DARK ATOMS AND PUZZLES OF DARK MATTER SEARCHES

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The nonbaryonic dark matter of the Universe is assumed to consist of new stable forms of matter. Their stability reflects symmetry of micro world and particle candidates for cosmological dark matter are the lightest particles that bear new conserved quantum numbers. Dark matter candidates can appear in the new families of quarks and leptons and the existence of new stable charged leptons and quarks is possible, if they are hidden in elusive “dark atoms”. Such possibility, strongly restricted by the constraints on anomalous isotopes of light elements, is not excluded in scenarios that predict stable double charged particles. The excessive -2 charged particles are bound in these scenarios with primordial helium in O-helium “atoms”, maintaining specific nuclear-interacting form of the dark matter, which may provide an interesting solution for the puzzles of the direct dark matter searches.

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1. Introduction

Extensions of the standard model imply new symmetries and new particle states. In particle theory Noether’s theorem relates the exact symmetry to conservation of respective charge. If the symmetry is strict, the charge is strictly conserved. The lightest particle, bearing this charge, is stable. It gives rise to the deep relationship between dark matter candidates and particle symmetry beyond the Standard model.

According to the modern cosmology, the dark matter, corresponding to ~ 25% of the total cosmological density, is nonbaryonic and consists of new stable forms of matter. These forms of matter (see e.g. Refs. 1–3 for review and reference) should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of matter dominated stage. The easiest way to satisfy these conditions is to involve neutral elementary weakly interacting particles. However it is not the only particle physics solution for the dark matter problem and more evolved models of the physical nature of dark matter are possible.
Formation of the Large Scale Structure of the Universe from small initial density fluctuations is one of the most important reasons for the nonbaryonic nature of the dark matter that is decoupled from matter and radiation and provides the effective growth of these fluctuations before recombination. It implies dark matter candidates from the physics beyond the Standard model (see Refs. 3–7 for recent review). On the other hand, the initial density fluctuations, coming from the very early Universe are also originated from physics beyond the Standard model. In the present review we give some examples, linking the primordial seeds of galaxy formation to effects of particle symmetry breaking at very high energies.

Here we don’t touch the exciting problems of the possible nature of dark matter related with extra dimensions and brane cosmology, but even in the case of our 1+3 dimensional space-time we find a lot of examples of nontrivial candidates for cosmological dark matter.

In the Section 2 we present examples of various types of particle candidates for dark matter. We then pay special attention to a possibility for stable charged species of new quarks and leptons to form dark matter, hidden in neutral dark atoms (Section 3). In Section 4 we consider specific form of O-helium (OHe) dark atoms that consist of heavy -2 charged heavy lepton-like particle surrounded by helium nuclear shell. The qualitative advantages of this OHe scenario and the problems of its proof on the basis of a strict quantum mechanical solution of the problem of OHe interaction with nuclei are discussed in Section 5. The conclusive Section 6 considers the challenges for experimental test of the OHe solution for the puzzles of dark matter searches.

2. Particle physics candidates for dark matter

Most of the known particles are unstable. For a particle with the mass \( m \) the particle physics time scale is \( t \sim 1/m \) \(^{\text{a}}\), so in particle world we refer to particles with lifetime \( \tau \gg 1/m \) as to metastable. To be of cosmological significance in the Big Bang Universe 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 \( t \sim (m_{\text{Pl}}/m) \cdot (1/m) \). 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.

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, and its properties reflect the fundamental physical scales of electroweak and strong interactions. Indeed, the mass of electron is related to the scale of the electroweak symmetry breaking, whereas the mass of proton

\(^{\text{a}}\)Here and further, if it isn’t specified otherwise we use the units \( h = c = k = 1 \)
reflects the scale of QCD confinement.

The new strict symmetry is then reflected in the existence of new stable particles, which should be present in the Universe and considered as candidates for dark matter.

2.1. **Stable relics. Freezing out. Charge symmetric case**

The simplest form of dark matter candidates is the gas of new stable neutral 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 $\sigma > 1/(mm_{pl})$ is sufficiently large to establish the equilibrium. At $T < m$ such particles go out of equilibrium and their relative concentration freezes out. This is the main idea of calculation of primordial abundance for Weakly Interacting Massive Particles (WIMPs, see e.g. Refs. 1–3 for details).

The process of WIMP annihilation to ordinary particles, considered in $t$-channel, determines their scattering cross section on ordinary particles and thus relates the primordial abundance of WIMPs to their scattering rate in the ordinary matter. Forming nonluminous massive halo of our Galaxy, WIMPs can penetrate the terrestrial matter and scatter on nuclei in underground detectors. The strategy of direct WIMP searches implies detection of recoil nuclei from this scattering.

The process inverse to annihilation of WIMPs corresponds to their production in collisions of ordinary particles. It should lead to effects of missing mass and energy-momentum, being the challenge for experimental search for production of dark matter candidates at accelerators, e.g. at LHC.

2.2. **Stable relics. Decoupling**

More weakly interacting and/or more light species decouple from plasma and radiation being relativistic at $T \gg m$, when

$$n \cdot \sigma v \cdot t \sim 1,$$

i.e. at

$$T_{dec} \sim (\sigma m_{pl})^{-1} \gg m.$$

After decoupling these species retain their equilibrium distribution until they become non-relativistic at $T < m$. Conservation of partial entropy in the cosmological expansion links the modern abundance of these species to number density of relic photons with the account for the increase of the photon number density due to the contribution of heavier ordinary particles, which were in equilibrium in the period of decoupling.
For the long time, it seemed possible that relic neutrinos can be the dominant form of cosmological dark matter and the corresponding neutrino-dominated Universe was considered as physical ground of Hot Dark Matter scenario of Large scale structure formation. Experimental discovery of neutrino oscillations together with stringent upper limits on the mass of electron neutrino exclude this possibility. Moreover, even neutrino masses in the range of 1eV lead to features in the spectrum of density fluctuations that are excluded by the observational data of CMB.

2.3. Stable relics. SuperWIMPs

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

$$\sigma < 1/(T_r m_p),$$

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.

In particular, thermal production of gravitino in very early Universe is proportional to the reheating temperature $T_r$, what puts upper limit on this temperature from constraints on primordial gravitino abundance.

