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Introduction

The unfolding of the physics of neutrinos has been a premier scientific achievement of the 20$^{\text{th}}$ century. The hallmark of this decades-long endeavor has been the intertwined contributions of experiment and theory in its advancement. This fascinating history has been the subject of many treatises. Our aim is to give an overview of the aggregate knowledge of neutrino physics today and to mark future pathways for still deeper understanding. In this enterprise we bring together, under one broad umbrella, what has been learned and what is now being pursued about neutrinos in a diversity of subareas–particle physics, nuclear physics, astrophysics, and cosmology. Neutrinos are of key importance in understanding the nature of our universe and there is a new synergy of these branches of physics in their study. A brief flashback to major milestones along the road of neutrino discovery is an appropriate beginning and the subject of this introduction.

The nuclear model of the atom circa 1930 was atomic electrons bound to a positive nucleus by the electromagnetic force. The nucleus was believed to be composed of both protons and electrons, in numbers such that the atomic number A and the nuclear charge Z were accounted for. A challenge to this description was that radioactive nuclei were observed to undergo spontaneous beta-decay $A \to A' + e$. By energy and momentum conservation, all the emitted electrons should have the same energy, but a continuous electron energy spectrum was observed. This totally unexpected phenomenon caused both Niels Bohr and Paul Dirac to consider the extreme possibility that energy was not conserved. Another apparent difficulty of the nuclear model was the "false" statistics of the ^{14}N and ^{19}Li nuclei. Because ^{14}N has 7 atomic electrons, its nucleus, supposedly consisting of 14 protons and 7 electrons, should have spin-$\frac{1}{2}$, but scattering experiments showed it to have integer spin. Wolfgang Pauli of Eidgenössische Technische Hochschule (ETH), Zurich, saw a way out of this conundrum. He proposed, in a letter to a conference that he was unable to attend, his desperate remedy: nuclei also have very light neutral constituents of spin-$\frac{1}{2}$, which he called neutrons [1]. His neutrons could solve the spin-statistics problem and explain the continuous beta spectrum, since the neutrons would be emitted in conjunction with electrons, $A \to A' + e + n$, so the energy spectrum of the emitted electrons would not be monoenergetic. To be consistent with the observed electron energy sprectrum, the mass of his neutron had to be less than one percent of the proton mass. Pauli was embarrassed by his rash proposal because he thought that his neutron could never be detected, because of the weakness of its interaction. Pauli's nuclear model was complex: the nucleus would consist of protons, electrons, and neutrons: e.g., 14 protons, 7 electrons, and 7 neutrons in the ^{14}N nucleus.

In 1932 James Chadwick, then at the Cavendish Laboratory of the University of Cambridge in England, discovered the neutron [2], but it was not the weakly interacting particle emitted in beta decays. Instead, the neutron was a strongly interacting neutral companion of the proton, and the nuclear model simplified to protons and neutrons bound by the strong force: 7 protons and 7 neutrons in the ^{14}N nucleus.

In 1934 Enrico Fermi, then at the University of Rome, reformulated Pauli's idea that a very light neutral particle was involved in radioactive decays. He renamed it the neutrino (the "little neutral one" in Italian). In his famous theory of beta decay [3], Fermi invoked antiparticles (predicted by Dirac in 1931), Pauli's emitted particle (the antineutrino), and quantum field theory (in which particles can be destroyed or created). In the weak interaction according to Fermi, neutrons decay to protons via a nonrenormalizable four-fermion interaction, $n \to p + e^- + \bar{\nu}_e$ where $\bar{\nu}_e$ is the electron-antineutrino. The electron and the antineutrino are created as a pair, rather than being emitted from the nucleus. Moreover, the process obtained by crossing initial and final lines in a Feynman diagram have the same strength. Thus, Fermi's theory predicts the inverse process $\bar{\nu}_e + p \to e^+ + n$, with an interaction of the same strength as that of neutron decay. The reality of the neutrino could thus be tested by observing this inverse reaction with an intense neutrino beta decay source from reactors.

