Photon Signals from Axion-Cosmic Ray Scattering

Alejandro Rodriguez[1], Ian Shoemaker[2], Natalia Tapia[2]

1. *The Department of Physics, The Pennsylvania State University, University Park, Pennsylvania*
2. *Center for Neutrino Physics, Virginia Polytechnical Institute and State University, Blacksburg, Virginia 24061*

Dark Matter is the most abundant form of matter in our Universe, yet the identity of the particles that comprise this form of matter remains unknown. Through our research, we propose that the theoretical Axion particle may be the elusive, fundamental particle that makes up Dark Matter. We will examine the effects of a cosmic ray electron collision with an Axion particle. This collision event can produce a specific signature that will be observed through a Gamma Ray telescope. For this project we will use data of the Local Interstellar Spectrum (LIS) and our own calculations to test whether the Axion could be a source of these signatures. With this information, this can become a new viable method of Dark Matter detection. This study could lead to answers not only regarding the ambiguities of Dark Matter, but regarding the Strong CP problem as well.

I. Introduction

The Axion is a theoretical particle that was first postulated as a solution to the Strong CP Problem [1,2]. If the Axion exists it can also be the elusive dark matter that has been the subject of many experiments. Dark Matter is nonluminous, massive enough to have gravitational effects on visible matter. We know it exists due to its gravitational affects and explains why we see certain gravitational effects in the Universe that could not normally be explained. With all this information, or rather lack thereof, the Axion is a great candidate to be the Dark Matter we are looking for.

To detect the Axion we have to know how it interacts with normal particles. The Axion can interact with photons and Electrons. When these interactions occur

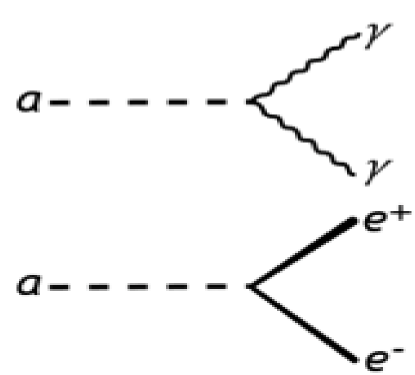

Figure 1: Fundamental Feynman diagram vertices for axion interactions.

we know that they can produce novel gamma/x-ray signals. We can expect to be able to detect these interactions from naturally occurring axions interacting with cosmic rays in our galaxy.

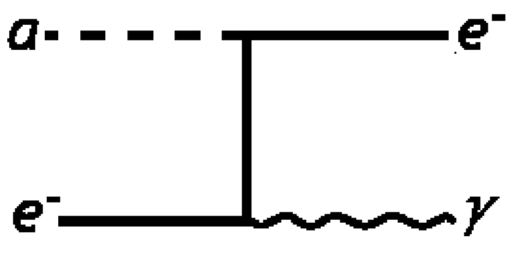

Figure 2: Cosmic ray electrons collide with axions to produce gamma-rays.

We will examine these interactions and estimate what type of signal we would expect to see from this interaction. Then compare to the Isotropic Gamma-Ray Background (IGRB)[4]:

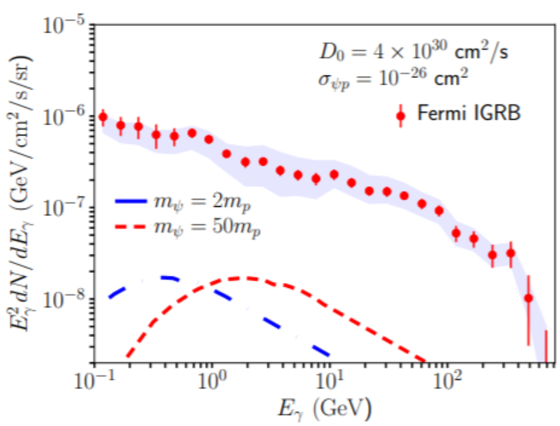

Figure 3: The Fermi IGRB from cosmic-ray scattering with Dark Matter in the halo of the milky way.

using data of the LIS [3] to further see if this is a viable method of detecting the Axion.

