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Abstract on the discipline
«Introduction to Cosmophysics»

Mirror world with $m_n = m_p$

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INTRODUCTION

The necessity to introduce additional worlds was caused by the observation of violation of CP-symmetry in a number of experiments, the priority on the preservation of which was expressed by many scientists, including Landau. The decay of a neutral kaon into two and also into three pions was interpreted by some scientists as a decay through shadow universes.

The existence of mirror particles was first proposed by the great theoretical physicists Zhengdao Li and Zhenning Yang. In their work they suggested that in weak decays parity is not conserved, which leads to non-equivalence of left and right oriented coordinate systems. Later, in a C.S. Wu experiment, they found a large left-right asymmetry in the β -decay of ^{60}Co and in $\pi \rightarrow \mu \rightarrow e$ decays. To restore the equivalence, they assumed the existence of a symmetric set of particles in which the parity non-preservation is in the opposite direction, and thus the reflection in a mirror yields the process that occurs in nature but with mirror doubles. Lee, Landau and co-workers speculated that CP-invariance might solve this problem, the experimental verification of which was a top priority. However, Christenson's work on the discovery of the $K_2^0 \rightarrow 2\pi$ decay "shut down" Landau's idea of strict CP-conservation, according to which antiparticles look exactly like mirror images of particles.

Later, other great physicists of the last century - I. Y. Kobzarev, L. B. Okun, and I. Y. Pomeranchuk - also spoke about the existence of mirror worlds in their reviews in their paper «On the possibility of experimental detection of mirror particles» [1]. Okun L.B. and his colleagues proposed a model of the mirror world with a new set of particles - they should not participate in the usual strong and electromagnetic interactions (including weak interactions, which became clear later, after the discovery of the Z boson), but should have their own interactions, and thus mirror particles formed mirror atoms, molecules, and hence - the mirror world itself. Various experiments on search of mirror particles, carried out by ARGUS collaboration, groups of experimenters of ITEP

and many other scientists only estimated upper limits for fractions of decays. Thus, the ARGUS collaboration searched for decays $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ in which $\Upsilon(1S)$ decays into "nothing" due to transitions into its mirror partner, but the fractions of these channels have only been estimated to be 2.3% with 90% [2] confidence. If the neutrino has a Dirac mass, then there must be a right neutrino, and it could be part of the mirror world, and it arises from transitions between our left and mirror right neutrinos, which would be some sort of a scaffolding between the worlds. At present, the theory of mirror worlds continues to develop [3], [4]. It is believed that the mirror world should be symmetric to the ordinary one from the point of view of physics, but asymmetric in terms of initial conditions - in this case there appears a possibility to describe the hidden mass by means of the mirror world. Methods of confirming the existence of mirror worlds are also being developed - in addition to the already widely used cosmological methods of gravitational lensing, correlation of gamma ray bursts with the distribution of dark matter in galaxies, as well as cosmic mirror strings, accelerator methods are also widely used. Thus, in Dubna in 2004 the LEPTA [5] was launched, one of the tasks of which is to search for mirror orthopositronium. Quite a number of papers discussing the invisible mirror Higgs boson decay channels born at the LHC had also been published years earlier.

This paper intends to investigate a mirror world in which the neutron mass equals the proton mass. The paper investigates the cosmologically relevant consequences of the model, how the model of such a world affects the physics of quenching in it, mirror world nucleosynthesis, and the evolution of the mirror universe.

MODEL DESCRIPTION

This paper considers a model based on the standard model of elementary particle physics with the addition of one generation of mirror particles. Masses of fermions, carriers of weak, strong and electromagnetic interactions, and Higgs boson completely match the standard model in the ordinary and mirror worlds. Interactions between particles in the mirror world are analogous to the corresponding interactions between particles in our world. The only difference between the mirror world and the ordinary world, apart from the first generation of particles discussed only, is the equivalence of the masses of the proton and neutron. In the ordinary world:

$$m_p = 938.272 \text{ MeV}, \quad m_n = 939.565 \text{ MeV} \quad [c = 1], \quad (1)$$

