J. Nucl. Phys. Mat. Sci. Rad. A. Vol. 7, No. 2, Feb. 2020, pp.153–157

CHITKARA

Journal of Nuclear Physics, Material Sciences, Radiation and Applications
Journal homepage: https://jnp.chitkara.edu.in/

Analysis of DDM into Gamma Radiation

C. Arellano-Celiz[1], A. Avilez-López[1], J. E. Barradas-Guevara[1], O. Félix-Beltrán[2*] and F. González-Canales[2]

[1]*Faculty of Mathematical Physical Sciences, Benemérita Universidad Autónoma de Puebla, Apdo. Postal 1152, Puebla, Pue.-72000, Mexico*
[2]*Faculty of Electronics Sciences, Benemérita Universidad Autónoma de Puebla, Apdo. Postal 542, Puebla, Pue.-72000, Mexico*

[*]Email: olga.felix@correo.buap.mx

ARTICLE INFORMATION

Received: October 10, 2019
Accepted: January 30, 2020
Published online: February 28, 2020

Keywords:
Dark matter, Dipolar dark matter, WIMP, Relic density

DOI: 10.15415/jnp.2020.72019

ABSTRACT

We are interested in the purpose of a dipolar fermionic particle as a viable candidate of Dark Matter (DDM). Then, we study the annihilation of dark matter into photons, considering it as a neutral particle with non-vanishing magnetic (*M*) and electric (*D*) dipolar moments. The total annihilation cross-section $\sigma\left(\chi\bar{\chi}\to\gamma\gamma\right)$ is computed by starting from a general form of coupling $\chi\bar{\chi}\gamma$ in a framework beyond to Standard Model (BSM). We found that candidates with $O(m_\chi)\sim 10^2\,\mathrm{GeV}, D\approx 10^{-16}\,\mathrm{e\,cm}$ are required in order to satisfy the current cosmic relic density.

1. Introduction

The enigma of dark matter is perhaps the most interesting problems in modern astrophysics. Moreover, 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 was first figured out by Zwicky (1933) [1] and later V. Rubin [2]. 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, a lot 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 [3]. The only no weakly interacting particle within the SM is the neutrino, which has been shown to be inadequate to explain the features of the major fraction of dark matter. One of the most studied and well understood candidates emerging beyond the Standard Model, are the weak interacting massive particles commonly called as WIMPs, examples of these are the neutralino [4] and the axion [5] but unfortunately, they have not been detected yet. In absence of the discovery of such particles it is worth exploring other possibilities. An alternative line of research is to take an independent model approach of the model and trying to phenomenologically explore the possible properties of a dark matter particle.

On this line, the restrictions for strongly interacting dark matter were considered in [6]. In addition, the self-interaction of dark matter has been considered in [7, 8]. Some people have studied whether dark matter could be charged [9] or have a milli-charge [10, 11]. Likewise, it has been considered among these phenomenological possibilities, that dark matter has an electric or/and magnetic dipole moment [12-15]. In this work we consider, precisely, the latter possibility that dark matter possesses an electrical and/or magnetic dipole moment and hence that it is able of emitting gamma radiation as a result of its annihilation.

The goal of this paper is to analyse the detection as well as the DDM mass order, in base of the current prior of relic density provided by Planck collaboration [16].

2. Dipolar Dark Matter

Dark matter (DM) seems to be made up of non-relativistic particles that interact only gravitationally and perhaps

ISSN No.: 2321-8649(Print) ISSN No.: 2321-9289(Online); Registration No.: CHAENG/2013/51628

by weak interaction. In general, the coupling of DM to photons is assumed to be negligible. So that electromagnetic interactions have not been seriously considered. This one changed following the observations of 21 cm. The possibility of a millicharged DM has been reconsidered again to conform a bound state along with an electron [17]. However, although the DM particles are assumed as chargeless, they could be coupled to photons at one loop to the electric and magnetic dipole moment [13]. For this reason, we assume that DDM is a class of weakly interacting massive particles (WIMPs), which are endowed with dipole moments. The particles proposed as DDM are Dirac fermions, that is, spin particles ½, because for a permanent electric and/or magnetic dipole moment the particle must have a spin other than zero [15].

