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## Indirect Searches for Dark Matter Signatures at INO

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Abstract. Neutrino fluxes could arise due to annihilation of Weakly Interactive Massive Particles (WIMPs) in the center of the sun. We study the prospects of search for muon events due to such neutrinos at the upcoming Iron CALorimeter (ICAL) detector to be housed at Indiabased Neutrino Observatory (INO). Although the atmospheric neutrinos will pose a serious background to the signal neutrinos produced through WIMP annihilation, the former could be supressed significantly by using the directional property of signal neutrinos. For  $50 \text{kt} \times 10$ years of ICAL running and WIMP masses  $(m_{\chi})$  between 3-100 GeV, we perform a  $\chi^2$  analysis and present expected exclusion regions in the  $\sigma_{SD} - m_{\chi}$  and  $\sigma_{SI} - m_{\chi}$  plane, where  $\sigma_{SD}$  and  $\sigma_{SI}$  are the WIMP-nucleon Spin-Dependent (SD) and Spin-Independent (SI) scattering crosssections, respectively. For  $m_{\chi} = 25$  GeV, the expected 90 % C.L. exclusion limit on  $\sigma_{SD}$  are  $\sigma_{SD} < 7.82 \times 10^{-41} \ cm^2$  for  $\tau^+ \tau^-$  channel and  $\sigma_{SD} < 1.23 \times 10^{-39} \ cm^2$  for  $b\bar{b}$  channel. For same  $m_{\chi}$ , the expected 90 % C.L. exclusion limits on  $\sigma_{SI}$  are  $\sigma_{SI} < 8.97 \times 10^{-43} \ cm^2$  for  $\tau^+ \tau^$ channel and  $\sigma_{SI} < 1.43 \times 10^{-41} \ cm^2$  for  $b\bar{b}$  channel.

#### 1. Introduction

Through various cosmological and astrophysical observations, we have strong evindences for the existence of the Dark Matter (DM) with an abundance of  $\sim 27\%$ . These evidences are mainly for the gravitational interactions of DM; the particle nature of DM remains largely unknown. Among the various possible candidates proposed, WIMPs seem to be the most promising ones with masses ranging from a few GeVs to hundreds of TeVs [1]. As the solar system moves through DM halo, WIMPs scatter off the nuclei in the celestial bodies like the sun and lose energy. They get trapped by the gravitational potential of the sun and gradually sink to its core. Over a course of time, WIMP concentration at the core increases. Since WIMP annihilation rate scales with the square of its density, WIMPs in the solar core could undergo annihilation, through different channels, into various Standard Model (SM) particles. These SM products may subsequently produce neutrinos whose energy spectra depend on the parent WIMP mass and the annihilation channel. In the sun, WIMPs interact with the dominant component hydrogen via both SI and SD coupling.

The neutrinos produced at the center of the sun, will undergo oscillations and interactions viz. CC, NC and regeneration as they propagate out of the core. On reaching detector, these

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neutrinos would interact with detector medium and produce leptons. By studying these leptons, in principle, we can reconstruct nature of DM viz. its branching ratio, mass and interaction cross section. The future facility like ICAL@INO is better equipped to probe muons in the energy region of a few GeVs to around 100 GeV. We study prospects of detecting such events at ICAL.

#### 2. Neutrino fluxes due to WIMP annihilation

The total number of WIMPs (N) inside the sun as a function of time is given by the following differential equation [1]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(N\right) = C - C_A N^2 - EN\tag{1}$$

where the terms on the right hand side corresponds to capture of WIMPs (C) in the sun, annihilation (C<sub>A</sub>) in its core and evaporation (E) respectively. For WIMP masses under consideration, we can neglect the evaporation term. The rate ( $\Gamma_A$ ) which accounts for the depletion of the WIMPs, is twice the annihilation rate:  $\Gamma_A = \frac{1}{2}C_AN^2$ . The quantity  $C_A$  depends on  $\langle \sigma_A v \rangle$ , which is the total self-annihilation cross sections of WIMPs times their relative velocity (in the limit of zero relative velocity), and also their distribution in the sun. Solving Eq. 1 for N, we find the annihilation rate at any given time is given by  $\Gamma_A = \frac{1}{2}C \tanh^2(t/\tau)$ , where  $\tau = (CC_A)^{-1/2}$  is the time required for the equilibrium to be established between capture rate and the annihilation rate. Since equilibrium between annihilation rate and capture rate has reached in the sun, we get a direct proportionality:  $\Gamma = \frac{1}{2}C$ . The interaction of WIMPs with



Figure 1. WIMP capture rate due to SD and SI scattering for some benchmark values of WIMP nucleon interaction cross sections.



