Dark atom solution for puzzles of direct dark matter searches

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Abstract. The puzzles of direct dark matter searches can find solution in the model of dark atoms, called O-helium, containing stable -2 charged lepton-like heavy particle O bound by ordinary Coulomb interaction with primordial helium 4 nuclei. Specific properties of this nuclear interacting dark matter can explain positive results of DAMA/NaI and DAMA/LIBRA experiments and negative results in cryogenic and heavy nuclei (like xenon) detectors. Astrophysical and collider probes for dark atom models as well as open questions of O-helium nuclear interaction with matter are discussed.

1. Introduction

The existence of nonbaryonic dark matter is strongly supported by the data of precision cosmology, but the experimental direct search for dark matter particles in underground detectors gives controversial results. The continuous increase of confidence level of positive results of DAMA/NaI and DAMA/LIBRA dark matter searches [1, 2, 3, 4, 5] seems to be in apparently growing tension with the negative results of other groups like CDMS [6, 7, 8], XENON100 [9] and LUX[10]. A possible explanation for this apparent contradiction may be related with the difference in strategy, methods and chemical content of detectors in these experiments. With the account for such difference even interpretation of DAMA result in terms of Weakly Interacting Massive Particles (WIMPs) may not be completely ruled out [5]. However, such interpretation seems highly unprobable and the co-existence of positive result of DAMA and negative results of other groups can appeal to non-WIMP dark matter effect, detected by DAMA.

WIMPs are the simplest miracluous solution for cosmoloical dark matter. This solution found strong theoretical motivation in supersymmetric models, predicting a few hundred GeV Lightest Suersymmetric Particle as a natural WIMP dark matter candidate. However, the lack of supersymmetric particles at the LHC as well as negative results of WIMP searches by most of experimental groups may be a hint to a non-WIMP nature of dark matter, which is detected by DAMA but missed in the strategy of other searches, aimed specifically to detection of WIMPs.

Here we draw attention to a possibility to explain these puzzles of direct dark matter searches in the model of dark atoms [11, 12, 13, 14, 15]. The model assumes that, similar to ordinary matter, dark matter consists of neutral atoms called O-helium (OHe), in which hypothetical stable -2 charged massive particles are bound by ordinary Coulomb force with primordial helium

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nucleus. This model is a simplest extension of the Standard model, since it involves only one parameter of new physics (the mass of double charged particle O^{--}) and reduces effects of dark atoms to the nuclear interaction of their helium shells that can be based on known laws of nuclear and atomic physics. The complication of the problem of *O*He nuclear interaction still leaves open its complete quantum mechanical solution, but the qualitative features of *O*He dark matter scenario and the possibility of its explanation for the puzzles of direct dark matter searches and some astrophysical anomalies appeal to development of this interesting approach.

After brief description of physical models predicting stable double charged particles as well as of structure of *O*He atoms, specifying the open problems of *O*He nuclear interaction (Section 2) we review main features of *O*He cosmological scenario in Section 3. We also show in the Section 3 that dark atom model can explain the observed excess of low and high energy cosmic positrons and specify the upper limit on the mass of double charged particles for such explanation. We consider in Section 4 specifics of dark atom interaction in the underground detectors and the possibility to explain the puzzles of direct dark matter searches. Searches for stable double charged particles particles at the LHC provide complete experimental test for explanation of low and high energy positron anomalies by effects of dark atoms (Section 5). We stipulate the advantages and problems of dark atom model in the final Section 6.

2. Dark atoms with stable double charged constituents

The idea on atoms of dark matter, in which electrically charged constituents are bound by ordinary Coulomb interaction was proposed by S.Glashow [16], but this possibility is severely constrained by the upper limits on anomalous hydrogen and helium, thus excluding existence of stable single charged particles [17]. Indeed, +1 charged species form anomalous hydrogen, bound with ordinary electrons, while primordial -1 charged species are bound after Big Bang Nucleosynthesis with nuclei of primordial helium, forming +1 charged ion, which also produces anomalous hydrogen after binding with electron. Therefore to save the idea of dark atoms the model should predict stable -2 charged particles O^{--} that form with primordial helium neutral O-helium atom, while single charged particles should be either absent or unstable.