DDM phenomenology 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 enough, a neutral particle with an electric dipole moment (*D*) can forma linked state to an electron, as observed by Fermi and Teller [18], but only if the dipole moment is greater than $0.639\,\mathrm{e\,a}_0 = 3.4\times10^{-9}\,\mathrm{e\,cm}$ (assuming that $m_\chi \gg m_e$), where a_0 is the radius of Bohr. For small dipole values, electron sees both poles of the dipole and lies 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 $m_{dipole} > m_p$ and $D \gg 1.8\times10^{-12}\,\mathrm{e\,cm}$ [19]. However, such D values can happen for punctual DM. Moreover, the dipole-dipole interaction weakness prevents the formation of stable dark matter atoms [20].

On the other hand, if the particles of dipolar dark matter (DDM) are the dark matter of our Universe, they had to undergo a thermal history similar to that of any WIMP. That is existed in the early Universe when the temperature $T > m_\chi$, and their interactions froze when T fell below m_x, resulting in some residual cosmological abundance [21]. Thus, for a weak-scale thermal particle, the relic abundance in the case of wave annihilation is approximately established by

$$\Omega h^2 \approx \frac{3\times10^{-26}\,\mathrm{cm^3 s^{-1}}}{\langle \sigma_{ann} v_{rel} \rangle} \qquad (1)$$

where $\sigma_{ann} \equiv \langle \sigma_{ann} v_{rel} \rangle$ is the thermally average of annihilation cross-section times v_{rel} and v_{rel} denotes the relative velocity. As one can see in equation (1), such mass density of residual DDM particles is fixed by the annihilation cross-section. Note that smaller annihilation sections correspond to higher relic 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 consists in measuring a nuclear recoil produced in elastic collision with the nuclei of the detector used as target in the laboratory [12, 13, 16]. Examples of these experiments are CRESST, XENON, CDMS, DAMA and COGENT. Instead, indirect methods allow us to detect a WIMP through the observation of the products emitted in their annihilation across the galactic halo or inside 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.

According with the Planck Collaboration, the dark matter density takes the value $\Omega_{cdm} h^2 = 0.120 \pm 0.001$ [16]. Next sections we compute the relic density Ωh^2 for the annihilation process $\chi\bar{\chi} \to \gamma\gamma$.

3. Annihilation Cross-section of the Process:

We consider the annihilation process with the same DDM particle as the propagator. Cross-section is computed in the frame of center of mass (CM), see [22]. For this process one have two contributions at low order. We compute $\langle \sigma_{ann} v_{rel} \rangle$ overall the phase-space parameters. Working within the non-relativistic limit and using the method given in [22], one obtain the following expression:

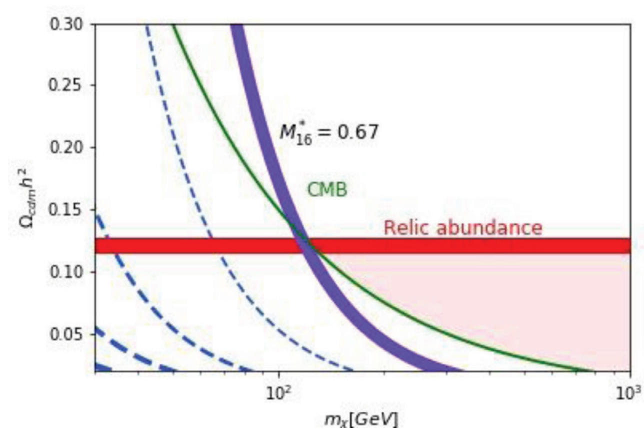

Figure 1: DM relative energy density. Red stripe shows current DM relic density (Planck measurement). Green line corresponds to CMB data. Theoretical predictions (purple lines) assuming that f=1 [22].

