Galactic 511 keV line from MeV millicharged dark matter

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(Received 28 November 2007; revised manuscript received 11 March 2008; published 3 June 2008)

We present a possible explanation of the recently observed 511 keV γ-ray anomaly with a new "millicharged" fermion. The new fermion is light [$\mathcal{O}$(MeV)] but has never been observed by any collider experiments mainly because of its tiny electromagnetic charge εe. We show that constraints from its relic density in the Universe and collider experiments allow a parameter range such that the 511 keV cosmic γ-ray emission from the galactic bulge may be due to positron production from this millicharged fermion.

DOI: 10.1103/PhysRevD.77.123503 PACS numbers: 95.35.+d, 12.60.Cn, 98.70.Rz

The SPI/INTEGRAL observation of the very sharp γ-ray peak at 511 keV from the galactic bulge [1,2] needs an explanation of its origin. Most probably, it may come from the positronium decay. For this explanation of the positronium decay, a sufficient number of positrons are needed in the first place. The positron abundance in the galaxy can arise from several origins.

Some obvious candidates are the astrophysical production mechanisms of positrons discussed in [3]. However, these mechanisms through astrophysical sources such as black holes and supernovae turn out to be inappropriate to explain the intensity of the positron annihilation flux, especially in emission region, because the astrophysical sources like black holes and supernovae are expected to be more spread out than observed. Therefore, now the most preferred interpretations of the 511 keV γ-rays rely on particle physics origins where new particles beyond the standard model (SM) are introduced.[1] Usually a new particle in the mass range 1–100 MeV is introduced [5].[2] Let us call this new particle χ. Recent analysis including the internal bremsstrahlung radiation and in-flight annihilation gives more stringent mass bound for the light particle in MeV region: $m \lesssim$ 3–4 MeV.[3] The needed positron abundance may arise from the χ decay and/or $\chi - \bar{\chi}$ annihilation to e^+e^-. The new light particle should have negligible couplings to photon and Z boson; otherwise it must have been observed at the LEP experiments. If the new particle is neutral under the gauge transformations of the SM as a heavy neutrino, it overcloses the Universe as noted by Lee and Weinberg [8]. Thus, we exclude the neutrino possibility toward the origin of the 511 keV line. This has led to a new particle, coupling to another gauge boson beyond the SM, e.g. as in Ref. [9].

If another light $U(1)$ gauge boson, which will be called "*exphoton*,"[4] beyond the SM exists, most probably a kinetic mixing can exist via loop effects [10] between the photon and exphoton without violating the charge conservation principle. After a proper diagonalization procedure of the kinetic energy terms, then the electromagnetic charge of χ can be millicharged. In heterotic string models, the extra E_8' gauge group may contain the exphoton, leading to the kinetic mixing [11]. Indeed, an explicit model for this kind from string exists in the literature [12].

Very light [$\mathcal{O}$(eV)] millicharged particles with a sufficiently small charge are phenomenologically acceptable as studied in recent papers [13]. On the other hand, the heavy millicharged particle idea as a dark matter (DM) candidate was suggested about 20 years ago [14] and it has been revived recently [15]. The intermediate $\mathcal{O}$(MeV) millicharged particles have not been ruled out by observations in the previous study [16] which, however, did not include the 511 keV line possibility. Earlier, the $\mathcal{O}$(MeV) millicharged particle effect on cosmic microwave background radiation was studied in the parameter region of the exphoton coupling constant ($\alpha_{\rm ex} \equiv e_{\rm ex}^2/4\pi \sim 0.1$) [17]. Here, we analyze the urgent problem of the $\mathcal{O}$(MeV) millicharged particles toward interpreting the 511 keV line within the limit provided by the DM constraint with reasonable exphoton coupling constants.[5]

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[1] We have noticed a recent claim that the 511 keV line distribution reported in the newest result from INTEGRAL seems to resemble the lopsided distribution of the "hard" low mass x-ray binaries (LMXBs) (low mass x-ray binaries with strong emission at $E_\gamma > 20$ keV) [4]. However quantitatively improved understanding of 511 keV gamma-ray flux coming from LMXBs is required to see if the LMXB can fully account the anomaly. More observation would also be required for this issue.

