Cosmic Gamma-ray from Inverse Compton Process in Unstable Dark Matter Scenario

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Abstract. Motivated by the PAMELA anomaly in the fluxes of cosmic-ray $e^+$ and $e^-$, we study the cosmic $\gamma$-ray induced by the inverse Compton (IC) scattering process in unstable dark matter scenario assuming that the anomaly is due to the $e^\pm$ emission by the decay of dark matter. We calculate the fluxes of IC-induced $\gamma$-ray produced in our Galaxy and that from cosmological distance, and show that both of them are significant. We discuss a possibility that large dark matter mass over TeV scale might be constrained by the $\gamma$-ray observation by Fermi Gamma-ray Space Telescope.

Keywords: Dark matter, Cosmic ray, Particle phenomenology

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INTRODUCTION

Recent observations of the fluxes of high-energy cosmic rays have made an impact on the understanding of the nature of dark matter (DM). In particular, the PAMELA experiment has observed an increasing behavior of the positron fraction in the cosmic ray in the energy range of $10 \text{ GeV} \lesssim E_e \lesssim 100 \text{ GeV}$ (with $E_e$ being the energy of $e^\pm$) [1], which cannot be explained if we consider the conventional $e^\pm$ fluxes in astrophysics. This fact suggests that there may exist a non-standard source of energetic positron (and electron) in our Galaxy.

One of the possibilities is unstable dark matter. If dark matter has lifetime of $O(10^{25} - 10^{26} \text{ sec})$, and also if positron is produced by the decay, the PAMELA anomaly may be explained; for early attempts, see, for example, [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. (Other possibilities of explaining the PAMELA anomaly include the dark-matter annihilation [15, 16, 17, 18, 19, 20, 21, 22, 23, 24] and the positron emission from pulsars [25].) In addition, a precise measurement of the total $(e^+ + e^-)$ flux has been performed by the Fermi Gamma-ray Space Telescope [26], whose results suggest that the flux of $(e^+ + e^-)$ is proportional to $\sim E^{-3}_e$. Although the interpretation of the Fermi result is still controversial, it has been discussed that the observed spectrum may be too hard to be consistent with the prediction of conventional astrophysical model, and that the $e^\pm$ observed by the Fermi experiment may be significantly contaminated by the $e^\pm$ produced by the decay of dark matter. Such a scenario suggests the mass of $m_{\text{DM}} \sim O(1 \text{ TeV})$ and the lifetime of $\tau_{\text{DM}} \sim O(10^{26} \text{ sec})$ [27, 28, 29].
If the decay of dark matter is the source of the extra positrons observed by the PAMELA experiment, the emitted positron and electron produce photon via synchrotron radiation and inverse Compton (IC) scattering. In our Galaxy, energy loss rates of the energetic $e^\pm$ via these processes are of the same order, but the typical energy of the photon emitted by these processes is different. Since the magnetic field in our Galaxy is expected to be $O(1 \, \mu G)$, the energy of the synchrotron radiation is typically $10^{-3} \, \text{eV}$ when the energy of $e^\pm$ is $O(1 \, \text{TeV})$. (The synchrotron radiation from the Galactic center is discussed in [30, 31].) On the contrary, the IC process produces $\gamma$-rays with higher energy. If an energetic $e^\pm$ with $E_e \sim O(1 \, \text{TeV})$ scatters off the cosmic microwave background (CMB) photon, $\gamma$-ray with $E_\gamma \sim O(1 - 10 \, \text{GeV})$ is produced. In addition, in our Galaxy, there exist background photons from stars, which have higher energy than the CMB radiation. The IC scattering with those photons produces $\gamma$-ray with higher energy. Importantly, the high-energy $\gamma$-ray flux can be precisely measured by the Fermi telescope. Thus, in order to examine the scenario in which the PAMELA anomaly is explained by the decay of dark matter, it is important to study the energetic $\gamma$-ray emitted by the IC process.

