Neutrinos and the Proposed India-based Neutrino Observatory*

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How the Sun shines has puzzled astronomers and biologists over the ages. The answer to this question led to a deeper understanding of an enigmatic particle, the neutrino, through the quantum mechanical phenomenon of neutrino oscillation. Neutrinos produced in various reactions change their type or ‘flavor’ as they propagate, and this requires them to possess a small but non-zero mass—they were earlier thought to be massless. The excitement in the area of studying neutrinos, about which we still know very little, led to the proposal for an India-based Neutrino Observatory (INO). We will review the physics of neutrinos, as well as the physics goals and current status of INO, in this article.

1. How Does the Sun Shine?

This question has puzzled scientists from Lord Kelvin to Charles Darwin [1] for centuries. Eventually, it was understood that the Sun shines through nuclear fusion, when, through the p-p set of reactions (Figure 1) effectively four protons (from the hydrogen gas that makes up most of the Sun), react to form a helium-4 nucleus, with about 27 MeV\(^1\) energy, resulting in heating up of the Sun’s interior. Only 0.63 MeV escapes via neutrinos.

The reaction does not take place in one step, and a high temperature is required for the process to be initiated. The high temperature results from the great pressure due to gravity, which is always attractive and squeezes the hydrogen gas together. The squeezed

\[1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}. \text{ The MeV} (= 10^6 \text{ eV}) \text{ is a convenient unit when we consider nuclear reactions. In comparison, atomic transitions are of the order of 10s of eV. For example, the ionisation potential of the electron in a hydrogen atom is 13.6 eV.}\]

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Figure 1. Various processes that lead to helium production in the Sun via the $p$-$p$ chain. The percentage values indicate the branching fraction for the particular process. It is seen that the dominant chain is from proton-proton fusion ($pp$) rather than the $p$-$p$ chain. Figure from Wikimedia Commons [5].

Keywords
Neutrinos, leptons, Sun, INO, antimatter, oscillations, ICAL experiment, resistive plate chamber.

2How do two protons of the same charge which normally repel each other come close enough to initiate these processes? George Gamow first calculated this tunnelling probability using quantum mechanics.

gas heats up and reaches a temperature where the most energetic protons (from the high energy tail of the Maxwellian distribution) form a deuterium nucleus and the first process of the $p$-$p$ chain\(^2\) shown in Figure 1 begins:

\[
p^+ + p^+ \rightarrow ^2\text{H} + e^+ + \nu_e.
\] (1)

Here, the positively charged anti-particle of the electron, called the positron, is emitted to conserve the electric charge in the process, along with the emission of the electron-type neutral particle called neutrino. There is a subscript ‘e’ associated with the neutrino. It turns out that there are three types or flavors of neutrinos associated with the three flavors of electron-like particles collectively called leptons. They are electron, muon, and tau represented as $e$, $\mu$, $\tau$ respectively. Hence the three neutrino flavors are $\nu_e$, $\nu_\mu$, $\nu_\tau$, so that there are six known leptons in all, three charged and three neutral. While $\mu$ and $\tau$ are heavier versions of the electron, they are not a part of ordinary matter and the reason for their existence is a mystery; it is also not known if there are more flavors or just three. In particular, the neutrino emitted along with the positron in (1) is of the electron type. This balances the
lepton number in the process since the positron and neutrino have opposite lepton numbers. This is because anti-particles have opposite charges and quantum numbers to their corresponding particles while having exactly the same masses.

The complete processes that power the Sun are shown in Figure 1. The net process can be summed up as

\[
p^+ + p^+ + p^+ + p^+ \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + Q,
\]

Here, \(Q\) refers to the energy released in this exothermic process. The positrons annihilate with the electrons in the solar matter to produce an energy equivalent twice their mass, as per the mass-energy equivalence of Einstein: \(2m_e c^2 = 1.022\ \text{MeV}\), and hence are no longer present in the second of the equations in (2).

