Heavenly Rays Illuminate Our Darkest Of Matter: Understanding Particle Physics of Dark Matter Through Cosmic Ray Dark Matter Interactions

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Despite being the most abundant form of matter in the cosmos, Dark Matter remains one of the galaxy's most perplexing enigmas. Both Dark Matter (DM) and Neutrinos present a tremendous gap in the standard model and thus our understanding of physics, therefore it may be possible that they may originate from the same source. As we have very little definitive proof about the physical properties of DM beyond gravitational impact, we should not necessarily assume that it possesses the same behavioral characteristics of normal matter. Particularly, the ratio of the rate at which DM protons and neutrons absorb energy deposited by charged particles such as Cosmic Rays may be different than that of normal matter and more similar to that of Neutrinos. Through theoretical calculations based on data gathered by the Xenon 1 Ton experiment and Bringmann and Pospelov's research [1], we can evaluate at what ratios of proton-neutron energy deposition from Cosmic Rays our current model for understanding DM breaks down. This factor may change the physics of how Dark Matter scatters within a physical detector and thus reshape our understanding of DM direct detection. Comprehending Dark Matter is an imperative step in understanding the physics of gravity and galaxies; hence devising a means of efficiently observing DM particles through direct detection is a crucial step to the progression of astrophysics as a whole.

I. INTRODUCTION

Astrophysicists can determine by observing the gravitational behavior of galaxies that there must be massive amounts of matter throughout the universe that we as of yet are unable to detect. This undetectable matter, known as Dark Matter, creates a major gap in the completion of the Standard Model. In order to detect Dark Matter, we need some range of properties that we know to look for. This is particularly difficult since we do not yet know what dark matter is. There is a theory however that since DM and neutrinos both present a gap in the Standard Model, then perhaps Dark Matter may interact with normal matter more similarly to neutrinos.

Neutrinos carry no charge and are the smallest of all subatomic particles. This allows them to travel extremely long distances without their path being affected by matter. If DM interacts with normal matter in a fashion more similar to neutrinos, then some of the scientific methods employed to directly detect neutrinos may be applicable to Dark Matter direct detection. This principle was explored in the Xenon 1T experiment. Xenon 1T attempted to directly detect Weakly Interacting Massive Particles (WIMPs) which are theorized to be the source of Dark Matter. While Xenon 1T did not directly detect any WIMPs, it did significantly narrow down the range of properties that DM must possess. We now know that for significantly small masses of

DM (less than 1 GeV) that the elastic scattering cross section must be between 10^{-31} and 10^{-28} cm^2. This constraint should allow physicists to detect Dark Matter at far smaller masses than was previously thought possible.

In order to directly detect Dark Matter however, we need to constrain it's physical properties even further. One way to do that is by measuring DM's flux as a function of it's mass after interacting with Cosmic Rays.

II. CALCULATING DARK MATTER FLUX

When Cosmic Ray (CR) particles such as protons and helium pass through Dark Matter they deposit energy onto the DM particles in a process known as "up-scattering". Despite not knowing many of the physical properties of DM, we can calculate the new flux as a result of this energy deposition using our more definitive understanding of CR properties. From this we can produce an equation to calculate the flux of dark matter particles as a function of very low unknown DM masses. [1]

$$\frac{d\Phi_x}{dT_x} = D_{eff}\frac{\rho_x}{m_x}\sum \sigma_x G^2 \int_{T_i^{min}}^{\infty} \frac{d\Phi_i/dT_i}{T_x^{max}} dT_i \quad (1)$$

$d\Phi_x/dT_x$ represents the resulting flux of DM, D_{eff} represents the effective distance which we assume to be equal to $1kpc$, m_x represents the theoretical DM mass, σ_x represents the DM cross sectional area which we assume to be equal to $10^{-30}cm^2$, G represents the form factor which is a function of DM mass and DM energy, T_x^{max} is the minimum possible amount of energy that CRs can deposit onto DM, T_x^{max} is the maximum possible energy of the DM particles after up-scattering, and $d\Phi_i/dT_i$ represents the CR flux as a function of CR energy.

Our results from this calculation aligned very closely with Bringmann and Pospelov's research [1] and reinforced the conclusions drawn in their publications.