II. Calculating Cross-Sections.

The first step in the process is to Calculate the type of Cross-Section we would expect to see in these interactions. There are two cases we look at, Axion-Electron coupling (g_{ae}) and Axion-Photon Coupling ($g_{a\gamma\gamma}$) with the axion being in the rest frame. We know the Mandelstam Variables for these processes to be:

$$s = (p+k)^2 \qquad t = (k-q)^2 \qquad u = (k-p')^2$$

$$p^\mu = (E_e, \vec{p}) \qquad k^\mu = (m_a, 0) \qquad p'^\mu = (E'_e, \vec{p}') \qquad q^\mu = (E_\gamma, \vec{p}_\gamma)$$

With these Mandelstam Variables we are ready to calculate and plot the cross-section over a range of photon energies using this formula:

$$\frac{d\sigma}{dE_\gamma} = \frac{|\mathcal{M}|^2}{32\pi m_a |\vec{p}|^2}$$

The case Axion-Electron coupling we have the matrix element of:

$$\frac{1}{2}|\mathcal{M}_a + \mathcal{M}_b|^2 = g_{ea}^2 e^2 \Bigg[-\frac{2\,(m^4 - m^2(2m_a^2 + s + u) + su)}{(u-m^2)^2} - \frac{2\,(m^4 - m^2(2m_a^2 + s + u) + su)}{(s-m^2)^2} + \frac{4\,(m^4 + 3m_a^2 m^2 - m^2(2s+t) + (s-m_a^2)(s+t))}{(s-m^2)(u-m^2)} \Bigg]$$

With this information we can produce the Cross-Section:

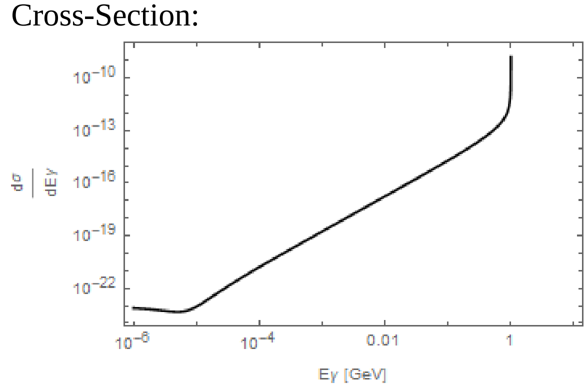

Figure 4: Cross section example via the axion-electron coupling. Here the axion mass = 10^{-3} eV

For the case of Axion-Photon coupling we have the matrix element of:

$$\frac{1}{2}|\mathcal{M}|^2 = \frac{e^2 g_{a\gamma\gamma}^2}{t^2}\left(m_a^2 t(m^2+s) - m_a^4 m^2 - t((s-m^2)^2 + st)\right)$$

and the cross-section:

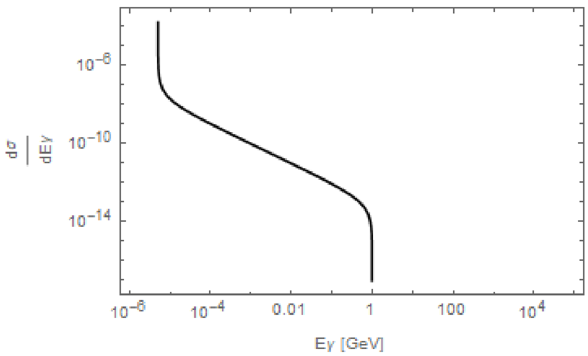

Figure 5: Cross section example via the axion-photon coupling. Here the axion mass is = 10^{-3} eV

It is important to note, we do not know the mass of the Axion so it is important to see how the cross-Section changes due to Axion mass for Various different masses.

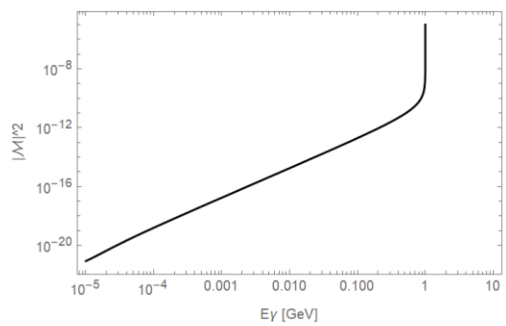

Figure 6: Cross section example via the axion-photon coupling. Here the axion mass is = 10^{-5} eV

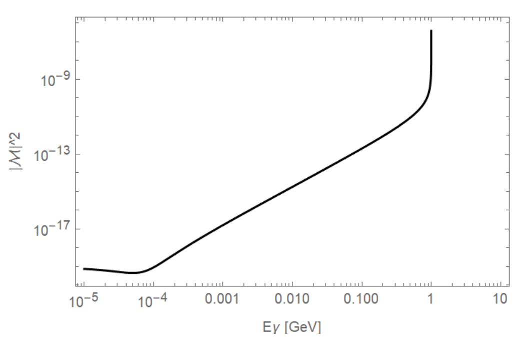

Figure 7: Cross section example via the axion-photon coupling. Here the axion mass is = 10^{-4} eV

Regardless of the mass of the Axion these plots retain the important similar features that are crucial to an accurate cross-section. However, we will be using a mass of 10^{-3} eV for the Axion.