but in the mirror world we assume $m_p = m_n$. In that case, the β -decay of a free neutron $n \rightarrow p + e^- + \bar{\nu}_e$ is forbidden in the mirror world: the non-zero mass of the electron and neutrino forbids decay by the law of conservation of energy. If one justifies mass equivalence at the quark level ($q_u = \frac{2}{3}, q_d = -\frac{1}{3}$, $p = uud$, $n = udd$ in the ordinary world), then the electric charge of the neutron becomes equal to the charge of the proton, which also leads to non-conservation of electric charge in decay. The non-preservation of the basic laws of particle decay leads us to postulate the neutron as a stable particle in the mirror world, according to this model, both in the free state and inside the nucleus. In order to describe mass equality at the quark level, one must either assume the same quark composition (which probably does not make sense in the general case - what is the difference between a proton and a neutron then? Complete chiral symmetry, same charge, mass, properties, stability, etc.), or introduce an additional generation of quarks that does not exist in the ordinary world, which could explain the equality on the mass side, but leave the neutron

as a neutral particle and the proton as a charged one. However, there is another way: suppose that in the mirror world the mass of the mirror u-quark equals the mass of the mirror d-quark, and in this way we preserve mass equality but do not change the other conditions, familiar from the point of view of the ordinary world. To describe the evolution of the Universe we will not touch upon the questions of occurrence of such conditions, but simply assume the mass equality "on faith". Concerning the stability of atoms, let us consider the standard formula for the binding energy of the atomic nucleus:

$$\begin{aligned}
 W &= Zm_p + (A - Z)m_n - M_{nucleus} \\
 W &= Zm_p + Am_n - Zm_n - M_{nucleus} \\
 W &= Am_n - M_{atom} + M_e
 \end{aligned}$$

$$\begin{aligned}
 W[{}^4_2He] &= Am_n - M_{nucleus} = 4 * 938.272 - 4.002603 * 931.5 + 2 * 0.511 \approx 25.7 > 0 \\
 W[{}^4_2He] &= Am_n - M_{nucleus} = 4 * 939.565 - 4.002603 * 931.5 + 2 * 0.511 \approx 30.9 > 0 \\
 W[{}^2_1H] &= Am_n - M_{nucleus} = 2 * 938.272 - 2.014102 * 931.5 + 0.511 \approx 0.9 > 0 \\
 W[{}^2_1H] &= Am_n - M_{nucleus} = 2 * 939.565 - 2.014102 * 931.5 + 0.511 \approx 3.5 > 0
 \end{aligned}$$

The example of the helium atom nucleus shows that its stability is ensured both in the case $m_p = m_n = 939.565$ and in the case $m_p = m_n = 938.272$. The same is true for the deuteron, but the binding energy is rather small in the second case. We can assume that background processes (elastic and inelastic collisions, Coulomb scattering, etc.) in the first moments of the existence of the Universe (to ensure a large density) had sufficient transfer energy to overcome the binding energy threshold, which would lead to the destruction of the deuteron. Since the big bang, when the universe cooled to 10^9 K, it became possible to form stable deuterium nuclei by the collision of the proton and neutron $p + n \rightarrow d + \gamma$. Further, deuterium actively participated in a chain of nuclear reactions leading to the birth of a stable helium nucleus. Overcoming the deuteron binding energy threshold would have led to a rapid decrease in its concentration, and because of the low density of matter, the collision of two deuterium nuclei to form a more stable nucleus would have been unlikely. The formation of the basic chemical elements would be impossible, the chemical composition of the universe would be scarce for the formation of stars. Assuming that the deuteron has a sufficient lifetime to allow helium fusion reactions to take place, this does not at all ensure life within our solar system: the main reactions of the pp-cycle in the sun ($p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.6%) and $p + e^- + p \rightarrow {}^2H + \nu_e$ (0.4%))

require the birth of a deuteron followed by fusion into the helium isotope ${}^3\text{He}$. When hydrogen burns out, helium begins to burn, and helium is then used to produce the carbon needed to start the CNO cycle. Because of all the above complexities that could occur in the Universe due to the low binding energy threshold of deuterium, we will further assume $m_p = m_n = 939.565$.