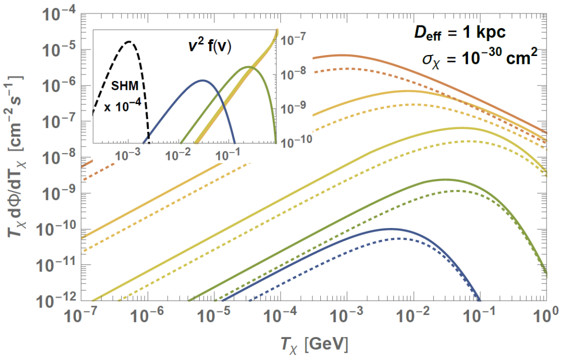

FIG. 1. Graph of possible fluxes of Dark matter as calculated from Bringmann and Pospelov's research [1] where exclusively proton Cosmic Ray energy deposition is represented by dashed lines, and the sum of proton and helium CR interactions are depicted in solid lines.

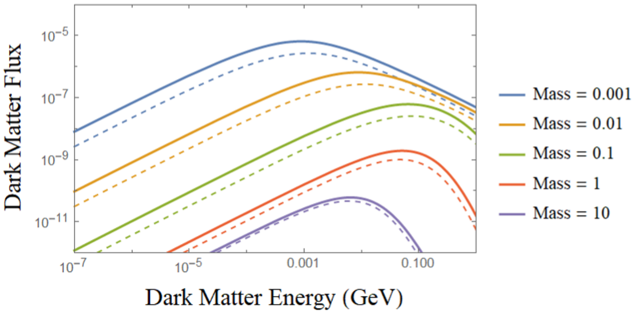

FIG. 2. Graph of possible fluxes of Dark Matter calculated from this experiment. The results are very similar to that of Bringmann and Pospelov's for several magnitudes of Dark Matter mass.

From this conclusion, we can then build upon Bringmann and Pospelov's research [1] and incorporate a wider variety of CR particles including carbon. By incorporating carbon into this calculation we utilize a more realistic picture of the impact of Cosmic Ray up-scattering and thus yield more accurate results particularly at higher energy levels.

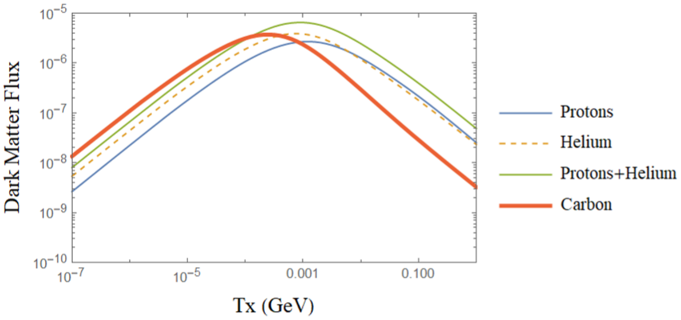

FIG. 3. Graph of Dark Matter flux for DM mass of 10^{-3} displaying an additional curve for the impact of carbon Cosmic Rays. The blue curve aligns with the dashed curve in the previous graphs and the green line aligns with the solid lines in the previous graphs.

Cosmic Rays are composed of about 90% protons, 9% helium, and 1% other heavier elements such as carbon. Although carbon composes a very small percentage of CR interactions, incorporating carbon would still nonetheless give us a more accurate depiction of DM CR interactions. In fact when we incorporate carbon into the DM flux as shown in in Figure 3, we notice that carbon does not precisely follow the same path as the Helium and Proton curves as we would have expected. Carbon seems to have a larger constructive impact than anticipated at lower energy levels (less than 0.001 Gev) and a greater destructive impact at higher energies (greater than 0.001 GeV).

III. PROTON NEUTRON COUPLINGS

When Cosmic Rays up-scatter onto normal matter, we assume that that energy is evenly deposited from both the CR protons and neutrons onto normal matter at a ratio of 1:1. Neutrinos however interact with Cosmic Rays differently and thus DM may not receive a simple 1:1 energy deposition from these CR neutrons and protons. Normally we calculate flux as a function of mass by incorporating a factor

$$a = (Z)f_p + (A - Z)f_n \tag{2}$$

where A represents atomic mass, Z represents atomic number, and f_p and f_n represent the couplings of protons and neutrons that effect the strength of Dark Matter Cosmic Ray interactions. With a bit of algebra this equation can be re-worked to produce a function of the ratio between f_p and f_n which will be denoted as $r \equiv f_n/f_p$.

$$a/f_p = Z + (A - Z)r \tag{3}$$

This framework of differing proton and neutron couplings for DM is referred to Isospin-Violating Dark Matter, and was originally invoked in an effort to understand anomalies in direct detection experiments [2]. The interaction strength of Cosmic Ray up-scattering at certain values of this coupling ratio can affect the energy deposition onto Dark Matter, and thus may need to be taken into account when attempting to analyze down-scattering detector data.

When creating a plot of this function, we observed several interesting things.

