



Proceeding Paper

Dark Atom Solution for the Puzzles of Direct Dark Matter Search [†]

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[†] Presented at the 1st Electronic Conference on Universe, 22–28 February 2021; Available online: <https://ecu2021.sciforum.net/>.

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Abstract: The puzzle of direct dark matter searches can be solved in the model of an OHe dark atom, which consists of a stable O^{--} lepton core and a nuclear interacting (alpha particle) shell of a primordial helium nuclei. In this model, positive results of the DAMA group can be explained by annual modulation of radiative capture of OHe atoms to low-energy bound states with sodium nuclei, which does not take place under the conditions of other underground experiments. The existence of such a low-energy bound state is the key problem of the OHe model of composite dark matter. The complexity of this problem, which has not found a correct solution during the last 15 years, requires a consistent approach to its solution. Within the framework of the proposed approach to such modeling, in order to reveal the essence of the processes of interaction of OHe with the nuclei of baryonic matter, a classical model is used, to which the effects of quantum physics and final size of nuclei are successively added. The numerical model of the interaction of the “dark” OHe atom with the nuclei is developed by successive addition of realistic features of a quantum-mechanical description to the initial classical problem of three point-like bodies (O^{--} particle, the He nucleus and the target nucleus). The developed approach leads to a numerical model describing the OHe-nucleus system with self-consistent accounting for nuclear attraction and electromagnetic interaction of dark atom with nuclei. The model can prove the interpretation of the results of the direct underground experimental dark matter search in the terms of the dark atom hypothesis.

Keywords: stable charged particles; O^{--} ; composite dark matter; dark atoms; OHe; nuclear interactions; Coulomb interaction



Citation: Bikbaev, T.; Khlopov, M.; Mayorov, A. Dark Atom Solution for the Puzzles of Direct Dark Matter Search. *Phys. Sci. Forum* **2021**, *2*, 3. <https://doi.org/10.3390/ECU2021-09263>

Academic Editor: Maxim Khlopov

Published: 22 February 2021

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1. Introduction

According to modern cosmology, dark matter is non-baryonic and is associated with a new, unknown physics. If it consists of particles, then they are predicted beyond the Standard Model. In order for these particles to be considered as candidates for the role of dark matter, we need them to explain as many astronomical observations as possible [1]. The most popular model is that in which elementary Weakly Interacting Massive Particles (WIMP) are proposed as dark matter particles. The search for WIMPs has been unsuccessful to date, so scientists are proposing alternative versions of dark matter particles [2], in particular, stable, electrically charged particles can exist.

Stable negatively charged particles can only have charge -2 —we will denote them by O^{--} or in the general case, even charge $-2n$, where n is any natural number [3].

In the present paper, we consider a scenario of composite dark matter, in which hypothetical stable O^{--} particles form neutral atom-like states OHe with primordial

helium, called “dark” atoms [4]. There are various scenarios in which such stable -2 charged particles are predicted [5,6]. The size of the OHe system is determined by its Bohr radius $R_b \approx 2 \times 10^{-13}$ cm, and the binding energy $I_0 \approx 1.6$ MeV [7]. In all models of O-helium, O^{--} behaves like a lepton or as a specific cluster of heavy quarks of new families with suppressed hadron interaction [8]. The existing limitation on this type of particle, according to the LHC accelerator, is about 1 TeV [9].

The existence of the O-helium hypothesis is important because it can explain the conflicting results of experiments on the direct search for dark matter due to the peculiarities of the interaction of “dark” atoms with the matter of underground detectors [10].

The main problem with OHe atoms is that their constituents can interact too strongly with matter. This happens because O-helium has an unshielded nuclear attraction to the outer cores of matter. This, in turn, can lead to the destruction of a bound system of “dark” matter atoms and the formation of anomalous isotopes. There are very strict experimental restrictions on the concentration of these isotopes in the earth’s soil and seawater [11]. To avoid the problem of overproduction of anomalous isotopes, it is assumed that the effective potential between OHe and nucleus will provide a barrier preventing the fusion of He and/or O^{--} with nucleus. In this work, we attempt to construct a theoretical model of such interaction. Our task is to consider the interaction of OHe with the nucleus by constructing a set of forces that act between all elements of the system in the chosen coordinate system. We must consider the electromagnetic forces acting between O^{--} and the core, O^{--} and He, He and the core, and the nuclear interaction between helium and the target nucleus. This problem is formulated as a three-body problem and does not have an exact analytical solution. Therefore, this paper proposes a numerical approach to reproduce the listed interactions.