In this paper, we study the flux of $\gamma$-ray produced by the IC process in the decaying dark matter scenario. We pay particular attention to the parameter space in which the positron fraction is in agreement with the PAMELA results. In our previous work [32], IC-induced $\gamma$-ray in various direction from Galactic and extra-Galactic region are shown; we have seen that the extra-Galactic contribution can be as large as Galactic one. In particular, if we see $\gamma$-ray in the direction off the Galactic center, signal of the IC-induced $\gamma$-ray from extra-Galactic region may be observed. Here, paying attention to the observation data by Fermi, we compare theoretically-calculated $\gamma$-ray with the observations. It will be shown that the parameter region $m_{DM} \gtrsim 4 \, \text{TeV}$, which is suggested by PAMELA and Fermi observations, might be constrained by the observation of isotropic $\gamma$-ray by Fermi [33]. We will also show that the flux of the IC-induced $\gamma$-ray in our Galaxy may be less than the observed flux in intermediate Galactic latitude (IGL) given by Fermi [34] when $\tau_{DM} \sim O(10^{26} \, \text{sec})$ to explain the PAMELA anomaly.

**FORMULA OF $\gamma$-RAY IN INVERSE-COMPTON PROCESS**

We first discuss the procedure to calculate the $\gamma$-ray flux. The following formula is based on [32].

The total $\gamma$-ray flux is given by the sum of two contributions:

$$\Phi_{\gamma \text{IC}} = \Phi_{\gamma \text{(Galaxy)}} + \Phi_{\gamma \text{(Cosmo)}},$$  \hspace{1cm} (1)

where the first and second terms in the right-hand side are fluxes of $\gamma$-ray produced in our Galaxy and that from cosmological distance (i.e., extra-Galactic contribution), respectively. Notice that $\Phi_{\gamma \text{(Cosmo)}}$ is isotropic, while $\Phi_{\gamma \text{(Galaxy)}}$ depends on direction we observe.

In order to discuss the IC-induced $\gamma$-ray, it is necessary to understand the spectrum of the parent $e^\pm$. In our Galaxy, energetic $e^\pm$ is approximately in a random-walk motion because of the entangled magnetic field. Then, the $e^\pm$ energy spectrum $f_e$ (i.e., number
density of \((e^+ + e^-)\) per unit energy) in our Galaxy is described by the following diffusion equation:

\[
K_e(E_e) \nabla^2 f_e(E_e, \vec{x}) + \frac{\partial}{\partial E_e} [b_{\text{loss}}(E_e, \vec{x}) f_e(E_e, \vec{x})] + Q_e(E_e, \vec{x}) = 0,
\]

(2)

where \(K_e(E_e)\) is the diffusion coefficient, \(b_{\text{loss}}(E_e, \vec{x})\) is the energy loss rate, and \(Q_e(E_e, \vec{x})\) is the \(e^\pm\) source term. In considering the long-lived dark matter, the source term is given by

\[
Q_e(E_e, \vec{x}) = \frac{1}{\tau_{\text{DM}}} \rho_{\text{DM}}^{(\text{Galaxy})}(\vec{x}) \frac{dN_e}{dE_e},
\]

(3)

where \(\rho_{\text{DM}}^{(\text{Galaxy})}\) is energy density of dark matter and \(dN_e/dE_e\) is energy distribution of \(e^\pm\) from the decay of single dark matter. In our study, we adopt the isothermal halo density profile \[35\]

\[
\rho_{\text{DM}}^{(\text{Galaxy})}(r) = \frac{r^2_{\text{core}} + r_\odot^2}{r^2_{\text{core}} + r^2},
\]

(4)

where \(\rho_\odot \simeq 0.43\ \text{GeV/cm}^3\) is the local halo density, \(r_{\text{core}} \simeq 2.8\ \text{kpc}\) is the core radius, \(r_\odot \simeq 8.5\ \text{kpc}\) is the distance between the Galactic center and the solar system, and \(r\) is the distance from the Galactic center. In studying the propagation of the cosmic-ray \(e^\pm\), we adopt the shape of the diffusion zone used in the so-called MED propagation model \[36\]; the diffusion zone is approximated by a cylinder with the half-height of \(L = 4\ \text{kpc}\) and the radius of \(R = 20\ \text{kpc}\). Notice that the solution of the diffusion equation is insensitive to the diffusion coefficient \(K_e(E_e)\) for high energy \(e^\pm\) \[31\], as we will discuss in the following. In addition, the energy loss rate \(b_{\text{loss}}\) is given by the sum of the contributions from the synchrotron-radiation and the IC processes:

