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EFFECTS OF DARK ATOM EXCITATIONS

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New stable quarks and charged leptons may exist and be hidden from detection, as they are bound by Coulomb interaction in neutral dark atoms of composite dark matter. This possibility leads to fundamentally new types of indirect effects related to the excitation of such dark atoms followed by their electromagnetic de-excitation. Stable -2 charged particles O^{--} , bound to primordial helium in O-helium (OHe) atoms, represent the simplest model of dark atoms. Here we consider the structure of OHe atomic levels which is a necessary input for the indirect tests of such composite dark matter scenarios, and we give the spectrum of electromagnetic transitions from the levels excited in OHe collisions.

Keywords: Elementary particles; composite dark matter; dark atoms; energy levels; cosmic electromagnetic radiation; indirect effects of dark matter.

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1. Introduction

According to modern cosmology, dark matter corresponds to $\sim 25\%$ of the total cosmological density, is nonbaryonic and consists of new stable particles. Such particles (see e.g. references 1 and 2 for a review) should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of the matter-dominated era. The easiest way to satisfy these conditions is to involve neutral elementary weakly interacting massive particles (WIMPs). However it is not the only particle physics solution for the dark matter problem and

more elaborate models of composite dark matter are possible. The simplest model of dark atoms is the O-helium (OHe) model, in which stable -2 charge particles O^{--} are bound by the Coulomb interaction with primordial helium.^{1,2}

Elementary particle frameworks 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;^{3–8} (b) AC-leptons,^{8–11} predicted in an extension⁹ of the standard model, based on the approach of almost-commutative geometry;¹² (c) Technileptons and anti-technibaryons¹³ in the framework of walking technicolor models (WTC).^{14–19}

If new stable species belong to non-trivial representations of the electroweak $SU(2)$ group, sphaleron transitions at high temperatures can relate the baryon asymmetry to the excess of -2 charge stable species, as it was demonstrated in the case of WTC in references 13, 21–24, 26. The only free parameter in this case is the mass of O^{--} .

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN), ${}^4\text{He}$ screens the excessive O^{--} charged particles in composite (${}^4\text{He}^{++}O^{--}$) O-helium (OHe) “atoms”.⁴ In all the considered forms of O-helium, O^{--} behaves either as a lepton or as a heavy quark cluster with strongly suppressed hadronic interaction. Therefore the O-helium interaction with matter is determined by the nuclear interactions of He. This neutral primordial nuclear-interacting species can play the role of a nontrivial form of strongly interacting dark matter,^{27–35} giving rise to a Warmer-than-Cold dark-matter scenario.^{20–22} It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints^{33–35} on strongly interacting dark matter particles (SIMPs)^{27–35} imposed by the XQC experiment.^{36,37}

Slowed down in the terrestrial matter OHe collisions cause negligible nuclear recoil in the underground detectors, thus avoiding severe constraints of direct dark matter searches in CDMS,³⁸ XENON100³⁹ and LUX⁴⁰ experiments. It makes indirect effects of OHe especially important to test OHe hypothesis.

Here we concentrate on the structure of OHe atoms, their excitation in collisions and the observable effects of electromagnetic radiation from their de-excitation.

2. The atomic structure of OHe

An OHe atom is made of a heavy O^{--} particle and a helium nucleus, of respective masses M_O and M_{He} such that $M_O \gg M_{He}$, bound by the Coulomb interaction in a hydrogen-like structure. While the O^{--} particle, of charge $Z_O = 2e$, is point-like, we approximate the charge distribution of the helium nucleus as a uniformly charged sphere of radius $R_{He} = 1.2 \times 4^{1/3}$ fm. This allows us to take the O-helium attractive interaction potential as that between a point and a sphere, i.e.:

$$\begin{aligned} V(r \geq R_{He}) &= -\frac{Z_O Z_{He} \alpha}{r} \\ V(r < R_{He}) &= -\frac{Z_O Z_{He} \alpha}{2R_{He}} \left(3 - \frac{r^2}{R_{He}^2} \right), \end{aligned} \quad (1)$$