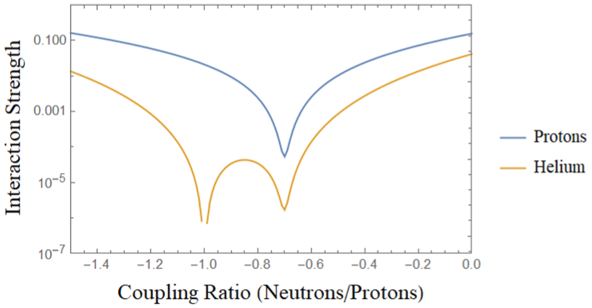

FIG. 4. Shows the strength of the Up-scattering interaction between Cosmic Rays and Dark Matter as a function of the ratio of neutron and proton couplings form Cosmic Rays. The dip at −1.0 is cut off to simplify the calculation, but would continue to 0.

When we plot the interaction strength as a function of the coupling ratio r for proton cosmic rays we see rather predictable behavior. There is a slight dip in the interaction strength at a ratio of $r = -0.7$ as a result of the down-scattering onto the xenon isotopes present in our detector. When we incorporate helium based Cosmic Rays however, we see an unexpected and very considerable dip at $r = -0.1$.

This second dip at $r = -0.1$ had not previously been theorized. This is extremely significant because it would indicate that when the coupling ratio is exactly -1.0 the interaction strength would be equal to zero, which would almost completely negate the impact of helium Cosmic Rays on the Dark Matter flux.

IV. FUTURE WORK

In the coming months research is planed to continue trying to recreate the Dark Matter cross section as a function of it's mass. Once this work has been replicated we can attempt to build on it with more variety in Cosmic Ray up-scattering such as incorporating carbon, and more flexibility in the coupling ratio to incorporate CR helium particles.

$$\begin{aligned}\sigma_x^{SIlim} = \kappa(v\rho_x)\left(\frac{m_x+m_N}{m_x+m_p}\right)^2\left(\frac{\sigma_{DM}}{m_{DM}}\right)\times \\ \times\left(\int_{T_1}^{T_2} dT_N \int_{T_x^{min}}^{\infty}\frac{d\Phi_x/dT_x}{T_r^{max}}\right)^{-1}\end{aligned}\tag{4}$$

Equation 4 is used to attempt to calculate constraints on the possible DM cross sections. Previous publications [1] used the same equation to produce the results displayed in Figure 5.

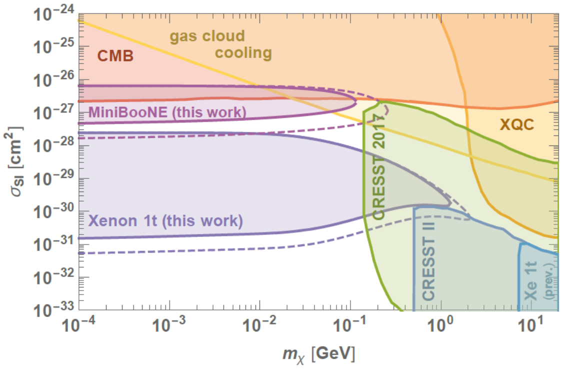

FIG. 5. Shows the cross section of Dark Matter as a function of verious theoretical Dark matter masses as calculated form various major experiments. [1]

Being able to recreate the calculations used to produce this graph would allow us to then make minor modifications to the calculation and see how this affects the end results. Specifically, we plan to test what the resulting cross section would be when variations are made in the CR proton neutron coupling ratio and how the addition of carbon based Cosmic Rays would modify the cross sectional curves.

V. CONCLUSION

Although previous analysis of Xenon 1T detector data have already been published using exclusively proton and helium based Cosmic Rays, it is still possible to get even more precise measurements from the data gathered. Incorporating carbon Cosmic Rays into Dark Matter flux calculations seems to have a larger impact than initially estimated despite carbon composing only a very small percentage of Cosmic Rays.

Additionally, considering the coupling rates of protons and neutrons to be variable rather than static would have great implications on the resulting DM flux calculations. Work is planned to continue attempting to re-create Figure 5 and to incorporate new findings of the influence of carbon Cosmic Rays and possible variations in proton neutron coupling ratios.

VI. ACKNOWLEDGEMENTS

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[1] T. Bringmann and M. Pospelov, Phys. Rev. Lett. **122**, 171801 (2019), arXiv:1810.10543 [hep-ph].

[2] J. L. Feng, J. Kumar, D. Marfatia, and D. Sanford, Phys. Lett. B **703**, 124 (2011), arXiv:1102.4331 [hep-ph].