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# Searching for Signals of Dark Matter Decay

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# Searching for Signals of Dark Matter Decay

**Abstract**

Dark matter is believed to make up approximately eighty-three percent of the matter in the universe. Despite its apparent abundance, it has not yet been directly detected, and it is not known what types of particles it is composed of. Efforts to understand what dark matter is made of and how it fits into the Standard Model of particle physics is currently an important and active area of research. In this paper we investigate a method of studying dark matter indirectly by using terrestrial neutrino telescopes to search for signs of dark matter decay. In particular, we study leptonically decaying dark matter and apply the results to models of spin-1/2, charge-asymmetric dark matter whose parameters have been fitted to describe the observed electron-positron flux seen at the PAMELA, H.E.S.S., and Fermi-LAT experiments.

**Keywords**

Dark Matter, IceCube, Neutrinos

**Cover Page Footnote**

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# Searching for Signals of Dark Matter Decay

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Dark matter is believed to make up approximately eighty-three percent of the matter in the universe. Despite its apparent abundance, it has not yet been directly detected, and it is not known what types of particles it is composed of. Efforts to understand what dark matter is made of and how it fits into the Standard Model of particle physics is currently an important and active area of research. In this paper we investigate a method of studying dark matter indirectly by using terrestrial neutrino telescopes to search for signs of dark matter decay. In particular, we study leptonically decaying dark matter and apply the results to models of spin-1/2, charge-asymmetric dark matter whose parameters have been fitted to describe the observed electron-positron flux seen at the PAMELA, H.E.S.S., and Fermi-LAT experiments.

## I. INTRODUCTION

All of the matter that makes up atoms, molecules, and all of the things around us in everyday life is now believed to comprise only about 17% of the total matter in the universe [1]. This type of matter is sometimes called ordinary matter and is ultimately composed of fundamental particles such as quarks and leptons. Protons and neutrons are made out of quarks, while electrons are a type of lepton. The rest of the matter is generically referred to as dark matter because it does not interact electromagnetically (it doesn't reflect, absorb, or emit light and is therefore dark). Dark matter is thought to be made out of a new type of fundamental particles. Although little is known about the nature of these particles, there are many experiments underway to search for them [2].

In this paper we consider models of leptonically decaying dark matter (dark matter particles that decay into leptons). These models are motivated by their potential to explain the observations of experiments such as PAMELA, H.E.S.S., and Fermi-LAT [3–5]. We begin with a basic summary of some of the evidence for dark matter. Using the methods developed in the work of Reference [6], we then proceed to calculate dark matter lifetime bounds using the next five years' worth of data at the IceCube Neutrino Observatory. We then apply our results to the work of Reference [7], which shows that leptonically decaying, spin-1/2, charge-asymmetric dark matter models can explain the PAMELA, H.E.S.S., and Fermi-LAT data.

## II. EVIDENCE FOR DARK MATTER

Despite the fact that dark matter has never been directly detected, there is an enormous wealth of evidence for its existence [8, 9]. One of the original arguments involves an apparent inconsistency in the measured speeds of distant galaxies. The galaxies in question are bound together in clusters by their mutual gravitational attraction. If the galaxies move too fast, their kinetic energy will be great enough for them to escape the gravitational pull of the other galaxies. In this case, the galactic cluster will fly apart. Astronomical observations indicate that these galaxies are in fact moving with speeds that exceed the threshold required to escape their respective clusters, but somehow they still remain bound together. The simplest possible explanation for this is that there is more matter in the clusters than we can see. The additional, unseen matter will increase the gravitational pull so that even the fast-moving galaxies remain bound.

Additional evidence comes from the observed rotational velocities of various galaxies. As a galaxy rotates, one expects that the rotational speeds of objects within the galaxy decrease as one moves farther from the galaxy's center. What is observed however, is that the rotational speed remains roughly constant as a function of distance from the galactic center. This is consistent with distributions of additional, non-luminous matter within the galaxy.

