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8 New Generations of Particles in the Universe

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Abstract. Extension of particle symmetry beyond the Standard Model implies new conserved charges and the lightest particles, possessing such charges, should be stable. A widely accepted viewpoint is that if such lightest particles are neutral and weakly interacting, they are most approriate as candidates for components of cosmological dark matter. Superheavy superweakly interacting particles can be also a source of Ultra High Energy cosmic rays. However it turns out that even stable charged leptons and quarks are not ruled out. Created in early Universe, stable charged heavy leptons and quarks can exist and, hidden in elusive atoms, can also play the role of dark matter. The necessary condition for such scenario is absence of stable particles with charge -1 and effective mechanism of suppression for free positively charged heavy species. These conditions are realised in a recently developed scenario, based on Walking Technicolor model, in which excess of stable particles with charge -2 is naturally related with a cosmological baryon excess.

8.1 Introduction

The problem of existence of new particles is among the most important in the modern high energy physics. This problem has a deep relationship with the problem of fundamental symmetry of microworld. Extension of symmetry beyond the Standard model, enlarges representations of symmetry group and their number. Therefore together with known particles vacant places for new particles are opened in such representations.

Noether's theorem relates the exact symmetry to conservation of respective charge. So, electron is absolutely stable, what reflects the conservation of electric charge. In the same manner the stability of proton is conditioned by the conservation of baryon charge. The stability of ordinary matter is thus protected by the conservation of electric and baryon charges.

Quarks and charged leptons of the known second and third generations do not possess strictly conserved quantum numbers and on this reason are not protected from decay. Extrapolating this tendency to quarks and leptons of heavier families, if they exist, we can expect that they also should be unstable and the strategy of their accelerator search uses usually effects of their decay products as signatures.

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However, extensions of the standard model imply new symmetries and new particle states. If the symmetry is strict, its existence implies new conserved charge. The lightest particle, bearing this charge, is stable. The set of new fundamental particles, corresponding to the new strict symmetry, is then reflected in the existence of new stable particles, which should be present in the Universe.

For a particle with the mass m the particle physics time scale is $t \sim 1/m$ (here and further, if not indicated otherwise, we use the units $\hbar = c = k = 1$), so in particle world we refer to particles with lifetime $\tau \gg 1/m$ as to metastable. To be of cosmological significance metastable particle should survive after the temperature of the Universe T fell down below $T \sim m$, what means that the particle lifetime should exceed $t \sim (m_{Pl}/m) \cdot (1/m)$. Such a long lifetime should find reason in the existence of an (approximate) symmetry. From this viewpoint, cosmology is sensitive to the most fundamental properties of microworld, to the conservation laws reflecting strict or nearly strict symmetries of particle theory.

Therefore fundamental theory, going beyond the Standard Model, inevitably confronts cosmological data and the forms of new physics in the Universe, which can stand confrontation with these data, serve as important guideline in its construction. To be realistic, particle theory beyond the Standard Model should with necessity provide explanation for inflation, baryon asymmetry and dark matter, and the approach to such realistic framework involves clear understanding of possible properties of these necessary elements.

Here we adress the question on possible properties of new stable particles with special emphasis on the exciting possibility for such particles to have a $U(1)$ gauge charge, either ordinary electromagnetic, or new one, which known particles do not possess. This charge is the source of Coulomb (or Coulomb-like) interaction, binding charged particles in atom-like states. Cosmological scenarios with various types of such composite dark matter are discussed.

8.2 Cosmophenomenology of new particles

The simplest primordial form of new physics is the gas of new stable massive particles, originated from early Universe. For particles with the mass m, at high temperature $T > m$ the equilibrium condition, $n \cdot \sigma v \cdot t > 1$ is valid, if their annihilation cross section $\sigma v > 1/(m m_{Pl})$ is sufficiently large to establish the equilibrium. At $T < m$ such particles go out of equilibrium and their relative concentration freezes out. More weakly interacting species decouple from plasma and radiation at $T > m$, when $n \cdot \sigma v \cdot t \sim 1$, i.e. at $T_{dec} \sim (\sigma m_{Pl})^{-1}$. The maximal temperature, which is reached in inflationary Universe, is the reheating temperature, T_r, after inflation. So, the very weakly interacting particles with the annihilation cross section $\sigma v < 1/(T_r m_{Pl})$, as well as very heavy particles with the mass $m \gg T_r$ can not be in thermal equilibrium, and the detailed mechanism of their production should be considered to calculate their primordial abundance.

Decaying particles with the lifetime τ, exceeding the age of the Universe, t_U, $\tau > t_U$, can be treated as stable. By definition, primordial stable particles survive to the present time and should be present in the modern Universe. The net effect of their existence is given by their contribution into the total cosmological density. They can dominate in the total density being the dominant form of cosmological dark matter, or they can represent its subdominant fraction. In the latter case more detailed analysis of their distribution in space, of their condensation in galaxies, of their capture by stars, Sun and Earth, as well as of the effects of their interaction with matter and of their annihilation provides more sensitive probes for their existence. In particular, hypothetical stable neutrinos of the 4th generation with the mass about 50 GeV are predicted to form the subdominant form of the modern dark matter, contributing less than 0,1 % to the total density. However, direct experimental search for cosmic fluxes of weakly interacting massive particles (WIMPs) may be sensitive to the existence of such component [1], [2], and may be even favors it [2]. It was shown in [3], [4], [5] that annihilation of 4th neutrinos and their antineutrinos in the Galaxy can explain the galactic gamma-background, measured by EGRET in the range above 1 GeV, and that it can give some clue to explanation of cosmic positron anomaly, claimed to be found by HEAT. 4th neutrino annihilation inside the Earth should lead to the flux of underground monochromatic neutrinos of known types, which can be traced in the analysis of the already existing and future data of underground neutrino detectors [5].

