

## Dark Atoms of the Universe: towards OHe nuclear physics

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### Abstract

The nonbaryonic dark matter of the Universe is assumed to consist of new stable particles. A specific case is possible, when new stable particles bear ordinary electric charge and bind in heavy "atoms" by ordinary Coulomb interaction. Such possibility is severely restricted by the constraints on anomalous isotopes of light elements that form positively charged heavy species with ordinary electrons. The trouble is avoided, if stable particles  $X^{--}$  with charge -2 are in excess over their antiparticles (with charge +2) and there are no stable particles with charges +1 and -1. Then primordial helium, formed in Big Bang Nucleosynthesis, captures all  $X^{--}$  in neutral "atoms" of O-helium (OHe). Schrodinger equation for system of nucleus and OHe is considered and reduced to an equation of relative motion in a spherically symmetrical potential, formed by the Yukawa tail of nuclear scalar isoscalar attraction potential, acting on He beyond the nucleus, and dipole Coulomb repulsion between the nucleus and OHe at small distances between nuclear surfaces of He and nucleus. The values of coupling strength and mass of  $\sigma$ -meson, mediating scalar isoscalar nuclear potential, are rather uncertain. Within these uncertainties and in the approximation of rectangular potential wells and wall we find a range of these parameters, at which the sodium nuclei have a few keV binding energy with OHe. The result also strongly depend on the precise value of parameter  $d_o$  that determines the size of nuclei. At nuclear parameters, reproducing DAMA results, OHe-nucleus bound states can exist only for intermediate nuclei, thus excluding direct comparison with these results in detectors, containing very light (e.g.  ${}^3\text{He}$ ) and heavy nuclei (like Xe).

## 1 Introduction

Ordinary matter around us consists of neutral atoms, in which electrically charged nuclei are bound with electrons. Ordinary matter is luminous because of electron transitions in atoms. It is stable owing to stability of its constituents. Electron is the lightest charged particle. It is stable due

to conservation of electromagnetic charge that reflects local gauge U(1) invariance. Electromagnetic charge is the source of the corresponding U(1) gauge field, electromagnetic field. Nuclei are stable because of stability of nucleons. The lightest nucleon - proton - is the lightest baryon and stable due to conservation of baryon charge. There is no gauge field related with baryon charge. Therefore there are two examples of stable charged particles of the ordinary matter: protected by gauge symmetry and protected by conserved charge. This excursus in known physics can give us some idea on possible constituents of dark atoms, maintaining the dark matter of the Universe.

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) 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 self-interacting dark matter are possible. In particular, new stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms would look nonluminous, since they radiate invisible light of U(1) photons. Historically mirror matter (see [1, 4] for review and references) seems to be the first example of such a nonluminous atomic dark matter.

Glashow's tera-helium [5] has offered a new solution for 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 [6], since the model [5] 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"  $\bar{U}\bar{U}\bar{U}$  formed by anti- $U$  quark of fourth generation [7, 8, 9, 10] (b) AC-leptons [10, 11, 12], predicted in the exten-

sion [11] of standard model, based on the approach of almost-commutative geometry [13]. (c) Technileptons and anti-technibaryons [14] in the framework of walking technicolor models (WTC) [15]. (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 [16]. 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,  $X^{--}$ . 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 [14, 17, 18, 19].

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN),  ${}^4\text{He}$  screens the  $X^{--}$  charged particles in composite ( ${}^4\text{He}^{++}X^{--}$ ) *O-helium* "atoms" [8]. For different models of  $X^{--}$  these "atoms" are also called ANO-helium [9, 10], Ole-helium [10, 12] or techni-O-helium [14]. We'll call them all O-helium (*OHe*) in our further discussion, which follows the guidelines of [20].

In all these forms of O-helium,  $X^{--}$  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 objects contribute to the modern dark matter density and play the role of a nontrivial form of strongly interacting dark matter [21, 22].

Here after a brief review of the qualitative picture of OHe cosmological evolution [8, 12, 14, 18, 23] we concentrate on some open questions in the properties of these dark atoms and their interaction with matter. This analysis is used in our second contribution to explain the puzzles of dark matter searches [24]

## 2 Some features of O-helium Universe

Following [8, 9, 10, 14, 18, 19, 20] consider charge asymmetric case, when excess of  $X^{--}$  provides effective suppression of positively charged species.

