Dark atoms and the positron-annihilation-line excess in the galactic bulge

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Abstract

It was recently proposed that stable particles of charge $-2$, $O^{-2}$, can exist and constitute dark matter after they bind with primordial helium in O-helium (OHe) atoms. We study here in details the possibility that this model provides an explanation for the excess of gamma radiation in the positron-annihilation line from the galactic bulge observed by INTEGRAL. This explanation assumes that OHe, excited to a 2s state through collisions in the central part of the Galaxy, de-excites to its ground state via an E0 transition, emitting an electron-positron pair. The cross section for OHe collisions with excitation to 2s level is calculated and it is shown that the rate of such excitations in the galactic bulge strongly depends not only on the mass of O-helium, which is determined by the mass of $O^{-2}$, but also on the density and velocity distribution of dark matter.

Given the astrophysical uncertainties on these distributions, this mechanism constrains the $O^{-2}$ mass to lie in two possible regions. One of these is reachable in the experimental searches for stable multicharged particles at the LHC.

1 Introduction

According to modern cosmology, dark matter corresponds to 25% of the total cosmological density, is nonbaryonic and consists of new stable particles. Such particles (see [1–6] for reviews and references) should be stable, provide the measured dark-matter density and be decoupled from plasma and radiation at least before the beginning of the matter-dominated era. It was recently shown that heavy stable particles of charge $-2$, $O^{-2}$, bound to primordial helium in OHe atoms, can provide an interesting explanation for cosmological dark matter [6, 7]. It should also be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints [8–10] on strongly-interacting dark-matter particles (SIMPs) [8–16] imposed by the XQC experiment [17, 18].

The hypothesis of composite O-helium dark matter, first considered to provide a solution to the puzzles of direct dark-matter searches, can offer an explanation for another puzzle of modern astrophysics [6, 7, 19]: this composite-dark-matter model can explain the excess of gamma radiation in the electron-positron annihilation line, observed by INTEGRAL in the galactic bulge (see [20] for a review and references). The explanation
assumes that OHe provides all the galactic dark matter and that its collisions in the central part of the Galaxy result in 2s-level excitations of OHe which are de-excited to the ground state by an E0 transition, in which an electron-positron pair is emitted. If the 2s level is excited, pair production dominates over the two-photon channel in the de-excitation, because electrons are much lighter than helium nuclei, and positron production is not accompanied by a strong gamma-ray signal.

According to [21] the rate of positron production $3 \cdot 10^{42} \text{s}^{-1}$ is sufficient to explain the excess in the positron annihilation line from the bulge measured by INTEGRAL. In the present paper we study the process of 2s-level excitation of OHe from collisions in the galactic bulge and determine the conditions under which such collisions can provide the observed excess. Inelastic interactions of O-helium with matter in interstellar space and subsequent de-excitation can give rise to radiation in the range from a few keV to a few MeV. In the galactic bulge with radius $r_b \sim 1 \text{kpc}$ the number density of O-helium can be of the order of $n_o \approx 3 \cdot 10^{-3} / S_3 \text{cm}^{-3}$ or larger, and the collision rate of O-helium in this central region was estimated in [19]:

$$\frac{dN}{dt} = n_o^2 \sigma v h 4 \pi r_b^3 / 3 \approx 3 \cdot 10^{42} S_3^{-2} \text{s}^{-1},$$

with $S_3 = m_{OHe} / 1 \text{TeV}$. 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 OHe levels with nonzero angular 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 similar transitions corresponding to the case $I_o = 1.287 \text{MeV}$) at the level $3 \cdot 10^{-4} S_3^{-2} (\text{cm}^2 \text{s MeV ster})^{-1}$.