The energy released in this process is seen by us as sunlight.
Since it is very easy to measure the amount of sunlight falling per unit area per unit time on Earth, and we also know the Sun-Earth distance, we can calculate the amount of energy released by the Sun every second. Since 27.732 MeV of this energy is associated with the release of two neutrinos, it is also straightforward to calculate the total number of neutrinos emitted by the Sun.

The Standard Model of Particle Physics

We talked about anti-particles, muons, taus, and neutrinos. None of these are part of matter as we know it. Physicists now know that the visible part of the Universe is made up of elementary particles. While the familiar electron is a lepton and is elementary, meaning it cannot further be broken up into constituent parts, the protons and neutrons inside the nucleus are not elementary. They are made up of elementary particles called quarks and gluons; see the list of elementary particles in Figure 2.

Unlike electrons, muons, and taus, quarks not only have (fractional) electrical charges, but also a colour charge that is responsible for the strong interactions between them, which bind the nucleons strongly within the nucleus of atoms. The (non-elementary) particles that are made of quarks—such as protons and neutrons—are called hadrons. Apart from the charged leptons and quarks, there are so-called mediator particles that are responsible for the interactions between various particles. In this way, the photons are responsible for mediating electromagnetic interactions, gluons for the strong interactions, and the weak $W^\pm$ and $Z^0$ bosons for weak interactions. Today, the standard model (SM) of particle physics is used to understand the various particles, as well as the interactions between them. For a non-technical review on particles and their interactions, see [3] or have an online adventure at [4].

A calculation by John Bahcall and his collaborators [6] shows that the number of neutrinos emitted per square cm per second (called the solar neutrino flux) from the dominant $pp$ channel is about
6 × 10^{10}. In comparison, the number from the next most dominant 7 Be channel is ten times smaller, at about 0.5 × 10^{10}/cm^2/s. In simple terms, considering that your thumb nail measures roughly one square centimeter, this means that at least 60 billion neutrinos from the Sun pass through your thumb nail every second. So trillions of solar neutrinos pass through your body every day. Since neutrinos have only weak interactions, they simply go through most matter (including us) without interacting and hence do not affect us.

1.1 How Do We Know It Shines This Way?

This is a question that many scientists have asked. One of the most direct ways to establish that the Sun shines through nuclear fusion is to observe these solar neutrinos. One of the earliest attempts to do this was begun in 1969 by Ray Davis [7]: he eventually got the Nobel Prize in 2002 for his contribution to increasing our understanding of the Sun as well as neutrinos themselves. His work can be summarised as follows:

- Davis used about 600 tons of perchloroethylene (dry cleaning fluid). When solar neutrinos interacted with the chlorine 37 Cl nuclei, argon was produced:

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

This radioactive argon was extracted by bubbling helium through the tank every two weeks and the number of argon atoms were counted, to obtain the number of neutrinos that had interacted.

- The whole detector was placed in a mine deep underground: this is a recurrent feature of all neutrino labs. They are placed deep underground so that Earth acts as a filter to absorb the background of cosmic rays and other particles that will overwhelm the signal from neutrinos. Since neutrinos are hardly affected by the Earth, the neutrino signal remains the same, while the background from cosmic rays and other charged particles decreases by several orders of magnitude underground, as can be seen from Figure 3. Here km-water-equivalent is the actual depth in kilometers times the density of the rock in gm/cc. So a 1 km depth

A calculation by John Bahcall and his collaborators shows that the number of neutrinos emitted per square cm per second from the dominant pp channel is about 6 × 10^{10}.

4 Neutrinos do interact a little with the Earth, since it is a large body, with dense matter. These matter interactions are tiny but crucial to achieve the goals of INO, as we will see later.

5 We know that 1 gm molecular weight of a substance contains an Avogadro number of molecules. So, in 600 tons of perchloroethylene, there are more than 10^{30} atoms of chlorine, but only a few of these interact per week. Finding a few argon atoms among such large numbers of chlorine is a remarkable achievement that only a radio-chemist like Davis could achieve.
**Figure 3.** Variation of cosmic muon intensity as a function of depth, along with a listing of various neutrino labs around the world at their corresponding depths. Figure (adapted to include the proposed INO lab) from [8].