In 1955, $\bar{\nu}_e$ scattering events were observed by Frederick Reines and Clyde Cowan, Jr., American physicists working at the Los Alamos National Laboratory, via the inverse beta decay process in an experiment at the Savannah River reactor in South Carolina [4]. The reactor provided an intense antineutrino flux of 5×10^{13}/cm^2/s. Scintillators in a tank of water were used to observe the oppositely directed gamma rays from positron annihilations and a time-delayed (by 200 μs) 2.2 MeV gamma ray from the capture of the neutron on cadmium in the water. The measured inverse beta decay cross section was later found to be consistent with the prediction, indicating that the antineutrinos had been detected.

In 1956, T. D. Lee of Columbia University and C. N. Yang, then of Brookhaven National Laboratory (BNL), interpreted the decays of two species of neutral kaons observed in experiments at BNL as a breakdown of the law of parity (P) conservation (invariance under spatial inversion) [5]. They suggested radioactive beta-decay experiments as a further test. Shortly thereafter, C. S. Wu of Columbia University carried out an experiment on the radioactive beta decays of ^{60}Co that confirmed parity violation [6].

The idea of a maximal parity violating $V - A$ chiral structure of the weak interaction (with vector and axial vector currents of equal strength) originated in 1957–1958 by George Sudarshan and Robert Marshak [7], of Harvard University and the University of Rochester, respectively, and by Richard Feynman and Murray Gell-Mann [8], of Caltech, at a time when some experiments favored a scalar-tensor interaction. According to the $V - A$ theory the neutrino is left-handed and the antineutrino is right-handed. This was confirmed in 1958 by Maurice Goldhaber, Lee Grodzins, and Andrew Sunyar at BNL by studying the circular polarization and resonant scattering of gamma rays following orbital electron capture in a metastable state of ^{152}Eu [9].

A major experimental leap forward occurred in 1962, when a team led by Leon Lederman, Melvin Schwartz, and Jack Steinberger used charged pions produced by the Alternating Gradient Synchrotron at the BNL to establish the existence of the muon-neutrino (ν_μ) [10]. Charged pions decay dominantly to muons and an associated neutrino. The interactions of these neutrinos in a 10-ton spark chamber were found to produce muons but not electrons.

In 1964, James Cronin and Val Fitch showed that, in the decays of the particles called neutral kaons, not only was the parity symmetry violated, but also the combination CP was violated [11], where C is the charge conjugation symmetry. This CP symmetry breaking is very small but could have created an initial asymmetry between matter and antimatter at the beginning of the universe (at the level of one part in a billion), which after matter-antimatter annihilation leads to the preponderance of matter in the known universe [12]. In the last decade, the BaBar [13] and Belle [14] experiments have shown that CP is violated in the B mesons decays, and much more strongly.

The question of whether neutrinos had mass persisted for decades. A direct probe is the energy spectrum of the electron emitted in beta decay, since a finite neutrino mass would cause a truncation of the spectrum at its endpoint. Experiments on tritium beta decays placed increasingly more restrictive upper bounds and currently restrict the neutrino mass to be less than a few electron-volts [15, 16].

The prescient idea of neutrino oscillations was made by Bruno Pontecorvo in 1957 [17], who proposed the idea of transitions between neutrinos and antineutrinos as an analogy to the K^0–$\bar{K}^0$ oscillations observed in the neutral kaon system. This process later became known as oscillations into sterile states. For oscillations to occur among different neutrino types, the neutrinos must have different masses and the quantum mechanical wave functions of the observed neutrino flavors (i.e., the neutrinos associated with the electron, muon, and tau) must be linear superpositions of the neutrino mass eigenstates. In 1962, the Japanese theorists Ziro Maki, Masami Nakagawa and Shoichi Sakata represented the mixing of two neutrinos by a 2×2 mixing matrix (now called the MNS matrix after the names of the pioneer theorists) [18].