New particles with electric charge and/or strong interaction can form anomalous atoms and contain in the ordinary matter as anomalous isotopes. For example, if the lightest quark of 4th generation is stable, it can form stable +2 charged hadrons, serving as nuclei of anomalous helium [6].

Primordial unstable particles with the lifetime, less than the age of the Universe, $< t_U$, can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition $(m_{Pl}=m)$ $(1=m)$, their existence in early Universe can lead to direct or indirect traces. The cosmophenomenoLOGICAL chains, linking the predicted properties of even unstable new particles to the effects accessible in astronomical observations, are discussed in [7–9].

8.3 Primordial bound systems of superheavy particles

If superheavy particles possess new U(1) gauge charge, related to the hidden sector of particle theory, they are created in pairs. The Coulomb-like attraction (mediated by the massless U(1) gauge boson) between particles and antiparticles in these pairs can lead to their primordial binding, so that the annihilation in the bound system provides the mechanism for UHECR origin [10].

Being created in some nonequilibrium local process (like inflaton field decay or miniPBH evaporation) the pair is localised within the cosmological horizon in the period of creation. If the momentum distribution of created particles is peaked below $p\ \ m c$, they don't spread beyond the proper region of their original localization, being in the period of creation $l\ \ c=H$, where H is the Hubble constant in the period of pair production. For relativistic pairs the region of localization is determined by the size of cosmological horizon in the period of their derelativization. In the course of successive expansion the distance l between particles and antiparticles grows with the scale factor, so that after reheating at the temperature

T it is equal to

$$l(T) = \left(\frac{m_{Pl}}{H}\right)^{1/2}\frac{1}{T}. \quad (8.1)$$

If the considered charge is the source of a long range field, similar to the electromagnetic field, which can bind particle and antiparticle into the atom-like system, analogous to positronium, it may have important practical implications for UHECR problem. The annihilation timescale of such bound system can provide the rate of UHE particle sources, corresponding to UHECR data.

The pair of particle and antiparticle with opposite gauge charges forms bound system, when in the course of expansion the absolute magnitude of potential energy of pair $V = \frac{\alpha_y}{l} \propto a^{-1}$ exceeds the kinetic energy of particle relative motion $T_k = \frac{p^2}{2m} \propto a^{-1}$, where a is the scale factor. The mechanism is similar to the proposed in [11] for binding of magnetic monopole-antimonopole pairs. It is not a recombination one. The binding of two opositely charged particles is caused just by their Coulomb-like attraction, once it exceeds the kinetic energy of their relative motion.

In case, plasma interactions do not heat superheavy particles, created with relative momentum $p \sim mc$ in the period, corresponding to Hubble constant $H \sim H_s$, their initial separation, being of the order of

$$l(H) = \left(\frac{p}{mH}\right), \quad (8.2)$$

experiences only the effect of general expansion, proportional to the inverse first power of the scale factor, while the initial kinetic energy decreases as the square of the scale factor. Thus, the binding condition is fulfilled in the period, corresponding to the Hubble constant H_c, determined by the equation

$$\left(\frac{H}{H_c}\right)^{1/2} = \frac{p^3}{2m^2\alpha_y H}, \quad (8.3)$$

where H is the Hubble constant in the period of particle creation and α_y is the "running constant" of the long range U(1) interaction, possessed by the superheavy particles.

Provided that the primordial abundance of superheavy particles, created on preheating stage corresponds to the appropriate modern density $\Omega_X \sim 0.3$, and the annihilation timescale exceeds the age of the Universe $t_U = 4 \cdot 10^{17}$ s, owing to strong dependence on initial momentum p, the magnitude $r_X = \frac{\Omega_X}{0.3}\frac{t_U}{\tau_X}$ can reach the value $r_X = 2 \cdot 10^{10}$, which was found in [12] to fit the UHECR data by superheavy particle decays in the halo of our Galaxy.

The gauge U(1) nature of the charge, possessed by superheavy particles, assumes the existence of massless U(1) gauge bosons (y-photons) mediating this interaction. Since the considered superheavy particles are the lightest particles bearing this charge, and they are not in thermodynamical equilibrium, one can expect that there should be no thermal background of y-photons and that their non equilibrium fluxes can not heat significantly the superheavy particles.

The situation changes drastically, if the superheavy particles possess not only new U(1) charge but also some ordinary (weak, strong or electric) charge. Due to this charge superheavy particles interact with the equilibrium relativistic plasma (with the number density $n \quad T^3$) and for the mass of particles $m \quad {}^2 m_{Pl}$ the rate of heating $n \; v \; E \quad {}^2 \frac{T^3}{m}$ is sufficiently high to bring the particles into thermal equilibrium with this plasma. Here is the running constant of the considered (weak, strong or electromagnetic) interaction.

While plasma heating keeps superheavy particles in thermal equilibium the binding condition $V \quad T_{kin}$ can not take place. At $T < T_N$, (where $N = e; QCD; w$ respectively, and $T_e \quad 100$keV for electrically charged particles; $T_{QCD} \quad 300$MeV for coloured particles and $T_w \quad 20$GeV for weakly interacting particles, see [10] for details) the plasma heating is suppressed and superheavy particles go out of thermal equilibrium.

