Puzzles of Dark Matter in the Light of Dark Atoms

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Abstract. The nonbaryonic dark matter of the Universe can consist of new stable charged leptons and quarks, if they are hidden in elusive "dark atoms" of composite dark matter. Such possibility is severely constrained, since free positively charged stable species remaining after recombination can form anomalous isotopes with electrons. This problem can be solved, if there exist stable particles with charge -2 and there are no stable particles with charges +1 and -1. These conditions can be satisfied in several recently developed alternative scenarios, linking excess of -2 particles (leptons or heavy quark clusters with suppressed hadronic interactions) to baryon asymmetry. The excessive -2 charged particles are bound with primordial helium in O-helium "atoms", maintaining specific nuclear-interacting form of the Warmer than Cold Dark Matter. O-helium looks like Bohr-like atom with heavy -2 surrounded by extended helium shell. When nuclei approach O-helium, the nuclear attraction of the helium shell polarizes O-helium. It causes dipole Coulomb repulsion, forming a shallow well outside nucleus, in which levels of O-helium-nucleus bound states can exist. The range of parameters of nuclear interaction is found, at which the binding energy of sodium with O-helium is equal to 3 keV. Annual modulations of radiative capture of O-helium to this level in the matter of DAMA/NaI and DAMA/LIBRA detectors can explain positive results of these experiments. The puzzles of direct dark matter searches appear in this case as a reflection of nontrivial nuclear physics of O-helium.

1. Introduction

According to the modern cosmology, the dark matter, corresponding to 25% of the total cosmological density, is nonbaryonic and consists of new stable particles. Such particles (see e.g. [1, 2, 3] for review and reference), created in very early Universe, should be stable, provide the measured dark matter density and be decoupled 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 massive particles (WIMPs). SUSY Models provide a list of possible WIMP candidates: neutralino, axino, gravitino etc.

However it may not be the only particle physics solution for the dark matter problem.

One of such alternative solutions is based on the existence of heavy stable charged particles bound in neutral "dark atoms". This idea of composite dark matter was first proposed by S.L. Glashow in [4]. According to [4] stable tera-U-quarks with electric charge +2/3 forms stable (UUU) +2 charged "clusters", which in combination with two -1 charged stable tera-electrons E produce neutral $[(UUU)EE]$ tera-helium "atoms" that behave like WIMPs. The

main problem for this solution is the over-abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium. This problem turned to be unresolvable, because in the early Universe as soon as primordial helium is formed it would capture all the free E^- and form positively charged $(HeE)^+$ ion, preventing any further suppression of positively charged species [5]. 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 of -2 only [6]. Stable particles with the charge of -2 turned to be the only solution that saved the idea of dark atoms of dark matter.

One should mention here that stable double charged particles can hardly find place in SUSY models, but there exist several alternative elementary particle frames, in which heavy stable -2 charged species, O^{--}, are predicted:

(a) AC-leptons, predicted in the extension of standard model, based on the approach of almost-commutative geometry [6, 7, 8, 9].

(b) Technileptons and anti-technibaryons in the framework of walking technicolor models (WTC) [10, 11].

(c) stable "heavy quark clusters" $\bar{U}\bar{U}\bar{U}$ formed by anti-U quark of fourth [6, 12, 13, 14] or 5th [15] generation.

All these models also predict corresponding +2 charge particles. If these positively charged particles remain free in the early Universe, they can recombine with ordinary electrons in anomalous helium, which is strongly constrained in the terrestrial matter. Therefore cosmological scenario should provide mechanism of suppression of anomalous helium. There are two possibilities, which require two different mechanisms of such suppression:

(i) The abundance of anomalous helium in the Galaxy may be significant, but in the terrestrial matter there exists a recombination mechanism suppressing this abundance below experimental upper limits.

(ii) Free positively charged particles are already suppressed in the early Universe and the abundance of anomalous helium in the Galaxy is negligible.

These two possibilities correspond to to two different cosmological scenarios of dark atoms. The first is realized in the scenario with AC leptons, which form WIMP-like neutral AC atoms.

The second, which is considered here following [10, 16, 17, 18, 19, 20, 21] assumes charge asymmetric case with the excess of O^{--} that form atom-like states with primordial helium. After it is formed in the Big Bang Nucleosynthesis, ^4He screens the O^{--} charged particles in composite $(^4He^{++}O^{--})$ *O-helium* "atoms" [13].

In all the forms of O-helium [6, 8, 10, 14, 19, 22], 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 its helium shell. These neutral primordial nuclear interacting objects contribute to the modern dark matter density and play the role of a nontrivial form of strongly interacting dark matter [23, 24].

If new stable species belong to non-trivial representations of electroweak SU(2) group, sphaleron transitions at high temperatures provide the relationship between baryon asymmetry and excess of -2 charge stable species. It makes possible to relate the density of asymmetric O-helium dark matter with the baryon density.

