Chapter 2

THE ICAL DETECTOR

The prime aim of INO is to study the neutrino oscillations with atmospheric neutrinos. Unlike the accelerator and reactor neutrino experiments where the energy ($E$) and the distance ($L$) between the neutrino source and the detector are fixed or within a narrow window, the atmospheric neutrinos provide a wide range of $E$ and $L$. The atmospheric neutrino flux is feeble, and hence the requirement of a detector with a large volume becomes essential to have significant event statistics. In order to fulfill this goal, the INO collaboration plans to build a huge magnetized Iron Calorimeter (ICAL) detector, which would be sensitive to the energy, direction and the electric charge of the final state leptons produced in charged–current (CC) interactions of the neutrinos with the target material [6]. It will use magnetized Iron plates as the target mass and Resistive Plate Chamber (RPC) detectors as the active detector elements [7]. It will be mostly sensitive to the muon neutrinos. The main physics goals of the ICAL are as listed below.

- The reconfirmation of the oscillations in the atmospheric neutrinos through explicit observation of the first oscillation swing in $\nu_\mu$ disappearance, as a function of $L/E$. 


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- The study of matter effects in $\nu_\mu$ and $\bar{\nu}_\mu$ separately through muon charge identification in order to determine the sign of $\Delta m^2_{32}$ and hence to determine the neutrino mass hierarchy.

- Precise determination of the atmospheric neutrino mixing parameters $\theta_{23}$ and $\Delta m^2_{32}$.

- Determination of the true octant of $\theta_{23}$ and its deviation from the maximal value.

Apart from the above, the ICAL will also search for the hint of new physics, such as

- Charge conjugation – parity – time (CPT) violation in the leptonic sector.

- The possible existence of sterile neutrinos.

- The signature of non standard interactions (NSI) in neutrino oscillations.

- Indirect search for dark matter.

The design of the ICAL is motivated by the physics goals mentioned above. In this chapter, the configuration of the ICAL along with a description of its active element RPC are discussed. The various neutrino interactions in ICAL with their specifications and importance to the physics study have also been mentioned.

2.1 THE STRUCTURE OF THE ICAL

The ICAL will mostly look for $\nu_\mu$ and $\bar{\nu}_\mu$ induced CC interactions using magnetized iron as the target and about 28,800 RPCs as the active detector elements. It will consist of three identical and adjacent modules, each of dimension $16 \text{ m} \times 16 \text{ m} \times 14.5 \text{ m}$. Each detector module will be made up of 151 horizontal layers of 5.6 cm thick low carbon iron plates interspersed with 4 cm gaps into which the Resistive Plate Chamber (RPC) assemblies. The total mass of the ICAL will be 50 kt.
Table 2.1: The specifications of the ICAL Detector.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of modules</td>
<td>3</td>
</tr>
<tr>
<td>Modular dimension</td>
<td>$16 , \text{m} \times 16 , \text{m} \times 14.4 , \text{m}$</td>
</tr>
<tr>
<td>Total dimension</td>
<td>$48 , \text{m} \times 16 , \text{m} \times 14.4 , \text{m}$</td>
</tr>
<tr>
<td>Number of layers</td>
<td>151</td>
</tr>
<tr>
<td>Iron plate thickness</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>Gap for RPC assembly</td>
<td>4 cm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1.4 T</td>
</tr>
<tr>
<td>RPC unit dimension</td>
<td>$195 , \text{cm} \times 184 , \text{cm} \times 2.4 , \text{cm}$</td>
</tr>
<tr>
<td>Readout strip width</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>Number of RPCs/Road/Layer</td>
<td>8</td>
</tr>
<tr>
<td>Number of Roads/Layer/Module</td>
<td>8</td>
</tr>
<tr>
<td>Number of RPC units/Layer</td>
<td>192</td>
</tr>
<tr>
<td>Total RPC units</td>
<td>28,800</td>
</tr>
<tr>
<td>Number of electronic channels</td>
<td>$3.7 \times 10^6$</td>
</tr>
</tbody>
</table>