In the course of successive expansion the binding condition is formally reached at T_c, given by

$$T_c = T_N \quad y^3 \quad 10^8 \left(\frac{x}{0:3}\right)^{1=3} \left(\frac{10^{14}\,\mathrm{GeV}}{m}\right)^{1=3} : \tag{8.4}$$

However, for electrically charged particles, the binding in fact does not take place to the present time, since one gets from Eq. (8.4) $T_c \quad 1$K. Bound systems of hadronic and weakly interacting superheavy particles can form, respectively, at $T_c \quad 0{:}3$eV and $T_c \quad 20$eV, but even for weakly interacting particles the size of such bound systems approaches a half of meter (30 m for hadronic particles!). It leads to extremely long annihilation timescale of these bound systems, that can not fit UHECR data. It makes impossible to realise the considered mechanism of UHECR origin, if the superheavy U(1) charged particles share ordinary weak, strong or electromagnetic interactions.

Disruption of primordial bound systems in their collisions and by tidal forces in the Galaxy reduces their concentration in the regions of enhanced density. Such spatial distribution, specific for these UHECR sources, makes possible to distinguish them from other possible mechanisms [13–15] in the AUGER and future EUSO experiments.

The lightest particle of four heavy generations of the model [16] can play the role of dark matter, if it is stable. It is interesting to investigate, if the considered mechanism of UHECR can be realised in the framework of this model.

8.4 Atom-like composite dark matter from stable charged particles

The question of the existence of new quarks and leptons is among the most important in the modern high energy physics. This question has an interesting cosmological aspect. If these quarks and/or charged leptons are stable, they should be present around us and the reason for their evanescent nature should be found.

Recently, at least three elementary particle frames for heavy stable charged quarks and leptons were considered: (a) A heavy quark and heavy neutral lepton (neutrino with mass above half the Z-boson mass) of a fourth generation [3,17,18], which can avoid experimental constraints [19,20], and form composite dark matter species [21–24]; (b) A Glashow's "Sinister" heavy tera-quark U and tera-electron E, which can form a tower of tera-hadronic and tera-atomic bound states with "tera-helium atoms" $(UUUEE)$ considered as dominant dark matter [25,26]; (c) AC-leptons, based on the approach of almost-commutative geometry [27,28], that can form evanescent AC-atoms, playing the role of dark matter [27,29,30].

In all these recent models, the predicted stable charged particles escape experimental discovery, because they are hidden in elusive atoms, composing the dark matter of the modern Universe. It offers a new solution for the physical nature of the cosmological dark matter. As it was recently shown in [31] that such a solution is possible in the framework of walking technicolor models [32–37] and can be realized without an *ad hoc* assumption on charged particle excess, made in the approaches (a)-(c), resolving in an elegant way the problems of various dark matter scenarios based on these approaches.

The approaches (b) and (c) try to escape the problems of free charged dark matter particles [38] by hiding opposite-charged particles in atom-like bound systems, which interact weakly with baryonic matter. However, in the case of charge symmetry, when primordial abundances of particles and antiparticles are equal, annihilation in the early Universe suppresses their concentration. If this primordial abundance still permits these particles and antiparticles to be the dominant dark matter, the explosive nature of such dark matter is ruled out by constraints on the products of annihilation in the modern Universe [19,29]. Even in the case of charge asymmetry with primordial particle excess, when there is no annihilation in the modern Universe, binding of positive and negative charge particles is never complete and positively charged heavy species should retain. Recombining with ordinary electrons, these heavy positive species give rise to cosmological abundance of anomalous isotopes, exceeding experimental upper limits. To satisfy these upper limits, the anomalous isotope abundance on Earth should be reduced, and the mechanisms for such a reduction are accompanied by effects of energy release which are strongly constrained, in particular, by the data from large volume detectors.

These problems of composite dark matter models [25,27] revealed in references [19,26,29,21], can be avoided, if the excess of only -2 charge A^{--} particles is generated in the early Universe. In walking technicolor models, technilepton and technibaryon excess is related to baryon excess and the excess of -2 charged particles can appear naturally for a reasonable choice of model parameters [31]. It distinguishes this case from other composite dark matter models, since in all the previous realizations, starting from [25], such an excess was put by hand to saturate the observed cold dark matter (CDM) density by composite dark matter.

After it is formed in Big Bang Nucleosynthesis, ^4He screens the A^{--} charged particles in composite $(^4He^{++}A^{--})$ *techni-O-helium* ($tOHe$) "atoms". These neutral primordial nuclear interacting objects saturate the modern dark matter density and play the role of a nontrivial form of strongly interacting dark matter [38,39]. The active influence of this type of dark matter on nuclear transformations seems to be incompatible with the expected dark matter properties. However, it turns out that the considered scenario is not easily ruled out [29,21,31] and challenges the experimental search for techni-O-helium and its charged techniparticle constituents. Let's discuss following [31] formation of techni-O-helium and scenario of techni-O-helium Universe.