\[
b_{\text{loss}}^{(\text{Galaxy})}(E_e, \vec{x}) = b_{\text{synch}}^{(\text{Galaxy})}(E_e, \vec{x}) + b_{\text{IC}}^{(\text{Galaxy})}(E_e, \vec{x}).
\]

For the calculation of \(b_{\text{synch}}^{(\text{Galaxy})}\), we approximate that the strength of the magnetic flux density \(B\) is independent of position in our Galaxy; then we obtain

\[
b_{\text{synch}}^{(\text{Galaxy})}(E_e) = \sigma_T \gamma_e^2 B^2,
\]

(5)

with \(\gamma_e = E_e/m_e\) and \(\sigma_T\) being the cross section of the Thomson scattering. In our numerical study, we use \(B = 3\ \mu\text{G}\). Furthermore, \(b_{\text{IC}}^{(\text{Galaxy})}\) is given by

\[
b_{\text{IC}}^{(\text{Galaxy})}(E_e, \vec{x}) = c \int dE_\gamma dE_{\text{BG}}(E_\gamma - E_{\text{BG}}) \frac{d\sigma_{\text{IC}}}{dE_\gamma} f_{\text{BG}}(E_{\text{BG}}, \vec{x}),
\]

(6)

where \(c\) is the speed of light and the differential cross section for the IC process is expressed as \[37\]

\[
\frac{d\sigma_{\text{IC}}}{dE_\gamma} = \frac{3\sigma_T}{4\gamma_e^2 E_{\text{BG}}} \left[ 2q \ln q + (1 + 2q)(1 - q) + \frac{(\Gamma_e q)^2 (1 - q)}{2(1 + \Gamma_e q)} \right],
\]

(7)
with $\Gamma_e = 4\gamma_e E_{\gamma G}/m_e$, $q = E_\gamma/E_e - E_\gamma$, and $f_{\gamma G}$ is the spectrum of the background radiation photon. Kinematically, $1/4\gamma_e^2 \leq q \leq 1$ is allowed. The background photon in our Galaxy has three components: (i) star light concentrated in the Galaxy, (ii) star light re-scattered by dust, and (iii) the CMB radiation. The spectrum of the CMB radiation is isotropic and well known, while those of the first and second components depend on the position. We use the data of interstellar radiation field provided by the GALPROP collaboration \[38\], which is based on \[39\], to calculate $f_{\gamma G}$ in our Galaxy.

The typical propagation length of electron per time scale of the energy loss is estimated to be $O(0.1 \text{ kpc})$ for $E_e \sim 100 \text{ GeV}$, and it becomes shorter as the energy increases. (Here, we have used the diffusion coefficient suggested in the MED propagation model, $K(E) \approx 0.0112 \text{ kpc}^2/\text{Myr} \times (E_e/1 \text{ GeV})^{0.70}$.) Then, the $e^\pm$ spectrum at the position $\vec{x}$ is well approximated by

$$f_e^{(\text{Galaxy})}(E_e, \vec{x}) = \frac{1}{b^{(\text{Galaxy})}_{\text{loss}}(E_e, \vec{x})} \frac{\rho_{\text{DM}}^{(\text{Galaxy})}(\vec{x})}{\tau_{\text{DM} \text{DM}}} \int_{E_e}^{\infty} dE'_e dN_e dE_e.$$  \(\text{(8)}\)

