Electron-positron Annihilation Lines and Decaying Sterile Neutrinos

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Abstract If massive sterile neutrinos exist, their decays into photons and/or electron-positron pairs may give rise to observable consequences. We consider the possibility that MeV sterile neutrino decays lead to the diffuse positron annihilation line in the Milky Way center, and we thus obtain bounds on the sterile neutrino decay rate $\Gamma_\nu \geq 10^{-28}$ s$^{-1}$ from relevant astrophysical/cosmological data. Also, we expect a soft gamma flux of $1.2 \times 10^{-4} - 9.7 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$ from the Milky Way center which shows up as a small MeV bump in the background photon spectrum. Furthermore, we estimate the flux of active neutrinos produced by sterile neutrino decays to be $0.02 - 0.1$ cm$^{-2}$ s$^{-1}$ passing through the earth.

Keywords dark matter, Milky Way

1 Introduction

Understanding the nature of dark matter remains a fundamental problem in astrophysics and cosmology. Since the discovery of neutrinos’ non-zero rest mass (Fukuda et al. 1998; Bilenky et al. 1998), the possibility that neutrinos contribute to cosmological dark matter has become a hot topic again. In particular, the sterile neutrinos belong to a class of candidate dark matter particles with no standard model interaction. Although the recent MiniBooNE data challenges the LSND result (Aguilar-Arevalo et al. 2007), more massive sterile neutrinos (e.g., keV, MeV) may still exist. The fact that active neutrinos have mass implies that right-handed neutrinos should exist which may indeed be massive sterile neutrinos. The existence of the sterile neutrinos has been invoked to explain many phenomena such as missing mass (Dodelson and Widrow 1994; Shi and Fuller 1999) and the high temperature of the hot gas in Milky Way and clusters (Chan and Chu 2007, 2008). Therefore, it is worthwhile to discuss observational consequences if massive sterile neutrinos exist, which may decay into light neutrinos, positron-electron pairs and photons. In this article, we consider the possibility that sterile neutrino decays give rise to the 511 keV lines in Milky Way and thus obtain bounds on the mass $m_\nu$ and total decay rate $\Gamma$ of the sterile neutrinos using relevant observational data.

2 511 keV photon flux

The bright 511 keV annihilation line from Milky Way has been observed for a few decades (Leventhal et al. 1978; Knödlseder et al. 2003), and its origin has been much debated. Recent values of the 511 keV photon flux from the bulge and disk are $(1.05 \pm 0.06) \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ and $(0.7 \pm 0.4) \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ respectively (Knödlseder et al. 2005). Assuming a positronium fraction of $f_p = 0.93$, one can translate these intensities to annihilation rates of $(1.5 \pm 0.1) \times 10^{43}$ s$^{-1}$ and $(0.3 \pm 0.2) \times 10^{44}$ s$^{-1}$ respectively (Knödlseder et al. 2005). The annihilation rate in the bulge is several times larger than that in the disk. The source of positrons in the disk can be explained by the decay of $^{26}$Al. Using a disk model, the photon flux is calculated to be $5 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$, which can account for 60 – 100% of the disk emission (Knödlseder et al. 2003). However, the origin of the bulge source is still an open question in astrophysics. Recent observation by INTEGRAL/IBIS indicates that the upper limit of photon flux for resolved single point sources is $1.6 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$ (De Cesare et al. 2005), which means that the 511 keV annihilation line

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comes from mainly diffuse sources rather than point sources.

There have been many models trying to explain the 511 keV annihilation line of bulge emission. Potential sources include neutron stars or blackholes (Lingenfelter and Ramaty 1983), supernova remnants (Dermer and Murphy 2001), Wolf-Rayet stars (Ramaty et al. 1973), pulsar wind (Chi et al. 1996; Wang et al. 2006), and Gamma Ray Bursts (Lingenfelter and Huetter 1984).

