Interpreting the bounds on Solar Dark Matter induced muons at Super-Kamiokande in the light of CDMS results

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ABSTRACT

We consider the recent limits on dark matter - nucleon elastic scattering cross section from the analysis of CDMS II collaboration using the two signal events observed in CDMS experiment. With these limits we try to interpret the Super-Kamiokande (SK) bounds on the detection rates of up-going muons induced by the neutrinos that are produced in the sun from the decay of annihilation products of dark matter (WIMPs) captured in the solar core. Calculated rates of up-going muons for different annihilation channels at SK using CDMS bounds are found to be orders below the predicted upper limits of such up-going muon rates at SK. Thus there exists room for enhancement (boost) of the calculated rates using CDMS limits for interpreting SK bounds. Such a feature is expected to represent the PAMELA data with the current CDMS limits. We also show the dependence of such a possible enhancement factor (boost) on WIMP mass for different WIMP annihilation channels.
Weakly interacting massive particles (WIMP) as dark matter in our galaxy can be trapped inside massive heavenly bodies like sun due to later’s gravity [1]. This gravitational trapping may happen when such dark matter in course of its passage through sun undergoes elastic scattering off the nuclei present in the solar core which causes its final velocity to fall below its velocity of escape from solar gravitational pull. These trapped dark matter may undergo the process of pair-annihilation producing primarily $b$, $c$ and $t$ quarks, $\tau$ leptons, gauge bosons etc. Mass and composition of dark matter determine the annihilation products which in turn produce neutrinos and antineutrinos either through decay or pair annihilation. Such neutrinos from the dark matter annihilation in solar environment have also been studied by previous authors (e.g. [2]). Detection of such solar neutrinos in terrestrial detectors not only provides indirect evidence of dark matter but along with the results from the direct detection experiments of dark matter such as CDMS [3], DAMA [4], XENON [5] etc. provides more insight into the nature of dark matter and its interactions. Analysis of recent observations of two dark matter signal events with the Cryogenic Dark Matter Search experiment (CDMS II) at the Soudan Underground Laboratory combined with all previous CDMS II data has been reported by CDMS collaboration [6]. It sets new upper limits on the WIMP-nucleon elastic scattering cross section ($\sigma$) as a function of WIMP mass ($m_\chi$) [6]. The indirect searches for WIMPs through their annihilation in sun, with 1679.6 live days of data from SK detector using neutrino-induced upward through-going muons provide WIMP-induced upward muon flux limits at SK as a function of WIMP mass [7]. In this work we use the 90% Confidence Level (C.L.) limits on $\sigma(m_\chi)$ from recent CDMS analysis [6] to calculate corresponding limits on detection rates of up-going muons at SK as a function of WIMP mass ($m_\chi$) and compare them with the results in [7].

The differential flux of neutrinos of type $i (i = \nu_\mu, \bar{\nu}_\mu)$ at earth from WIMP annihilation products in the sun is given by [8]

$$\left(\frac{d\phi}{dE}\right)_i = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left(\frac{dN}{dE}\right)_{F,i}$$

where $R$ is sun-earth distance and $B_F$ is the annihilation branch for channel $F$. $(dN/dE)_{F,i}$ is the differential spectrum of neutrinos of type $i$ in the sun for the annihilation channel $F$. The total rate for WIMP annihilation in the sun, $\Gamma_A$ is given in [10]

$$\Gamma_A = \frac{1}{2}C \tanh^2[(aC)^{1/2}\tau]$$

where $\tau \approx 4.5$ Gyr is the age of sun. $a = \langle \sigma v \rangle / 4\sqrt{2}V$ is a function of the average WIMP annihilation cross section and the effective volume $V$ of WIMPs in the sun [10, 11, 1, 12, 13, 14]. Under the astrophysical assumptions on density and velocity distribution as mentioned in [10, 11] (local dark matter density, $\rho_\chi = 0.3$ GeV cm$^{-3}$, mean velocity of dark matter, $\bar{v} = 300$ km sec$^{-1}$, a Maxwellian distribution of velocities etc.) the dark matter capture rate $C$ in the sun is approximated as a function of the ratio of the WIMP-nucleus elastic scattering cross section to the dark matter mass as [10, 1]

$$C \approx 10^{29} \frac{\sigma_\chi}{m_\chi} \text{ GeV pb}^{-1}\text{sec}^{-1}$$
For such indirect detections of WIMPs at SK, neutrinos are detected through up-going muons produced by charged current interactions of neutrinos with the rock below the detector. With numerical values of this cross section, the muon range in the rock and expressing the energy distribution of neutrino flux in terms of its second moments, the total detection rate at SK detector of up-going muons induced by neutrinos from WIMP annihilation in the sun is given by [8]

\[ \Gamma_{\text{detect}} = (1.27 \times 10^{-20} \text{yr}^{-1}) \frac{C}{\text{sec}^{-1}} \left( \frac{m_\chi}{\text{GeV}} \right)^2 \sum_{i=\nu,\bar{\nu}} a_i b_i \sum_F B_F \left< N^2 \right}_{F,i} \times A_{\text{eff}} \]  

