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Annihilation of Dipolar Dark Matter: $\chi\bar{\chi} \rightarrow \gamma\gamma$

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ABSTRACT

In this work we study the annihilation of dark matter, considering it as a neutral particle with magnetic and/or electric moments not null. The calculation of the effective section of the process $\chi\bar{\chi} \rightarrow \gamma\gamma$ is made starting from a general form of coupling $\chi\bar{\chi}\gamma$ in the framework of an extension of the Standard Model. We found, when taking into account an annihilation of DDM-antiDDM to monoenergetic photons, that for small masses, $m_\chi \leq 0$ GeV, an electric dipole moment $\sim 10^{-6}$ e cm is required to satisfy the current residual density, while for the range of greater sensitivity of HAWC, 10 TeV $< E_g <$ 20 TeV, the electrical dipole moment must be of the order of 10^{-8} e cm.

1. Introduction

The enigma of dark matter is perhaps the most interesting problem of modern astrophysics, so much so that it has led to the incursion of elementary particle physics. The joint work of these two disciplines has as one of its main objectives to determine the nature and properties of dark matter, either through direct or indirect detection. This enigma of the missing mass has been a problem since Zwicky in 1933 measured the masses of extragalactic systems [1]. Nowadays, given the evidences of the galactic dynamics (rotation curves), galaxy clusters, structure formation, as well as the Big Bang's nucleosynthesis and the cosmic background radiation, it is suggested that baryons can only explain matter, the majority of the missing mass must be non-baryonic. The non-baryonic nature of dark matter is clear evidence that our understanding of the matter components of elementary particle physics, beautifully described by the Standard Model (SM) is incomplete. For this reason, theoretical physicists have considered new physics beyond the Standard Model in order to accommodate (at least) a non-baryonic candidate as dark matter (DM), since the only dark matter candidate in the SM is the neutrino, which is inadequate to explain most of the DM [2]. The most promising candidates that emerge beyond the Standard Model, are the massive particles of weak interaction, commonly known as WIMPs, examples of these are the neutralino [3] and the axion [4], but unfortunately they have not been detected. In the absence of the discovery of such particles it is worth exploring other possibilities. An alternative line of research is to take an approach independent of the model and try to phenomenologically explore the possible properties of a dark matter particle. On this line, the restrictions for strongly interacting dark matter were considered in Ref. [5]. In addition, the autointeraction of dark matter has been considered in the Refs. [6,7]. Some people have studied whether dark matter could be charged [8] or have a milichargue [9,10]. Likewise, it has been studied that within these phenomenological possibilities, dark matter has an electric or magnetic dipole moment [11, 12, 13-15]. In this work we consider, precisely, the possibility that dark matter possesses an electrical and/or magnetic dipole moment and can emit gamma radiation as a result of its annihilation. In the next section, we introduce the effective Lagrangian for the interaction of dipolar dark matter with photons. The calculation of the annihilation cross-section by the thermally averaged relative velocity is calculated in section 3. In section 4 we speak of monoenergetic gamma radiation, while in section 5 conditions are established on the magnetic and electric dipole moment to satisfy the current residual abundance. We give our conclusions in section 6.