None of these can provide a satisfactory explanation as they are mainly point sources. Boehm et al. (2004) proposed the annihilation of dark matter as a diffuse source. Recently, Picciotto and Pospelov (2005) and Khalil and Seto (2008) suggested that heavy sterile neutrinos with $m_s \geq 1$ MeV can be a diffuse source of the 511 keV photon flux. In the following, we extend the idea from these two papers and obtain bounds on the decay rate of sterile neutrinos from observational data of the 511 keV annihilation line.

### 2.1 Decay of Sterile Neutrinos

A sterile neutrino $\nu_s$ can decay into an electron-positron pair, photons and lighter neutrinos $\nu$ through different channels. The major channel is $\nu_s \rightarrow 3\nu$ with decay rate (Barger et al. 1995)

$$\Gamma_{3\nu} = \frac{G_F^2}{384\pi^3} \sin^2 2\theta m_s^5 = 1.77 \times 10^{-20} \sin^2 2\theta \left( \frac{m_s}{1 \text{ keV}} \right)^5 \text{s}^{-1}$$

(1)

where $G_F$ and $\theta$ are the Fermi constant and mixing angle of sterile neutrino with active neutrinos respectively. The radiative channel is $\nu_s \rightarrow \nu + \gamma$ with decay rate (Barger et al. 1995)

$$\Gamma_{\gamma} = \frac{9\alpha G_F^2}{1024\pi^3} \sin^2 2\theta m_s^5 = 1.38 \times 10^{-22} \sin^2 2\theta \left( \frac{m_s}{1 \text{ keV}} \right)^5 \text{s}^{-1}$$

(2)

where $\alpha$ is the fine structure constant. An electron-positron pair is produced through $\nu_s \rightarrow \nu + e^+ + e^-$ with decay rate (Picciotto and Pospelov 2005)

$$\Gamma_e = \frac{G_F^2}{384\pi^3} \sin^2 2\theta m_s^5 \left( \frac{|V|^2}{2} + \frac{1}{8} \right) \approx \Gamma_{3\nu} \left( \frac{|V|^2}{2} + \frac{1}{8} \right).$$

(3)

where $|V| < 1$ is a parameter. Therefore, the total decay rate is

$$\Gamma = \Gamma_{3\nu} + \Gamma_\gamma + \Gamma_e \approx \Gamma_{3\nu} + \Gamma_e = \Gamma_e \left( 4|V|^2 + 9 \right).$$

(4)

### 2.2 Positron channel

The positrons produced will be slowed down due to ionization losses. The power loss is approximately given by (Longair 1981)

$$\frac{dE}{dt} \sim -2 \times 10^{-10} \left( \frac{n}{1 \text{ cm}^{-3}} \right) (\ln \gamma + 6.6) \text{ eV/s},$$

(5)

where $\gamma$ is the Lorentz factor of the positron and $n$ is the average number density of electrons in the galactic bulge. The stopping distance $d$ for 1 MeV positrons in this process is about $10^{24}$ cm. Also we should consider the magnetic field in the Milky Way. The Larmor radius of positrons with energy $E_{e^+}$ is given by

$$r = \frac{E_{e^+}}{eB} = 10^{13} \left( \frac{E_{e^+}}{10^4 \text{ MeV}} \right) \left( \frac{B}{10^{-5} \text{ G}} \right) \text{ cm}.$$ 

(6)

The magnetic field strength in the Milky Way is about $B = 10^{-5}$ G. Therefore, for a 1 MeV positron, the Larmor radius is about $10^9$ cm. The stopping distance for the simple random walk of a positron, the distance that a positron is confined, is about $\sqrt{rd} \sim 1$ pc or less (Boehm et al. 2004), which is much shorter than the mean free path of the $e^\pm$ annihilation:

$$\bar{l}_{e^\pm} = \frac{1}{n\sigma_a} \sim 30 \text{ kpc},$$

(7)

where

$$\sigma_a = \frac{\pi e^2}{m_e c^2 (\gamma + 1)} \left[ \frac{\gamma^2 + 4\gamma + 1}{\gamma^2 - 1} \ln(\gamma + \sqrt{\gamma^2 - 1}) - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}} \right]$$

