National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute)

Small thesis on the discipline

"Cosmoparticle physics"

Mirror world with $m_n < m_p - m_e$

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1. INTRODUCTION

The first serious argument in favor of the presence of physics beyond the Standard Model (SM), built on the symmetry group $SU(3)\times SU_L(2)\times U_Y(1)$ to describe the strong and electroweak interactions, was the experimental observation of neutrino oscillations [1], which indicates the presence of non-zero mass neutrinos. A possible indication of the presence of new physics is the ultra-precise measurement of the anomalous magnetic moment of the muon [2]. Difficulties arise in deriving some properties of QCD from the first principles (for example, interquark potential, glueball production, static properties of hadrons). There are also internal problems of the SM, for example, in the Higgs sector. At the moment, there is no agreed upon theory of quantum gravity, nor is there a clear understanding of what dark (or hidden) matter and dark energy are. A notable cosmophysical observation is the very existence of the Universe: the fact that the observable Universe consists of matter means the presence of baryon asymmetry, which does not follow from the SM.

Some theories introduce a so-called "mirror world," a hypothetical hidden sector of new particles and interactions, to compensate for the asymmetry of observed particles. Back in 1956, T.D. Lee and C.N. Yang discussed [3] the possibility of the existence of mirror partners of the observed particles. It was assumed that in the case of P-parity violation (mirror coordinate transformation), that is, left-right asymmetry, in known particles, then perhaps there are "mirror" partner particles with the opposite asymmetry, so that the overall symmetry is preserved.

Only a year later, P-parity violation was actually discovered in the experiment of Ch. Sh. Wu in the β-decay of cobalt ^{60}Co [4]. After the discovery of CP parity violation in 1964 (C is charge conjugation), it became clear that antiparticles cannot be mirror partners [5]. In 1966, I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk [6] showed that mirror particles cannot participate in electromagnetic and strong interactions with ordinary particles, since this would lead to an increase in the number of electron states in the atom and other effects not detected in the experiment. With the discovery of W- and Z-bosons, it became clear that mirror particles cannot participate in weak interactions.

Thus, we have the following idea of a set of mirror particles:

$$(O) \equiv \begin{pmatrix} \nu \\ e \\ W \\ Z \\ \gamma \\ q \\ g \end{pmatrix}_O \rightarrow (M) \equiv \begin{pmatrix} \nu \\ e \\ W \\ Z \\ \gamma \\ q \\ g \end{pmatrix}_M , \qquad (1)$$

where the index “O” denotes ordinary particles, and “M” denotes mirror particles. Mirror particles have their own strong, weak and electromagnetic interactions, and gravity is the main way of interaction for ordinary and mirror particles.

The only “bridge” between ordinary and mirror particles can be a neutral particle with non-zero mass (possible kinetic mixing of photons is not taken into account). If a neutrino has mass, and there is a mixing of ordinary and mirror neutrinos, then it can become this “bridge”, that is, through reactions involving neutrinos, ordinary particles can turn into mirror ones and vice versa, due to which it is possible to observe mirror particles experimentally. So far no such mixing has been detected.

The work of S.I. Blinnikov and M.Yu. Khlopov [7] shows that the presence of a mirror world with particle masses and coupling constants of its “mirror” interactions, the same as in the SM, would lead to a contradiction with experimental data. Therefore, in models of the mirror world, it is reasonable to use assumptions about some differences from the world of ordinary particles. In models of mirror worlds different from ours, some mirror particles and even astronomical objects made of mirror particles can play a hidden role.

This paper considers a model of a mirror world in which $m_n < m_p - m_e$.

2. MODEL DESCRIPTION

The model considers one generation of particles. The masses of mirror leptons and antileptons in this model are similar to the masses in the SM. The masses of neutrinos are much smaller than the masses of leptons and quarks. The Higgs mechanism is responsible for the presence of particle mass. Mirror particles can interact with ordinary particles using gravitational interaction. The only difference between the mirror model is the difference in quark masses. For quantitative assessments, the model uses certain masses of protons and neutrons:

$$(m_n)^M = \left(m_p\right)^O = 938.272 \text{ MeV}, \ \left(m_p\right)^M = (m_n)^O = 939.565 \text{ MeV}, \quad (2)$$

where the superscripts "M" and "O" still denote particles of the mirror and ordinary world, respectively. Mirror protons and neutrons with such masses can appear if in the Standard Model the masses of u and d quarks are changed or, what is the same, their electric charges are changed:

$$(m_u)^M = (m_d)^O = 4.8 \text{ МэВ}, \ (m_d)^M = (m_u)^O = 2.3 \text{ MeV}, \quad (3)$$

$$(q_u)^M = (q_d)^O = -\frac{1}{3}, \ (q_d)^M = (q_u)^O = \frac{2}{3}. \quad (4)$$

In a world with such first-generation quarks, the picture of hadron interaction will undoubtedly change to one degree or another, but the work examines the consequences from the point of view of protons and neutrons, which makes it possible to assess the influence of the model on the evolution of the Universe.