The schematic of the ICAL detector is shown in Fig 2.1. The blue lines in the three modules as shown in the figure show the placement of the Copper coils through which a current will be passed to generate a non-uniform magnetic field. There will be four coils in each module with 32 turns/coil. The ICAL will be magnetized to a non-uniform field peaking at 1.4 T, to distinguish between the muon and the antimuons produced in the $\nu_\mu$ and $\bar{\nu}_\mu$ interactions respectively. The total number of readout channels will be about 3.7 million. The important detector specifications have been highlighted in Table 2.1.
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Figure 2.1: (a) The schematic representation of the ICAL detector with dimensions. All the three modules are shown here. The blue lines represent the current coils which magnetize the detector. (b) The placement of the iron plates and the RPC assembly in the ICAL. Each of the three modules of the ICAL consists of 151 such layers.
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2.2 THE RPC DETECTORS

The Resistive Plate Chambers (RPCs) are gaseous parallel plate detectors, made of highly resistive electrodes such as glass or Bakelite, to track charged particles. The concept of the RPC was introduced in 1981 by R. Santonico and R. Cardarelli as an alternative to the localized discharge spark counters [118]. The main features of the RPCs are excellent detection efficiency, good spatial as well as position resolutions, wide area coverage and low production cost.

![Figure 2.2: The configuration of an RPC detector.]

A schematic diagram of the RPC detector configuration is shown in Fig. 2.2. A gas mixture is enclosed by two planar electrodes (glass in our case) with a bulk resistivity of about $10^{12} \, \Omega \, \text{cm}$. The gas gap is maintained by cylindrical polycarbonate spacers (bulk resistivity $> 10^{13} \, \Omega \, \text{cm}$). The sides of this chamber are sealed by gluing certain spacers, with inlets and outlets for a continuous gas flow. The two electrodes have conductive graphite coat at their outer surfaces, and they are connected to a high voltage power supply, in order to maintain a uniform and fixed electric field (about 5 kV/mm) across the gas gap.

The formation of the electric signal in the RPC detectors is based on electron multiplication process. When a charged particle passes through the detector, a certain number of primary electrons are produced. These electrons may be grouped into
some clusters. The electrons in any cluster are accelerated by the electric field and they start multiplication. This process is characterized by the following two parameters – the number of ionization per unit length $\alpha$ (first Townsend coefficient), and the number of electrons captured by the gas per unit length $\beta$ (attachment coefficient). The number of electrons $n$ that reaches the anode can be expressed by the following formula \cite{119}

$$n = n_0 \exp[(\alpha - \beta)x],$$  

(2.1)

where $n_0$ is the number of primary electrons in that cluster, and $x$ is the distance between the point at which the cluster was created and the anode.

The gain of the detector is given by

$$M = \frac{n}{n_0}.$$  

(2.2)

Depending on the value of the gain, the mode of operation of the RPCs are classified as streamer or avalanche. When $M > 10^8$, the primary ionizations will give rise to streamers with high probability. On the other hand, for $M \ll 10^6$, smaller amount of charge is created through simple charge multiplication, and the RPC is said to be operated in the avalanche mode. The mode of operation, as can be seen from Eq. (2.1), is governed by the two parameters $\alpha$ and $\beta$ which are characteristics of the gas used. A gas mixture of R134a, Isobutane and SF$_6$ has been used to operate the RPCs in the ICAL R&D program in avalanche mode \cite{7, 120}.

When the gas is ionized by the passage of a charged particle, the avalanches of electrons originate a discharge. Due to the high resistivity of the electrodes, the discharge is prevented from spreading through the whole gas volume, and the electric field drops down in a small area around the point where the discharge initiates. The discharged area recharges slowly through the high resistive glass plates and recovery time is about 2 s. The propagation of the electron avalanche induces a current on external electrodes. This is collected by external copper pickup strips of width
2.8 cm. As shown in Fig. 2.2, the pickup strip on the two electrodes are mounted orthogonal to each other, which enables the detection of the location of the passage of the particle in pixels of area 2.8 cm × 2.8 cm. In the rest of this thesis, the measured location of a charged particle in the RPCs will be termed as hits. A complete detail of the working principle and design of the RPC detectors can be found in [120].