With the knowledge now of what the Cross-sections of these interactions will look like, we also know the range of energies we would expect to see these Interactions.

III. Calculating the Flux

Now that we have the Cross-Sections for these interactions, we have the information needed to calculate the flux we would expect to see for a given photon energy. The equation for the Axion flux is:

$$\frac{d\Phi_\gamma}{dE_\gamma} = \int_V dV \int_{E_e^{\min}} dE_e \frac{d^2\Gamma_{e\to\gamma}}{dE_e E_\gamma}$$

$$= D_{\rm eff}\frac{\rho_{\rm DM}}{m_a}\int_{E_e^{\min}} dE_e \frac{d\sigma_{e\gamma}}{dE_\gamma}\frac{d\Phi_e^{\rm LIS}}{dE_e}$$

where E_e^{min} is the minimum incoming electron energy to produce a given photon energy. We get the electron flux from data gathered from HELMODs in the works paper [3]. We will multiply the flux of electrons by the cross-sections we calculated previously. We integrate over all possible Electron energies we would expect to see in these interactions. We multiply this by the Distance we are calculating the flux for: 1 Kilaparsec. We as well multiply by the density of Dark matter we expect to see in space divided by the mass we are taking for the Axion.

The current results we have for the flux is the following:

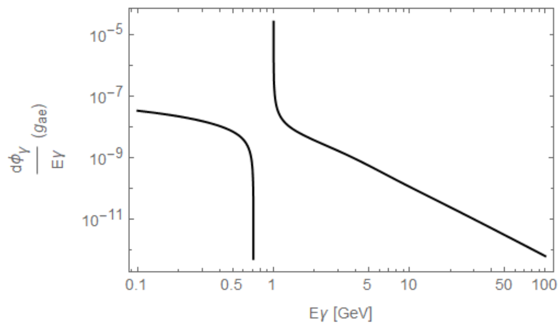

Figure 8: Calculated flux for Axion-Electron Coupling (g_{ae})

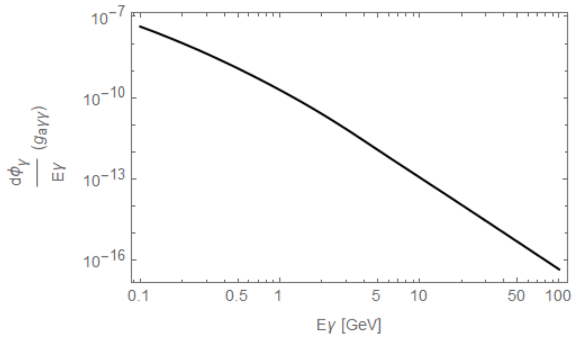

Figure 8: Calculated flux for Axion-Electron Coupling ($g_{a\gamma\gamma}$)

These results, however, need to be further investigated to be insure its validity. Once this is done the next step is to compare these results with the IGRB.

IV. Conclusions

We have begun investigating the impact of cosmic-ray electron scattering on axions as a source of photons. Depending on the unknown strength of the axion interaction, this effect may lead to a detection of axions. Conversely, if data shows the absence of any anomalous photons, new constraints on axion-electron and axion-photon interactions can be placed for further investigation into the detection of Axions and Dark Matter.

References

[1] Peccei, Roberto D.; Quinn, Helen R. "CP Conservation in the Presence of Pseudoparticles". Physical Review Letters. 38 (25): 1440–1443.

[2] Peccei, Roberto D.; Quinn, Helen R. "Constraints imposed by CP conservation in the presence of pseudoparticles". Physical Review D. 16 (6): 1791–1797.

[3] Boschini, M.J., et. al., "HelMod in the works: from direct observations to the local interstellar spectrum of cosmic-ray electrons." Astrophys.J. 854 (2018) no.2, 94.

[4] Hooper, Dan; D. McDermott, Samuel. "Robust Constraints and Novel Gamma-Ray Signatures of Dark Matter That Interacts Strongly With Nucleons". Physics Review D. 97, 115006 (2018)