![Diagram showing variation of cosmic muon intensity](image)

- In 3 gm/cc (constant) density rock corresponds to a depth of 3 km-water-equivalent.

- Davis detected about 2000 neutrino-induced events over 30 years, a tremendous achievement in those times. However, these events accounted for roughly one-third of the solar neutrinos predicted by John Bahcall and his collaborators; see for instance, [6] for a later calculation.

  There were several criticisms of this work, including the important fact that Davis could not prove that the neutrinos he had detected were indeed from the Sun. There was a lot of doubt regarding the theoretical predictions as well, and Bahcall and his collaborators spent many years refining their calculations and reducing the uncertainties.

- The question of whether these were indeed solar neutrinos was answered in the 1980s by Masatoshi Koshiba and his collaborators at the Kamiokande lab in Japan. They used 3000 tons of pure water as their detector in the Kamioka underground mine.
They searched for solar neutrinos through the process,

\[ \nu_e + e^- \rightarrow \nu_e + e^- , \]  

(4)

where the electrons in the water are scattered in the forward direction by the solar neutrinos. An important feature of this experiment was that the scattered electrons pointed back to the instantaneous position of the Sun in the sky, thus proving that the bulk of the detected neutrinos were indeed solar neutrinos over a constant-angle background. However, the number of detected events was roughly half the expected ones. Hence the Kamioka experiment confirmed that the Sun shines through nuclear fusion with the production of solar neutrinos and that the observed neutrinos were less than the predicted number. Koshiba and Davis shared the Nobel Prize in 2002. The upgraded Super-Kamiokande experiment [9] also observed oscillations in atmospheric neutrinos (discussed below) and shared the Nobel Prize in 2015.

2. Where Are The Missing Neutrinos?

Many more experiments were performed in search of the missing solar neutrinos. One of the most important studies was by the Sudbury Neutrino Observatory (SNO) in Canada [10], which proved an incredible result using heavy water rather than water: solar neutrinos are produced at practically the exact rate as predicted by the model of Bahcall. However, on their way from the Sun to the Earth, these electron-neutrinos transform or oscillate into other flavors of neutrinos such as \( \nu_\mu \) or \( \nu_\tau \), thus explaining the deficit seen by Davis and Kamioka\(^6\). On the other hand, if all the flavors of neutrinos from the Sun were measured together, as done by SNO in the so-called neutral current channel, the total number exactly matches with the theoretical prediction.

This result reinforced the idea of neutrino oscillation: neutrino flavors can oscillate into one another as they propagate. The neutrino flavor that is produced in an interaction can thus be observed as a different flavor after some time.

\(^6\)The discrepancy between the 1/3 and 1/2 factor in the depletion of neutrinos observed by Davis and Koshiba is because the Kamioka experiment also measures a small fraction of the oscillated \( \nu_\mu \) and \( \nu_\tau \) neutrinos while Davis’ experiment detects only \( \nu_e \) neutrinos.
Neutrino oscillations is a quantum mechanical phenomenon and depends on the fact that neutrinos, which were thought to be massless, actually have tiny, non-zero masses.

2.1 Neutrino Mixing and Oscillations

How do we understand neutrino oscillations? It is a quantum mechanical phenomenon and depends on the fact that neutrinos, which were thought to be massless, actually have tiny, non-zero masses. Moreover, the flavor eigenstates of neutrinos, viz., the \( \nu_e \), \( \nu_\mu \), and the \( \nu_\tau \), are not mass eigenstates. In other words, any flavor \( f \) of neutrino can be expressed as:

\[
\nu_f = \sum_{\alpha} U_{f,\alpha} \nu_{\alpha}.
\]

(5)

Here, \( \nu_f \) is any flavor eigenstate, \( f = e, \mu, \tau \), while \( \nu_{\alpha} \) are the mass eigenstates with \( \alpha = 1, 2, 3 \). That is, the flavor states are mixtures of the mass eigenstates; furthermore, the mass eigenstates all have different masses.