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

ionization potential is<sup>1</sup>

$$I_o = Z_x^2 Z_{He}^2 \alpha^2 m_{He} / 2 \approx 1.6 \text{ MeV}, \quad (1)$$

where  $\alpha$  is the fine structure constant,  $Z_{He} = 2$  and  $Z_x = 2$  stands for the absolute value of electric charge of  $X^{--}$ . The size of these “atoms” is [8, 12]

$$R_o \sim 1 / (Z_x Z_{He} \alpha m_{He}) \approx 2 \cdot 10^{-13} \text{ cm} \quad (2)$$

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

Due to 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 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  $T < T_{od} \approx 200 S_3^{2/3} \text{ eV}$  the energy and momentum transfer from baryons to O-helium is not effective [8, 14] because

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

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

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

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  $t \sim 10^{12} \text{ s}$  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 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

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

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 [14]

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

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<sup>1</sup>The account for charge distribution in *He* nucleus leads to smaller value  $I_o \approx 1.3 \text{ MeV}$  [31].

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  $M_o = M_{od}(T_{od}/T_o)^3 = 10^{37}$  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  $v_o = \sqrt{2T_{od}/m_o}$ . 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 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.

### 3 Signatures of O-helium dark matter in the Galaxy

The composite nature of O-helium dark matter results in a number of observable effects, which we briefly discuss following [18].

#### 3.1 Anomalous component of cosmic rays

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

O-helium can be ionized due to nuclear interaction with cosmic rays [8, 20]. Estimations [8, 25] 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  $X^{--}$  is negligible. Near the Solar system it leads to concentration of free  $X^{--}$   $n_X = 3 \cdot 10^{-10} S_3^{-1} \text{ cm}^{-3}$ . After OHe destruction free  $X^{--}$  have momentum of order  $p_X \cong \sqrt{2 \cdot M_X \cdot T_o} \cong 2 \text{ GeV} S_3^{1/2}$  and velocity  $v/c \cong 2 \cdot 10^{-3} S_3^{-1/2}$  and due to effect of Solar modulation these particles initially can hardly reach Earth [17, 25]. Their acceleration by Fermi mechanism or by the collective acceleration forms power spectrum of  $X^{--}$  component at the level of  $X/p \sim n_X/n_g = 3 \cdot 10^{-10} S_3^{-1}$ , where  $n_g \sim 1 \text{ cm}^{-3}$  is the density of baryonic matter gas.

At the stage of red supergiant 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  $\sim 10^{-9} S_3^{-1}$  of O-helium atoms per nucleon can be captured [17, 25]. In the Supernova explosion these OHe atoms are disrupted in collisions with particles in the front of shock wave and acceleration of free  $X^{--}$  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  $X^{--}$  acceleration are effective, the anomalous low  $Z/A$  component of  $-2$  charged  $X^{--}$  can be present in cosmic rays at the level  $X/p \sim n_X/n_g \sim 10^{-9} S_3^{-1}$ , and be within the reach for PAMELA and AMS02 cosmic ray experiments.

In the framework of Walking Technicolor model the excess of both stable  $X^{--}$  and  $Y^{++}$  is possible [17], 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  $(X^{--}Y^{++})$  bound systems. Technibaryons and technileptons can be metastable and decays of  $X^{--}$  and  $Y^{++}$  can provide explanation for anomalies, observed in high energy cosmic positron spectrum by PAMELA and in high energy electron spectrum by FERMI and ATIC.

### 3.2 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 [20]:  $dN/dt = n_o^2 \sigma v_h 4\pi r_b^3 / 3 \approx 3 \cdot 10^{42} S_3^{-2} \text{ s}^{-1}$ . At the velocity of  $v_h \sim 3 \cdot 10^7 \text{ cm/s}$  energy transfer in such collisions is  $\Delta E \sim 1 \text{ MeV} S_3$ . These collisions can lead to excitation of O-helium. If 2S 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 [26] 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 [27] for review and references). 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  $3 \cdot 10^{-4} S_3^{-2} (\text{cm}^2 \text{ s MeV ster})^{-1}$ .

It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints [22] on strongly interacting dark matter particles (SIMPs) [21, 22] imposed by the XQC experiment [28]. Therefore, a special strategy of direct O-helium search is needed, as it was proposed in [29].

