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Essay

on astroparticle physics

"Mirror world with $m_p = m_n$"

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CONTENT

1. INTRODUCTION

Modern astronomical observations give very weighty arguments for the existence of dark matter [1]. One of the hypotheses explaining the nature of dark matter is the hypothesis of the existence of the mirror world. The first theoretical work in which a violation of P-parity was considered is the paper of Lee and Yang[2], published in 1956. In addition, the possibility of the existence of mirror partners for ordinary particles was considered for the first time. The basis for this idea was the assumption about P-parity violation. The existence of the mirror matter allowed to compensate P-parity violation of the ordinary world. Experimental violation of P-parity was found in the experiment of Wu in 1957 [3]. After that Lev Landau hypothesized the strict CP-parity conservation [4] and suggested that the role of mirror particles can pretend the antiparticle of the ordinary world. However, the discovery of $K_2^0 \to \pi^+\pi^-$ decay by Christenson and other [5] has refuted the Landau's hypothesis of strict CP-parity conservation. Later there were some attempts to "save" CP-parity. In 1965 Nishijima and Saffuri hypothesized a so called "shadow" Universe [6]. According to this hypothesis $K_2^0 \to \pi^+\pi^-$ decay belonged not to CP-odd K_2^0-meson but to CP-even “shadow” K_1^0-meson, in which the usual K_1^0 transformed in vacuum. This is the way how CP-invariance could be “saved”. But soon it was shown [7] that this hypothesis conflicted the results of neutrino experiments because “shadow” K_1^0-mesons had to penetrate the detector's protection and decay into the pair of pions there. However, such events were not observed in the experiment.

In 1966 the I.J. Kobzarev, L.B. Okun and I.J. Pomeranchuk have published an article [8] in which it was shown that usual and mirror particles could not participate in strong and electromagnetic interactions. A general weak interaction was also excluded by discovering the Z-boson and measuring it's decay width. So the easiest way to resolve this conflict is to extend the gauge group of the Standard Model, for example, to group $[U(1) \otimes SU(2) \otimes SU(3)] \otimes [U(1) \otimes SU(2) \otimes SU(3)]_M$, or to the similar one. The main feature of this group is the absence of the usual electromagnetic, strong and weak interactions in the mirror world. In this case mirror gauge bosons also appear. If the mirror particles exist, in any case they interact with ordinary particles gravitationally. Other possibilities to construct the renormalizable interactions between two sectors are very limited. In particular, it is the mixing of the neutrinos [9], the interaction of the Higgs bosons: $L_{int} = \eta(H^+H^-)(H^{'+}H^{'-})$ [10] and the mixing of gauge bosons: $L_{int} = \epsilon F^{\mu\nu}F^{'}_{\mu\nu}$ [11]. However, the constants of all these types of interactions should be small. For an observer from the ordinary world the clusters of the mirror matter would look like voids in space, but, nevertheless, he could feel the gravitational field created by the mirror matter.

In addition it should be noted that if the scenario of the mirror world was trully realized, there should be much less mirror matter than ordinary matter in our solar system. Due to the fact that the macroobjects should be formed of mirror matter, the presence of any considerable amount of mirror matter in our solar system would not be remained practically unnoticed (but the possibility of the existence of the mirror planet inside the Sun is not excluded [12]). So, if the mirror particles are present in the Universe, they are outside the solar system (or inside the Sun, as already noted). The properties of these macroobjects are determined by model parameters of the mirror world.

The purpose of this essay is to examine the mirror world in which the masses of the proton and the neutron are equal. Also there will be a conclusion about some properties of macroscopic bodies made of mirror particles.

2. DESCRIPTION OF THE MODEL

Practically all of the elementary particles in the mirror world, as well as in an ordinary one, are massive. In particular, the proton and the neutron are massive (however, the mass of the hadron is also determined by the scale of confinement). The measurements of the masses of ordinary protons and neutrons, conducted up to date, give for them the following values [13].

$$m_p = 938.272046(21)\frac{MeV}{c^2}$$

$$m_n = 939,565378(21)\frac{MeV}{c^2}$$

The fact that the masses of the proton and the neutron in the world of ordinary particles are not equal to each other has far reaching consequences. Otherwise, the physical picture of the world would be completely different. In this paper the model of the mirror world, where $m_p = m_n$, will be considered.