Another clue for dark matter comes from observation of gravitational lensing. Gravitational lensing is a phenomenon famously predicted by Einstein in 1936 in which light rays are bent around a large distribution of mass. It is caused by the mass's warping of space. When the light passes through the region of bent space, its path is deflected accordingly. Gravitational lensing can be seen in astronomical images such as the Hubble Ultra-Deep Field. In situations where gravitational lensing is evident, but there is no visible source of mass present, dark matter provides the only compelling explanation.

A natural question is whether dark matter is actually just ordinary matter that is either obscured or nonradiating so that we simply can't see it. This possibility was believed to be plausible for a long time, but we now know that this can't be the case. There are primarily two

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reasons why we now believe that dark matter is composed of new types of particles (though a small amount of the dark matter may still be composed of ordinary matter). The first reason is that the observed cosmic microwave background radiation is inconsistent with ordinary particles playing the role of dark matter [10]. The second reason comes from our understanding of nuclear physics. If dark matter were made of ordinary particles, the nuclear reactions taking place during the early phases of the universe would not result in the correct abundance of light atomic elements [11].

Although additional evidence for dark matter exists, it will not be discussed here. Our conclusion is that we are very likely surrounded by a sea of unseen particles. Dark matter is extremely difficult to detect directly because it only interacts with ordinary matter through gravitation and possibly weak nuclear forces. This means that dark matter particles can pass through ordinary matter almost entirely unaffected.

## III. THE ICECUBE EXPERIMENT

The IceCube [12] neutrino observatory is a large array of photodetectors buried deep within the ice at the south pole. It consists of 86 vertical cables that are frozen in place and separated from one another to form a hexagonal grid from a bird's eye perspective. The cables span a vertical distance of one kilometer, beginning at a depth of 1,450 meters and ending at a depth of 2,450 meters. Each of the cables contains 60 Digital Optical Modules (DOMs) spaced periodically along its length. Collectively, the buried cables contain a total of 5,160 DOMs and fill in a volume of approximately one cubic kilometer.

The ice that fills in the ambient space between and around the cables acts as a target for incoming neutrinos. Neutrinos passing through the volume of the detector have a small probability of interacting with the electrons, protons, and neutrons in the ice molecules via the weak nuclear force. Though the chances of such an interaction are extremely low for any individual neutrino, the large number of neutrinos passing through the detector combined with the large volume of ice within the detector make the occurrence of occasional interactions inevitable.

When such an interaction does occur, it may happen in one of two ways. The first way, called the neutral-current interaction, entails an incoming neutrino exchanging a $Z$ boson with an electron or nucleon belonging to some ice molecule. The neutrino then flies off, having imparted some of its energy and momentum to this particle. The second way, called the charged-current interaction, entails an incoming neutrino exchanging a $W$ boson with an electron or nucleon belonging to some ice molecule. The result of this exchange transforms the neutrino into a charged lepton and changes the particle off of which it scattered into its corresponding product.

For the purposes of this work, we shall be primarily concerned with charged-current interactions with high energy neutrinos. The result of such an interaction is an energetic lepton, sent flying through the ice at an extremely high speed. Because of its high speed, the lepton releases Cherenkov radiation as it travels through the ice. This Cherenkov radiation is subsequently detected by the nearby DOMs. The location and timing of the DOMs detecting radiation can be used to resolve the vicinity and energy of the neutrino event that triggered the process. This is the basis behind neutrino detection at IceCube.

Muons that are produced by such a neutrino interaction event are relatively long lived and are therefore able to travel a decent distance through the ice before scattering away all of their energy. Thus muon interactions produces clean "track-like" events as seen by the DOMs (they light up all the DOMs along the track of the muon). These are the events on which we will be focused. Because of the obvious difficulty in controlling unknown sources of addition photons, a sophisticated computer system is used to automatically reject any event registered by the DOMs that does not satisfy a stringent set of conditions to ensure that it is the result of a neutrino interaction.

