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The Greatest Ellusionist : Mystery of The Ghost Particle

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ABSTRACT

The Physics of neutrino has been going through a revolutionary phase in recent period. While standard model of particle physics has been extremely successful for other observable particles, it fails to harmonize mass for neutrinos, which are necessary to describe the phenomena of neutrino oscillations observed by several different experiments. The present study is an attempt to revisit the theory and phenomenology of neutrino physics which has a potential for exploring the Physics beyond the standard model, making it extremely useful for our fundamental understanding of this mysterious nature. This piece of work tries to analyse all the latest developments along with major findings on the subject. The emphasis of the present study is on neutrino oscillations which, given their implication on neutrino masses, and being an observable phenomenon could be explored in the domain where results are not describable in the standard model, such as presence of majorana neutrinos and gaining of mass without interaction with Higgs field. Moreover, the recent results obtained from KATRIN experiment, Karlsruhe, Germany is very encouraging and promising, and they have setup the new upper limit for neutrino mass is 0.8 eV. We have briefly highlighted the ongoing status of India based neutrino observatory (INO) for neutrino detection. Finally, this research article ends with a brief self-composed poem about ghost particle (neutrinos).

Keywords: Neutrino oscillations, Standard model, Katrin experiment, Beta decay, INO

I. INTRODUCTION

A century later when Lavoisier proposed that all substances are made up of chemical elements, Dalton put forward his theory that atoms are elementary particles of all the chemical elements. Since then, physics as a discipline has evolved, passing through the stages of “atoms consist of dense nuclei orbited by electrons” in early 20th century to “nuclei consist of protons and neutrons” in 1930s. From Thompson to Rutherford, the model of nucleus has evolved, even worked well but was unable to explain few observable phenomena like continuous energy spectrum and conservation of angular momentum in nuclear beta (β) decay process. Furthermore, Enrico Fermi in 1933 developed the theory of nuclear beta decay in which a neutron becomes a proton plus an electron and an anti-electron neutrino (ν_e^-), or a proton becomes a neutron plus a positron and a neutrino, inside an atomic nucleus, changing the atomic number by +1 to -1 respectively as depicted below in Fig. 1. Indeed, the neutrino was first proposed particle, which was not a constituent of matter. It is interesting to mention that neutrinos were generally thought to be undetectable until 1956.