8.5 Dark Matter from Walking Technicolor

The minimal walking technicolor model [32–37] has two techniquarks, i.e. up U and down D, that transform under the adjoint representation of an $SU(2)$ technicolor gauge group. The global symmetry of the model is an $SU(4)$ that breaks spontaneously to an $SO(4)$. The chiral condensate of the techniquarks breaks the electroweak symmetry. There are nine Goldstone bosons emerging from the symmetry breaking. Three of them are eaten by the W and the Z bosons. The remaining six Goldstone bosons are UU, UD, DD and their corresponding antiparticles. For completeness UU is $U^{>}CU$, where C is the charge conjugate matrix and the Greek indices denote technicolor states. For simplicity the contraction of Dirac and technicolor indices is omitted. Since the techniquarks are in the adjoint representation of the $SU(2)$, there are three technicolor states. The UD and DD have similar Dirac and technicolor structure. The pions and kaons which are the Goldstone bosons in QCD carry no baryon number since they are made of pairs of quark-antiquark. However in the considered case, the six Goldstone bosons carry technibaryon number since they are made of two techniquarks or two anti-techniquarks. This means that if no processes violate the technibaryon number, the lightest technibaryon will be stable. The electric charges of UU, UD, and DD are given in general by $y+1$, y, and $y-1$ respectively, where y is an arbitrary real number. For any real value of y, gauge anomalies are cancelled [37]. The model requires in addition the existence of a fourth family of leptons, i.e. a "new neutrino" ^{0} and a "new electron" in order to cancel the Witten global anomaly. Their electric charges are in terms of y respectively $(1-3y)=2$ and $(-1-3y)=2$. The effective theory of this minimal walking technicolor model has been presented in [36,40].

There are several possibilities for a dark matter candidate emerging from this minimal walking technicolor model. For the case where $y = 1$, the D techniquark (and therefore also the DD boson) become electrically neutral. If one assumes that DD is the lightest technibaryon, then it is absolutely stable, because there is no way to violate the technibaryon number apart from the sphalerons that freeze out close to the electroweak scale. This scenario was studied in Refs. [36,37].

Within the same model and electric charge assignment, there is another possibility. Since both techniquarks and technigluons transform under the adjoint representation of the $SU(2)$ group, it is possible to have bound states between a D and a technigluon G. The object $D\ G$ (where denotes technicolor states) is techni-colorless. If such an object has a Majorana mass, then it can account for the whole dark matter density without being excluded by CDMS, due to the fact that Majorana particles have no SI interaction with nuclei and their non-coherent elastic cross section is very low for the current sensitivity of detectors [41].

Finally, if one choose $y = 1=3$, ^{0} has zero electric charge. In this case the heavy fourth Majorana neutrino ^{0} can play the role of a dark matter particle. This scenario was explored first in [43] and later in [41]. It was shown that indeed the fourth heavy neutrino can provide the dark matter density without being excluded by CDMS [1] or any other experiment. This scenario allows the possibility for new signatures of weakly interacting massive particle annihilation [44].

Scenario of composite dark matter corresponds mostly the first case mentioned above, that is $y = 1$ and the Goldstone bosons UU, UD, and DD have electric charges 2, 1, and 0 respectively. In addition for $y = 1$, the electric charges of ^{0} and are respectively -1 and -2. There are three possibilities for a scenario where stable particles with -2 electric charge have substantial relic densities and can capture $^4He^{++}$ nuclei to form a neutral atom. The first one is to have a relic density of $\bar{U}\bar{U}$, which has -2 charge. For this to be true we should assume that UU is lighter than UD and DD and no processes (apart from electroweak sphalerons) violate the technibaryon number. The second one is to have abundance of that again has -2 charge and the third case is to have both $\bar{U}\bar{U}$ (or DD or $\bar{D}\bar{D}$) and . For the first case to be realized, UU although charged, should be lighter than both UD and DD. This can happen if one assumes that there is an isospin splitting between U and D. This is not hard to imagine since for the same reason in QCD the charged proton is lighter than the neutral neutron. Upon making this assumption, UD and DD will decay through weak interactions to the lightest UU. The technibaryon number is conserved and therefore UU (or $\bar{U}\bar{U}$) is stable. Similarly in the second case where is the abundant -2 charge particle, must be lighter than ^{0} and there should be no mixing between the fourth family of leptons and the other three of the Standard Model. The L^0 number is violated only by sphalerons and therefore after the temperature falls roughly below the electroweak scale $_{EW}$ and the sphalerons freeze out, L^0 is conserved, which means that the lightest particle, that is in this case, is absolutely stable. It was also assumed in [31] that technibaryons decay to Standard Model particles through Extended Technicolor (ETC) interactions and therefore the technibaryon number $TB = 0$. Finally there is a possibility to have both the technilepton number L^0 and TB conserved after sphalerons have frozen out. In this case, the dark matter would be composed of bound atoms $(^4He^{++}\ ^{--})$ and either $(^4He^{++}(\bar{U}\bar{U})^{--})$ or neutral DD (or $\bar{D}\bar{D}$).

8.6 Formation of techni-O-helium

8.6.1 Techniparticle excess

The calculation of the excess of the technibaryons with respect to the one of the baryons was pioneered in Refs. [45–47]. In [31] the excess of $\bar{U}\bar{U}$ and was calculated along the lines of [37]. The technicolor and the Standard Model particles are in thermal equilibrium as long as the rate of the weak (and color) interactions is larger than the expansion of the Universe. In addition, the sphalerons allow the violation TB, B, L, and L^0 as long as the temperature of the Universe is higher than roughly $_{EW}$. It is possible through the equations of thermal equilibrium, sphalerons and overall electric neutrality for the particles of the Universe, to associate the chemical potentials of the various particles. The realtionship between these chemical potentials with proper account for statistical factors, , results in relationship between TB, baryon number B, lepton number L, and L^0 after sphaleron processes are frozen out

$$\frac{TB}{B} = - {}_{UU} \frac{L^0}{B}\frac{1}{3} + 1 + \frac{L}{3B} \quad : \tag{8.5}$$

Here ${}_i$ $(i = UU;\ )$ are statistical factors. It was shown in [31] that there can be excess of techni(anti)baryons, $(\bar{U}\bar{U})^{--}$, technileptons ${}^{--}$ or of the both and parameters of model were found at which this asymmetry has proper sign and value, saturating the dark matter density at the observed baryon asymmetry of the Universe.

