



## Sensitivity for detection of decay of dark matter particle using ICAL at INO

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**Abstract.** We report on the simulation studies addressing the possibility of dark matter particle (DMP) decaying into  $\mu^+\mu^-$  channel. While not much is known about the properties of dark matter particles except through their gravitational effect, it has been recently conjectured that the so-called ‘anomalous Kolar events’ observed some decades ago may be due to the decay of unstable dark matter particles. The aim of this study is to see if this conjecture can be verified at the proposed iron calorimeter (ICAL) detector at INO. We study the possible decay to  $\mu^\pm$  mode which may be seen in this detector with some modifications. For the purposes of simulation, we assume that the channel saturates the decay width for the mass ranging from 1 to 50 GeV/ $c^2$ . The aim is not only to investigate the decay signatures, but also, more generally, to establish lower bounds on the lifetime of DMP even if no such decay takes place.

**Keywords.** India-based neutrino observatory; iron calorimeter; kolar event; dark matter particle; lifetime.

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### 1. Introduction

It is now established that dark matter particles (DMPs) constitute 80–85% of all the matter in the Universe. But we know very little about the properties of these particles. Even though they are non-luminous in nature, their presence has been inferred through their gravitational effect. The presence of dark matter was investigated in detail by Vera Rubin [1] using their kinematical study of the galaxies during 1960–1970, using the rotational curves. Further evidence came recently from the study of gravitation lensing. It is known that most of the DMPs must be non-baryonic and they do not interact via the electromagnetic interaction.

They may be composed of hypothetical neutral particles such as weakly interacting massive particles (WIMPs), axions, or sterile neutrinos which are beyond the purview of the Standard Model. While properties such as spin and parity of DMPs are completely

unknown, there are theoretical estimates of their interaction cross-section with nuclei and their lifetime. Cryogenic bolometer-based experiments like CDMS [2], LUX [3], CRESST [4] are trying to detect it directly through their recoil against the detector nuclei. The indirect space-based experiments like PAMELA [5], Fermi-LAT [6], AMS [7] are trying to detect the DMP by measuring the decay or annihilation products in the form of excess antimatter in the Universe. Similarly, the water and ice Cherenkov-based detectors like Super-Kamiokande [8] and IceCube [9] have put limits on the lifetime of the DMP by detecting the neutrino signal, mostly from dark matter annihilation in the centre of the Sun, the centre of the Earth and in the Galactic centre. Both direct and indirect experiments have provided some hints of DMPs.

It is not known whether DMPs are stable or not. However, if they are unstable, their lifetime should be of the order of or longer than the age of the Universe. It has been recently conjectured that some anomalous events observed at the deep underground laboratory at Kolar Gold Fields (KGF) in south India, the so-called Kolar events, may be due to the decay of unstable dark matter particles whose mass is in the range of several  $\text{GeV}/c^2$  [10]. These events, discussed in refs [11–13], have neither been confirmed nor shown to be spurious. They constitute 25% of the total recorded events over two decades at a depth of 2.3 km. There were interpretations [14–16] for the anomalous events, none of which were confirmed in other experiments, including those using neutrino beams [17,18].

While these anomalous events have evaded any conventional, Standard Model-based, interpretation until now, the conjecture that the anomalous events are due to the decay of unstable dark matter opens up a new possibility. This may be established by future neutrino detectors, like the iron calorimeter (ICAL) at India-based neutrino observatory (INO) [19]. The sensitivity to dark matter decays may be enhanced by placing the detector elements on the walls and ceiling of the large cavern housing ICAL.

In this paper, we report on the simulation of the DMP decaying into  $\mu^+\mu^-$  channel. For the purpose of simulation we assume that the channel saturates the width with the mass ranging from 1 to 50  $\text{GeV}/c^2$ . The aim is not only to investigate the conjecture, but also, more generally, to determine the lower limits on the lifetime of DMP by assuming a certain DM energy density in a limited volume of the ICAL cavern.

