The Impacts of Cosmic Ray Interactions on Dark Matter Detection

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Dark matter detection is currently being explored using two different methods: direct and indirect detection. A third method, reverse direct detection, is being researched and relies on cosmic rays interacting with dark matter. This collision causes the previously slow dark matter to begin traveling relativistically. Standard direct detection methods can only detect heavier dark matter particles of masses of a GeV or more, travelling at approximately 200 kilometers per second, but with cosmic ray interaction, dark matter particles of smaller masses and higher velocities can be observed through these direct detection methods. This interaction between dark matter and cosmic rays produces an energy dependent cross section, which is used to determine the interaction lengths and energy loss lengths. By exploring the interaction between cosmic rays and dark matter, more can be learned about these interactions such as their cross sections, interaction lengths, and energy loss lengths for a variety of cosmic ray energies, including extragalactic cosmic rays of energies greater than 10^{15} eV. This project will examine the extent of the energy dependence on these characteristics of the interaction, and the impacts of this dependence. Models of these interactions can be plotted and compared to known standard model interactions, giving new information about these collisions at a variety of energies.

I. Introduction

Dark matter's existence is established by gravitational affects, where objects in space are held together when there is not enough normal matter present to do so. The dark matter is massive, has no or very little charge, and therefore, does not interact, and is travelling at non-relativistic speeds on average, so it is classified as cold. It is believed that it accounts for eighty-five percent of the mass in the universe, and twenty-four percent of the energy density.

There are only a few methods used to study dark matter. Dark matter is detected directly by placing a nucleus in a detection chamber and waiting for it to interact with a heavy dark matter particle. The chamber is placed deep underground to reduce background. This interaction causes the nucleus to recoil, emitting a few keV's of some form of energy, such as photons. The mass of the dark matter particle is known, but the velocity is assumed to be approximately 200 km/s [1]. This method is only capable of detecting dark matter particles of a GeV or more, as a lighter particle does not provide enough nuclear recoil energy to be detected [1]. A second method, indirect detection, where particles and anti-particles that make up dark matter interact, annihilating each other and producing a pair of standard model particles and anti-particles or gamma rays, which emit signals that can be detected on earth.

A third method is reverse direct detection, which relies on cosmic ray dark matter interaction in space. Since cosmic rays are travelling at such high speeds, the dark matter in the interaction is essentially at rest. Following the interaction, the dark matter begins travelling at relativistic speeds. These relativistic dark matter particles can then interact within the detection chamber used in direct detection. This method would allow dark matter particles with smaller masses to be detected [2].

II. Standard Model Interactions

The first step is to create a graph of the interaction length, energy loss length, and the pair production propagation losses using the standard model. This graph, figure 1, will allow for comparisons to be easily made when looking at dark matter-cosmic ray interactions. The calculations to be completed should be done in the center of mass frame [3], to make the interpretation of the resulting curves simpler. This transformation can be done utilizing the total center of mass frame energy given by the expression:

$$s = {m_p}^2 + 2E_pE_\gamma(1-\beta\cos\theta)$$
$$= {m_p}^2 + 2m_pE_\gamma'$$

where β is approximately one in our case, and E_γ' is the photon energy in the nucleon rest frame [4].

The interaction length, or mean free path to interaction, gives the distance travelled between interactions. To find the interaction length as a function of the proton energy for photo-pion production, the following equation can be used:

$$L_{int}(E_p) = \frac{1}{\int \sigma\left(E_p, E_\gamma\right) n\left(E_\gamma\right) dE_\gamma}$$

where the function for cross section can be found from data, and the number density is a Bose-Einstein distribution such as this:

$$n\left(E_\gamma\right) = \frac{8\pi}{c^3h^3}\frac{(E_\gamma q)^2 * E_\gamma q}{e^{\frac{E_\gamma q}{Tq}} - 1}$$

where T is the Cosmic Microwave Background (CMB) temperature, approximately 2.7 Kelvin. When this integral is computed over a range of proton energies, in our case, we used 10^{19} to 10^{22} eV, the resulting curve, the blue line in figure 1, shows the distance between collisions for extragalactic cosmic rays.