## 4 O-helium interaction with nuclei

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. In underground detectors,  $OHe$  “atoms” are slowed down to thermal energies and give rise to energy transfer  $\sim 2.5 \cdot 10^{-4} \text{ eVA}/S_3$ , far below the threshold for direct dark matter detection. It makes this form of dark matter insensitive to the severe CDMS constraints [30]. However,  $OHe$  induced processes in the matter of underground detectors can result in observable effects. These effects, considered in a separate contribution [24], strongly depend on the details of the  $OHe$  interaction with nuclei, which we consider here.

### 4.1 Structure of $X^{--}$ atoms with nuclei

The properties of  $OHe$  interaction with matter are determined first of all by the structure of  $OHe$  atom that follows from the general analysis of the bound states of  $X^{--}$  with nuclei.

Consider a simple model [31], in which the nucleus is regarded as a sphere with uniform charge density and in which the mass of the  $X^{--}$  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

$$H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{2R} + \frac{ZZ_x\alpha}{2R} \cdot \left(\frac{r}{R}\right)^2, \quad (5)$$

for short distances  $r < R$  and

$$H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{R}, \quad (6)$$

for long distances  $r > R$ , where  $\alpha$  is the fine structure constant,  $R = d_o A^{1/3} \sim 1.2A^{1/3}/(200MeV)$  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  $Am_p \ll M_X$  the reduced mass is  $1/m = 1/(Am_p) + 1/M_X \approx 1/(Am_p)$ .

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

$$E_b = \frac{1}{2}Z^2Z_x^2\alpha^2Am_p. \quad (7)$$

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

$$E_b = \frac{3}{2}\left(\frac{ZZ_x\alpha}{R} - \frac{1}{R}\left(\frac{ZZ_x\alpha}{Am_pR}\right)^{1/2}\right). \quad (8)$$

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 [31] gives

$$E_b = \frac{1}{Am_pR^2}F(ZZ_x\alpha Am_pR), \quad (9)$$

where the function  $F(a)$  has limits

$$F(a \rightarrow 0) \rightarrow \frac{1}{2}a^2 - \frac{2}{5}a^4 \quad (10)$$

and

$$F(a \rightarrow \infty) \rightarrow \frac{3}{2}a - (3a)^{1/2}, \quad (11)$$

where  $a = ZZ_x\alpha Am_pR$ . 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  $a = ZZ_x\alpha Am_pR \leq 1$ , what proves its Bohr-atom-like structure, assumed in our earlier papers [8, 9, 10, 14, 18, 19, 20]. However, the size of He, rotating around  $X^{--}$  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.

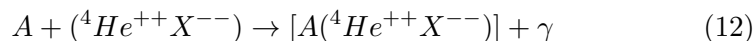
Bohr atom like structure of OHe seems to provide a possibility to use the results of atomic physics for description of OHe interaction with matter.



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.

## 4.2 Potential of O-helium interaction with nuclei

Our explanation [18, 19, 32] 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 nucleus, in which OHe is situated **beyond** the nucleus. Therefore the positive result of these experiments is explained by reaction



with nuclei in DAMA detector.

In our earlier studies [18, 19, 32] the conditions were found, under which both sodium and iodine nuclei have a few keV bound states with OHe, explaining the results of DAMA experiments by OHe radiative capture to these levels. Here we extend the set of our solutions by the case, when the results of DAMA experiment can be explained by radiative OHe capture by sodium only and there are no such bound states with iodine and Tl.

Schrodinger equation for OHe-nucleus system is reduced (taking apart the equation for the center of mass) to the equation of relative motion for the reduced mass

$$m = \frac{Am_p m_o}{Am_p + m_o}, \quad (13)$$

where  $m_p$  is the mass of proton and  $m_o \approx M_X + 4m_p$  is the mass of OHe. Since  $m_o \approx M_X \gg Am_p$ , center of mass of Ohe-nucleus system approximately coincides with the position of  $X^{--}$ .

In the case of orbital momentum  $l=0$  the wave functions depend only on  $r$ .

The approach of [18, 19, 32] assumes the following picture: at the distances larger, than its size, OHe is neutral, being only the source of a Coulomb field of  $X^{--}$  screened by  $He$  shell

$$U_c = \frac{Z_X Z \alpha \cdot F_X(r)}{r}, \quad (14)$$

where  $Z_X = -2$  is the charge of  $X^{--}$ ,  $Z$  is charge of nucleus,  $F_X(r) = (1 + r/r_o)exp(-2r/r_o)$  is the screening factor of Coulomb potential (see e.g.[35]) of  $X^{--}$  and  $r_o$  is the size of OHe. Owing to the negative sign of  $Z_X = -2$ , this potential provides attraction of nucleus to OHe.