The ICAL detector is proposed to be placed in a cavern at INO which is much larger than that at KGF. It is planned to construct a 51 kton magnetized ICAL under a rock cover of at least 1 km all around. The main goal of the ICAL is to study atmospheric muon neutrinos and identify the neutrino mass hierarchy. However, it can also be used for other purposes such as searching for magnetic monopole [20], to observe or set limits on the lifetime of DMP by considering their number in the ICAL cavern and also from the annihilation or decay products of the DMP by looking at the centre of the solar system.

This paper is organized as follows: in §2, we briefly discuss the methods used to detect DMP. In §3, we focus on the proposed detector for DMP detection at ICAL cavern. In §4 and 5, we present the analysis and results of the simulation study for DMP decay in the ICAL cavern. We conclude the paper in §6.

## **2. Detection mechanism of dark matter particle**

The search for DMP has been carried out both directly and indirectly. In the latter category, one looks for the missing mass in events in particle colliders measured in a  $4\pi$

detector assuming that they can then be ascribed to the production of DMP. In the former category, the search involves the detection of nuclear recoils resulting from DMPs colliding with the atoms in a detector. These detectors consist of rare gases such as argon or xenon in the liquid or gas phase, scintillators (NaI(Tl), CaF<sub>2</sub> etc.), semiconductors (HPGe or Si) and cryogenic bolometers. In space-based experiments, one looks for the products of annihilation or decay of the DMP. The experiments looking for high-energy neutrinos, try to observe distinctive high-energy neutrinos obtained from the annihilation or decay of the DMPs at the centre of the Sun, the Earth and the Galactic halo because of the concentration of dark matter particles there.

Here, we introduce yet another method to look for the possible decays of DMP. As the DMP is present everywhere, a deep underground neutrino detector should be able to detect the possible decay of DMP provided the mass of DMP is in a suitable range and its decay products are easily detectable. If no such decay is observed, one should be able to put lower bounds on the possible partial lifetimes after sufficiently long exposure. As pointed out in ref. [10], based on the analysis of Kolar events, a large cavern located deep underground, as in the case of neutrino detectors, should be able to identify the DMP decay if the lifetime is approximately the age of the Universe. Either way, this provides a novel way of putting limits on the DMP decay or its detection.

We consider the last scenario mentioned above in this paper to detect DMP using the ICAL detector at INO assuming that it decays to Standard Model particles. If not, we obtain appropriate limits. For convenience, in this simulation, it is assumed that DMP is a neutral scalar particle ( $\Phi_{\text{DM}}$ ) that decays to lepton pairs only and the assumption is guided by the results from different satellite-based experiments [5,7]. They show a significant excess in positron-to-electron ratio above 10 GeV/c<sup>2</sup> but not in the antiproton-to-proton ratio. A similar mode of decay is also the most suitable method for detecting DMP using the ICAL detector. The ICAL is a sampling calorimeter and is especially suitable for tracking muons which may arise from DMP decays to  $\mu^+\mu^-$  pairs. Therefore, we look for the decay mode of the type

$$\Phi_{\text{DM}} \rightarrow \mu^+ + \mu^- . \quad (1)$$

In order to detect such events at INO, a detector configuration with ICAL as the central detector and some additional detectors around it is proposed. This is described in the next section.

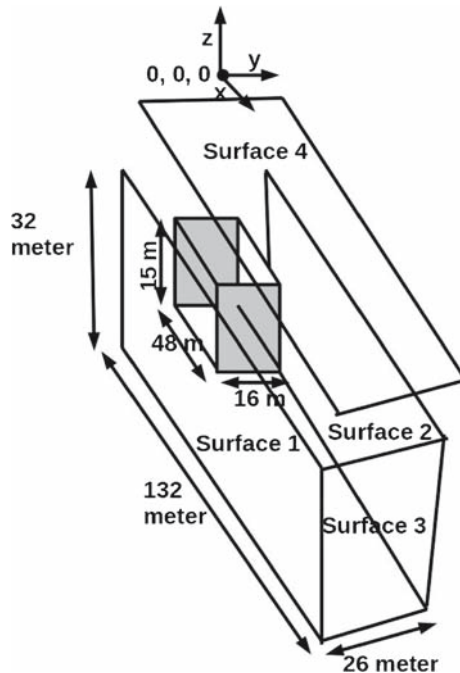
### **3. A detector for dark matter particle decay**