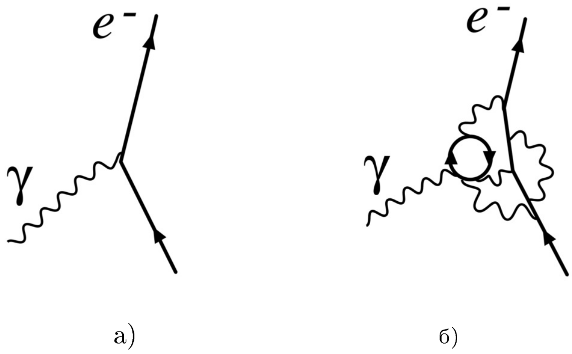
Because the model of the mirror world assumes the existence of a partner for each particle of the ordinary world, this model contains the following mirror particles:

- 6 leptons (3 generations of 2 particles with the charges -e and 0, respectively) and 6 antileptons
- 6 quarks (3 generations of 2 particles with the charges $-\frac{1}{3}e$ и $+\frac{2}{3}e$ respectively) and 6 antiquarks
- 12 gauge bosons (8 gluons, 3 bosons of the weak interaction and 1 photon)
- 1 Higgs boson

Fundamental fermions of the second and third generations are unstable and decompose into fundamental fermions of the first or second generations. Matter is composed of the particles of the first generation, the particles of the second and third generations are born only at large energy densities. The mass of neyrino of any sort is many orders smaller than the mass of any of the leptons or quarks. The Higgs mechanism is responsible for the presence of the masses of all elementary particles (The mechanism of confinement also makes its contribution to the mass of the hadrons). The particles of the mirror world can interact with the particles of the ordinary world through gravitational interaction. The kinetic mixing of gauge bosons is also possible ($L_{int} = \epsilon F^{\mu\nu} F^{'}_{\mu\nu}$), the interaction of Higgs bosons ($L_{int} = \eta(H^+H^-)(H^{'+}H^{'-})$) and mixing of neutrinos . Because the difference of masses between the proton and neutron in our model is equal to zero, then both of these particles will be stable in the free state (beta decay is forbidden by the law of conservation of energy). Being inside the nuclei, the neutron and proton are also stable and can not to transform to each other.

The nature of the inflation and baryogenesis can be described by the mechanisms that go beyond the scope of this paper. At the same time, within the model the mirror of the world the assumption can be made that about the observable baryon asymmetry of the Universe: if the ordinary world of matter is dominated by particles with positive baryon charge, than the particles with negative baryon charge may dominate in the mirror matter. Baryon asymmetry is a consequence of the Sacharov's conditions of the early Universe.

To explain the nature of dark matter in the mirror world with symmetric initial conditions nucleons should be$\sim 4 \div 5$ times heavier, maybe, because of different scale of confinement. Let us review this question in more details. As it is known, the constants of the fundamental interactions have different values in different energy scales. For example, the electromagnetic coupling constant at low energies ($E \ll 1$ MeV) is approximately equal to $\alpha_{em} \approx \frac{1}{137}$, while at energies of 200 MeV, it becomes $\alpha_{em} \approx \frac{1}{127}$. The reason for this effect is as follows. The constants of fundamental interactions determine vertex values specific to each particular type of interactions. For example the vertex, which is proportional to the coupling constant of the electromagnetic interaction in QED, is $e \to e + \gamma$. On the low-energy scale the given vertex has the form shown in Fig.1a. However, with increasing energy scale the further amendments related to the creation and annihilation of virtual particles begin to make a contribution to this vertex (Figure 1b). Consequently, the coupling constant for this peak will have a different value.



Pic.1 The $e \to e + \gamma$ vertex at low-energy ($E \ll 1$ MeV) and high-energy ($E \gtrsim 1$ MeV) scales.

Mathematical apparatus, allowing to carry out a systematic study of changes in physical systems in considering these systems at different spatial scales, is the renormalization group analysis. Its essence is that renormalizable theories for any scale may be obtained analogously from theories in any other, random, scale, using the group conversion. More details on this technique are described, for example, in articles [14] and [15].

In the group renormalization analysis the coupling parameter in theory $g(\mu)$ is described by the following equation.

$$g(\mu) = G^{-1}(\,(\tfrac{\mu}{M})^d G(g(M))\,), \text{ where} \tag{3.1}$$

G - some scaling function, M - characteristic scale of the theory, μ - efficient scale, d - some constant. Efficient scale μ is not fixed and can be varied to determin the theory in any other scale. The communication constant of theories and effective masses of interacting particles are described by β and γ - functions.