(4)

where, \( A_{\text{eff}} \approx 1200 \text{m}^2 \) is the muon effective area of the SK detector [15], \( a_i \)’s are the neutrino scattering coefficients. The range of neutrino induced muons in the rock are given as the coefficients \( b_i \). These coefficients are given by \( a_\nu = 6.8, a_\bar{\nu} = 3.1, b_\nu = 0.51, b_\bar{\nu} = 0.67 \) [8]. \( \left< N^2 \right>_{F,i} \)’s are the second moments of the spectrum of neutrino type \( i \) for the WIMP annihilation channel \( F \) in the sun. The \( \left< N^2 \right>_{F,i} \) for different channels relevant for the present calculations are listed below [8, 9].

(a) \( \tau \bar{\tau} \) channel:

\[ \left< N^2 \right>_{i}(E_{\text{inj}}) = \Gamma_{\tau \rightarrow \mu \nu} h_{\tau,i}(E_{\text{inj}} \tau_i) \quad (i = \nu, \bar{\nu}) \]  

(5)

where \( E_{\text{inj}} \) is the injection energy of the decaying WIMP annihilation product inside the sun, the branching ratio \( \Gamma_{\tau \rightarrow \mu \nu} \simeq 0.18, \tau_\nu(\tau_\bar{\nu}) = 1.01 \times 10^{-3} (3.8 \times 10^{-4}) \text{ GeV}^{-1} \) are the stopping coefficients for \( \nu(\bar{\nu}) \) and

\[ h_{\tau\nu}(y) = \frac{4 + y}{30(1 + y)^4} \]

\[ h_{\tau\bar{\nu}}(y) = \frac{168 + 354y + 348y^2 + 190y^3 + 56y^4 + 7y^5}{1260(1 + y)} \]  

(6)

(b) \( b\bar{b} \) channel:

\[ \left< N^2 \right>_{i}(E_{\text{inj}}) \approx \Gamma_{b \rightarrow \mu X} \left( \frac{E_d}{E_i} \right)^2 h_{b,i} \left( \sqrt{\left< E_d^2 \right>_{\tau_i}} \right) \]  

where, the branching ratio \( \Gamma_{b \rightarrow \mu X} = 0.103 \). The hadronization and the decay processes of the quarks from WIMP annihilation in the sun are characterized by the mean energy \( \left< E_d \right> \) of the hadron, \( \left< E_d \right> = E_c \exp \left( \frac{E_{d0}}{E_{d0}} \right) \left( \frac{E_d}{E_{d0}} \right) \), \( E_c = 470 \text{ GeV} \) [9]. \( E_{d0} = Z_f E_{\text{inj}} \) is the initial hadron energy for quarks injected with energy \( E_{\text{inj}} \) and \( Z_f(=0.73) \) is the quenching fraction for \( b \)-quarks to account for the loss of energy during hadronization, \( E_1(x) = \int_x^\infty \frac{e^{-y}}{y}dy \). Also \( \left< E_d^2 \right> = E_c \left( E_0 - \left< E_d \right> \right) \) and \( h_{b,i} \) is same as \( h_{\tau,i} \).

(c) \( W^+W^- \) and \( Z\bar{Z} \) channel:

\[ \left< N^2 \right>_{i}(E_{\text{inj}}) \bigg|_W \approx \frac{\Gamma_{W \rightarrow \mu \bar{\nu}}}{\beta} \frac{2 + 2E_\tau i(1 + \alpha_i) + E_\tau^2 \alpha_i(1 + \alpha_i)}{E_{\text{inj}}^2 \alpha_i(\alpha_i^2 - 1)(1 + E_\tau)^{\alpha_i+1}} \bigg|_{E=E_{\text{inj}}(1-\beta)/2} \bigg|_{E=E_{\text{inj}}(1+\beta)/2} \]  