Dark matter is believed to be present everywhere. The biggest cavern at INO is the ICAL cavern having dimensions of  $\sim 132 \text{ m} \times 26 \text{ m} \times 32 \text{ m}$  and a cavern volume of  $\sim 10^{11} \text{ cm}^3$ . As estimated using arguments in ref. [10], a large volume will lead to an increase in the number of detected DMP decay events which is around  $\sim 1/\text{y}$  based on the analysis of Kolar events. So to increase the efficiency for the detection of all the decay products in the form of visible particles, we have done the simulation with additional detectors on four walls of the ICAL cavern.

The ICAL is a magnetized calorimeter consisting of 150 layers of iron plates as the absorber, each having a thickness of 5.6 cm interleaved with an air gap of 4 cm to accommodate the active detector element viz. the resistive plate chamber (RPC). The RPC uses

a gas mixture of R134A (95.15%), isobutane (4.51%) and SF<sub>6</sub> (0.34%). The gas mixture and the appropriate high voltage allow the RPC to be operated in the avalanche mode. The passage of a charged particle through the detector ionizes the gas medium which induces a signal and is collected by honey-comb patterned pick-up panels, which are placed orthogonally on either side of the detector. They give the X, Y coordinates of a hit point with a position resolution of ~1 cm and time resolution of 1 ns. The iron plates are magnetized with an average field of 1.3 Tesla allowing a measurement of the curvature of the muon track. The proposed ICAL detector will occupy 48 m × 16 m × 15 m of the ICAL cavern. In principle, the remaining space of the ICAL cavern can be used for additional DMP detector installations. One such simple configuration is proposed in this paper.

As the ICAL detector will be located towards one end of the cavern, four scintillator detectors (SDs) are mounted close to the walls of the cavern. A schematic diagram of the detector is shown in figure 1. As shown in the figure, surfaces 1, 2, 3 and 4 depict the scintillator detectors. Two of these detectors are placed along the length of the cavern with a dimension of 132 m × 0.04 m × 32 m. The third one is placed in the YZ plane with an area of cross-section of 26 m × 32 m, having a thickness of 4 cm. The fourth one is above the ICAL surface at a height of 17 m from the top surface of the ICAL. This can also be used as a muon veto for ICAL. In the simulation, only one layer of the detector is used for each surface. So, no energy measurement is available from these detectors. On the other hand, they provide the signals for identifying back-to-back  $\mu^\pm$  as decays of DMPs.



**Figure 1.** Schematic view of the DMP detector with scintillator detectors and the iron calorimeter.

ICAL uses around 30,000 RPCs of 2 m × 2 m dimensions. If RPCs with the same dimension were to be used instead of the scintillator detector, around 3000 of them would be needed for a single-layer lining on each plane. This is one-tenth of what is required by the ICAL.

#### **4. Simulation of decay of dark matter particle**

The simulation is carried out in two regions separately. These two regions are: the air region i.e., the gap between the ICAL and the scintillator planes and the other inside the ICAL detector. During simulation, 100% branching ratio ( $B$ ) for the DMP decay to dimuon channel has been considered.

