Positron/Gamma-Ray Signatures of Dark Matter Annihilation and Big-Bang Nucleosynthesis

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The positron excess observed by the PAMELA experiment may come from dark matter annihilation, if the annihilation cross section is large enough. We show that the dark matter annihilation scenarios to explain the positron excess may also be compatible with the discrepancy of the cosmic lithium abundances between theory and observations. The wino-like neutralino in the supersymmetric standard model is a good example for it. This scenario may be confirmed by Fermi satellite experiment.

I. INTRODUCTION

Dark matter (DM) in the Universe is one of the most striking clues to the physics beyond the standard model (SM). Many methods are proposed for the direct or indirect DM detection [1], and experiments for the DM search are reaching to the sensitivities to find an evidence of the dark matter. Actually the HEAT [2] and PAMELA [3] experiments reported an excess of positron flux in cosmic rays. While astrophysical sources, such as pulsar(s) [4] or a gamma-ray burst [5], are proposed for the observed positron excess, it may be also accounted for by the high-energy positron injection from the DM annihilation [6, 7].

Supersymmetry (SUSY) introduces natural DM candidates as the lightest SUSY particle (LSP). Neutralinos in the SUSY SM are predicted to be the LSP in many SUSY-breaking models. The neutralino annihilation may explain the observed positron excess. However, this generally requires the annihilation cross section larger than expected from the thermal relic abundance, \( \langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \).

It should be noted that DM with such large annihilation cross section significantly affects big-bang nucleosynthesis (BBN) [8]. (See also Ref. [9] for early attempts.) A small fraction of the relic LSPs still annihilates each other and injects high-energy particles into thermal bath even after the freezeout epoch, and this may alter the abundances of light elements significantly. In this paper we show that the DM, which is compatible with the positron excess, may also solve the discrepancy of the primordial lithium abundances between theory and observations. The wino-like neutralino in SUSY models is an explicit example for such DM. We notice that it may be confirmed by the gamma-ray signals from the Galactic center by the Fermi experiment.

II. SIGNATURES OF WINO-LIKE DARK MATTER

Wino is a superpartner for the standard-model SU(2) gauge boson. The wino-like neutralino becomes the LSP in anomaly-mediated SUSY-breaking models [10], in which the wino mass \( m_3/2 \) is directly related to the gravitino mass \( m_3/2 \) as \( m_3/2 \sim 400 \times m_\chi \). The much heavier gravitino than the weak scale is welcome from a viewpoint of the cosmological gravitino problem [11]. The gravitino with \( m_3/2 \gtrsim 50 \text{ TeV} \) decays well before the BBN begins, and the gravitino abundance after inflation is not constrained from the observed light element abundances.

Thermal production of winos in the early Universe is not much enough to explain the observed DM abundance, unless its mass is around 3 TeV [12]. However, even in the lighter wino cases, the non-thermal production of winos by the gravitino decay may explain it without spoiling the BBN. The gravitino number-to-entropy ratio \( Y_{3/2} \) after inflation is given by \( Y_{3/2} \simeq 2.3 \times 10^{-14} (T_R/10^9 \text{ GeV}) \), where \( T_R \) denotes the reheating temperature of the Universe [11, 13]. The current wino abundance is almost the same as that of the gravitino since the annihilation of winos is neglected after the gravitino decay, except for the mass range where the non-perturbative effect significantly enhances the annihilation cross section [12]. Thus the observed DM abundance in the Universe is explained by the non-thermal wino production if \( T_R \sim 10^{9-10} \text{ GeV} \) and \( m_\chi \sim 100 \text{ GeV} - 2 \text{ TeV} \). This value of the reheating temperature is also favored from the thermal leptogenesis, which requires \( T_R \gtrsim 10^9 \text{ GeV} \) [14].

Now let us discuss observational implications of wino-like DM scenario.

A. Cosmic positron flux

The wino-like neutralinos mainly annihilate into the weak bosons, and yields positrons, anti-protons, gamma’s and neutrinos in cosmic rays, which may give clues to the
DM properties, if detected. In this paper we consider the positron and gamma-ray fluxes. We will comment on the other signals later.