Let us simplify this to try and understand the phenomenon. Let us consider a 2-generation simplification so that only \( \nu_\mu \) and \( \nu_\tau \) exist, and let there be two mass eigenstates, \( \nu_1 \) and \( \nu_2 \). From the orthogonality condition, we can express these states as:

\[
\begin{align*}
|\nu_\mu\rangle &= \cos \theta \ |\nu_1\rangle + \sin \theta \ |\nu_2\rangle; \\
|\nu_\tau\rangle &= -\sin \theta \ |\nu_1\rangle + \cos \theta \ |\nu_2\rangle.
\end{align*}
\]

(6)

Hence the mixing matrix is given by the usual one:

\[
U_{f,\alpha} = \begin{pmatrix} 
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}.
\]

(7)

Consider a process where \( \nu_\mu \) is produced at the interaction vertex at time \( t = 0 \) (for example, in \( \pi \to \mu \nu_\mu \)).

After a time \( t \), the state, which was purely \( \nu_\mu \) at \( t = 0 \) is now the following admixture:

\[
\begin{align*}
|\nu_\mu(t)\rangle &= \cos \theta \ |\nu_1(t)\rangle + \sin \theta \ |\nu_2(t)\rangle; \\
&= \cos \theta \ e^{-iE_1 t / \hbar} |\nu_1(0)\rangle + \sin \theta \ e^{-iE_2 t / \hbar} |\nu_2(0)\rangle.
\end{align*}
\]

(8)
Here, we have used the usual state evolution in time according to their respective energies, \( E_1 \) and \( E_2 \).

If \( E_1 \neq E_2 \), the coefficients of the mass eigenstates in (8) change with time, and hence the state, after a time \( t \), is a different admixture of the mass eigenstate. In fact, it is a mixture of \( \nu_\mu \) and \( \nu_r \) states. To find out the extent of this mixing, we can take the overlap of the state at time \( t \) with both the initial muon and tau flavor state at time \( t = 0 \); see (6). This gives us the probability amplitude that the pure state \( \nu_\mu \) at \( t = 0 \) remains a \( \nu_\mu \), or has oscillated into a \( \nu_r \) state\(^7\). Squaring the probability amplitude, we obtain the corresponding probability. Using orthonormality: \( \langle \nu_i | \nu_j \rangle = \delta_{ij} \), we get the probability of \( \nu_\mu \) transforming into \( \nu_r \) or surviving till time \( t \) as:

\[
\begin{align*}
    P_{\mu r} & \equiv |\langle \nu_\mu(t) | \nu_r(0) \rangle|^2 = \sin^2 2\theta \sin^2 \left( \frac{(\Delta m^2 c^2) L}{4p\hbar} \right), \\
    P_{\mu\mu} & \equiv 1 - P_{\mu r}.
\end{align*}
\tag{9}
\]

Here, we have used \( E_i = (p^2c^2 + (m_i c^2)^2)^{1/2} \approx pc + (m_i c^2)^2/(2pc) \), where \( m_i \), \( i = 1, 2 \), are the masses of the two mass eigenstates, with \( p \) their common momentum and \( \Delta m^2 = m_2^2 - m_1^2 \). We have also replaced time \( t \) for the relativistic neutrinos that are traveling at practically the speed of light by \( ct = L \). The argument of the last term can be simplified to \( (1.27\Delta m^2 L/p) \), where \( \Delta m^2 \) is in units of eV\(^2 \), \( L \) is in metres and \( p \) in MeV/c. (9) shows that the probability of survival (or transformation) of \( \nu_\mu \) oscillates in space/time with an angular frequency \( \omega = \Delta m^2 / (4p) \) (in natural units, where \( \hbar = c = 1 \)) or a wavelength \( \lambda = 2\pi/\omega \). Symmetrically, \( \nu_r \) can also change into \( \nu_\mu \). So, as they travel, the neutrino flavor states oscillate\(^8\) into each other.