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2. Dipolar Dark Matter

Dark matter seems to be made up of non-relativistic particles that interact only gravitationally and perhaps by weak interaction. In general, the coupling to photons is assumed to be non-existent or very weak, so that electromagnetic interactions have not been seriously considered [12]. However, although the DM particles are considered chargeless, that is, they have no electrical charge, they could be coupled to photons through loops in the electric and magnetic dipole moment [13]. For this reason, we assume that dipolar dark matter is a class of WIMPs, which are endowed with dipole moments, so they can interact weakly via electromagnetic interaction. The particles proposed as DM are Dirac fermions, that is, spin particles 1/2, because for a permanent electric and/or magnetic dipole moment the particle must have a spin other than zero [15]. The phenomenology of the dark matter particles charged is determined to a large extent by the ability of these particles to form bound states, such as atoms, with electrons, protons or each other. Interestingly, a neutral particle with an electric dipole moment (D) can make a state linked with an electron, as observed by Fermi and Teller [16], but only if the dipole moment is greater than 0.639e $a_0 = 3.4 \times 10^{-9}$ e cm (assuming that $m_g >> m_e$), where a_0 is the radius of Bohr. For small dipole values, the electron sees both poles of the dipole and is in an unstable orbit. This critical electric dipole moment scales inversely with the reduced electron-dipole mass, so a state bound to a proton can occur if the mass of the dipole is $>> m_p$ and $D >> 1.8 \times 10^{-12}$ e cm, however, such D values can not occur for point dipole dark matter. Also, the weakness of the dipole-dipole interaction prevents the formation of stable dark matter atoms [15]. On the other hand, if the particles of dipolar dark matter (DDM) are the dark matter of our Universe, had to undergo a thermal history similar to that of any WIMP, that is, existed in the early Universe when the temperature $T > m_\gamma$, and their interactions froze when T fell below m_χ resulting in some residual cosmological abundance [17]. For a weak-scale thermal particle, the residual abundance in the case of s wave annihilation is approximately established by [18]

$$\Omega h^2 \approx \frac{3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v\rangle}. \tag{1}$$

Said mass density of residual DDM particles is fixed by the annihilation cross section, σ_{ann}, of all the lighter particles multiplied by the relative velocity v. Note that smaller effective annihilation sections correspond to much higher residual densities. For the detection of DDM particles (WIMPs), supposedly integrating the galactic halo, both direct and indirect methods are used. To detect the WIMP by the direct method is done by the nuclear recoil that they produce in their elastic dispersion with the nuclei of the detector used as target in the laboratory [11, 12, 13], examples of these experiments are CRESST, XENON, CDMS, DAMA and COGENT. Instead indirect methods allow us to detect the WIMP through the observation of the products emitted in their annihilation in the galactic halo or in the interior of the Sun and the Earth where they could have been gravitationally trapped. In this annihilation certain types of radiation would be emitted, such as: high energy photons (gamma rays), neutrinos, electron-positron pairs, proton-antiproton pairs, among others. An example of this type of experiments is HAWC (High Altitude Water Cherenkov). This gamma ray observatory is built on a site located 4,100 meters above sea level on the northern slope of the Sierra Negra volcano, which is located in the State of Puebla, Mexico. It is a set of 300 Cherenkov water detectors sensitive to gamma rays and charged particles with energies from 100 GeV to 100 TeV [19].

2.1 The Effective Lagrangian for Coupling

The effective Lagrangian for the coupling of a Dirac fermion with a magnetic dipole moment and an electric dipole moment with the electromagnetic field is

$$L_{\chi\gamma} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(M+\gamma^5 D)\chi F^{\mu\nu} \tag{2}$$

For low energies compared to the mass of dark matter, the photon is blind to the differences between M and D. For the interaction of Equation (2), pairs of DDM-antiDDM particles in the galactic halo or contained in any region of the Universe with high densities (centers of galaxies, clusters of galaxies), can annihilate directly to gX, where X can be some other neutral state, such as: γ, Z or a Higgs boson. In this work we assume that the annihilation of DDM particles is towards two photons through the diagrams shown in Figure 1. Said annihilations take place through s waves, so $\sigma_{\mathrm{ann}} v$ is almost independent of the speed and therefore independent of the temperature [17].

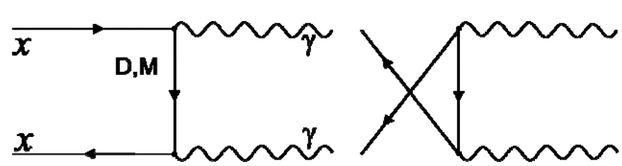

Figure 1. Feynman diagrams for the annihilation of a pair of DDM-antiDDM to two photons.