2.4. Axions and axion-like particles

A wide class of particle models possesses a symmetry breaking pattern, which can be effectively described by pseudo-Nambu–Goldstone (PNG) field (see Refs. 3,15,16 for review and references). The coherent oscillations of this field represent a specific type of CDM in spite of a very small mass of PNG particles $m_a = \Lambda^2/f$, where $f \gg \Lambda$, since these particles are created in Bose-Einstein condensate in the ground state, i.e. they are initially created as nonrelativistic in the very early Universe. This feature, typical for invisible axion models can be the general feature for all the axion-like PNG particles.

At high temperatures the pattern of successive spontaneous and manifest breaking of global U(1) symmetry implies the succession of second order phase transitions. In the first transition at $T \sim f$, continuous degeneracy of vacua leads, at scales exceeding the correlation length, to the formation of topological defects in the form of a string network; in the second phase transition at $T \sim \Lambda \ll f$, continuous transitions in space between degenerated vacua form surfaces: domain walls surrounded by strings. This last structure is unstable, but, as was shown in the example of the invisible axion,17–19 it is reflected in the large scale inhomogeneity of distribution of energy density of coherent PNG (axion) field oscillations. This energy density is proportional to the initial value of phase, which acquires dynamical meaning of
amplitude of axion field, when axion mass $m_a = C m_\pi f_\pi / f$ (where $m_\pi$ and $f_\pi \approx m_\pi$ are the pion mass and constant, respectively, the constant $C \sim 1$ depends on the choice of the axion model and $f \gg f_\pi$ is the scale of the Peccei-Quinn symmetry breaking) is switched on in the result of the second phase transition.

The value of phase changes by $2\pi$ around string. This strong nonhomogeneity of phase leads to corresponding nonhomogeneity of energy density of coherent PNG (axion) field oscillations. Usual argument (see e.g. Ref. 20 and references therein) is essential only on scales, corresponding to mean distance between strings. This distance is small, being of the order of the scale of cosmological horizon in the period, when PNG field oscillations start. However, since the nonhomogeneity of phase follows the pattern of axion string network this argument misses large scale correlations in the distribution of oscillations’ energy density.

Indeed, numerical analysis of string network (see review in the Ref. 21) indicates that large string loops are strongly suppressed and the fraction of about 80% of string length, corresponding to long loops, remains virtually the same in all large scales. This property is the other side of the well known scale invariant character of string network. Therefore the correlations of energy density should persist on large scales, as it was revealed in Refs. 17–19. Discussion of such primordial inhomogeneous structures of dark matter go beyond the scope of the present paper and we can recommend the interested reader Refs. 3, 15, 16 for review and references.

### 2.5. Self interacting dark matter

Extensive hidden sector of particle theory can provide the existence of new interactions, which only new particles possess. Historically one of the first examples of such self-interacting dark matter was presented by the model of mirror matter. Mirror particles, first proposed by T. D. Lee and C. N. Yang in Ref. 22 to restore equivalence of left- and right-handed co-ordinate systems in the presence of P- and C- violation in weak interactions, should be strictly symmetric by their properties to their ordinary twins. After discovery of CP-violation it was shown by I. Yu. Kobzarev, L. B. Okun and I. Ya. Pomeranchuk in Ref. 23 that mirror partners cannot be associated with antiparticles and should represent a new set of symmetric partners for ordinary quarks and leptons with their own strong, electromagnetic and weak mirror interactions. It means that there should exist mirror quarks, bound in mirror nucleons by mirror QCD forces and mirror atoms, in which mirror nuclei are bound with mirror electrons by mirror electromagnetic interaction.\(^{24, 25}\) If gravity is the only common interaction for ordinary and mirror particles, mirror matter can be present in the Universe in the form of elusive mirror objects, having symmetric properties with ordinary astronomical objects (gas, plasma, stars, planets...), but causing only gravitational effects on the ordinary matter.\(^{26, 27}\)

Even in the absence of any other common interaction except for gravity, the observational data on primordial helium abundance and upper limits on the local dark matter seem to exclude mirror matter, evolving in the Universe in a fully symmetric
way in parallel with the ordinary baryonic matter.\textsuperscript{28,29} The symmetry in cosmological evolution of mirror matter can be broken either by initial conditions,\textsuperscript{30,31} or by breaking mirror symmetry in the sets of particles and their interactions as it takes place in the shadow world,\textsuperscript{32,33} arising in the heterotic string model. We refer to Refs. 2,34,35 for current review of mirror matter and its cosmology.

If new particles possess new $y$-charge, interacting with massless bosons or intermediate bosons with sufficiently small mass ($y$-interaction), for slow $y$-charged particles Coulomb-like factor of "Gamov-Sommerfeld-Sakharov enhancement"\textsuperscript{36–38} should be added in the annihilation cross section

\[ C_y = \frac{2\pi\alpha_y/v}{1 - \exp(-2\pi\alpha_y/v)},\]

where $v$ is relative velocity and $\alpha_y$ is the running gauge constant of $y$-interaction. This factor may not be essential in the period of particle freezing out in the early Universe (when $v$ was only few times smaller than $c$, but can cause strong enhancement in the effect of annihilation of nonrelativistic dark matter particles in the Galaxy.

\subsection*{2.6. Subdominant dark matter}

If charge symmetric stable particles (and their antiparticles) represent only subdominant fraction of the cosmological dark matter, more detailed analysis of their distribution in space, of their condensation in galaxies, of their capture by stars, Sun and Earth, as well as effects of their interaction with matter and of their annihilation provides more sensitive probes for their existence.

In particular, hypothetical stable neutrinos of 4th generation with mass about 50 GeV should be the subdominant form of modern dark matter, contributing less than 0.1\% to the total density.\textsuperscript{39,40} However, direct experimental search for cosmic fluxes of weakly interacting massive particles (WIMPs) may be sensitive to existence of such component (see Refs. 41–53 and references therein). It was shown in Refs. 54–57 that annihilation of 4th neutrinos and their antineutrinos in the Galaxy is severely constrained by the measurements of gamma-background, cosmic positrons and antiprotons. 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.\textsuperscript{56,58–60}

An interesting multi-component scenario, based on millicharges and presented in Ref. 61, proposes a dark sector composed of traditional collisionless particles and of a subdominant more complex part, where two new kinds of fermions are introduced and form hydrogen-like atoms through a dark $U(1)$ gauge coupling carried out by a dark massless photon. While one of the two species is light and plays the role of a dark electron, the other one is heavy and is seen as the nucleus of the atom. The latter is coupled to a dark neutral scalar via a Yukawa coupling, creating a finite-range attraction between dark nuclei. Non-gravitational interactions between the
dark and the ordinary sectors come into play through the kinetic and mass mixings between the photon and the dark photon and between the standard $\sigma$ meson and the dark scalar respectively. These have straightforward consequences in direct-dark-matter-search experiments since both dark fermions have small effective couplings to the standard photon while the dark nucleus is coupled to the $\sigma$ meson, making it capable of interacting with nucleons. The dark atoms of the halo, that might form a disk, hit the surface of the Earth and collide with terrestrial atoms until they lose all their energy and thermalize. This happens before they reach an underground detector, typically located at a depth of 1 km, after what they start sinking down, driven by gravity, and arrive in the detector with thermal energies. This makes it impossible to produce nuclear recoils but the dark nuclei bind to the nuclei of the active medium via radiative capture, which causes the emission of photons that produce the observed signal. The model, thanks to its complex subdominant part, can reproduce well the results from DAMA/LIBRA and CoGeNT without contradicting with the negative results from XENON100, LUX and CDMS-II/Ge.