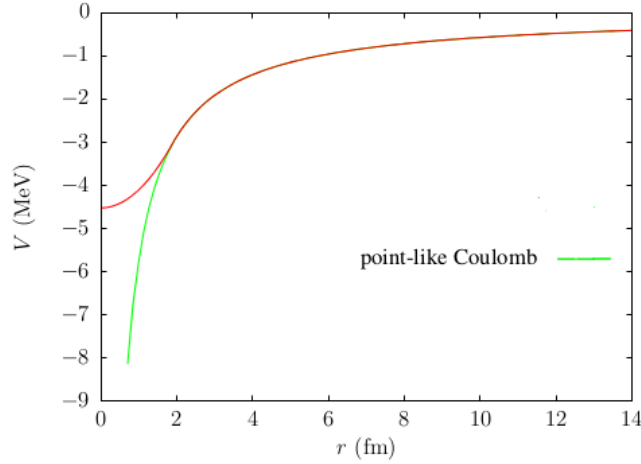


Fig. 1. The O-helium interaction potential (red) and the elementary Coulomb potential (green) obtained for a point-like helium nucleus, as a function of the distance r between O^{--} and the center of the helium nucleus.

where $\alpha = e^2/4\pi$ is the fine structure constant and r is the distance between O^{--} and the center of the helium nucleus. The potential is represented in Figure 1 together with the elementary Coulomb potential obtained when the helium nucleus is assumed to be point-like.

To obtain the eigenstates of an OHe atom, we solve the radial time-independent Schrödinger equation with the potential (1), written in the center-of-mass frame of the system, which corresponds almost exactly to the O^{--} particle as $M_{\text{O}} \gg M_{\text{He}}$. At zero angular momentum l , we use the non-modified WKB approximation as the potential V is regular at the origin ($\lim_{r \rightarrow 0} rV(r) = 0$). For the states at higher l , we use the modified WKB approximation, which consists in replacing $l(l+1)$ by $(l + \frac{1}{2})^2$ in the centrifugal term of the effective potential.²⁵

The eigenvalues $E_{n,l}$ are shown in Table 1 for the first ten values of the principal quantum number n and the corresponding angular momenta $l = 0, \dots, n-1$, together with the pure hydrogen-like solutions $E_n^H = -\frac{1}{2}M_{\text{He}} \frac{(Z_{\text{O}}Z_{\text{He}}\alpha)^2}{n^2}$. We notice a lift of degeneracy on l because the potential (1) is no longer $\propto 1/r$, so that the energy levels now depend on both n and l . Also, the energy of the ground state $1s$ has been increased significantly with respect to E_1^H , due to the finiteness of the well at $r = 0$ when the charge distribution of the helium nucleus is taken into account. In general, at fixed n , the pure hydrogen-like energy levels constitute a lower limit to which the levels $E_{n,l}$ tend as l increases, i.e. as the states are excited and thus as O^{--} and He lie further apart from each other, making the helium nucleus increasingly point-like. At very high n the differences between both types of levels are very small and we

Table 1. Energy levels $E_{n,l}$ (MeV) of the OHe atom, for the first ten values of the principal quantum number n and the corresponding angular momenta $l = 0, \dots, n-1$. In the last column are also shown the pure hydrogen-like solutions E_n^H (MeV) obtained when the helium nucleus is assumed to be point-like. The exponents indicate the power of 10 by which the numbers have to be multiplied to obtain the energy in MeV.

| n | $l = 0$ | $l = 1$ | $l = 2$ | $l = 3$ | $l = 4$ | E_n^H |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|
| 1 | -1.1760 | - | - | - | - | -1.5879 |
| 2 | -0.3446 | -0.3969 | - | - | - | -0.3970 |
| 3 | -0.1607 | -0.1764 | -0.1764 | - | - | -0.1764 |
| 4 | -9.2538^{-2} | -9.9230^{-2} | -9.9240^{-2} | -9.9239^{-2} | - | -9.9244^{-2} |
| 5 | -6.0057^{-2} | -6.3511^{-2} | -6.3511^{-2} | -6.3511^{-2} | -6.3510^{-2} | -6.3516^{-2} |
| 6 | -4.2097^{-2} | -4.4106^{-2} | -4.4106^{-2} | -4.4106^{-2} | -4.4106^{-2} | -4.4108^{-2} |
| 7 | -3.1136^{-2} | -3.2404^{-2} | -3.2404^{-2} | -3.2404^{-2} | -3.2404^{-2} | -3.2406^{-2} |
| 8 | -2.3957^{-2} | -2.4808^{-2} | -2.4811^{-2} | -2.4810^{-2} | -2.4810^{-2} | -2.4811^{-2} |
| 9 | -1.9002^{-2} | -1.9602^{-2} | -1.9602^{-2} | -1.9602^{-2} | -1.9602^{-2} | -1.9604^{-2} |
| 10 | -1.5439^{-2} | -1.5878^{-2} | -1.5878^{-2} | -1.5878^{-2} | -1.5878^{-2} | -1.5879^{-2} |
| n | $l = 5$ | $l = 6$ | $l = 7$ | $l = 8$ | $l = 9$ | E_n^H |
| 1 | - | - | - | - | - | -1.5879 |
| 2 | - | - | - | - | - | -0.3970 |
| 3 | - | - | - | - | - | -0.1764 |
| 4 | - | - | - | - | - | -9.9244^{-2} |
| 5 | - | - | - | - | - | -6.3516^{-2} |
| 6 | -4.4105^{-2} | - | - | - | - | -4.4108^{-2} |
| 7 | -3.2403^{-2} | -3.2406^{-2} | - | - | - | -3.2406^{-2} |
| 8 | -2.4810^{-2} | -2.4810^{-2} | -2.4810^{-2} | - | - | -2.4811^{-2} |
| 9 | -1.9604^{-2} | -1.9602^{-2} | -1.9602^{-2} | -1.9602^{-2} | - | -1.9604^{-2} |
| 10 | -1.5878^{-2} | -1.5878^{-2} | -1.5878^{-2} | -1.5878^{-2} | -1.5879^{-2} | -1.5879^{-2} |