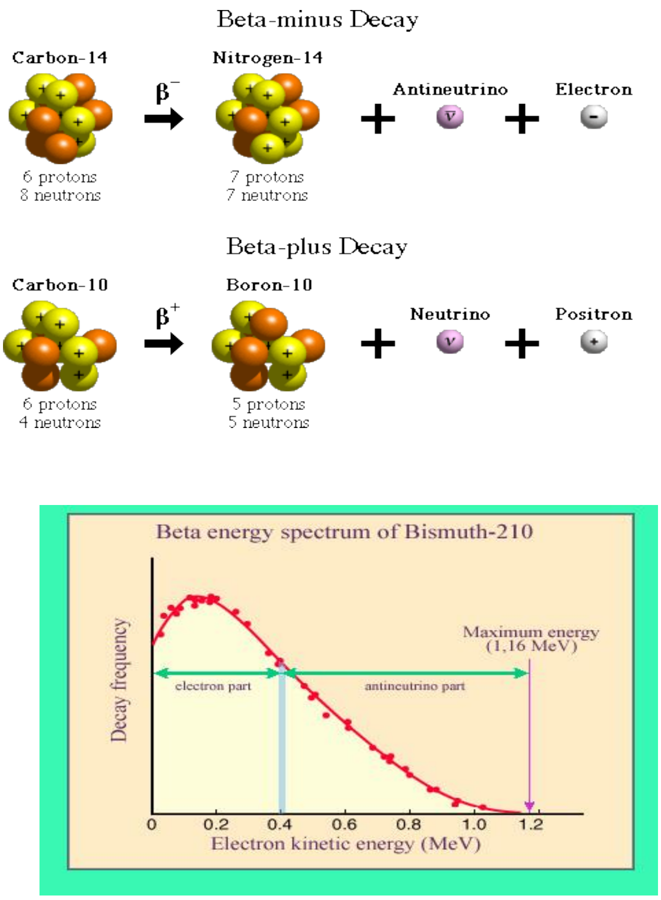

Fig. 1 $\beta^{\pm}$ decays and continuous energy spectrum of beta decay (Bi-201 nucleus). The nucleus, an electron, and an antineutrino all contribute to the decay energy.

For a particular nuclear decay, alpha particles and gamma rays have a constant energy, whereas beta radiation has a range of energies. "When the nucleus of a radioactive atom disintegrates, the energy it emits must equal the energy it originally contained. But in fact, scientists observed that nucleus was losing more energy than detectors were picking up. This puzzled Niels Bohr so much that he proposed that perhaps energy was not conserved, a deadly sin for a physicists.

In December 1930, Swiss scientist Wolfgang Pauli proposed the existence of an electrically neutral, low-mass particle that would be expelled together with the beta particles in order to preserve the rule of conservation of energy. This hypothetical third body would then absorb any energy not delivered to the beta particle. Thus, resolving the most perplexing of problems. Mystery begins with the proposal itself. *"I have done something terrible today by proposing a particle that cannot be detected."* Pauli penned a note in his journal, *"It is something no theorist should ever do."*

Neutrinos belong to the family of particles called leptons, which are not subject to the strong force. Rather, neutrinos are subject to the weak force that underlies certain processes of radioactive decay. There are three types of neutrinos called neutrino flavours, each associated with a charged lepton-i.e., the electron, the muon, and the tau and therefore, given the corresponding names electron-neutrino, muon-neutrino, and tau-neutrino as depicted in figure 2 and other properties of neutrinos are listed in table 1. Each type of neutrino also has an antimatter component, called an anti-neutrino; the term neutrino is sometimes used to refer to both neutrino and its antiparticle. Their tendency to react only through weak interactive forces, not getting affected by electromagnetic forces, is the reason they remain undetected for so long.

It is interesting to mention that neutrinos are invisible and difficult to detect, which is a major concern for particle physicists. However, for comparison, even stainless steel is mainly empty space to neutrinos, as wide open as a solar system is to a comet, and any device built to do so may seem substantial to the touch. Furthermore, unlike other subatomic particles, neutrinos have no electric charge i.e., they are neutral. Hence, the term "neutrino"- So, scientists were unable to catch them using electric or magnetic forces. Therefore, they are referred to as "ghost particles" by particle physicists. Seeing their strange and illusionist behaviour it's uncertain if researching neutrinos will have any practical uses. Boris Kayser, a theoretical physicist at Fermi lab in Batavia, Illinois, adds, “we have no idea where it's going to lead."

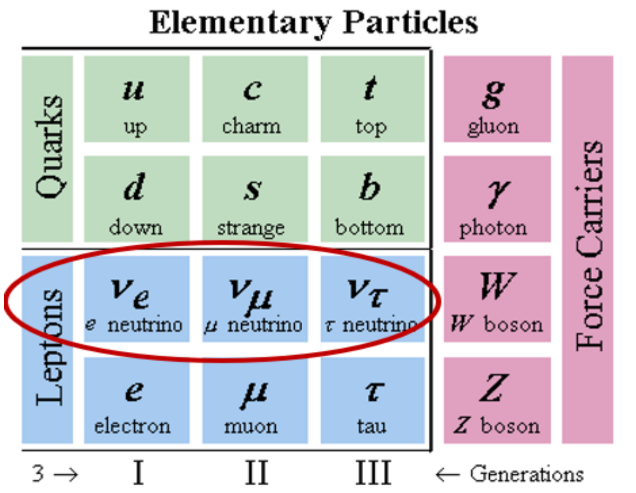

Fig. 2 Three categories of particles from the Standard Model.