## 2 Collisonal excitation cross section

The studied reaction is the collision between two incident OHe atoms in their ground states $1s$ giving rise to an OHe in an excited $s$-state $ns$ while the other one remains in its ground state:

$$\text{OHe}(1s) + \text{OHe}(1s) \rightarrow \text{OHe}(1s) + \text{OHe}(ns) \quad (1)$$

If we work in the rest frame of the OHe that gets excited, and if we neglect its recoil after the collision, the differential cross section of the process is given by

$$d\sigma (1s \rightarrow ns) = 2\pi \left| \langle ns, \vec{p}' | U | 1s, \vec{p} \rangle \right|^2 \frac{\delta}{2M} \left( \frac{\vec{p}^2}{2M} + E_{ns} - \frac{\vec{p}'^2}{2M} - E_{1s} \right) \frac{d^3p'}{(2\pi)^3} \quad (2)$$

where $M$ is the mass of OHe, $\vec{p}$, $\vec{p}'$ are the momenta of the incident OHe before and after the collision, $E_{1s}, E_{ns}$ are the ground-state and excited-state energies of the target OHe and $U$ is the interaction potential between the incident and the target OHe’s.

We shall neglect the internal structure of the incident OHe, so that its wave functions are plane waves. $\psi_{\vec{p}}$ is normalized to obtain a unit incident current density and the normalisation of $\psi_{\vec{p}'}$ is chosen for it to be pointlike, i.e. the Fourier transform of $\delta^{(3)}(\vec{r})$ [22]:

$$\psi_{\vec{p}} = \sqrt{\frac{M}{p}} e^{i \vec{p} \cdot \vec{r}} \quad (3)$$

$$\psi_{\vec{p}'} = e^{i \vec{p}' \cdot \vec{r}}.$$
where \( \vec{r} \) is the position vector of the incident OHe and \( p = |\vec{p}| \).

In the following, we shall be lead to considering \( O^- \) masses which are much larger than the mass of helium or the bound state energies. Therefore, the origin of the rest frame of the target OHe coincides with the position of its \( O^- \) component and its reduced mass \( \mu \) can be taken as the mass of helium \( M_{He} \).

The OHe that gets excited is described as a hydrogenoid atom, with energy levels \( E_{ns} = -0.5M_{He} (Z_{He}Z_O \alpha)^2 /n^2 \) and initial and final bound-state wave functions \( \psi_{1s} \) and \( \psi_{ns} \) of a hydrogenoid atom with a Bohr radius \( a_0 = (M_{He}Z_{He}Z_O \alpha)^{-1} \).

The incident OHe interacts with the \( O^- \) and helium components in the target OHe, so that the interaction potential \( U \) is the sum of the two contributions \( U_O \) and \( U_{He} \):

\[
U(\vec{r}) = U_O(\vec{r}) + U_{He}(\vec{r} - \vec{r}_{He})
\]

where \( \vec{r}_{He} \) is the position vector of the helium component.

The first term \( U_O \) gives a zero contribution to the integral of expression (2) since the states \( \psi_{1s} \) and \( \psi_{ns} \) are orthogonal. For the second term, we treat the incident OHe as a heavy neutron colliding on a helium nucleus through short-range nuclear forces. The interaction potential can then be written in the form of a contact term:

\[
U_{He}(\vec{r} - \vec{r}_{He}) = -\frac{2\pi}{M_{He}} a_0 \delta(\vec{r} - \vec{r}_{He}),
\]

where we have normalised the delta function to obtain an OHe-helium elastic cross section equal to \( 4\pi a_0^2 \).

Going to spherical coordinates for \( \vec{p}' \) and integrating over \( p' = |\vec{p}'| \) in the differential cross section (2), together with the previous expressions (3), (4) and (5), we get

\[
d\sigma(1s \rightarrow ns) = \left( \frac{M}{M_{He}} \right)^2 a_0^2 \left( \frac{p'}{p} \right)^2 \left| \int e^{-i\vec{q}\cdot\vec{r}_{He}} \psi_{ns}^* \psi_{1s} d^3r_{He} \right|^2 d\Omega
\]

where \( \vec{q} = \vec{p}' - \vec{p} \) is the transferred momentum and \( d\Omega \) is the solid angle. From the integration over the delta function in (2), we have obtained the conservation of energy during the process:

\[
p'^2 = p^2 + 2M(E_{1s} - E_{ns}).
\]