(8)

is the cross section of electron-positron annihilation (Heitler 1954). Therefore, the positrons will become non-relativistic before annihilation. However, the rate for a positron to annihilate with an electron in the diffuse region of Milky Way is

$$P \sim n\sigma_a v_e \sim 10^{-18} \text{ s}^{-1},$$

(9)

where $n \approx 0.1 \text{ cm}^{-3}$ (Muno et al 2004) and $v_e \approx 10^7 \text{ cm s}^{-1}$ is the mean speed of electrons in Milky Way (Marconi and Hunt 2003). In order to produce $10^{43} \text{ s}^{-1}$ $e^\pm$ annihilations, there must exist a large positron cloud with $10^{61}$ positrons in the Milky Way, and the initial production rate should be much greater than the annihilation rate.

Suppose a sterile neutrino halo is formed and the positron production rate is much higher than the annihilation rate during the galaxy formation due to the
small $n$ in the protogalaxy. The positrons will accumulate in the protogalaxy. The rate of change in the positron number density $n_{e^+}$ is given by

$$\dot{n}_{e^+} = n_s(t) \Gamma_e - n_{e^+} n \sigma_a v_e,$$  \hspace{0.5cm} (10)

where $n_s(t)$ is the number density of sterile neutrinos in the Milky Way at time $t$. Since we have $n_s(t) = n_{s0} e^{-t/\tau}$, where $n_{s0}$ is the initial number density of sterile neutrinos, the solution of Eq. (10) is

$$n_{e^+} = e^{-n \sigma_a v_e t} \left( \int n_{s0} \Gamma_e (n \sigma_a v_e - \Gamma_e) e^{-t/\tau} dt + C \right),$$  \hspace{0.5cm} (11)

where $C$ is a constant. After a long time, assuming an equilibrium is established at present time $t_0$, we have $n_s(t_0) \Gamma_e = n_{e^+} n \sigma_a v_e$. The total annihilation rate in the bulge is given by

$$A_{\text{bulge}} \approx \int_{R_B}^{R_B} 4\pi r^2 n_s(t_0) \Gamma_e dr,$$  \hspace{0.5cm} (12)

where $R_B$ is the bulge radius, which is assumed to be 2.40–3.71 kpc in the model used by Knödlseder et al. (2005). Similarly, the annihilation rate in the disk is given by

$$A_{\text{disk}} \approx \int_{R_B}^{R_D} 4\pi r h n_s(t_0) \Gamma_e dr,$$  \hspace{0.5cm} (13)

where $R_D$ and $h$ are the radius and half of the thickness of the disk respectively. In the disk models used by Knödlseder et al. (2005), the maximum $R_D$ is 15 kpc, and the scale heights of young and old disk models are 70 pc and 200 pc respectively. Here we assume that the sterile neutrino profile follows the dark matter profile, which can be modelled by the isothermal $n(s) = n_0 r^{-2}$ or NFW profile [Navarro, Frenk and White 1996]:

$$n_s = \frac{n_0}{r/a(1 + r/a)^2},$$  \hspace{0.5cm} (14)

where $a$ and $n_0$ are parameters in the NFW profile. In the isothermal profile, the ratio of the annihilation rate in the bulge to that in the disk is

$$\frac{A_{\text{bulge}}}{A_{\text{disk}}} = \frac{R_B}{h \ln (R_D/R_B)} \approx 6 - 13.$$  \hspace{0.5cm} (15)

In the NFW profile, the ratio is

$$\frac{A_{\text{bulge}}}{A_{\text{disk}}} = \frac{a}{h} \left[ \ln \left( \frac{R_B}{a} + 1 \right) - \frac{R_B/a}{R_B/a + 1} \right] \left( \frac{1}{R_B/a + 1} - 1 \right).$$  \hspace{0.5cm} (16)