Then helium shell of OHe starts to feel Yukawa exponential tail of attraction of nucleus to  $He$  due to scalar-isoscalar nuclear potential. It should be noted that scalar-isoscalar nature of He nucleus excludes its nuclear interaction due to  $\pi$  or  $\rho$  meson exchange, so that the main role in its nuclear interaction outside the nucleus plays  $\sigma$  meson exchange, on which nuclear physics data are not very definite. The nuclear potential depends on the relative distance between He and nucleus and we take it in the form

$$U_n = -\frac{A_{He}Ag^2exp(-\mu|\vec{r} - \vec{\rho}|)}{|\vec{r} - \vec{\rho}|}. \quad (15)$$

Here  $\vec{r}$  is radius vector to nucleus,  $\vec{\rho}$  is the radius vector to He in OHe,  $A_{He} = 4$  is atomic weight of helium,  $A$  is atomic weight of nucleus,  $\mu$  and  $g^2$  are the mass and coupling of  $\sigma$  meson - mediator of nuclear attraction.

Strictly speaking, starting from this point we should deal with a three-body problem for the system of He, nucleus and  $X^{--}$  and the correct quantum mechanical description should be based on the cylindrical and not spherical symmetry. In the present work we use the approximation of spherical symmetry and take into account nuclear attraction beyond the nucleus in a two different ways: 1) nuclear attraction doesn't influence the structure of OHe, so that the Yukawa potential (15) is averaged over  $|\vec{\rho}|$  for spherically symmetric wave function of He shell in OHe; 2) nuclear attraction changes the structure of OHe so that He takes the position  $|\vec{\rho}| = r_o$ , which is most close to the nucleus. Due to strong attraction of He by the nucleus the second case (which is labeled "b" in successive numerical calculations) seems more probable. In the lack of the exact solution of the problem we present both the results, corresponding to the first case (which are labeled "m" in successive numerical calculations), and to the second case (which is labeled "b") in order to demonstrate high sensitivity of the numerical results to choice of parameters.

In the both cases nuclear attraction results in the polarization of OHe and the mutual attraction of nucleus and OHe is changed by Coulomb repulsion of  $He$  shell. Taking into account Coulomb attraction of nucleus by  $X^{--}$  one obtains dipole Coulomb barrier of the form

$$U_d = \frac{Z_{He}Z\alpha r_o}{r^2}. \quad (16)$$

When helium is completely merged with the nucleus the interaction is reduced to the oscillatory potential (17) of  $X^{--}$  with homogeneously

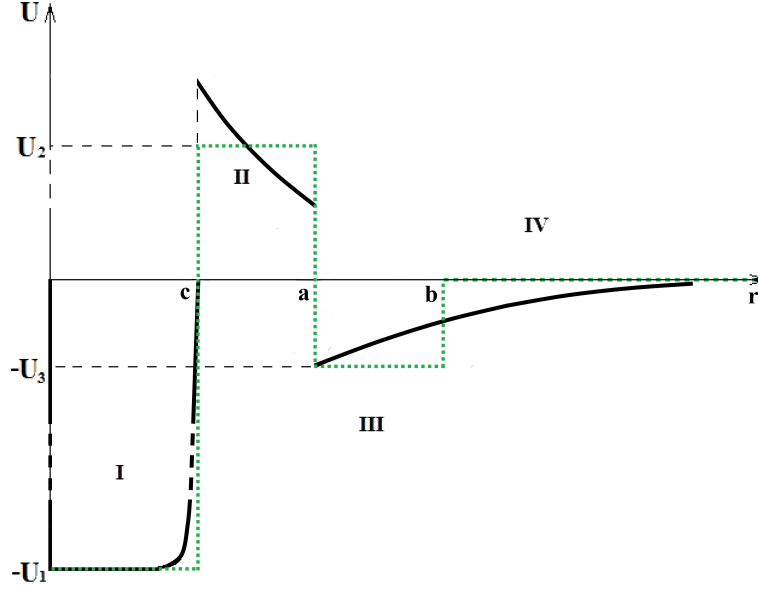


Figure 1: The approximation of rectangular well for potential of OHe-nucleus system.

charged merged nucleus with the charge  $Z + 2$ , given by

$$E_m = \frac{3}{2} \left( \frac{(Z+2)Z_x\alpha}{R} - \frac{1}{R} \left( \frac{(Z+2)Z_x\alpha}{(A+4)m_p R} \right)^{1/2} \right). \quad (17)$$