NEUTRON FREEZE-OUT

At sufficiently high temperature of the Universe and abundance of electrons, positrons and neutrinos in comparison with nucleons, n and p are in thermodynamic equilibrium due to weak processes:

$$p + e^- \leftrightarrow n + \nu_e, \quad n + e^+ \leftrightarrow p + \bar{\nu}_e \quad (2)$$

Thus, there is a freeze-out of the ratio of the number of neutrons and protons. The characteristic energy scales are $\Delta m = m_n - m_p = 1.3$ MeV in the ordinary world, or $\Delta m = 0$ in the mirror world. Given thermodynamic equilibrium, the chemical potential equilibrium $\mu_p = \mu_e = \mu_n + \mu_\nu$ is also observed, hence $\mu_n = \mu_p + \mu_e - \mu_\nu$. In the ordinary world, the quenching temperature is defined as

$$T_n = \frac{1}{(C_n M_{Pl}^* G_F^2)^{\frac{1}{3}}}, \quad (3)$$

where $M_{Pl}^* = \frac{M_{Pl}}{1.66\sqrt{g_*}}$, $g_* = 2 + \frac{7}{8} \cdot 4 + \frac{7}{8} \cdot 2 \cdot N_\nu$. Using the kinematic equations, we obtain the most accurate value of $T_n \approx 0.8$ MeV. Formula for estimating the residual neutron concentration after freeze-out:

$$n_n = g_n \left(\frac{m_n T}{2\pi} \right)^{\frac{3}{2}} e^{-\frac{\mu_n - m_n}{T}} \quad (4)$$

At $T \gg \Delta m$ the concentration of neutrons at the moment of freezing-out would be strongly suppressed, and at $T \ll \Delta m$ - protons and neutrons in the plasma would be equal, practically all nucleons after the epoch of nucleosynthesis would be bound in ${}^4\text{He}$ nuclei, and hydrogen in the Universe would be absent [6]. In the ordinary world we observed $T_n \sim \Delta m$ (0.8 vs 1.3 MeV), but in the mirror world $T \gg \Delta m$ is observed. The asymmetry of initial conditions with respect to the ordinary and mirror matter is observed. Assuming for relativistic electrons and

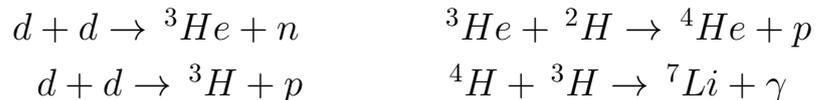
positrons a very small chemical potential $\left(\frac{n_{e^-} - n_{e^+}}{T^3} \sim \frac{n_p}{T^3} \sim \frac{n_p}{n_\gamma} \sim \frac{\mu_e}{T^3} \sim 10^{-9}\right)$, as well as the absence of strong lepton asymmetry in the Universe (i.e., $n_\nu - n_{\bar{\nu}} \ll n_\nu + n_{\bar{\nu}} \sim T^3 \Rightarrow \frac{\mu_\nu}{T}$ is also small), we determine with good accuracy the equality $\mu_n = \mu_p$. Hence,

$$\frac{n_p}{n_n} = \frac{g_p \left(\frac{m_p T}{2\pi}\right)^{\frac{3}{2}} e^{\frac{\mu_p - m_p}{T}}}{g_n \left(\frac{m_n T}{2\pi}\right)^{\frac{3}{2}} e^{\frac{\mu_n - m_n}{T}}} = e^{\frac{\mu_p - m_p - \mu_n + m_n}{T}} = 1 \quad (5)$$

In this way, the number of neutrons and protons as a result of quenching is the same, while in the ordinary world we estimate the ratio $\frac{n_p}{n_n} = 5/1$. The preservation of this ratio after quenching is not guaranteed - even though the neutron is now a stable particle, it remains to be seen what bound states and with what probabilities can form pairs of free neutrons. Perhaps, the fusion of heavier nuclei will be more efficient with the participation of more neutrons, since in fact we get rid of Coulomb pushing in the processes.