Since over 60% of disk emission can be explained by the decay of $^{26}$Al, the lower bound of the ratio of the diffuse emission should be about 7. Therefore, the isothermal profile agrees better with the observed ratio. Furthermore, since $A_{\text{bulge}} = (1.5 \pm 0.1) \times 10^{43}$ s$^{-1}$, from Eq. (12), we have $n_0 \Gamma_e \sim 10^{22}$ m$^{-1}$ s$^{-1}$. The upper limit of central mass density in isothermal model constrains $m_s n_0 \leq 5.5 \times 10^{19}$ kg m$^{-1}$. For $m_s \geq 1$ MeV, we get $n_0 \leq 3 \times 10^{49}$ m$^{-3}$. Therefore, $\Gamma \geq 3 \times 10^{-28}$ s$^{-1}$. Similarly, for NFW model, we have $n_0 \Gamma_e \sim 4 \times 10^{-19}$ m$^{-3}$ s$^{-1}$ and $m_s n_0 \leq 3.2 \times 10^{-22}$ kg m$^{-3}$. For $m_s \geq 1$ MeV, we get $n_0 \leq 2 \times 10^8$ m$^{-3}$ and $\Gamma_e \geq 2 \times 10^{-27}$ s$^{-1}$. If $\Gamma_e \sim 10^{-28}$ s$^{-1}$ and $m_s \sim 1$ MeV, we can get $\sin^2 \theta \sim 10^{-24}$, which is consistent with the diffuse X-ray background constraint [Bovarsky et al. 2003].

2.3 Radiative channel

There exists another radiative decay channel which gives a photon flux $\Phi_{\gamma}$ with energy $m_s/2$:

$$\Phi_{\gamma} = \int_{\text{line of sight}} n_s \Gamma_e ds.$$  \hspace{0.5cm} (17)

The branching ratio is given by [Picciotto and Pospelov 2005]

$$\frac{\Phi_{\gamma}}{\Phi_{e^\pm}} = \frac{0.031}{4|V|^2 + 1},$$  \hspace{0.5cm} (18)

and therefore the photon flux should be $\Phi_{\gamma} = (1.2 \times 10^{-4} - 9.7 \times 10^{-4})$ ph cm$^{-2}$ s$^{-1}$. Basically, all the emitted photons are monochromatic with energy $E = m_s/2$. However, some of the photons will scatter with interstellar medium before reaching us. The probability of the scattering is

$$P_s = \int_{\text{line of sight}} n \sigma_s ds,$$  \hspace{0.5cm} (19)

where $\sigma_s$ is the Compton cross section. For $n \approx 1$ cm$^{-3}$, the total $P_s$ from the disk and bulge is $\approx 1 \times 10^{-2}$. Due to the scattering, the energy distribution of the photons reaching us is broadened slightly. Fig. 1 shows the contribution of the emitted photon flux (we assumed $E = 1$ MeV) together with the diffuse background photon flux $dE/dE = 2.62 (E/0.1$ MeV)$^{-2.75}$ MeV$^{-1}$ cm$^{-2}$ s$^{-1}$ [Kinzer et al. 1997]. The emitted photons contribute $2 + 15\%$ of the background flux at around 1 MeV, which shows a small MeV bump in the spectrum. The MeV bump is a classical problem in observational astronomy which is long conjectured to be a real feature in the spectrum [Kinzer et al. 1997]. However, the MeV bump is now commonly believed to be an artifact of
2.4 Active neutrino channel

The lighter active neutrinos are produced in the main decay channel. The total active neutrino flux due to sterile neutrino decays passing through the earth is \(0.02 - 0.1\) cm\(^{-2}\) s\(^{-1}\). The total number of active neutrinos passing through IceCube - the largest neutrino detector in the world - is about \(10^9\) s\(^{-1}\) (Wiebusch 2009). Although this flux is theoretically detectable, the energy of the decayed neutrinos is too small to be detected in current experiments (Lunardini 2006).

