependences 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.

It is convenient to divide lightest nuclei into isotope groups: H group - (p, d, t), He group - $(^3He, ^4He)$, Li group - (^{6-9}Li), etc.

Neutrons play the role of electrons.

At the final stage all neutrons are caught by nuclei. Ionization reaction chain can be recorded for each isotope-group:

$$A \to (A-1) + n, \; (A-1) \to (A-2) + n, \; (A-2) \to (A-3) + n, \; \cdots \tag{1.4}$$

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

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 dealing 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 “slow” processes connected with overcoming the Coulomb barrier.

2. Nuclear equilibrium

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:

$$\frac{c_t}{c_d c_n} = PK_1(T), \quad \frac{2c_d}{c_n(c_n - c_d)} = PK_2(T) \tag{2.1}$$

Here c_t is triton concentration, c_d means that of deutrons, c_n - neutrons. Equilibrium constants are as follows:

$$PK_1 = \frac{1}{3}M(T)\exp(I_1/T), \quad I_1 = \varepsilon_t - \varepsilon_d \approx 6,25MeV, \tag{2.2}$$

and

$$PK_2 = \frac{3}{4}M(T)\exp(I_2/T), \quad I_2 = \varepsilon_d \approx 2,23MeV, \tag{2.3}$$

where for the adiabatic process:

$$M(T) \approx C_M T^{-0,01} \approx 10^{-6}. \tag{2.4}$$

An initial quantity $c_n \approx 0,13$ [3]. Then, coordinated values of concentrations can be gained according to Eqs. (2.1).

T (MeV)	0.3	0.25	0.2	0.1
c_n	0.13	0.05	$0.7 \cdot 10^{-2}$	$\sim 10^{-8}$
c_d	$0.63 \cdot 10^{-5}$	$0.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-6}$	$\sim 10^{-13}$
$2c_t$	$2.7 \cdot 10^{-4}$	0.08	0.12	0.13

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

It should be noted that c_t rapidly grows from 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 $T < 0,25MeV$ neutron component is rapidly degenerated.

In He group the key reaction is $^{3}He+n\to^{4}He+\gamma$, then:

$$\zeta(T)=\frac{c_4}{c_3^2}=PK(T)\approx\frac{C_M}{4}\exp(20.57/T) \tag{2.5}$$

where $c_{3,4}$ are concentrations of corresponding isotopes, and T in MeV as above.

It is witnessing that ζ dramatically increases when T goes down from $\zeta(0.3)\sim 10^{23}$ to $\zeta(0.2)\sim 10^{38}$ and $\zeta(0.1)\sim 10^{84}$, for example.

In Li group the chain of transformations is the following: $^{6}Li+n\to^{7}Li+\gamma$, $^{7}Li+n\to^{8}Li+\gamma$, $^{8}Li+n\to^{9}Li+\gamma$, results in the set of Eqs. like (2.1) - (2.3).

Initial quantity of ^{6}Li indicated as c_6 is taken in accordance with a simple Boltsmann's distribution [3].

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	$\sim 10^{-12}$	$\sim 10^{-10}$	$\sim 10^{-10}$	$\sim 10^{-11}$
$2c_8$	$\sim 10^{-21}$	$\sim 10^{-17}$	$\sim 10^{-16}$	$\sim 10^{-15}$
$3c_9$	$\sim 10^{-27}$	$\sim 10^{-22}$	$\sim 10^{-18}$	$\sim 10^{-10}$

Table 2: Concentrations of *Li*-group isotopes at different temperature.

3. Conclusion

Free neutrons are very quickly caught by the nuclei. This process leads to a drastic increase of senior isotope concentrations in every isotope group. Free neutrons disappear in energetic flame of nuclear reactions not using even a quarter of their own lifetime.

In H isotope group a number of tritons abruptly increases. A great number of tritons may be a reason of ^{3}He abundance in nature at the present. In He isotope group ^{3}He transforms to ^{4}He immediately.

An increase of Li senior isotope's concentration can contribute to solving the issue of *Be* primordial abundance.

References

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