8.6.2 Techni-O-helium in Big bang Nucleosynthesis

In the Big Bang nucleosynthesis, ^4He is formed with an abundance $r_{He} = 0{:}1 r_B = 8\quad 10^{12}$ and, being in excess, binds all the negatively charged techni-species into atom-like systems.

At a temperature $T < I_o = Z_{TC}^2 Z_{He}^2 \ {}^2 m_{He}=2 \quad 1{:}6\,\mathrm{MeV}$; where is the fine structure constant, and $Z_{TC} = -2$ stands for the electric charge of $\bar{U}\bar{U}$ and/or of , the reaction

$$^{--} + {}^4He^{++} \ ! \quad + ({}^4He \ ) \tag{8.6}$$

and/or

$$(\bar{U}\bar{U})^{--} + {}^4He^{++} \ ! \quad + ({}^4He(\bar{U}\bar{U})) \tag{8.7}$$

can take place. In these reactions neutral techni-O-helium "atoms" are produced. The size of these "atoms" is [21,29]

$$R_o \quad 1=(Z_{TC} Z_{He} \ m_{He}) \quad 2 \quad 10^{13}\ \mathrm{cm}: \tag{8.8}$$

Virtually all the free $(\bar{U}\bar{U})$ and/or (which will be further denoted by A^{--}) are trapped by helium and their remaining abundance becomes exponentially small.

For particles Q^- with charge -1, as for tera-electrons in the sinister model [25] of Glashow, ^4He trapping results in the formation of a positively charged ion $(^4He^{++}Q^-)^+$, result in dramatic over-production of anomalous hydrogen [26]. Therefore, only the choice of -2 electric charge for stable techniparticles makes it possible to avoid this problem. In this case, ^4He trapping leads to the formation of neutral *techni-O-helium* "atoms" $(^4He^{++}A^{--})$.

The formation of techni-O-helium reserves a fraction of ^4He and thus it changes the primordial abundance of ^4He. For the lightest possible masses of the techniparticles $m \quad m_{TB} \quad 100\,\mathrm{GeV}$, this effect can reach 50% of the ^4He abundance formed in SBBN. Even if the mass of the techniparticles is of the order of TeV, 5% of the ^4He abundance is hidden in the techni-O-helium atoms. This can lead to important consequences once we compare the SBBN theoretical predictions to observations.

The question of the participation of techni-O-helium in nuclear transformations and its direct influence on the chemical element production is less evident. Indeed, techni-O-helium looks like an particle with a shielded electric charge. It can closely approach nuclei due to the absence of a Coulomb barrier. Because of this, it seems that in the presence of techni-O-helium, the character of SBBN processes should change drastically. However, it might not be the case.

The following simple argument [29,31] can be used to indicate that the techni-O-helium influence on SBBN transformations might not lead to binding of A^{--} with nuclei heavier than ${}^4He$. In fact, the size of techni-O-helium is of the order of the size of ${}^4He$ and for a nucleus ${}^A_Z Q$ with electric charge $Z > 2$, the size of the Bohr orbit for an QA^{--} ion is less than the size of the nucleus ${}^A_Z Q$. This means that while binding with a heavy nucleus, A^{--} penetrates it and interacts effectively with a part of the nucleus of a size less than the corresponding Bohr orbit. This size corresponds to the size of ${}^4He$, making techni-O-helium the most bound QA^{--} atomic state. It favors a picture, according to which a techni-O-helium collision with a nucleus, results in the formation of techni-O-helium and the whole process looks like an elastic collision.

The interaction of the ${}^4He$ component of $(He^{++}A^{--})$ with a ${}^A_Z Q$ nucleus can lead to a nuclear transformation due to the reaction

$$ {}^A_Z Q + (HeA) \to {}^{A+4}_{Z+2} Q + A^{--}; \qquad (8.9) $$

provided that the masses of the initial and final nuclei satisfy the energy condition

$$ M(A;Z) + M(4;2) - I_o > M(A+4;Z+2); \qquad (8.10) $$

where $I_o = 1.6$ MeV is the binding energy of techni-O-helium and $M(4;2)$ is the mass of the ${}^4He$ nucleus.

This condition is not valid for stable nuclei participating in reactions of the SBBN. However, tritium ${}^3H$, which is also formed in SBBN with the abundance ${}^3H/H \sim 10^{-7}$ satisfies this condition and can react with techni-O-helium, forming ${}^7Li$ and opening the path of successive techni-O-helium catalyzed transformations to heavy nuclei. This effect might strongly influence the chemical evolution of matter on the pre-galactic stage and needs a self-consistent consideration within the Big Bang nucleosynthesis network. However, the following arguments [29,31] show that this effect may not lead to immediate contradiction with observations as it might be expected.

On the path of reactions (8.9), the final nucleus can be formed in the excited $(\alpha; M(A;Z))$ state, which can rapidly experience an α- decay, giving rise to techni-O-helium regeneration and to an effective quasi-elastic process of $({}^4He^{++}A^{--})$-nucleus scattering. It leads to a possible suppression of the techni-O-helium catalysis of nuclear transformations.