Active neutrinos may interact with neutrons or protons in a pulsar to produce electrons or positrons. The cross section of such interactions is \(\sigma_\nu \sim 10^{-41}(E_\nu/10\text{ MeV})\) where \(E_\nu\) is the energy of the neutrinos. For example, in a typical pulsar, the average number density is about \(10^{26}\) cm\(^{-3}\), and the mean free path for a 1 MeV neutrino in the pulsar is \(10^5\) cm. As the crust thickness is also of order \(10^5\) cm, almost every neutrino passing through a pulsar will interact with the neutrons and protons to produce electrons and positrons. As a result, a huge amount of electrons and positrons is produced and affected by the strong magnetic field \(B\) in the pulsars to emit synchrotron radiation. The synchrotron frequency of the electrons is given by

\[
f = \frac{\gamma_e^2 e B}{2\pi m_e c} = 2.8 \times 10^{18} \gamma_e^2 \left(\frac{B}{10^{12}\text{ G}}\right) \text{ Hz},
\]

where \(\gamma_e\) is the Lorentz factor of the electrons. Therefore, the frequency of the synchrotron radiation lies within the x-ray band. The power emitted by one electron is

\[
P_{\text{syn}} = \frac{2e^4 B^2 \gamma_e^2}{3m_e^2 c^3} = 7.9 \times 10^8 \gamma_e^2 \left(\frac{B}{10^{12}\text{ G}}\right)^2 \text{ erg s}^{-1}.
\]

For a pulsar with radius 10 km nearby, the total number of active neutrinos due to sterile neutrino decays passing through the pulsar is \(10^{12}\) s\(^{-1}\). Assuming \(B = 10^{12}\) G and \(\gamma_e = 4\), the total power emitted is \(\sim 10^{22}\) erg s\(^{-1}\), which is much less than the upper limit of the non-thermal x-ray luminosity in a typical pulsar \(10^{36}\) erg s\(^{-1}\) (Zavlin and Pavlov 2004). Therefore, only a very small peak near the synchrotron frequency may appear in the x-ray spectrum. Assuming that the \(10^5\) or so pulsars in Milky Way all see similar neutrino flux, the resulting synchrotron radiation can contribute about \(10^{27}\) erg s\(^{-1}\) to the background x-ray (Lyne et al. 1998).

### 3 Discussion and Summary

The fact that active neutrinos have finite masses implies that right-handed neutrinos should exist which may indeed be massive sterile neutrinos. The existence of the sterile neutrinos has been invoked to explain many astrophysical phenomena such as the cooling flow problem in clusters (Chan and Chu 2007). In this article, we consider the possibility that the decays of MeV sterile neutrinos act as a source of the 511 keV flux line. The decaying sterile neutrinos provide a diffuse source of positrons which can account for the required flux. The large bulge to disk ratio of 511 keV luminosity can also be accounted for if the decaying sterile neutrinos follow the isothermal distribution. From the observed 511 keV photon flux in the Milky Way, we obtain the allowed ranges of the sterile neutrino decay rate \(\Gamma \geq 10^{-28}\) s\(^{-1}\).

Although we do not have representative tight bounds on decay rate of sterile neutrinos, the results are still compatible with cosmological bounds and cluster cooling flow \(\Gamma \leq 10^{-17}\) s\(^{-1}\) (Chan and Chu 2007). The radiative decay channel produces soft gamma rays, with an expected flux of \(1.2 \times 10^{-4} - 9.7 \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\), which show up as a small MeV bump in the background photon spectrum. The total active neutrino flux due to sterile neutrino decays is estimated to be \(0.02 - 0.1\) cm\(^{-2}\) s\(^{-1}\) in the vicinity of the earth. These active neutrinos interact with neutrons and protons in pulsars to produce x-ray photons which may be detectable in the future.

### 4 Acknowledgements

This work is partially supported by a grant from the Research Grant Council of the Hong Kong Special Administrative Region, China (Project No. 400805).
References