Here after a brief review of main features of OHe structure, interaction with matter and evolution in the Universe we concentrate on the nuclear radiative capture of O-helium in underground detectors that might explain puzzles of dark matter searches.

2. O-helium formation, interaction and evolution of in the Universe

2.1. O-helium structure

Following [6, 10, 13, 14, 17, 18, 19, 21, 22] consider charge asymmetric case, when excess of O^{--} provides effective suppression of positively charged species.

In the period $100\,\mathrm{s} \leq t \leq 300\,\mathrm{s}$ at $100\,\mathrm{keV} \geq T \geq T_o = I_o/27 \approx 60\,\mathrm{keV}$, ^4He has already been formed in the SBBN and virtually all free O^{--} are trapped by ^4He in O-helium "atoms" $(^4He^{++}O^{--})$. Here the O-helium ionization potential is[1]

$$I_o = Z_o^2 Z_{He}^2 \alpha^2 m_{He}/2 \approx 1.6\,\mathrm{MeV}, \tag{1}$$

where α is the fine structure constant, $Z_{He} = 2$ and $Z_o = 2$ stands for the absolute value of electric charge of O^{--}. The size of these "atoms" is [8, 13]

$$R_o \sim 1/(Z_o Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13}\,\mathrm{cm} \tag{2}$$

Here and further, if not specified otherwise, we use the system of units $\hbar = c = k = 1$.

The analysis [19] favors Bohr-atom-like structure of O-helium, assumed in [6, 10, 13, 14, 17, 18, 22]. However, the size of He, 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 "proton" 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 in [6, 10, 13, 14, 17, 18, 19, 22, 26], as only a first step approaching true nuclear physics of OHe.

2.2. O-helium interaction with nuclei

The approach of [17, 18, 19, 21] assumes the following picture:

(i) At the distances larger, than its size, OHe is neutral, being only the source of a Coulomb field of O^{--} screened by He shell. Owing to the negative sign of $Z_o = -2$, this potential provides attraction of nucleus to OHe.

(ii) Then helium shell of OHe starts to feel Yukawa exponential tail of attraction of nucleus to He due to scalar-isoscalar nuclear potential.

(iii) Nuclear attraction results in the polarization of OHe and the mutual attraction of nucleus and OHe is changed by Coulomb repulsion of He shell.

(iv) 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 $Z + 2$.

It should be noted that scalar-isoscalar nature of He nucleus excludes its nuclear interaction due to π or ρ meson exchange, so that the main role in its nuclear interaction outside the nucleus plays σ meson exchange, on which nuclear physics data are not very definite. The nuclear potential depends on the mass μ of the σ-meson, coupling to nucleon g^2 and on the relative distance between He and nucleus. It would imply axial symmetric quantum mechanical description. In the approximation of spherical symmetry nuclear attraction beyond the nucleus was taken into account in [19] in a two different ways:

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[1] The account for charge distribution in He nucleus leads to smaller value $I_o \approx 1.3\,\mathrm{MeV}$ [25].
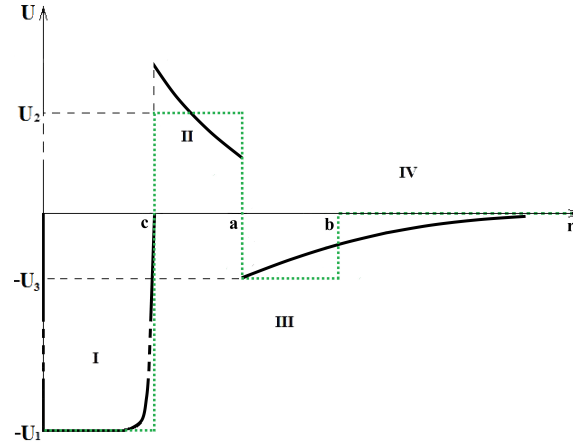
Figure 1. The approximation of rectangular well for potential of OHe-nucleus system.

(m) The nuclear Yukawa potential was averaged over the orbit of He in OHe,

(b) The potential was taken at the position of He most close to the nucleus.

These two cases (m) and (b) correspond to the larger and smaller distance effects of nuclear force, respectively, so that the true picture should be between these two extremes.

To simplify the solution of Schrodinger equation the rectangular potential was considered in [19] that consists of

 (i) a potential well with the depth U_1 at $r < c = R$, where R is the radius of nucleus;

(ii) a rectangular dipole Coulomb potential barrier U_2 at $R \leq r < a = R + R_o + r_{he}$, where r_{he} is radius of helium nucleus;

(iii) an outer potential well U_3, formed by the Yukawa nuclear interaction and residual Coulomb interaction.

It lead to the approximate potential, presented on Fig. 1. Solutions of Schrodinger equation for each of the four regions, indicated on Fig. 1, are given in textbooks (see e.g.[27]) and their sewing determines the condition, under which OHe-nucleus bound states do exist.