The mass of the electron remains unchanged:

$$(m_e)^M = (m_e)^O = 0.511 \text{ MeV}. \quad (5)$$

The mass of the "mirror" proton turns out to be less than the mass of the neutron and, accordingly, the difference between the masses of the proton and neutron is positive: $\Delta m_{p-n} > m_e$. Thus, the "mirror" neutron is a stable particle, and the "mirror" proton is unstable. It decays spontaneously via β-decay: $p \rightarrow n + e^+ + \nu_e$. The proton lifetime can be estimated using the formula:

$$\tau_p \sim \frac{1}{G_F^3 \Delta m_{p-n}^5} \approx 900 \text{ seconds}. \quad (6)$$

3. EVOLUTION OF THE EARLY UNIVERSE

3.1. Inflation mechanism

It is believed that the mirror world in question includes the same mechanisms of inflation and baryosynthesis as the normal one.

Thus, to implement the inflation mechanism, a scalar inflaton field is introduced. For the mirror world, an additional inflaton field is introduced [8]; thus, there is one for normal and one for mirror particles. At the same time, in order to satisfy the cosmological constraint on the number of particle types (from observational data on primordial helium) [9], we assume that the temperature of mirror particles at the time of detachment of ordinary particles is quite low (about 3-4 times lower than the temperature of ordinary particles), which means that the inflation of mirror particles occurred and ended somewhat earlier than in our world. Also, in order to allow the possibility of explaining dark matter by particles of the mirror world, we assume the initial conditions for mirror and ordinary particles such that after quenching the cosmological density of mirror particles (and as will be shown below, mirror neutrons are of particular interest) is equal to

$$(\Omega_n)^M = \Omega_{DM} = 0.25 \quad (7)$$

Thus, in the model under consideration, the asymmetry of the initial conditions with respect to ordinary and mirror matter is postulated.

Within the chaotic inflation model, the initial amplitudes of ordinary and mirror inflatons can be different, which leads to the formation of a domain structure in the distribution of ordinary and mirror matter.

In regions where the amplitude of ordinary inflatons is higher, after inflation ordinary particles should dominate, and the admixture of mirror particles should be small. Conversely, the dominance of mirror inflatons leads to a low density of ordinary particles after inflation.

If the inflaton does not have a certain specularity and after inflation an equal number of mirror and ordinary particles are born, then a domain structure can be formed due to random local asymmetry of the amplitudes of the ordinary and mirror fields in different periods after general inflation.

3.2. The mechanism of baryosynthesis

To implement the baryosynthesis mechanism in the ordinary world, the “see-saw” mechanism of the formation of a small Majorana neutrino mass can be used, in which a heavy state of neutrinos arises, the processes involving which violate the lepton number L. Subsequently, this lepton number is distributed between leptons and baryons due to sphaleron processes, preserving more global symmetry B-L=0.

The same mechanism of baryosynthesis is assumed for mirror particles. Since the temperature of the mirror world during baryosynthesis in the model under consideration is lower than in ours, the excess of mirror baryons may turn out to be different from the excess of ordinary baryons ($\sim 10^{-9}$). However, this will not significantly affect further analysis, since, as mentioned above, the initial conditions are chosen in such a way as to explain the hidden mass by the mirror substance, and the background of mirror gamma rays cannot be detected experimentally within this model, since kinetic mixing of photons is not taken into account.

The fact that the proton is now heavier than the sum of the masses of the neutron and the electron (whose mass is equal to the mass of the positron) will affect the n/p concentration ratio at the time of quenching ($T_f \sim 1$ MeV, $t \sim 1$ seconds after the Big Bang), which is given by the relation:

$$n/p = e^{-\frac{\Delta m}{T_f}} \approx 6, \qquad p/n = \frac{1}{6}. \tag{8}$$

At $\Delta m < 0$ the residual neutron concentration will exceed the proton concentration.

By the time nucleosynthesis begins ($t \sim 1$ s), there is a certain concentration of protons and a 6-fold higher concentration of neutrons. In this case, protons decay with the birth of neutrons and positrons, as well as neutrinos: $p \to n + e^+ + \nu_e$.

In 3 minutes, during which nucleosynthesis occurs, about 10% of protons have time to decay, which leads to a change in the ratio $p/n = 1/7$.