2.7. Decaying dark matter

Decaying particles with lifetime $\tau$, 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. However, even small effect of their decay can lead to significant contribution to cosmic rays and gamma background.\(^{62}\) Leptonic decays of dark matter are considered as possible explanation of the cosmic positron excess, measured in the range above 10 GeV by PAMELA,\(^{63}\) FERMI/LAT\(^{64}\) and AMS02.\(^{65}\)

Primordial unstable particles with the lifetime, less than the age of the Universe, $\tau < t_U$, can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition $\tau \gg (m_P/\langle m \rangle) \cdot (1/m)$, their existence in early Universe can lead to direct or indirect traces.\(^{66}\)

Weakly interacting particles, decaying to invisible modes, can influence Large Scale Structure formation. Such decays prevent formation of the structure, if they take place before the structure is formed. Invisible products of decays after the structure is formed should contribute in the cosmological dark energy. The Unstable Dark matter scenarios\(^{67,75}\) implied weakly interacting particles that form the structure on the matter dominated stage and then decay to invisible modes after the structure is formed.

Cosmological flux of decay products contributing into the cosmic and gamma ray backgrounds represents the direct trace of unstable particles.\(^{66,76}\) If the decay products do not survive to the present time their interaction with matter and radiation can cause indirect trace in the light element abundance\(^{10,12,77}\) or in the fluctuations of thermal radiation.\(^{78}\)
2.8. Charge asymmetry of dark matter

The fact that particles are not absolutely stable means that the corresponding charge is not strictly conserved and generation particle charge asymmetry is possible, as it is assumed for ordinary baryonic matter. At sufficiently strong particle annihilation cross section excessive particles (antiparticles) can dominate in the relic density, leaving exponentially small admixture of their antiparticles (particles) in the same way as primordial excessive baryons dominate over antibaryons in baryon asymmetric Universe. In this case Asymmetric dark matter doesn’t lead to significant effect of particle annihilation in the modern Universe and can be searched for either directly in underground detectors or indirectly by effects of decay or condensation and structural transformations of e.g. neutron stars (see Ref. 79 for recent review and references). If particle annihilation isn’t strong enough, primordial pairs of particles and antiparticles dominate over excessive particles (or antiparticles) and this case has no principle difference from the charge symmetric case. In particular, for very heavy charged leptons (with the mass above 1 TeV), like "tera electrons", discussed in 3, their annihilation due to electromagnetic interaction is too weak to provide effective suppression of primordial tera electron-positron pairs relative to primordial asymmetric excess. 81

2.9. Charged stable relics. Dark atoms

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 charged hadrons, serving as nuclei of anomalous atoms of e.g. anomalous helium. 81–86 Therefore, stringent upper limits on anomalous isotopes, especially, on anomalous hydrogen put severe constraints on the existence of new stable charged particles. However, as we discuss in the rest of this review, stable doubly charged particles can not only exist, but even dominate in the cosmological dark matter, being effectively hidden in neutral "dark atoms". 87

3. Stable charged constituents of Dark Atoms

New stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms cannot be luminous, since they radiate invisible light of U(1) photons. Historically mirror matter (see subsubsection 2.5 and Refs. 1, 34 for review and references) seems to be the first example of such an atomic dark matter.

However, it turned out that the possibility of new stable electrically charged leptons and quarks is not completely excluded and Glashow’s tera-helium 80 has offered a new solution for this type of dark atoms of dark matter. Tera-U-quarks with electric charge +2/3 formed stable (UUU) +2 charged "clusters" that formed with two -1 charged tera-electrons E neutral [(UUU)EE] tera-helium "atoms" that
behaved like Weakly Interacting Massive Particles (WIMPs). The main problem for this solution was to suppress the abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium. This problem turned to be unresolvable, since the model predicted stable tera-electrons $E^-$ with charge -1. As soon as primordial helium is formed in the Standard Big Bang Nucleosynthesis (SBBN) it captures all the free $E^-$ in positively charged $(HeE)^+$ ion, preventing any further suppression of positively charged species. Therefore, in order to avoid anomalous isotopes overproduction, stable particles with charge -1 (and corresponding antiparticles) should be absent, so that stable negatively charged particles should have charge -2 only.

Elementary particle frames for heavy stable -2 charged species are provided by: (a) stable "antibaryons" $\bar{UU}$ formed by anti-$U$ quark of fourth generation (b) AC-leptons, predicted in the extension of standard model, based on the approach of almost-commutative geometry. (c) Technileptons and anti-technibaryons in the framework of walking technicolor models (WTC). (d) Finally, stable charged clusters $\bar{u}_5\bar{u}_5\bar{u}_5$ of (anti)quarks $\bar{u}_5$ of 5th family can follow from the approach, unifying spins and charges. Since all these models also predict corresponding +2 charge antiparticles, cosmological scenario should provide mechanism of their suppression, what can naturally take place in the asymmetric case, corresponding to excess of -2 charge species, $O^{--}$. Then their positively charged antiparticles can effectively annihilate in the early Universe.

If new stable species belong to non-trivial representations of electroweak SU(2) group, sphaleron transitions at high temperatures can provide the relationship between baryon asymmetry and excess of -2 charge stable species, as it was demonstrated in the case of WTC in Refs. 91,103–107.

3.1. Problem of tera-fermion composite dark matter

Glashow's Tera-helium Universe was first inspiring example of the composite dark matter scenario. $SU(3)_c \times SU(2) \times SU(2)' \times U(1)$ gauge model was aimed to explain the origin of the neutrino mass and to solve the problem of strong CP-violation in QCD. New extra $SU(2)'$ symmetry acts on three heavy generations of tera-fermions linked with the light fermions by $CP'$ transformation. $SU(2)'$ symmetry breaking at TeV scale makes tera-fermions much heavier than their light partners. Tera-fermion mass spectrum is the same as for light generations, but all the masses are scaled by the same factor of about $10^6$. Thus the masses of lightest heavy particles are in tera-eV (TeV) range, explaining their name.