Nuclear reactions with OHe can play interesting role in Big Bang and stellar nucleosynthesis, but these studies are only under way. The first results of these studies confirm the earlier guess about the dominance of OHe elastic collisions with nuclei and sufficiently strong suppression of the inelastic processes. That is why we follow qualitative picture of [6, 10, 13, 14, 17, 18, 19, 22, 26] in the description of OHe cosmological evolution.

2.3. O-helium dark matter
Due to elastic nuclear interactions of its helium shell with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (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 $T < T_{od} \approx 200 S_3^{2/3}$ eV the energy and momentum transfer from baryons to O-helium is not effective [10, 13] because

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

where m_o is the mass of the OHe atom and $S_3 = m_o/(1\,\mathrm{TeV})$. Here

$$\sigma \approx \sigma_o \sim \pi R_o^2 \approx 10^{-25}\,\mathrm{cm}^2, \qquad (3)$$

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 $t \sim 10^{12}\,\mathrm{s}$ at $T \leq T_{RM} \approx 1\,\mathrm{eV}$ 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 [10]

$$M_{od} = \frac{T_{RM}}{T_{od}}m_{Pl}(\frac{m_{Pl}}{T_{od}})^2 \approx 2\cdot 10^{44}S_3^{-2}\,\mathrm{g} = 10^{11}S_3^{-2}M_\odot, \qquad (4)$$

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 $M_o = M_{od}(T_{od}/T_o)^3 = 10^{37}\,\mathrm{g}$.

On the RD stage before decoupling, the Jeans length λ_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 $v_o = \sqrt{2T_{od}/m_o}$. 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.

Being decoupled from baryon matter, the OHe gas does not follow the formation of baryon 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 baryon matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryon objects like stars and planets are opaque for it.

O-helium atoms can be destroyed in astrophysical processes, giving rise to acceleration of free O^{--} in the Galaxy. If the 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 $O/p \sim n_O/n_g \sim 10^{-9}S_3^{-1}$, and be within the reach for PAMELA and AMS02 cosmic ray experiments [16, 28].

Collisions in the galactic bulge can lead to excitation of O-helium. If 2S level is excited, pair production dominates over two-photon channel and positron production is sufficient to explain the excess in positron annihilation line from bulge[29], measured by INTEGRAL [30].

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 (SIMPs) [23, 24] imposed by the XQC experiment [31]. Therefore, a special strategy of direct O-helium search is needed, as it was proposed in [32].

3. O-helium effects in underground detectors

3.1. 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

$$V = \frac{g}{n\sigma v} \approx 80 S_3 A^{1/2} \, \text{cm}/\text{s}. \tag{5}$$

Here $A \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A \, \text{cm}^{-3}$ is the number density of terrestrial atomic nuclei, σv is the rate of nuclear collisions, $m_o \approx M_X + 4m_p = S_3 \, \text{TeV}$ is the mass of O-helium, M_O is the mass of the O^{--} component of O-helium, m_p is the mass of proton and $g = 980 \, \text{cm}/\text{s}^2$.

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

The in-falling O-helium flux from dark matter halo is

$$F = \frac{n_0}{8\pi} \cdot |\overline{V_h} + \overline{V_E}|,$$

where V_h-speed of Solar System (220 km/s), V_E-speed of Earth (29.5 km/s) and $n_0 = 3 \cdot 10^{-4} S_3^{-1} \, \text{cm}^{-3}$ is the local density of O-helium dark matter. For qualitative estimation we don't take into account here velocity dispersion and distribution of particles in the incoming flux that can lead to significant effect.

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

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

$$n_{oE} = \frac{2\pi \cdot F}{V} = n_0 \frac{n\sigma v}{4g} \cdot |\overline{V_h} + \overline{V_E}|, \tag{6}$$

where, with account for $V_h > V_E$, relative velocity can be expressed as

$$|\overline{V_o}| = \sqrt{(\overline{V_h} + \overline{V_E})^2} = \sqrt{V_h^2 + V_E^2 + V_h V_E sin(\theta)} \simeq$$

$$\simeq V_h \sqrt{1 + \frac{V_E}{V_h} sin(\theta)} \sim V_h (1 + \frac{1}{2} \frac{V_E}{V_h} sin(\theta)).$$

Here $\theta = \omega(t - t_0)$ with $\omega = 2\pi/T$, $T = 1yr$ and t_0 is the phase. Then the concentration takes the form

$$n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot sin(\omega(t - t_0)) \tag{7}$$