The path of reactions (8.9) does not stop on ${}^7Li$ but goes further through ${}^{11}B$, ${}^{15}N$, ${}^{19}F$, ... along the table of the chemical elements.

The cross section of reactions (8.9) grows with the mass of the nucleus, making the formation of the heavier elements more probable and moving the main output away from a potentially dangerous Li and B overproduction.

Such a qualitative change of the physical picture appeals to necessity in a detailed nuclear physics treatment of the (A^{--} + nucleus) systems and of the whole set of transformations induced by techni-O-helium. Though the above arguments do not seem to make these dangers immediate and obvious, a detailed study of this complicated problem is needed.

8.7 Techni-O-helium Universe

8.7.1 Gravitational instability of the techni-O-helium gas

Due to nuclear interactions of its helium constituent with nuclei in cosmic plasma, the techni-O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (RD) stage, and the energy and momentum transfer from the plasma is effective. The radiation pressure acting on plasma is then effectively transferred to density fluctuations of techni-O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon. However, as it was first noticed in [21], this transfer to heavy nuclear-interacting species becomes ineffective before the end of the RD stage and such species decouple from plasma and radiation. Consequently, nothing prevents the development of gravitational instability in the gas of these species. This argument is completely applicable to the case of techni-O-helium.

At temperature $T < T_{od} \approx 45 S_2^{2/3}$ eV, first estimated in [21] for the case of OLe-helium, the energy and momentum transfer from baryons to techni-O-helium is not effective because $n_B \langle \sigma v \rangle (m_p/m_o) t < 1$, where m_o is the mass of the $tOHe$ atom and $S_2 = \frac{m_o}{100\,\mathrm{GeV}}$. Here

$$\sigma \approx \sigma_o \sim \pi R_o^2 \approx 10^{-25}\,\mathrm{cm}^2, \tag{8.11}$$

and $v = \sqrt{2T/m_p}$ is the baryon thermal velocity. The techni-O-helium gas decouples from the plasma and plays the role of dark matter, which starts to dominate in the Universe at $T_{RM} = 1$ eV.

The development of gravitational instabilities of the techni-O-helium gas triggers large scale structure formation, and the composite nature of techni-O-helium makes it more close to warm dark matter.

The total mass of the $tOHe$ gas with density $\rho_d = \frac{T_{RM}}{T_{od}} \rho_{tot}$ within the cosmological horizon $l_h = t$ is

$$M = \frac{4\pi}{3} \rho_d t^3.$$

In the period of decoupling $T = T_{od}$, this mass depends strongly on the techni-particle mass S_2 and is given by

$$M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl} \left(\frac{m_{Pl}}{T_{od}}\right)^2 \approx 2 \cdot 10^{46} S_2^{-8/3}\,\mathrm{g} = 10^{13} S_2^{-8/3} M_{\odot}, \tag{8.12}$$

where $M_{\odot}$ is the solar mass. The techni-O-helium is formed only at T_{rHe} and its total mass within the cosmological horizon in the period of its creation is $M_o = M_{od}(T_o/T_{od})^3 = 10^{37}$ g.

On the RD stage before decoupling, the Jeans length λ_J of the $tOHe$ gas was of the order of the cosmological horizon $\lambda_J \sim l_h \sim t$. After decoupling at $T = T_{od}$, it falls down to $\lambda_J \sim v_o t$, where $v_o = \sqrt{2T_{od}/m_o}$. Though after decoupling the Jeans mass in the $tOHe$ gas correspondingly falls down

$$M_J \sim v_o^3 M_{od} \sim 3 \cdot 10^{-14} M_{od},$$

one should expect strong suppression of fluctuations on scales $M < M_o$, as well as adiabatic damping of sound waves in the RD plasma for scales $M_o < M <$

M_{od}. It provides suppression of small scale structure in the considered model for all reasonable masses of techniparticles.

The cross section of mutual collisions of techni-O-helium "atoms" is given by Eq. (8.11). The $tOHe$ "atoms" can be considered as collision-less gas in clouds with a number density n_o and a size R, if $n_o R < 1/\sigma_o$. This condition is valid for the techni-O-helium gas in galaxies.

Mutual collisions of techni-O-helium "atoms" determine the evolution time-scale for a gravitationally bound system of collision-less $tOHe$ gas

$$t_{ev} = 1/(n\sigma_o v) \approx 2 \cdot 10^{20}(1\,\mathrm{cm}^{-3}/n)^{7/6}\,\mathrm{s};$$

where the relative velocity $v = \sqrt{GM/R}$ is taken for a cloud of mass M_o and an internal number density n. This timescale exceeds substantially the age of the Universe and the internal evolution of techni-O-helium clouds cannot lead to the formation of dense objects. Being decoupled from baryonic matter, the $tOHe$ gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies.

8.7.2 Techniparticle component of cosmic rays

The nuclear interaction of techni-O-helium with cosmic rays gives rise to ionization of this bound state in the interstellar gas and to acceleration of free techniparticles in the Galaxy. During the lifetime of the Galaxy $t_G \approx 3 \cdot 10^{17}$ s, the integral flux of cosmic rays

$$F(E > E_0) \approx 1 \cdot \left(\frac{E_0}{1\,\mathrm{GeV}}\right)^{-1.7} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

can disrupt the fraction of galactic techni-O-helium $\sim F(E > E_{min})\sigma_o t_G \leq 10^{-3}$, where we took $E_{min} \sim I_o$. Assuming a universal mechanism of cosmic ray acceleration, a universal form of their spectrum, taking into account that the ^4He component corresponds to $\sim 5\%$ of the proton spectrum, and that the spectrum is usually reduced to the energy per nucleon, the anomalous low Z/A -2 charged techniparticle component can be present in cosmic rays at a level of

$$\frac{A^{--}}{He} \geq 3 \cdot 10^{-7} \cdot S_2^{-3.7}. \tag{8.13}$$

This flux may be within the reach for PAMELA and AMS02 cosmic ray experiments.