## IV. CALCULATING BOUNDS

In order to calculate the measured signal for track-like events, we must first know how many neutrinos are moving through the IceCube detector. Following the methods of Reference [13] we may express the flux of neutrinos in terms of their energy spectrum using the equation

$$\frac{d\Phi_\nu}{dE} = \frac{\Delta\Omega}{4\pi}\left(\frac{R\rho_0^m}{M_\chi \tau_\chi}\right)\frac{dN_\nu}{dE} J_M(\Delta\Omega) \ . \qquad (1)$$

In this equation, $\Delta\Omega$ is the solid angle of view from the detector (the half sky facing the Galactic Center in our case, i.e., $2\pi$), $R = 8.5$ kpc $= 8.5 \times 3.08 \times 10^{21}$ cm is the distance from the Sun to Galactic Center, $\rho_0^m = 0.3$ GeV cm$^{-3}$ is the dark matter density in the solar neighborhood, $M_\chi$ is the dark matter mass, and $\tau_\chi$ is the dark matter lifetime. The quantity $J_M(\Delta\Omega)$, is the line-of-sight integral and is given by

$$J_M(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{\mathcal{P}} \frac{d\ell}{R}\left[\frac{\rho_M(r)}{\rho_0^m}\right] \ , \qquad (2)$$

where $\rho_M(r)$ is the Navarro-Frenk-White (NFW) halo profile for the dark matter density distribution in our galaxy. The $\ell$ integration is performed over the range, $\mathcal{P}$, which extends from Earth to the edge of the galaxy (though extending it to infinity is usually acceptable since the profile falls off quickly). Lastly, the function $dN_\nu/dE$

is the neutrino source spectrum, which is a function of energy that we determine using PYTHIA [14] simulations.

By multiplying the neutrino flux by the detector's effective area, $A(E)$, and integrating over an energy range $(E_{\rm Min}, E_{\rm Max})$ we obtain the track-like event rate corresponding to that range

$$\Gamma_{_{\rm Tr}} = \int_{E\ {\rm Min}}^{E_{\rm Max}} dE A(E) \frac{d\Phi_{\nu_\mu}}{dE} \ . \tag{3}$$

In our case, we carry the integration out from $E_{\rm Min} = M_\chi/10$ to $E_{\rm Max} = M_\chi/2$. The effective area of the detector, $A(E)$, is given by

$$A(E) = \rho_{\rm ice} N_a V_{_{\rm Tr}} \sigma^{\rm cc}_{\nu N}(E) \ , \tag{4}$$

where $\rho_{\rm ice} = 0.9$ g cm$^{-3}$ is the density of ice, $N_a = 6.022 \times 10^{23}$ g$^{-1}$ is Avogadro's number, $V_{_{\rm Tr}} = 4 \times 10^{13}$ cm$^3$ is the effective volume of the detector for track-like events, and $\sigma^{\rm cc}_{\nu N}(E)$ is the neutrino-nucleon cross section. The cross section is associated with the probability of an individual neutrino scattering off of an individual nucleon via the charged-current interaction. It can be found in Reference [15]. Putting these equations together, we find that the track-like event rate for muon neutrinos is therefore

$$\Gamma_{_{\rm Tr}} = \frac{\xi_\chi}{\tau_\chi} \int_{E_{\rm Min}}^{E\ {\rm Max}} dE \frac{dN_\nu}{dE} \sigma^{\rm cc}_{\nu N}(E) \ , \tag{5}$$

where

$$\xi_\chi = \frac{\Delta\Omega}{4\pi} \left( \frac{R\rho_0^m}{M_\chi} \right) \left( \rho_{\rm ice} N_a V_{_{\rm Tr}} \right) J_M(\Delta\Omega) \ . \tag{6}$$