3. Calculation of the Effective Section of the Annihilation Process: $\chi\chi \rightarrow \gamma$

We consider the process of annihilation, at tree level, of dipolar dark matter (DDM) to two photons. The calculation of the cross section is made from the frame of reference mass center (MC). It is proposed as a propagator to the dipolar dark matter itself. For this process we have two contributions of low order (see Figure 2), so the amplitude of annihilation of dipolar dark matter will be $M = M_1 + M_2$. The amplitude of the first diagram is given as

$$M_1 = -k_{2\nu} k_{1\mu} \varepsilon^*_\rho(k_2)\varepsilon^*_\lambda(k_1)[\bar{u}(p_2)\sigma^{\nu\rho}(M+\gamma^5 D)]\left(\frac{\not{q}_1 + m_\chi}{q_1^2 - m_\chi^2}\right) \times[\sigma^{\mu\lambda}(M+\gamma^5 D)u(p_1)], \quad (3)$$

while, the amplitude of the second diagram is

$$M_2 = -k_{1\nu} k_{2\mu} \varepsilon^*_\lambda(k_1)\varepsilon^*_\rho(k_2)[\bar{u}(p_2)\sigma^{\nu\lambda}(M+\gamma^5 D)]\left(\frac{\not{q}_2 + m_\chi}{q_2^2 - m_\chi^2}\right) \times[\sigma^{\mu\rho}(M+\gamma^5 D)u(p_1)]. \quad (4)$$

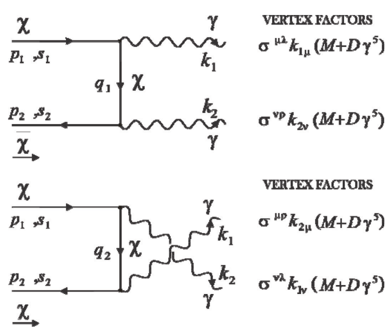

Figure 2. diagram 1 at the top and diagram 2 at the bottom.

So, the total amplitude M considering the two diagrams for this process is

$$M = -\varepsilon^*_\rho(k_2)\varepsilon^*_\lambda(k_1)\bar{u}(p_2)\Bigg[k_{2\nu}k_{1\mu}\sigma^{\nu\rho}(M+\gamma^5 D)\left(\frac{\not{q}_1 + m_\chi}{q_1^2 - m_\chi^2}\right) \times[\sigma^{\mu\lambda}(M+\gamma^5 D) + k_{1\nu}k_{2\mu}\sigma^{\nu\lambda}(M+\gamma^5 D) \times\left(\frac{\not{q}_2 + m_\chi}{q_2^2 - m_\chi^2}\right)[\sigma^{\mu\rho}(M+\gamma^5 D)\Bigg]u(p_1) \quad (5)$$

where $k_{1m(v)}$ and $k_{1v(m)}$ are the components of the four-moment k_1 and k_2, respectively; q_1 and q_2 are the transferred moments and m_χ is the mass of the particle of dipolar dark matter. Before obtaining the square of the amplitude $|M_2|$, some simplifications can be made, since $p_1^2 = m_\chi$, $k_1^2 = 0$, and $k_2^2 = 0$ given that the resulting particles are photons, the denominators of the propagators are $q_1^2 - m_\chi^2 = -2p_1 \cdot k_1$ and $q_2^2 - m_\chi^2 = -2p_1 \cdot k_2$. In addition, Ward's identity is used, $\sum_{s_1} u(p_1)_b \bar{u}(p_1)_c = (\not{p}_1 + m_\chi)_{bc}$, as well as the relationships of completes $\sum_{pol} \varepsilon^*_\mu \varepsilon_\nu \to -g_{\mu\nu}$ and $\sum_{s_2} u(p_2)_d \bar{u}(p_2)_a = (\not{p}_2 - m_\chi)_{da}$. Considering all the above we have that the square amplitude averaged over the spins is