2.1. Models of stable double charged particles

The simplest example of stable double charged particles gives a model of stable U-quark of sequential 4th generation [11]. If asymmetry in the 4th generation has opposite sign relative to baryon asymmetry in three known generations, $\bar{U}\bar{U}\bar{U}$ is a stable species with charge -2. Such definite relationship between the excess of -2 charged species over their +2 charge partners and baryon asymmetry finds quantitative description in the Walking Technicolor (WTC) model, predicting two types of stable doublecharged species - technibaryons UU and technileptons ζ [13, 18]. Electroweak sphaleron transitions relate techniparticle excess to baryon asymmetry and reasonable choice of the scale of freezing out of sphaleron transition gives the ratio of techniparticle to baryon densities that can explain the observed dark matter by techni-O-helium atoms.

The discovery and precise measurements of Higgs boson (125 GeV) parameters that appear to be very close to the predictions of the Standard model put severe constraints on the model of sequential 4th quark-lepton generation and imply strong suppression of the coupling of these particles to 125 GeV Higgs boson [19]. These constraints also imply modification of the WTC model [20].

Strong QCD interaction is either strongly suppressed or absent for all the examples of stable double charged particles. Therefore O^{--} are either leptons or lepton-like particles [11, 12, 13, 14, 15].

2.2. O-helium dark atoms

The structure of an *O*He atom can be described following a general analysis of the bound states of massive negatively charged lepton-like particle with nuclei [21, 22, 23]. This analysis shows that bound states with light nuclei look like Bohr atoms with negatively charged particle in the core and nucleus moving along the Bohr orbit, while bound states with heavy nuclei look like Thomson atoms, in which the body of nucleus oscillates around the heavy negatively charged particle. The solution depends on the value of parameter $a = ZZ_o\alpha Am_pR$, where Z, R and A are charge, radius and atomic number of the nucleus, Z_o is the charge of negatively charged particle, α is the fine structure constant and m_p is the mass of proton. For 0 < a < 1 the Coulomb model gives a good approximation, while at $2 < a < \infty$ the harmonic oscillator approximation is appropriate (see [24] for review and references).

In the case of OHe $a = ZZ_o \alpha Am_p R \leq 1$, which proves its Bohr-atom-like structure [11, 13, 24]. The radius of Bohr orbit in these "atoms" [11, 13, 24] is

$$r_o = \frac{1}{Z_o Z_{He} \alpha 4 m_p} = 2 \cdot 10^{-13} \,\mathrm{cm},$$
 (1)

being of the order of and even a bit smaller than the size of He nucleus. Therefore non-point-like charge distribution in He leads to a significant correction to the *O*He binding energy.

In contrast to the ordinary atoms, having electroweakly interacting shell and the core much smaller, than the atomic size, *O*He has strongly interacting helium shell and the size of the orbiting He is of the order of radius of orbit. Therefore, in the lack of these usual approximations of atomic physics proper description of *O*He interaction with nuclei remains an open problem. The most complicated is the self consistent treatment of simultaneous action of nuclear attraction to the He shell of approaching nucleus and its Coulomb repulsion.

In the approximation of rectangular wells and walls the simplified approach of [24, 25] assumed the form of *O*He-nucleus interaction shown on Fig. 1. Its crucial point is the existence of a potential barrier due to polarization of *O*He atom by nuclear attraction of approaching mucleus. It leads to a shallow well outside the nucleus, in which a low lying bound state can exist for intermediate mass nuclei [24, 25].





Figure 1. Potential of OHe nucleus interaction in the square walls and wells approximation

Figure 2. Polarization $\langle z \rangle$ (fm) of *O*He as a function of the distance *R* (fm) of an external sodium nucleus

The calculations with the use of perturbation theory [26] gave some evidence in favor of this picture. They showed that OHe polarization changes sign, as the nucleus approaches OHe (Fig. 2), but the perturbation approach was not valid for the description at smaller distances.

The existence of dipole potential barrier is crucial for dominance of elastic processes in OHe-nucleus interaction. Such dominance supports the qualitative picture of OHe cosmological evolution, which avoids the problem of anomalous element overproduction.