Glashow’s model takes into account that very heavy quarks $Q$ (or antiquarks $\bar{Q}$) can form bound states with other heavy quarks (or antiquarks) due to their Coulomb-like QCD attraction, and the binding energy of these states substantially exceeds the binding energy of QCD confinement. Then stable $(QQq)$ and $(QQQ)$ baryons can exist.

According to Ref. primordial heavy quark $U$ and heavy electron $E$ are stable
and may form a neutral \((UUUEE)\) "atom" with \((UUU)\) hadron as nucleus and two \(E^-\)s as "electrons". The gas of such "tera-helium atoms" was proposed in Ref. 80 as a candidate for a WIMP-like dark matter.

The problem of such scenario is an inevitable presence of "products of incomplete combustion" and the necessity to decrease their abundance.

Unfortunately, as it was shown in Ref. 81, this picture of Tera-helium Universe can not be realized.

When ordinary \(^4\text{He}\) is formed in Big Bang Nucleosynthesis, it binds all the free \(E^-\) into positively charged \((^4\text{He}E^-)^+\) "ions". This puts Coulomb barrier for any successive \(E^-E^+\) annihilation or any effective \(EU\) binding. It removes a possibility to suppress the abundance of unwanted tera-particle species (like \((eE^+), \(^4\text{He}Ee\) etc). For instance the remaining abundance of \((eE^+)\) and \((^4\text{He}E^-e)\) exceeds the terrestrial upper limit for anomalous hydrogen by 27 orders of magnitude.\(^81\)

### 3.2. Composite dark matter from almost commutative geometry

The AC-model is based on the specific mathematical approach of unifying general relativity, quantum mechanics and gauge symmetry.\(^84,90\) This realization naturally embeds the Standard model, both reproducing its gauge symmetry and Higgs mechanism with prediction of a Higgs boson mass. AC model is in some sense alternative to SUSY, GUT and superstring extension of Standard model. The AC-model\(^84\) extends the fermion content of the Standard model by two heavy particles, \(SU(2)\) electro-weak singlets, with opposite electromagnetic charges. Each of them has its own antiparticle. Having no other gauge charges of Standard model, these particles (AC-fermions) behave as heavy stable leptons with charges \(-2e\) and \(+2e\), called \(A^{--}\) and \(C^{++}\), respectively.

Similar to the Tera-helium Universe, AC-lepton relics from intermediate stages of a multi-step process towards a final \((AC)\) atom formation must survive in the present Universe. In spite of the assumed excess of particles \((A^{--} \text{ and } C^{++})\) the abundance of relic antiparticles \((\bar{A}^{++} \text{ and } \bar{C}^{--})\) is not negligible. There may be also a significant fraction of \(A^{--}\) and \(C^{++}\), which remains unbound after recombination process of these particles into \((AC)\) atoms took place. As soon as \(^4\text{He}\) is formed in Big Bang nucleosynthesis, the primordial component of free anion-like AC-leptons \((A^{--})\) is mostly trapped in the first three minutes into a neutral O-helium atom \(^4\text{He}^{++}A^{--}\). O-helium is able to capture free \(C^{++}\) creating \((AC)\) atoms and releasing \(^4\text{He}\) back. In the same way the annihilation of antiparticles speeds up. \(C^{++}\)-O-helium reactions stop, when their timescale exceeds a cosmological time, leaving O-helium and \(C^{++}\) relics in the Universe. The catalytic reaction of O-helium with \(C^{++}\) in the dense matter bodies provides successive \((AC)\) binding that suppresses terrestrial anomalous isotope abundance below the experimental upper limit. Due to screened charge of AC-atoms they have WIMP-like interaction with the ordinary matter. Such WIMPs are inevitably accompanied by a tiny component of nuclear interacting O-helium.
3.3. **Stable charged techniparticles in Walking Technicolor**

The minimal walking technicolor model\(^{92-97}\) has two techniquarks, i.e. up \(U\) and down \(D\), that transform under the adjoint representation of an \(SU(2)\) technicolor gauge group. The six Goldstone bosons \(UU, UD, DD\) and their corresponding antiparticles carry technibaryon number since they are made of two techniquarks or two anti-techniquarks. This means that if there is no process violating the technibaryon number the lightest technibaryon will be stable.

The electric charges of \(UU, UD,\) and \(DD\) are given in general by \(q + 1, q,\) and \(q - 1\) respectively, where \(q\) is an arbitrary real number. The model requires in addition the existence of a fourth family of leptons, i.e. a “new neutrino” \(\nu'\) and a “new electron” \(\zeta\). Their electric charges are in terms of \(q\) respectively \((1 - 3q)/2\) and \((-1 - 3q)/2\).

There are three possibilities for a scenario of dark atoms of dark matter. The first one is to have an excess of \(\bar{U}\bar{U}\) (charge \(-2\)). The technibaryon number \(TB\) is conserved and therefore \(UU\) (or \(\bar{U}\bar{U}\)) is stable. The second possibility is to have excess of \(\zeta\) that also has \(-2\) charge and is stable, if \(\zeta\) is lighter than \(\nu'\) and technilepton number \(L'\) is conserved. In both cases stable particles with \(-2\) electric charge have substantial relic densities and can capture \(^{4}He^{++}\) nuclei to form a neutral techni-O-helium atom. Finally there is a possibility to have both \(L'\) and \(TB\) conserved. In this case, the dark matter would be composed of bound atoms \((^{4}He^{++}\zeta^{--})\) and \((\zeta^{--}(UU)^{++})\). In the latter case the excess of \(\zeta^{--}\) should be larger, than the excess of \((UU)^{++}\), so that WIMP-like \((\zeta^{--}(UU)^{++})\) is subdominant at the dominance of nuclear interacting techni-O-helium.

The technicolor and the Standard Model particles are in thermal equilibrium as long as the timescale of the weak (and color) interactions is smaller than the cosmological time. The sphalerons allow violation of \(TB\), of baryon number \(B\), of lepton number \(L\) and \(L'\) as long as the temperature of the Universe exceeds the electroweak scale. It was shown in\(^{91}\) that there is a balance between the excess of techni(anti)baryons, \((\bar{U}\bar{U})^{--}\), technileptons \(\zeta^{--}\) or of the both over the corresponding particles \((UU)^{++}\) and the observed baryon asymmetry of the Universe. It was also shown the there are parameters of the model, at which this asymmetry has proper sign and value, explaining the dark matter density.