The next curve to calculate is the energy loss for the same interaction. Energy loss length gives the distance a particle can travel at a specific energy before losing this energy.

$$x_{loss}\left(E_p\right) = \frac{1}{\int \sigma\left(E_p, E_\gamma\right) n\left(E_\gamma\right) K(E_p, E_\gamma) dE_\gamma}$$

It is a very similar equation to that of the interaction length, the difference being in the inclusion of the inelasticity, K, which is the energy lost per interaction. This value can be found by:

$$K = \frac{\Delta E_p}{E_p} = \frac{1}{2}\left(\frac{{m_p}^2 - {m_\pi}^2}{s}\right)$$

where s is the invariant mass of the system. When this integral is computed with the same range of proton energies as for interaction length, the orange curve in figure 1 is the result.

Finally, the energy loss length for pair production should be calculated. This interaction is known as the Bethe-Heitler process. It uses the following cross section:

$$\sigma_{BH}(E_p, E_\gamma) = \alpha\, r_e^{\,2}\left[\frac{28}{9}\ln\left(\frac{2\,E_p\,E_\gamma}{m_p\,m_e}\right) - \frac{106}{9}\right]$$

In order to transform this equation from the CMB frame to the center of mass frame, the following Lorenz boost is used for this transformation:

$$\gamma(E_p, E_\gamma) = \frac{E_p + E_\gamma}{\sqrt{m_p^{\,2} + 2\,E_p\,E_\gamma}}$$

With these equations, the energy loss length can be calculated as a proton cooling time, which is equivalent to the length in natural units, given by the following equation [5,6].

$$x_{loss,pair\ production}(E_p) = \frac{E_p}{2\,m_e \int \sigma_{BH}(E_p, E_\gamma)\, n(E_\gamma)\, \gamma(E_p, E_\gamma)\, dE_\gamma}$$

This integral was calculated from 10^{17} to 10^{22} eV, and is shown in figure 1 as the green curve.

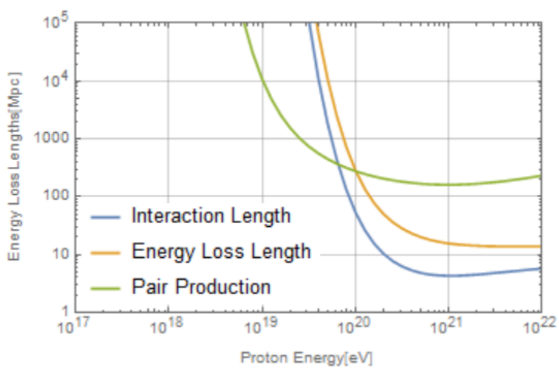

Figure1: the resulting curves for the standard model interactions between a CMB proton and a photon. The proton energy (x-axis) is in eVs, and the length values (y-axis) are in Mpc.

III. Cosmic Ray-Dark Matter Interactions

When looking at the cosmic ray-dark matter interactions, the cross section is dependent of both the energy of the dark matter and of the cosmic ray. In this case, we assumed a scalar mediator, and the differential cross section equation used was as follows:

$$\frac{d\sigma}{dE_\chi}(E_p, E_\chi) = g_{s\chi}^{\,2} g_{sCR}^{\,2} *$$

$$\left[\frac{4m_\chi m_p^{\,2} + 2E_\chi\left(m_\chi^{\,2} + m_p^{\,2}\right) + m_\chi E_\chi^{\,2}}{8\pi\left(2m_\chi E_\chi + m_\phi^{\,2}\right)^2\left(E_p^{\,2} + 2m_p E_p\right)}\right]$$

where $g_{s\chi}$ and g_{sCR} are the coupling constants. These values are determined experimentally, but since there are no experimental results for dark matter-cosmic ray interaction, there are no established values. Since we wanted reasonable values for these constants, we chose to set both equal to one.

While the mass of the proton is an established value, the mass of the dark matter particle and the mediator are unknown, so a range of values were tested. For the dark matter mass, keV to MeV values were used. For masses of dark matter particles that are 1 keV or smaller, it would have to be bosonic, not fermionic, since this mass would make the number density too large for fermions to be packed into the space, due to the Pauli Exclusion Principle. For the mediator mass, keV to GeV values were used.