[2] See also [6] where $\mathcal{O}$(100) GeV weakly interacting massive particles are considered.

[3] This constraint can be released by a factor of two by a possible ionization of the propagation medium [7].

[4] In the literature, the term "paraphoton" is commonly used. However, we use "exphoton" to emphasize the word "extra" which only directly couples to the extra matter field χ and it is the gauge boson of the extra $U(1)$. Moreover, this can show the fact that the extra E_8' gauge group may contain the exphoton in heterotic string models.

[5] The laboratory and cosmological bound of millicharged particles was studied sometime ago [16], but the study toward 511 keV line and the subeV mass range has not been included.

Consider two Abelian gauge groups $U(1)_{\rm QED}$ and $U(1)_{\rm ex}$.[6] The kinetic mixing of $U(1)_{\rm QED}$ photon and $U(1)_{\rm ex}$ exphoton is parameterized as

$$\mathcal{L} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\xi}{2}\hat{F}_{\mu\nu}\hat{X}^{\mu\nu}, \quad (1)$$

where $\hat{A}_\mu(\hat{X}_\mu)$ is the $U(1)_{\rm QED}(U(1)_{\rm ex})$ gauge boson and its field strength tensor is $\hat{F}_{\mu\nu}(\hat{X}_{\mu\nu})$. The kinetic mixing is parameterized by ξ which is generically allowed by the gauge invariance and the Lorentz symmetry. In the low-energy effective theory, ξ is considered to be a completely arbitrary parameter. An ultraviolet theory is expected to generate the kinetic mixing parameter ξ [10]. The usual diagonalization procedure of these kinetic terms leads to the relation,

$$\begin{pmatrix} A_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\xi^2} & 0 \\ \xi & 1 \end{pmatrix}\begin{pmatrix} \hat{A}_\mu \\ \hat{X}_\mu \end{pmatrix}, \quad (2)$$

and we obtain

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - \tfrac{1}{4}X_{\mu\nu}X^{\mu\nu}, \quad (3)$$

where the new field strengths are $F_{\mu\nu}$ and $X_{\mu\nu}$. Photon corresponds to A_μ and *exphoton* corresponds to X_μ. If the exphoton is exactly massless, there exists an $SO(2)$ symmetry in the $A_\mu - X_\mu$ field space: $A_\mu \to \cos\theta A_\mu + \sin\theta X_\mu$ and $X_\mu \to -\sin\theta A_\mu + \cos\theta X_\mu$. Any physical observable, however, does not depend on θ.

Using the above $SO(2)$ symmetry, let us take the following simple interaction Lagrangian of a SM fermion, i.e. electron, with a photon in the original basis as

$$\mathcal{L} = \bar{\psi}(\hat{e}Q\gamma^\mu)\psi\hat{A}_\mu. \quad (4)$$

Note that in this basis there is no direct interaction between the electron and the hidden sector gauge boson $\hat{X}$. If there exists a hidden sector Dirac fermion χ with the $U(1)_{\rm ex}$ charge Q_χ, its interaction with the hidden sector gauge boson is simply represented by

$$\mathcal{L} = \bar{\chi}(\hat{e}_{\rm ex}Q_\chi\gamma^\mu)\chi\hat{X}_\mu, \quad (5)$$

where $\hat{e}_{\rm ex}$ can be different from $\hat{e}$ in general. In this case, there is also no direct interaction between the hidden fermion and the visible sector gauge boson $\hat{A}$. We can recast the Lagrangian (4) in the transformed basis A and X,

$$\mathcal{L} = \bar{\psi}\left(\frac{\hat{e}}{\sqrt{1-\xi^2}}Q\gamma^\mu\right)\psi A_\mu. \quad (6)$$

Here, one notices that the standard model fermion has a coupling only to the visible sector gauge boson A even after changing the basis of the gauge bosons. However, the coupling constant $\hat{e}$ is modified to $\hat{e}/\sqrt{1-\xi^2}$, and so the physical visible sector coupling e is defined as $e \equiv \hat{e}/\sqrt{1-\xi^2}$. Similarly, we derive the following for χ,

$$\mathcal{L} = \bar{\chi}\gamma^\mu\left(\hat{e}_{\rm ex}Q_\chi X_\mu - \hat{e}_{\rm ex}\frac{\xi}{\sqrt{1-\xi^2}}Q_\chi A_\mu\right)\chi. \quad (7)$$