PRIMARY NUCLEOSYNTHESIS

Nucleosynthesis is the process of transformation of one chemical element into another, which occurs during nuclear reactions. The set of processes that led to the formation of the primary chemical composition of matter in the Universe before the appearance of the first stars is called primary nucleosynthesis. By the beginning of primary nucleosynthesis in the ordinary world, 3 minutes after the Big Bang, the ratio of neutrons to protons was 1 to 7. At 20 minutes after the Big Bang, primary nucleosynthesis was complete: hydrogen (75% of mass) and helium (25% of mass) dominated the baryonic mass of the Universe. Deuterium, helium-3, and lithium-7 were formed in smaller quantities, and other elements were formed in insignificant quantities. Neutrons combined with protons to form deuterium nuclei $n + p \rightarrow d + \gamma$. Accumulation of deuterium due to this reaction at first is prevented by intensive destruction of deuterium by photons in the reverse process of photodissociation. The ratio of the number of photons n_γ to the number of baryons n_B was determined as $\frac{n_\gamma}{n_B} = 10^9 \div 10^{10}$. Therefore, the beginning of deuterium synthesis and the whole chain of primary nucleosynthesis is delayed until about the 100th second after the Big Bang, when the average kinetic energy of particles decreases to 0.1 MeV, and the Universe cools down to 10^9 by this time. After cooling down, nuclei accumulate and further reactions take place:



The reactions do not proceed further because there are no stable chemical elements with atomic number 5 in nature, and the concentration of He nuclei is still too low for the reactions ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be}$, $3 {}^4\text{He} \rightarrow {}^{12}\text{C}$ to proceed effectively. The era of primary nucleosynthesis in the ordinary world ends by the time $t \sim 200\text{s}$. The formation of ${}^7\text{Be}$, ${}^7\text{Li}$ was completed when 20 minutes had passed after the Big Bang.

Let us assume that in the mirror world the beginning of nucleosynthesis follows the same scenario - free neutrons and protons form stable deuterium, which forms the primary isotopes of hydrogen and helium. First, let's determine the temperature at which it is thermodynamically advantageous to start the deuterium fusion reaction in the mirror world. In equilibrium:

$$n_n = 2 \left(\frac{m_p T}{2\pi} \right)^{3/2} e^{(\mu_n - m_n)/T} \quad (6)$$

$$n_p = 2 \left(\frac{m_p T}{2\pi} \right)^{3/2} e^{(\mu_p - m_p)/T} \quad (7)$$

Let us redefine μ_A : $\mu_A = \mu_p Z + \mu_n(A - Z)$ is a consequence of equilibrium, then

$$n_A = g_A \left(\frac{Am_p T}{2\pi} \right)^{3/2} e^{(\mu_A - m_A)/T} = |\Delta_A = Zm_p + (A - Z)m_n - m_A| = \quad (8)$$

$$= g_A \left(\frac{Am_p T}{2\pi} \right)^{3/2} e^{[Z(\mu_p - m_p) + (A - Z)(\mu_n - m_n) + \Delta_A]/T} \quad (9)$$

Let us consider each exponential term separately, denoting $2 \left(\frac{m_p T}{2\pi} \right)^{3/2}$ as ψ (for convenience):

$$e^{(\mu_p - m_p)/T} = \frac{n_p}{\psi} \quad (10)$$

$$e^{Z(\mu_p - m_p)/T} = \left(\frac{n_p}{\psi} \right)^Z \quad (11)$$

$$e^{(A - Z)(\mu_n - m_n)/T} = \left(\frac{n_n}{\psi} \right)^{A - Z} \quad (12)$$

Thus, we obtain the formula Saha:

$$n_A = g_A \left(\frac{Am_p T}{2\pi} \right)^{3/2} \left[\frac{n_p}{2 \left(\frac{m_p T}{2\pi} \right)^{3/2}} \right]^Z \left[\frac{n_n}{2 \left(\frac{m_p T}{2\pi} \right)^{3/2}} \right]^{A-Z} e^{\Delta_A/T} = \quad (13)$$

$$= g_A n_p^Z n_n^{A-Z} 2^{-A} A^{3/2} \left(\frac{2\pi}{m_p T} \right)^{\frac{3}{2}(A-1)} e^{\Delta_A/T} \quad (14)$$

