Abstract

Dark matter is believed to comprise approximately eighty-three percent of the matter in the universe, yet little is known about how it fits into our picture of the elementary particles that make up the world around us. There are now many great efforts underway to try and detect dark matter and probe the nature of its relation to the Standard Model of particle physics. In this work we investigate the possibility of leptonically decaying dark matter using terrestrial neutrino telescopes. We 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.

Evidence for Dark Matter

There is an accumulating wealth of evidence for the existence of dark matter [8, 9]. One of the original arguments involves the measurement of distant galaxy speeds. The galaxies in question are bound together by their mutual gravitational attraction and make up large galactic clusters. If the speed of any individual galaxy within a cluster is great enough, it will overcome the gravitational pull of the other galaxies and fly off out of the cluster. Astronomical observations indicate that such galaxies are moving with speeds that far exceed the threshold required to escape their respective clusters, and yet they remain bound together. This suggests the presence of additional, unseen mass within the clusters that adds to the gravitational pull enough to prevent these fast-moving galaxies from escaping.

More evidence comes from observations of the rotational velocities of various galaxies. As a galaxy rotates, one naively expects the rotational speeds of objects within the galaxy to 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. Observations of gravitational lensing provide further evidence for dark matter. Gravitational lensing is the result of light being bent around a large distribution of mass. Its consequences are visible 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.

For a long while it was not known whether dark matter was simply obscured or non-radiating ordinary matter, or whether it was made of new kinds of particles as described in the Introduction. There are primarily two reasons why it is now believed to be the latter scenario (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].

Additional evidence for dark matter exists but will not be discussed here. The conclusion is that we are very likely surrounded by a sea of unseen particles that interact with known matter only through gravitation and possibly weak nuclear forces.

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 number of protons and neutrons contained 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 a very high speed. Because of its speed, as the lepton travels through the ice, it releases Cherenkov radiation that is subsequently detected by the nearby DOMs. This is the basis for detecting neutrinos at IceCube: they are indirectly inferred by observing the Cherenkov radiation from energized leptons produced in the collision between neutrinos and...
ice molecules.

When the lepton produced is a muon, it is relatively long lived and is able to travel much farther through the ice before scattering away all its energy. Thus it produces a clean “track-like” event as seen by the DOMs in its vicinity. 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.

Calculating Bounds

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

$$\frac{d\Phi_\nu}{dE} = \frac{\Delta \Omega}{4\pi} \left( \frac{R \rho_0^m}{M_\chi \tau_\chi} \right) \frac{dN_\nu}{dE} J_M(\Delta \Omega) .$$  \hspace{1cm} (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., $2\pi$). $R = 8.5 \text{ kpc} = 8.5 \times 3.08 \times 10^{21} \text{ cm}$ is the distance from the Sun to Galactic Center, $\rho_0^m = 0.3 \text{ GeV cm}^{-3}$ 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

$$J_M(\Delta \Omega) = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega \int_{R} d\rho \frac{\rho_M(r)}{\rho_0^m} ,$$ \hspace{1cm} (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 carried 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 ($E_{\text{Min}}, E_{\text{Max}}$) we obtain the track-like event rate corresponding to that range

$$\Gamma_{\text{Tr}} = \int_{E_{\text{Min}}}^{E_{\text{Max}}} dE A(E) \frac{d\Phi_\nu}{dE} .$$  \hspace{1cm} (3)

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

$$A(E) = \rho_{\text{ice}} N_\text{a} V_{\text{Tr}} \sigma_{\nu N}^{cc}(E) ,$$ \hspace{1cm} (4)

where $\rho_{\text{ice}} = 0.9 \text{ g cm}^{-3}$ is the density of ice, $N_\text{a} = 6.022 \times 10^{23} \text{ g}^{-1} / \text{mol}$ is Avogadro’s number, $V_{\text{Tr}} = 4 \times 10^{13} \text{ cm}^3$ is the effective volume of the detector for track-like events, and $\sigma_{\nu N}^{cc}(E)$ 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 [15]. Putting these equations together, we find that the track-like event rate for muon neutrinos is therefore

$$\Gamma_{\text{Tr}} = \frac{\xi_\chi}{\tau_\chi} \int_{E_{\text{Min}}}^{E_{\text{Max}}} dE dN_\nu \frac{dE}{dE} \sigma_{\nu N}^{cc} (E) ,$$ \hspace{1cm} (5)

where

$$\xi_\chi = \frac{\Delta \Omega}{4\pi} \left( \frac{R \rho_0^m}{M_\chi} \right) \left( \rho_{\text{ice}} N_\text{a} V_{\text{Tr}} \right) J_M(\Delta \Omega) .$$ \hspace{1cm} (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 $\sigma_{\nu N}^{cc}(E) \rightarrow \sigma_{\bar{\nu} N}^{cc}(E)$ and $dN_\nu/dE \rightarrow dN_{\bar{\nu}}/dE$ 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

$$S_{\nu + \bar{\nu}} = \frac{\xi \chi T}{\tau} \int_{E_{\text{Min}}}^{E_{\text{Max}}} dE dN_{\nu} dN_{\bar{\nu}} \sigma_{cc}^{\nu + \bar{\nu}}(E) ,$$  
(7)

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

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 \cite{16}.

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 $\tau_{\text{min}}$ such that $S = 2\sqrt{B}$ holds. Solving for $\tau_{\text{min}}$ we obtain the following condition for $2\sigma$ exclusion

$$\tau_{\text{min}} = \frac{N_{\nu + \bar{\nu}}}{2\sqrt{B}} ,$$  
(8)

where

$$N_{\nu + \bar{\nu}} = \xi \chi T \int_{E_{\text{Min}}}^{E_{\text{Max}}} dE dN_{\nu} dN_{\bar{\nu}} \sigma_{cc}^{\nu + \bar{\nu}}(E) ,$$  
(9)

and

$$B = \rho_{\text{ice}} N_a V_{\gamma} T \int_{E_{\text{Min}}}^{E_{\text{Max}}} dE \varphi(E) .$$  
(10)

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

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

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

![Figure 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.](image)

**Application and Results**

We now apply the results from the previous section to the work of Reference \cite{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 in the decay of dark matter give rise to showers of neutrinos that propagate throughout the galaxy. This results in a boosted event rate at neutrino telescopes such as IceCube, which can then be used to bound 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.

Figure 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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References