It leads to the threshold energy corresponding to \( p'^2 = 0 \) and to a minimum incident velocity \( v_{min} = \sqrt{2(E_{ns} - E_{1s})/M} \). The previous expression for \( p' \) allows us to express the squared modulus of \( \vec{q} \) as

\[
q^2 = 2 \left( p^2 + M(E_{1s} - E_{ns}) - p\sqrt{p^2 + 2M(E_{1s} - E_{ns})\cos^2\theta} \right),
\]

where \( \theta \) is the deviation angle of the incident OHe with respect to the collision axis in the rest frame of the target OHe.

\( e^+e^- \) pairs will be dominantly produced if OHe is excited to a \( 2s \) state, since the only de-excitation channel is in this case from \( 2s \) to \( 1s \). As \( e^+e^- \) pair production is the only possible channel, the differential pair production cross section \( d\sigma_{ee} \) is equal to the

\[
\int \frac{d\sigma(1s \rightarrow ns)}{d\Omega} \frac{d\Omega}{4\pi} = \frac{2\pi}{M_{He}} a_0^2 \frac{E_{1s} - E_{ns}}{M}.
\]
differential collisional excitation cross section. By particularizing expression (6) to the case \( n = 2 \), one finally gets

\[
\frac{d\sigma_{ee}}{d\cos \theta} = 512^2 \left( \frac{2\pi M^2}{M_{He}^2} \right) a_0^6 \left( \frac{p'}{p} \right) \frac{q^4}{2 \left( 4a_0^2 q^2 + 9 \right)^6}
\]  

(9)

3 The \( e^+e^- \) pair-production rate in the galactic bulge

The total \( e^+e^- \) pair production rate in the galactic bulge is given by

\[
\left. \frac{dN}{dt} \right|_{ee} = \int_{V_b} \frac{\rho_{DM}^2 \left( \vec{R} \right)}{M^2} \left( \sigma_{ee}v \right) \left( \vec{R} \right) d\vec{R}
\]  

(10)

where \( V_b \) is the volume of the galactic bulge, which is a sphere of radius \( R_b = 1.5 \) kpc, \( \rho_{DM} \) is the energy density distribution of dark matter in the galactic halo and \( \left( \sigma_{ee}v \right) \) is the pair production cross section \( \sigma_{ee} \) times relative velocity \( v \) averaged over the velocity distribution of dark matter particles. The total pair-production cross section \( \sigma_{ee} \) is obtained by integrating (9) over the diffusion angle. Its dependence on the relative velocity \( v \) is contained in \( p, p' \) and \( q \) through \( p = Mv \) and the expressions (7) and (8) of \( p' \) and \( q \) in terms of \( p \).

We use a Burkert [23] flat, cored, dark matter density profile known to reproduce well the kinematics of disk systems in massive spiral galaxies and supported by recent simulations including supernova feedback and radiation pressure of massive stars [24] in response to the cuspy halo problem:

\[
\rho_{DM} \left( R \right) = \rho_0 \frac{R_0^3}{\left( R + R_0 \right) \left( R^2 + R_0^2 \right)},
\]  

(11)

where \( R \) is the distance from the galactic center. The central dark matter density \( \rho_0 \) is left as a free parameter and \( R_0 \) is determined by requiring that the local dark matter density at \( R = R_\odot = 8 \) kpc is \( \rho_\odot = 0.3 \) GeV/cm\(^3\). The dark matter mass enclosed in a sphere of radius \( R \) is therefore given by

\[
M_{DM} \left( R \right) = \rho_0 \pi R_0^3 \left\{ \log \left( \frac{R^2 + R_0^2}{R_0^2} \right) + 2 \log \left( \frac{R + R_0}{R_0} \right) - 2 \arctan \left( \frac{R}{R_0} \right) \right\}.
\]  