Figure 2.  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$  fluxes for annihilation of 25 GeV WIMP in the sun assuming  $\sigma_{SD} = 10^{-39} cm^2$ .

the nuclei in the sun could happen through SD or SI interactions or both. Correspondingly, the capture rate C is a function of  $\sigma_{SD}$  or  $\sigma_{SI}$  (see Fig. 1). The neutrino fluxes  $\Phi_{\nu}(\text{in units of GeV}^{-1}m^{-2}\Omega^{-1}s^{-1})$  at ICAL due to WIMP annihilation in the sun is given by :  $\Phi_{\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_{i=1} \text{BR}_i \frac{dN_i}{dE_{\nu}}$ , where the summation is over all the possible channels (indicated by index i) and their corresponding branching ratios  $(BR_i)$ . R is the distance travelled by neutrinos. We use WIMPSIM [2] to calculate energy spectra of neutrino  $\frac{dN_i}{dE_{\nu}}$ . Fig. 2 shows the  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$  fluxes at the detector, integrated over all directions, due to annihilation of a 25 GeV WIMP for an assumed WIMP-nucleon cross section. The propagation of neutrinos incorporates full three flavor neutrino oscillations with the following oscillation parameters :  $\theta_{12} = 34^{\circ}$ ,  $\theta_{13} = 9.2^{\circ}$ ,  $\theta_{23} = 45^{\circ}$ ,  $\delta = 0$ ,  $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{eV}^2$  and  $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{eV}^2$ . We consider normal mass hierarchy for the neutrinos in our analysis.

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#### 3. Event generation at ICAL

The ICAL detector is an upcoming 50kt iron calorimeter detector at the proposed INO facility in Theni district of Tamil Nadu, India. It would consist of 150 layers of glass RPCs (Resistive Plate Chamber) interspersed with iron plates [3]. Although primarily proposed for detecting neutrino Mass-Hierarchy, we tend to explore the versatility of the detector for probing new physics. ICAL has an excellent angular resolution of muons which is crucial for an effective background suppression.

We use a modified version of GENIE monte-carlo for generating neutrino events. Events are generated with ICAL geometry 50 kt mass and 150 layers of RPC. For simulation of atmospheric neutrino background we use Honda fluxes [4] calculated for Theni site. For simulation of signal, we calculate fluxes as described in Section 2.

We carry out signal and background event generation separately. These events are then passed through our reconstruction code whereby we apply detector energy and angle resolutions, reconstruction and charge identification efficiencies to get the final events. Our analysis is in terms of muons, which are binned in reconstructed energy and zenith angle bins. The muon reconstruction efficiency, muon charge identification efficiency, muon zenith angle resolution and muon energy resolution values used in this work have been obtained though dedicated Geant4 based simulations for ICAL geometry [5].

#### 4. Atmospheric neutrino background



Figure 3. The reconstructed  $\mu^-$  event distribution at ICAL due to atmospheric neutrino background for 500 kton-years of exposure. Cos $\theta$  = 1 represents upward going muon.



Figure 4. The reconstructed  $\mu^-$  event distribution at ICAL due to atmospheric neutrino background after applying the background suppression scheme.  $\cos\theta = 1$  represents upward going muon.

Fig. 3 shows the reconstructed  $\mu^-$  event distribution due to atmospheric neutrino background. The atmospheric neutrinos pose a large background to the indirect detection signal as these neutrinos have energies in the same range as signal neutrinos from WIMP annihilation for WIMP masses in range 3-100 GeV. However, the signal neutrinos are different from the atmospheric neutrinos in two aspects. Firstly, the signal flux in Section 2, has an energy dependence that is quite different from the energy dependence of the atmospheric neutrinos which falls sharply as  $\sim E_{\nu}^{-2.7}$ . Secondly, and more importantly, unlike the neutrinos from WIMP annihilation which come from the direction of the sun, the atmospheric neutrinos have a distribution over all zenith and azimuth angular bins. We define a cone opening angle  $\theta_{90}$ , for a given WIMP mass, such that 90 % of the signal events are contained within this angle (see Fig. 5). We use this  $\theta_{90}$  as a cone-cut criteria to reduce the atmospheric neutrino background. The reduced background is then weighted by the solar exposure function (Fig. 6) at INO to obtain the final background spectrum for a given WIMP mass. Fig. 4 shows the events at ICAL after applying the background suppression scheme.