Energetic positrons produced by the DM annihilation lose their energy quickly through their propagation in the Galaxy due to synchrotron emission and inverse Compton processes with CMB photons and star light. As a result, only positrons from the region within a few kpc can reach to the Earth. The propagation of positrons is described by the following diffusion equation [15],

\[
\frac{\partial}{\partial t} f(E, \vec{x}) = K(E) \nabla^2 f(E, \vec{x}) + \frac{\partial}{\partial E} [b(E)f(E, \vec{x})] + Q(E, \vec{x}),
\]

(1)

where \( f(E, \vec{x}) \) denotes the positron number density with energy \( E \), \( K(E) \) is the diffusion constant, and \( b(E) \) denotes the energy loss rate. The positron flux at the Earth \((\vec{x} = \vec{x}_0)\) is given by \( \Phi^{(DM)}_{1+}(E, \vec{x}_0) = (c/4\pi)f(E, \vec{x}_0) \). The source term from the DM annihilation \( Q(E, \vec{x}) \) is given as

\[
Q(E, \vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{dN_f^{(e^+)}}{dE},
\]

(2)

where \( \rho(\vec{x}) \) is the DM mass density and \( dN_f^{(e^+)}/dE \) is the fragmentation function of the DM annihilation products \( f \) into positrons. We adopt the so-called M2 propagation model [16], where \( K(E) = 0.00595 \text{kpc}^2/\text{Myr}(E/1 \text{GeV})^{0.55} \), \( b(E) = 1 \times 10^{-16} \text{GeV s}^{-1} \), \( L=1 \text{kpc} \) (\( L \) is the half-height of the diffusion cylinder) and derive the steady state solution of Eq. (1) semi-analytically [17].

The positron flux from the DM annihilation is less sensitive to the global structure of the DM halo density profile. However, DM may not be distributed smoothly in our Galaxy and there may be clumpy structures in the Galactic halo. If this is the case, the positron flux may be enhanced [18]. This effect is characterized by the boost factor, denoted by \( B_F \). Smooth distribution corresponds to \( B_F = 1 \), and may reach to \( \sim 5 \).

Fig. 1 shows the positron flux from the wino-like DM annihilation using the positron fraction \( R(E) \), that is the ratio of the positron flux to sum of electrons and positrons fluxes. The results of the HEAT [2] and PAMELA [3] experiments are also shown. In the evaluation of positron fraction, we include the background positron and electron fluxes from cosmic ray simulations [19]. It is found that the wino-like DM with \( m_\chi \sim 200 \text{ GeV} \) explains the PAMELA results. Notice that the low energy positron flux with energy less than \( \lesssim 10 \text{ GeV} \) is somewhat uncertain due to the solar modulation.

The ATIC balloon experiment reported an excess of the sum of the electron and positron fluxes, whose peak energy is around 600 GeV [20]. If we believe the excess, the DM mass with 600-1000 GeV is favored. However, the ATIC excess may not be so significant if one takes into account large uncertainty of the data and also poor agreement with other experiments [21] in the similar energy range. Thus, in this paper we consider wino with mass around 200 GeV, since this mass range is interesting from a viewpoint of the cosmic lithium problem, as we will see.

B. Big-Bang Nucleosynthesis

Even after the freezeout time of the LSPs, a small fraction of them would still continue to annihilate each other and produce high-energy hadrons and photons. Those emitted particles by this residual annihilation can change the abundances of light elements [8] such as D, T, \(^3\text{He}, \(^4\text{He}, \(^6\text{Li}, \(^7\text{Li} \) and \(^7\text{Be} \) further after/during the BBN.

High-energy hadrons scatter off the background proton and \(^4\text{He} \), and induce the hadronic shower [11, 22], which produces copious neutron, D, T and \(^6\text{Li} \), respectively. This non-thermal neutron also induces sequential reactions to reduce \(^7\text{Be} \) (i.e., \(^7\text{Li} \) at a later time) through \(^7\text{Be}(n, p)^7\text{Li}(p, \gamma)^4\text{He} \) (see also Ref. [22] for the original idea).