For the oscillations of two neutrinos in vacuum, the probability of a neutrino produced by the weak interaction as a flavor eigenstate ν_α being detected as the same flavor at a distance $L = ct$ from the source is

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\right), \tag{1.1}$$

where L is the distance from the source to the detector, E is the neutrino energy, θ is the angle that describes the mixing between the flavor eigenstates and the mass eigenstates ν_1 and ν_2, and $\delta m^2 = m_2^2 - m_1^2$ is the mass-squared difference between the mass eigenvalues. This probability, that the initial neutrino is observed as the same flavor, is known as the "survival" probability. The deviation of the survival probability from unity is sometimes called the "disappearance" probability. The "appearance" probability that a new flavor is observed is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{\delta m^2 L}{4E} \right), \tag{1.2}$$

where $\beta \neq \alpha$. The sum of the survival and appearance probabilities is necessarily unity. The oscillation probability has a sinusoidal dependence with an amplitude that depends on the neutrino mixing angle and a wavelength that depends on the mass-squared difference and neutrino energy. The L/E dependence of the oscillation argument is characteristic of vacuum neutrino oscillations due to neutrino masses and mixing.

Later, after the mixing of 3 generations of quarks was described by the CKM matrix [19] (named after Cabibbo, Kobayashi and Maskawa), the MNS matrix was extended to a 3×3 matrix appropriate to three generations of neutrinos. The third lepton (the tau) was discovered at the Stanford Linear Accelerator Center in the mid-seventies by Martin Perl and collaborators [20] and the tau-neutrino was discovered in 2000 at Fermilab by the DONUT (Direct Observation of the NU Tau) collaboration [21]. Measurements of the invisible width of the weak neutral Z-boson at the Large Electron Positron Collider at CERN determined in 1989 that the number of neutrinos coupled to the Z-boson was 2.984 ± 0.008, as anticipated from 3 generations of leptons.

Looking for neutrino oscillation effects was a huge experimental challenge, since the neutrino mixing angles and mass-squared differences were a priori unknown parameters. A range of dedicated accelerator searches for evidence of neutrino oscillations over four decades placed only upper bounds on the oscillation probabilities. It turned out that astrophysical sources, cosmic rays, and the sun led to the discoveries of the phenomena.

The first indications that neutrino oscillations may in fact occur was an apparent deficit in the flux of ν_e with MeV energies that originate from the nuclear fusion chain in the core of the the Sun (called solar neutrinos) and detected via the charged-current (CC) weak interaction. In 1964, an experiment was proposed by Raymond Davis, Jr. of BNL to extract and count radioactive isotopes of argon created when neutrinos interacted with chlorine atoms in a 10^5-gallon tank of perchloroethylene [22]. The first results from the experiment, located in the Homestake Mine in South Dakota, reported an upper bound [23] for solar neutrinos that was a factor of two to three times below predictions of the Standard Solar Model (SSM) developed concurrently by John Bahcall of the Institute for Advanced Study and collaborators [24], which gave predictions for the solar neutrino flux based on the fusion reactions in the solar core. The first observation of ν_e from the Sun [25] was experimental confirmation that these fusion reactions were indeed occurring, although neutrinos were not seen at the rate predicted by the SSM. This became known as the solar neutrino problem.

Vladimir Gribov and Pontecorvo suggested in 1968 that the apparent deficit of solar neutrinos could be due to neutrino oscillations [26], whereby the ν_e produced in the fusion processes in the sun oscillated to ν_μ during their propagation to earth. The Homestake experiment operated for more than thirty years; as the experiment and the theory improved over the years, both the observed and theory values went down, but the deficit persisted, although a neutrino oscillation interpretation of the flux deficit was initially met with skepticism by many particle physicists.