In the case of QCD the equations for these functions have the following form.

$$\beta(\alpha_s) \equiv -\mu\frac{d\alpha_s}{d\mu} = \sum_{i=1}^{\infty}\beta_i\alpha_s^{i+1} \tag{3.2}$$

$$\gamma(\alpha_s) \equiv -\frac{\mu}{m}\frac{dm}{d\mu} = \sum_{i=1}^{\infty}\gamma_i\alpha_s^{i}, \text{ where} \tag{3.3}$$

α_s - strong interaction constant, m - effective quark mass. Coefficients β_i and γ_i as of 2006 were calculated up to fourth order [10]. Coefficients β_1, β_2, γ_1 and γ_2 in QCD have the following form [16]

$\beta_1 = \frac{1}{4\pi}(11 - \frac{2}{3}N_f),$

$\beta_2 = \frac{1}{(4\pi)^2}(102 - \frac{38}{3}N_f),$

$\gamma_1 = \frac{1}{4\pi} \cdot 4,$

$$\gamma_2 = \frac{1}{(4\pi)^2}\left(\frac{202}{3} - \frac{20}{9}N_f\right), \tag{3.4}$$

where N_f - number of quark flavors, born on this energy scale.

Depending on the energy scale it is needed to consider a different number of terms in the expansions(3.2) and (3.3). However, in QCD, unlike QED, the situation is diametrically opposite: since β - function (like γ) is negative, then to find α_s on the low-energy scale we have to use more terms in the expressions (3.2) and (3.3), than on the high-energy scale. This fact has a direct physical meaning: at low energies, the quarks inside hadrons interact strongly with each other by gluons and the emission of quarks and gluons at high energies can be described with great precision by vertex $q \to q + g$. For example, to calculate the value of the strong coupling constant in the one-loop approximation ($\mu \gtrsim 300$ GeV) , it is needed to consider the equation

$$-\mu\frac{d\alpha_s}{d\mu} = \beta_1\alpha_s^2, \tag{3.5}$$

and the solution is

$$\alpha_s(\mu) = \frac{1}{\beta_1 ln\left(\frac{\mu^2}{\Lambda^2}\right)}, \tag{3.6}$$

where Λ - constant, characterizing the confinement scale. This constant can be found from the following Cauchy problem

$$\begin{cases} -\mu\frac{d\alpha_s}{d\mu} = \beta_1\alpha_s^2 + \beta_2\alpha_s^3 \\ \alpha_s(M_z) = 0.119 \end{cases}, \tag{3.7}$$

where the initial condition$\alpha_s(M_z) = 0.119$ is obtained experimentally. Energy scale $\mu \sim M_z$ requires the use of two-loop approximation in the problem (3.7).

Now consider in more detail (3.3). It can be directly integrated by way of separation of variables.

$$\int\limits_{m(\mu_2)}^{m(\mu_2)} \frac{dm}{m} = ln\left(\frac{m(\mu_2)}{m(\mu_1)}\right) = -\int\limits_{\mu_1}^{\mu_2}\frac{\gamma(\alpha_s)d\mu}{\mu} = \int\limits_{\alpha_s(\mu_1)}^{\alpha_s(\mu_2)}\frac{\gamma(\alpha_s)}{\beta(\alpha_s)}d\alpha_s \tag{3.8}$$

Finally, we obtain

$$m(\mu_2) = m(\mu_1)exp\left\{\int\limits_{\alpha_s(\mu_1)}^{\alpha_s(\mu_2)}\frac{\gamma(\alpha_s)}{\beta(\alpha_s)}d\alpha_s\right\} \tag{3.9}$$

Equation (3.9) contains the confinement scale Λ and the number of quark flavors, born at this energy scale. The resulting equation can be used to predict the masses of other mirror particles, if we know the masses of the quarks in any one hadron state. In this paper, mass of the proton and the neutron is known, which is 4.1 GeV. So $m(\mu_1) = \frac{4.1}{3}$ GeV. Confinement scale can not be determined in the renormalization group analysis, this requires further experimental study. So there are two possible options for obtaining of protons and neutrons with the mass of 4.1 GeV in terms of this model [1].

[1]. Further, the following notations are used: m $-$ *mirror*, o $-$ *ordinary*.

1. $\Lambda_m \neq \Lambda_o$. The reasons for this are more fundamental and go beyond the renormalization group analysis. However, in that case, the following condition must be satisfied in this model: $\Lambda_m > \Lambda_o$.
2. $\Lambda_m = \Lambda_o$.In this case, the strong interaction constant may change due to N_f, that, in turn, can be caused either by displacement of the mass scale of current quarks or by the presence of new quark generations.