In our numerical analysis, we adopt the above approximated formula for the $e^\pm$ spectrum in our Galaxy. Then, $\gamma$-ray flux from direction $(b, l)$, where $b$ and $l$ are Galactic latitude and longitude, respectively, is obtained by line-of-sight (l.o.s) integral of $\gamma$-ray energy density per unit time and unit energy as

$$\Phi^{(\text{Galaxy})}_\gamma(b, l) = \frac{1}{4\pi} \int_{\text{l.o.s}} d\vec{l} L_{\text{IC}}(E_\gamma, \vec{l}),$$  \(\text{(9)}\)

where

$$L_{\text{IC}}(E_\gamma, \vec{x}) = c \int dE_e dE_{\gamma G} \frac{d\sigma_{\text{IC}}}{dE_e} f_{\gamma G}(E_{\gamma G}, \vec{x}) f_e^{(\text{Galaxy})}(E_e, \vec{x}).$$  \(\text{(10)}\)

In studying the $\gamma$-ray from cosmological distance, we need to understand the $e^\pm$ spectrum in the extra-Galactic region. In such a region, the $e^\pm$ spectrum is independent of the position, so the spectrum should obey

$$\frac{\partial f_e(t, E_e)}{\partial t} = HE_e \frac{\partial f_e(t, E_e)}{\partial E_e} + \frac{\partial}{\partial E_e} [b^{(\text{loss})}(t, E_e) f_e(t, E_e)] + Q(t, E_e),$$  \(\text{(11)}\)

where $H$ is the expansion rate of the universe. Contrary to the case in our Galaxy, only the IC process with the CMB radiation contributes to the energy-loss process. Since the typical energy of the CMB radiation is so low that $e^\pm$ becomes non-relativistic in the center-of-mass energy of the IC process. Then, taking into account the red-shift of the CMB radiation, the energy loss rate is given by

$$b_{\text{loss}}^{(\text{Cosmo})}(t, E_e) = \frac{4}{3} \sigma_T \gamma_e^2 \rho_{\text{CMB}}^{(\text{now})} (1+z)^4,$$  \(\text{(12)}\)

where $\rho_{\text{CMB}}^{(\text{now})} \approx 0.26 \text{ eV/cm}^3$ is the present energy density of the CMB, and $z$ is the red-shift.
The typical time scale of the energy loss due to the IC process is estimated to be $E_e/b_{\text{loss}}^{(\text{Cosmo})}$, and is of the order of $10^{14}$ sec for $E_e = 100$ GeV (and becomes shorter as $E_e$ increases). Because the energetic $e^\pm$ loses its energy via the IC process before the energy is red-shifted, we neglect the terms of $O(H)$ in Eq. (11) and obtain

$$f_e^{(\text{Cosmo})}(t,E_e) = \frac{1}{b_{\text{loss}}^{(\text{Cosmo})}(t,E_e)} \rho_{\text{DM}}^{(\text{now})}(1+z)^3 \int_{E_e}^\infty \frac{dN_e}{dE_e} \frac{dN_e}{dE_e'},$$

(13)

where $\rho_{\text{DM}}^{(\text{now})} \approx 1.2 \times 10^{-6}$ GeV/cm$^3$ is the present energy density of dark matter. Then, taking into account red-shift of scattered photon spectrum and the dilution due to the expansion of the universe, we obtain the $\gamma$-ray from cosmological distance as

$$\Phi_{\gamma}^{(\text{Cosmo})} = \frac{c}{4\pi} \int dt \frac{1}{(1+z)^3} L_{\text{IC}}(t,E_{\gamma}),$$

(14)

where

$$L_{\text{IC}}(t,E_{\gamma}) = (1+z)c \int dE_e dE_{\gamma}^{\text{BG}} \left[ \frac{d\sigma_{\text{IC}}}{dX'} \right]_{E_{\gamma}'=(1+z)E_{\gamma}} f_{\gamma_{\text{BG}}}(t,E_{\gamma}^{\text{BG}}) f_e^{(\text{Cosmo})}(t,E_e),$$

(15)

with $f_{\gamma_{\text{BG}}}(t,E_{\gamma}^{\text{BG}})$ being the spectrum of the CMB radiation at the time $t$. Notice that the astrophysical uncertainty is small in the extra-Galactic contribution, as is obvious from the above expression.