3.4. **Stable particles of 4th generation matter**

Modern precision data on the parameters of the Standard model do not exclude\(^{108}\) the existence of the 4th generation of quarks and leptons. The 4th generation follows from heterotic string phenomenology and its difference from the three known light generations can be explained by a new conserved charge, possessed only by its quarks and leptons.\(^{85,88,109-111}\) Strict conservation of this charge makes the lightest particle of 4th family (neutrino) absolutely stable, but it was shown in Refs. 109–111 that this neutrino cannot be the dominant form of the dark matter. The same conservation law requires the lightest quark to be long living.\(^{85,88}\) In principle
the lifetime of $U$ can exceed the age of the Universe, if $m_U < m_D$.\textsuperscript{85, 88} Provided that sphaleron transitions establish excess of $\bar{U}$ antiquarks at the observed baryon asymmetry ($UU\bar{U}$) can be formed and bound with $^4He$ in atom-like state of O-helium.\textsuperscript{85}

In the successive discussion of OHe dark matter we generally don’t specify the type of $-2$ charged particle, denoting it as $O^{--}$. However, one should note that the AC model doesn’t provide OHe as the dominant form of dark matter, so that the quantitative features of OHe dominated Universe are not related to this case.

4. Dark atoms with helium shell

Here we concentrate on the properties of OHe atoms, their interaction with matter and qualitative picture of OHe cosmological evolution\textsuperscript{84, 85, 91, 105, 112–114} and observable effects. We show following Refs. 87, 115 that interaction of OHe with nuclei in underground detectors can explain positive results of dark matter searches in DAMA/NaI (see for review Ref. 42) and DAMA/LIBRA\textsuperscript{43} experiments by annual modulations of radiative capture of O-helium, resolving the controversy between these results and the results of other experimental groups.

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN), $^4He$ screens the excessive $O^{--}$ charged particles in composite ($^4He^{++}O^{--}$) O-helium (OHe) “atoms.”\textsuperscript{85}

In all the considered forms of O-helium, $O^{--}$ behaves either as lepton or as specific "heavy quark cluster" with strongly suppressed hadronic interaction. Therefore O-helium interaction with matter is determined by nuclear interaction of $He$. These neutral primordial nuclear interacting species can play the role of a nontrivial form of strongly interacting dark matter,\textsuperscript{116–124} giving rise to a Warmer than Cold dark matter scenario.\textsuperscript{103, 104, 112}

4.1. OHe atoms and their interaction with nuclei

The structure of OHe atom follows from the general analysis of the bound states of $O^{--}$ with nuclei.

Consider a simple model,\textsuperscript{125–127} in which the nucleus is regarded as a sphere with uniform charge density and in which the mass of the $O^{--}$ is assumed to be much larger than that of the nucleus. Spin dependence is also not taken into account so that both the particle and nucleus are considered as scalars. Then the Hamiltonian is given by

$$H = \frac{p^2}{2Am_p} - \frac{ZZ\alpha}{2R} + \frac{ZZ\alpha}{2R} \cdot \left(\frac{r}{R}\right)^2,$$

for short distances $r < R$ and

$$H = \frac{p^2}{2Am_p} - \frac{ZZ\alpha}{R},$$

for $r > R$.\textsuperscript{85}
for long distances $r > R$, where $\alpha$ is the fine structure constant, $R = d_0 A^{1/3} \sim 1.2 A^{1/3}/(200 \text{MeV})$ is the nuclear radius, $Z$ is the electric charge of nucleus and $Z_x = 2$ is the electric charge of negatively charged particle $X^-$. Since $A_{mp} \ll M_X$ the reduced mass is $1/m = 1/(A_{mp}) + 1/M_X \approx 1/(A_{mp})$.

For small nuclei the Coulomb binding energy is like in hydrogen atom and is given by

$$E_b = \frac{1}{2} \frac{Z^2 Z_x^2 \alpha^2 A_{mp}}{R}.$$  (3)

For large nuclei $X^-$ is inside nuclear radius and the harmonic oscillator approximation is valid for the estimation of the binding energy

$$E_b = \frac{3}{2} \left( \frac{Z Z_x \alpha}{R} \right) - \frac{1}{R} \left( \frac{Z Z_x \alpha}{A_{mp} R} \right)^{1/2}. \quad (4)$$

For the intermediate regions between these two cases with the use of trial function of the form $\psi \sim e^{-\gamma r/R}$ variational treatment of the problem$^{125-127}$ gives

$$E_b = \frac{1}{A_{mp} R^2} F(ZZ_x \alpha A_{mp} R), \quad (5)$$

where the function $F(a)$ has limits

$$F(a \to 0) \to \frac{1}{2} a^2 - \frac{2}{5} a^4,$$  \quad (6)

and

$$F(a \to \infty) \to \frac{3}{2} a - (3a)^{1/2},$$ \quad (7)

where $a = ZZ_x \alpha A_{mp} R$. For $0 < a < 1$ the Coulomb model gives a good approximation, while at $2 < a < \infty$ the harmonic oscillator approximation is appropriate.

In the case of OHe $a = ZZ_x \alpha A_{mp} R \leq 1$, what proves its Bohr-atom-like structure, assumed in Refs. 85, 91, 105–107. The radius of Bohr orbit in these “atoms”$^{85,112}$ $r_o \sim 1/(Z_o Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13}$ cm. However, the size of He nucleus, rotating around $O^-$ in this Bohr atom, turns out to be of the order and even a bit larger than the radius $r_o$ of its Bohr orbit, and the corresponding correction to the binding energy due to non-point-like charge distribution in He is significant.

Bohr atom-like structure of OHe seems to provide a possibility to use the results of atomic physics for description of OHe interaction with matter. However, the situation is much more complicated. OHe atom is similar to the hydrogen, in which electron is hundreds times heavier, than proton, so that it is proton shell that surrounds "electron nucleus". Nuclei that interact with such "hydrogen" would interact first with strongly interacting "protonic" shell and such interaction can hardly be treated in the framework of perturbation theory. Moreover in the description of OHe interaction the account for the finite size of He, which is even larger than the radius of Bohr orbit, is important. One should consider, therefore, the analysis, presented below, as only a first step approaching true nuclear physics of OHe.
The approach of Refs. 103, 112 assumes the following picture of OHe interaction with nuclei: OHe is a neutral atom in the ground state, perturbed by Coulomb and nuclear forces of the approaching nucleus. The sign of OHe polarization changes with the distance: at larger distances Stark-like effect takes place - nuclear Coulomb force polarizes OHe so that nucleus is attracted by the induced dipole moment of OHe, while as soon as the perturbation by nuclear force starts to dominate the nucleus polarizes OHe in the opposite way so that He is situated more close to the nucleus, resulting in the repulsive effect of the helium shell of OHe. When helium is completely merged with the nucleus the interaction is reduced to the oscillatory potential of $O^{-+}$ with homogeneously charged merged nucleus with the charge $Z+2$.