(12)

For the baryons in the bulge, we use an exponential profile [25] of the form

\[
\rho_b \left( R \right) = \frac{M_{bulge}}{8\pi R_b^3} e^{-R/R_b},
\]  

(13)

where \( M_{bulge} = 10^{10} M_\odot \) [26] is the mass of the bulge. This gives the baryonic mass distribution in the galactic bulge

\[
M_b \left( R \right) = M_{bulge} \left\{ 1 - e^{-R/R_b} \left( 1 + \frac{R}{R_b} + \frac{R^2}{R_b^2} \right) \right\}.
\]  

(14)
We assume a Maxwell-Boltzmann velocity distribution for the dark matter particles of the galactic halo, with a velocity dispersion $u(R)$ and a cutoff at the galactic escape velocity $v_{esc}(R)$:

$$f(R, \vec{v}_h) = \frac{1}{C(R)} e^{-v^2_h/u^2(R)}$$  (15)

where $\vec{v}_h$ is the velocity of the dark matter particles in the frame of the halo and $C(R) = \pi u^2 \left( \sqrt{\pi} u \text{erf}(v_{esc}/u) - 2v_{esc}e^{-v^2_{esc}/u^2} \right)$ is a normalization constant such that $\int_{v_{esc}(R)}^{0} f(R, \vec{v}_h) d\vec{v}_h = 1$.

The radial dependence of the velocity dispersion is obtained via the virial theorem:

$$u(R) = \sqrt{GM_{tot}(R)/R}$$  (16)

where $M_{tot} = M_{DM} + M_b$, while $v_{esc} = \sqrt{2}u$.

Using the velocity distribution (15), going to center-of-mass and relative velocities $\vec{v}_{CM}$ and $\vec{v}$ and performing the integrals over $\vec{v}_{CM}$, we obtain for the mean pair-production cross section times relative velocity:

$$\langle \sigma_{ee} v \rangle = \frac{1}{u^2} \frac{\sqrt{2\pi} u \text{erf}(\sqrt{2}v_{esc}/u) - 4v_{esc}e^{-2v^2_{esc}/u^2}}{(\sqrt{\pi} u \text{erf}(v_{esc}/u) - 2v_{esc}e^{-v^2_{esc}/u^2})^2} \int_{0}^{2v_{esc}} \sigma_{ee}(v) v^3 e^{-v^2/2u^2} dv, \quad (17)$$

which is also a function of $R$ through $u$ and $v_{esc}$. Putting [9], [11], [12], [14], [16] and [17] together allows us to compute the pair production rate in the galactic bulge defined in [10] as a function of $\rho_0$ and $M$.

4 Results

The rate of excessive $e^+e^-$ pairs to be generated in the galactic bulge was estimated in [21] to be $dN/dt|_{obs} = 3 \times 10^{42}$ s$^{-1}$ We computed $dN/dt|_{ee}$ for a large range of central dark-matter densities, going from 0.3 GeV/cm$^3$ to a ultimate upper limit of $10^4$ GeV/cm$^3$ [27]. For each value of $\rho_0$, we searched for the mass $M$ of OHe that reproduces the observed rate. The results are shown in Figure [1].

The observed rate can be reproduced from a value of $\rho_0 \approx 115$ GeV/cm$^3$, corresponding to an OHe mass of $M \approx 1.25$ TeV. As $\rho_0$ gets larger, two values of $M$ are possible, the lower one going from 1.25 TeV to 130 GeV and the upper one going from 1.25 to 130 TeV as $\rho_0$ goes from 115 to $10^4$ GeV/cm$^3$.