9th International Symposium on Large TPCs for Low-Energy Rare Event DetectionIOP PublishingIOP Conf. Series: Journal of Physics: Conf. Series 1312 (2019) 012011doi:10.1088/1742-6596/1312/1/012011

3. Dark atoms cosmology

OHe cosmological evolution [11, 12, 13, 24, 25] starts by creation of OHe as soon as primordial helium is produced in Big Bang Nucleosynthesis. Since the mass of O^{--} is in TeV range, the number density of these particles is by two orders of magnitude smaller, than He abundance, and the frozen out concentration of free O^{--} is exponentially suppressed. In principle, OHe interaction with nuclei can catalize formation of primordial heavy elements, but the corresponding analysis implies further development of OHe nuclear physics.

3.1. Large scale structure formation

Due to elastic nuclear interactions of helium shell with nuclei (dominantly protons) *O*He gas is in thermal equilibrium with plasma and radiation, while energy and momentum transfer from plasma is effective. In this period radiation pressure is transferred to *O*He density fluctuations, transforming them in acoustic waves at scales up to the size of the cosmological horizon.

The energy and momentum transfer from baryonic plasma to *O*He cannot support thermal equilibrium at temperature $T < T_{od} \approx 1 S_3^{2/3} \text{ keV}$ [11, 13] since

$$n_B \left\langle \sigma v \right\rangle (m_p/m_o) t < 1, \tag{2}$$

where m_o is the mass of O^{--} , which determines the mass of OHe atom and $S_3 = m_o/(1 \text{ TeV})$. Here n_B is the baryon number density, the cross section is given by

$$\sigma \approx \sigma_o \sim \pi r_o^2 \approx 10^{-25} \,\mathrm{cm}^2,\tag{3}$$

and $v = \sqrt{2T/m_p}$ is the baryon thermal velocity. Then *O*He gas decouples from plasma and starts to dominate in the Universe after $t \sim 10^{12}$ s at $T \leq T_{RM} \approx 1 \text{ eV}$.

Decoupled from plasma and radiation *O*He atoms play the role of dark matter in the development of gravitational instability, triggering large scale structure formation. Nuclear interacting nature of *O*He determines specifics of its spectrum of density fluctuations. Conversion in sound waves leads to suppression on the corresponding scales and the spectrum acquires the features of Warmer than Cold Dark Matter scenario [11, 12, 13, 24, 25]. Decoupled from baryonic matter *O*He gas doesn't follow formation of baryonic objects, forming dark matter halos of galaxies.

3.2. Indirect effects of OHe dark matter

In spite of strong (hadronic) cross section *O*He gas is collisionless on the scale of galaxies, since its collision timescale is much larger than the age of the Universe. Baryonic matter in the Galaxy is also transparent in the average, so that *O*He can be captured only by sufficiently dense matter proto-object clouds and objects, like planets and stars.

Being asymmetric dark matter, OHe collisions cannot lead to indirect effects like WIMP annihilation (first considered in [27]) contributing by its products to gamma background and cosmic rays. However, OHe excitations in such collisions can result in pair production in the course of de-excitation and the estimated emission in positron annihilation line can explain the excess, observed by INTEGRAL in the galactic bulge [28]. For realistic estimation of the dark matter density in the center of Galaxy such explanation is possible for a narrow range of O^{--} mass near 1.25 TeV [29].

In the two-component dark atom model, based on the Walking Technicolor, together with the dominant component of OHe a subdominant WIMP-like component $UU\zeta$ is present, with metastable technibaryon UU, having charge +2. Decays of this technibaryon to the same sign (positive) lepton pairs can explain excess of high energy cosmic positrons observed by PAMELA and AMS02 [30]. However, any source of positrons inevitably is also the source of gamma radiation. Therefore the observed level of gamma background puts upper limit on the mass of UU, not exceeding 1 TeV [29].

These upper limits on the mass of stable double charged particles challenges their search at the LHC (see section 5 and [29] for recent review and references)

4. Dark atoms in underground detectors

Owing to their nuclear interacting nature OHe particles are captured by Earth and slowed down in the terrestrial matter (see e.g. [15]).

At a depth L below the Earth's surface, the drift timescale is $t_{dr} \sim L/V$, where $V \sim 400S_3 \text{ cm/s}$ is the drift velocity and $m_o = S_3$ 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 is given by

$$n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot \sin(\omega(t - t_0))$$
(4)

with $\omega = 2\pi/T$, T = 1yr and t_0 the phase. So, there is a averaged concentration given by

$$n_{oE}^{(1)} = \frac{n_o}{320S_3 A_{med}^{1/2}} V_h \tag{5}$$

and the annual modulation of concentration characterized by the amplitude

$$n_{oE}^{(2)} = \frac{n_o}{640S_3 A_{med}^{1/2}} V_E.$$
(6)

Here V_h -speed of Solar System (220 km/s), V_E -speed of Earth (29.5 km/s) and $n_0 = 3 \cdot 10^{-4} S_3^{-1} \text{ cm}^{-3}$ is the local density of O-helium dark matter.

