Chapter 1

Introduction

1.1 The Standard Model: A brief summary

The Standard Model describes the theory of elementary constituents of matter and forces that act between them (excluding gravitation) [1, 2]. The known elementary building blocks of the standard model are quarks, leptons, antiparticles of quarks and leptons, and force carriers of the fundamental interactions between these particles. The force carriers are called as the gauge bosons. The Standard Model is a gauge theory based on the local symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$, where the subscripts $C, L$ and $Y$ indicate color, left-handed chirality and weak hypercharge, respectively. The gauge group uniquely determines the interactions and the number of vector gauge bosons that correspond to the generators of the group. They are eight massless gluons, corresponding to the eight generators of $SU(3)_C$, that mediate strong interactions; four gauge bosons, of which three are massive ($W^\pm$ and $Z$) and one is massless ($\gamma$, the photon), corresponding to the three generators of $SU(2)_L$ and one generator of $U(1)_Y$, responsible for electroweak interactions [3]. The building blocks of the standard model and some of their quantum numbers are summarized in table 1.1. The quarks and leptons are grouped into three generations of four particles each. Between generations, particles differ by their flavor quantum number and mass, but their interactions are identical.
Table 1.1: Building blocks of the standard model and some of their quantum numbers. The spin is given in units of $h$ and the charge is given in units of elementary charge $e$. The antiparticles of quarks and leptons have the quantum numbers $\bar{B}$, $\bar{L}$ and $\bar{Q}$ with opposite sign [4, 5].

<table>
<thead>
<tr>
<th>Category</th>
<th>Particle</th>
<th>Mass (MeV/c$^2$)</th>
<th>Spin</th>
<th>Baryon number (B)</th>
<th>Lepton number (L)</th>
<th>Charge (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks</td>
<td>$u$</td>
<td>1.5 - 4</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$d$</td>
<td>4 - 8</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td></td>
<td>$c$</td>
<td>($1.15 - 1.35) \times 10^3$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td>80 - 130</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td></td>
<td>$t$</td>
<td>174.3 ± 5.1 \times 10^3</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>($4.1 - 4.4) \times 10^3$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>Leptons</td>
<td>$e$</td>
<td>0.511</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>105.7</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>$1.777 \times 10^3$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\nu_e$</td>
<td>$&lt;2.2 \times 10^{-6}$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\nu_\mu$</td>
<td>$&lt;0.17$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$\nu_\tau$</td>
<td>$&lt;15.5$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Gauge bosons</td>
<td>$g_i$ ($i = 1, 2, ...$ gluons)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(force carriers)</td>
<td>$\gamma$ (photon)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$W^\pm, Z$ (weak bosons)</td>
<td>$80.4 \times 10^3, 91.2 \times 10^3$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$\pm 1, 0$</td>
</tr>
</tbody>
</table>
The typical interactions, force carriers and interaction properties of the elementary particles are given in table 1.2. Quarks participate in all the interactions, whereas leptons participate in all the interactions except strong interactions. Quarks are elementary components of hadrons but do not exist as free particles.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Participating particles</th>
<th>Force carrier</th>
<th>Charge</th>
<th>Range</th>
<th>Strength</th>
<th>Typical lifetime (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Quarks</td>
<td>Gluon</td>
<td>Color</td>
<td>1 fm</td>
<td>10</td>
<td>$10^{-23}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>All charged particles</td>
<td>$\gamma$ (photon)</td>
<td>Electric charge ($e$)</td>
<td>$\infty$</td>
<td>$10^{-2}$</td>
<td>$10^{-20} \sim 10^{-16}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Quarks, Leptons</td>
<td>$W^\pm$, $Z$</td>
<td>Weak charge</td>
<td>$10^{-3}$ fm</td>
<td>$10^{-13}$</td>
<td>$10^{-12}$ or longer</td>
</tr>
</tbody>
</table>

The detailed list of elementary constituents of the standard model, some of their quantum numbers and their interaction properties are summarized in figure 1.1 as well.