The signal is the total number of events detected over a time $T$. It is simply the product of the event rate and time $S = \Gamma \cdot T$. Since IceCube cannot distinguish between neutrinos and antineutrinos, the total number of track-like events detected will be the sum of those caused by neutrinos and those caused by antineutrinos. Substituting $\sigma^{\rm cc}_{\nu N}(E) \to \sigma^{\rm cc}_{\bar\nu N}(E)$ and $dN_\nu/dE \to dN_{\bar\nu}/dE$ in the above equations validates them for antineutrinos. In our case however, the neutrino and antineutrino energy spectra are the same, so we need only worry about the neutrino-nucleon cross sections. The full $\nu + \bar\nu$ signal is therefore given by

$$S_{\nu+\bar\nu} = \frac{\xi_\chi T}{\tau_\chi} \int_{E_{\rm Min}}^{E\ {\rm Max}} dE \frac{dN_\nu}{dE} \sigma^{cc}_{\nu+\bar\nu}(E) \ , \tag{7}$$

where $\sigma^{cc}_{\nu+\bar\nu}(E)$ is simply the sum of the neutrino-nucleon and antineutrino-nucleon cross sections $\sigma^{cc}_{\nu+\bar\nu}(E) = \sigma^{cc}_{\nu N}(E) + \sigma^{cc}_{\bar\nu N}(E)$.

We now compare the signal to the background, which is given by the product of the background event rate and time $B = \Gamma_B \cdot T$. To obtain the background event rate, we use Equation (3) with the background neutrino flux instead of the flux of neutrinos coming from dark matter decay. For high energy neutrinos, careful event selection can reduce the background neutrino flux to that of atmospheric neutrinos, which have been studied and modeled extensively. Fluxes for atmospheric neutrinos and antineutrinos are given as functions of energy by Reference [16].

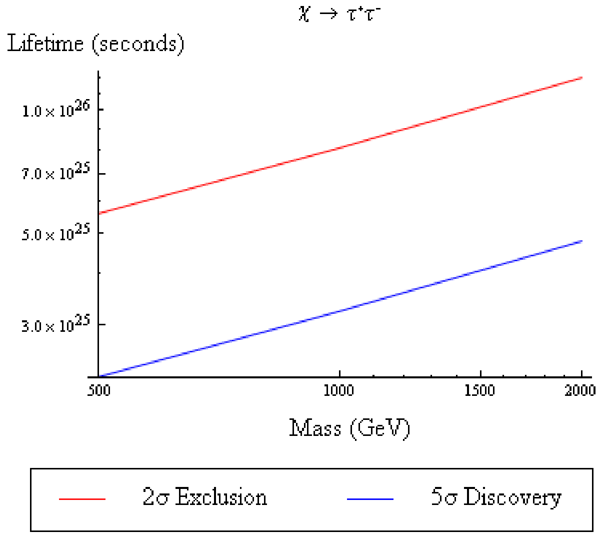

FIG. 1: Bounds from 5 years of projected data acquisition at IceCube are given for the dark matter lifetime as a function of the dark matter mass. The bounds correspond to the leptonic decay of dark matter into tau pairs $\chi \to \tau^+\tau^-$. Note that the result is displayed as a log-log plot.

The condition for $2\sigma$ exclusion is $S = 2\sqrt{B}$ since this entails the possibility that the signal can be generated as a statistical fluctuation two standard deviations from the expected background. The condition for a $5\sigma$ discovery is similarly $S = 5\sqrt{B}$. As can be seen from Equation (7), the signal is inversely proportional to the dark matter lifetime $\tau_\chi$. If the lifetime is too short, ambient dark matter will decay too frequently resulting in too large a neutrino flux, which would be detectable at IceCube. If the dark matter lifetime is very long, then the resulting neutrino flux would be very small and consequently very difficult to detect at IceCube. To $2\sigma$, the minimum lifetime allowed is $\tau_{\rm min}$ such that $S = 2\sqrt{B}$ holds. Solving for $\tau_{\rm min}$ we obtain the following condition for $2\sigma$ exclusion