The DMP decay to  $\mu^+\mu^-$  channel can be identified unambiguously in the ICAL, provided its energy is 0.5 GeV or more, because there are two muon tracks back-to-back, which can easily be distinguished from other events. Events with at least hits in five layers in the ICAL detector are needed to reconstruct the energy of the muon, by assuming  $\sim 100$  MeV of energy loss in 5.6 cm thick iron plate. So the minimum energy of muon has been considered as 0.5 GeV. Due to the non-relativistic speed of DMP, which is almost at rest, its decay will be isotropic. For a given mass of the DMP, the energies of the daughter particles are obtained by two-body kinematics. Assuming the mass of the decay particle and antiparticle pair to be  $m$ , the mass of the DMP to be  $M$ , the momentum of each of the daughter particles,  $p_1$  and  $p_2$ , is given by

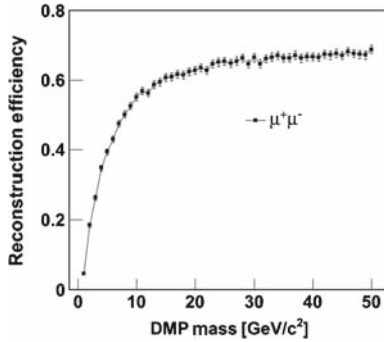
$$|\vec{p}_1| = |\vec{p}_2| = \sqrt{\frac{M^2}{4} - m^2}. \quad (2)$$

Hence the mass of the DMP is taken as input to the simulation instead of the daughter particle energy. The mass of the DMP, decaying into  $\mu$  pairs, is varied from 1 to 50 GeV/ $c^2$  in 1 GeV/ $c^2$  steps. In the simulation, two daughter particles start from a single vertex in opposite directions and with momenta given in eq. (2). To obtain isotropic flux during the decay process, the zenith angle ( $\cos\theta$ ) is smeared from 0 to  $\pi$  and the azimuthal angle ( $\phi$ ) by  $2\pi$ . The charge of one of the daughter particles in a decay event is chosen randomly and the other daughter particle has the opposite charge.

##### *4.1 Simulation of dark matter particle decay in the air region*

The high energy physics (HEP) simulation tool-kit GEANT4 [21] is used to do the simulation for DMP decay in the air region. In the simulation, the defined detector geometry is the same as mentioned in §3. The events are generated in the air gap, i.e., between the SDs and the ICAL detector. In a fraction of the simulated events, the trajectories of the daughter particles are such that at least one of them enters the ICAL detector and its partner hits the SD. Thus, it will be possible to measure the energy of at least one decay product.

If the DMP decays to a pair of muons, one of them will give rise to a clean track in the ICAL detector and the other one will have hits in the SD in the opposite direction. The background for such events will be the cosmic ray muon or the muon produced by the interaction of neutrino with the rock and detection in the ICAL detector. But this can



**Figure 2.** The reconstruction efficiency for DMP decays to  $\mu^+\mu^-$  in air region.

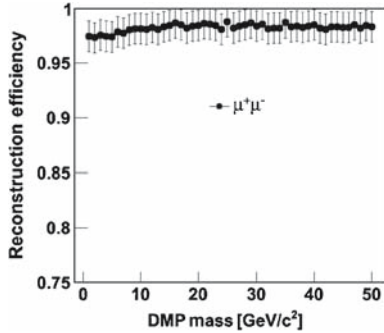
be eliminated by using the timing information from the detector. The genuine events are selected by considering the reconstructed momentum within  $\pm 3$  times the incident momentum measured by the ICAL detector. The Kalman filter algorithm is used to reconstruct the momentum of the muon inside the ICAL. It is also possible to reconstruct the vertex position and direction cosine inside ICAL. The position of the other muon in the scintillator is obtained by extrapolating the hit position in it using the reconstructed vertex and direction cosine. If the extrapolated position and the simulated position match within a certain range, then these events contribute to the efficiency. The uncertainty in the measurement of the extrapolated position is taken as 1 m individually for each position component. Decreasing this reduces the efficiency of detecting low-mass DMP decay. The reconstruction efficiency is shown in figure 2. With the increase in mass, the efficiency increases. The increased scattering at lower energies decreases the efficiency of reconstruction at lower mass of the DMP. A single layer of the SD may not help to distinguish the DMP event from the background. So, to improve this situation at least two layers of the detector should be in place. At least 6–8 layers are needed for good energy resolution.