To simplify the solution of Schrodinger equation we approximate the potentials (14)-(17) by a rectangular potential that consists of a potential well with the depth  $U_1$  at  $r < c = R$ , where  $R$  is the radius of nucleus, of 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, and of the outer potential well  $U_3$ , formed by the Yukawa nuclear interaction (15) and residual Coulomb interaction (14). The values of  $U_1$  and  $U_2$  were obtained by the averaging of the (17) and (16) in the corresponding regions, while  $U_3$  was equal to the value of the nuclear potential (15) at  $r = a$  and the width of this outer rectangular well (position of the point b) was obtained by the integral of the sum of potentials (15) and (14) from  $a$  to  $\infty$ . It leads 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.[35]) and their sewing determines the condition, under which a low-energy OHe-nucleus bound state appears in the region III.

### 4.3 Low energy bound state of O-helium with nuclei

The energy of this bound state and its existence strongly depend on the parameters  $\mu$  and  $g^2$  of nuclear potential (15). 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 [36]. The lower shaded region on Fig. 2 corresponds to the case of nuclear Yukawa potential  $U_{3m}$ , averaged over the orbit of He in OHe, while the upper region corresponds to the case of nuclear Yukawa potential  $U_{3b}$  with the position of He most close to the nucleus at  $\rho = r_o$ . The result is also sensitive to the precise value of  $d_o$ , which determines the size of nuclei  $R = d_o A^{1/3}$ . The two narrow strips in each region correspond to the experimentally most probable value  $d_o = 1.2/(200 \text{ MeV})$ . In these calculations the mass of OHe was taken equal to  $m_o = 1 \text{ TeV}$ , however the results weakly depend on the value of  $m_o > 1 \text{ TeV}$ .

### 4.4 Energy levels in other nuclei

The important qualitative feature of the presented solution is the restricted range of intermediate nuclei, in which the OHe-nucleus state beyond nuclei is possible. For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, we can calculate the binding energy of OHe-nucleus states in nuclei, corresponding to chemical composition of set-ups in other experiments. It turns out that there are no such states for light and heavy nuclei. In the case of nuclear Yukawa potential  $U_{3b}$ , corresponding to the position of He most close to the nucleus at  $\rho = r_o$ , the range of nuclei with bound states with OHe corresponds to the part of periodic table between B and Ti. This result is stable independent on the used scheme of numerical calculations. The upper limits on the nuclear parameters  $\mu$  and  $g^2$ , at which there exists OHe-nucleus bound state are presented for this case on Fig.3. In the case of potential  $U_{3m}$ , averaged over the orbit of He in OHe, there are no OHe bound states with nuclei, lighter than Be and heavier than Ti. However, 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  $\mu$  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. The results for the case (m) are shown on Fig.4. Both for the cases (b) and (m) there is a stable conclusion that there are no OHe-nucleus bound states with Xe, I and Tl.

For the experimentally preferred value  $d_o = 1.2/(200 \text{ MeV})$  the results