$$\overline{|M|^2} = \frac{1}{8} Tr\Bigg[g_{\rho\eta}g_{\lambda\beta}(\not{p}_2 - m_\chi)\Bigg(\frac{k_{2\nu}k_{1\mu}}{p_1 \cdot k_1}\sigma^{\nu\rho}(M+\gamma^5 D)(\not{q}_1 + m_\chi)\sigma^{\mu\lambda} \times(M+\gamma^5 D) + \frac{k_{1\nu}k_{2\mu}}{p_1 \cdot k_2}\sigma^{\nu\lambda}(M+\gamma^5 D)(\not{q}_2 + m_\chi)\sigma^{\mu\rho}(M+\gamma^5 D)\Bigg)(\not{p}_1 + m_\chi) \times\left(\frac{k_{2\delta}k_{1\alpha}}{p_1 \cdot k_1}(M-\gamma^5 D)\sigma^{\alpha\beta}(\not{q}_1 + m_\chi)(M-\gamma^5 D)\sigma^{\delta\eta} + \frac{k_{1\delta}k_{2\alpha}}{p_1 \cdot k_2}(M-\gamma^5 D)\sigma^{\alpha\eta}(\not{q}_2 + m_\chi)(M-\gamma^5 D)\sigma^{\delta\beta}\right)\Bigg]. \quad (6)$$

The calculation of this last trace results in 199 terms, but when taking into account that the particles resulting from this process are photons, then the terms that have a factor a k_1^2 and k_2^2 will be canceled because $k_1^2 = k_2^2 = 0$. Therefore, the trace is reduced to only 33 terms expressed as four-moment products p_1, p_2, k_1 and k_2, which at the same time we can write in terms of the basic kinematic variables: energies and dispersion angle of the CM system. Finally, in terms of these variables and with a bit of algebra, we arrive at the following expression of the square amplitude averaged over the spins:

$$\overline{|M|^2} = \frac{E_\chi^2}{E_\chi^2 - p^2\cos^2\theta} \times\Bigg[16\left(\begin{array}{r}-m_\chi^4 + p^2 m_\chi^2 + E_\chi^4 + m_\chi^2 E_\chi^2 - (2p^2 m_\chi^2 + 2p^2 E_\chi^2)\cos^2\theta \\ +p^4\cos^4\theta\end{array}\right)(M^4 + D^4) + 32\left(\begin{array}{r}m_\chi^4 + 3p^2 m_\chi^2 - E_\chi^4 + 3m_\chi^2 E_\chi^2 + (-6p^2 m_\chi^2 \\ +2p^2 E_\chi^2)\cos^2\theta - p^4\cos^4\theta\end{array}\right)M^2 D^2\Bigg] \quad (7)$$

where E_χ and m_χ, are the energy and mass of the dipolar dark matter (or antiDDM), respectively, p is the moment of the incident dark matter particles and θ is the scattering angle of the outgoing particles.

Because there are only two particles in the final state and we are working in the frame of reference of the center of mass, we will use the Golden Rule of dispersion for the case $1 + 2 \to 3 + 4$:

$$\frac{d\sigma}{d\Omega}=\frac{1}{64\pi^2}\frac{1}{(E_1+E_2)^2}\frac{|\mathbf{p}_3|}{|\mathbf{p}_1|}\overline{|M|^2} \qquad (8)$$

For our problem and based on the conservation of momentum and energy, we have to: $|\mathbf{p}_1|=\mathrm{p}$, $E_1=E_2=E_\chi=\sqrt{\mathrm{p}^2+m_\chi^2}$, $E_3=E_4=|\mathbf{p}_3|=E_\chi$, $|v_1-v_2|=v_{rel}=2\mathrm{p}/E_\chi$, with $E_\chi=(|\mathbf{p}_1|^2+m_\chi^2)^{1/2}$. Substituting the above in Equation (10), we find that the differential effective section of annihilation of dipolar dark matter to photons is:

$$\frac{d\sigma_{ann}}{d\Omega}=\frac{1}{64\pi^2}\frac{E_\chi}{(2E_\chi)^2\mathrm{p}}\frac{E_\chi^2}{E_\chi^2-\mathrm{p}^2\cos^2\theta}\times\Big[16\left(-m_\chi^4+\mathrm{p}^2m_\chi^2+E_\chi^4+m_\chi^2E_\chi^2-(2\mathrm{p}^2m_\chi^2+2\mathrm{p}^2E_\chi^2)\cos^2\theta+\mathrm{p}^4\cos^4\theta\right)(M^4+D^4)$$
$$+32\left(m_\chi^4+3\mathrm{p}^2m_\chi^2-E_\chi^4+3m_\chi^2E_\chi^2+(-6\mathrm{p}^2m_\chi^2+2\mathrm{p}^2E_\chi^2)\cos^2\theta-\mathrm{p}^4\cos^4\theta\right)M^2D^2\Big] \qquad (9)$$

Then, taking into account that the process is symmetric with respect to the collision axis, the phase space is written as an integral over the polar angle θ of the reference frame of the CM, so when performing the corresponding integrals we have to:

$$\sigma_{ann}v_{rel}=\frac{m_\chi^2}{6\pi}\left[\left(M^4+D^4\right)\left(-\frac{6y^2\,Arc\,\mathrm{Tan}\left(\sqrt{y^2-1}\right)}{\sqrt{y^2-1}}+\frac{2}{y^2}+7\right)+M^2D^2\left(-\frac{12y^2\,Arc\,\mathrm{Tan}\left(\sqrt{y^2-1}\right)}{\sqrt{y^2-1}}-\frac{4}{y^2}+34\right)\right] \qquad (10)$$

where $y=m_\chi/E_\chi$.

Finally, if we want to know about the average of the thermal distribution of the WIMPs we do it by means of the effective section of annihilation by the thermally averaged relative velocity, $\langle\sigma_{ann}v_{rel}\rangle$. Because we are working within the non-relativistic limit, it is possible to use the method described in Ref. [20], which qualitatively allows us to perform the integrals to obtain $\sigma_{ann}v_{rel}$ and then expand on v_{rel}, we expand on v_{rel} and then we make the remaining integrals on analytically simple trigonometric functions to arrive at the final answer:

$$\langle\sigma_{ann}v_{rel}\rangle=1.71423\times10^{34}\,\mathrm{cm^3s^{-1}}\times m_{\mathrm{GeV}\chi}^2\left[6\left(M^4+6M^2D^2+D^4\right)+\left(3M^4+2M^2D^2+3D^4\right)\langle v_{rel}^2\rangle\right] \qquad (11)$$

So that, using $\langle\sigma_{ann}v_{rel}\rangle\approx a_{rel}+b_{rel}\langle v_{rel}^2\rangle=a_{rel}+6b_{rel}/x$ [21]:

$$\langle\sigma_{ann}v_{rel}\rangle=1.71423\times10^{34}\,\mathrm{cm^3s^{-1}}\times m_{\mathrm{GeV}\chi}^2\left[6\left(M^4+6M^2D^2+D^4\right)+\left(3M^4+2M^2D^2+3D^4\right)\frac{6}{x}\right] \qquad (12)$$

where $m_{GeV\chi}=m_\chi/\mathrm{GeV}$ y $x=m_\chi/\mathrm{T}$ is the decoupling energy that within this non-relativistic limit $x>>1$ (o $T<<m_\chi$); for WIMPs $x\cong22$ [22].