The evidence for solar neutrino oscillations continued to build through the 1990s as experiments with sensitivities to different MeV energy ranges all found rate deficits of 0.3 to 0.7 compared to the SSM. The low energy solar neutrinos from the primary *pp* fusion process were measured in the SAGE [27], GALLEX [28] and GNO [29] radiochemical experiments based on the neutrino capture reaction $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$ with a threshold of about 0.23 MeV. The solar neutrino flux at high energies, 4 to 15 MeV, was measured in water Cherenkov detectors (Kamiokande and Super-Kamiokande [30–32] in Japan) and in heavy water in the Sudbury Neutrino Observatory (SNO) [33] in Canada.

The definitive proof that oscillations are the right interpretation of the solar flux discrepancies came from the neutrino neutral-current (NC) measurements of the SNO experiment [33, 34] that determined the combined flux of all three neutrinos, as well as the ν_e flux from the charged-current process. The survival probability of solar ν_e was thus determined from the measured charged-current to neutral-current flux ratio, independent of the solar flux calculations in the SSM.

A crucial aspect in interpreting solar neutrino oscillations is the effect of matter on neutrino propagation. As the ν_e travel through the dense solar core, they undergo coherent forward $\nu_e + e \to \nu_e + e$ scattering, as first discussed by Wolfenstein [35]. Matter effects can produce large changes in the oscillation amplitude and wavelength compared to vacuum oscillations, as first shown by Barger, Whisnant, Pakvasa and Phillips [36] who studied a medium of constant density (appropriate for neutrinos propagating through the mantle of the earth in long-baseline neutrino experiments). They found a resonant enhancement that depended on the neutrino energy. Mikheyev and Smirnov later applied the enhancement at a given neutrino energy to the propagation of solar neutrinos through the varying electron density in the sun [37]. A matter enhancement can be realized only for neutrinos or antineutrinos, but not both.

Because of the prevailing prejudice that neutrino mixing would be small, there was a strong theoretical bias in favor of a resonant solar solution, which was the original solution to the solar neutrino problem proposed by Mikheyev and Smirnov (the so-called Mikheyev-Smirnov-Wolfenstein or MSW solution). Initial studies assumed adiabatic propagation of neutrinos through the sun [38, 39], but it was subsequently realized that for small mixing angles nonadiabatic propagation was also possible [40–42]. In addition to this small mixing angle solution (known as SMA), other solutions with matter effects and a large vacuum mixing angle were later identified that could account for the solar neutrino flux suppression [43].

The other solutions were named LMA (large mixing angle), LOW (low δm^2, low probability) [44], QVO (quasi-vacuum oscillations) [45] and VO (vacuum oscillations) [46]. These solutions correspond to isolated islands in the $(\delta m^2, \tan^2\theta)$ parameter space of the solar neutrino oscillations. The flat energy spectrum relative to the SSM and the absence of a significant day/night difference caused by earth-matter effects [32, 47], favored the LMA solution with adiabatic propagation. The SNO salt phase data [48] in conjunction with other solar neutrino data selected the LMA solution uniquely at a high confidence level. The mass-squared difference indicated by the solar neutrino data is $\sim 8 \times 10^{-5}\ \mathrm{eV}^2$ and the mixing is large but not maximal, $\theta \simeq 34^\circ$. The large size of the mixing angle was surprising since all quark mixing angles were known to be small.

The averaged probability of vacuum neutrino oscillations accounts for the suppression by approximately a factor of two of the low energy neutrinos, while the suppression of the high energy neutrinos from ^{8}B decay by approximately a factor of three is caused by matter effects with an adiabatic level crossing of the transition of $\nu_e \to \nu_\mu$. The Borexino experiment [49], with a liquid scintillator detector in the Gran Sasso Laboratory in Italy, is doing real time detection of the solar neutrino flux from the ^{7}Be line at 0.86 MeV via elastic scattering of neutrinos on electrons. Their measured oscillation probability is consistent with the predicted oscillation probability in the transition region from matter effects to averaged vacuum oscillations [50–53].