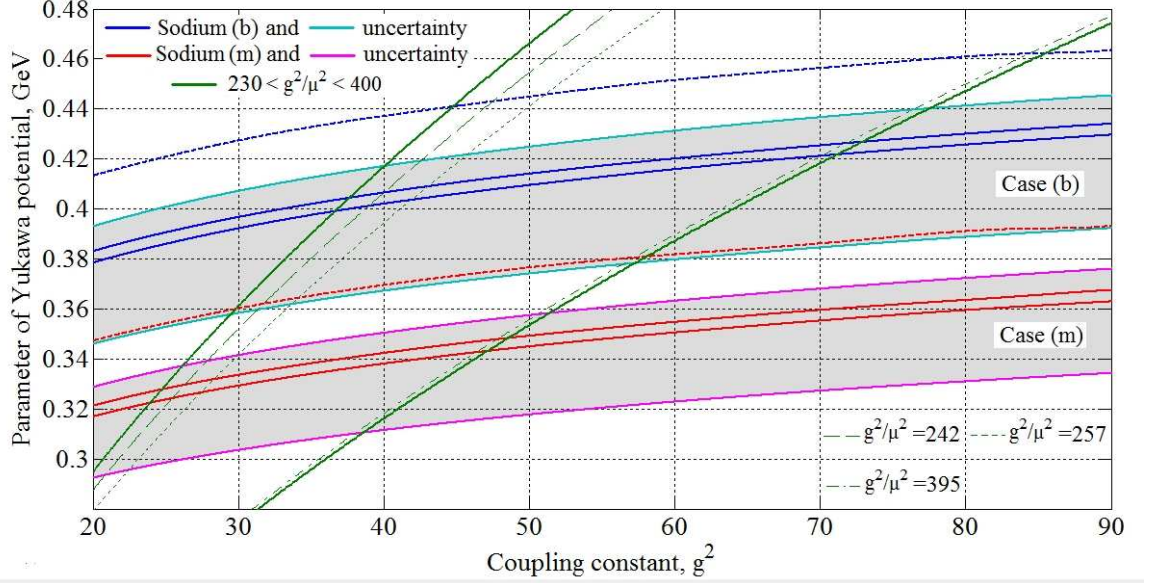


Figure 2: The region of parameters  $\mu$  and  $g^2$ , for which Na-OHe system has a level in the interval 4 keV. Two lines determine at  $d_o = 1.2/(200 \text{ MeV})$  the region of parameters, at which the bound system of this element with OHe has a 4 keV level. In the region between the two strips the energy of level is below 4 keV. There are also indicated the range of  $g^2/\mu^2$  (dashed lines) as well as their preferred values (thin lines) determined in [37] 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  $\mu$  and  $g^2$  shown by the shaded regions surrounding the lines. The case of nuclear Yukawa potential  $U_{3m}$ , averaged over the orbit of He in OHe, corresponds to the lower lines and shaded region, while the upper lines and shaded region around them illustrate the case of nuclear Yukawa potential  $U_{3b}$  with the position of He most close to the nucleus at  $\rho = r_o$ .

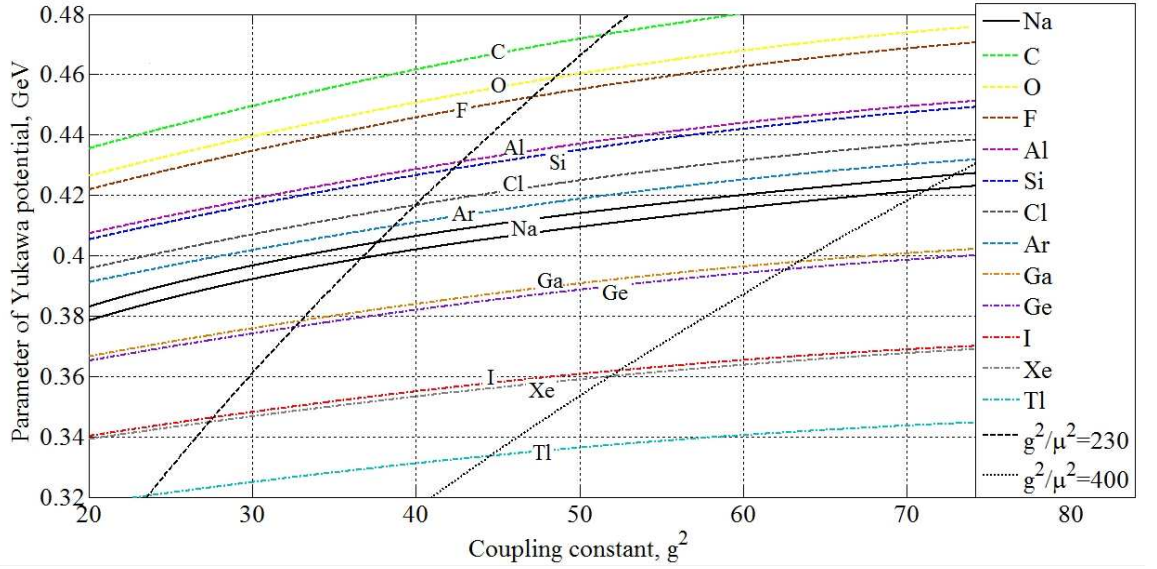


Figure 3: Existence of low energy bound states in OHe-nucleus system in the case b for nuclear Yukawa potential  $U_{3b}$  with the position of He most close to the nucleus at  $\rho = r_o$ . The lines, corresponding to different nuclei, show the upper limit for nuclear physics parameters  $\mu$  and  $g^2$ , at which these bound states are possible. The choice of parameters corresponding to 4 keV OHe-Na bound state, excludes region below Na line.