### 1.2 Gravity

The gravitational force is the most evident in everyday life. This is by far the weakest force known. As a result, it has no measurable effects on a subatomic scale and no manifestations that can guide to a quantum field theory. Therefore, the standard model could not adequately explain the gravity and is called as beyond standard model problem. Finally, on September 14, 2015 the gravitational-wave signals were observed at Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), USA [6].
Figure 1.1: Standard model of the particle physics showing the electric charge, color charge, mass and spin of each particle [7].

1.3 Neutrino physics

1.3.1 A historical introduction

The history of neutrino started when in 1914 James Chadwick demonstrated that the \( \beta \)-spectrum was continuous, in contrast to \( \alpha \) and \( \gamma \) spectra that are discrete. The same result was subsequently confirmed in 1927 by Sir Charles Drummond Ellis and William Wooster. This led to the idea that the missing energy could be explained either by the existence of a new particle or, as proposed by Niels Bohr, abandoning of fundamental classical laws: conservation of energy and momentum.

In order to explain the continuous energy spectrum and spin statistics in \( \beta \)-decay, Wolfgang Pauli proposed a new particle, in a famous letter to a physics conference at Tübingen on 4 December 1930, addressed to “Dear Radioactive Ladies and Gentlemen”, that an additional neutral fermion, emitted along with the \( \beta \)-particle, might exist in the nucleus. He called the neutral fermion as neutron. In 1932, James Chadwick discovered the neutron as we know it today and later Enrico
Fermi renamed the Pauli particle the *neutrino* [3, 8].

By following the suggestion from Bruno Pontecorvo, Frederick Reines and Clyde Cowan conducted an experiment in 1953 at Savannah River reactor, USA and discovered the neutrino. The basic detection reaction was:

\[
\overline{\nu}_e + p \rightarrow e^+ + n,
\]  

(1.1)

where, \(\overline{\nu}_e\) is electron antineutrino, \(p\) is proton, \(e^+\) is positron and \(n\) is neutron. The detection principle was a coincident measurement of the 511 keV photons associated with positron annihilation and a neutron capture reaction a few \(\mu s\) later [3, 9, 10]. Again as suggested by Pontecorvo, in 1955 Raymond Davis, Jr. conducted an experiment in an attempt to induce the radiochemical reaction:

\[
\overline{\nu}_e + ^{37}Cl \rightarrow e^- + ^{37}Ar.
\]

(1.2)

For this experiment, Davis used antineutrino source from Brookhaven reactor, USA. He could not observe this reaction and concluded that neutrinos and antineutrinos are not identical particles [3, 10, 11, 12]. Later in 1968, Davis and his collaborators used the same detection principle in a large scale version in the successful detection of solar neutrinos [3, 10, 12, 13]. The experiment was conducted at Homestake gold mine at South Dakota, USA. The detection reaction was:

\[
\nu_e + ^{37}Cl \rightarrow e^- + ^{37}Ar.
\]

(1.3)

In 1959, Pontecorvo investigated whether the neutrino emitted in \(\beta\)-decay is the same as the one emitted in pion decay. If \(\nu_\mu\) and \(\nu_e\) are identical particles, then the reactions:

\[
\nu_\mu + n \rightarrow \mu^- + p,
\]

(1.4)

\[
\overline{\nu}_\mu + p \rightarrow \mu^+ + n,
\]