$$\langle \sigma_{ann} v_{rel} \rangle = \tilde{c}_0 m_{GeV}^2 \Big[6\left(M_{16}^4 + 6M_{16}^2 D_{16}^2 + D_{16}^4\right) + \left(3M_{16}^4 + 2M_{16}^2 D_{16}^2 + 3D_{16}^4\right)\Big] < v_{rel} > \mathrm{cm^3 s^{-1}}, \qquad (2)$$

where $\tilde{c}_0 = 1.71423\times10^{-30}$, $m_{GeV} = {m_\chi}/{\text{GeV}}$, and $D, M \to D_{16} = {D}/{10^{-16}}, M_{16} = {M}/{10^{-16}}$. On the other hand, using the relation $\langle\sigma_{ann}v_{rel}\rangle \approx a_{rel} + b\langle v^2\rangle$ given in [23], can be written down as

$$\langle\sigma_{ann}v_{rel}\rangle = \tilde{c}_0 m_{GeV}^2 M_{16} H(f,x). \tag{3}$$

Dimensionless function $H(f, x)$ is expressed as

$$H(f,x) = 6\left(1+6f^2+f^4\right) + \frac{6}{x}\left(3+2f^2+3f^4\right), \tag{4}$$

where $f = \frac{D_{16}}{M_{16}}$ (f_e a not perfect absorption efficiency is assumed) and $x = \frac{m_\chi}{T}$, where x is the decoupling energy and T the asocated temperature [22].

4. Special case with f=1

The particular case when $D_{16} = M_{16}$ (or $f_e = 1$), thermally average of annihilation cross-section by the relative speed is given as

$$\langle\sigma_{ann}v_{rel}\rangle = 48\tilde{c}_0 m_{GeV}^2 D_{16}^2\left[1+\frac{1}{x}\right]\text{cm}^3\text{s}^{-1}, \tag{5}$$

where $D_{16} \le 3$ [13], $x \approx 22$ in case of the purposed DM particle is a WIMP. Usually, this quantity set as $<\sigma_{ann}v_{rel}>_{D_{16}=3} \cong 3\times10^{-26}\,\text{cm}^3\text{s}^{-1}$ [14, 22].

From the equations (1) and (5), we compute the relic density $\Omega_{cdm}h^2$ as function of the DM mass m_χ. Figure 1 shows numerical results $\Omega_{cdm}h^2$ & m_χ. Experimental relic abundance value $\Omega_{cdm}h^2 = 0.120\pm0.001$ is plot as a red stripe, Green line plots the CMB results whereas dashed lines (purple) correspond to theoretical results with some values of M_{16}. We can see than $m_\chi \sim O(10^2)$ meets with the constraits.

Conclusions

In this work we studied the DM annihilation, considering it as a neutral particle with non-vanishing magnetic and/or electric moments, $M \sim D$ laying below the upper bound of $3\times10^{-16}\,\text{e cm}$. We restricted the parameters space involved in the thermally averaged annihilation cross-section in order that the DDM model to be consistent with cosmological data. By imposing CMB bounds and fixing M_{16}, f values, there exists an upper bound for DDM particle mass, with $m_\chi \sim O(10^2)\,\text{GeV}$, and if $f \sim 1$ then the allowed range of is consistent with the CMB data-set. With CMB constraint implications and the relic abundance measurement as well, we found the upper cutoff $M_{16}^* = 0.67$ for the magnetic dipolar moment.

Acknowledgments

This work has been partially supported by CONACYT-SNI (México). O.F.B. and F.G.C. thank the financial support received through VIEP-BUAP 2019 projects.

References

[1] F. Zwicky, Helv. Phys. Acta **6**, 110–127 (1933).