2. Results

2.1. Numerical Simulation of the Interaction of OHe with the Nucleus

2.1.1. Simulation of OHe

The “dark” atom of O-helium (the OHe system) consist of two point-like and bound together particles: the He nucleus and the O^{--} particle. A spherical coordinate system located at the center of a O^{--} particle, and around it along the surface of the sphere—the radius of which is equal to the radius of the atom OHe R_b —the He nucleus moves stochastically, with a constant Bohr velocity V_α .

Let us construct a numerical scheme of a simulation of OHe dynamics [12].

(1) An α -particle in the bound OHe system has only two independent degrees of freedom, which are taken as the polar and azimuthal angles. ϕ_0 and θ_0 are the initial values of the angles through which the initial components of the radius vector of the α -particle r_0 are calculated.

(2) Changes in the polar $d\theta$ and azimuthal $d\phi$ angles are defined as the increments of the angles when moving from point r_{i-1} to point r_i along the sphere, where i is the iteration number.

(3) We check the condition for the increment of angles:

$$\left(d\theta\right)^2 + \left(\cos\theta d\phi\right)^2 \leq \left(\frac{V_\alpha dt}{R_b}\right)^2. \quad (1)$$

This condition is necessary so that the trajectory of the alpha particle, calculated through the increments of the angles $d\theta$ and $d\phi$, does not exceed the real distance that the alpha particle has traveled over the sphere in time dt .

As a result, according to the obtained data, the matrix contains the values of the components of the radius vector of the α -particle at each moment of time r , and the program builds its trajectory along the surface of a sphere of the Bohr radius R_b (see Figure 1). Figure 1 shows a sphere of radius R_b , on the surface of which, the blue dots mark

the location of the α -particle between times dt . Filling the sphere with dots depends on the number of loop iterations.

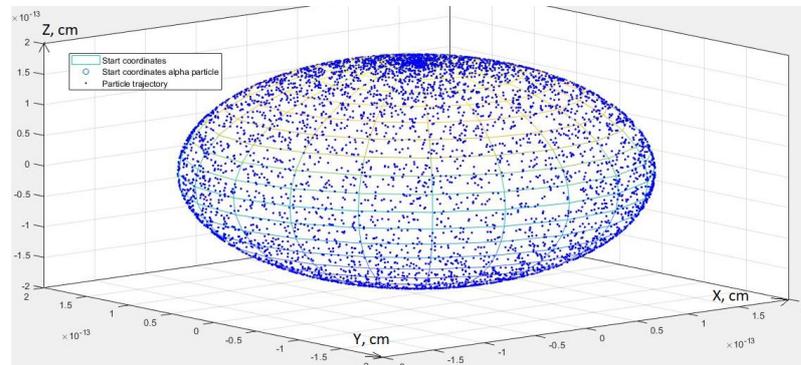


Figure 1. The density of the distribution of the coordinates of the α -particle in the orbit corresponding to the ground state of the system.

2.1.2. Coulomb Interaction in the OHe—Nucleus System

Consider an OHe—nucleus system. We locate the coordinate system at the center of the nucleus A . In this coordinate system, O-helium is a moving system. The radius vector $O^{--} \vec{r}$ and the radius vector of α -particle \vec{r}_α are introduced (see Figure 2). In this case, \vec{r}_α is determined as follows:

$$\vec{r}_\alpha = \vec{r} + \vec{R}_b. \tag{2}$$

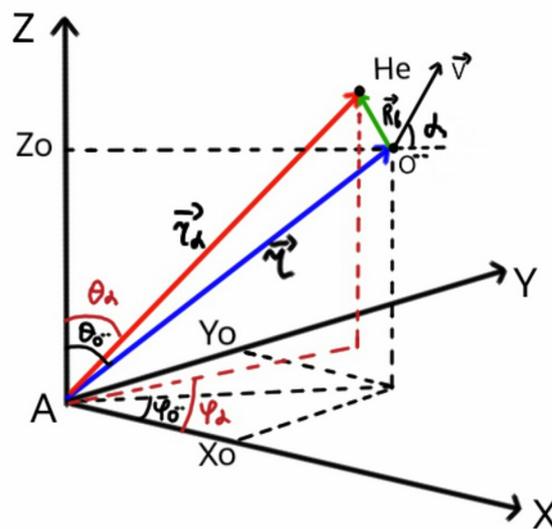


Figure 2. Coordinate system OHe—nucleus.