Let us introduce the dimensionless number of nucleons bound in the nuclei and the baryon number density:

$$X_A = \frac{An_A}{n_B} \quad (15)$$

$$n_b = 0.24\eta_B T^3 \quad (16)$$

and we obtain the Saha equation for the fraction of primary nuclei

$$X_A = X_p^Z X_n^{A-Z} 2^{-A} g_A A^{5/2} \eta_B^{A-1} \left(\frac{2.5T}{m_p} \right)^{\frac{3}{2}(A-1)} e^{\Delta_A/T} \quad (17)$$

The small entropy multiplier $\eta_B^{A-1} \left(\frac{2.5T}{m_p} \right)^{\frac{3}{2}(A-1)}$ can be suppressed by the exponent only at temperatures much lower than the binding energy of the nucleus. Only from this point onwards the concentration of nuclei is no longer small. Deuteron synthesis begins when the concentration of nuclei is no longer small [7], in the case of

$$X_D(T_{NS}) \sim \eta_B \left(\frac{2.5T_{NS}}{m_p} \right)^{\frac{3}{2}} e^{\Delta_D/T_{NS}} \sim 1 \quad (18)$$

Baryon-photon ratio $\eta_B \sim 0.6 \times 10^{-9}$, deuteron binding energy $\Delta_D \approx 3.505$ MeV (taking into account deuteron stability, see earlier in chapter Model Description). Let us substitute the known expressions into 17, taking into account 18, and

obtain

$$T_{NS} \approx 104.6 \text{ MeV} \quad (19)$$

The calculation was carried out by the graphical method, because the numerical calculation by Newton's method (and others), taking into account the expansion of the exponent in the McLorean series, gives unphysical values (about 1 GeV and more). In the ordinary world, the temperature was somewhat lower: $T_{NS} \approx 65 \text{ KeV}$, and the corresponding Universe time at which the deuterium fusion reaction became thermodynamically favourable was $t_{NS} \approx 4.5 \text{ min}$.

The age of the universe at this point in the mirror world:

$$t_{NS} \approx \frac{1}{H(T_{NS})} \approx \frac{M_{Pl}^*}{T_{NS}^2} \quad (20)$$

$$M_{Pl}^* = \frac{M_{Pl}}{1.66\sqrt{g_*}}, \quad g_* = 2 + \frac{7}{8} \cdot 4 + \frac{7}{8} \cdot 2 \cdot N_\nu \cdot \left(\frac{4}{11}\right)^{4/3} \quad (21)$$

$$t_{NS}^{mirr} = \frac{M_{Pl} 1.66\sqrt{g_*^{ord}} T_{NSord}^2 t_{NSord}}{M_{Pl} 1.66\sqrt{g_*^{mirr}} T_{NSmirr}^2}, \quad (22)$$

where $t_{NSord} = 245\text{s}$, the time of the Universe at the moment of the end of nucleosynthesis in the ordinary world; $\sqrt{g_*^{mirr}}$ takes into account one considered generation in the mirror world and three generations of neutrinos of the ordinary world interacting with it, and hence $N_\nu = 4$; and T_{NSord}^2 is the temperature at the moment of the end of nucleosynthesis in the ordinary world. As a result, we get:

$$t_{NS}^{mirr} \approx 88.7 \text{ c} \approx 1.5 \text{ min} \quad (23)$$

This is how long it took from the moment of the Big Bang in the mirror world to the appearance of deuterium nuclei and the beginning of synthesis of heavier elements. The difference in initial conditions in the mirror and ordinary worlds leads to an earlier onset of nucleosynthesis by $\Delta t = 156$ seconds. Further nucleosynthesis consists of the birth of heavier nuclei such as lithium and beryllium. The latter is likely to be unstable. The reaction $d + T \rightarrow {}^4\text{He} + n$ produces helium. Let us estimate the mass fractions of helium and hydrogen among the baryons:

$$X(^4He) = \frac{2\frac{n}{p}}{1 + \frac{n}{p}} = 1 \quad (24)$$

$$X(H) = \frac{1 - \frac{n}{p}}{1 + \frac{n}{p}} = 0 \quad (25)$$

Thus, in a mirror world, primary helium makes up 100% of the mirror matter. Because of the high concentration of born helium, beryllium born as a result of fusion will also interact with helium and give birth to carbon-12 and so on.