Some information related with the scale of confinement in the mirror world, can be obtained from a comparison of this theory with the Standard Model, using the one-loop renormalization group approach. On the energy scale$\mu_o \approx 1\,\mathrm{GeV}$ и $\mu_m \approx 4.1\,\mathrm{GeV}$ coupling constant, determined by the equation (3.6) become the order of unity. Then, using (3.4), we can write

$$\frac{\alpha_{sm}(\mu_m)}{\alpha_{so}(\mu_o)} = \frac{(11-\frac{2}{3}N_o)ln\left(\frac{\mu_o}{\Lambda_o}\right)}{(11-\frac{2}{3}N_m)ln\left(\frac{\mu_m}{\Lambda_m}\right)} \approx 1$$

We obtain that at the confinement scale mirror world $\Lambda_m \approx 1.35\,\mathrm{GeV}$ the number of flavors of quarks born in the energy scale $\mu_m = 4.1\,\text{ГэВ}$ should be equal to two. So the massive scale of current quarks in ordinary and mirror worlds will vary.

Now we discuss the problem of the initial conditions.

If the initial conditions for ordinary and mirror matter are symmetrical, the assumption that the difference between the masses of the nucleons and the usual mirror matter seems quite natural, since the proportion of the observable matter is of the order of 5% of the mass of the universe, and the proportion of dark matter is about 22%.

If the initial conditions for ordinary and mirror matter were asymmetrical, the reason for the difference between their contributions to the mass of the universe becomes apparent. Most models of the mirror world, which are intended to explain the nature of dark matter, consider exactly asymmetric initial conditions.

In this paper we consider a scenario in which the initial conditions are symmetric, and the masses of mirror protons and neutrons are 4.1 GeV. Excess of mirror baryons is assumed to be an excess of ordinary baryons.

The most important cosmological consequence of this model is explanation of the nature of dark matter, on which role mirror matter pretends.

3. PHYSICAL PICTURE OF THE EVOLUTION OF THE MIRROR WORLD

In this paper the review of the evolution of the universe begins from the lepton era.

LEPTON ERA (10^{-6}–0.3 s)

When the temperature of the universe fell below the of the hadronization ($T_{hadr} \sim \Lambda$), colored quarks and gluons could no longer be in a free state. Hadronization began to occur - the union of colored particles in colorless combinations (hadrons). In addition, after hadronization the annihilation of baryon-antibaryon pairs started to happen. At this stage of the Universe baryon symmetry had already been broken by an earlier generation of baryon excess.

During this time interval the uncoupling of neutrinos occurs. Until the moment of uncoupling the neutrinos were in the thermodynamic equilibrium with the other matter, but after that they are propogate in the Universe freely. For the further evaluations it is needed to introduce some auxiliary quantities.

The effective number of ultrarelativistic degrees of freedom defined by the formula

$$g_\varepsilon = \sum_{\substack{bosons \\ with\, m \ll T}} g_i + \frac{7}{8} \sum_{\substack{fermions \\ with\, m \ll T}} g_i \tag{3.1}$$

The summation in (3.1) produced by the mirror bosons and fermions, which are ultrarelativistic particles for a given temperature, ie they satisfy the condition$m \ll T$.

Next we introduce the parameter, which is a modified Planck mass

$$M_{pl}^* = \frac{M_{pl}}{1.66\sqrt{g_\varepsilon}}, \tag{3.2}$$

where g_ε represents the number of ultrarelativistic degrees of freedom.

From a comparison of the rate of neutrino processes with the rate of expansion of the Universe a formula can be obtained for estimating the temperature of uncoupling of neutrinos.

$$T_\nu \sim \left(\frac{1}{G_F^2 M_{pl}^*}\right)^{\frac{1}{3}} \tag{3.3}$$

Immediately after the uncoupling of the neutrinos the photons, electrons, positrons and neutrinos will make a contribution in the number of ultrarelativistic degrees of freedom. The number of ultrarelativistic degrees of freedom is equal to$g_\varepsilon = 2 + \frac{7}{8}(4 + 2N_\nu) = \frac{43}{4}$.