**NUMERICAL RESULTS**

Now, we are at the position to show our numerical results. First we will discuss the case where dark matter dominantly decays into $\mu^+\mu^-$ pair as an example. In such a case, energetic $e^\pm$ are produced by the decay of $\mu^\pm$. Then, the positron fraction can be in good agreement with the PAMELA result while the total $(e^+ + e^-)$ flux can be consistent with the Fermi data if $m_{\text{DM}} \sim O(1$ TeV) and $\tau_{\text{DM}} \sim O(10^{26}$ sec). In order to choose best-fit value with PAMELA data for $\tau_{\text{DM}}$ in a given $m_{\text{DM}}$, we calculate $\chi^2$. In this analysis, we simulate background flux of $e^\pm$ by the use of GALPROP code [38]. In the simulation, we adopt “conventional” model which is presented in [40].

In Fig. 1 we show the simulated cosmic $\gamma$-ray in the IC process. Here, we chose to take $m_{\text{DM}} = 250$ GeV, 500 GeV, 1 TeV, 2 TeV, and 4 TeV, and the lifetime is taken as $\tau_{\text{DM}} = 1.0 \times 10^{27}$ sec, $6.2 \times 10^{26}$ sec, $3.4 \times 10^{26}$ sec, $1.7 \times 10^{26}$ sec, and $1.5 \times 10^{26}$ sec, respectively. For Galactic contribution, we plot the averaged flux in $10^\circ < b < 20^\circ$. One can see Galactic contribution is much less than the observed IGL flux. On the other hand, the flux from extra-Galactic region makes a large contribution, especially when $m_{\text{DM}} \gtrsim 4$ TeV, and it becomes comparable to the observed isotropic component of $\gamma$-ray. Since the isotropic $\gamma$-ray flux observed by Fermi contains the extra-Galactic $\gamma$-ray
**FIGURE 1.** IC $\gamma$-ray flux in the case where dark matter decays to $\mu^+\mu^-$ pair. The solid line is the flux from the cosmological distance, which is isotropic, while the dashed ones are Galactic contributions. For each line, we take $(m_{\text{DM}}, \tau_{\text{DM}}) = (250 \text{ GeV}, 1.0 \times 10^{27} \text{ sec}), (500 \text{ GeV}, 6.2 \times 10^{26} \text{ sec}), (1 \text{ TeV}, 3.4 \times 10^{26} \text{ sec}), (2 \text{ TeV}, 1.7 \times 10^{26} \text{ sec}), (4 \text{ TeV}, 8.5 \times 10^{26} \text{ sec})$ from left to right. Here, we also plot observation data by EGRET [41] and Fermi [33, 34].

**FIGURE 2.** IC $\gamma$-ray flux in the case where gravitino dark matter dominantly decays to second generation lepton. For each line, we take $(m_{\text{DM}}, \tau_{\text{DM}}) = (250 \text{ GeV}, 4.0 \times 10^{26} \text{ sec}), (500 \text{ GeV}, 2.7 \times 10^{26} \text{ sec}), (1 \text{ TeV}, 2.0 \times 10^{26} \text{ sec}), (2 \text{ TeV}, 1.8 \times 10^{26} \text{ sec}), (4 \text{ TeV}, 1.6 \times 10^{26} \text{ sec})$ from left to right.
and those from the other sources which are not identified, the extra-Galactic component should not exceed the observation; thus, such large dark matter mass may be constrained.