(8)

\[ \left< N^2 \right>_{i}(E_{\text{inj}}) \bigg|_Z \approx \frac{2\Gamma_{Z \rightarrow \mu \bar{\nu} \mu}}{\beta} \frac{2 + 2E_\tau i(1 + \alpha_i) + E_\tau^2 \alpha_i(1 + \alpha_i)}{E_{\text{inj}}^2 \alpha_i(\alpha_i^2 - 1)(1 + E_\tau)^{\alpha_i+1}} \bigg|_{E=E_{\text{inj}}(1-\beta)/2} \bigg|_{E=E_{\text{inj}}(1+\beta)/2} \]  

(9)
The injection energy $E_{\text{inj}}$ is the energy with which the WIMP annihilation products $b\bar{b}$, $\tau\bar{\tau}$, $W$ and $Z$ etc. are produced. In this work we present our results for two benchmark scenarios namely $E_{\text{inj}} = m_\chi$ and $E_{\text{inj}} = m_\chi/3$.

Recently the CDMS collaboration announced two dark matter signal events with 90% C.L.[6] which set new limits on dark matter-nucleon scattering cross-section $\sigma$ for different $m_\chi$’s [6]. In this work we choose our set of $\sigma$’s and corresponding $m_\chi$’s from this limit (exclusion plot for “Soudan(all)” in Fig. 4 of Ref. [6]). With these CDMS limits on $\sigma$ we compute the detection rates for neutrino induced muons (from the product of the Dark Matter annihilation in the sun) for different annihilation channels. Thus we calculate the CDMS induced limits on event rates in SK. We compute the detection rate for neutrino induced muons (from the product of WIMP annihilation in the sun) using Eq. 4.

In this work we present our results for two benchmark scenarios namely $E_{\text{inj}} = m_\chi$ and $m_\chi/3$. A conservative estimate for neutrino production from WIMP annihilation in the sun is obtained by considering the dominating effect of $b\bar{b}$ production in the region $m_b < m_\chi < m_W$, that of $\tau\bar{\tau}$ and $W, Z$ production in the regions $m_W < m_\chi < m_t$ and $m_\chi > m_t$ respectively [8], where $m_b, m_t, m_W$ are respective masses of $b$-quark, $t$-quark and $W$-boson. The estimated limits of WIMP induced muon detection rates at SK using Eqs. (4-9) in the annihilation channels $b\bar{b}, \tau\bar{\tau}$ and $W, Z$ as a function of WIMP mass has been shown in Fig. (1). These rates are calculated for $E_{\text{inj}} = m_\chi$ (left panel of Fig. 1) and $E_{\text{inj}} = m_\chi/3$ (right panel of Fig. 1). Plots for each channel in Fig. (1) are obtained by taking the value of branching fraction ($B_F$) for that channel to be 1. This can be justified by the fact that each channel is effective in a particular $m_\chi$ region as discussed above. However, we have shown in our results broader $m_\chi$ ranges for each of the channels. Also shown in
Figure 2: Plot of $B$ vs $m_\chi$ in each channel with $E_{\text{inj}} = m_\chi$ (left panel) and $E_{\text{inj}} = m_\chi/3$ (right panel).

This figure is the corresponding SK limit [7] and our results indicate existence for room for an $m_\chi$ dependent enhancement of order $10^3 - 10^5$ of the detection rate in order to interpret SK bounds in terms of the CDMS $\sigma_\chi(m_\chi)$ limit.

In a recent work, Cao et al [16] have shown that to study the anti-proton fraction of the results of satellite borne PAMELA experiment [17, 18] using the recent CDMS results one needs to invoke a boost factor ($\sim 10^3$) for the annihilation of WIMPs into quarks. This, in general is consistent with the enhancement needed to explain the excess of positron fraction as observed by PAMELA experiment [17]. Our results also indicate similar trends that if one uses the CDMS limit as is done in the work, one is allowed to enhance the detection rate for the present of SK bounds. We redefine $B_F$ in our framework (Eq. 4) as $B \times B'_F$ where $B'_F$ is the branching fraction for a particular process and $B$ is some boost factor. For a single channel to represent the entire neutrino production process, $B_F' = 1$. Then we estimate the upper limits of $B$’s for different dark matter annihilation channels in the sun for the recent $\sigma_\chi - m_\chi$ CDMS limit. We do this by comparing the detection rates of neutrinos – obtained from the decays of the dark matter annihilation products in the sun – at Super-Kamiokande (SK) detector. The upper limits on WIMP induced up-going muons at SK as a function of WIMP mass is given by the SK Collaboration [7]. In Fig. 2 (left panel) we show the variation of $B$ with $m_\chi$ for $E_{\text{inj}} = m_\chi$. Right panel of Fig. 2 shows similar plots for $E_{\text{inj}} = m_\chi/3$. From Fig. 2 (left panel) we see $B$ varies (with $m_\chi$) between $\sim 10^5 - \sim 10^4$ for $bb$ channel, $\sim 10^4 - \sim 10^3$ for $\tau\tau$ channel, $\sim 10^3$ for each of W and Z channels etc. For $E_{\text{inj}} = m_\chi/3$ case (right panel of Fig. 2) however, the variation of $B$’s for each of W and Z channels is between $\sim 10^3 - \sim 10^2$ and for $\tau\tau$ channel it is from $\sim 10^4 - 10^2$. These limits are consistent with the order $10^3$ as discussed earlier.