Table 1: Values of lepton masses in energy unit mc^2.

LEPTONS SPIN = 1/2		
Flavour	Neutral Lepton Mass	Charged Lepton Mass
e	$m_{\upsilon_e} \leq$ 2.8 eV	m_e = 0.511 MeV
μ	$m_{\upsilon_\mu} \leq$ 0.16 MeV	m_μ = 105.6 MeV
τ	$m_{\upsilon_\tau} \leq$ 18 MeV	m_τ = 1777 MeV

There has been a great advancement in neutrino physics over the last 10-15 years. Physics of neutrino oscillation has now entered the precision era. All over the world new neutrino laboratories are growing. It may not be out of place to mention that recent results obtained from KATRIN experiment, Karlsruhe, Germany is very encouraging and positive, and they have found conclusive evidence and have crossed the important barrier in neutrino physics and have setup the new upper limit for neutrino mass is 0.8 eV [1].

Furthermore, there is a proposed India based neutrino observatory (INO) (https://www.info.tifr.res.in/info/). The proposed 50 KT of magnetized iron calorimeter detector will detect the atmospheric neutrinos and antineutrinos over a wide range of energies and path lengths and has the advantage of distinguishing between ν_μ and $\bar{\nu}_\mu$ interactions via the measurement of μ^+ and μ^- charges respectively.

Finally, it is interesting to mention that this proposed particle might be the ‘Ghost Particle’ of particle physics, but it can teach us a few life changing lessons too, which we have tried to express through the self-composed poetry given in appendix A.

II. JOURNEY OF NEUTRINOS DETECTION (EXPERIMENTAL EVIDENCES)

Experimentalists begin looking for it anyway. In the early 1950s, Los Alamos physicist Frederick Reines and his colleague Clyde Cowan set out to detect this tiny, neutral, very weakly interacting particle. In June 1956, after 26 years when Pauli made the proposal Cowan and Reines detected the antineutrinos (El-Monstro, as they named it) using the inverse beta decay process, resulting from beta decay in a nuclear reactor at Savannah River [2-4]. To capture neutrinos in Reines and Cowan reactor experiment, the reaction that was studied during the experiment is

$$\bar{\nu}_e + p \rightarrow n + e^+$$

When an anti-neutrinos coming from accelerator collides with a proton in water, a positron and a neutron are produced. The positron is slowed by the water and then annihilated together with an electron (matter meets antimatter), resulting in the creation of two photons (light particles). These photons are captured simultaneously in both detectors at the same time and proving neutrino has been captured and it is depicted schematically in Fig. 3. It may not be out of place to mention here is that the Noble prize in physics (1995) was shared equally between Martin L. Perl “for the discovery of the tau lepton” and Frederick Reines “for the detection of the neutrino.

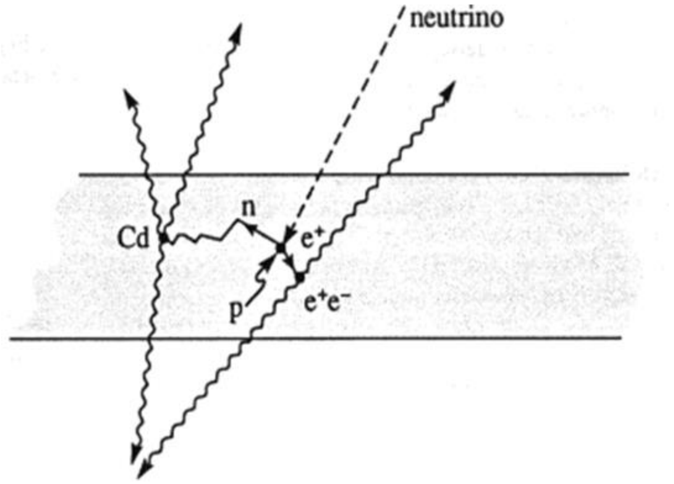

Fig. 3 Reines and Cowan's neutrino detector is depicted schematically in this diagram.