(1.5)

and
\[ \nu_\mu + n \rightarrow e^- + p, \]  
(1.6) 
\[ \bar{\nu}_\mu + p \rightarrow e^+ + n \]  
(1.7)

should happen in the same rate, because the later could be done by \( \nu_e \) and \( \bar{\nu}_e \); otherwise the last two reactions should not be observed at all [10]. In 1960, M. Schwartz discussed about the use of high-energy accelerators as neutrino sources [14]. Then in 1962, G. Danby and his collaborators conducted an experiment at Brookhaven Alternating Gradient Synchrotron (AGS), USA using proton beam hitting a beryllium (Be) target. Due to this interaction secondary pions and kaons are generated, and their decay in flight produced an almost pure \( \nu_\mu \) beam. This beam strikes through a thick iron wall and the interactions were observed in an aluminum spark chamber located behind the iron wall. In total, 29 muon-like (single tracks) and six electron-like (showers) events were observed in the chamber. The electron events were expected from \( \nu_e \) beam contaminations due to kaon decays (for example, \( K^+ \rightarrow e^+ + \nu_e + \pi^0 \)). Therefore, it concludes that \( \nu_\mu \) and \( \nu_e \) are different particles (i.e., \( \nu_\mu \neq \nu_e \)) [10, 15]. In 1964, the experiment was repeated at CERN with higher statistics and confirmed the result [10, 16].

In 1975, Martin Lewis Perl and his collaborators detected the \( \tau \) lepton using Stanford Linear Accelerator Center’s (SLAC’s) then new \( e^+ - e^- \) colliding ring, called Stanford Positron Electron Asymmetric Rings (SPEAR), and the Lawrence Berkeley National Laboratory (LBNL) magnetic detector. The detection reaction was:

\[ e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles.} \]  
(1.8)

In July 2000, Direct Observation of the NU Tau (DONUT) experiment at Fermilab, USA announced the first observation of \( \nu_\tau \) events [17]. In the experiment, protons accelerated by the Tevatron were used to produce tau neutrinos via decay of charmed mesons (\( D_S \)). The detection principle was as following:

\[ \nu_\tau + N \rightarrow \tau^- + X \]  
(1.9)
and then

\[ \tau^- \rightarrow \mu^- (e^-) + \nu_\tau (\nu_e) + \nu_\tau \quad \text{or} \quad \tau^- \rightarrow h^- + \nu_\tau. \quad (1.10) \]

### 1.3.2 Neutrino sources

Neutrinos are produced both naturally and in the laboratory. To understand the intrinsic properties of neutrinos, each of these sources provides information, sometimes overlapping.

**Solar neutrinos**

We begin with solar neutrino problem because of its historical importance. The Sun generates heat and light through thermonuclear fusion reactions. There are cycles of such reactions which take place in the Sun, for example the $pp$ chain, the CNO cycle, etc., where neutrinos are produced at different stages. The effective process is the $pp$ chain reaction and is summarized as following:

\[ p + p + p + p \rightarrow ^4\text{He} + 2e^- + 2\nu_e + 26.73 \text{ MeV}. \quad (1.11) \]

The energy released in the process accounts for the luminosity of the Sun. From this, the solar neutrino flux at the Earth is calculated to be 70 billion/cm$^2$/sec. The Sun produces only electron neutrinos and they carry only MeVs of energy. The solar neutrinos were first discovered by Davis and his collaborators at Homestake gold mine, USA, as discussed in section 1.3.1.

**Atmospheric neutrinos**

The primary cosmic-rays interact with the Earth’s atmospheric nuclei and produce showers of particles. Many of these particles are unstable and produce neutrinos when they decay as following:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \quad (1.12) \]

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (1.13) \]

7
and

\[ \mu^+ \rightarrow e^+ + v_e + \bar{v}_\mu \]  \hspace{1cm} (1.14)

\[ \mu^- \rightarrow e^- + \bar{v}_e + v_\mu \]  \hspace{1cm} (1.15)

The atmospheric neutrino flux is \(10^3 / \text{m}^2 / \text{s}\) and they carry energies in GeV scale. The atmospheric neutrinos were first discovered at the Kolar Gold Field (KGF) mines in South India [18] and East Rand Proprietary Gold mines in South Africa [19].