So, if OHe reacts with nuclei in the matter of underground detector, there are two parts of the signal of such reaction: constant and annual modulation, as it is expected in the strategy of dark matter search in DAMA experiments [33, 34].
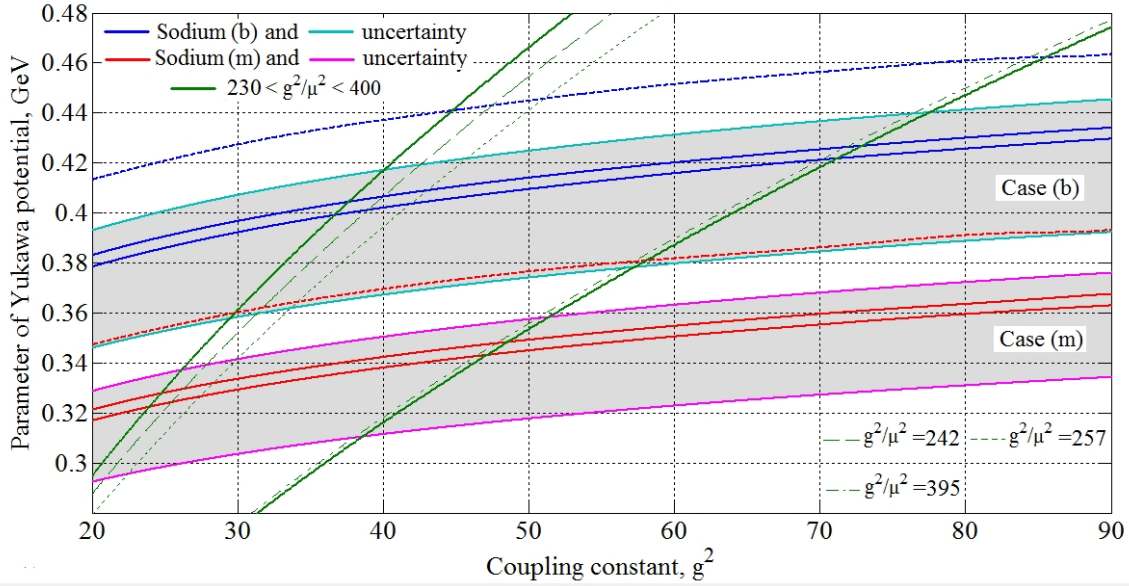
Figure 2. The regions of parameters μ and g^2, for which Na-OHe system has a level in the interval 4 keV for the cases (m) and (b). Two lines determine at $d_o = 1.2/(200\,\text{MeV})$ the region of parameters, at which the bound system of this element with OHe has a 4 keV level. In the region between the two strips the energy of level is below 4 keV. There are also indicated the range of g^2/μ^2 (dashed lines) as well as their preferred values (thin lines) determined from parametrization of the relativistic $(\sigma - \omega)$ model for nuclear matter. The uncertainty in the determination of parameter $1.15/(200\,\text{MeV}) < d_o < 1.3/(200\,\text{MeV})$ results in the uncertainty of μ and g^2 shown by the shaded regions surrounding the lines.

*3.2. Low energy bound state of O-helium with Na nuclei*

The explanation [17, 18, 19, 20] of the results of DAMA/NaI [33] and DAMA/LIBRA [34] experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nuclei, in which OHe is situated **beyond** the nucleus (i.e. in region III on Fig. 1). Therefore the positive result of these experiments is explained by reaction

$$A + (^4He^{++}X^{--}) \rightarrow [A(^4He^{++}X^{--})] + \gamma \tag{8}$$
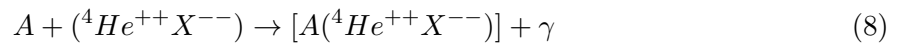
with nuclei in DAMA detector.

The energy of this bound state and its existence strongly depend on the parameters μ and g^2 of nuclear potential. On the Fig. 2 the regions of these parameters, giving 4 keV energy level in OHe bound state with sodium are presented. Radiative capture to this level can explain results of DAMA/NaI and DAMA/LIBRA experiments with the account for their energy resolution [35]. The lower shaded region on Fig. 2 corresponds to the case (m) of nuclear Yukawa potential averaged over the orbit of He in OHe, while the upper region corresponds to the case (b) of this potential taken at the position of He most close to the nucleus. The result is sensitive to the precise value of d_o, which determines the size of nuclei $R = d_o A^{1/3}$. The range of g^2/μ^2 and their preferred values were determined in [36]. In the calculations [19] the mass of OHe was taken equal to $m_o = 1TeV$, however the results weakly depend on the value of $m_o > 1TeV$. It is interesting that the values of μ on Fig. 2 are compatible with the results of recent experimental measurements of mass of sigma meson [37].