In the 1960s, a new neutrino enigma emerged, this time at the Homestake gold mine in South Dakota. Ray Davis, a nuclear chemist at Brookhaven National Laboratory, set out to study solar neutrinos by observing what happens when a neutrino collides with a chlorine atom, producing radioactive Argon that can be detected using a radiochemical method based on the inverse beta-decay, which is characterised by:

$$\nu_e + Cl_{17}^{37} \rightarrow Ar_{18}^{37} + e^-$$

In Davis' and associates' wonderful attempt to detect solar neutrinos for the first time in 1968, the findings were rather confusing. The experiment barely detected one-third of the estimated number of neutrinos. This disparity became known as the solar neutrino conundrum [5] which confirmed the general description of the nuclear reactions which power the stars, including the Sun. As is well known, the Sun's energy comes from a sequence of nuclear processes that transform hydrogen into helium. and produce solar neutrinos with a predicted flux of about 10^{11} cm^{-3} sec^{-1} at the Earth.

2.1 SOURCES OF NEUTRINOS

2.1.1 SOLAR NEUTRINOS

Solar neutrinos are produced in a series of thermonuclear reactions in solar core. There are the following three main sources of solar neutrino.

(a) The p-p neutrinos are the most copiously produced and have continuous energy spectrum with an end-point energy of 0.42 MeV:

$$p + p \rightarrow H_1^2 + e^+ + \nu_e + 0.42 \text{ MeV}$$

(b) Ninety percent of the mono energetic neutrinos having energies 0.862 MeV and 10% having energies 0.388 MeV with an integrated flux of about 0.08 times that of the p-p neutrinos are produced through the following process:

$$Be_4^7 + e^- \rightarrow Li_3^7 (or\ {}_3^7Li^* + \nu_e\ (E_\nu = 0.682 \text{ 0r } 0.388 \text{ MeV})$$

(c) The decays of B_5^8 produce the most energetic neutrinos with the end-point energy of 14 MeV and integrated flux of only 10^4 times the p-p neutrino flux

$$B_5^8 \rightarrow Be_4^8 + \nu_e + e^+$$
$${}_4^8B^* \rightarrow 2He_2^4$$

(d) There is also a contribution to the solar neutrino flux from the following reaction

$$\text{P} + e^- + P \rightarrow {}_1^2H + \nu_e\ (E_\nu = 1.44\text{MeV})$$

2.1.2 ATMOSPHERIC NEUTRINOS

Cosmic rays interact with nuclei in the atmosphere to produce pions. The μ pions decay to produce muons and μ_ν. The muons in turn decay to electrons $(e^- + e^+)$ producing $\nu_e, \bar{\nu_e}, \nu_\mu$ or $\bar{\nu_\mu}$. It may be of interest to stress that the flux of atmospheric neutrino peaks around 1 GeV energy.

2.1.3 ACCELERATOR NEUTRINOS

These are mostly muon neutrinos and muons antineutrinos of energies up to approximately100 GeV arising from the decays of fast pions, produced by the beams of energetic hadrons.

2.1.4 REACTOR NEUTRINOS

Electron antineutrinos are copiously produced in nuclear reactors during the fission process. Investigations have been carried out principally with $\overline{\nu_e}$ beams of from nuclear reactors. Reactor neutrinos are of low energies extending up to 10 MeV.

2.1.5 NEUTRINOS FROM EARTH

Natural radioactivity is produced by many radioactive atomic nuclei on Earth. The power generated by this natural radioactivity is estimated to be around 20 billion watts and neutrinos emitted from their radioactivity are expected to be around 6 millions/cm^2/sec. Furthermore, around 100 trillion neutrinos flow through our bodies every second but for particle physicists it's a challenging task to see neutrinos and very difficult to detect them.