**Figure 5.**  $\theta_{90}$  as a function of  $m_{\chi}$  for the case of annihilation in the sun.



Figure 6. The probability of solar exposure for each zenith and azimuthal angle bin for INO's geographical coordinates.

#### 5. Analysis

We perform a  $\chi^2$  analysis to obtain various 90 % C.L. sensitivity limits on SD and SI WIMPnucleon cross-sections. We carry out the event generation of signal and background seperately. In our theory, we consider events due to WIMP annihilation and atmospheric background and fit it with data comprising atmospheric background events only. This is consistent with a no-WIMP scenario and thus we calculate exclusion limits. In our case, we add the the  $\mu^+$  and  $\mu^$ events and do a combined analysis. Our  $\chi^2$  definition and systematics are same as the previous work [5].

#### 6. Results

The expected sensitivity of ICAL to indirect detection of dark matter are presented here. The ICAL sensitivity limits are for 500 kt-years of exposure and assuming 100 % BR in  $\tau^+\tau^-$  (red solid line) and  $b\bar{b}$  (red dashed line) channels for both SD and SI case. The 90 % C.L. expected sensitivity from 10 years of running of ICAL is shown in Fig. 7 in the  $\sigma_{SD} - m_{\chi}$  plane for the spin dependent cross-section. Limits from other complementary indirect detection experiments like IceCube, Super-Kamiokande (SK) and BAKSAN have been shown. For comparison, the 90 % C.L. limits from direct detection experiments PICASSO and SIMPLE are also included. The blue-gray shaded region is the  $3\sigma$  C.L. area compatible with the signal claimed by DAMA/LIBRA is also shown. Limits from experiments other than ICAL have been taken from [6]. We find that the expected sensitivity from 10 years of running of ICAL is comparable to SK for both the  $\tau^+\tau^-$  and  $b\bar{b}$  channels, with ICAL performing a slightly better for all WIMP masses greater than 10 GeV. In comparison to direct as well as other indirect experiments which have placed limits on the WIMP-nucleon spin-dependent scattering cross-section, ICAL is expected to be better. Further, for all ranges of WIMP masses  $m_{\chi}$ , the limits on  $\sigma_{SD}$  from the direct detection experiments is weaker than those from indirect detection experiments.

The 90 % C.L. expected sensitivity from 10 years of running of ICAL for the spin-independent cross-section is shown in the  $\sigma_{SI} - m_{\chi}$  plane in Fig. 8. The current limits from earlier and on-going experiments are also shown. For the SI cross-sections, the limits from the direct detection experiments are significantly better than those from the indirect detection experiments.

 $10^{-3}$ DAMA/LIBRA 10<sup>-3</sup> **b** IceCut  $10^{-37}$ (cm<sup>2</sup>) \_\_\_\_\_\_ م Baks b b sk  $10^{-39}$ Baksan 10 RELIMINAR 10 10  $10^{2}$ m<sub>γ</sub> (GeV)



The ICAL expected 90 % C.L. Figure 7. sensitivity limit on the WIMP-nucleon spindependent cross-sections as a function of the Current 90 % C.L. limits from WIMP mass. other indirect detection and direct detection experiments have been shown.

Figure 8. The ICAL expected 90 % C.L. sensitivity limit on the WIMP-nucleon spinindependent cross-sections as a function of Current 90 % C.L. limits from WIMP mass. other indirect detection and direct detection experiments have been shown.

Also shown are the allowed regions from the direct searches claiming positive signal for dark matter: DAMA/LIBRA at  $3\sigma$  C.L., CoGeNT at 90 % C.L., CRESSTII at  $2\sigma$  C.L. and CDMS II Si at 90 % C.L. The limits on SI cross-sections from direct detection experiments are shown for SuperCDMS, CDMSlite, XENON-1T and LUX. We also show less competitive limits from indirect searches at IceCube and SK for  $\tau^+\tau^-$  and  $b\bar{b}$  channels. Although the limits on SI case from indirect detection experiments are expected to be poorer than from direct detection experiments, they provide a complementary probe of the WIMP paradigm.

#### 7. Conclusion

This work is a part of ongoing studies to probe the physics potential of the ICAL detector. Neutrinos arising out of WIMP annihilation in the sun could be used to probe dark matter signatures. We perform a study of muon events arising at ICAL due to such neutrinos through  $\tau^+\tau^-$  and  $b \bar{b}$  WIMP annihilation channels. With an effective atmospheric background suppression scheme, the upper limits on 90 % C.L. expected limits from about 10 years of running of ICAL for SD and SI WIMP-nucleon scattering cross-sections are competitive to the most stringent bounds till date.

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