Neutrinos are the second most abundant particles in the universe. The study of neutrinos has advanced our understanding of fundamental particles and their interactions. It has also made an impact in other fields such as cosmology, astrophysics, nuclear physics and geophysics. In the standard model of particle physics, there are three flavors of neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$ and they are massless. The phenomenon of neutrino oscillations has been established experimentally and implies that at least two mass eigenstates have non-zero masses. The extraction of the neutrino mixing parameters has been possible through various experiments carried out using neutrinos from different sources viz: atmospheric, solar, reactor and accelerator. Results from these experiments led to the current three-neutrino mixing paradigm, in which the three active neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$, with definite flavour, are superpositions of three neutrinos $\nu_1$, $\nu_2$, $\nu_3$, with definite masses, $m_1$, $m_2$, $m_3$, respectively.

The necessary and sufficient conditions for the existence of neutrino oscillations is that neutrinos have non-zero mixing of at least 2 mass eigenstates and that at least 2 masses are non-zero. This phenomenon cannot be understood within the standard model (SM) of particle physics and is a hint of physics beyond the SM.

In three flavor neutrino oscillation, the oscillation parameters are the three mixing angles, $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, charge parity violating phase, $\delta_{CP}$, and two independent squared mass differences, $\Delta m^2_{21}$ and $\Delta m^2_{31}$. The amplitude of neutrino oscillation probability is decided by the mixing angle while the position of maxima or minima depends on the squared mass difference. The mixing parameters $\theta_{12}$ and $\Delta m^2_{21}$ are precisely determined by the solar neutrino experiments. The KamLAND reactor neutrino experiment while confirming neutrino oscillation provided the most precise value of $\Delta m^2_{21}$ and improved the precision of $\theta_{12}$ in combination with solar neutrino data. The mixing angle $\theta_{23}$ has been measured by the Super-Kamiokande collaboration using atmospheric neutrinos and by the long-baseline accelerator experiments such as MINOS and T2K. The latter have also measured $\sin^2\theta_{23}$ with good accuracy. The non-zero value of $\theta_{13}$, hinted by the results of T2K and MINOS, has been accurately measured by the short baseline reactor neutrino experiments DayaBay, RENO and DoubleChooz. As of now the sign of $\Delta m^2_{31}$ and value of $\delta_{CP}$ are unknown. The sign of $\Delta m^2_{31}$ will help determine the hierarchy of neutrino masses. If CP-violation is observed in the neutrino sector, leptogenesis is a possible means of explaining the observed asymmetry between matter and antimatter.

The anomalies observed, albeit at not very large significance, in several experiments viz. LSND, MiniBooNE, SAGE, GALLEX are not explained by 3-$\nu$ oscillation theory. The
observed appearance probability $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations in LSND showed an excess of electron anti-neutrino events above the expected background with a $3.8\sigma$ significance. The smallness of $\Delta m^2_{sol} \approx 7.5 \times 10^{-5}$ eV$^2$ and $\Delta m^2_{atm} \approx 2.4 \times 10^{-3}$ eV$^2$ coupled with the large $\Delta m^2$ required by LSND, for example, requires a fourth neutrino. The MiniBooNE experiment was motivated by the LSND results and studied $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. In the $\nu_\mu \rightarrow \nu_e$ study, MiniBooNE found no evidence for an excess of $\nu_e$ candidate events above 475 MeV; however, a $3 \sigma$ excess of electron like events was observed below 475 MeV. The LSND data is consistent with $\nu_\mu \rightarrow \nu_e$ oscillations in the $\Delta m^2 \sim 0.1$ to 1.0 eV$^2$. The experimental results from the LSND, MiniBooNE and $\bar{\nu}_e$ disappearance revealed by the reactor anomaly indicates the necessity of possible short-baseline neutrino experiments. Also radioactive source calibration of the Gallium solar neutrino experiments SAGE and GALLEX showed an event rate which is somewhat lower than expected. This effect can be explained by the hypothesis of $\nu_e$ disappearance due to oscillations with $\Delta m^2 \geq 1$ eV$^2$ (“Gallium anomaly”). Their results cannot be explained within the standard three active neutrino oscillation formalism and suggest the existence of additional neutrinos with masses at the eV scale. Such neutrinos may not participate in the weak interaction due to the constraint on the invisible width of the Z boson and are therefore called “sterile” neutrinos. The existence of sterile neutrinos which have been thermalized in the early Universe is compatible with Big-Bang Nucleosynthesis data. The combined analysis of data from CMB+lensing+BAO(baryon acoustic oscillation) experiments provide a robust frequentist upper limit $\sum m_\nu \leq 0.26$ eV with 95 % CL. There is no preferred theoretical model or framework that has emerged so far from the above mentioned experimental results. There have been several attempts to interpret these anomalies in terms of 3 + N neutrino oscillation models involving 3 active neutrinos and N additional sterile neutrinos. The possible existence of sterile neutrinos is very interesting because they are new particles which could give us valuable information on the physics beyond the standard model. The down-going atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ fluxes can be significantly altered due to the presence of eV$^2$-scale active-sterile oscillations. A large magnetized iron detector like the proposed iron calorimeter (ICAL) at the India-based Neutrino Observatory (INO) may be used to study these oscillations.