When $N_\nu = 3$ numerically obtain

$$T_\nu \sim \left(\frac{1}{G_F^2 M_{pl}^*}\right)^{\frac{1}{3}} \approx 2 \text{ MeV}$$

Hence, we can estimate the age of the universe at the moment of uncoupling of the neutrinos.

$$t_\nu \sim \frac{1}{2H(T_\nu)} = \frac{M_{pl}^*}{2T_\nu^2} \tag{3.4}$$

Substituting$T_\nu = 2.5$ MeV and $N_\nu = 3$ we obtain

$$t_\nu \sim \frac{M_{pl}^*}{2T_\nu^2} \approx 0.1 \text{ s}$$

Thus, the uncoupling of the neutrinos of happened exactly in the lepton era.

THE EPOCH OF NUCLEOSYNTHESIS (0.3 s - 3 min)

The earliest era of the hot Universe about which today there are reliable experimental data - the era of primordial nucleosynthesis, which lasted about three minutes.

The first stage of nucleosynthesis is hardening neutrons. It occurred at about 1 MeV, when the formation of light nuclei has not yet begun. Until the moment of disengagement neutrinos the thermodynamic equilibrium between nucleons provided the reaction

$$n + \nu_e \leftrightarrow p + e \tag{3.5}$$

Approximate expression for the the hardening temperature of neutrons can be obtained from dimensional considerations. For simplicity, assume that we are dealing with a rather high temperatures, namely

$$T \gtrsim \triangle m,\, m_e \tag{3.6}$$

In mirror world $\triangle m = 0$, thus (3.5) can be written as

$$T \gtrsim 0.511 \text{ MeV} \tag{3.7}$$

Then free path time of neutrons to the reaction (3.5) can be estimated from dimensional considerations

$$\tau_{np} = \Gamma_{np}^{-1}$$

$$\Gamma_{np} = C_{np} G_F^2 T^5, \tag{3.8}$$

where C_{np}- a certain constant of order unity. Processes of the type (3.5) cease when free path time becomes of the order of the Hubble time, ie

$$\tau_{np} \sim H(T) = \frac{T^2}{2M_{pl}^*} \tag{3.9}$$

From (3.7) and (3.8) we obtain the temperature at which the processes of the type (3.5) are terminated

$$T_n \approx \left(\frac{1}{C_{np} G_F^2 M_{pl}^*}\right)^{\frac{1}{3}} \tag{3.10}$$

ConstantC_{np} is determined from the four-fermion vertex (3.5) in the Fermi theory. Numerically, $C_{np} = 1.2$. Also at the time of hardening of neutrons $g_\varepsilon = 2 + \frac{7}{8}(4 + 2N_\nu) = \frac{43}{4}$. The first term is due to the contribution of the photons, the second - the electrons and positrons, the third - the neutrinos.

Finally, for the the hardening temperature of neutrons we have

$$T_n \approx \left(\frac{1}{C_{np} G_F^2 M_{pl}^*}\right)^{\frac{1}{3}} = 1.4 \text{ MeV}$$

Therefore the condition (3.6) is obviously satisfied.

Lifetime of the universe by the time of hardening of neutrons is determined by the ratio

$$t_n = \frac{1}{2H(T_n)} = \frac{M_{pl}^*}{2T_n^2} \tag{3.11}$$

Substituting$T_n = 1.4$ MeV and $N_\nu = 3$ numerically we obtain

$$t_n = \frac{M_{pl}^*}{2T_n^2} = 0.4 \text{ s}$$

Thus, primordial nucleosynthesis began to flow through 0.4 seconds after the Big Bang.

Neutron-proton ratio at the time of hardening is determined from the Saha equation and has the form

$$\frac{n_n}{n_p} = e^{-\frac{\triangle m}{T_n}} \tag{3.12}$$

Mass difference $\triangle m = m_n - m_p$ is equal to zero in our model. So in this case we obtain

$$\frac{n_n}{n_p} = 1$$

Because proton and neutron are stable in the free state, the ratio between the number of protons and neutrons will not change later.

Thermonuclear reactions of mirror matter begin with the formation of deuterium in the reaction

$$p + n \to D + \gamma$$

The formation of deuterium began when its rate of photodisintegration had become smaller than the expansion rate of the Universe.

Furthermore, since the cosmological expansion of the universe took place continuously, not all of the nucleons managed to unite the in deuterium. A certain amount of protons and neutrons remained in the free state.