A look at (9) immediately tells us that the oscillation probability is zero, unless the mixing angle \( \theta \) and the mass squared difference, \( \Delta m^2 \), are both non-zero. Hence, mixing between states and non-zero (and different) masses are required for neutrinos to exhibit the quantum mechanical phenomenon of oscillation.

\(^7\) Since the particle must be detected in either of the two states, the total probability must add up to unity.

\(^8\) You must have come across oscillation phenomena in classical situations such as the behaviour of coupled pendulums and beat frequencies of tuning forks of nearly equal frequencies. Even an electron’s magnetic moment vector precesses about an external magnetic field with a fixed frequency (Larmor precession).
The extension to three flavors is straightforward; however, there is one more interaction and one more phenomenon to account for. They are the matter effect as the neutrinos travel through a medium, and the effect of CP violation.

### 2.2 Neutrino Oscillations in the Presence of Matter

The mixing of two neutrino flavors is represented by a single mixing angle, $\theta$. When three flavors are mixing, so that the flavor state can be expressed in terms of the mass eigenstates $\nu_1$, $\nu_2$ and $\nu_3$, there are three masses, three mixing angles ($\theta_{12}$, $\theta_{23}$, the across generation mixing angle $\theta_{13}$) and an additional so-called CP phase, $\delta_{CP}$. Here CP stands for charge conjugation and parity, and the phase accounts for the fact that particles and anti-particles have opposite quantum numbers, except for their masses, which are the same. Hence, the CP phase associated with neutrinos and anti-neutrinos will be opposite, and what is produced in the Sun is the electron neutrino and not its anti-particle.

The matter effects are not as easy or straightforward to understand. But the underlying physics captures the journey of the neutrino as it is produced in the core of the Sun and then moves outwards through the highly dense solar matter. Although neutrinos interact rarely, they are affected by the presence of matter. More importantly, neutrinos and anti-neutrinos are differently affected by the term. Hence, the interaction with matter accentuates the intrinsic CP phase difference between neutrinos and antineutrinos. Since both the Sun and Earth are made up of matter, and contain no anti-matter, therefore, neutrinos and anti-neutrinos will interact differently with them.

### 3. Where Are The Anti-neutrinos?

So far, we have seen only neutrinos from the Sun. But radioactivity (radioactive decay) produces anti-neutrinos copiously in nuclear reactors. Also, cosmic ray particles from outside our galaxy hit our atmosphere and produce muons, which decay to produce both neutrinos and anti-neutrinos; these are called atmospheric neutrinos.
neutrinos. So for instance, the upgraded Kamioka detector, called Super-Kamioka (with 50,000 tons of water) has indeed seen these atmospheric neutrinos and anti-neutrinos and has observed neutrino oscillations in these processes as well. An atmospheric neutrino entering the detector from above was produced in the atmosphere just overhead and hence has traveled about 10–15 km (the thickness of the atmosphere). But an atmospheric neutrino entering the detector from below has not only traversed the atmosphere on the other side of the Earth but has also traversed the Earth itself before reaching the detector. This can be understood from Figure 4.

Hence, up-going neutrinos and anti-neutrinos should show differing behavior because of their different interactions with Earth matter. Since the Super-Kamioka experiment cannot distinguish neutrino-induced events from anti-neutrino-induced events, this has not been directly verified. An attempt to study this is the main goal of the proposed India-based Neutrino Observatory (INO).

4. India-based Neutrino Observatory (INO)

The India-based Neutrino Observatory is an ambitious pan-Indian project that proposes to study these intriguing properties of neutrinos. One of the major goals of INO is to determine the neu-

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Figure 5. Possible neutrino mass orderings. Figure from the APS multidivisional study, 2004 [11].