Roughly one half of work reported here is on the design of the ICAL magnet, its response to muons for various strengths of magnetic field and its sensitivity to sterile neutrino mixing. The proposed ICAL detector will measure precisely the oscillation parameters using atmospheric neutrinos. In particular, it aims at identifying the neutrino mass hierarchy, normal or inverted. To reduce the cosmic rays background, the detector will be placed
under the mountain with an all round rock cover of at least 1 km. The rectangular shaped 51 kton magnetized ICAL detector, will also provide the target nuclei of iron for neutrino interactions to facilitate their detection via the charged particles produced in these interactions. The ICAL detector consists of three modules each weighing \( \sim 17 \) kton with dimensions of \( 16 \text{ m} \times 16 \text{ m} \times 14.5 \text{ m} \) and 151 layers of low carbon steel. The layers are alternated with gaps of 40 mm in which will be placed active gas detectors, of the Resistive Plate Chambers (RPC) type, to measure the charged particles produced due to charged current (CC) and neutral current interaction of \( \nu_\mu \) and \( \bar{\nu}_\mu \) respectively with the nucleons of iron. The RPC detectors give the position and time information. The mutually perpendicular readout strips in each RPC provide X, Y-position information and the layer number gives Z-position information. The main advantage of the magnetized ICAL detector is to identify, separately, \( \nu_\mu \) and \( \bar{\nu}_\mu \) induced events. The calorimeter will be magnetized with a piecewise uniform magnetic field \( (B = 1-1.5 \text{ T}) \) to distinguish the \( \mu^- \) and \( \mu^+ \) events from the opposite curvature of their tracks in the presence of a magnetic field.

In order to measure the oscillation parameters more precisely, it is important that the energy and incoming direction of the detected neutrino have to be determined with very good accuracy. In case of atmospheric neutrinos, the source to detector distance is estimated using their incoming zenith angle. The neutrinos (anti-neutrinos) interact with nucleons of iron in the detector through quasi-elastic, resonance and deep inelastic scattering processes. In a CC muon neutrino interaction, a muon is produced along with hadrons. The muon gives a clear track inside the detector. On the other hand, a strongly interacting hadron produces a hadronic shower in the detector. The hit multiplicity of charged particles distinct from the muon track are used to estimate the total energy of hadrons in an event. The muon momentum can be measured either from the track length of stopped muons in the detector or from the curvature of the track due to the magnetic field. The magnetic field helps not only in the momentum measurement of muons that do not stop in ICAL but also increases the fiducial volume of the detector. In a magnetized detector, the muon momentum resolution, at the highest energy, depends upon the strength and uniformity of magnetic field.