A detailed discussion on the elimination of backgrounds for detecting the decay of dark matter particle is presented in §5.

#### 4.2 Simulation of dark matter particle decay in the ICAL

In this case all the events are generated inside the ICAL detector within a fiducial volume of  $40\text{ m} \times 14\text{ m} \times 12\text{ m}$ . The fiducial volume of the ICAL excludes the top two and bottom two layers of the RPC detectors in the ICAL and three strips of the RPC detectors on all four sides of the ICAL. This ensures that the fully contained events are considered for detecting DM decay particles. Inside the ICAL, it is possible to measure the energy of two muons and hence the invariant mass.

For DMP decays to  $\mu^+\mu^-$ , the timing and trajectory information can be used to separate them from background due to cosmic ray muons and neutrinos. The Monte-Carlo technique is used to simulate DMP decays, uniformly distributed within the fiducial volume of ICAL, and track the decay muons. For each energy and theta bin, the momentum resolution and direction resolution are used separately for  $\mu^+$  and  $\mu^-$  from muon look-up table [22]. Figure 3 shows the detection efficiency for DMP decays, to the  $\mu^+\mu^-$  channel, inside the ICAL detector.

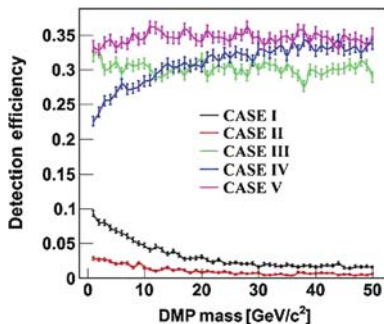


**Figure 3.** The reconstruction efficiency inside the ICAL for the DMP decays to  $\mu^+\mu^-$  pair.

Inside the ICAL, the background for such events will arise from neutrino interactions. However, the main difference between them is that in neutrino-induced events all the particles will be in one direction, whereas in DMP decay, the decay products will be on either side of a single vertex resulting in an increase in the time with hit position in both the directions.

#### 4.3 Detector acceptance

In the above two cases, we forced the particles to be generated in their respective regions. But to get the detector acceptance, the events are generated uniformly all over the ICAL cavern i.e., including the ICAL detector and the air region. Only the DMP decays to  $\mu^\pm$  channel are considered and the simulation is carried out using GEANT4. Figure 4 shows the detection efficiency for five different situations. Bands with different markers represent five different cases. The classification is based on the type of detection. The efficiency is obtained by taking the ratio between the number of events with hit in the respective detector to the total number of simulated events. The error bars on each case are the



**Figure 4.** The detector acceptance by considering the DMP decays to  $\mu$  pair in the whole ICAL cavern. Case I: Not detected, Case II: 2 or 1 in ICAL not in SD, Case III: 2 in SD and not in ICAL, Case IV: 1 or 2 in ICAL and 1 or 2 in SD and Case V: 1 in SD and another one is not detected.



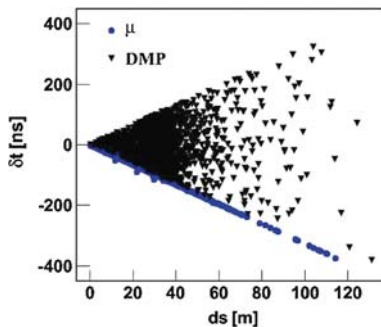
statistical uncertainty. Cases I and II have small number of events resulting in smaller absolute error. Cases II and IV are sensitive to DMP decay detection.

### 5. Studies of possible background

The sources of backgrounds for the DMP event decaying in the air region that we have considered are cosmic ray muons and events from neutrino interactions with the rock of the ICAL cavern. These events originate from outside the ICAL cavern while those that arise from DMP decay are generated inside the ICAL cavern. The former events, due to the backgrounds mentioned, can be identified and eliminated by using time-of-flight method as shown in figures 5 and 6.