We use Saha equation to analyze the process of nucleosynthesis of heavier elements. For this analysis, we shall use Saha equation as follows [17]

$$X_A = X_p^Z X_n^{A-Z} n_B^{A-1} 2^{-A} g_A A^{\frac{5}{2}} \left(\frac{2\pi}{m_p T}\right)^{\frac{3}{2}(A-1)} e^{\frac{\triangle A}{T}} \tag{3.13}$$

In equation(3.8) $X_A = \frac{A n_A}{n_B}$ - the dimensionless ratio of the number of nucleons in nuclei (A, Z) to the total number of nucleons, n_B - baryon number density, g_A - the number of spin states of the nucleus, $\triangle A = Z m_p + (A-Z) m_n - m_A = A m_p - m_A$ - the nuclear binding energy.

Baryon density is given by

$$n_B = \eta_B n_\gamma = \eta_B \frac{2\zeta(3)}{\pi^2} T^3 = 0.24 \eta_B T^3, \tag{3.14}$$

whereη_B- the pre-exponential factor.

As a result, we obtain

$$X_A = X_p^Z X_n^{A-Z} \eta_B^{A-1} 2^{-A} g_A A^{\frac{5}{2}} \left(\frac{2.5T}{m_p}\right)^{\frac{3}{2}(A-1)} e^{\frac{\triangle A}{T}} \tag{3.15}$$

Formula (3.9) shows that the equilibrium concentration of nuclei ceases to be small only if $T \ll \triangle A$.

Nucleosynthesis begins to occur when the formation of deuterium becomes energetically favorable. This is achieved under the condition$X_D(T_{NS}) \sim 1$. Therefore, neglecting factors of order unity in (3.10), we obtain for the deuterium

$$X_D(T_{NS}) \sim \eta_B \left(\frac{2.5 T_{NS}}{m_p}\right)^{\frac{3}{2}} e^{\frac{\triangle D}{T_{NS}}} \sim 1 \tag{3.16}$$

Since it is assumed that the masses of the mirror nucleons are 4.4 times more than masses corresponding ordinary nucleons, put the binding energy of mirror deuterium$\triangle D_m = 4.4 \triangle D_o \simeq 10.7$ MeV. Substituting well as the value $\eta_B = 6.1 \cdot 10^{-10}$ and solving (3.11) numerically, we obtain

$$T_{NS} \approx 314 \text{ keV}$$

However, in reality the most energetically favorable formation is^4He. The synthesis of ^4He occurs by various nuclear reactions that will be discussed below.

Let's define the age of the Universe in the era of nucleosynthesis. By analogy with (3.4) and (3.6) we obtain

$$t_{NS} = \frac{1}{2H(T_{NS})} = \frac{M_{pl}^*}{2T_{NS}^2} \tag{3.17}$$

At a temperature$T_{NS} \approx 314$ keV only photons and neutrinos make a contribution in the number of ultrarelativistic degrees of freedom. But neutrinos no longer interact with the plasma, so their contribution will be suppressed. Expression (3.12) includes $g_{\varepsilon} = 2 + 2N_{\nu}\frac{7}{8}\left(\frac{11}{4}\right)^{\frac{4}{3}}$, $N_{\nu} = 3$. And the age of the universe at the time of nucleosynthesis

$$t_{NS} = \frac{M^*_{pl}}{2T^2_{NS}} = 5.2 \text{ s}$$

The^4He mass fraction of baryons can be estimated using the following formula

$$X_{^4He} \approx \frac{m_{^4He} n_{^4He}(T_{NS})}{m_p(n_p(T_{NS})+n_n(T_{NS}))} = \frac{2}{\frac{n_p(T_{NS})}{n_n(T_{NS})}+1} = 100\%$$

At the same time the proportion of hydrogen is determined by the formula

$$X_{H_2} \approx \frac{1-\frac{n_p(T_{NS})}{n_n(T_{NS})}}{1+\frac{n_p(T_{NS})}{n_n(T_{NS})}} = 0\%$$

TThus, the primary helium in the mirror world will be almost 100% of all matter.

THE KINETICS OF NUCLEOSYNTHESIS

Now consider in details the types of processes which lead to the synthesis of^4He from primordial protons and neutrons.

The main reactions of primary nucleosynthesis can be divided into the following stages

- $p+n \to D+\gamma$ - the beginning of nucleosynthesis, the formation of deuterium.
- $p + D \to {}^3He + \gamma$, $D + D \to {}^3He + n$, $D + D \to T + p$ - intermediate reactions, providing further synthesis^4He.
- $T + D \to n + {}^4He$, $n + {}^3He \to \gamma + {}^4He$, $D + {}^3He \to p + {}^4He$ - the formation of ^4He.