**Neutrinos from supernovae**

Neutrinos are copiously emitted during stellar collapse. The first such observation of neutrinos from a supernova took place in 1987. During the early stage of stellar collapse neutrinos are produced through neutronization as following:

\[ e^- + p \rightarrow n + v_e, \]  \hspace{1cm} (1.16)

where only \(v_e\)s are produced. The main neutrino emission is during the cooling phase where the thermal \(\nu/\bar{\nu}\)s are produced through the pair production as one of the processes as following:

\[ e^+ + e^- \rightarrow \nu + \bar{\nu}. \]  \hspace{1cm} (1.17)

Neutrinos from supernovae are visible just beyond the energy range of solar neutrinos. Hence, they can be observed in detectors dedicated to solar neutrino experiments. The approximate neutrino flux observed from SN1987a Supernova was \(10^{12} / \text{m}^2 / \text{s}\).

**Geoneutrinos**

The radioactive isotopes \(^{238}\text{U}\) and \(^{232}\text{Th}\) present in the Earth produce \(v_e\)s as a result when they naturally decay [20]. They can provide the information on the Earth’s interior. The flux of geologically produced neutrinos is about \(5 \times 10^{10} / \text{m}^2 / \text{s}\).
Reactor neutrinos

The very first experimental detection of neutrinos was in fact made with the reactor neutrinos at Savannah River reactor, USA, as discussed in section 1.3.1. The fission reactors are the major source of the human-generated neutrinos and they produce huge number of anti-electron neutrinos ($\bar{\nu}_e$s). The reactor neutrinos carry MeVs of energy. A standard nuclear power reactor produces about $2 \times 10^{20} \bar{\nu}_e$/GWth.

Accelerator neutrinos

The particle accelerators are used to produce neutrino beams as following. An accelerated proton beam strikes a thick nuclear target, producing secondaries, such as pions and kaons. These unstable secondaries leave the target and are boosted in the forward direction. They decay in flight and produce neutrinos. This facility is called as neutrino factory.

The spectra of neutrinos from different sources as a function of their energies are shown in figure 1.2.

![Figure 1.2: Neutrino spectra from different sources as a function of energy [21].](image)
1.3.3 Neutrino oscillations

In the standard model, neutrinos of all flavors are assumed to be massless. This would mean that neutrinos produced with certain flavor would remain in the same flavor at all times. However, if neutrinos are not massless then there is a possibility that neutrinos can change flavor as they propagate in space. This phenomenon is called as neutrino oscillation and originates from the mixing of flavor eigenstates. Neutrinos produced via weak interaction carry definite flavor. However, when it propagates in space, its mass eigenstate remains the same as that at production but its flavor content can change. The probability of flavor change depends on the mixing angle between flavors, the masses of the eigenstates, the energy of neutrino and the distance travelled between the points of production and detection. Observation of change in neutrino flavor is of great importance in particle physics since this will be the signature of breakdown of some of the vital assumptions made in the Standard Model. The first experimental signature of the neutrino oscillation phenomenon was observed in Davis’s solar neutrino experiment at the Homestake gold mine, USA. It was observed 70% deficit in the solar neutrino flux than the theoretically predicted.

Neutrino flavor conversion is fundamentally a quantum mechanical effect. The discovery of neutrino oscillations implies that the neutrino flavor states are not mass eigenstates but superpositions of such states. Consider $\nu_\alpha$ refers to the known flavor eigenstates, $\alpha = e, \mu$ and $\tau$. These are related to the mass eigenstates, $\nu_i, i = 1, 2, 3$, through a $3 \times 3$ unitary matrix as following:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i. \quad (1.18)$$

The mixing matrix is parametrized in terms of the mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$ and the CP violating phase $\delta$ [22], as

$$U = \begin{pmatrix}
c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\
-c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & c_{13}s_{23} \\
s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23}
\end{pmatrix}, \quad (1.19)$$

where, $c_{12}$ and $s_{12}$ refer to $\cos \theta_{12}$ and $\sin \theta_{12}$, etc. Also, it can be observed that the CP violating
phase always occurs with $s_{13}$, as highlighted in the matrix [23].