recover the pure hydrogen-like case when $n \rightarrow \infty$. As it is well known that the WKB approximation is less accurate for the deeper bound states, we computed the energy of the ground state by a variational method using up to 11 hydrogen-like s -orbitals and found the result -1.1771 MeV, which shows that the error on the values given in Table 1 is less than 1 %.

3. Some signatures of O-helium excitation

3.1. Positron annihilation line in the galactic bulge

It was first noted in ref. 26 that OHe collisions in the galactic bulge can lead to OHe de-excitation by pair production, which can provide a positron-production rate sufficient⁴¹ to explain the excess in the positron annihilation line from the bulge measured by INTEGRAL (see ref. 42 for a review and references). Indeed, if the 2S level is excited in an OHe collision, pair production dominates over the two-photon channel as the de-excitation can go through an E0 transition, so that positron production is not accompanied by a strong gamma signal. A more detailed analysis of this possibility⁴³ has shown that the rate of positron production strongly depends on the velocity and density profiles of OHe in the center of the Galaxy and a range of parameters was found for which this rate is sufficient to explain the

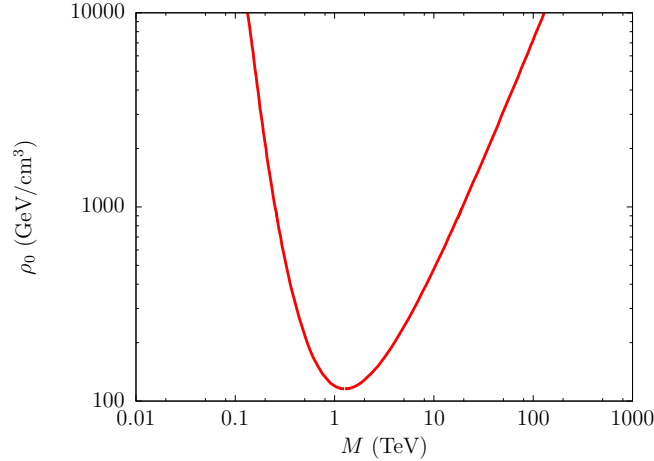


Fig. 2. Values of the central dark matter density ρ_0 (GeV/cm³), assuming a Burkert profile, and of the OHe mass M_O (TeV) reproducing the excess of e^+e^- pair production from the galactic bulge. Below the red curve, the predicted rate is too low.

INTEGRAL data. These results are shown in Figure 2 taken from ref. 43.

3.2. *O-helium de-excitation*

It was noted in ref. 26 that if OHe levels with non-zero angular momentum are excited through collisions, gamma lines should appear from E1 transitions from levels with principal quantum numbers n and m with $n > m$, which would have energies $E_{nm} = 1.5879 \text{ MeV}(1/m^2 - 1/n^2)$ for hydrogen-like OHe, or from the similar transitions corresponding to the more realistic case discussed in Section 2. These predictions may be of interest for the analysis of the possible nature of unidentified lines, observed in the center of the Galaxy. The lines with energies above 20 keV can be searched for in the INTEGRAL data, while a forest of lines of lower energy may be found in X-ray observations. In particular, high-level transitions can lead to a number of lines around 3.5 keV, which can be checked in the XMM-Newton data which are sensitive to the range 0.1 – 12 keV.