The important qualitative feature of this solution is the restricted range of intermediate
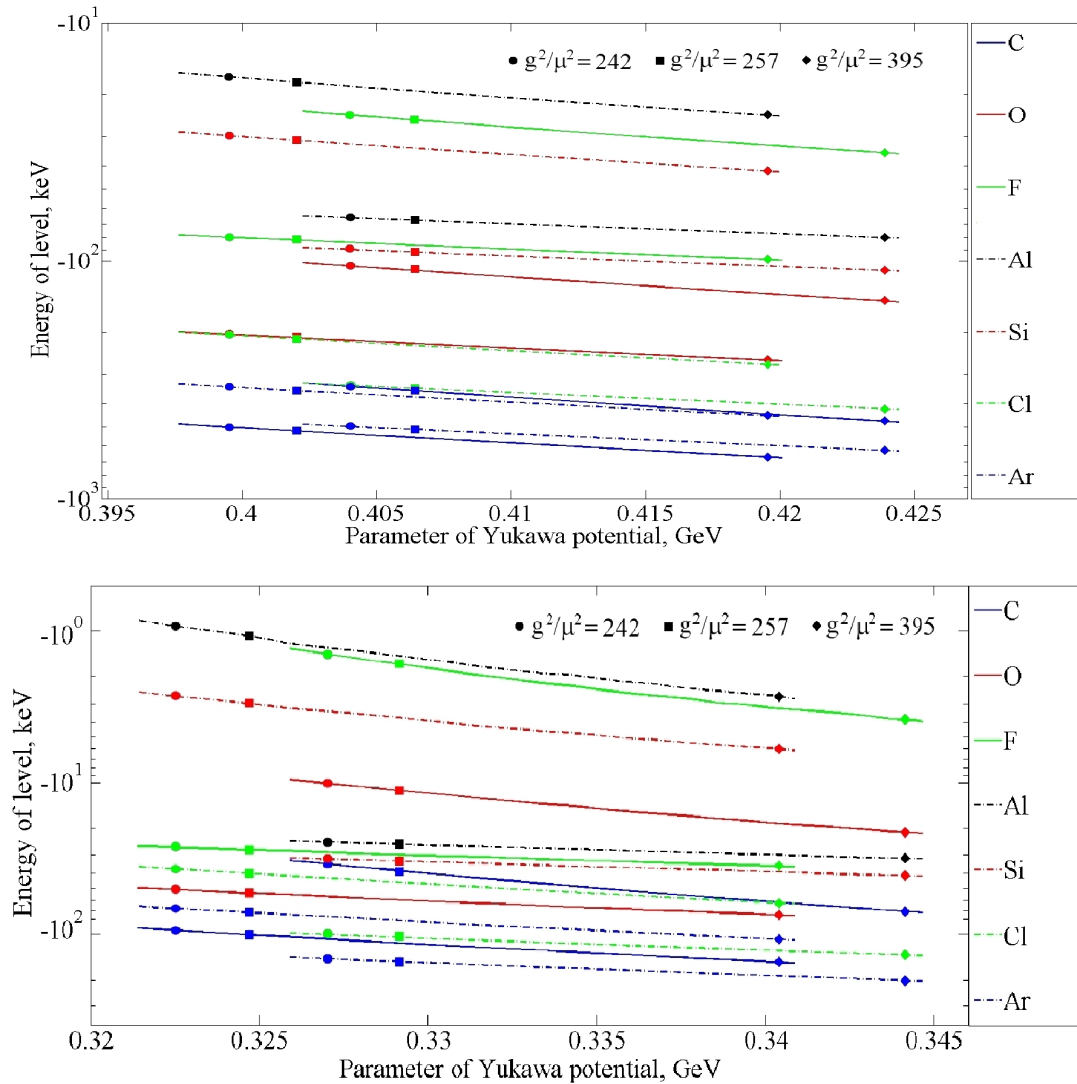
Figure 3. Energy levels in OHe bound system with carbon, oxygen, fluorine, argon, silicon, aluminium and chlorine for the case of the nuclear Yukawa potentials (b - upper plot) and (m - lower plot). The preferred values of g^2/μ^2 are indicated by the corresponding marks (squares or circles).

nuclei, in which the OHe-nucleus bound state is possible. On the Fig. 3 the energy levels for OHe bound states with carbon, oxygen, fluorine, argon, silicon, aluminium and chlorine are plotted for the cases of the nuclear Yukawa potentials (b - upper plot) and (m - lower plot). The predictions are given for the range of g^2/μ^2 determined in [36] from parametrization of the relativistic ($\sigma - \omega$) model for nuclear matter. The energy range for the signals of radiative capture of OHe in detectors with the chemical content different from the one in DAMA/NaI and DAMA/LIBRA is predicted to differ strongly from the signal in DAMA experiments.

The range of nuclei with bound states with OHe corresponds to the part of periodic table between B and Ti. The results are very sensitive to the numerical factors of calculations and

the existence of OHe-Ge and OHe-Ga bound states at a narrow window of parameters μ and g^2 turns to be strongly dependent on these factors so that change in numbers smaller than 1% can give qualitatively different result for Ge and Ga (see [19] for more details).

3.3. Radiative capture of O-helium
In the essence, the explanation [17, 18, 19, 20] of the results of experiments DAMA/NaI and DAMA/LIBRA is based on the idea that OHe concentration in the matter of DAMA detectors possess annual modulation and its radiative capture to a few keV bound state with sodium nuclei leads to the corresponding energy release and ionization signal, detected in DAMA experiments.