An amazing orthogonal confirmation of the solar neutrino oscillations comes from the energy dependence of the flux of antineutrinos with MeV energies from reactors (called reactor neutrinos). Assuming CPT invariance the probabilities of $\nu_e \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_e$ oscillations should be equal at the same values of L/E. In the KamLAND reactor experiment [54, 55] nuclear reactors in Japan are distributed such that a centrally placed detector can measure the L/E dependence of the antineutrino flux. At the average distance $L \sim 180$ km of the reactors from the KamLAND detector and the typical energies of a few MeV of the reactor $\bar{\nu}_e$, the experiment has very good sensitivity to the δm^2 value of the LMA solar solution. The KamLAND [56, 57] data show precisely the L/E dependence of the oscillation probability expected from the solar LMA solution, a dramatic vindication of the oscillation interpretation of the solar neutrino problem. The KamLAND determination of the δm^2 value is a factor of about 3 more precise than the value inferred from the solar neutrino data, but the solar neutrino analysis better determines the mixing angle. Thus, the two probes are very complementary.

Underground water Cherenkov detectors of many-kiloton size that were built primarily to search for proton decay (not found to a sensitivity of around 10^{34} years) turned out to be key neutrino observatories. The Kamiokande detector was constructed in Japan, and the IMB (Irvine-Michigan-Brookhaven) experiment was located in a salt mine near Lake Erie, USA. Fortuitously, both experiments observed neutrino events from a supernova explosion in the Large Magellanic Cloud, SN1987A [58, 59]. The time-energy spectrum of the neutrino events confirmed the basic tenets of the physics of supernova. Neutrino observations of a future supernova in our galaxy can yield fundamental insights about the neutrino dynamics in the explosion.

The first confirmed neutrino oscillations were of neutrinos of GeV energies that originated in the weak decays of pions, kaons, and muons produced by the interactions of cosmic rays with the earth's atmosphere (called atmospheric neutrinos). In the early studies of atmospheric neutrino events by the Kamiokande [60] and IMB [61] experiments (c.1988), the electron to muon event ratio was found to be about a factor of 2 above expectations. A deficit of ν_μ compared to flux calculations was found for neutrinos produced in the atmosphere on the other side of the earth from an underground detector (upward events, with large L), but not for events on the same side (downward events, with small L). This result was interpreted as evidence for oscillations with neutrino mass-squared difference $\delta m^2 \sim 10^{-2}$ eV^2 and near maximal neutrino mixing [62]. However, due to the prevailing theoretical prejudice at the time that neutrino mixing angles would be small like quark mixings, this interpretation of the atmospheric neutrino data did not receive widespread acceptance.

The conclusive evidence that atmospheric ν_μ oscillate, and ν_e do not, came in 1988 from the Super-Kamiokande experiment [63]. With the capability to make high-statistics measurements of the zenith angle (or, equivalently, path distance) and energy distributions of both electron and muon events, the Super-K experiment convincingly established that the observed L/E dependence was consistent with $\nu_\mu \to \nu_\tau$ oscillations due to neutrino masses and mixing, with approximately maximal mixing at a mass-squared-difference scale $\delta m^2 \sim 2.5 \times 10^{-3}$ eV^2.

It was originally thought that the energy and angular resolutions of the atmospheric neutrinos in the Super-K experiment would be too coarse to allow the first minimum in the $\nu_\mu \to \nu_\mu$ oscillation to be resolved and hence that accelerator-based long-baseline (LBL) experiments would be essential to make the important confirmation of ν_μ oscillations and rule out non-standard interpretations, such as neutrino decay [64, 65] or neutrino decoherence [66, 67]. Unexpectedly, Super-K succeeded in reconstructing the L/E distribution of atmospheric ν_μ events and strongly disfavored the non-oscillation alternatives. Other experiments that measured the atmospheric neutrino flux (the MACRO [69] and Soudan-2 detectors [68]) with different detector technologies found results in accord with Super-K.