The electromagnetic simulation of the ICAL magnet was done for various configurations to optimize the design of ICAL detector. These simulations were carried out using a finite element method based 3-D commercial software. In the simulation, we have defined the geometry and assigned the magnetic properties (B-H-properties, where B is the magnetic induction and H is the magnetic field) of the iron plates. The B-H profile of the soft iron
was obtained from the measurement of toroidal samples using a BH-loop tracer. The motivation of the simulation was to find the optimal slot configuration (through which pass the copper coils, for energizing ICAL), tiling of plates and to study the magnetic field strength, and its uniformity for the baseline design and the effect of various kinds of departure from this design. The computation time to simulate the ICAL magnet having 151 layers of iron plate is very large, therefore most of the studies were carried out considering a single layer of iron plate. This result matches, within 4 %, that for the configuration which consists of three iron layers at the bottom, middle and top, respectively, carrying four coils, each having height of 15 m.

It may be observed that the configuration with continuous slots for accommodating the coils, gives a superior B-field uniformity compared with those with two or four pairs of discrete slots. It was found that, the fractional area for which $|B| \geq 1$ T is $\sim 75$ % at 20 kA turns and increased to $\sim 90$ % at 60 kA-turns. The study shows that for the case of the plates with continuous slots, the B-field distribution can be optimized by choosing proper slots dimension and their position. The iron plate with larger slot length than the standard baseline design gives marginally better B-field distribution. The B-field distribution in iron increases with increase of plate thickness and gets saturated beyond the plate thickness $\sim 4$ cm justifying the choice of 5.6 cm. It was also found that the B-field distribution depends on the soft magnetic properties of the material in which carbon content is crucial.

Practically, however, building the ICAL detector using $16 \times 16 \times 0.056$ m size plate is not feasible due to difficulties in manufacturing and handling. Therefore, the $16 \times 16$ m area will be tiled with plates of size $2 \times 4$ m. Due to mechanical tolerances, there are air gaps among tiles. The magnetic lines of forces fringe out at air gaps, which lead to the reduction of flux linkage amongst them. The electromagnetic simulation was carried out considering tile gaps of 2 mm, 4 mm and 6 mm. It shows that the B-field in iron reduces with increase of air gaps among tiles. A study of 4 possible different tile configurations was also carried out, with a nominal 2 mm gap between plates, to get the maximum B-field at minimum ampere-turns. Two configurations, C2 and C3, appear to give better results at lowest power dissipation in coils. As expected, it was found that an increase of air gap between adjacent tiles leads to a reduction of B-field for a given excitation current. Although the smallest gap is desirable, a gap of 2 mm may be a practical compromise. There are magneto-static forces among tiles which try to reduce the air gaps. The estimated magneto-static force among tiles is $\sim 100$ kN which needs to be taken into account while designing the mechanical structure and for assessing the stability of the ICAL magnet.
The measurement of neutrino oscillation parameters using a magnetized ICAL detector depends on the reconstructed muon energy and angular resolution. It is also important to identify the neutrinos by discriminating the corresponding produced leptons. For this purpose, a Monte Carlo (MC) simulation using the object oriented simulation toolkit GEANT4 at various strength of B-fields was done to estimate these parameters. The magnetic field map in a grid size of 5 cm × 5 cm of the iron plate obtained from the electromagnetic simulation of ICAL magnet was interpolated for the 16 m × 16 m area and used for muon tracking. A sample of \(10^4\) muons (\(\mu^-\)) with fixed energies 1-20 GeV, originate in the central region of the detector where the B-field is nearly uniform, in all azimuthal directions and at fixed zenith angles (\(\theta_z\)) such that \(\cos \theta_z\) takes on values between 0.1 to 1.0 in bins of \(\Delta \cos \theta_z = 0.1\). The strengths of magnetic field chosen for this study are 1.1 T, 1.5 T and 1.8 T. At a given magnetic field strength, the energy resolution improves with increasing muon energy. The lowest energy resolution obtained is \(\sim 10\%\) for 5 GeV muons incident at \(\cos \theta_z = 0.95\) for a magnetic field strength of 1.5 T. It is observed that, the charge identification efficiency is more than 90 % for all energies for a magnetic field greater than 1.5 T. A similar behaviour has been observed for the energy resolution and charge identification efficiency for a range of values of \(\cos \theta_z\) between 0.85 and 0.15. It is concluded that the energy resolution as well as charge identification efficiency of muons improve with increase of the magnetic field strength, but a choice of 1.5 T B-field appears to give satisfactory results and there was not much gain by increasing the field to 1.8 T. The angular resolution of ICAL detector is less than 1° for energy greater than about 4 GeV. The study shows that the behavior of angular resolution with magnetic field is almost independent of its strength. The response of ICAL to muons is used to study its sterile neutrino mixing sensitivity.