For comparison, we also calculated IC-induced $\gamma$-ray for scenario in which gravitino $\psi_\mu$ becomes dark matter. In the scenario, gravitino mainly decays to $Wl$, $Z\nu$, and $h\nu$. Then, $e^\pm$ is produced from charged lepton $l$, as well as weak- or higgs bosons; such $e^\pm$ can become a source of the cosmic ray\cite{42} to explain PAMELA anomaly\cite{5,43}. Furthermore, total $(e^+ + e^-)$ flux can be consistent with Fermi data. Even in this scenario, high energy $\gamma$-ray is inevitably by $e^\pm$ in IC process. In Fig. 2 we show IC-induced $\gamma$-ray in the scenario. Here, we especially consider the case where gravitino dominantly decays to second-generation lepton, and plot for $m_{DM} = 250$ GeV, 500 GeV, 1 TeV, 2 TeV, and 4 TeV, by choosing best-fit lifetime with PAMELA as $\tau_{DM} = 4.0 \times 10^{26}$ sec, $2.7 \times 10^{26}$ sec, $2.0 \times 10^{26}$ sec, $1.8 \times 10^{26}$ sec, and $1.6 \times 10^{26}$ sec, respectively. One can see that the Galactic and extra-Galactic fluxes from dark matter is much less than the present IGL- and isotropic-flux observations. This result is the consequence of softer $e^\pm$ spectrum from the decay of weak- or higgs bosons, compared to the previous $\mu^+\mu^-$ case. Besides, in $\psi_\mu$-DM scenario, the direct production of energetic photon by the dark matter decay is not negligible. In the scenario, $\gamma$-ray is produced directly from the decay of $\psi_\mu$, or following weak- and higgs bosons’ decay; those photons also become the source of high energy cosmic $\gamma$-ray. In Fig. 3 we plot the primarily produced $\gamma$-ray. Here, we consider the same decay scenario and parameters as in Fig. 2. One can see that the Galactic and extra-Galactic fluxes from dark matter is much less than the present IGL- and isotropic-flux observations. Thus, with the observation data which is currently available, the primarily $\gamma$-ray is not constrained. However, if data for higher energy region is obtained, the scenario may be tested or constrained. For the other dark matter scenario, the spectrum of the cosmic $\gamma$-ray

![Gravitino LSP, Lepton: µ](image)

**FIGURE 3.** Primarily produced $\gamma$-ray flux in the case where gravitino dark matter dominantly decays to second generation lepton. The parameters are taken as the same as Fig. 2.
depends on the properties of the decaying dark matter. Detailed discussion for several specific dark matter models will be given elsewhere [44].

CONCLUSION AND DISCUSSION

In this paper, we have studied the IC-induced $\gamma$-ray, assuming that the PAMELA anomaly in the $e^+$ fraction is due to the decay of dark matter. We have calculated the Galactic and extra-Galactic contributions separately, and shown that both of them are important. In our study, we have considered the case that dark matter dominantly decays into $\mu^+\mu^-$ pair, as well as the case of gravitino dark matter. However, as far as the PAMELA anomaly is explained in the decaying dark matter scenario, the IC-induced $\gamma$-ray flux is expected to be of the same order irrespective of dominant decay process. This is because, in order to explain the PAMELA anomaly, energetic $e^\pm$ should be produced by the decay, which induces the IC process. In our analysis, we found that large dark matter mass over nearly 4 TeV might be constrained by Fermi observation in the case the dark matter dominantly decays to $\mu^+\mu^-$ pair, while gravitino dark matter scenario is not constrained by the present observation.

It should be also noticed that the production rate of energetic $e^\pm$ is extremely suppressed in the extra-Galactic region in another scenario of explaining the PAMELA anomaly, like the pulsar scenario. Furthermore, it is notable that the procedure to calculate this contribution has less uncertainty, and that the flux is isotropic. Therefore, if detailed data about the $\gamma$-ray spectrum becomes available for various directions by the Fermi experiment, it will provide a significant information about the unstable dark matter scenario. In particular, study of the $\gamma$-ray flux from directions away from the Galactic center is important. For such directions, the $\gamma$-rays from the Galactic activities are suppressed. Thus, the background flux is expected to be comparable to or even smaller than the extra-Galactic contribution of the IC-induced $\gamma$-ray flux.

At present, Fermi experiment provides the isotropic $\gamma$-ray, by analyzing the flux data off Galactic center region [33]. According to their work, however, the isotropic component may contain contribution from unknown source in Galaxy, as well as extra-Galactic $\gamma$-ray, and it is mentioned that more detailed analysis is needed in the future work. Therefore, if the $\gamma$-ray spectrum for extra-Galactic component is precisely determined, we may see a signal of the IC-induced $\gamma$-ray. Furthermore, it can be one of the possible tool for test of dark matter scenario. Also we note that the measurement of the flux from directions close to the Galactic center, which is sensitive to the Galactic contribution, is also important.

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