In this basis, the hidden sector matter field χ now can couple to the visible sector gauge boson A with the coupling $-\hat{e}_{\rm ex}\xi/\sqrt{1-\xi^2}$. In terms of the aforementioned $SO(2)$ symmetry, it simply means the mismatch between the gauge couplings of the electron and other fermions. Thus, we can set the physical hidden sector coupling $e_{\rm ex}$ as $e_{\rm ex} \equiv \hat{e}_{\rm ex}$ and we define the coupling of the field χ to the visible sector gauge boson A, introducing the millicharge parameter ε, as $\varepsilon e \equiv -e_{\rm ex}\xi/\sqrt{1-\xi^2}$. Note in general that $e \neq e_{\rm ex}$. Since $\xi \simeq \varepsilon e/e_{\rm ex}$ is expected to be small, the condition $\xi < 1$ gives $\alpha_{\rm ex}/\alpha > \varepsilon^2$. From a fundamental theory, one can calculate the ratio $e_{\rm ex}/e$ in principle, which is possible with the detail knowledge of the compactification radius [20]. Here, we simply take the ratio as a free parameter.

For the cosmological study of χ, we need the annihilation cross sections of DM: $\chi\bar{\chi} \to e^-e^+$, $\chi\bar{\chi} \to 2\gamma_{\rm ex}$, $\chi\bar{\chi} \to \gamma\gamma_{\rm ex}$, and $\chi\bar{\chi} \to \gamma\gamma$. The ratio for these cross sections is given by

$$\sigma_{2\gamma_{\rm ex}}:\sigma_{e+e-}:\sigma_{\gamma\gamma_{\rm ex}}:\sigma_{2\gamma} \simeq \alpha_{\rm ex}^2:\varepsilon^2\alpha^2:\varepsilon^2\alpha\alpha_{\rm ex}:\varepsilon^4\alpha^2. \quad (8)$$

We noticed that the first two channels (depicted in Fig. 1) are important and the last two channels are quite suppressed in the parameter region where ε and $\alpha_{\rm ex}/\alpha$ are quite *small* as is required by the observational data. If $\alpha_{\rm ex}/\alpha > 0.01(0.1)$, the background diffuse gamma-ray flux could be larger than 1(10)% of the 511 keV flux, so the region is already excluded by the INTEGRAL and COMPTEL measurements [7,21] (see Fig. 2). As we will see below, $\chi\bar{\chi} \to 2\gamma_{\rm ex}$ channel [(b) in Fig. 1] overwhelmingly dominates in the first two main channels of Fig. 1.

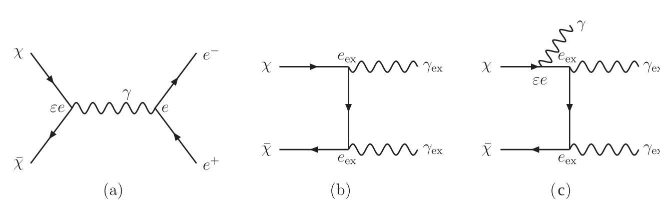

FIG. 1. The millicharge annihilation diagrams to, (a) e^+e^- and (b) $2\gamma_{\rm ex}$; (c) the bremsstrahlung diagram related to (b). The cross diagram in (b) is not shown.

[6]One should note that the $U(1)$ mixing in the observable and hidden sectors should be considered carefully. For the simple assumption of the charges given in Ref. [18], the χ coupling with the full strength to the massive exphoton does not couple to the massless photon, or at least suppressed by ε. Converting this argument, the massive Z-boson mixing with the massless exphoton gives the neutrino coupling to the exphoton suppressed by ε. Thus, the very stringent supernovae cooling constraint which gives a bound for the low-energy dark matter ($m >$ 10 MeV) [19] does not apply to our case since $\nu\chi$ cross section is suppressed by ε^2 compared to that of [19].