The general expression for the probability that an initial flavor state $\nu_{\alpha}$ ($\bar{\nu}_{\alpha}$) of energy $E_{\nu}$ gets converted to a flavor state $\nu_{\beta}$ ($\bar{\nu}_{\beta}$) after travelling a distance $L$ in vacuum is:

$$
P_{\nu_{\alpha}(\bar{\nu}_{\alpha}) \rightarrow \nu_{\beta}(\bar{\nu}_{\beta})} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} |U_{\alpha i}^{*} U_{\beta j}| \sin^{2} \left( \frac{\Delta m_{ij}^{2} L}{4E_{\nu}} \right)$$

$$+ (-) 2 \sum_{i>j} \text{Im} |U_{\alpha i}^{*} U_{\beta j}| \sin \left( \frac{\Delta m_{ij}^{2} L}{2E_{\nu}} \right),$$

where, $\delta_{\alpha\beta} = \sum_{i} U_{\alpha i} U_{\beta i}^{*}$ and $\Delta m_{ij}^{2} = m_{i}^{2} - m_{j}^{2}$ is the mass squared difference [3].

The propagation of neutrinos of energy $E_{\nu}$ in matter is determined by:

$$
\frac{d\nu_{\alpha}}{dt} = \sum_{\beta} \left( \sum_{j} U_{\alpha j} U_{\beta j}^{*} \frac{m_{j}^{2}}{2E_{\nu}} + \frac{\Lambda}{2E_{\nu}} \delta_{\alpha e} \delta_{\beta e} \right) \nu_{\beta},
$$

where, $\Lambda/(2E_{\nu})$ refers to the amplitude for coherent forward CC scattering in electronic matter, i.e., $\nu_{e}$ scattering. The matter dependent term is given by:

$$
\Lambda = 2\sqrt{2}G_{F} Y_{e} \rho E_{\nu} \sim 1.52 \times 10^{-4} Y_{e} \rho (E_{\nu}/\text{GeV}) \text{ eV}^{2},
$$

where, $\rho$ is the density of Earth matter in gm/cc and $Y_{e}$ is the electron fraction in the matter, while $G_{F}$ is the universal Fermi coupling constant [23].

### 1.3.4 Neutrino mixing parameters and mass hierarchy

As discussed in the previous section, the current accelerator, reactor, solar and atmospheric neutrino data can be described within the framework of a $3 \times 3$ mixing matrix between the flavor eigenstates $\nu_{e}$, $\nu_{\mu}$, and $\nu_{\tau}$ and mass eigenstates $\nu_{1}$, $\nu_{2}$, and $\nu_{3}$. The neutrino experiments have not only established the neutrino oscillations, but also have made the precision measurements of the oscillation parameters. All the three mixing angles $\theta_{12}$, $\theta_{13}$ and $\theta_{23}$ as well as the two mass squared differences $\Delta m_{21}^{2}$ and $\Delta m_{32}^{2}$ have been measured. The current best fit values and errors on these parameters for the analysis of global neutrino data are summarized in table 1.3.
Table 1.3: Current best fit values of the neutrino oscillation parameters for the analysis of global neutrino data [22]. NH and IH are normal and inverted hierarchies, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304 \pm 0.014$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.514^{+0.055}_{-0.056}$ (NH)</td>
</tr>
<tr>
<td></td>
<td>$0.511 \pm 0.055$ (IH)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.0219 \pm 0.0012$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$(7.53 \pm 0.18) \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{32}^2</td>
</tr>
<tr>
<td></td>
<td>$(2.49 \pm 0.06) \times 10^{-3}$ eV$^2$ (IH)</td>
</tr>
</tbody>
</table>

The sign of $\Delta m_{21}^2$ is determined to be positive from the solar neutrino data [22]. This allows for two different arrangements of the three neutrino mass states as shown in figure 1.3. If $\Delta m_{32}^2 > 0$, then the mass hierarchy (MH) is defined to be normal. If $\Delta m_{32}^2 < 0$, the mass hierarchy is defined to be inverted.