The rate of radiative capture of OHe by nuclei was calculated [17, 18, 20] 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

$$\sigma v = \frac{f\pi\alpha}{m_p^2} \frac{3}{\sqrt{2}} (\frac{Z}{A})^2 \frac{T}{\sqrt{Am_p E}}. \tag{9}$$

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of the approach [17, 18, 19, 20, 21] 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 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 (measured in counts per day per kg, cpd/kg) is given by

$$\zeta = \frac{3\pi\alpha \cdot n_o N_A V_E t Q}{640\sqrt{2}A_{med}^{1/2}(A_I + A_{Na})} \frac{f}{S_3 m_p^2}(\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}} = a_i \frac{f}{S_3^2}(\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}}. \tag{10}$$

Here N_A is Avogadro number, i denotes Na, for which numerical factor $a_i = 4.3 \cdot 10^{10}$, $Q = 10^3$ (corresponding to 1kg of the matter of detector), $t = 86400$ s, E_i is the binding energy of Na-OHe system and $n_0 = 3 \cdot 10^{-4} S_3^{-1}$ cm^{-3} is the local density of O-helium dark matter near the Earth. The value of ζ should be compared with the integrated over energy bins signals in DAMA/NaI and DAMA/LIBRA experiments and the result of these experiments can be reproduced for $E_{Na} = 3$ keV. The account for energy resolution in DAMA experiments [35] 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 values of μ and g^2 there is no binding of OHe with iodine and thallium [19].

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.

Since OHe capture rate is proportional to the temperature, 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 the suppression relative to room temperature is only $\sim m_A/m_o$. Then the rate of OHe radiative capture in cryogenic detectors, containing nuclei with atomic number A is given by

Eq.(9), in which room temperature T is multiplied by factor m_A/m_o, and the ionization signal (measured in counts per day per kg, cpd/kg) is given by Eq.(10) with the same correction for T supplemented by additional factors $2V_h/V_E$ and $(A_I + A_{Na})/A$.

Effects of OHe-nucleus binding should strongly differ in detectors with the content, different from NaI. For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, there are no levels in the OHe-nucleus systems for heavy and very light (e.g. ^3He) nuclei [19]. In particular, there are no such levels in Xe and most probably in Ge, what causes problems for direct comparison with DAMA results in CDMS experiment [38] and seem to prevent such comparison in XENON100 [39] experiments. Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very difficult task and the puzzles of dark matter search can reflect the nontrivial properties of composite dark matter.

4. Conclusions

The existence of heavy stable charged particles may not only be compatible with the experimental constraints but can even lead to composite dark matter scenario of nuclear interacting Warmer than Cold Dark Matter. This new form of dark matter can provide explanation of excess of positron annihilation line radiation, observed by INTEGRAL in the galactic bulge. The search for stable -2 charge component of cosmic rays is challenging for PAMELA and AMS02 experiments. Decays of heavy charged constituents of composite dark matter can provide explanation for anomalies in spectra of cosmic high energy positrons and electrons, observed by PAMELA and FERMI. In the context of our approach search for heavy stable charged quarks and leptons at LHC acquires the significance of experimental probe for components of cosmological composite dark matter.

The results of dark matter search in experiments DAMA/NaI and DAMA/LIBRA can be explained in the framework of our scenario without contradiction with the results of other groups. Our approach contains distinct features, by which the present explanation can be distinguished from other recent approaches to this problem [40] (see also for review and more references in [41]).

OHe concentration in the matter of underground detectors is determined by the equilibrium between the incoming cosmic flux of OHe and diffusion towards the center of Earth. It is rapidly adjusted and follows the change in this flux with the relaxation time of few minutes. Therefore the rate of radiative capture of OHe should experience annual modulations reflected in annual modulations of the ionization signal from these reactions. Within the uncertainty of the allowed nuclear physics parameters there exists a range at which OHe binding energy with sodium is in the interval 2-4 keV. Radiative capture of OHe to this bound state leads to the corresponding energy release observed as an ionization signal in DAMA detector. The rate of OHe radiative capture by nuclei is sufficiently low so that there is no significant absorption of OHe by the matter in the course of OHe diffusion to the center of Earth.

An inevitable consequence of the proposed explanation is appearance in the matter of DAMA/NaI or DAMA/LIBRA detector anomalous superheavy isotopes of sodium, having the mass roughly by 1 TeV larger, than ordinary isotopes of this element.

Since in the framework of our approach there should be no OHe radiative capture in detectors, containing heavy or light nuclei, 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 [8] and can be realized in models of Walking technicolor [16].

The presented approach sheds new light on the physical nature of dark matter. In this context positive result of DAMA/NaI and DAMA/LIBRA experiments may be a signature for exciting phenomena of O-helium nuclear physics.