Therefore OHe-nucleus potential can have qualitative feature, presented on Fig. 1: the potential well at large distances (regions III-IV) is changed by a potential wall in region II. The existence of this potential barrier is crucial for all the qualitative features of OHe scenario: it causes suppression of reactions with transition of OHe-nucleus system to levels in the potential well of the region I, provides the dominance of elastic scattering while transitions to levels in the shallow well (regions III-IV) should dominate in reactions of OHe-nucleus capture. The proof of this picture implies accurate and detailed quantum-mechanical treatment, which was started in Ref. 128. With the use of perturbation theory it was shown that OHe polarization changes sign, as the nucleus approaches OHe (as it is given on Fig. 2), but the perturbation approach was not valid for the description at smaller distances, while the estimations indicated that this change of polarization may not be sufficient for creation of the potential, given by Fig. 1. If the picture of Fig. 1 is not proved, one may need more sophisticated models retaining the ideas of OHe scenario, which involve more elements of new physics, as proposed in Ref. 61.

On the other hand, O-helium, being an $\alpha$-particle with screened electric charge, can catalyze nuclear transformations, which can influence primordial light element abundance and cause primordial heavy element formation. It is especially important for quantitative estimation of role of OHe in Big Bang Nucleosynthesis and in stellar
evolution. These effects need a special detailed and complicated study and this work is under way.

The qualitative picture of OHe cosmological evolution is presented below following Refs. 3, 84, 85, 87, 91, 103, 105, 112, 113 and is based on the idea of the dominant role of elastic collisions in OHe interaction with baryonic matter.

4.2. Large Scale structure formation by OHe dark matter

Due to elastic nuclear interactions of its helium constituent with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Domiance (RD) stage, while the energy and momentum transfer from plasma is effective. The radiation pressure acting on the plasma is then transferred to density fluctuations of the O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon.

At temperature $T < T_{od} \approx 1 S_3^{2/3} eV$ the energy and momentum transfer from baryons to O-helium is not effective$^{85,91}$ because

$$n_B \langle \sigma v \rangle (m_p/m_o)t < 1,$$

where $m_o$ is the mass of the OHe atom and $S_3 = m_o/(1$ TeV). Here

$$\sigma \approx \sigma_o \sim \pi r_o^2 \approx 10^{-25} \text{ cm}^2,$$  

(8)

and $v = \sqrt{2T/m_p}$ is the baryon thermal velocity. Then O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12}$ s at $T \leq T_{RM} \approx 1$ eV and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding dark matter scenario.

At $T > T_{RM}$ the total mass of the OHe gas with density $\rho_d = (T_{RM}/T)\rho_{tot}$ is
equal to

\[ M = \frac{4\pi}{3} \rho_d t^3 = \frac{4\pi}{3} \frac{T_{RM}}{T} m_{Pl}(\frac{m_{Pl}}{T})^2 \]

within the cosmological horizon \( l_h = t \). In the period of decoupling \( T = T_{od} \), this mass depends strongly on the O-helium mass \( S_3 \) and is given by

\[ M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl}(\frac{m_{Pl}}{T_{od}})^2 \approx 2 \cdot 10^{44} S_3^{-2} \text{ g} = 10^{11} S_3^{-2} M_\odot, \]

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

On the RD stage before decoupling, the Jeans length \( \lambda_J \) of the OHe gas was restricted from below by the propagation of sound waves in plasma with a relativistic equation of state \( p = \epsilon/3 \), being of the order of the cosmological horizon and equal to \( \lambda_J = l_h/\sqrt{3} = t/\sqrt{3} \). After decoupling at \( T = T_{od} \), it falls down to \( \lambda_J \sim v_o t \), where \( v_o = \sqrt{2 T_{od}/m_o} \). Though after decoupling the Jeans mass in the OHe gas correspondingly falls down

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

one should expect a 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 can provide some suppression of small scale structure in the considered model for all reasonable masses of O-helium. The significance of this suppression and its effect on the structure formation needs a special study in detailed numerical simulations. In any case, it can not be as strong as the free streaming suppression in ordinary Warm Dark Matter (WDM) scenarios, but one can expect that qualitatively we deal with Warmer Than Cold Dark Matter model.

At temperature \( T < T_{od} \approx 1 S_3^{2/3} \text{ keV} \) the energy and momentum transfer from baryons to O-helium is not effective\(^8\), and O-helium gas decouples from plasma. It starts to dominate in the Universe after \( t \sim 10^{12} \text{ s} \) at \( T \leq T_{RM} \approx 1 \text{ eV} \) and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding warmer than cold dark matter scenario.

Being decoupled from baryonic matter, the OHe gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies. It can be easily seen that O-helium gas is collisionless for its number density, saturating galactic dark matter. Taking the average density of baryonic matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryonic objects like stars and planets are opaque for it.
4.3. Anomalous component of cosmic rays

O-helium atoms can be destroyed in astrophysical processes, giving rise to acceleration of free $O^{--}$ in the Galaxy.

O-helium can be ionized due to nuclear interaction with cosmic rays. Estimations show that for the number density of cosmic rays $n_{CR} = 10^{-9} \text{cm}^{-3}$ during the age of Galaxy a fraction of about $10^{-6}$ of total amount of OHe is disrupted irreversibly, since the inverse effect of recombination of free $O^{--}$ is negligible. Near the Solar system it leads to concentration of free $O^{--}$ $n_O = 3 \times 10^{-10} S^{-1} \text{cm}^{-3}$. After OHe destruction free $O^{--}$ have momentum of order $p_O \sim \sqrt{2 \cdot m_o \cdot I_o} \sim 2 \text{GeV} S^{1/2}$ and velocity $v/c \sim 2 \cdot 10^{-3} S^{-1/2}$ and due to effect of Solar modulation these particles initially can hardly reach Earth. Their acceleration by Fermi mechanism or by the collective acceleration forms power spectrum of $O^{--}$ component at the level of $O/p \sim n_O/n_g = 3 \cdot 10^{-10} S^{-1}$, where $n_g \sim 1 \text{cm}^{-3}$ is the density of baryonic matter gas.