4. Monoenergetic Gamma Radiation

The DDM-antiDDM pairs can be annihilated to two photons through the diagrams shown in Figure 1. Because the particles move with speeds below one thousandth part the speed of light, $v\cong230\mathrm{km\ s^{-1}}$, the photons produced will be very closely monoenergetic with energies equal to the resting mass of the DDM particles $E_\gamma=m_\chi$, which allows the gamma rays, in the GeV and TeV range, to access the most relevant mass range of dark matter particles. Gamma rays are ideal for studying the annihilation of dark matter, because they do not deviate in intermediate magnetic fields and, therefore, point to the place where they are created. This allows us to look for gamma-ray signatures not only in our neighborhood of the galaxy, but also in distant objects such as satellite galaxies or even clusters of galaxies. Another advantage of the use of gamma rays is that, in the local Universe, gamma rays do not suffer attenuation and, therefore, retain the source spectral information intact on Earth [23]. These characteristics of gamma rays make the HAWC observatory ideal for studying candidates for dark matter, specifically, dipolar dark matter. Although HAWC is sensitive to photons from 100 GeV to 100 TeV, it has a maximum sensitivity in the range of 10 to 20 TeV, which makes it sensitive to diverse searches for dark matter annihilation, including extended sources, emission diffuse of gamma rays, and the emission of gamma rays of subhalos of non-luminous dark matter. A subset of these sources includes dwarf galaxies, galaxy M31, the Virgo cluster and the galactic center. Likewise, the response of HAWC to gamma rays from these sources has been simulated in several channels of well-motivated dark matter annihilation ($b\bar{b}$, $t\bar{t}, \tau^+\tau^-, W^+W^-$) [24].

5. Results

For our analysis, we consider that $D = M$, so that the expression of the effective section of annihilation by the relative thermally averaged speed for the process $X\bar{X} \rightarrow \gamma\gamma$ is:

$$\langle \sigma_{ann} v_{rel} \rangle = 1.71423 \times 10^{34}\,\mathrm{cm^3 s^{-1}} m^2_{\mathrm{GeV}\chi} \left[48D^4 + \frac{48D^4}{x} \right] \tag{13}$$

We are taking into account the upper limit for dipolar moments, $D = M \leq 3 \times 10^{-16}$ (e cm), reported by K. Sirgurdson *et al.* (Ref. [15]) and the decoupling energy for the WIMPs, $x \cong 22$, we can write the previous expression as follows

$$\langle \sigma_{ann} v_{rel} \rangle = 0.66649 \times 10^{-26}\,\mathrm{cm^3 s^{-1}} m^2_{\mathrm{GeV}\chi} \left[D^4_{16} + \frac{D^4_{16}}{22} \right] \tag{14}$$

where $D^4_{16} = (D/3 \times 10^{-16})^4$. Note that $\langle \sigma_{ann} v_{rel} \rangle$ has the order of magnitude corresponding to the total self-annihilation cross section for a generic WIMP, which is usually set as $\langle \sigma\ v \rangle \approx 3 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}$ [25].

On the other hand, since the residual density of cold dark matter estimated by WMAP is $\Omega h^2 \approx 0.11$ [26], we can relate Equation (14) with Equation (1) to obtain:

$$\Omega h^2 \approx \frac{3 \times 10^{-26}\,\mathrm{cm^3/s}}{\langle \sigma_{\mathrm{ann}} v_{rel} \rangle} = 0.11. \tag{15}$$

Then, if DDM particles are cold dark matter, Equation (15) implies that the DDM particle mass density depends on the electrical dipole moment D and the mass m_χ, therefore, for electrical dipole moments below $\leq 3 \times 10^{-16}$ e cm and masses $m_\chi \geq 6$ GeV it is always satisfied with the residual abundance given by WMAP (see Figure 3).

The value of the electrical dipole moment that causes equality to be met, in the mass range of the DMM particles $6\ \mathrm{GeV} \leq m_\chi \leq 100\ \mathrm{TeV}$, becomes up to 126 times more smaller than D = 3×10^{-16} e cm, as can be seen in Figure 4. But, for values in the small mass range, GeV, an electric dipole moment of the order of $\sim 10^{-18}$ e cm, is required to satisfy the current residual abundance, in accordance with Ref. [8]; while in the range of greater sensitivity of HAWC, 10 TeV $\leq m_g \leq$ 20 TeV, the electric dipole moment must be of the order of $\sim 10^{-18}$ e cm, taking into account an annihilation of DDM-anti DDM to monoenergetic photons (see Table 1).

Table 1: Required masses of dipolar dark matter and range of values of electrical dipole moment that satisfies residual abundance $\Omega h^2 = 0.11$.