2.1.6 MEASURING THE SEEMINGLY IMMEASURABLE

Pontecorvo's idea that neutrinos may oscillate and, therefore, must have masses has started getting experimental support due to the observed deficiency of the solar neutrinos. Results of several outstanding experiments performed with the neutrinos from Heaven as well as with the man-made neutrinos hint towards the possibility of flavor oscillations.

Investigations involving solar neutrinos provide compelling evidence regarding neutrino oscillations because of the appearance of ν_μ and ν_τ in the flux of solar neutrinos, ν_e. This, incidentally, is supported well by the "disappearance" of anti-electron–neutrinos produced at the nuclear reactors.

Scientists hypothesise that neutrinos may oscillate or s witch from one kind to another as they travel across s pace. Because the Davis experiment was only sensitive to electron neutrinos, two-thirds of the neutrinos were missed. One of the main important reasons for attempting to understand neutrino properties and their roles in astrophysics and particle physics is to disentangle information about the neutrino mass. Fortunately, neutrino oscillations offer a unique opportunity of measuring neutrino masses or their squared mass differences which is envisaged to be very-very small. A positive and conclusive evidence about neutrino flavour oscillation would provide concrete evidence regarding non-zero neutrino mass. It's worth noting that the idea of neutrino flavour oscillations, while traversing through space, was initially proposed by Bruno Pontecorvo in 1957. Subsequently, in 1962 Maki and his collaborators conceptualized the possibility of mixing of one variety of neutrinos into another. It should be noted that the hypothesis of flavour oscillations between electrons and muon- neutrinos acquired significant support following the discovery of muon-neutrinos in 1963.

III.NEUTRINO OSCILLATIONS

The idea of neutrino oscillations arose because of the wave property of the particle. So, one must think of a neutrino as wave rather than a particle. The neutrino waves propagate through space as superposition of energy eigenstates or mass eigenstates of the neutrinos. Flavour conversion occurs basically as a result of phase difference arising on account of frequency difference or energy difference, which in turn arise on account of mass difference. As stated earlier, neutrinos are believed to propagate as superposition of mass eigen states, the weak interaction eigen states can, therefore, be expressed as combination of mass eigen states, ν_1, ν_2, ν_3. For simplicity if we consider only ν_e and ν_μ and express these as combination of mass eigen states ν_1 and ν_2 through unitary transformations involving an arbitrary mixing angle θ [6].

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}, \quad (1)$$

Hence, one may obtain

$$\nu_\mu = \nu_1\ cos\theta + \nu_2\ sin\theta$$
$$\nu_e = -\nu_1\ cos\theta + \nu_2\ sin\theta \quad (2)$$

Propagation in space-time is governed by the characteristic frequencies of the mass eigen states. Consequently, $\nu_1(t)$ and $\nu_2(t)$ can be expressed as:

$$\nu_1(t) = \nu_1(0)\ e^{iE_1t}$$
$$\nu_2(t) = \nu_2(0)\ e^{iE_2t} \quad (3)$$

Where we have taken $\hbar$ = c =1. Here E_1 and E_2 denote the total energies of the two eigen states. From the conservation law of momentum, the two states, $\nu_1(t)$ and $\nu_2(t)$, must have the same momentum, say p. If $m_i \ll E_i$ (i = 1,2), E_i may be expressed as [6]:

$$E_i = p_i + \frac{m_i^2}{2p_i} = p + \frac{m_i^2}{2p} \quad (4)$$

If we were to start at t = 0 with muon type of neutrino, then

$\nu_\mu(0) = 1$ and $\nu_e(0) = 0$

Yielding

$$\left.\begin{aligned} \nu_1(0) &= \nu_\mu(0)\ cos\theta \\ \nu_2(0) &= \nu_\mu(0)\ sin\theta \end{aligned}\right\} \quad (5)$$

$$\nu_\mu(t) = \nu_1(0)\ e^{iE_1t}\cos\theta + \nu_2(0)\ e^{-iE_2t} sin\theta$$

or

$$\nu_\mu(t) = \nu_\mu(0)\ (e^{iE_1t}\cos^2\theta + e^{-iE_2t}\sin^2\theta) \quad (6)$$