At the stage of red supergiants stars have the size $\sim 10^{15} \text{cm}$ and during the period of this stage $\sim 3 \cdot 10^{15} \text{s}$, up to $\sim 10^{-9} S^{-1} \text{cm}^{-3}$ of O-helium atoms per nucleon can be captured. In the Supernova explosion these OHe atoms are disrupted in collisions with particles in the front of shock wave and acceleration of free $O^{--}$ by regular mechanism gives the corresponding fraction in cosmic rays. However, this picture needs detailed analysis, based on the development of OHe nuclear physics and numerical studies of OHe evolution in the stellar matter.

If these mechanisms of $O^{--}$ acceleration are effective, the anomalous low $Z/A$ component of $-2$ charged $O^{--}$ can be present in cosmic rays at the level $O/p \sim n_O/n_g = 3 \cdot 10^{-10} S^{-1}$, and be within the reach for PAMELA and AMS02 cosmic ray experiments.

In the framework of Walking Technicolor model the excess of both stable $\zeta^{--}$ and $(UU)^{++}$ is possible, the latter being two-three orders of magnitude smaller, than the former. It leads to the two-component composite dark matter scenario with the dominant OHe accompanied by a subdominant WIMP-like component of $(\zeta^{--}(UU)^{++})$ bound systems. Technibaryons can be metastable and decays of $(UU)^{++}$ can provide explanation for anomalies, observed in high energy cosmic positron spectrum by PAMELA, FERMI-LAT and AMS02.

4.4. Positron annihilation and gamma lines in galactic bulge

Inelastic interaction of O-helium with the matter in the interstellar space and its de-excitation can give rise to radiation in the range from few keV to few MeV. In the galactic bulge with radius $r_b \sim 1 \text{kpc}$ the number density of O-helium can reach the value $n_o \approx 3 \cdot 10^{-3} / S_3 \text{cm}^{-3}$ and the collision rate of O-helium in this central region was estimated in Refs. $104,107$: $dN/dt = n_o^2 \sigma v_b 4 \pi r_b^3 / 3 \approx 3 \cdot 10^{24} S_3^{-2} \text{s}^{-1}$. At the velocity of $v_b \sim 3 \cdot 10^7 \text{cm/s}$ energy transfer in such collisions is $\Delta E \sim 1 \text{MeV} S_3$. These collisions can lead to excitation of O-helium. If $nS (n \geq 3)$ level is excited, pair production dominates over two-photon channel in the de-excitation by $E0$ transition.
and positron production with the rate $3 \cdot 10^{42} S_3^{-2} \text{s}^{-1}$ is not accompanied by strong gamma signal. According to Ref. 130 this rate of positron production for $S_3 \sim 1$ is sufficient to explain the excess in positron annihilation line from bulge, measured by INTEGRAL (see Ref. 131 for review and references). The dependence of this effect on the mass of O-helium, as well as on its density profile and velocity dispersion in the galactic bulge is studied in Ref. 132.

If OHe levels with nonzero orbital momentum are excited, gamma lines should be observed from transitions $(n > m)$

$$E_{nm} = 1.598 \text{MeV}(1/m^2 - 1/n^2)$$

(or from the similar transitions corresponding to the case $I_o = 1.287 \text{MeV}$) at the level $3 \cdot 10^{-4} S_3^{-2}(\text{cm}^2\text{s}\text{MeV}\text{ster})^{-1}$.

5. O-helium solution for dark matter puzzles

It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints on strongly interacting dark matter particles (SIMP) posed by the XQC experiment. Therefore, a special strategy of direct O-helium search is needed, as it was proposed in Ref. 135.

5.1. O-helium in the terrestrial matter

The evident consequence of the O-helium dark matter is its inevitable presence in the terrestrial matter, which appears opaque to O-helium and stores all its in-falling flux.

After they fall down terrestrial surface, the in-falling OHe particles are effectively slowed down due to elastic collisions with matter. Then they drift, sinking down towards the center of the Earth with velocity

$$V = \frac{g}{n \sigma v} \approx 80 S_3 A^{1/2} \text{cm/s.}$$

Here $A_{med} \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A$ is the number of terrestrial atomic nuclei, $\sigma v$ is the rate of nuclear collisions and $g = 980$ cm/s$^2$.

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

At a depth $L$ below the Earth’s surface, the drift timescale is $t_{dr} \sim L/V$, where $V \sim 400 S_3$ cm/s is the drift velocity and $m_o = S_3 \text{TeV}$ is the mass of O-helium. It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth $L \sim 10^5$ cm to the corresponding change in the equilibrium underground concentration of OHe on the timescale $t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1}$ s.

The equilibrium concentration, which is established in the matter of underground detectors at this timescale, is given by

$$n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot \sin(\omega(t - t_0))$$
with \( \omega = 2\pi / T, T = 1 \text{yr} \) and \( t_0 \) the phase. So, there is a averaged concentration given by

\[
n_{oE}^{(1)} = \frac{n_0}{320S^3A_{med}^{1/2}}V_h
\]

and the annual modulation of concentration characterized by the amplitude

\[
n_{oE}^{(2)} = \frac{n_0}{640S^3A_{med}^{1/2}}V_E.
\]

Here \( V_h \)-speed of Solar System (220 km/s), \( V_E \)-speed of Earth (29.5 km/s) and \( n_0 = 3 \cdot 10^{-4} S^{-1}_3 \text{cm}^{-3} \) is the local density of O-helium dark matter.

5.2. OHe in the underground detectors

The explanation\(^{57,112,115} \) of the results of DAMA/NaI\(^{42} \) and DAMA/LIBRA\(^ {43} \) experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nucleus, in which OHe is situated beyond the nucleus. Therefore the positive result of these experiments is explained by annual modulation in reaction of radiative capture of OHe

\[
A + (^4He^{++}O^{-}) \rightarrow [A(^4He^{++}O^{-})] + \gamma
\]

by nuclei in DAMA detector.

To simplify the solution of Schrodinger equation the potential was approximated in Refs. 103, 112 by a rectangular potential, presented on Fig. 1. Solution of Schrodinger equation determines the condition, under which a low-energy OHe-nucleus bound state appears in the shallow well of the region III and the range of nuclear parameters was found, at which OHe-sodium binding energy is in the interval 2-4 keV.