The idea of explanation of positive result of DAMA experiment is the annual modulation of the rate of radiative capture of OHe by sodium nuclei to the low-energy level with energy about 3 keV.

The existence of such level for *O*He-sodium system was found in [25] in square wall and well approximation, corresponding to potential Fig. 1. Similar low-energy levels were found in [25] for intermediate mass nuclei, while for nuclei lighter than carbon and heavier than gernmanium such levels are absent.

If such level exist for *O*He radiative capture by sodium the analogy with the radiative capture of neutron by proton can be used [15]. Taking into account

- absence of M1 transition that follows from conservation of orbital momentum
- 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 ,

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 [15]

$$\sigma v = \frac{f\pi\alpha}{m_p^2} \frac{3}{\sqrt{2}} (\frac{Z}{A})^2 \frac{T}{\sqrt{Am_p E}}.$$
(7)

Under these conditions the signal, measured in DAMA/NaI and DAMA/LIBRA experiments, is reproduced [25].

This approach also explains the negative result of other experiments - there are no such levels in heavy nuclei, like Xe, while the rate of radiative capture of OHe in cryogenic detectors is suppressed.

5. Accelerator test for indirect effects of dark atoms

The widely accepted approach to collider search for dark matter particles is related to search for effects of missing energy and momentum in particle collisions. This approach links freezing out of dark matter particles in early Universe, indirect effects of their annihilation in the Galaxy and direct underground searches for dark matter particles.

Such relationships are strongly modified in the case of dark atoms. In particular, in the context of dark atom model, accelerator probe for dark matter is reduced to search for stable double charged constituents of composite dark matter that acquires the significance of direct experimental test for dark atom model. Upper limits on the mass of double charged particles, at which the detected anomalies in positron annihilation line radiation from the center of Galaxy and the excess of cosmic high energy positrons find explanation in the framework of dark atom model provide a possibility of *experimentum crucis* for such explanation [31].

Experimental lower limits on the mass of stable double charged particles, deduced in CMS and ATLAS experiments from the data of 8 TeV Run, are currently around 700 GeV. However the expected range, which can be reached in the analysis of the data of Run2, can cover all the range of masses that provide explanation for indirect effects of dark atoms. [31].

6. Conclusion

Dark atom hypothesis offers a nontrivial solution for the puzzles of direct and indirect dark matter searches. This approach involves minimal extension of the particle content of the Standard model and relates most of the signatures of dark atoms to the processes of known atomic and nuclear physics. However it doesn't simplify the predictibility of dark atom model in the lack of simplifying approximations of ordinary atomic physics.

*O*He interaction with matter loses usual approximations related with the small parameters of ordinary atoms:

- the helium shell is nuclear interacting with its strong coupling instead of fine structure constant that characterizes interaction of electronic shells;
- radius of Bohr orbit in *O*He is of the order of the size of He nucleus, so that there is no usual smallness of the ratio of nuclear core and the size of electronic shell in the ordinary atom;
- at the most important stage of *O*He interaction with approaching nucleus all the distances are comparable with the size of nuclei;
- nuclear attraction of the nucleus by the helium shell leads to polarization of *O*He, at which dipole barrier is created. The significance and effect of this barrier is crucial for the selfconsistent *O*He dark atom scenario.

These complications hinder proper quantum mechanical description of *O*He interaction with the matter that is needed for detailed analysis of cosmological, astrophysical and physical signatures of dark atoms. However, qualitative advantages of this approach, presented here, appeal to its further development that will find solution to overcome these complicated problems.

Acknowledgments

I express my gratitude to all my-co-authors of original papers on which the present report is based and to CERN TH for hospitality in the period of the work on the final version of this paper. The work was supported by grant of the Russian Science Foundation (Project No-18-12-00213).

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9th International Symposium on Large TPCs for Low-Energy Rare Event Detection IOP Conf. Series: Journal of Physics: Conf. Series 1312 (2019) 012011 doi:10.1088/1742-6596/1312/1/012011

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