Recombination of free techniparticles with protons and nuclei in the interstellar space can give rise to radiation in the range from few tens of keV - 1 MeV. However such a radiation is below the cosmic nonthermal electromagnetic background radiation observed in this range.

8.7.3 Effects of techni-O-helium catalyzed processes in the Earth

The first evident consequence of the proposed excess is the inevitable presence of $tOHe$ in terrestrial matter. This is because terrestrial matter appears opaque to $tOHe$ and stores all its in-falling flux.

If the $tOHe$ capture by nuclei is not effective, its diffusion in matter is determined by elastic collisions, which have a transport cross section per nucleon

$$\sigma_{tr} = \pi R_o^2 \frac{m_p}{m_o} \approx 10^{-27}/S_2 \, \mathrm{cm}^2. \quad (8.14)$$

In atmosphere, with effective height $L_{atm} = 10^6$ cm and baryon number density $n_B = 6 \cdot 10^{20}$ cm^{-3}, the opacity condition $n_B \sigma_{tr} L_{atm} = 6 \cdot 10^{-1}/S_2$ is not strong enough. Therefore, the in-falling $tOHe$ particles are effectively slowed down only after they fall down terrestrial surface in $16 S_2$ meters of water (or $4 S_2$ meters of rock). Then they drift with velocity $V = \frac{g}{n \sigma v} \approx 8 S_2 A^{1/2}$ cm/s (where $A \sim 30$ is the average atomic weight in terrestrial surface matter, and $g = 980$ cm/s^2), sinking down the center of the Earth on a timescale $t = R_E/V \approx 1.5 \cdot 10^7 S_2^{-1}$ s, where R_E is the radius of the Earth.

The in-falling techni-O-helium flux from dark matter halo is $F = n_o v_h/8\pi$, where the number density of $tOHe$ in the vicinity of the Solar System is $n_o = 3 \cdot 10^{-3} S_2^{-1}$ cm^{-3} and the averaged velocity $v_h \approx 3 \cdot 10^7$ cm/s. During the lifetime of the Earth ($t_E \approx 10^{17}$ s), about $2 \cdot 10^{38} S_2^{-1}$ techni-O-helium atoms were captured. If $tOHe$ dominantly sinks down the Earth, it should be concentrated near the Earth's center within a radius $R_{oc} \sim \sqrt{3T_c/(m_o 4\pi G \rho_c)}$, which is $\sim 10^8 S_2^{-1/2}$ cm, for the Earth's central temperature $T_c \sim 10^4$ K and density $\rho_c \sim 4$ g/cm^3.

Near the Earth's surface, the techni-O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes. It gives

$$n_{oE} = 2\pi F/V = 3 \cdot 10^3 \cdot S_2^{-2} \cdot A^{-1/2} \, \mathrm{cm}^{-3};$$

or for $A \sim 30$ about $5 \cdot 10^2 \cdot S_2^{-2}$ cm^{-3}. This number density corresponds to the fraction

$$f_{oE} \sim 5 \cdot 10^{-21} \cdot S_2^{-2}$$

relative to the number density of the terrestrial atoms $n_A \approx 10^{23}$ cm^{-3}.

These neutral $(^4He^{++}A^{--})$ "atoms" may provide a catalysis of cold nuclear reactions in ordinary matter (much more effectively than muon catalysis). This effect needs a special and thorough investigation. On the other hand, if A^{--} capture by nuclei, heavier than helium, is not effective and does not lead to a copious production of anomalous isotopes, the $(^4He^{++}A^{--})$ diffusion in matter is determined by the elastic collision cross section (8.14) and may effectively hide techni-O-helium from observations.

One can give the following argument for an effective regeneration and quasi-elastic collisions of techni-O-helium in terrestrial matter. The techni-O-helium can be destroyed in the reactions (8.9). Then, free A^{--} are released and due to a hybrid Auger effect (capture of A^{--}, ejection of ordinary e from the atom with atomic number A, and charge of the nucleus Z), A^{--}-atoms are formed, in which A^{--} occupies highly an excited level of the $(^A_Z Q A)$ system, which is still much deeper than the lowest electronic shell of the considered atom. The $(^A_Z Q A)$ atomic transitions to lower-lying states cause radiation in the intermediate range between atomic and nuclear transitions. In course of this falling down to the center of the $(Z - A^{--})$ system, the nucleus approaches A^{--}. For $A > 3$ the energy of the lowest state n (given by $E_n = \frac{M\ ^{-2}}{2n^2} = \frac{2A m_p Z^2\ ^2}{n^2}$) of the $(Z - A^{--})$ system (having reduced mass $M \quad A m_p$) with a Bohr orbit $r_n = \frac{n}{M\ -} = \frac{n}{2A Z m_p}$, exceeding the size of the nucleus $r_A \quad A^{1=3} m^{-1}$ (m being the mass of the pion), is less than the binding energy of $tOHe$. Therefore the regeneration of techni-O-helium in a reaction, inverse to (8.9), takes place. An additional reason for the domination of the elastic channel of the reactions (8.9) is that the final state nucleus is created in the excited state and its de-excitation via -decay can also result in techni-O-helium regeneration. If regeneration is not effective and A^{--} remains bound to the heavy nucleus, anomalous isotope of $Z - 2$ element should appear. This is a serious problem for the considered model.