While solar neutrino measurements established that $\Delta m_{21}^2 \sim 7.6 \times 10^{-5}$ eV$^2$, other neutrino experiments have only established the magnitude of the other mass squared difference to be $|\Delta m_{31}^2| \sim 2.5 \times 10^{-3}$ eV$^2$.

Hence, there are two possibilities: $m_3$ is the most massive mass eigenstate (see left-hand side of Figure 5), or $m_3$ is the lightest (see the right-hand side figure). This is called the mass ordering problem. While solar neutrino experiments clearly indicate that $m_2 > m_1$, we do not know the corresponding sign of $\Delta m_{31}^2$.

Interestingly, only the mass squared differences are known; the absolute values of the masses themselves are still unknown, as indicated by the question marks in Figure 5. There exist upper limits from direct measurement of $m_{\nu_e} < 1.1$ eV/c$^2$ [12] and on the sum of the neutrino masses from cosmology, suggesting an upper bound of about 1 eV/c$^2$ [13]. This result on the masses depends on the chosen cosmological model as well as the neutrino mass ordering, whether it is normal (LHS of Figure 5) or inverted (RHS of the figure). If the absolute values of the masses turn out to be such that they are well separated, then they have a well-
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}$ (in $^\circ$)</td>
<td>$33.44^{+0.78}_{-0.75}$</td>
</tr>
<tr>
<td>$\theta_{23}$ (in $^\circ$)</td>
<td>$49.2^{+0.9}_{-1.2}$</td>
</tr>
<tr>
<td>$\theta_{13}$ (in $^\circ$)</td>
<td>$8.57^{+0.12}_{-0.12}$</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$ (in eV$^2$)</td>
<td>$7.42^{+0.21}_{-0.20} \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$ (in eV$^2$)</td>
<td>$(+2.517^{+0.026}_{-0.028}) \times 10^{-3}$ eV$^2$ (NO)</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ (in eV$^2$)</td>
<td>$(-2.498^{+0.028}_{-0.028}) \times 10^{-3}$ eV$^2$ (IO)</td>
</tr>
<tr>
<td>$\delta_{CP}$ (in $^\circ$)</td>
<td>$197^{+27}_{-24}$ (NO)</td>
</tr>
<tr>
<td>$\delta_{CP}$ (in $^\circ$)</td>
<td>$282^{+26}_{-30}$ (IO)</td>
</tr>
</tbody>
</table>

Table 1. Current values of neutrino mixing angles and mass squared differences, from [14]. The two values of $\Delta m^2_{31}$ and $\Delta m^2_{32}$ refer to the cases of normal (NO) or inverted (IO) ordering and hence the overall sign of these quantities is unknown, since either is allowed.

defined mass hierarchy, which is normal or inverted, depending on whether $m_3$ is the heaviest or lightest mass. Otherwise, they are quasi-degenerate.

Figure 5 also uses color coding to indicate the amount of mixing of the three flavors in each mass eigenstate. For instance, the very small ‘red’ colored content in the third mass eigenstate indicates the very small $\nu_e$ component in $\nu_3$ and is a reflection of the fact that the across-generation mixing angle, $\theta_{13}$, is small, about $8^\circ$. The currently known values of the mixing angles and mass squared differences are given in Table 1. It can be seen that the mass ordering of the third state is not known; also, that the value of the CP phase depends on the true nature of this ordering, and currently all values, $\pi \leq \delta_{CP} \leq 2\pi$, are allowed, at three standard deviations. Finally, it must be pointed out that neither the ordering nor the phase can be determined unless the across-generation mixing angle, $\theta_{13}$ is different from zero. The discovery of a small but non-zero value of this parameter in 2012 was a major boost for the field.

The INO collaboration proposed the magnetized iron calorimeter (ICAL) detector in this context. As stated earlier, its main goal was to determine the mass ordering. While many other experi-
ments around the world are also currently taking data or being built to determine this and other unknown neutrino parameters, the uniqueness of ICAL at INO lies in its ability to determine the mass ordering, irrespective of the true value of $\delta_{CP}$. In other experiments, the value of the two are correlated, and hence there is no such clean determination of the mass ordering.