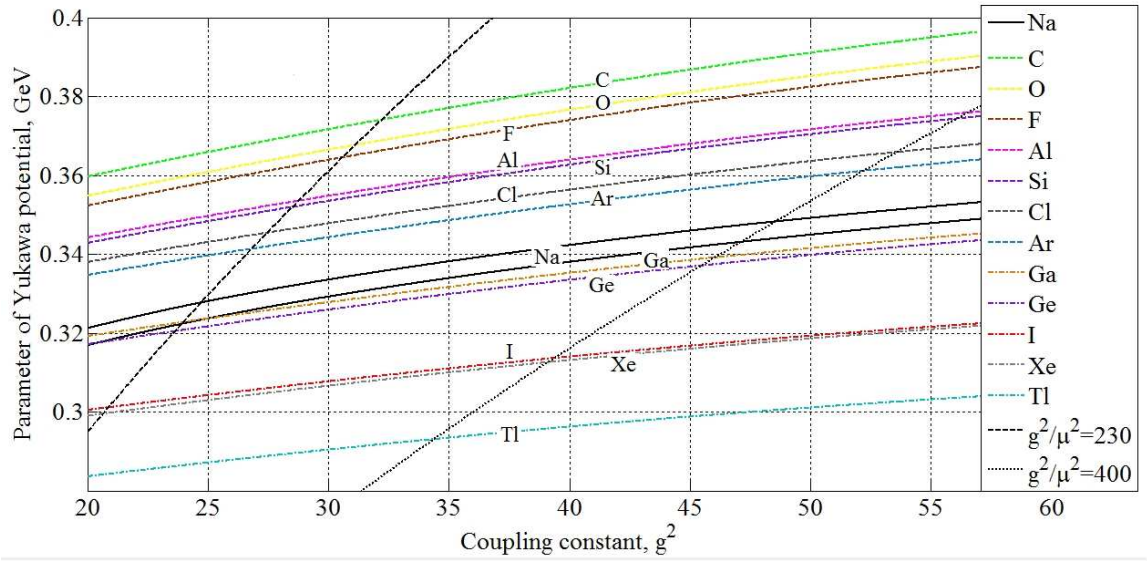


Figure 4: Existence of low energy bound states in OHe-nucleus system in the case m for nuclear Yukawa potential  $U_{3m}$ , averaged over the orbit of He in OHe. The lines, corresponding to different nuclei, show the upper limit for nuclear physics parameters  $\mu$  and  $g^2$ , at which these bound states are possible. The choice of parameters corresponding to 4 keV OHe-Na bound state, excludes region below Na line.

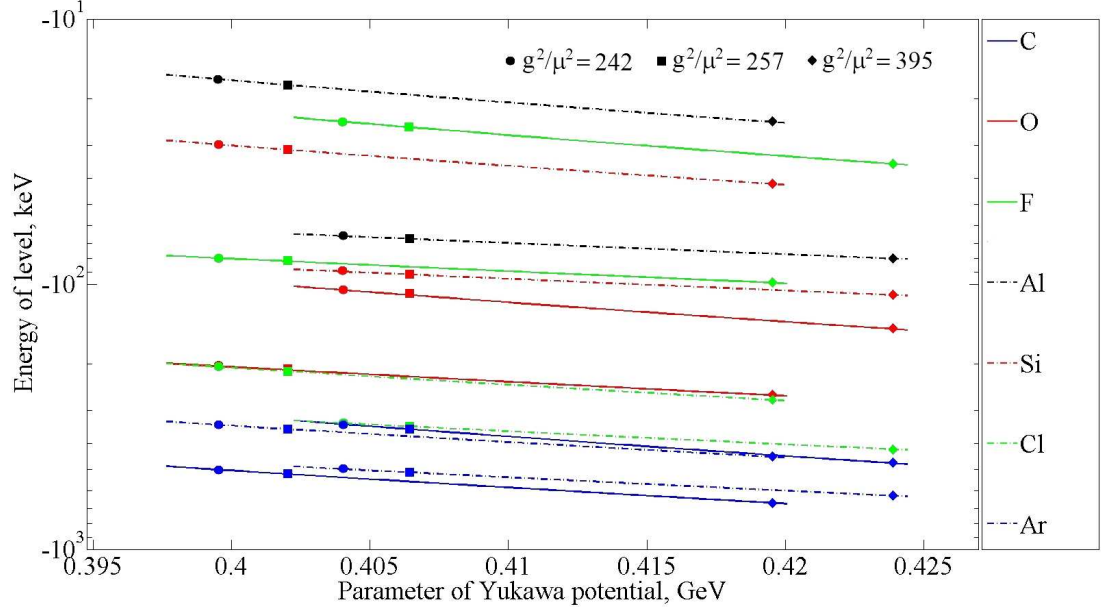


Figure 5: Energy levels in OHe bound system with carbon, oxygen, fluorine, argon, silicon, aluminium and chlorine for the case of the nuclear Yukawa potential  $U_{3b}$ . The predictions are given for the range of  $g^2/\mu^2$  determined in [37] from parametrization of the relativistic  $(\sigma - \omega)$  model for nuclear matter. The preferred values of  $g^2/\mu^2$  are indicated by the corresponding marks (squares or circles)