Currently the observational \(^7\text{Li} \) abundance does not agree with the theoretical prediction of the standard BBN when we use the baryon-to-photon ratio, \( \eta = (6.225 \pm 0.170) \times 10^{-10} \), obtained by WMAP 5-year [24]. Then, the theoretical value of \(^7\text{Li} \) is much larger than the observational one even if we adopt a relatively high value of the observational abundance, \( \log_{10}^{10}(\text{Li}/\text{H})_{\text{obs}} = -9.36 \pm 0.06 \) [25]. See also Ref. [26] for a lower value of \(^7\text{Li} \) abundance \( \log_{10}^{10}(\text{Li}/\text{H})_{\text{obs}} = -9.90 \pm 0.06 \), which is much more difficult to fit. This situation has got worse when we use an updated reaction rate of \(^4\text{He}(\gamma, \gamma)^7\text{Be} \)
As for $^6\text{Li}$ abundance, on the other hand, recent observation shows that the theoretical value is much smaller than that of the observation, $(^6\text{Li}/^7\text{Li})_{\text{obs}} = 0.046 \pm 0.022$ [28]. These two discrepancies may be collectively called "lithium problem". In the hadron injection scenario, however, there is a tendency to solve the lithium problem because it can reduce $^7\text{Li}$ and produce $^6\text{Li}$ as explained above.

It should be also checked simultaneously if the abundances of the other elements, D, $^3\text{He}$ and $^4\text{He}$, meet the observational constraints. We adopt both low and high values of D/H, Low (D/H)$_{\text{obs}} = (2.82 \pm 0.26) \times 10^{-5}$ [29], and High (D/H)$_{\text{obs}} = (3.98^{+0.59}_{-0.67}) \times 10^{-5}$ [30]. The observational value of the $^4\text{He}$ mass fraction is taken to be $Y_{^4\text{He}} = 0.2516 \pm 0.0040$ [31] with large systematic errors. The abundance of the $^3\text{He}$ to D ratio is constrained by the observational upper bound, $(^3\text{He}/\text{D})_{\text{obs}} = 0.83 + 0.27$ [33].

The allowed region in the plane of the annihilation cross section and the DM particle mass is shown in Fig. 2. For comparison, we show the wino-like neutralino annihilation cross sections, including the non-perturbative effect on the annihilation processes [34]. Even if we adopted the low value of D/H, it is found that there is still an allowed region at around $m_\chi \sim 250$ GeV to solve the lithium problem, while satisfying all the constraints.

If we allow depletion of Li in stars, a larger parameter region is allowed as shown in Fig. 3. In the figure we take the Li depletion as $\Delta \log_{10}(^7\text{Li}/\text{H}) = 0.4 \Delta \log_{10}(^6\text{Li}/\text{H}) = 0.25$ which is implied from study of rotational mixing in stars [35]. In this case it is found that the lithium problem is solved even if we adopt the small value for the observed $^7\text{Li}$ abundance for the wino mass around 150 GeV - 300 GeV. Interestingly, the wino-like neutralino with this mass range can also explain the observed positron excess, as already described.

The wino-like neutralino with mass around 2 TeV can also explain the positron excess due to the enhancement of the cross section by the non-perturbative effect [17]. It is consistent with the BBN after the depletion of Li with $\Delta \log_{10}(^7\text{Li}/\text{H}) \gtrsim 0.25$ is taken into account.