Although in Figs. (1-2) we have shown the results for W and Z channels separately but as discussed earlier both are dominant in the region $m_\chi > m_t$. Therefore we consider the effect of
both of them together in calculating the rate using Eq. (4). In Fig. 3 (left panel) we present in $B \times B_F'$ (W channel) – $B \times B_F$' (Z channel) plane the iso $m_\chi$ plots for $E_{\text{inj}} = m_\chi$ that represent the required rate to interpret the SK limits [7]. Right panel of Fig. 3 gives the similar plots but with $E_{\text{inj}} = m_\chi/3$.

In the present work we compute the WIMP induced upward going muon rates at SK. They are induced by neutrinos from WIMP annihilation products in the sun. We use recent CDMS bounds on WIMP-nucleon scattering cross sections for different WIMP masses in our rate calculation. It is observed that representation of SK upper bounds on WIMP induced up-going muon rates allows an enhancement in the calculated rates in all individual channels. We made an estimation of this enhancement as a function of WIMP mass assuming branching fractions for each different channels to be 1 (maximum). Interpretation of PAMELA data in terms of CDMS limits also demand such enhancements of WIMP annihilation.

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References

[1] A. Gould, Astrophys. J. 321, 571 (1987).

[2] K. M. Belotsky, M. Yu. Khlopov and C. Kouvaris, Phys. Rev. D 79, 083520 (2009) [arXiv: 0810.2022 [astro-ph]]; K.M. Belotsky, T. Damour and M. Yu. Khlopov, Phys. Lett. B 529,
[3] D. S. Akerib et al. [CDMS Collaboration], Phys. Rev. Lett. 96, 011302 (2006) [arXiv:astro-ph/0509259]; Z. Ahmed et al. [CDMS Collaboration], Phys. Rev. Lett. 102, 011301 (2009) [arXiv:0802.3530 [astro-ph]].

[4] R. Bernabei et al. [DAMA Collaboration], Eur. Phys. J. C 56, 333 (2008) [arXiv:0804.2741 [astro-ph]]; R. Bernabei et al., Riv. Nuovo Cim. 26N1, 1 (2003) [arXiv:astro-ph/0307403]. R. Bernabei et al., Int. J. Mod. Phys. D 13, 2127 (2004) [arXiv:astro-ph/0501412].

[5] J. Angle et al. [XENON Collaboration], Phys. Rev. Lett. 100, 021303 (2008).

[6] Z. Ahmed et al. [The CDMS-II Collaboration], arXiv:0912.3592 [astro-ph.CO].

[7] S. Desai et al. [Super-Kamiokande Collaboration], Phys. Rev. D 70, 083523 (2004) [Erratum-ibid. D 70, 109901 (2004)].

[8] G. Jungman and M. Kamionkowski, Phys. Rev. D 51, 328 (1995).

[9] S. Ritz and D. Seckel, Nucl. Phys. B 304, 877 (1988).

[10] J. L. Feng, J. Kumar, J. Learned and L. E. Strigari, JCAP 0901, 032 (2009).

[11] D. Hooper, F. Petriello, K. M. Zurek and M. Kamionkowski, Phys. Rev. D 79, 015010 (2009) [arXiv:0808.2464 [hep-ph]].

[12] K. Griest and D. Seckel, Nucl. Phys. B 283, 681 (1987) [Erratum-ibid. B 296, 1034 (1988)].

[13] M. Kamionkowski, K. Griest, G. Jungman and B. Sadoulet, Phys. Rev. Lett. 74, 5174 (1995).

[14] A. Gould, Astrophys. J. 321, 560 (1987).

[15] A. Menon, R. Morris, A. Pierce and N. Weiner, arXiv:0905.1847 [hep-ph].

[16] Q-H Cao, I. Low and G. Shaughnessy, arXiv:0912.4510 [hep-ph].

[17] O. Adriani et al. [PAMELA collaboration], Nature 458, 607 (2009).

[18] O. Adriani et al., Phys. Rev. Lett. 102, 051101 (2009).