In the process of nucleosynthesis, as a result of thermonuclear reactions of neutrons with protons, deuterium nuclei are first formed:

$$n + p \to D + \gamma. \tag{9}$$

And then heavier nuclei of helium, lithium and others:

$$n + p \rightarrow T + \gamma, \tag{10}$$

$$D + D \rightarrow T + p, \tag{11}$$

$$D + T \rightarrow {}^4He + n, \tag{12}$$

$$p + T \rightarrow {}^4He + \gamma, \tag{13}$$

$$p + D \rightarrow {}^3He + \gamma, \tag{14}$$

$$D + D \rightarrow {}^3He + n, \tag{15}$$

$$T + 4He \rightarrow {}^7Li + \gamma. \tag{16}$$

Their relative concentrations can be estimated using the formulas:

$$X(n) = \frac{1 - \frac{p}{n}}{1 + \frac{p}{n}} \approx 0.75, \tag{17}$$

$$X({}^4He) = \frac{\frac{2p}{n}}{1 + \frac{p}{n}} \approx 0.25. \tag{18}$$

Thus, after the era of nucleosynthesis, the Universe mainly consists of neutral, stable neutrons and helium nuclei. Heavier nuclei are present in significantly lower concentrations.

4. SOME SPECIFIC IMPLICATIONS OF THE MODEL

4.1. The mass of π-mesons

Similar to the assumption that replacing the charges of u and d quarks will recharge the proton and neutron, we can conclude that the masses of the charged and neutral π -meson in the mirror and ordinary worlds will be exactly the same.

In the chiral effective theory (CET) model [10], the mass of the π-meson is mainly determined by the mass of the incoming quarks. In this case, electromagnetic corrections are small and weakly affect the nucleon mass.

Thus, one can talk about the equality of nuclear forces in the normal and mirror worlds.

4.2.Bound state (*nn*)

The possibility of the existence of a stable dineutron (*nn*) would significantly change the picture of nucleosynthesis in the mirror world. This would be reflected in the hardening of the p/n ratio upward due to the reaction

$$p + nn \rightarrow T + \gamma, \tag{19}$$

as well as on the isotopic composition of the early Universe (Fig. 1) [11].

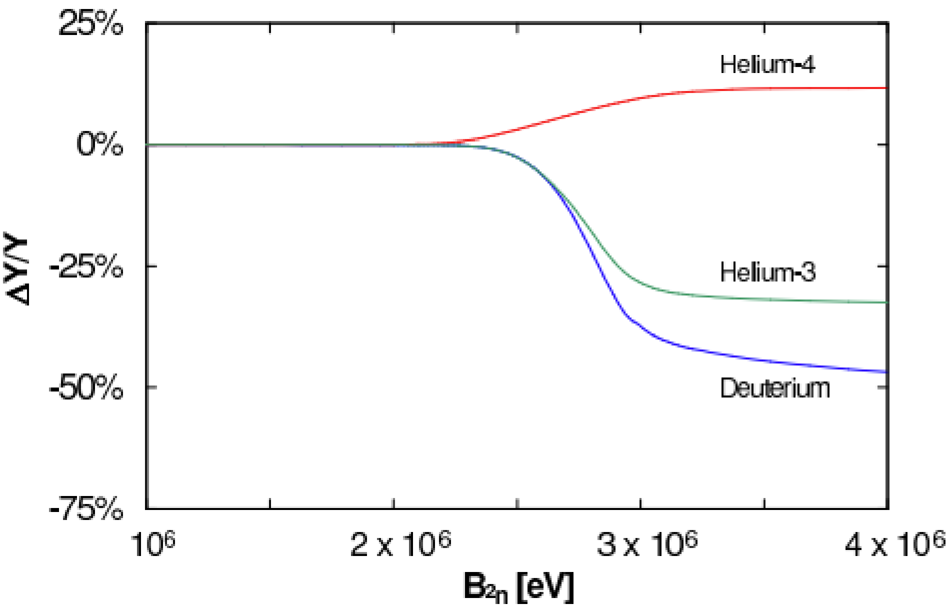

Figure 1. Change in the proportion of primary deuterium, helium-3 and helium-4 depending on the dineutron binding energy

The stability of the state (*nn*) in the era of nucleosynthesis depends not on the neutron lifetime and the β-decay rate, but on the binding energy of this state. Despite the fact that "our" neutron is β-radioactive, dineutrons could have been created in the early Universe and would have influenced the concentration of primordial helium. Moreover, the effect on concentration would depend on the binding energy of the state (*nn*). Thus, for the ordinary world, a cosmological constraint on the dineutron binding energy of 2.5 MeV was obtained [11].