Let us make a more detailed estimate of the final hydrogen concentration. The birth of deuterium, passing through the channel $n + p \rightarrow d + \gamma$, undergoes "freezing" as the velocity of protons and neutrons becomes lower against the background of the expansion of the Universe. The freezing conditions are estimated as:

$$\sigma n v t = 1 \quad (26)$$

where $\sigma = 2.43 \times 10^{-26} \text{ cm}^{-2}$ - cross section of the deuterium birth reaction. The methods for calculating the quenching temperature, and hence the age of the Universe, are often omitted in the literature because non-trivial kinematic methods are used. Also, for the sake of estimation we will omit that the number of neutrino varieties also differs, in the first approximation it is acceptable. Then it will be fair to assume that the quenching moment in the mirror world is approximately the same as in the ordinary world, and hence $T \approx 0.1 \text{ MeV}$. Substituting the parameters into 26, we obtain that $n_p = 9 \times 10^{14} \text{ cm}^{-3}$. Assuming that the concentration of mirror baryons is about 10% of the concentration of baryons in our world, we obtain $n_b = 187 \times 10^{16} \text{ cm}^{-3}$, and hence the relative concentration of protons is $0.000481 \approx 0.05\%$.

COROLLARIES. STABLE NEUTRON, DINEUTRON FORMATION

In the paper [8] the effect of a bound dineutron, a stable state of fusion of two neutrons, was studied. The authors of the paper assume the existence (in the context of this paper - in the mirror world) of such reactions as:

$$n + n \leftrightarrow {}^2n + \gamma, \quad Q = B_{2n} \quad (27)$$

$${}^2n \leftrightarrow d \quad (28)$$

$${}^2n + p \leftrightarrow T + \gamma, \quad Q = 8.48 - B_{2n}, \quad (29)$$

where B_{2n} is a function of the binding energy and does not exceed 2.5 MeV. Possible reactions that could take place during nucleosynthesis:

$$p + {}^2n \leftrightarrow d + n, \quad Q = 2.22\text{MeV} - B_{2n}, \quad (30)$$

$$d + {}^2n \leftrightarrow T + n, \quad Q = 6.26\text{MeV} - B_{2n}, \quad (31)$$

$${}^3\text{He} + {}^2n \leftrightarrow {}^4\text{He} + n, \quad Q = 28.29\text{MeV} - B_{2n}, \quad (32)$$

$${}^3\text{He} + {}^2n \leftrightarrow T + d, \quad Q = 2.99\text{MeV} - B_{2n} \quad (33)$$

The synthesis of deuterium and tritium leads to the synthesis of helium and its isotope (helium-3). The paper also investigates the weak subprocesses of dineutron to deuterium, electron and antineutrino transitions and the reverse processes with $Q = 3.52 - B_{2n}$. Additional helium fusion could also affect star formation in mirror galaxies. It would most strongly affect nucleosynthesis in the big bang, when stable neutrons and tritium would arise, and He-3 would be unstable to reverse beta decay to tritium. Thus hydrogen, deuterium, tritium, helium, lithium, and neutrons are produced. Under initial conditions, the neutrons are mostly neutrons, and so a lot of He-4 and very little H-1 is produced. If the dineutron channel is sufficiently efficient, most of the