The current and future neutrino oscillation experiments, NOvA [24], LBNE [25], LBNO [26], PINGU [27], ORCA [28], JUNO [29], RENO-50 [30], HK [31], T2HK [32] and INO [33] would try to address the mass hierarchy in neutrino sector and the CP violating phase $\delta$.

The current constraints on the absolute neutrino masses have been obtained from cosmological data [34, 35, 36], neutrinoless double beta decay [37, 38] and from tritium beta decay [39, 40] experiments. The neutrinoless double beta decay experiments will also seek to answer the question of whether the neutrinos are Dirac or Majorana particles.
Figure 1.3: Pattern of neutrino masses for the normal and inverted hierarchies as mass squared [41].

1.4 The INO-ICAL experiment

The India-based Neutrino Observatory (INO) is an upcoming underground project in South India. The Iron Calorimeter (ICAL) experiment is going to be one of the INO experimental facilities for studying the neutrino oscillations. Additionally, it will host the experiments for neutrinoless double beta decay (NDBD), direct dark matter search, etc. The cavern for the INO will be constructed under the mountain, which will provide a rock cover of minimum 1 km in all directions to shield the experiments from the atmospheric muons. The layout of the INO cavern is shown in figure 1.4. The hall for the ICAL will have sufficient space for a 100 kiloton detector. A 3 km long access tunnel will be constructed under the mountain to reach the ICAL experiment hall [33].

The ICAL is a 50 kiloton magnetized detector to detect the atmospheric neutrinos and antineutrinos separately. The ICAL detector will comprise of three modules of $16 \times 16 \times 14.5 \, \text{m}^3$. Each module will consist of a stack of 151 horizontal layers of 5.6 cm thick iron plates interleaved with 4 cm gaps to house the active detector layers. The modular structure of the detector allows flexibility in the construction and operation. Data taking can start as soon as one of the modules is complete. The iron plates act as the target mass for the neutrino interactions. The collaboration has chosen glass Resistive Plate Chambers (RPCs) of $2 \times 2 \, \text{m}^2$ in size as the active detector elements
Figure 1.4: Layout of the proposed INO cavern.

and they will be operated in the avalanche mode. The ICAL detector is going to use 28,800 such RPCs. The iron plates are magnetized with an average magnetic field of 1.5 T. The magnetic field causes a charged particle to travel along a curved path. The layout of proposed modular form of the ICAL detector and its construction sequence are shown in figures 1.5a and 1.5b, respectively. The current specifications of the ICAL detector and RPCs are given in table 1.4 [33].

Figure 1.5: (a) Layout of the proposed INO-ICAL detector and (b) construction sequence of the ICAL detector.

The major components of the ICAL experiment are under research and development at the various INO collaborating institutes, universities and at industrial facilities. An engineering prototype
of the ICAL with the RPCs, iron plates and the magnet is planned at the Madurai center.

Table 1.4: Current specifications of the ICAL detector and RPCs.

<table>
<thead>
<tr>
<th>ICAL</th>
<th>RPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modules</td>
<td>RPC unit dimension</td>
</tr>
<tr>
<td>Module dimension</td>
<td>Readout strip width</td>
</tr>
<tr>
<td>Detector dimension</td>
<td>Number of RPC units/layer/module</td>
</tr>
<tr>
<td>Number of layers</td>
<td>Total no. of RPC units</td>
</tr>
<tr>
<td>Iron plate thickness</td>
<td>No. of electronic readout channels</td>
</tr>
<tr>
<td>Gap for RPC trays</td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2 × 2 m²</td>
</tr>
<tr>
<td>16 × 16 × 14.5 m³</td>
<td>2.8 cm</td>
</tr>
<tr>
<td>48 × 16 × 14.5 m³</td>
<td>64</td>
</tr>
<tr>
<td>151</td>
<td>28,800</td>
</tr>
<tr>
<td>5.6 cm</td>
<td></td>
</tr>
<tr>
<td>4 cm</td>
<td></td>
</tr>
<tr>
<td>1.5 Tesla</td>
<td></td>
</tr>
</tbody>
</table>