Aguilar-Arevalo, A. A. et al. 2007, Phys. Rev. Lett., 98, 231801.
Barger, V., Phillips, R. J. N. and Sarkar, S. 1995, Phys. Lett. B, 352, 365.
Bilenky, S. M., Giunti, C. and Grimus, W. 1998, European Physical Journal C 1, 247.
Boehm, C. et al. 2004, Phys. Rev. Lett., 92, 101301.
Boyarsky, A., Ruchayskiy, O. and Shaposhnikov, M. 2009, Ann. Rev. Nucl. Part. Sci. 59, 191.
De Cesare, G. et al. 2006, Advances in Space Research, 38, 1457.
Chan, M. H. and Chu, M.-C. 2007, ApJ, 658, 859.
Chan, M. H. and Chu, M.-C. 2008, MNRAS, 389, 297.
Chi, X., Cheng, K. S. and Young, E. C. M. 1996, ApJ, 459, L83.
Choudhury, T. R. and Ferrara, A. 2006, [astro-ph/0603149].
Dermer, C. D. and Murphy, R. J. 2001, Proc. 4th INTEGRAL workshop (Alicante), ESA SP-459, 115.
Dodelson, S and Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17.
Fixsen, D. J. et al. 1996, ApJ, 473, 576.
Fukuda, Y. et al. 1998, Phys. Rev. Lett., 81, 1562.
Gelmini, G., Osoba, E., Palomares-Ruiz, S. and Pascoli, S. 2008, JCAP, 10, 29.
Hansen, S. H. and Haiman, Z. 2004, ApJ 600, 26.
Heitler, W. 1954, The Quantum Theory of Radiation, Clarendon Press, Oxford.
Hinshaw, G. et al. 2009, ApJS, 180, 225.
Katz, N., Weinberg, D. H. and Hernquist, L. 1996, ApJS, 105, 19.
Khalil, S. and Seto, O. 2008, JCAP, 10, 24.
Kinzer, R. L. et al. 1997, ApJ, 475, 361.
Knödlseder, J. et al. 2005, Astron. Astrophys, 441, 513.
Leventhal, M., MacCallum, C. J. and Stang, P. D. 1978, ApJ, 225, L11.
Lingenfelter, R. E. and Ramaty, R. 1983, in Positron-Electron Pairs in Astrophysics, ed. M. L. Burn, A. K. Harding and Ramaty, AIP conf. Proc., 267.
Lingenfelter, R. E. and Hueter, G. J. 1984, in High-Energy Transients in Astrophysics, ed. S. E. Woosley, AIP Conf. Proc., 558.
Longair, M. S. 1981, High-Energy Astrophysics, Vol. 2, Ch. 19.
Lunardini, C. 2006, [astro-ph/0610534].
Mapelli, M. and Ferrara, A. 2005, MNRAS, 364, 2.
Lyne, A. G. et al. 1998, MNRAS, 295, 743.
Marconi, A. and Hunt, L. K. 2003, ApJ, 589, L21.
Muno, M. P. et al. 2004, ApJ, 613, 326.
Munyaneza, F. and Viollier, R. D. 2002, ApJ, 564, 274.
Navarro, J. F., Frenk, C. S. and White, S. D. M. 1996, ApJ, 462, 563.
Osterbrock, D. E. 1974, Astrophysics of Gaseous Nebulae, W. H. Freeman and Company, San Francisco.
Piccioni, C. and Pospelov, M. 2005, Phys. Lett. B, 605, 15.
Pierpaoli, E. 2004, Phy. Rev. Lett., 92, 031301.
Ramaty, R., Kozlovsky, B. and Lingenfelter, R. E. 1979, ApJS, 40, 487.
Sasaki, S. and Umemura, M. 1996, ApJ, 462, 104.
Schrödel, R. et al. 2002, Nature, 419, 694.
Shi, X.-d. and Fuller, G. M. 1999, Phys. Rev. Lett., 82, 2832.
Sorel, M., Conrad, J. M. and Shaevitz, M. 2004, Phys. Rev. D, 70, 073004.
Spergel, D. N. et al. 2003, ApJS, 148, 175.
Spergel, D. N. et al. 2007, ApJS, 170, 377.
Tegmark, M., Silk, J. and Evrard, A., 1993, ApJ, 417, 54.
Viollier, R. D., Trautmann, D. and Tupper, G. B. 1993, Phys. Lett. B, 306, 79.
Wang, W., Pun, C. S. J. and Cheng, K. S. 2006, Astron. Astrophys., 446, 943.
Wiebusch, C. 2009, astro-ph/0907.2263.
Zavlin, V. E. and Pavlov, G. G. 2004, ApJ, 616, 452.
Fig. 1  The spectrum of the background photons including the MeV photons coming from sterile neutrino decays.