mass of the universe will consist of stable neutrons and alpha particles, since otherwise there will be few free neutrons. These neutrons can collide to form gravitationally bound neutron clusters. Neutrons are neutral and have difficulty dissipating energy, but they can eventually settle into neutron-stellar objects. Since helium can only burn at higher temperatures than hydrogen, the clusters could only form neutron dwarfs, and in rare enough cases give rise to helium-burning stars in the mirror world, whose lifetimes would be shorter because of the high reaction rates. Synthesised helium could also be candidates for warm hidden matter, which would also include mirror matter. Although helium is quite heavy, and it would be fair to refer it to cold hidden matter, the perturbation of ionised helium is suppressed by dissipation effects that are related to the radiation pressure. In this way, short-wavelength perturbations are suppressed, and only those perturbations that correspond to the horizon scale at the time when helium recombination occurs survive. Consequently, helium in the mirror world model should be attributed, if not to the hot, then to the warm hidden mass. Formed neutron also stars can be a source of dineutron to sterile antineutrino transition, which is one of the dark matter candidates [9].

It is important to note that the authors of the paper varied only one parameter, the binding energy of the dineutron, and further work to study the interdependence of cross sections and binding energies in nuclear theory, necessary to reduce the errors presented in the paper and to establish a more specific relationship to the underlying fundamental constants, will be done in the future.

CONCLUSION

In this paper we consider a model of a mirror world with $m_p = m_n$. In the paper we give hypotheses in what conditions such a world could exist and what laws it could be described by. For a correct description of the world, we assume the equality of the masses of quarks in the mirror world, as well as the stability of the free neutron.

In the course of the work we analysed the neutron freeze-out process in the mirror world, according to the results of which the number of protons and neutrons is equal. In view of this, in a mirror world, primary helium would make up almost 100% of the mirror matter, and mirror hydrogen would be strongly suppressed, approximately 0.05%.

The process of nucleosynthesis in the mirror world would be completed earlier:

$$T_{NS} \approx 104.6 \text{ MeV}$$
$$t_{NS}^{mirr} \approx 88.7, c \approx 1.5, \text{ min}$$

The difference in initial conditions in the mirror and ordinary worlds leads to an earlier onset of nucleosynthesis by $\Delta t = 156$ seconds.

The work also analysed a paper whose authors assume a stable state of two bound neutrons. Given the stability of neutrons, as well as the neutron saturation of the Universe in a mirror world, the assumed scenario would be helium-4 fusion. The only reactions in mirror world stars would be combustion of ${}^4\text{He}$ with further formation of some heavier elements, whose lifetimes would be shorter due to the high rate of reactions. Basically, a mirror universe would be filled with gravitational bound neutron clusters and its chemical composition would be poor. Presumably, mirror helium would be a candidate for warm dark matter.

REFERENCES

1. *Okun' L. B.* Mirror particles and mirror matter: 50 years of speculation and searching // *Physics-Uspekhi*. — 2007. — Т. 50, № 4. — С. 380—389. — ISSN 1468-4780.
2. *Albrecht H., Binder U., al P. B. et.* Search for exotic decay modes of the $\Upsilon(1S)$ // *Physics Letters B*. — 1986. — Т. 179, № 4. — С. 403—408. — ISSN 0370-2693.
3. Neutron-Mirror Neutron oscillations in Matter / *Y. Kamyshkov [и др.]*. — 2021. — arXiv: 2111.01791 [hep-ph].
4. *Berezhiani Z.* Anti-dark matter: a hidden face of mirror world. — 2016. — arXiv: 1602.08599 [astro-ph.CO].
5. SOME ASPECTS OF POSITRONIUM PHYSICS / *S. N. Gninenko [и др.]*. — 2016. — arXiv: 1602.08599 [astro-ph.CO].
6. *Майоров А. Г.* Лекции по происхождению Вселенной. — 2019. — Accessed on 23.12.2023.
7. *Панов А. Д.* Лекции по физике космоса. — 2018. — Accessed on 21.12.2023.
8. *Kneller J. P., McLaughlin G. C.* Effect of bound dineutrons upon big bang nucleosynthesis // *Physical Review D*. — 2004. — Т. 70, № 4. — ISSN 1550-2368.
9. *Hao Y., Ni D.* Dineutron decay into sterile antineutrinos in neutron stars and its observable consequences // *Physical Review D*. — 2023. — Т. 107, № 3. — ISSN 2470-0029.