$$\tau_{\rm min} = \frac{\mathcal{N}_{\nu+\bar\nu}}{2\sqrt{B}} \ , \tag{8}$$

where

$$\mathcal{N}_{\nu+\bar\nu} = \xi_\chi T \int_{E_{\rm Min}}^{E\ {\rm Max}} dE \frac{dN_\nu}{dE} \sigma^{cc}_{\nu+\bar\nu}(E) \ , \tag{9}$$

and

$$B = \rho_{\rm ice} N_a V_{_{\rm Tr}} T \int_{E_{\rm Min}}^{E\ {\rm Max}} dE \varphi(E) \ . \tag{10}$$

The quantity $\varphi(E)$ dictates the background signal and is given by

$$\varphi(E) = \sigma^{\mathrm{cc}}_{\nu N}(E)\left(\frac{d\Phi_\nu}{dE}\right)_{\mathrm{bkg}} + \sigma^{\mathrm{cc}}_{\bar{\nu} N}(E)\left(\frac{d\Phi_{\bar{\nu}}}{dE}\right)_{\mathrm{bkg}} .$$

To obtain the minimum lifetime at $5\sigma$, simply substitute $2 \to 5$ in Equation (8). Results for the case of the two-body decay $\chi \to \tau^+\tau^-$ are shown above in Figure (1).

## V. APPLICATION AND RESULTS

We are now ready to apply the results of the previous section to the work of Reference [7]. In this work, the general decay amplitude is parameterized in terms of a collection of operator coefficients and used to determine the energy spectra of electrons and positrons that are observed by experiments such as PAMELA and Fermi-LAT. Preferred values of dark matter mass and lifetime can be found by fitting the resultant electron-positron fluxes to match what is seen by these experiments.

Leptons produced by decaying dark matter give rise to showers of neutrinos that propagate throughout the galaxy. In particular, this increases the neutrino flux through Earth, which leads to an increased event rate at neutrino telescopes such as IceCube. This can then be used to place a bound on models for such dark matter decay. We calculate the neutrino source spectra resulting from the work of Reference [7] using PYTHIA and use it in Equation (1) to determine the expected signal at IceCube. The results are shown in Figure (2) and include the point preferred by cosmic-ray observatories.

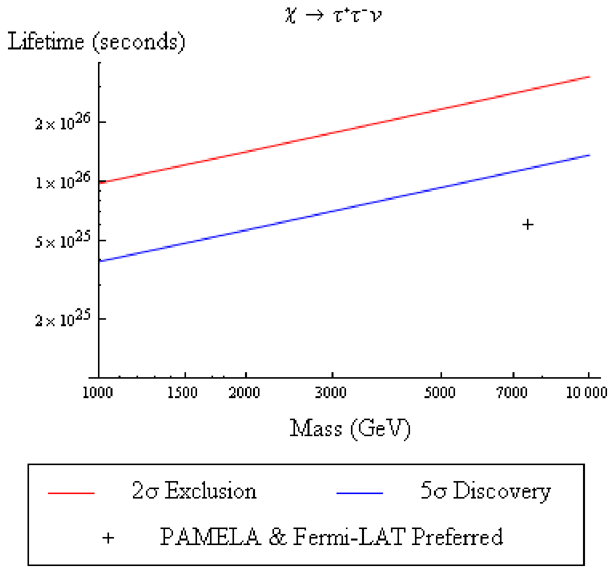

FIG. 2: Bounds from 5 years of projected data acquisition at IceCube are given for the dark matter lifetime as a function of the dark matter mass. The bounds correspond to the three-body decay of dark matter into tau pairs and a neutrino $\chi \to \tau^+\tau^-\nu$. Note that the result is displayed as a log-log plot.

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