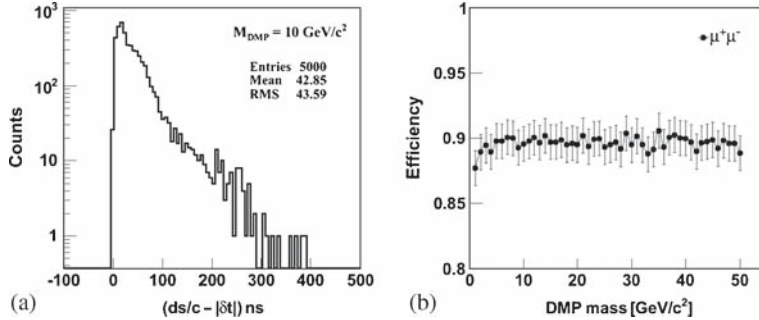
A background event of the variety mentioned above, results in a time sequential firing of the relevant detector channels (SD or ICAL RPCs) in the path of the charged particle. But, in the case of the DMP decay products, this time of firing of the detector channels increases in the two, essentially opposite directions with respect to the vertex position of the DMP decay. If the vertex position is near the SD or ICAL, it could arise from outside the cavern. The time taken by the outside particle to travel a distance from the SD to the first layer of the ICAL detector is, on the average, much larger than that for the DMP decay products, where one looks for an origin away from the cavern walls. The latter event leads to a smaller time difference than the former. Such a type of event can be captured by using an appropriate gate on the time difference between the firing of the SD and the RPC detectors ( $\delta t$ ). The  $\delta t$  vs. distance ( $ds$ ) plot is shown in figure 5. Events with blue dot correspond to down-going muons.

The difference between the time taken for a relativistic particle to travel the distance between the SD and RPC detector and the magnitude of  $\delta t$  is close to 0 for a charged particle coming from outside the cavern. However, in the case of DMP decay halfway between the two detectors, this time difference will be  $\sim ds/c$ , where  $c$  is the velocity of light. This time difference will generally be a positive quantity. The negative portion arises from the finite detector time resolution  $\sim 1$  ns. Figure 6a shows such a distribution for a DMP with mass of  $10 \text{ GeV}/c^2$  and the other plot (figure 6b) represents the fraction of events having time difference  $> 8.5$  ns. Such a bound on time difference decreases the number of background events to  $\sim 10^{-3}$  in 10 y.



**Figure 5.** The distance between hit points vs. time difference.





**Figure 6.** (a) The distribution of difference between propagation time of relativistic decay products of  $10 \text{ GeV}/c^2$  DMP and mod of  $\delta t$ . (b) The fraction of events obtained by putting gate on the time difference vs. DMP mass.

In the case of decay of the DMP inside the ICAL detector, the possible backgrounds are eliminated by considering the fiducial volume of the ICAL detector and by estimating the probability of getting such a type of event due to the random coincidences.

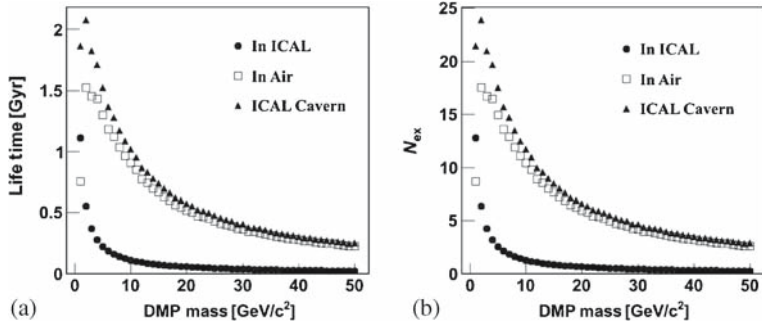
The events having hits in at least five layers of RPC detectors of the ICAL were considered for energy reconstruction. So, for the decay of DMP inside the ICAL, where each muon leads to hits in at least five layers, the background rate arising from random coincidences is negligibly small viz.  $\sim 4 \times 10^{-22}$  for 10 y. This is estimated by assuming the time window of 10 ns and RPC strip rate of 200 Hz (incl. noise). As this is much smaller than 1, this background can be safely ignored.