We consider the process of radiative neutron capture $(p + n \to D + \gamma)$. As stated above, it is energetically favorable to form deuterium at a temperature $T_{NS} \approx$ 314 keV. It is important to find out how fast neutrons are captured, because the Universe is expanding at this stage and not all the neutrons can be captured by protons.

For this we use a rough estimate of cross sections of deuterium

$$< \sigma\upsilon >_{p(n,\gamma)D} \sim \frac{\alpha}{m^2_{\pi}} \simeq \frac{1}{137}\frac{1}{(600 \text{ MeV})^2} = 2 \cdot 10^{-19}\frac{\text{cm}^3}{\text{s}}$$

Also, since the deuterium nucleus is weakly bound, there is an additional suppression factor.

Finally, we obtain

$$< \sigma\upsilon >_{p(n,\gamma)D} \approx 6 \cdot 10^{-21}\frac{\text{cm}^3}{\text{s}}$$

The burning rate of neutrons is defined as the frequency of collisions between protons and neutrons, as a result deuterium is formed. Then the reaction rate at $T = T_{NS} = 314$ keV and $\eta_B = 6.1 \cdot 10^{-10}$ we have

$$\Gamma_{p(n,\gamma)D} = n_p < \sigma\upsilon >_{p(n,\gamma)D} = \eta_B \frac{2\zeta(3)}{\pi^2} T^3 < \sigma\upsilon >_{p(n,\gamma)D} \simeq 3.5\ c^{-1}$$

The obtained value of the burning rate of neutrons significantly exceeds the expansion rate of the universe $\Gamma_{p(n,\gamma)D} \gg H(T_{NS}) = 4 \cdot 10^{-3} c^{-1}$, so the burning process of neutrons flows very active and all the neutrons tend to transform in deuterium.

Proton concentration at the time of nucleosynthesis is given by (3.9) and is

$$n_P = \eta_B \frac{2\zeta(3)}{\pi^2} T_{NS}^3 = 0.24 \eta_B T_{NS}^3 = 6 \cdot 10^{20} \text{ см}^{-3}$$

The concentration of free protons can be found from the following Cauchy problem

$$\begin{cases} \frac{dn_p}{dt} = -n_p n_n < \sigma v >_{p(n,\gamma)D} \\ n_p(0) = 6 \cdot 10^{20} \text{ см}^{-3} \end{cases} \tag{3.18}$$

Solving (3.13) we obtain for the proton concentration expression

$$n_p(t) = n_p(0) e^{-n_n < \sigma v >_{p(n,\gamma)D} t} \tag{3.19}$$

So the hardened concentration is

$$n_p(t_{NS} - t_n) = 10^{11} \text{ cm}^{-3}$$

Thus the fraction of protons remaining in a free state, is

$$\frac{n_p(t_{NS} - t_n)}{n_p(0)} = 1.7 \cdot 10^{-10}$$

Now consider the process of burning of the deuterium ($D + D \to {}^3He + n$ и $D + D \to T + p$). The cross sections of these reactions can also be estimated as geometric, but the Coulomb barrier must be taken into account, since both of the colliding nuclei have a positive electric charge. To form a new nucleus, the colliding nuclei have to overcome the Coulomb barrier. This is achieved as a result of the tunnel junction. After spending some calculations, we obtain the cross section for deuterium burning the following formula

$$\sigma v = \sigma_0 \cdot \frac{2\pi\alpha Z_1 Z_2}{v} \cdot e^{-\frac{2\pi\alpha Z_1 Z_2}{v}},$$

where σ_0 - geometrical cross section of the reaction.

Now it is needed to take the average of the cross section, which takes into account the velocity spread in the primary plasma.

As a result, we obtain

$$< \sigma v >= 9.3 \sigma_0 \cdot (Z_1 Z_2)^{\frac{4}{3}} \overline{A}^{\frac{2}{3}} T_9^{-\frac{2}{3}} e^{-4.26 (Z_1 Z_2)^{\frac{2}{3}} \overline{A}^{\frac{1}{3}} T_9^{-\frac{1}{3}}},$$

where $T_9 = \frac{T}{10^9 K}$ и $\overline{A} = \frac{M}{m_p}$

Then for the burning rate of deuterium we can write

$$\Gamma_{DD} = n_D(T_{NS}) < \sigma v >_{DD} (T_{NS}) = 1.4 \cdot 10^{-3} s^{-1}$$

This value of the reaction rate also suggests that deuterium can burn not only according to the reaction which is discussed above, but also through other channels, which together convert deuterium by the chain reactions in ^4He.