Neutrinos produced by accelerators and detected at long baselines from the sources—the K2K experiment [70] from KEK to Super-K in Japan and the MINOS experiment [71] from Fermilab to the Soudan mine in Minnesota—have independently confirmed and improved the measurement of the atmospheric oscillation parameters, just as reactor experiments improved our knowledge of solar neutrino parameters. These long-baseline experiments verified the depletion of events at the first oscillation minimum. So far, the Super-K, K2K, and MINOS experiments have only measured the disappearance of ν_μ. The detection of $\nu_\mu \to \nu_e$ appearance oscillations remains as an important goal of MINOS and future accelerator based neutrino oscillation experiments.

The four parallel paths of experimental endeavor (atmospheric, solar, reactor, and accelerator neutrinos) have conclusively established oscillations of the three types of neutrinos (e, μ, τ). The CHOOZ [72] and Palo Verde [73] reactor neutrino experiments found no disappearance of $\bar{\nu}_e$ at an L/E similar to that in atmospheric neutrino experiments, confirming evidence that the primary oscillations of atmospheric neutrinos is $\nu_\mu \to \nu_\tau$. It is interesting that all of the solid evidence for neutrino oscillations comes from measurements of survival probabilities. We note, however, that the long-baseline OPERA experiment [74] from CERN to the Gran Sasso Laboratory in Italy has reported one tau-appearance event [75] from a ν_μ beam, which could also confirm $\nu_\mu \to \nu_\tau$ oscillations.

Since solar ν_e and reactor $\bar{\nu}_e$ oscillate with one characteristic δm^2 and atmospheric and accelerator ν_μ (but not ν_e) oscillate with a different δm^2, a full three-neutrino description of oscillations is clearly needed. The oscillations of three neutrinos are described by the 3×3 MNS mixing matrix, with three mixing angles (θ_{12}, θ_{23}, and θ_{13}) and a CP-violating phase (δ) [18, 76–79]. Two of the angles, θ_{12} for solar neutrinos and θ_{23} for atmospheric neutrinos, are large. The lack of detected participation of ν_e in oscillations of atmospheric and long-baseline experiments, as well as $\bar{\nu}_e$ in the CHOOZ and Palo Verde reactor experiments, indicates that the third mixing angle (θ_{13}) is small, and that atmospheric and solar neutrino oscillations are nearly decoupled from each other. There are only two independent mass-squared differences, δm^2_{31} for atmospheric neutrinos and δm^2_{21} for solar neutrinos.

We now have a fairly precise knowledge of the solar neutrino oscillation parameters δm^2_{21} (its sign is known from solar matter effects) and θ_{12}, and the atmospheric neutrino oscillation parameters δm^2_{31} (its sign is not known) and θ_{23}. The major challenge before us now is the measurement of θ_{13}, which has been established as nonzero in reactor experiments, and the CP phase, which is completely unknown.

Ongoing reactor experiments (Double Chooz [80] in France, Daya Bay [81] in China, RENO [82] in Korea) will precisely measure the value of $\sin^2 2\theta_{13}$, independently of the CP phase, down to the 1% level or better by measuring $\bar{\nu}_e$ survival. Accelerator based experiments, such as T2K [83] in Japan and NOνA [84] in the USA, may also be able to measure θ_{13} through ν_e appearance in a ν_μ beam.

The accelerator experiments can also test for CP nonconservation associated with the complex phase in the 3×3 neutrino mixing matrix. In order that δ be measurable, both δm^2 scales must contribute to the oscillation [77]. Therefore the size of CP violation in long-baseline experiments also depends on the value of δm^2_{21} in addition to δm^2_{31}. Also, the CP-violating phase enters oscillations via a factor $\sin\theta_{13}e^{-i\delta}$. Nonzero θ_{13} allows us to pursue the measurement of δ and admits interesting matter effects in long-baseline neutrino oscillations. A further complication exists due to an eight-fold oscillation parameter ambiguity [85] that must be resolved by the experiments to obtain a unique solution. If neutrinos are Majorana [86], two further CP-violating phases (ϕ_2, ϕ_3) enter in the calculation of neutrinoless double-beta decay [87] but not oscillations [88].