However, if the general picture of sinking down is valid, it might give no more than the ratio $f_{oE} \quad 5 \quad 10^{21} \quad S_2^2$ of number density of anomalous isotopes to the number density of atoms of terrestrial matter around us, which is below the experimental upper limits for elements with $Z \quad 2$. For comparison, the best upper limits on the anomalous helium were obtained in [49]. It was found, by searching with the use of laser spectroscopy for a heavy helium isotope in the Earth's atmosphere, that in the mass range 5 GeV - 10000 GeV, the terrestrial abundance (the ratio of anomalous helium number to the total number of atoms in the Earth) of anomalous helium is less than $2 \quad 10^{19}$ - $3 \quad 10^{19}$.

8.7.4 Direct search for techni-O-helium

It should be noted that the nuclear cross section of the techni-O-helium interaction with matter escapes the severe constraints [39] on strongly interacting dark matter particles (SIMPs) [38,39] imposed by the XQC experiment [50].

In underground detectors, $tOHe$ "atoms" are slowed down to thermal energies and give rise to energy transfer $2{:}5 \quad 10^3$ eV$A = S_2$, far below the threshold for direct dark matter detection. It makes this form of dark matter insensitive to the CDMS constraints. However, $tOHe$ induced nuclear transformation can result in observable effects.

Therefore, a special strategy of such a search is needed, that can exploit sensitive dark matter detectors on the ground or in space. In particular, as it was revealed in [52], a few g of superfluid ^3He detector [51], situated in ground-based laboratory can be used to put constraints on the in-falling techni-O-helium flux from the galactic halo.

8.8 Discussion

To conclude, the existence of heavy stable particles can offer new solutions for dark matter problem. To be stable, particles should have a conserved charge. If this charge is gauged and strictly conserved, a long range interaction between such particles exists. Superheavy particles, having no ordinary charges, but possessing some new U(1) charge can form primordial bound systems, which can survive to the present time and be a source of Ultra High Energy Cosmic Rays. Earlier annihilation in such systems dominantly to invisible $U(1)$ massless bosons can make them a form of Unstable Dark matter.

If stable particles have electric charge, dark matter candidates can be atom-like states, in which negatively and positively charged particles are bound by Coulomb attraction. In this case there is a serious problem to prevent overproduction of accompanying anomalous forms of atomic matter.

Indeed, recombination of charged species is never complete in the expanding Universe, and significant fraction of free charged particles should remain unbound. Free positively charged species behave as nuclei of anomalous isotopes, giving rise to a danger of their over-production. Moreover, as soon as ^4He is formed in Big Bang nucleosynthesis it captures all the free negatively charged heavy particles. If the charge of such particles is -1 (as it is the case for tera-electron in [25]) positively charged ion $(^4He^{++}E^-)^+$ puts Coulomb barrier for any successive decrease of abundance of species, over-polluting modern Universe by anomalous isotopes. It excludes the possibility of composite dark matter with -1 charged constituents and only -2 charged constituents avoid these troubles, being trapped by helium in neutral OLe-helium or O-helium (ANO-helium) states.

The existence of -2 charged states and the absence of stable -1 charged constituents can take place in AC-model and in charge asymmetric model of 4th generation.

Recently there were explored the cosmological implications of a walking technicolor model with stable doubly charged technibaryons and/or technileptons. The considered model escapes most of the problems of previous realistic scenarios.

To avoid overproduction of anomalous isotopes, an excess of -2 charged techniparticles over their antiparticles should be generated in the Universe. In all the previous realizations of composite dark matter scenario, this excess was put by hand to saturate the observed dark matter density. In walking technicolor model this abundance of -2 charged techibaryons and/or technileptons is connected naturally to the baryon relic density. These doubly charged A^{--} techniparticles bind with ^4He in the techni-O-helium neutral states.

A challenging problem is the nuclear transformations, catalyzed by techni-O-helium. The question about their consistency with observations remains open, since special nuclear physics analysis is needed to reveal what are the actual techni-O-helium effects in SBBN and in terrestrial matter. Another aspect of the considered approach is more clear. For reasonable values of the techniparticle mass, the amount of primordial ^4He, bound in this atom like state is significant and should be taken into account in comparison to observations.

The destruction of techni-O-helium by cosmic rays in the Galaxy releases free charged techniparticles, which can be accelerated and contribute to the flux of cosmic rays. In this context, the search for techniparticles at accelerators and in cosmic rays acquires the meaning of a crucial test for the existence of the basic components of the composite dark matter. At accelerators, techniparticles would look like stable doubly charged heavy leptons, while in cosmic rays, they represent a heavy -2 charge component with anomalously low ratio of electric charge to mass.

The presented arguments enrich the class of possible particles, which can follow from extensions of the Standard Model and be considered as dark matter candidates. One can generalize the generally accepted point that DM particles should be neutral and weakly interacting as follows: they can also be charged and play the role of DARK matter because they are hidden in atom-like states, which are not the source of visible light. The constraints on such particles are very strict and open a very narrow window for this new cosmologically interesting degree of freedom in particle theory.

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