^4He burning processes is stars by the following scheme [13].

When the temperature in the central part of the star consisting of helium reaches 108 K, a new nuclear reaction is activated – the helium burning. At this time, the density of the central core $(10^4 - 10^5)\frac{g}{\text{см}^3}$. Helium burning reactions feature is that the main reaction $^4He + {}^4He \to {}^8Be + \gamma$ leads to the formation of an unstable nucleus^8Be, whose lifetime is $10^{-16}s$. Others reaction involving two helium nuclei occur with energy absorption. However, - due to the high density of nuclei ^4He it turns out that before the nucleus ^8Be again splits into two α-particles, it managed to react with another nucleus^4He (so-called "triple" α-process) with the formation of the isotope^{12}C in the excited state in the process

$$^4He + {}^4He + {}^4He \to {}^8Be + {}^4He \to {}^{12}C \tag{3.20}$$

The rate of the reaction$^8Be + {}^4He$ significantly affected by the fact that the energy of the reaction$^8Be({}^4He, \gamma)^{12}C$, which is equal to 7.37 MeV, is located near the second excited state of ^{12}C with the energy of 7.65 MeV ($J^P = 0^+$). That is, the reaction has a resonance character, which significantly increases its speed.

Finally, we consider positron decay of nuclei in details in the mirror world. For this we use an approximate formula Weizsacker-Williams for the binding energy of the nucleon in the atom

$$E_{B_N} = \alpha - \beta\frac{1}{A^{\frac{1}{3}}} - \gamma\frac{Z^2}{A^{\frac{4}{3}}} - \varepsilon\frac{(\frac{A}{2}-Z)^2}{A^2} + \delta, \tag{3.21}$$

$$\text{где } \delta = \begin{cases} +\chi A^{-\frac{7}{4}} & \text{, for even-even nuclei} \\ 0 & \text{, for even-odd nuclei} \\ -\chi A^{-\frac{7}{4}} & \text{, for odd-odd nuclei} \end{cases}$$

The coefficientsα, β, γ, ε, χ are obtained by statistical processing of the results of experiments. Using this formula, you can obtain an approximate expression for the equilibrium amount of protons in the nucleus, defined by the maximum of binding energy.

$$Z_{eq} = \frac{2\varepsilon A}{\gamma A^{\frac{2}{3}} + 4\varepsilon} \tag{3.22}$$

The nucleus is sensitive to the positron decay and electron capture at

$$Z > Z_{eq} \tag{3.23}$$

For the positron decay the mass difference of final and initial nuclei must be above the two masses of the electron, which is 1022 keV.

From (3.16) it can be seen that the dominant in the mirror world^4He is β^+-stable. Positron decay is observed in nuclei with a sufficiently large compared with the^4He number of nucleons in the nucleus, for example ^{10}C, ^{20}Na, ^{25}Al etc.

4. CONCLUSION

The evolution of the mirror world was considered in this work, where $m_p = m_n = 4.1$ GeV. . In considering the script it was found the following. Inflationary expansion of the universe in the early stages of evolution can be explained in various ways, for example by means of an oscillating scalar field. In this paper, a concrete realization of the mechanism for inflation is not considered. Baryon asymmetry is due to the conditions of Sakharov in the early universe. However, realization of this idea also allows a variety of options. The initial conditions for ordinary and mirror matter are considered symmetrical.

The main properties of considered model are:

- ^4He will dominate in the Universe .
- Because the primary hydrogen is practically absent, and there will be no stars, in which the hydrogen burns. Only nuclear reactions in mirror stars are combustion reactions of burning of the^4He forming^{12}C and some other elements.
- The chemical composition will be different from ours due to the specifics of stellar processes in the mirror world. There will be much less heavy elements in the mirror world than in usual, and they will be synthesized through other channels.
- The process of burning of stars will be more intense because combustion processes of ^ {4} He have a resonant character.
- The dominant^4He and a small admixture of nucleons claim on the role of dark matter.
- The positron decay of nuclei will be more actively because it will be possible to replace the protons by neutrons in the nuclei, which will increase the energy due to the absence of additional Coulomb barrier. It will be possible to form new types of baryons.
- No additional Coulomb barrier associated with the replacement of protons by neutrons opens up new reaction channels and shifts the energy restrictions on mutual nuclear transformation.

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