The Coulomb interaction between α -particle and target nucleus and Coulomb interaction between O^{--} and target nucleus are given by the following formulas:

$$\vec{F}_{Z\alpha}^e = \vec{F}_{Z\alpha}^e(\vec{r}_\alpha) = \frac{ZZ_\alpha e^2 \vec{r}_\alpha}{r_\alpha^3}, \tag{3}$$

$$\vec{F}_{ZO}^e = \vec{F}_{ZO}^e(\vec{r}) = \frac{ZZ_O e^2 \vec{r}}{r^3}, \tag{4}$$

where Z is the charge of nucleus, $Z_{O^{--}}$ and Z_α —electric charges of O^{--} particle and nuclei He, respectively.

Let us construct a numerical scheme for calculating these forces depending on the distance between objects. In this case, the previously proposed model for describing the OHe system will be used for calculations in the OHe—nucleus system.

(1) We use the following initial conditions: the initial coordinates of O^{--} [x_0, y_0, z_0] (or r_0) and the initial components of its velocity [$V_{x_0}, V_{y_0}, V_{z_0}$] (or V_0) ($i = 0$).

(2) Consider the state of the system at the next time instant, taken at time interval dt . The i -th value of the increment of α -particle $d\vec{P}_{\alpha_i}$ momentum is determined:

$$d\vec{P}_{\alpha_i} = \vec{F}_{\alpha_i}^e dt. \tag{5}$$

The break condition of the program when the excess of dT_i kinetic energy transferred to He exceeds the ionization potential of O-helium I_0 , which results in the destruction of the bound O-helium system:

$$dT_i = \frac{d\vec{P}_{\alpha_i}^2}{2m_\alpha} < I_0 \approx 1.6 \text{ MeV}. \tag{6}$$

(3) At each loop, the program calculates the total force acting on the OHe system:

$$\vec{F}_{isum} = \vec{F}_{iZO}^e + \vec{F}_{i\alpha}^e. \tag{7}$$

The increment of the momentum $d\vec{P}_i$ of OHe system is calculated, which is, in the aggregate, the increment of the momentum of O^{--} :

$$d\vec{P}_i = \vec{F}_{isum} dt. \tag{8}$$

Using the momentum increment $d\vec{P}_i$, the O^{--} velocity increment $d\vec{V}_i$ is calculated for the subsequent finding of the new velocity used in the next iteration:

$$d\vec{V}_i = \frac{d\vec{P}_i}{m_{O^{--}} + m_\alpha}. \tag{9}$$

The result of the algorithm is the reconstructed trajectories of α -particle and O^{--} (see Figure 3). In Figure 3, the black circle shows the location of the target nucleus, the yellow asterisk and the red rhombus are the initial locations of the α -particle and the O^{--} particle, respectively. The blue dots and the green dashed line show the trajectories of the α -particles and particles O^{--} , respectively. In the figure under consideration, one can observe the deviation of the trajectory O^{--} from the initial direction, which is associated with the Coulomb interaction between the He nucleus and the target nucleus. This happens because He is closer to the origin and is repelled from the target nucleus more strongly than the O^{--} particle is attracted to it.

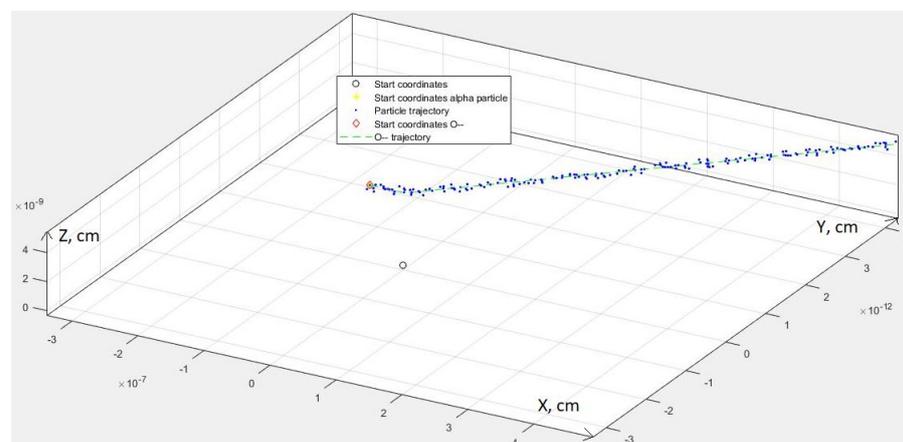


Figure 3. α -particle and particle O^{--} trajectories.