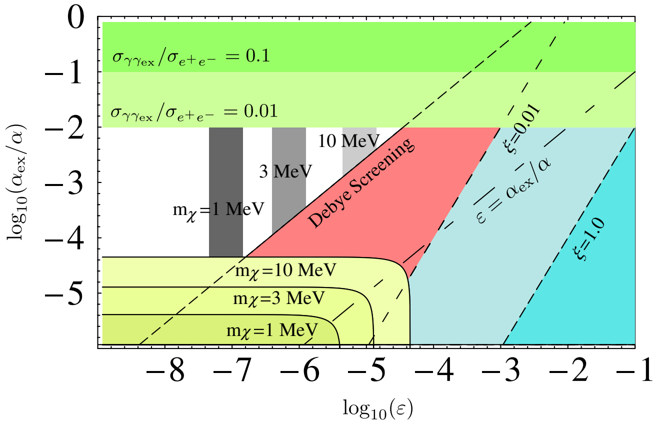

FIG. 2 (color online). The plot for $\alpha_{\rm ex}/\alpha$ versus ε. The lower left corner (yellow shaded regions) is excluded by the DM relic density constraint: the lines correspond to $\Omega_\chi h^2 = 0.11$ and $m_\chi = 1$, 3, and 10 MeV, respectively. The vertical bands (grey shaded regions) are the allowed range of ε that will be given by the 511 keV γ-ray flux constraint analysis: the regions correspond to $m_\chi = 1$, 3, and 10 MeV, respectively. The region excluded by the Debye screening is shown from the central (pink shaded) region to the lower right corner marked by Debye screening.. The (green) region $\alpha_{\rm ex}/\alpha > 0.01(0.1)$ is excluded since more than 1(10)% diffuse gamma-ray flux compared to the 511 keV flux is expected.

Then it seems that the gamma-ray flux from the real bremsstrahlung [(c) in Fig. 1] could be of considerable amount. However, the bremsstrahlung cross section is suppressed by a factor of $\varepsilon^2\alpha$ compared to that of diagram (b) in Fig. 1. Thus, $\sigma^{\rm brem}_{2\gamma_{\rm ex}} \sim \alpha(\alpha_{\rm ex}/\alpha)^2\sigma_{e^+e^-}$ and is negligible. The annihilation cross sections determine the relic density of the hidden sector fermion χ. The process $\chi\bar\chi \to e^-e^+$ determines the flux of the eventual 511 keV photons as well. Let us assume that the charge of the χ particle is $(0, \hat e_{\rm ex})$ in the basis of $(\hat A, \hat X)$. The millicharge εe comes from the shift of the exphoton field in Eq. (7) and $e_{\rm ex}$ is for the hidden sector $U(1)_{\rm ex}$ gauge interaction.

The cross section for the process $\chi\bar\chi \to e^-e^+$, shown in Fig. 1(a), is given by

$$\sigma_{\chi\bar\chi\to e^-e^+} = \frac{4\pi}{3}\frac{\varepsilon^2\alpha^2}{s}\frac{\beta_e}{\beta_\chi}\left[1 + 2\frac{m_e^2 + m_\chi^2}{s} + \frac{4m_e^2m_\chi^2}{s^2}\right], \tag{9}$$

where $\beta_i = \sqrt{1 - 4m_i^2/s}$ is the velocity of the particle-i and $\alpha \equiv e^2/4\pi$. In the nonrelativistic regime, the approximation $E \sim m_\chi + \frac{1}{2}m_\chi(v_{\rm rel}/2)^2$ makes sense and we obtain

$$\sigma_{\chi\bar\chi\to e^-e^+} = \pi\varepsilon^2\alpha^2\frac{1}{m_\chi^2}\frac{1}{v_{\rm rel}}\left[1 - \frac{m_e^2}{m_\chi^2}\right]^{1/2}\left[1 + \frac{m_e^2}{2m_\chi^2}\right] + \cdots. \tag{10}$$