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References

[1] M.Yu. Khlopov *Cosmoparticle physics* (World Scientific, Singapore, 1999).
[2] M.Yu. Khlopov in *Cosmion-94*, Eds. M.Yu.Khlopov et al. (Editions frontieres, 1996) P. 67; M. Y. Khlopov in hep-ph/0612250 , p 51.
[3] M. Y. Khlopov, *Bled Workshops in Physics* **8**, 114 (2007); in arXiv:0711.4681, p. 114; M. Y. Khlopov and N. S. Mankoc-Borstnik, ibid, p. 195.
[4] S. L. Glashow, arXiv:hep-ph/0504287.
[5] D. Fargion and M. Khlopov, arXiv:hep-ph/0507087.
[6] M. Y. Khlopov, arXiv:astro-ph/0607048.
[7] C. A. Stephan, arXiv:hep-th/0509213.
[8] D. Fargion *et al*, *Class. Quantum Grav.* **23**, 7305 (2006); M. Y. Khlopov and C. A. Stephan, arXiv:astro-ph/0603187.
[9] A. Connes *Noncommutative Geometry* (Academic Press, London and San Diego, 1994).
[10] M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D **77**, 065002 (2008).
[11] F. Sannino and K. Tuominen, *Phys. Rev.* D **71**, 051901 (2005); D. K. Hong *et al*, *Phys. Lett.* B **597**, 89 (2004); D. D. Dietrich *et al*, *Phys. Rev.* D **72**, 055001 (2005); D. D. Dietrich *et al*, arXiv:hep-ph/0510217; S. B. Gudnason *et al*, *Phys. Rev.* D **73**, 115003 (2006); S. B. Gudnason *et al*, *Phys. Rev.* D **74**, 095008 (2006).
[12] K.M.Belotsky *et al*, *Gravitation and Cosmology* **11**, 3 (2005)
[13] M.Yu. Khlopov, *JETP Lett.* **83**, 1 (2006).
[14] K. Belotsky *et al*, arXiv:astro-ph/0602261. K. Belotsky *et al*, *Gravitation and Cosmology* **12**, 1 (2006); K. Belotsky *et al*, arXiv:0806.1067 [astro-ph].
[15] N.S. Mankoč Borštnik, This Volume; A. Borštnik Bračič, N.S. Mankoč Borštnik, *Phys. Rev.* D **74**, 073013 (2006); N.S. Mankoč Borštnik, *Mod. Phys. Lett.* A **10**, 587 (1995); N.S. Mankoč Borštnik, *Int. J. Theor. Phys.* **40**, 315 (2001); G. Bregar, M. Breskvar, D. Lukman, N.S. Mankoč Borštnik, *New J. of Phys.* **10**, 093002 (2008).
[16] M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D **78**, 065040 (2008)
[17] M. Y. Khlopov, AIP Conf. Proc. **1241** (2010) 388 [arXiv:0911.5685 [astro-ph.CO]].
[18] M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, Int. J. Mod. Phys. D **19** (2010) 1385 [arXiv:1003.1144 [astro-ph.CO]].
[19] M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *Bled Workshops in Physics* **11**, 73 (2010) arXiv:1011.4586
[20] M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, *Bled Workshops in Physics* **11**, 186 (2010) arXiv:1011.4587
[21] M. Y. Khlopov, A. G. Mayorov and E. Y. Soldatov, Prespace. J. **1** (2010) 1403 [arXiv:1012.0934 [astro-ph.CO]].
[22] M. Y. Khlopov, arXiv:0806.3581 [astro-ph].
[23] C. B. Dover *et al*, *Phys. Rev. Lett.* **42**, 1117 (1979); S. Wolfram, *Phys. Lett.* B **82**, 65 (1979); G. D. Starkman *et al*, *Phys. Rev.* D **41**, 3594 (1990); D. Javorsek *et al*, *Phys. Rev. Lett.* **87**, 231804 (2001); S. Mitra, *Phys. Rev.* D **70**, 103517 (2004); G. D. Mack *et al*, *Phys. Rev.* D **76**, 043523 (2007);
[24] B. D. Wandelt et al., arXiv:astro-ph/0006344; P. C. McGuire and P. J. Steinhardt, arXiv:astro-ph/0105567; G. Zaharijas and G. R. Farrar, *Phys. Rev.* D **72**, 083502 (2005)
[25] R. N. Cahn and S. L. Glashow, *Science* **213**, 607 (1981); M. Pospelov, *Phys. Rev. Lett.* **98**, 231301 (2007); K. Kohri and F. Takayama, *Phys. Rev.* D **76**, 063507 (2007).
[26] M. Y. Khlopov, arXiv:0801.0167 [astro-ph]; M. Y. Khlopov, arXiv:0801.0169 [astro-ph]; M. Yu. Khlopov, A. G. Mayorov, E.Yu. Soldatov, *Bled Workshops in Physics* **10**, 79 (2009); arXiv:0911.5606; M. Yu. Khlopov, A. G. Mayorov, E.Yu. Soldatov, *Bled Workshops in Physics* **9**, 24 (2008)
[27] L. D. Landau, E. M. Lifshitz *Quantum Mechanics: Non-Relativistic Theory* (Fizmatlit, Moscow, 2004).
[28] K.M.Belotsky, A.G.Mayorov, M.Yu.Khlopov. Charged particles of dark matter in cosmic rays. ISBN 978-5-7262-1280-7, Scientific Session NRNU MEPhI-2010, V.4, P.127
[29] D. P. Finkbeiner and N. Weiner, *Phys. Rev.* D **76**, 083519 (2007)
[30] B. J. Teegarden *et al*, *Astrophys. J.* **621**, 296 (2005)
[31] D. McCammon *et al*, *Nucl. Instrum. Methods* A **370**, 266 (1996); D. McCammon *et al*, *Astrophys. J.* **576**, 188 (2002).
[32] K. Belotsky *et al*, arXiv:astro-ph/0606350.