Hence, the probability of finding ν_μ or ν_e after elapse of time t.

$$\left.\begin{aligned} P\ (\nu_\mu \longrightarrow \nu_\mu) &= 1-\sin^2 2\theta\ \sin^2(E_2 - E_1)t/2 \\ P\ (\nu_\mu \longrightarrow \nu_e) &= \sin^2 2\theta\ \sin^2(E_2 - E_1)t/2 \end{aligned}\right\} \quad (7)$$

On writing = $\Delta m^2 = m_2^2 - m_1^2$ *and* taking t = $\frac{L}{e}$, where L is the distance travelled, probabilities of finding ν_μ or ν_e after the time t would become

$$\left.\begin{aligned} P\ (\nu_\mu \longrightarrow \nu_\mu) &= 1-\sin^2 2\theta\ \sin^2(1.27\ \Delta m^2 L/E) \\ P\ (\nu_\mu \longrightarrow \nu_e) &= \sin^2 2\theta\ \sin^2(1.27\ \Delta m^2\ L/E) \end{aligned}\right\} \quad (8)$$

Efforts of finding evidence about neutrino oscillations have been going on for the last 48 years. All experiments that measured the solar neutrino flux, Homestake, Gallex, SAGE, SNO, Kamiokande and Super Kamiokande, have discovered neutrino deficiency ranging from ~ 1/3 to ½ as compared to the corresponding value predicted by the solar neutrino model.

The Super Kamiokande experiment in Japan was the first to discover atmospheric neutrino oscillations in 1998. The Sudbury Neutrino Observatory in Canada then released the first evidence of solar neutrino oscillations in 2001, followed by definitive evidence in 2002, thereby addressing the solar neutrino conundrum [7].

The latest results reported from the KamLAND experiment, which essentially consists of a balloon of diameter 13 metre filled with a liquid scintillator viewed by more than 1800 photo multiplier tubes have provided new and conclusive proof of neutrino oscillations in the energy range of a few MeV. It is located at Japan's main Island of Honshu near Toyama. It is exposed to $\overline{\nu_e}$'s produced from 51 nuclear reactors in Japan and 18 in South

Korea. The average distance between the detector and the $\overline{\nu_e}$ sources is 180Km. After two years of data taking, KamLAND has reported 258 neutrino events compared with an expected 365 events.

Because neutrinos oscillate, we know they must have mass. However, neutrinos have exactly zero mass in the standard model of particle physics. This is because the model contains only left-handed neutrinos and does not consider the right-handed ones without which it is not possible to normalise the mass term to the standard model. Experiments, however, prove that neutrinos spontaneously change flavour which signifies that neutrinos have some mass, how small it may be. The best constraint on the absolute mass of neutrinos earlier was from precision measurements of tritium decay from the Karlsruhe Tritium Neutrino Experiment or KATRIN to be 1.1eV, but recently, a study led UCL have set an upper limit of just 0.086 eV for the lightest neutrinos. For comparison, electrons are more than 6000000 times as bulky, at about 511000 eV, meaning it is at least 6 million times lighter than electron. The three neutrino flavours together have an upper bound of 0.26 eV [4, 8]. Table 2 shows the World-wide major oscillation experiments that have been performed and correspondingly measured and predicted neutrino fluxes in SNU.

Table 2: Name of the major World-wide experiments and measured and predicted neutrino fluxes in SNU.