The experimental searches for the dineutron have shown that it is capable of existing as a short-lived resonance with a binding energy of no more than 70 keV [12, 13]. The obtained result is consistent with theoretical predictions [14, 15], since the system of two neutrons is forbidden in the $^1S_0$ state. Within the framework of the discussed model, there are no prerequisites for the fact that the binding energy of two neutrons with opposite spins (suppressed due to the spin-tensor component of the strong interaction) would increase to the value of a stable bound state.

5. FORMATION OF GALAXIES AND STARS

The main component in the mirror world under consideration will be neutrons. Since they are electrically neutral, they will lose almost no energy through the process of "friction" of intergalactic gas, as a result of which they will not form disk structures like galaxies, but will form only spherically symmetrical halos. This means that in terms of their properties, neutrons are close to dark matter. In this case, the neutrons will be "collisional" dark matter with an interaction cross section on the order of the size of the neutron. As shown in [16], a noticeable deviation from the sphericity of the halo in the case of "collisional" dark matter can be noticed when:

$$\frac{\sigma}{m} \sim 1 \ {cm^2}/{g}. \tag{20}$$

For neutrons, relation (20) is ~0.01 cm^2/g; therefore, no noticeable deviation of the shape of the halo of mirror neutrons from spherically symmetric is expected.

Disk structures and galaxies will be formed from helium atoms, since the cross section for the interaction of atoms is much higher than the cross section for neutron collisions, as a result of which helium can lose energy and settle into the disk. The helium concentration is 3 times less than the neutron concentration; moreover, the cross section for the electromagnetic interaction of helium atoms, approximately equal to the radius of the atom, is smaller than the cross section for the interaction of hydrogen atoms in our world (due to the charge of the helium nucleus 2). For this reason, we can expect that by the present moment there will be few disk structures and galaxies in the mirror world.

Long after the formation of a halo of mirror neutrons, the density of such clumps may be sufficient for the start of thermonuclear reactions of the burning of neutrons, similar to the burning of hydrogen in our stars, that is, the fusion of neutrons to form deuterium, electron and antineutrino with the release of energy. This is possible if we assume:

$$2m_n > m_D + m_e, \tag{21}$$

which is a fairly natural assumption by analogy with $2m_p > m_D + m_e$ in our world. Unlike hydrogen combustion, neutron combustion does not involve overcoming a potential barrier (neutrons are neutral), so reaching a threshold temperature is not required and the formation of a hot core is not required. Thus, we can expect that at some point the mirror neutrons throughout the halo volume will begin to slowly "burn", releasing energy through mirror gamma rays and neutrinos, with the formation of deuterium and then helium.

Since the burning will be slow, this effect will not produce much change in the properties of mirror halos by the present age of the Universe. If condition (21) is not met, then the mirror neutrons will not "burn" at all, only their elastic scattering on each other will take place.

In mirror galaxies, star formation is expected only from helium, which, as is known, begins to "burn" in thermonuclear reactions at much higher temperatures than hydrogen. Most clumps in mirror galaxies will have insufficient mass to start burning helium and form helium dwarfs, in which electrons (before ionization, contained in helium atoms) form a degenerate gas, into which fully ionized helium nuclei are immersed with a temperature insufficient to overcome the potential barrier and start thermonuclear reactions. Some rare clumps will have a large mass, sufficient to form a star with helium burning at the center. Such stars will be similar to stars in the ordinary world, with the difference that their number will be much smaller.

6. CANDIDATE FOR DARK MATTER

Obviously, in the model under consideration, the role of dark matter could be played by neutrons, the concentration of which is 3 times higher than the concentration of mirror helium nuclei, and which form spherically symmetrical halos around galaxies. It is possible that the considered model of the mirror world is compatible with the available observational data, if we consider the neutrons of the mirror world to be cold dark matter (CDM).

7. CONCLUSION

The paper considers a model of a mirror world with $m_n < m_p - m_e$. It is shown that with a certain choice of initial data and assumptions (about the mechanism of inflation and baryosynthesis in the mirror world, about the concentration and temperature of detachment of mirror particles, etc.), such a model can be compatible with known observational data.

The simplest consequences of the discussed model are: a mirror neutron is a stable particle, a mirror proton is an unstable particle and decays through a channel $p \to n + e^+ + \nu_e$, the quenching of mirror neutrons is replaced by the quenching of mirror neutrons, the ratio of the concentrations of mirror protons and neutrons is ~0.18.

The greatest interest in such model is the formation of structures: halos, galaxies, stars and similar astronomical objects, since these processes in the mirror world are very different from the ordinary world.

It has been shown that mirror neutrons, which have a sufficient density, are almost stable and form gravitationally bound spherically symmetrical halos and clamps, can serve as candidates for the role of our dark matter.

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