Now, the cosmologically interesting average of the cross section times velocity, $\langle\sigma v\rangle_{e^-e^+}$, becomes $\langle\sigma v\rangle_{e^-e^+} = a_{e^-e^+} + b_{e^-e^+}\langle v^2\rangle + \mathcal{O}(\langle v^4\rangle)$ where $a_{e^-e^+}$ and $b_{e^-e^+}$ are given by Eq. (10),

$$a_{e^-e^+} = \frac{\pi\varepsilon^2\alpha^2}{m_\chi^2}\left[1 - \frac{m_e^2}{m_\chi^2}\right]^{1/2}\left[1 + \frac{1}{2}\frac{m_e^2}{m_\chi^2}\right],$$
$$b_{e^-e^+} = \frac{23\pi\varepsilon^2\alpha^2}{96m_\chi^2}\left[1 - \frac{m_e^2}{m_\chi^2}\right]^{-1/2}\left[\frac{59}{46}\frac{m_e^4}{m_\chi^4} + \frac{1}{2}\frac{m_e^2}{m_\chi^2} - 1\right]. \tag{11}$$

Similarly, for the process $\chi\bar\chi \to 2\gamma_{\rm ex}$ shown in Fig. 1(b), we obtain

$$\frac{d\sigma_{\chi\bar\chi\to2\gamma_{\rm ex}}}{d\cos\theta} = \frac{2\pi\alpha_{\rm ex}^2}{s\beta_\chi} \times\left[\frac{1 + 2\beta_\chi^2\sin^2\theta - \beta_\chi^4(2\sin^2\theta + \cos^4\theta)}{(1 - \beta_\chi^2\cos^2\theta)^2}\right], \tag{12}$$

where $\alpha_{\rm ex} \equiv e_{\rm ex}^2/4\pi$. The total cross section is given by $\sigma_{\chi\bar\chi\to2\gamma_{\rm ex}} = \int_0^1 d(\cos\theta)\frac{d\sigma}{d\cos\theta}$. In this case also, the cosmological average of the annihilation cross section times velocity, $\langle\sigma v\rangle_{2\gamma_{\rm ex}}$, is expressed in powers of v^2 as $\langle\sigma v\rangle_{2\gamma_{\rm ex}} = a_{2\gamma_{\rm ex}} + b_{2\gamma_{\rm ex}}\langle v^2\rangle + \mathcal{O}(\langle v^4\rangle)$ where $a_{2\gamma_{\rm ex}} = \pi\alpha_{\rm ex}^2/m_\chi^2$ and $b_{2\gamma_{\rm ex}} = \frac{11}{32}a_{2\gamma_{\rm ex}}$. Again, we neglected the contributions from $\chi\bar\chi \to \gamma\gamma_{\rm ex}$, $\gamma\gamma$ because of the smallness of ε and $\alpha_{\rm ex}/\alpha$.

The relic density of a generic relic, X, can be expressed as

$$\Omega_X h^2 \approx \frac{1.07\times10^9\ {\rm GeV}^{-1}}{M_{\rm Pl}}\frac{x_F}{\sqrt{g_*}}\frac{1}{(a + 3b/x_F)}$$
$$\approx 8.77\times10^{-17}\ {\rm MeV}^{-2}\frac{x_F}{\sqrt{g_*}}\frac{1}{(a + 3b/x_F)}, \tag{13}$$

where g_* is evaluated at the freeze-out temperature T_F, a and b are the velocity independent and dependent coefficients, respectively, and $x_F = m_X/T_F \simeq 17.2 + \ln(g/g_*) + \ln(m_X/{\rm GeV}) + \ln\sqrt{x_F} \sim 12$–$19$ for particles in the MeV–GeV range [22]. We can approximate $x_F \approx 11.6 + \ln(m_X/{\rm MeV})$ for $1\ {\rm MeV} \lesssim m_X \lesssim 100\ {\rm MeV}$. Therefore, we can estimate the relic density of the millicharged particle, χ, as

$$\Omega_\chi h^2 \approx 1.60\times10^{-13}\frac{(11.6 + \ln\bar m)\bar m^2}{(\frac{\alpha_{\rm ex}}{\alpha})^2 + \varepsilon^2(1 - \frac{m_e^2}{m_\chi^2})^{1/2}(1 + \frac{m_e^2}{2m_\chi^2})}, \tag{14}$$

where $\bar m \equiv m_\chi/{\rm MeV}$ and we put $g_* \simeq 10.75$ for $1 < T_F/{\rm MeV} < 100$.[7] Finally, we can find a constraint