Experiment	Location	Reaction	Measured Flux	Predicted Flux
SAGE	Baskan, George, Russia	${}^{71}_{31}Ga + \nu_e \rightarrow {}^{71}_{32}Ge + e^-$	70.8 ±5.3	128±9
GALLEX	Gran Sasso, Italy	${}^{71}_{31}Ga + \nu_e \rightarrow {}^{71}_{32}Ge + e^-$	77.5 ±6.2	128±7
HOMESTAKE	South, Dakota, USA	$\nu_e + Cl_{17}^{37} \rightarrow Ar_{18}^{37} + e^-$	2.56 ±0.16	7.6±1.3
KAMIOKANDE	Kamioka, Japan	$\nu_e + e^- \rightarrow \nu_e + e^-$	2.8±0.19	5.05
SUPER-KAMIOKANDE	Kamioka, Japan	$\nu_e + e^- \rightarrow \nu_e + e^-$	2.350±0.025	5.05
SNO	Sudbury, Canada	$\nu_e + d \rightarrow p + p + e^-$ $\nu_x + d \rightarrow n + p + \nu_x$	65.2±6.4	128±9

After eighty years of research on neutrinos, certain puzzles remain that may yield insights into physics beyond the standard model. Particle physicists are still working to unravel the real nature of this illusory particle, such as if the neutrino has its own antiparticle. Do neutrinos defy physics' symmetries? What is the neutrino mass state hierarchy? What is the neutrino's absolute mass? Is it true that there are more than three kinds of neutrinos? Is it true that neutrinos break charge parity symmetry? These are only a few of the unsolved questions.

If we could understand neutrinos, maybe we could answer some of the most essential questions in Physics- why the universe has so much more matter than antimatter? how the universe is created and held together among others- at the heart of our very existence? Neutrinos always seem to surprise us; we think something is fairly straight forward and it turns out not to be. “Not having all the answers about neutrinos is what makes it exciting,” says Keith Rielage, a neutrino researcher at the Department of Energy’s Los Alamos National Laboratory. “The problems that are left are challenging, but we often joke that if it were easy, someone would have already figured it out by now.” In order to get solutions, we must think beyond the box [9].

IV. CONCLUDING OBSERVATIONS

Neutrinos can be summarised as, the most fascinating particles of particle physics who got nicknamed as "ghost particles" because of their elusive nature. They are an active area of research in particle physics, and are important for our understanding of this universe, the dominance of matter over antimatter, the physics beyond Standard Model and the very essence of our own existence.

The recent development in the field is the ground breaking research published in nature in Jan 2023 (https://www.nature.com/articles/s41586-022-05478-3), led by scientists from University of Rochester, scientists from international collaboration MINERvA* have used a beam of neutrinos to study the structure of protons at Fermilab, for the very first time. Using neutrino beam in study of protons might not give us a sharper image than traditional technique of using high energy particles but it may give us a fresh practical view on how neutrinos and protons interact, that currently we get using theoretical predictions only. Another active area of research in particle physics is the precise measurements of neutrinos' mass. The ongoing experiments, for instance, KATRIN experiment at Germany, are continuing to refine our understanding of their masses.

*MINERvA—the Main Injector Neutrino Experiment to study V-A interactions—is a particle physics experiment to study neutrinos.

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Appendix- A

LIFE LESSONS FROM THE SMALLEST ENTITY

If your plinth equal charge, And you are absolutely charge less;
If your wealth equals mass, And you are near mass less;
Then you do not bother about charge, Only because you are in an electrostatic world;
And do not get tensed about mass, Because you are an exception to Higgs world.
Celebrate because you are different, Celebrate because opportunities awaits you;
If Higgs field isn't accepting you, Be your own Majorana particle.
If it is shaping you as an exception, Be ready and amuse the world;
Let not your support define you, Neither the tiny mass obstructs you;
Take the road less travelled by, Carve your own Unique Identity;
Be the neutrino of particle physics, Be the author of your own destiny.

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