Mass range m_χ [GeV]	Range of D [e cm]
$6 \leq m_\chi \leq 10$	$2.37 \times 10^{-16} \leq D \leq 3 \times 10^{-6}$
$10 \leq m_\chi \leq 100$	$7.5 \times 10^{-17} \leq D \leq 2.37 \times 10^{-6}$
$100 \leq m_\chi \leq 1000$	$2.38 \times 10^{-17} \leq D \leq 7.5 \times 10^{-17}$
$1000 \leq m_\chi \leq 100000$	$2.38 \times 10^{-18} \leq D \leq 2.37 \times 10^{-17}$
$10\ \mathrm{TeV} \leq m_\chi \leq 20\ \mathrm{TeV}$	$5.3 \times 10^{-18} \leq D \leq 7.5 \times 10^{-18}$

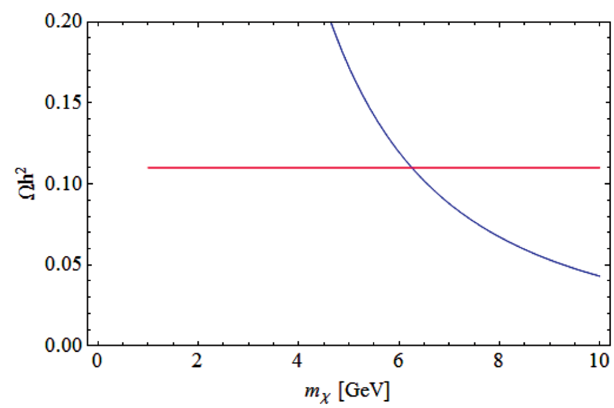

Figure 3. The graph shows the residual abundance, Equation (15), for $D = 3 \times 10^{-16}$ e cm

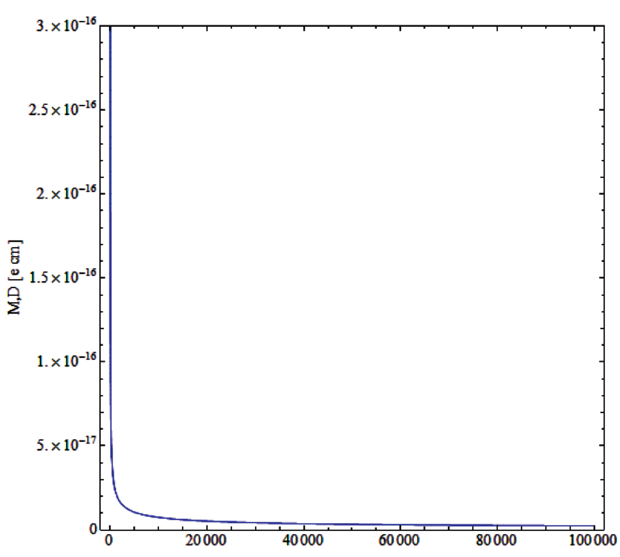

Figure 4. The graph shows the range of values of both D and m_χ, of in which the residual abundance is satisfied $\Omega h^2 = 0.11$.

6. Discussion and Conclusions

In this work we study the annihilation of dark matter, considering it as a neutral particle with magnetic and/or electric moments not null. For this reason, a neutral WIMP with an associated magnetic and/or electrical dipole moment of the order of $D = M \leq 3 \times 10^{-16}$ e cm is proposed. The effective section of annihilation $\chi\overline{\chi} \to \gamma\gamma$ was calculated in analytical form. Likewise, this effective section was analyzed numerically $\langle \sigma_{ann} v_{rel} \rangle$, where it was found that for small masses, $\leq \theta$ GeV, an electrical dipole moment ~10^{-16} e cm, is required to satisfy the current residual abundance, while considering that HAWC is sensitive to the photons of 100 GeV at 100 TeV we need a dipole electric moment $D \leq 7.5 \times 10^{-17}$ e cm. In addition, it was found that in the HAWC's highest sensitivity range, 10 TeV $\leq m_\chi \leq$ 20 TeV, the electrical dipole moment must be of the order of 10^{-18} e cm.

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