[33] R. Bernabei *et al.*, *Rivista Nuovo Cimento* **26**, 1 (2003)

[34] R. Bernabei *et al.* [DAMA Collaboration], Eur. Phys. J. C **56** (2008) 333 [arXiv:0804.2741 [astro-ph]];
R. Bernabei *et al.*, Eur. Phys. J. C **67** (2010) 39 [arXiv:1002.1028 [astro-ph.GA]]; R. Bernabei *et al.*,
arXiv:1007.0595 [astro-ph.CO].

[35] R. Bernabei *et al.* [DAMA Collaboration], Nucl. Instrum. Meth. A **592** (2008) 297 [arXiv:0804.2738 [astro-
ph]].

[36] A. b. A. Dadi, Phys. Rev. C **82** (2010) 025203 [arXiv:1005.2030 [nucl-th]].

[37] Yu. A. Troyan, A. V. Beljaev, A. Y. Troyan, E. B. Plekhanov, A. P. Jerusalimov and S. G. Arakelian,
arXiv:1011.3124 [hep-ex].

[38] D. S. Akerib *et al.* [CDMS Collaboration], *Phys. Rev. Lett.* **96**, 011302 (2006); Z. Ahmed *et al.* [CDMS
Collaboration], arXiv:0802.3530 [astro-ph]; O. Kamaev for the CDMS Collaboration, arXiv:0910.3005 [hep-
ex].

[39] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **105** (2010) 131302 [arXiv:1005.0380 [astro-
ph.CO]].

[40] F. Petriello and K. M. Zurek, *JHEP* **0809**, 047 (2008); R. Foot, *Phys. Rev.* D **78**, 043529 (2008); J. L. Feng,
J. Kumar and L. E. Strigari, arXiv:0806.3746 [hep-ph]; J. L. Feng, J. Kumar, J. Learned and L. E. Strigari,
arXiv:0808.4151 [hep-ph]; E. M. Drobyshevski, arXiv:0811.0151 [astro-ph]; B. Feldstein, A. L. Fitzpatrick
and E. Katz, JCAP **1001** (2010) 020 [arXiv:0908.2991 [hep-ph]]; Y. Bai and P. J. Fox, JHEP **0911** (2009)
052 [arXiv:0909.2900 [hep-ph]]; B. Feldstein, A. L. Fitzpatrick, E. Katz and B. Tweedie, JCAP **1003** (2010)
029 [arXiv:0910.0007 [hep-ph]]; A. L. Fitzpatrick, D. Hooper and K. M. Zurek, Phys. Rev. D **81** (2010)
115005 [arXiv:1003.0014 [hep-ph]]; S. Andreas, C. Arina, T. Hambye, F. S. Ling and M. H. G. Tytgat,
Phys. Rev. D **82** (2010) 043522 [arXiv:1003.2595 [hep-ph]]; D. S. M. Alves, S. R. Behbahani, P. Schuster
and J. G. Wacker, JHEP **1006** (2010) 113 [arXiv:1003.4729 [hep-ph]]; V. Barger, M. McCaskey and
G. Shaughnessy, Phys. Rev. D **82** (2010) 035019 [arXiv:1005.3328 [hep-ph]]; C. Savage, G. Gelmini,
P. Gondolo and K. Freese, arXiv:1006.0972 [astro-ph.CO]; D. Hooper, J. I. Collar, J. Hall and D. McKinsey,
arXiv:1007.1005 [hep-ph]; S. Chang, R. F. Lang and N. Weiner, arXiv:1007.2688 [hep-ph]; S. Chang,
N. Weiner and I. Yavin, arXiv:1007.4200 [hep-ph]; V. Barger, W. Y. Keung and D. Marfatia, arXiv:1007.4345
[hep-ph]. A. L. Fitzpatrick and K. M. Zurek, arXiv:1007.5325 [hep-ph]; T. Banks, J. F. Fortin and
S. Thomas, arXiv:1007.5515 [hep-ph]; B. Feldstein, P. W. Graham and S. Rajendran, arXiv:1008.1988
[hep-ph].

[41] G. B. Gelmini, Int. J. Mod. Phys. A **23** (2008) 4273 [arXiv:0810.3733 [hep-ph]]; E. Aprile, S. Profumo, New
J. Phys. **11** (2009) 105002. J. L. Feng, arXiv:1003.0904 [astro-ph.CO].