of calculation of the binding energy of OHe-nucleus systems for carbon, oxygen, fluorine, argon, silicon, aluminium and chlorine are presented on Fig. 5 for the case of the nuclear Yukawa potential  $U_{3b}$  and on Fig. 6 for the case of the potential  $U_{3m}$ . The difference in these results demonstrates their high sensitivity to the choice of parameters.

## 5 Conclusions

To conclude, the results of dark matter search in experiments DAMA/NaI and DAMA/LIBRA can be explained in the framework of composite dark matter scenario without contradiction with negative results of other groups. This scenario can be realized in different frameworks, in particular in Minimal Walking Technicolor model or in the approach unifying spin and charges and contains distinct features, by which the present explanation



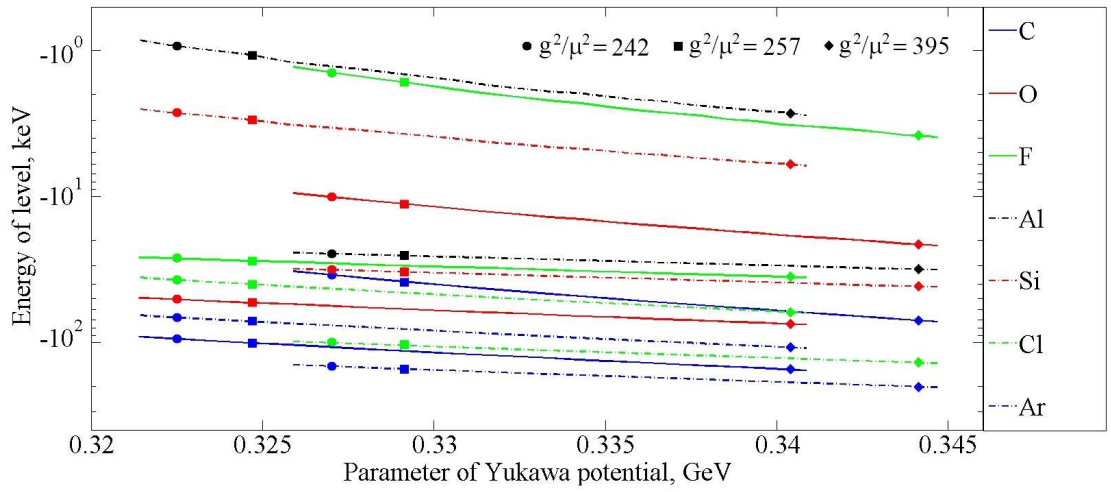


Figure 6: Energy levels in OHe bound system with carbon, oxygen, fluorine, argon, silicon, aluminium and chlorine for the case of the nuclear Yukawa potential  $U_{3m}$ . The predictions are given for the range of  $g^2/\mu^2$  determined in [37] from parametrization of the relativistic  $(\sigma - \omega)$  model for nuclear matter. The preferred values of  $g^2/\mu^2$  are indicated by the corresponding marks (squares or circles)

can be distinguished from other recent approaches to this problem [38] (see also review and more references in [39]).

Our explanation is based on the mechanism of low energy binding of OHe with nuclei. We have found that within the uncertainty of nuclear physics parameters there exists their range at which OHe binding energy with sodium is equal to 4 keV and there is no such binding with iodine and thallium.

With the account for high sensitivity of our results to the values of uncertain nuclear parameters and for the approximations, made in our calculations, the presented results can be considered only as an illustration of the possibility to explain effects in underground detectors by OHe binding with intermediate nuclei. However, even at the present level of our studies we can make a conclusion that effects of such binding should strongly differ in detectors with the content, different from NaI, and can be absent in detectors with very light (e.g.  ${}^3\text{He}$ ) and heavy nuclei (like xenon and probably germanium). Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very nontrivial task.

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