## 6. Analysis and results

The efficiency obtained in different regions from §4 is used to estimate the lifetime of a DMP for a finite number of observed events using the Frequentist method [23]. If  $\rho$  ( $\text{GeV}/\text{cm}^3$ ) is the local dark matter density,  $V$  ( $\text{cm}^3$ ) is the detection volume,  $\epsilon$  is the detection efficiency,  $B$  is the branching ratio,  $M$  ( $\text{GeV}/c^2$ ) is the DMP mass and  $R$  ( $\text{y}^{-1}$ ) is the rate of decay, then the lifetime  $T$  (y) of the DMP is given by

$$T = \frac{\rho V \epsilon B}{MR}. \quad (3)$$

Here and for further calculation, the local dark matter density is taken as  $0.39 \text{ GeV}/\text{cm}^3$  [23]. The limit on the lifetime is obtained by considering the upper limit for 0 observed events with 90% confidence level for 0 background in 1 y of detector running time using eq. (3). The limits are obtained for different simulated regions and are shown in figure 7 by different symbols. With increase in the mass of DMP, the limit on the lifetime of the DMP is decreasing due to the decrease in number density in a fixed volume. From Super-Kamiokande (SK) [8] results there is a stringent limit on the lifetime of a DM particle with a mass greater than about  $10 \text{ GeV}/c^2$ , decaying into a  $\nu_\mu$  and  $\bar{\nu}_\mu$ . Each would have an energy of  $M/2$  and one of them could interact via a charged current interaction producing a definite energy muon in the final state. The much smaller detection efficiency for the neutrinos from DM decay is more than compensated by the much larger spatial volumes



**Figure 7.** (a) The lower limit in the lifetime of DMP vs. its mass for  $\mu^+\mu^-$  decay channel. (b) The number of expected events due to the DMP decays to  $\mu^\pm$  with a lifetime of 2 Gy at ICAL cavern for 10 y of detector running period.

accessed. For 10 GeV/c<sup>2</sup> DMP mass, the lifetime is of the order of 10<sup>7</sup> Gy as obtained by SK. The ICAL detector can be used, like SK, to place bounds on the lifetime of DM particle in the core of the Earth, or the Sun or our galaxy.

Alternatively, using the higher limit of DMP lifetime (2 Gy) from the above result and the local dark matter density, the number of expected events due to the decay of DMP is obtained separately for events simulated in air region between the cavern wall and the ICAL detector, inside the ICAL detector and the whole of the ICAL cavern by combining the first two results. The expression for expected number of events ( $N_{ex}$ ) due to the decay of DMP is given by

$$N_{ex} = \frac{\rho V \epsilon B}{MT}. \quad (4)$$

Figure 7b shows the number of expected events for 10 y of counting for the three cases mentioned above.

## 7. Conclusions

If the reinterpretation of the Kolar events as being due to the decay of DMP is correct, it should be possible to observe them in much larger numbers in the ICAL cavern at the India-based neutrino observatory. Due to the larger volume of the ICAL cavern and the size of the ICAL detector, the expected number of events is doubled in only 10 years compared to those observed at Kolar Gold Fields. In addition to addressing the issues for understanding the anomalous Kolar events, a non-observation of such events at INO will be able to place bounds on the lifetime of the DMP with mass between 1 and 50 GeV/c<sup>2</sup>. Alternatively, it can place lower bounds on the lifetime of the DMP with mass below 10 GeV/c<sup>2</sup> by searching for a peak in the muon energy spectrum.

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