### 2.3 NEUTRINO INTERACTIONS IN THE ICAL

The ICAL has been configured to make it primarily sensitive to the \( \nu_\mu \) induced charged–current CC events. Typically a 1 GeV muon can pass through 5 – 12 RPC layers in the detector depending on the angle of its incidence [9]. The electrons generated in \( \nu_e \) induced events will hardly cross a few layers, and suitable criteria on the number of layers crossed by the particle can be used to remove such events.

![Figure 2.3](image.png)

(a) (b)

Figure 2.3: The cross sections of (a) CC \( \nu_\mu \) interaction processes, and (b) CC \( \bar{\nu}_\mu \) interaction processes. [121]

The atmospheric \( \nu_\mu \) and \( \bar{\nu}_\mu \) interact with the iron target through quasi–elastic (QE), resonance scattering (RS) and deep inelastic scattering (DIS) processes as well as a negligible fraction of diffractive and coherent processes. The CC interactions produce muons as well as hadrons. Fig. 2.3 presents the current knowledge on the cross sections of the three prominent CC \( \nu_\mu \) and CC \( \bar{\nu}_\mu \) interactions [121]. As can be seen from these figures, in the sub–GeV range the QE processes dominate, and apart from the recoil nucleons they do not have any other hadrons in the final state. As the
energy increases RS and DIS processes start dominating and at a few GeVs DIS becomes the most prominent process. Resonance events typically contain a single pion in the final state, though in a small fraction of events there are multiple pions. DIS events produce multiple hadrons. In the neutral–current (NC) interactions, the final state consists of a neutrino and hadrons. The secondary neutrino would hardly interact with the target, and thus the hadronic parts are the only observables for those events. For the atmospheric neutrinos passing through the Earth’s core, maximum matter effects would be experienced by the neutrinos in the energy range $4 – 6 \text{ GeV}$, which would have prominent fractions of RS and DIS interactions. Thus it is crucial to obtain information on all the final state particles to improve the sensitivity of ICAL in reaching its physics goals.

2.4 ICAL FOR NEUTRINO OSCILLATION STUDY

The ICAL detector would be optimized to be most sensitive to the atmospheric muon neutrinos in the energy range $1 – 10 \text{ GeV}$. The modular structure of the detector, with the horizontal layers of the iron plates and the RPC detectors allows it to have an wide coverage to the direction of the incoming neutrinos, except the ones producing muons traveling almost horizontally. While the atmospheric neutrino flux provides a wide spectrum in the neutrino energy ($E_\nu$), the detector structure enables it to be sensitive to a broad range of the path length ($L$) for the neutrinos penetrating through the Earth.

The ICAL would be sensitive to both the energy and direction of the muons produced in the CC interactions of the atmospheric muon neutrinos and the antineutrinos with the iron absorber plates. The upward–going and downward–going muon events can also be identified using the fast response time of the RPCs, which is of the order of nanoseconds. This distinction would allow the separation of the neutrinos with short path lengths from those with longer ones. This would be very useful to study neutrino oscillations, as the oscillation probability strongly depends on the
path length $L$.

In addition, ICAL, being a magnetized detector, would be able to differentiate between muons and antimuons, which makes it capable of separating events induced by muon neutrinos and muon antineutrinos. Since the neutrinos and the antineutrinos experience different matter effects while propagating through the Earth, the ability to discriminate between neutrinos and antineutrinos makes the detector sensitive to the neutrino mass hierarchy, which is the main goal of the ICAL experiment. The presence of the magnetic field also improves the momentum resolution of the muons by measuring the extent of bending of the muon track in the local magnetic field.

As have been mentioned above, the structure and good tracking ability of ICAL makes it suitable to explore the neutrino oscillations in the atmospheric muon neutrino interactions. The ICAL is also sensitive to the energy deposited by the hadrons in the multi–GeV range. It is very crucial to estimate the capability of ICAL in reconstructing various particles, which in turn would provide the expected sensitivity of the detector in reaching its physics goals. Hence a simulation of the ICAL detector has been performed using the GEANT4 simulation package in the CERN–library \cite{8}. The simulation framework and the response of the detector to various particles like muons and hadrons, and the physics reach of ICAL using those information has been described in the following chapters.