The rate of radiative capture of OHe by nuclei can be calculated with the use of the analogy with the radiative capture of neutron by proton with the account for: i) absence of M1 transition that follows from conservation of orbital momentum and ii) suppression of E1 transition in the case of OHe. Since OHe is isoscalar, isovector E1 transition can take place in OHe-nucleus system only due to effect of isospin nonconservation, which can be measured by the factor \( f = (m_n - m_p)/m_N \approx 1.4 \cdot 10^{-3} \), corresponding to the difference of mass of neutron, \( m_n \), and proton, \( m_p \), relative to the mass of nucleon, \( m_N \). In the result the rate of OHe radiative capture by nucleus with atomic number \( A \) and charge \( Z \) to the energy level \( E \) in the medium with temperature \( T \) is given by

\[
\sigma v = \frac{f \pi \alpha Z^2}{m_p^2} \sqrt{\frac{3}{A}} \frac{T}{\sqrt{Am_pE}}
\]

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at
energies above 6 keV means that binding energy $E_{Na}$ of Na-OHe system in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV. The amplitude of annual modulation of ionization signal can reproduce the result of DAMA/NaI and DAMA/LIBRA experiments for $E_{Na} = 3$ keV. The account for energy resolution in DAMA experiments\(^{138}\) can explain the observed energy distribution of the signal from monochromatic photon (with $E_{Na} = 3$ keV) emitted in OHe radiative capture.

At the corresponding nuclear parameters there is no binding of OHe with iodine and thallium.\(^{112}\)

It should be noted that the results of DAMA experiment exhibit also absence of annual modulations at the energy of MeV-tens MeV. Energy release in this range should take place, if OHe-nucleus system comes to the deep level inside the nucleus. This transition implies tunneling through dipole Coulomb barrier and is suppressed below the experimental limits.

For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, the results of Ref. 112 indicate that there are no levels in the OHe-nucleus systems for heavy nuclei. In particular, there are no such levels in Xe, what seem to prevent direct comparison with DAMA results in XENON100 experiment\(^{51}\) or LUX experiment.\(^{52}\) The existence of such level in Ge and the comparison with the results of CDMS\(^{47–49}\) and CoGeNT\(^{53}\) experiments need special study. According to Ref. 112 OHe should bind with O and Ca, what is of interest for interpretation of the signal, observed in CRESST-II experiment.\(^{136}\)

In the thermal equilibrium OHe capture rate is proportional to the temperature. Therefore it looks like it is suppressed in cryogenic detectors by a factor of order $10^{-4}$. However, for the size of cryogenic devices less, than few tens meters, OHe gas in them has the thermal velocity of the surrounding matter and this velocity dominates in the relative velocity of OHe-nucleus system. It gives the suppression relative to room temperature only $\sim m_A/m_o$. Then the rate of OHe radiative capture in cryogenic detectors is given by Eq.(15), in which room temperature $T$ is multiplied by factor $m_A/m_o$. Note that in the case of $T = 70$ K in CoGeNT experiment relative velocity is determined by the thermal velocity of germanium nuclei, what leads to enhancement relative to cryogenic germanium detectors.

### 6. Conclusions

The existence of heavy stable particles is one of the popular solutions for the dark matter problem. Usually they are considered to be electrically neutral. But potentially dark matter can be formed by stable heavy charged particles bound in neutral atom-like states by Coulomb attraction. Analysis of the cosmological data and atomic composition of the Universe gives the constrains on the particle charge showing that only $-2$ charged constituents, being trapped by primordial helium in neutral O-helium states, can avoid the problem of overproduction of the anomalous isotopes of chemical elements, which are severely constrained by observations. Cosmological model of O-helium dark matter can even explain puzzles of direct dark
The proposed explanation is based on the mechanism of low energy binding of OHe with nuclei. Within the uncertainty of nuclear physics parameters there exists a range at which OHe binding energy with sodium is in the interval 2-4 keV. Annual modulation in radiative capture of OHe to this bound state leads to the corresponding energy release observed as an ionization signal in DAMA/NaI and DAMA/LIBRA experiments.

With the account for high sensitivity of the numerical results to the values of nuclear parameters and for the approximations, made in the calculations, the presented results can be considered only as an illustration of the possibility to explain puzzles of dark matter search in the framework of composite dark matter scenario. An interesting feature of this explanation is a conclusion that the ionization signal may be absent in detectors containing light (e.g. $^3$He) or heavy (e.g. Xe) elements. Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very nontrivial task. Recent indications to positive result in the matter of CRESST detector, in which OHe binding is expected together with absence of signal in xenon detectors, may qualitatively favor the presented approach. For the same chemical content an order of magnitude suppression in cryogenic detectors can explain why indications to positive effect in CoGeNT experiment can be compatible with the constraints of CDMS/Ge experiment. The model predicts a possibility of OHe binding with silicon, but this effect should be suppressed at low temperature in CDMS/Si experiment.

The present explanation contains distinct features, by which it can be distinguished from other recent approaches to this problem. An inevitable consequence of the proposed explanation is appearance in the matter of underground detectors anomalous superheavy isotopes, having the mass roughly by $m_o$ larger, than ordinary isotopes of the corresponding elements.

It is interesting to note that in the framework of the presented approach positive result of experimental search for WIMPs by effect of their nuclear recoil would be a signature for a multicomponent nature of dark matter. Such OHe+WIMPs multicomponent dark matter scenarios naturally follow from AC model and can be realized in models of Walking technicolor.

Stable $-2$ charge states ($O^{--}$) can be elementary like AC-leptons or technileptons, or look like technibaryons. The latter, composed of techniquarks, reveal their structure at much higher energy scale and should be produced at LHC as elementary species. The signature for AC leptons and techniparticles is unique and distinctive what allows to separate them from other hypothetical exotic particles.

Since simultaneous production of three $U\bar{U}$ pairs and their conversion in two doubly charged quark clusters $UUU$ is suppressed, the only possibility to test the models of composite dark matter from 4th generation in the collider experiments is a search for production of stable hadrons containing single $U$ or $\bar{U}$ like $Uud$ and $\bar{U}u/\bar{U}d$.

The presented approach sheds new light on the physical nature of dark matter.
Specific properties of dark atoms and their constituents are challenging for the experimental search. The development of quantitative description of OHe interaction with matter confronted with the experimental data will provide the complete test of the composite dark matter model. It challenges search for stable double charged particles at accelerators and cosmic rays as direct experimental probe for charged constituents of dark atoms of dark matter.

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