[7]In this step, we use the total annihilation cross section, i.e. $a = a_{e^-e^+} + a_{2\gamma_{\rm ex}}$ and $b = b_{e^-e^+} + b_{2\gamma_{\rm ex}}$.

for the mass m_χ and the charge ε of the millicharged DM and the hidden sector coupling $\alpha_{\rm ex}$, based on the relic density of DM from the WMAP three-year results [23]. In Fig. 2, we present the excluded parameter space for typical DM masses ($m_\chi = 1, 3$ and 10 MeV) as the yellow shaded regions from our analysis of the DM relic density.

In charged medium, the photon can effectively obtain mass via the interaction with charged particles. Therefore, this effective mass should be smaller than the limit of the photon mass. As a result, the Debye screening length in the DM medium around Earth $\lambda_D = \sqrt{T_\chi/\varepsilon^2 e^2 n_\chi}$ is required to be larger than the limit of the inverse photon mass [24,25]. Putting $n_\chi = \rho_\chi/m_\chi \simeq 0.3\ {\rm GeV/cm^3} \times \Omega_\chi/(\Omega_{\rm DM} m_\chi)$ and $\Omega_{\rm DM} \simeq 0.23$, we finally get the simple relation $\frac{\alpha_{\rm ex}}{\alpha} \gtrsim 282\varepsilon$. One should note that the relic density of χ is essentially proportional to m_χ^2 so that the Debye screening length is not sensitive to the mass. The lower right corner from the central region (colored by pink) is excluded by this constraint. Interestingly, $m_\chi \gtrsim 3$ MeV does not have the parameter space which can fully accommodate the dark matter density $\Omega_{\rm DM} \simeq 0.23$.

The line $\varepsilon = \alpha_{\rm ex}/\alpha$ corresponds to the line of equal couplings that divides where the diagrams (a) and (b) in Fig. 1 dominate: in the upper part of the line the process $\chi\bar{\chi} \to 2\gamma_{\rm ex}$ and in the lower part the process $\chi\bar{\chi} \to e^- e^+$ dominate. In addition, we show the allowed range of ε for typical DM masses ($m_\chi = 1$, 3, and 10 MeV) as the (grey) vertical bands, which will be obtained from the following analysis of the 511 keV γ-ray flux constraint. For example, if $m_\chi = 3$ MeV, the middle (grey) shaded vertical band for ε in the left corner is allowed. The smallness requirement of ξ is buried in the Debye screening length constraint. The study of [17] is buried in the lower right corner around $\xi = 1$. As can be seen from the figure, a significant region is excluded. However, we note that there still remains an available space.

The observed flux of dark matter annihilation products can be obtained by integrating the density squared along the line of sight as

$$\Phi_i(\psi, E) = \sigma v \frac{dN_i}{dE} \frac{1}{4\pi m_{\rm DM}^2} \int_{\text{line of sight}} ds \rho^2(r(s, \psi)), \tag{15}$$

where $\rho(r)$ is the mass density of the DM, σ is the DM annihilation cross section, v is the velocity, dN_i/dE is the spectrum of secondary particles of species i, and s is the coordinate running along the line of sight, in a direction making an angle, ψ, from the direction of the galactic center. It is convenient to introduce the quantity $J(\psi)$ [26]:

$$J(\psi) = \frac{1}{8.5\ \text{kpc}} \left(\frac{1}{0.3\ \text{GeV/cm}^3}\right)^2 \int_{\text{line of sight}} ds \rho^2(r(s, \psi)), \tag{16}$$

by which the expression in Eq. (15) can be separated into "halo profile depending" factors and "particle physics depending" factors as

$$\Phi_i(\Delta\Omega, E) \simeq 5.6 \frac{dN_i}{dE} \left(\frac{\sigma v}{\text{pb}}\right) \times \left(\frac{1\ \text{MeV}}{m_{\rm DM}}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega\ \text{cm}^{-2}\,\text{s}^{-1}, \tag{17}$$

where $\bar{J}(\Delta\Omega)$ is defined as the average of $J(\psi)$ over a spherical region of solid angle, $\Delta\Omega$, centered on $\psi = 0$ [22].