The experiment will detect and measure only naturally occurring atmospheric neutrinos\textsuperscript{10} with the static detector. In particular, the focus is on muon neutrinos that produce muons through charged current (CC) interactions in the detector:

$$\nu_\mu + N \rightarrow \mu^- + X ,$$
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X .$$

(10)

Here, $N$ is a nucleon or nucleus, typically an iron nucleus, in the detector. The neutrino interacts with it to produce a charged muon, along with some hadronic debris, $X$, produced when the nucleon/nucleus breaks up in the interaction. Note that neutrinos produce negatively charged muons, while the anti-neutrinos produce positively charged anti-muons.

4.1 The ICAL Experiment

How does ICAL plan to determine the mass ordering, independent of the CP phase? At the heart of the proposed detector is the magnetic field. A schematic of the detector is shown in Figure 6.

The detector will comprise three modules, each containing 151 layers of iron, with a 4 cm gap in which the active detectors called resistive plate chambers (RPCs) will be inserted. The copper coils seen in each module generate a nearly uniform magnetic field of about 1.5 T in the central region of each module, with the field decreasing towards the edges.
4.2 The RPCs

RPCs are the heart of the detector. They are glass plates, separated by a gap of about 2 mm, and sealed (see Figure 7), allowing the continuous flow of an appropriate gas mixture. A high DC voltage of about 10 KV is applied across the glass plates.

When a charged particle passes through the RPC, it causes a discharge in the gas flowing through the detector. The ions move towards the electrodes, and the signal is picked up by copper pick up panels, one above and one below the glass plates (and insulated from them). These are present in strips of 3 cm thickness such that the strips are transverse to each other. Hence, the strips

Figure 6. Schematic of the proposed magnetised ICAL detector to be built at INO. Figure from [15].

Figure 7. Schematic of a resistive plate chamber (RPC) that is the active detector in ICAL.

When a charged particle passes through the RPC, it causes a discharge in the gas flowing through the detector. The ions move towards the electrodes, and the signal is picked up by copper pick up panels, one above and one below the glass plates.
at the top give the $x$ coordinate of the signal, and the ones at the bottom give the $y$ coordinate; of course, the layer in which this occurs gives the $z$ coordinate. In this way, the $(x, y, z)$ location of the signal, called 'hit', is known. As the charged particle passes through, it leaves several such hits in the detector and hence forms a 'track' in the detector that can be identified.

Finally, the magnetic field bends the track of the charged particle, depending on its charge. So, for instance, a $\mu^+$ and $\mu^-$ particle entering the detector with the same momentum (implying the same direction), bend in opposite directions due to their opposite charges. The presence of the magnetic field thus allows us to distinguish $\mu^+$ and $\mu^-$ particles in the detector. From (10), it is immediately seen that this, in turn, allows us to determine whether a neutrino or anti-neutrino induced the interaction. Since these have different interactions with Earth matter, as we mentioned before, measuring the neutrino and anti-neutrino events separately thus allows us to get a handle on the neutrino mass ordering.

4.3 Validating the Physics

Since INO is not built, many detailed computer simulations have been performed to find out the sensitivity of the detector to various physics parameters of interest. The interested reader is urged to read the INO White Paper listing the full physics potential\(^\text{11}\) of the detector [15].

5. Current Status of INO

An underground laboratory needs many clearances before it can be built. This process is ongoing for INO. Meanwhile, it is clear that building such a massive detector, which will be equivalent to a 5-storey building, with 4 million channels of electronics, is a huge engineering and physics challenge. When built, ICAL will be one of the most massive detectors/magnets in the world. Its construction will, therefore, require a large amount of R&D, as well as participation from various industries.