1.4.1 Physics potentials of the ICAL detector

The ICAL detector is contemplated as both a detector for atmospheric neutrinos as well as a future end-detector for a neutrino factory beam. In both the cases, the primary detection mechanism is via detection of muons produced in charged current neutrino interactions such as:

\[ \nu_\mu + n \rightarrow \mu^- + p. \]  \hspace{1cm} (1.23)

The major physics goals of the ICAL detector are summarised as following:

The atmospheric neutrino physics program possible with ICAL is substantial. It is possible to observe a clear signal of oscillation by observing one full oscillation period so that the precision of the parameters \( \Delta m^2_{32} \) and \( \theta_{23} \) can be improved. An unambiguous evidence for matter effects can be obtained, and the sign of mass-squared difference \( \Delta m^2_{32} \) can be determined. The atmospheric neutrinos can be used to probe CPT invariance which is one of the fundamental paradigms of quantum field theories.

Apart from their charge discrimination capability, iron calorimeters have a large range in sensi-
tivity to $L/E$ variations compared to water Cerenkov detectors and can substantiate the evidence of neutrino mass and oscillation already observed by the Super-K experiment, via the observation of dips and peaks in the event rate versus $L/E$. Therefore, ICAL can be used as an end-detector for a neutrino factory that matches the magic baseline to determine the CP violating phase $\delta$ in neutrino sector.

The multi-TeV cosmic-ray muons can be studied through pair-meter technique. The technique is used to measure the energy and frequency of electron-positron pair cascades produced by the passage of a high energy muon in dense matter. Such studies in the high energy (TeV–PeV) region can throw light on possible extensions of the Standard Model.

1.5 Organization of the thesis

A brief introduction of the standard model of particle physics, gravity, neutrino physics, the INO-ICAL experiment and its physics potentials are summarized in chapter 1. The RPC and its principle of operation, designs and types of RPCs are discussed in chapter 2.

The INO collaboration has chosen glass RPCs as the active elements and is going to deploy in an unprecedented scale for the ICAL detector. Therefore, it is imperative that we study the electrode material aspects of RPCs in detail. A systematic material characterization studies on the glasses were undertaken and the detailed results are reported in chapter 3.

Several numbers of cosmic-ray paddles were developed and characterized as discussed in chapter 4. A cosmic-ray muon telescope was set up using these paddles. The RPCs of $30 \times 30$ cm$^2$ built using the glass electrodes and characterized using the cosmic-ray muon telescope. The performances of these RPCs were compared with the glass electrode material properties. The results are reported in chapter 5.

The ICAL experiment is expected to run for more than 10 years in order to record statistically significant number of neutrino interaction data. Therefore, long-term stability and performance of the RPCs over the duration of the experiment are of prime concern. The contaminants are known
cause for serious degradation in the performance or permanent damage of the RPCs. Therefore, the effect of water vapor on the performance of glass RPCs in avalanche mode operation was studied and reported in chapter 6.

For the ICAL detector, the INO collaboration has proposed two geometries: 1) default and 2) staggered. The response of these two geometries to muons ($\mu^-$s) was studied and the results are compared in chapter 7.

Finally, the conclusions and future outlooks of the thesis are drawn in chapter 8 based on various studies reported in the previous chapters.

1.6 Chapter summary

As a beginning, the elementary constituents of matter in the standard model and their interaction forces are summarized in this chapter. The proposal of neutrino and its discovery are discussed. The various sources of neutrinos, neutrino oscillations, neutrino mixing parameters and about the mass hierarchy issue in the neutrino sector are summarized. The INO-ICAL experiment and its physics goals are described in detail.