If the mass of the DM particle is less than the muon mass, the low velocity annihilations can produce electron-positron pairs. Most positrons lose energy through their interactions with the interstellar medium (ISM) and bremsstrahlung radiation and go rest. Then positron annihilation takes place via the positronium formation ($\sim 96.7 \pm 2.2\%$) [2] and partly via the direct annihilation into two 511 keV gamma rays. Only 25% of the time, a singlet positronium state decaying to two 511 keV photons is formed while 75% of the time, a triplet state decaying to three continuum photons is formed. This means that the 511 keV photon emission occurs only by a quarter of the total positron production through DM annihilation. After taking all this into account, the flux of 511 keV γ-rays from the galactic center can be given as

$$\Phi_{\gamma,511} \simeq 0.275 \times 5.6 \left(\frac{\sigma v}{\text{pb}}\right) \times \left(\frac{1\ \text{MeV}}{m_\chi}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega\ \text{cm}^{-2}\,\text{s}^{-1}, \tag{18}$$

where $\Delta\Omega$ is the observed solid angle toward the direction of the galactic center.

The observed γ-ray profile has a full width at half maximum of $\sim 6°$ with a $4°$–$9°$ 2σ confidence interval and the flux $\Phi_{\gamma,511} \simeq (1.02 \pm 0.10) \times 10^{-3}\ \text{ph}\,\text{cm}^{-2}\,\text{s}^{-1}$ [1,2]. Thus, we consider a solid angle of 0.0086 sr, corresponding to a 6° diameter circle. In this model, positron is produced from the process $\chi\bar{\chi} \to e^- e^+$. Therefore, we can find the charge ε of the millicharged DM as a function of its mass m_χ from the resultant cross section $\langle\sigma v\rangle_{e^- e^+}$ for this process and Eq. (18). The relation is given by

$$\varepsilon \simeq 1.0 \times 10^{-6} \frac{\bar{m}^2}{\sqrt{\bar{J}}} \left[1 - \frac{m_e^2}{m_\chi^2}\right]^{-1/4} \left[1 + \frac{m_e^2}{2m_\chi^2}\right]^{-1/2}, \tag{19}$$

where $\bar{m} \equiv m_\chi/\text{MeV}$. To estimate the required parameter space, we use the width of the observed distribution $\bar{J}(0.0086\ \text{sr}) \sim 50$–500, approximately corresponding to $\gamma \simeq 0.6$–1.2 essentially following the approach of Ref. [27].[8]

[8] If the main source of 511 keV γ rays from galactic bulge is from the DM annihilation, the observed distribution of 511 keV emission line would constrain the shape of the DM halo profile because DM annihilation rate is proportional to the DM density squared.

There already exist various bounds from experimental and observational results, which are summarized in [16]. Among them, the limit from the millicharged particle search experiment at SLAC [28] is relevant to the mass-charge parameter space, which is considered in this analysis. In principle, the DM can contribute to the anomalous magnetic moment [29], but it can only occur at the two-loop level with an additional ε^2 suppression factor. The expected recoil energy by the DM-nucleon scattering is too small to be measured by the existing or near-future experiments because of the lightness of the proposed DM candidate.

The result from the study of the 511 keV γ-ray flux and the SLAC experiment is presented in Fig. 3 in the $\varepsilon - m_\chi$ space. Even after taking into account the SLAC bound for the millicharged particle, a large parameter region is still remaining. Recent analysis such as the internal bremsstrahlung radiation and in-flight annihilation gives strong mass bound for the light dark matter in MeV region: $m \lesssim 3$–4 MeV.[9] Therefore, the lower left corner is magnified. In the allowed parameter region ($1 \gg \alpha_{\rm ex}/\alpha > \varepsilon$), the relic density of DM is essentially determined by $\chi\bar{\chi} \to 2\gamma_{\rm ex}$. However, the observed 511 keV photon flux is mostly explained by $\chi\bar{\chi} \to e^- e^+$. In this respect, the difficulty of explaining both quantities in Ref. [27] is easily avoided in our model.