### C. Gamma-ray flux from Galactic center

DM annihilation in the Galactic halo also yields high-energy gamma-rays. The continuum gamma-ray flux from the neutralino annihilation at the Galactic center is expressed as [36]

$$\Phi_\gamma(\psi, E) = \frac{\langle \sigma v \rangle_f}{8\pi m_\chi^2} \int_{l_{\text{o.s.}}} \rho^2(l) d\psi,$$

(3)

where $\psi$ is the angle from the Galactic center, $l(\psi)$ is the distance from us along the angular direction $\psi$ and $dN_f(\gamma)/dE$ is the fragmentation function of the annihilation products $f$ into gamma’s. The density profile $\rho$...
models, can account for the positron excess for the mass as is realized in the anomaly-mediated SUSY breaking of wino-like neutralino dark matter in the SUSY SM, of the dark matter. As an example, the annihilation particle physicists, since it may be a striking evidence by PAMELA experiment now, draw a great attention of first observed by HEA T experiments and is confirmed tralino with mass lighter than 300 GeV. DM annihilation if the DM consists of the wino-like neutralino with mass 150 GeV for both NFW and isothermal profile, and 200 GeV for NFW profile from the Galactic center within the region $-5^\circ < l < 5^\circ$ and $-2^\circ < b < 2^\circ$. The result of EGRET observation is also shown.

around the Galaxy is still unknown, and this leads to an uncertainty on the gamma-ray flux coming from the DM annihilation at the Galactic center. Here we consider two typical models of the DM halo: the isothermal and Navarro-Frenk-White (NFW) profiles [37]. In Fig. 4 we show the gamma-ray flux from the Galactic center for the wino mass 150 and 200 GeV, which are favored from the observed positron excess and the lithium abundances. We average the gamma-ray flux over the region of the Galactic longitude $-5^\circ < l < 5^\circ$ and latitude $-2^\circ < b < 2^\circ$. The EGRET data is also shown [38]. It is seen that the gamma-ray flux is comparable to the EGRET observation depending on the DM density profile. It is expected that the Fermi experiment [39] may discover excess of gamma-rays and confirm the signal of DM annihilation if the DM consists of the wino-like neutralino with mass lighter than 300 GeV.

III. CONCLUSIONS AND DISCUSSION

The positron flux excess in cosmic rays, which was first observed by HEAT experiments and is confirmed by PAMELA experiment now, draw a great attention of particle physicists, since it may be a striking evidence of the dark matter. As an example, the annihilation of wino-like neutralino dark matter in the SUSY SM, as is realized in the anomaly-mediated SUSY breaking models, can account for the positron excess for the mass $m_\chi \sim 150$-200 GeV. Interestingly enough, this can also solve the current discrepancy of the primordial lithium abundances between BBN prediction and observations. Such models with large annihilation cross section also predict large gamma-ray flux from the Galactic center, which may be observed by on-going Fermi experiments.

Some comments are in order. The annihilation of wino-like neutralino yields $W$-bosons and they produce anti-protons, which should be compared with observations [7]. As opposed to the case of positron, the anti-proton flux sensitively depends on the choice of the diffusion zone, leading to orders of magnitude uncertainty in the resultant anti-proton flux [40]. Within these uncertainties, the anti-proton flux from light wino DM with mass of a few hundred GeV is consistent with observations [41]. Another constraint may come from the synchrotron radiation emitted by the electron/positrons from DM annihilation in the Galactic center [42, 43]. However, it also suffers from large astrophysical uncertainty such as distribution of the Galactic magnetic field, which also leads to orders of magnitude uncertainty in the synchrotron flux, and it is too early to regard the synchrotron emission as a robust constraint on the DM annihilation model [44]. Finally, we comment on the neutrino flux coming from the DM annihilation, which can also be constrained from the observation of Super-Kamiokande [45]. In the case of wino-like neutralino, this constraint is safely satisfied.

Although we have focused on the wino-like DM case, similar analyses can be applied to other DM candidates. The Higgsino-like neutralino has about one order of magnitude smaller annihilation cross section than that of the wino, with similar annihilation modes. Thus, in order to explain the positron excess by the Higgsino-like dark matter, boost factor larger than 10 is required. The BBN constraint is easily satisfied in this case though the lithium problem is not solved. Generic, non-thermal DM production scenarios [46] predict enhancements of the indirect signals [47, 48], and such scenarios may account for the currently observed positron excess and cosmic lithium abundances simultaneously.

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