By considering all the possible electric dipole transitions (E1) between the states presented in Table 1, we find several hundreds of allowed lines, with energies from the eV range to the MeV range, even for the limited sample $n \leq 10$. In Figure 3, we show the number N of E1 transitions as a function of the energy E , from 20 keV to 1.162 MeV, the latter being the largest energy of the sample and corresponding to the transition from the state $(n = 10, l = 1)$ to the ground state. This was obtained by counting the number of E1 transitions with energies contained within logarithmic bins in energy of width $\Delta \log(E) = \log(1162 \text{ keV}/20 \text{ keV})/100$. The lines with energies between 3 and 4 keV are listed in Table 2. The comparison of our predictions with the observations provides an effective tool to test the OHe

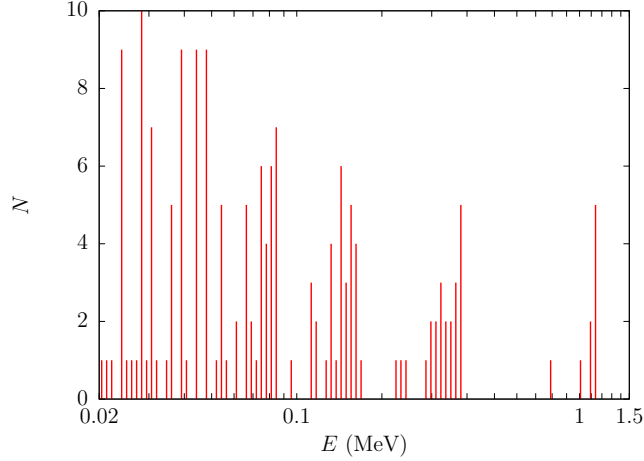
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Fig. 3. The number N of E1 transitions with energies contained within logarithmic bins in energy of width $\Delta \log(E/20 \text{ keV}) = \log(1162 \text{ keV}/20 \text{ keV})/100$, as a function of the energy E of the transition.

Table 2. E1 transitions of an OHe atom with energies between 3 and 4 keV.

| Initial state (n, l) | Final state (n', l') | Energy (keV) |
|--------------------------|--------------------------|--------------|
| (5, 0) | (5, 1) | 3.4542 |
| (10, 1) | (9, 0) | 3.1236 |
| | (9, 2) | 3.7243 |
| (10, 2) | (9, 1) | 3.7243 |
| | (9, 3) | 3.7241 |
| (10, 3) | (9, 2) | 3.7245 |
| | (9, 4) | 3.7242 |
| (10, 4) | (9, 3) | 3.7243 |
| | (9, 5) | 3.7258 |
| (10, 5) | (9, 4) | 3.7246 |
| | (9, 6) | 3.7243 |
| (10, 6) | (9, 5) | 3.7260 |
| | (9, 7) | 3.7245 |
| (10, 7) | (9, 6) | 3.7240 |
| | (9, 8) | 3.7240 |
| (10, 8) | (9, 7) | 3.7245 |
| (10, 9) | (9, 8) | 3.7233 |

composite-dark-matter model.

4. Conclusions

The existence of heavy stable particles is one of the popular solutions for the dark matter problem. These particles are usually considered to be electrically neutral, but dark matter can also be formed by stable heavy charged particles bound in neutral atom-like states by the ordinary Coulomb attraction. The analysis of the cosmo-

logical evolution and atomic composition of the Universe constrains the particle charge to be -2 . These doubly charged constituents will be trapped by primordial helium in neutral O-helium states, and this can avoid the problem of overproduction of anomalous isotopes of chemical elements, which are severely constrained by observations. O-helium dark matter might explain puzzles of direct dark matter searches.⁴⁴ However, such an explanation implies specific properties of the OHe-nucleus interaction, which may not be realized.⁴⁵ Then OHe can be elusive for direct dark matter searches, making its indirect effect of special interest.

The present work sheds new light on the indirect effects of dark matter. Specific electromagnetic signatures of dark atoms are challenging for the experimental searches and are, possibly, already observed as the excess of the positron annihilation line radiation from the galactic bulge in the INTEGRAL data. Confrontation of the predicted spectrum of OHe de-excitation with the cosmic X-ray and gamma ray data provides a new way for an indirect probe of the composite dark matter hypothesis.

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