One final comment is about the spontaneously broken $U(1)_{\rm ex}$ symmetry which results in the nonvanishing exphoton mass. In this case, the electrically charged particles such as electron and proton can couple to the exphoton though the hidden fermion (χ) does not directly couple to the on-shell photon [18]. In principle, this case can be also relevant to our DM problem and the related 511 keV photon line. Theoretically, spontaneous symmetry breaking generally gives finite ranges of parameter space both for massless and massive exphotons and hence our study on massless exphoton covers a finite range of the parameter space. In the future, we would like to discuss the cosmology of $\mathcal{O}$(MeV) exphoton.

In conclusion, we presented an allowed parameter range of a new millicharged particle χ with $\mathcal{O}$(MeV) mass toward a possible solution to the recently observed 511 keV cosmic γ-ray anomaly. It couples to photon with a "milli" electric charge strength, εe. In the mass range of $m_\chi \lesssim$ 1 MeV, the millicharged particle can constitute a sizable ($\gtrsim 10\%$) portion of the DM content of the Universe but might have escaped detection so far in any collider experiments basically because of its tiny electric charge. This millicharged particle may arise in a more fundamental theory such as string as an interplay between the observable and hidden sectors.

[9] As already stated in the beginning, this constraint can be reduced by a factor of two by a possible ionization of the medium [7].

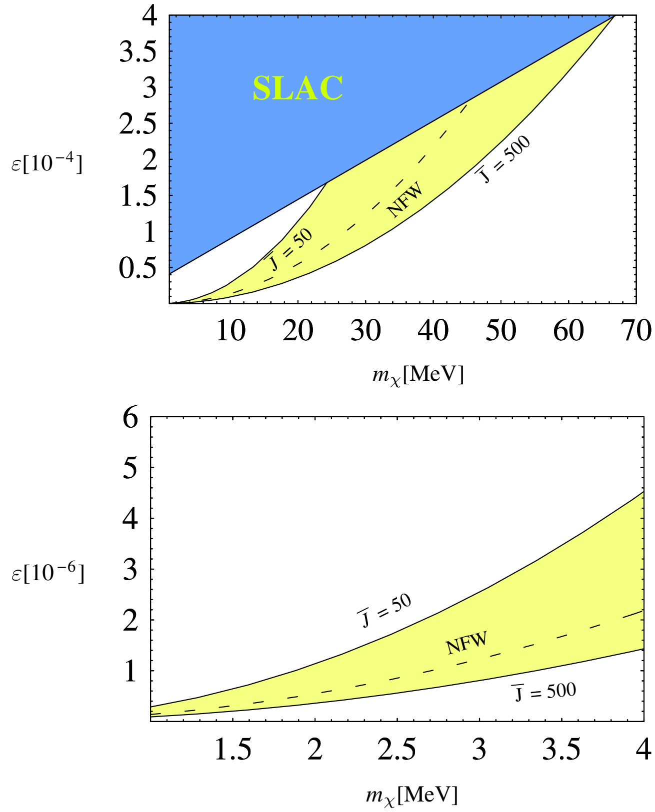

FIG. 3 (color online). The plot for ε versus m_χ. The dark (blue) shaded region is excluded by the SLAC search of millicharged particles [28]. We plot the Navarro-Frenk-White profile [30] model line (dotted) using the fitting parameter ($R =$ 20 kpc, $\rho_0 = 0.347$ GeV/cm^3) and the lightly shaded (yellow) region for the uncertainty range $\bar{J}(0.0086$ sr$) \sim 50$–500. After considering the recently given strong constraint on the light dark matter mass [7], the allowed region is $m_\chi \lesssim 4$ MeV (bottom).

This work was supported in part by the Korea Research Foundation Grant funded by the Korean Goverment (MOEHRD) (No. KRF-2005-084-C00001 and No. R14-2003-012-01001-0). S. C. P. is supported by the BK21 program of the Ministry of Education.

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