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\(^\text{11}\) Note that there are synergies between many different experiments. Hence, combining the results of several different experiments, including INO, as and when they become available, will yield better results than the individual experiments themselves.
The R&D component for building and testing RPCs has been particularly strong. From test RPCs of size $30 \times 30\ \text{cm}^2$, now RPCs of the required $2\times2\ \text{m}^2$ dimensions are being made. Every aspect of RPCs, the associated electronics, power supply, software, has been built and tested in research labs in India. A sample of some of the electronics developed in-house is shown in Figure 8.

Moreover, some industries are also involved in RPC construction and its automation. This is required since ICAL will require about 30,000 RPCs and these cannot be built by any research lab in India or abroad. Figure 9 shows a set-up for automated graphite-coating of the RPC glass.

Figure 8. ICAL electronics, showing various parts of the front-end, back-end electronics, data acquisition systems, etc.

Figure 9. Automation of RPC manufacture by industry.
**Figure 10.** The mini-ICAL test detector at Madurai.

A massive detector like ICAL cannot be built in one step. Additionally, since it will be built *in-situ*, underground, every component must be of a size that can be transported via an access tunnel into the underground cavern. Hence it is crucial to build and test smaller scale versions of the detector. One such, called the mini-ICAL, is currently operating at the IICHEP centre in Madurai since June 2018. It comprises 11 layers of iron, of size $4 \times 4$ m$^2$, interspersed with active RPCs. A set of copper coils serves to magnetize the detector; see Figure 10.

A unique feature of INO is the training of students, scientists, and engineers. It is an open collaboration and has about 100 scientists from several universities, IITs, and research institutions across India. It's graduate programme, where students work towards obtaining a PhD degree, is more than 10 years old and has been extremely successful. While some of the early students are already faculty members, many of them are placed in prestigious post-doctoral positions across the world. The picture Figure 11 shows a group of students putting together an RPC for the mini-ICAL.

INO students and staff\textsuperscript{12} have also been involved, from the beginning, in reaching out to local students in both schools and colleges, as well as to the local people living near the vicinity of the proposed site [16]. INO also has a robust summer students
programme, where students from across India spend a month or two getting hands-on training at a sophisticated, state-of-the-art detector that has been indigenously built. Most students return enthused and fired up about the potential to work on such cutting-edge projects.

6. In Conclusion

This article has tried to give a flavor (no pun intended) of neutrino physics and the excitement in the field due to the discoveries of various surprising properties of these particles. Several experiments are currently taking data, or have been proposed, to measure different neutrino properties, the chief ones being the actual neutrino masses, the neutrino mass ordering, and the CP phase; see [17] for non-technical details about the various experiments and their goals. Above all, the CP phase measurement is exciting because the asymmetric nature of the interactions of neutrinos and anti-neutrinos with matter could, in principle, feed into the all-important question of why the Universe is full of galaxies made of matter and not anti-matter as well [18].

The discoveries of the properties of neutrinos motivated many scientists in India to propose a home-grown experiment—the India-based Neutrino Observatory (INO)—to study some key proper-
ties of neutrinos. Of particular interest is the knowledge of the neutrino mass ordering, although there is a rich and varied physics programme possible with the proposed magnetized iron calorimeter (ICAL) detector at INO [15]. Due to various reasons, although this project was proposed as early as 2000, it is yet to take off with respect to construction. Meanwhile, the world has also taken note of the importance of measuring neutrino parameters, the mass ordering in particular. Many experiments, such as the T2K experiment in Japan, the NOvA and (upcoming) DUNE experiments in the United States, and the upcoming JUNO experiment in China, are moving quickly [17] to measure this quantity. Each is a beautiful experiment. Due to the difficulty in detecting these weakly interacting neutrinos, regardless of who reaches the goal first, each experiment will obtain its result in an independent, unique way, and hence will be complementary to each other. In this sense, INO has the potential to be a world-class experiment, and ICAL the seed for many more experiments that explore the fantastic world that we live in.

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Suggested Reading


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