2.1.3. Nuclear Interaction in the OHe—Nucleus System

At this stage, the program was supplemented with a nuclear interaction of the Saxon-Woods type, between the He nucleus and the target nucleus $\vec{F}_{i\alpha}^N$. The total force acting on the system OHe, \vec{F}_{iSum} , calculated as follows:

$$\vec{F}_{iSum} = \vec{F}_{iZO}^e + \vec{F}_{i\alpha}^N \tag{10}$$

where $\vec{F}_{i\alpha}$ is total force acting on an α -particle:

$$\vec{F}_{i\alpha} = \vec{F}_{i\alpha}^e + \vec{F}_{i\alpha}^N \tag{11}$$

The simulation is performed according to the iteration algorithm described in the previous paragraph, where $d\vec{P}_{i\alpha}$, the increment of the α -particle momentum, is calculated as follows:

$$d\vec{P}_{i\alpha} = \vec{F}_{i\alpha} dt \tag{12}$$

Based on the data obtained, the program builds the trajectories of the α -particle and O^{--} (see Figure 4). In Figure 4, which shows the result of the program, the black circle shows the location of the target nucleus, blue dots and the red dashed line show the trajectories of the α -particle and the O^{--} particle in the XY plane, respectively.

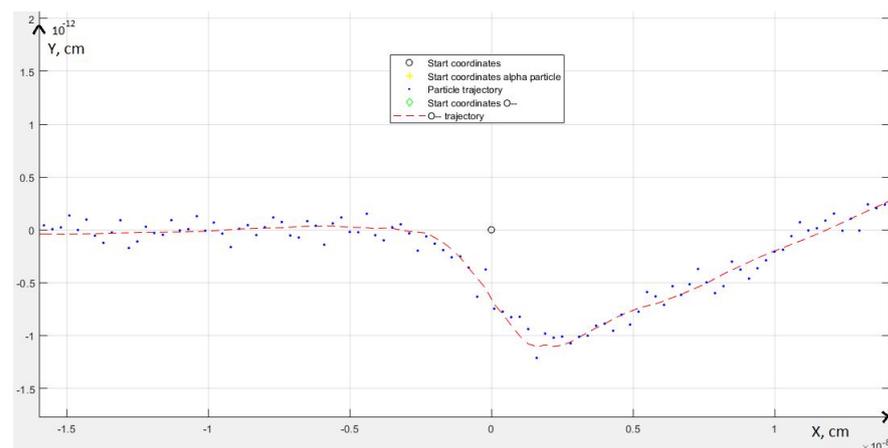


Figure 4. The trajectory of α -particle and the O^{--} in the XY plane.

Figure 4 shows one of the results of our simulation. It can be seen that the trajectory O^{--} experiences some beats in contrast to the previous case. This is due to the added nuclear interaction between the α -particle and the nucleus, which leads to the attraction of the α -particle. Accordingly, the closer the α -particle is to the nucleus, the greater this force and the more distorted the trajectory O^{--} .

3. Discussion

Our task was to construct a numerical model of the interaction of OHe with the target nucleus. Such a numerical model is constructed in the work. It describes a system of three point-like particles, interacting with each other by means of Coulomb and nuclear forces. A simulation was carried out and the following effects were observed: the trajectory of the O^{--} particle deviates from the initial direction, due to the action of the Coulomb force between the α -particle and the target nucleus, and O^{--} trajectory undergoes beats in the vicinity of the nucleus, due to the action of the nuclear interaction between the α -particle and the target nucleus. In the future, it is planned to study the constructed model by varying various free parameters, for example, the impact parameter of the model and the energy of the incident particle.

4. Conclusions

Dark atom hypothesis can explain the puzzles of direct dark matter searches. Slowed down in the terrestrial matter, dark atoms cannot cause significant recoil in the matter of underground detectors, in which most of the experiments are conducted. The positive result of DAMA/NaI and DAMA/LIBRA experiments is then explained by annual modulation of low energy binding of OHe atoms with sodium nuclei. This explanation implies a correct quantum mechanical treatment of self-consistent account of Coulomb and nuclear interactions of OHe with nuclei in the nontrivial conditions of dark atom specifics, losing the main advantages of the ordinary atomic physics (smallness of nuclear core relative to the Bohr radius and of electroweak interactions of the electronic shells). In the case of dark atoms, we have to deal with a strongly interacting helium shell and a Bohr radius equal to the size of a helium nucleus. To overcome the difficulty of the problem of dark atom interaction with nuclei, we develop an approach of successive addition of realistic physical and quantum mechanical features to the classical three-body problem of point-like particles. We hope that our strategy can lead to a realistic description of OHe interactions with matter, which can provide a solution to the puzzles of dark matter searches.

Author Contributions: Article by T.B., M.K. and A.M. The authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: The work by M.K. and A.M. has been performed with a support of the Ministry of Science and Higher Education of the Russian Federation, Project “Fundamental problems of cosmic rays and dark matter”, No. 0723-2020-0040.

Conflicts of Interest: The authors declare no conflict of interest.

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