The second part of the thesis is based on a study of the sensitivity of ICAL to sterile neutrino mixing. From among the various models that could be used for studying the sterile neutrino sensitivity, the present analysis used the “3 + 1” model where ‘3’ and ‘1’ stand for active and sterile neutrinos, respectively. The MC simulation code used was developed for the physics analysis of ICAL at INO. The code NUANCE, duly modified for INO, has been developed by the collaboration, and used as a MC generator for generating atmospheric neutrino events and HONDA atmospheric neutrino flux is given as input to the generator. In order to reduce the MC fluctuations in the event sample, events were generated corresponding to \(50 \times 1000\) kton-years exposure. Since, it takes a fairly long time to run the Nuance code to generate such a large event sample, running it over and over again for each set of oscillation parameters is practically impossible. Therefore events
are first generated without imposing the neutrino oscillation. Thereafter, the reweighting algorithm is imposed to generate the event sample for any set of oscillation parameters. Finally the events are folded with detector efficiencies and resolution, calculated by the INO collaboration, to get the reconstructed muon events in ICAL. The events are finally normalized to a realistic number of years for running the ICAL. The ICAL physics simulations are performed not in terms of the neutrino energy and angle, but using muon and hadron information of an event. Then, $\chi^2$ was calculated considering the no-sterile and sterile oscillated events taking into account both statistical and systematic errors. The variable bins used took into consideration the detector resolution in the energy range 1-20 GeV and zenith angles for downward-going as well as upward-going neutrinos such that the bin content should be $\geq 1$.

The analysis was carried out separately considering neutrino events which reach the detector (a) only in the downward-going (zenith angle $\theta_z: 0^\circ \leq \theta_z \leq 90^\circ$) direction and (b) coming from all directions ($0^\circ \leq \theta_z \leq 180^\circ$). The details of the neutrino induced events used for the analysis are muon energy, its zenith angle and the hadron energy. In one part of the study, the sterile neutrino sensitivity is carried out considering the reconstructed energy and zenith angle of the muon. In another case, the muon energy and zenith angle combined with hadron energy are considered. It was concluded, that the downward-going atmospheric neutrinos will show the signatures of eV$^2$- scale oscillation due to their variable energy and path length. The upper limit for $\sin^2 2\theta_{\mu\mu}$ is $\sim 0.16$ considering combined muon and hadron information from neutrino induced events at an exposure of 1 Mt.yr. The sensitivity to the sterile neutrino mixing angle is further improved by considering neutrinos coming from all directions and reaching the detector. There was about 35% enhancement in sensitivity over all $\Delta m^2_{41}$. A comparative study was carried out between the results from SciBooNE/MiniBooNE with ICAL at INO using neutrino and muon events. It was found that, at lower values of $\Delta m^2_{41}$, the ICAL detector has better sensitivity compared to the short baseline experiments like SciBooNE and MiniBooNE. Further, exclusion plots have been generated for various mixing angle combinations considering only muon energies and zenith angles. To estimate the $\chi^2$ with the simulated data, the best fit values for $\theta_{14} = \theta_{24} = \theta_{34} = 10^\circ$ and at $\Delta m^2_{41} = 1$ eV$^2$ were considered. While generating the exclusion plots for two mixing angles, the third mixing angle and $\Delta m^2_{41}$ have been marginalized and also the corresponding priors were added. It showed that the upper limit for the mixing angles $\theta_{14}$, $\theta_{24}$ and $\theta_{34}$ were about $20^\circ$ - $30^\circ$ at 90% confidence level. As a final remark it may be mentioned that, the confirmation of the existence of sterile neutrinos is a great challenge for upcoming neutrino physics experiments.