[2] V. C. Rubin, J. Burley, A. Kiasatpoor, B. Klock, G. Pease, E. Rutscheidt and C. Smith, Phys **67**, 491 (1962). https://doi.org/10.1086/108758

[3] N. Fornengo, Adv. Space Res. **41**, 2010 (2008). https://doi.org/10.1016/j.asr.2007.02.067

[4] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rept. **267**, 195 (1996). https://doi.org/10.1016/0370-1573(95)00058-5

[5] M. S. Turner, Phys. Rept. **197**, 67 (1990). https://doi.org/10.1016/0370-1573(90)90172-X

[6] G. D. Starkman, A. Gould, R. Esmailzadeh, and S. Dimopoulos, Phys. Rev. D **41**, 3594 (1990). https://doi.org/10.1103/PhysRevD.41.3594

[7] E. D. Carlson, M. E. Machacek, and L. J. Hall, The Astrophysical Journal **398**, 43 (1992). https://doi.org/10.1086/171833

[8] D. N. Spergel, and P. J. Steinhardt, Phys. Rev. Lett. **84**, 3760 (2000). https://doi.org/10.1103/PhysRevLett.84.3760

[9] A. Gould, B. T. Draine, R.W. Romani, and S. Nussinov, Phys. Lett. B **238**, 337 (1990). https://doi.org/10.1016/0370-2693(90)91745-W

[10] S. Davidson, S. Hannestad and G. Raffelt, JHEP **05**, 003 (2000). https://doi.org/10.1088/1126-6708/2000/05/003

[11] S. L. Dubovsky, D. S. Gorbunov, and G. I. Rubtsov, JETP Lett. **79**, 1 (2004). https://doi.org/10.1134/1.1675909

[12] J. H. Ho, Phys. Lett. B **693**, 255 (2010). https://doi.org/10.1016/j.physletb.2010.08.035

[13] E. Masso, S. Mohanty, Subhendra and S. Rao, Phys. Rev. D **80**, 036009 (2009). https://doi.org/10.1103/PhysRevD.80.036009

[14] S. Profumo, and K. Sigurdson, Phys. Rev. D **75**, 023521 (2007). https://doi.org/10.1103/PhysRevD.75.023521

[15] R. R. Caldwell, and M. Kamionkowski, Phys. Rev. D **70**, 083501 (2004). https://doi.org/10.1103/PhysRevD.70.083501

[16] N. Aghanim et al. (Planck Collaboration), arXiv:1807.06209 [astro-ph.CO] (2018).

[17] J. H. Heo, Phys. Lett. B **702**, 205 (2011). https://doi.org/10.1016/j.physletb.2011.06.088

[18] E. Fermi, and E. Teller, Phys. Rev. **72**, 399 (1947). https://doi.org/10.1103/PhysRev.72.399

[19] K. Sigurdson, M. Doran, A. Kurylov, R. R. Caldwell, and M. Kamionkowski, Phys. Rev. D **70**, 083501 (2004). https://doi.org/10.1103/PhysRevD.70.083501

[20] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, Phys. Rev. D **79**, 015014 (2009). https://doi.org/10.1103/PhysRevD.79.015014

[21] L.Bergström, Reports on Progress in Physics **63**, 793 (2000). https://doi.org/10.1088/0034-4885/63/5/2r3

[22] C. Arellano-Celiz, A. Avilez-López, J. E. Barradas-Guevara, and O. Félix-Beltrán, arXiv:1908.05695 [hep-ph].

[23] M. Cannoni, Eur. Phys. J. C **76**, 137 (2016), arXiv:1506.07475 [hep-ph].

Journal of Nuclear Physics, Material Sciences, Radiation and Applications

Chitkara University, Saraswati Kendra, SCO 160-161, Sector 9-C,
Chandigarh, 160009, India

Volume 7, Issue 2 **February 2020** **ISSN 2321-8649**