When computing the cross section, the integral of the differential is evaluated from zero to E_χ^{max}, which is a function of the proton energy.

$$E_\chi^{max}(E_p) = \frac{{E_p}^2 + 2m_pE_p}{E_p + \frac{(m_p + m_\chi)^2}{2m_\chi}}$$

The resulting curve is shown in figure 2, below.

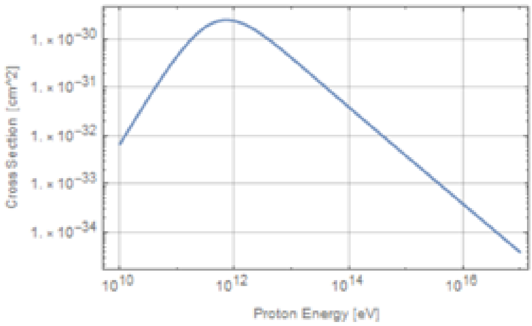

Figure 2: The cross section of the DM-CR interaction at a range of proton energies. This graph uses m_χ=1 MeV, m_ϕ=1 GeV. The cross section is in cm^2.

Next, the interaction length should be calculated using the following equation:

$$L_{int}(E_p) = \frac{1}{\int_0^{E_\chi^{Max}} \frac{d\sigma}{dE_\chi}(E_p, E_\chi)\, n_\chi\, dE_\chi}$$

For this calculation, the number density of dark matter particles is needed. Since dark matter makes up approximately 24 percent of the energy density in the universe, so the number density can be found using the following equation.

$$n_\chi = 24\% * \frac{\rho_{crit}}{m_\chi}$$

where ρ_{crit} is the critical density of the universe, with a value of 4845.07 eV/cm^3.

With these equations, the interaction length curve can be calculated for various values of dark matter masses and mediator masses. One example is shown in figure 3.

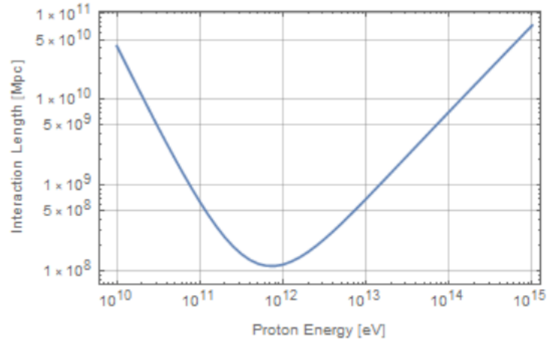

Figure 3: The interaction length of DM-CR interactions using m_χ=1 MeV, m_ϕ=1 GeV. The length is in Mpc.

Next, the energy loss length of this interaction should be found. In order to do this, we would need the inelasticity of the interaction. Unfortunately, there was not enough time for me to complete this task this summer.

IV. Conclusions

From these graphs, we can see a large difference in length scales between the standard model and the dark matter-cosmic ray interactions. This large contrast can be seen best when all of the curves are placed on the same graph, which can be seen in figure 4.

Although the dark matter-cosmic ray interaction length would vary slightly with different dark matter and mediator masses, overall, the length for the extragalactic cosmic rays would be much longer than the results from the standard model, so they would take over at those energies.

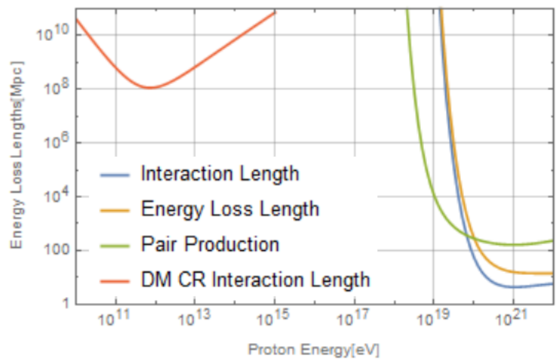

Figure 4: The standard model curves and the DM-CR interaction length on the same graph (m_χ=1 MeV, m_ϕ=1 GeV). The lengths are in Mpc.

This result leads us to believe that it would be best to constrain our future research to galactic cosmic rays. Once we know more about the cross section and the interaction length, a numerical code, such as GALPROP could be used to explore the effects.

Acknowledgments

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