5 Conclusion

The existence of heavy stable particles is one of the most popular solutions for the dark matter problem. Usually they are considered to be electrically neutral. But dark matter can potentially be made of stable heavy charged particles bound in neutral atom-like states by Coulomb attraction. An analysis of the cosmological data and of the
atomic composition of the Universe forces the particle to have charge $-2$. $O^{-2}$ is then trapped by primordial helium in neutral O-helium states and this avoids the problem of overproduction of anomalous isotopes, which are severely constrained by observations. Here we have shown that the cosmological model of O-helium dark matter can explain the puzzle of positron line emission from the center of our Galaxy.

The proposed explanation is based on the assumption that OHe dominates the dark-matter sector. Its collisions can lead to $E0$ de-excitations of the $2s$ states excited by the collisions. The estimated luminosity in the electron-positron annihilation line strongly depends not only on the mass of $O^{-2}$, but also on the density profile and velocity distribution of dark matter in the galactic bulge. Note that the density profile we considered is used only to obtain a reasonable estimate for the uncertainties on the density in the bulge. It indeed underestimates the mass of the galaxy, but it shows that the uncertainties on the astrophysical parameters are large enough to reproduce the observed excess for a rather wide range of masses of $O^{-2}$. For a fixed density profile and a fixed velocity distribution, only two values of the $O^{-2}$ mass lead to the necessary rate of positron production. The lower value of this mass, which doesn’t exceed 1.25 TeV, is within the reach of experimental searches for multi charged stable heavy particles at the LHC.
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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 frontières, 1996) p. 67.
[3] M. Y. Khlopov, *Bled Workshops in Physics* 7, 51 (2006).
[4] M. Y. Khlopov, *Bled Workshops in Physics* 8, 114 (2007).
[5] M. Yu. Khlopov *Fundamentals of Cosmoparticle physics* (CISP-Springer, Cambridge, 2012).
[6] M. Yu. Khlopov, *Int. J. Mod. Phys. A* 28, 1330042 (2013).
[7] M. Yu. Khlopov, *Mod. Phys. Lett. A* 26, 2823 (2011).
[8] B. D. Wandelt et al., arXiv:astro-ph/0006344
[9] P. C. McGuire and P. J. Steinhardt, arXiv:astro-ph/0105567.
[10] G. Zaharijas and G. R. Farrar, *Phys. Rev. D* 72, 083502 (2005).
[11] C. B. Dover et al, *Phys. Rev. Lett. A* 42, 1117 (1979).
[12] S. Wolfram, *Phys. Lett. B* 82, 65 (1979).
[13] G. D. Starkman et al, *Phys. Rev. D* 41, 3594 (1990).
[14] D. Javorsek et al, *Phys. Rev. Lett. A* 87, 231804 (2001).
[15] S. Mitra, *Phys. Rev. D* 70, 103517 (2004).
[16] G. D. Mack et al, *Phys. Rev. D* 76, 043523 (2007).
[17] D. McCammon et al, *Nucl. Instrum. Methods A* 370, 266 (1996);
[18] D. McCammon et al, *Astrophys. J.* 576, 188 (2002).
[19] M. Y. Khlopov, “Composite dark matter from stable charged constituents,” arXiv:0806.3581 [astro-ph].
[20] B. J. Teegarden et al, *Astrophys. J.* 621, 296 (2005).
[21] D. P. Finkbeiner and N. Weiner, *Phys. Rev. D* 76, 083519 (2007).
[22] L. D. Landau, E. M. Lifshitz, *Quantum Mechanics*. Pergamon Press, 1965.

[23] A. Burkert, IAU Symp. **171** (1996) 175 [Astrophys. J. **447** (1995) L25] [astro-ph/9504041].

[24] A. V. Maccio et al, *Astrophys. J.* **744**, L9 (2012)

[25] O. Y. Gnedin et al, *Astrophys. J.* **616**, 16 (2004).

[26] H. Mo, F. van den Bosch, and S. White, *Galaxy Formation and Evolution*. Cambridge University Press, 2010.

[27] X. Hernandez and W. H. Lee, “An upper limit to the central density of dark matter haloes from consistency with the presence of massive central black holes,” arXiv:1002.0553.