The anticipated steps in the long-baseline program are off-axis beams [83,89,90], superbeams [91,92], wide-band beams [93–95], and detectors with larger fiducial volumes and sophistication [83, 96, 97]. Beta beams, which utilize $\bar{\nu}_e$ from beta decay, are also under consideration [98]. The ultimate sensitivities can be derived from neutrino factories [99,100], where the neutrino beams are obtained from the decays of muons that are stored in a ring with straight sections.

Although neutrino oscillations have established that neutrinos have mass, oscillations do not probe the absolute neutrino mass scale. In particle and nuclear physics, the only avenues for this are tritium beta decay and neutrinoless double-beta decay, and the latter works only if neutrinos are Majorana particles. These experiments currently probe the interesting eV scale of neutrino mass. Another route to the absolute mass is the power spectrum of galaxies, which gets modified on small length scales when the sum of neutrino masses is nonzero [101]. Several cosmological analyses of the Cosmic Microwave Background (CMB) and large-scale structure data have already given an upper limit on $\sum m_\nu$ below 1 eV [102]. Big Bang Nucleosynthesis (BBN), at the time scale of a few minutes in the early universe, determines the number of relativistic neutrino degrees of freedom, with results consistent with either $N_\nu = 3$ or 4. Neutrinoless double-beta decay experiments are the only known means of determining the Majorana nature of light neutrinos. An ambitious experimental program is underway to probe below the present upper limits of order 1 eV on the diagonal mass matrix element associated with ν_e using this process.

The theory of neutrino masses and mixings is a wide open area of investigation. If neutrinos are massless, there are 19 free parameters in the Standard Model (SM) Lagrangian: three gauge couplings, six quark masses, three quark mixing angles, and a CP-violating phase in the quark mixing matrix, the strong CP phase, three charged-lepton masses, and the Higgs boson self-coupling and vacuum expectation value. If neutrinos have mass, there are at least seven more: three neutrino masses, and the three mixing angles, and one leptonic CP-violating phase in the leptonic mixing matrix. If neutrinos are Majorana particles, there are also two other CP-violating phases. Therefore understanding neutrino masses is an essential part in the development of any theory of elementary particles.

The starting point in the construction of models is to account for the tribimaximal mixing pattern [103] ($\theta_{23} = 45^\circ$, $\theta_{12} = 35^\circ$, $\theta_{13} = 0^\circ$) that is favored by neutrino data. There are diverse models by which this pattern can be realized, such as having a flavor symmetry, of which the A_4 group is a popular example [104]. With perfect tribimaximal mixing, the angle θ_{13} is zero and all the interesting physical phenomena that would be associated with a nonzero θ_{13} go away. Thus, perturbations from exact tribimaximal mixing are the essence of model constructions and their tests.

The incorporation of neutrinos in the framework of a Grand Unified Theory (GUT) is an attractive possibility [105]. The existence of a right-handed neutrino at the GUT mass scale can provide an explanation of the light neutrino mass scale through the seesaw mechanism [106]. In the simplest form of the seesaw the light neutrinos are predicted to be Majorana particles, hence the importance of the neutrinoless double beta decay experimental program.

There is the potential for fundamental neutrino physics beyond what is now apparent. A dramatic example is a possible environmental dependence of the neutrino masses on the density of the medium in which they propagate. In a model in which neutrinos have a new interaction with a very light scalar field, neutrinos may be connected with the dark energy in the universe [107].

Unexplained deviations from standard three-neutrino expectations that have been reported by several experiments could, if confirmed, be of new physics origin, such as possible CPT violation [108, 109] and the existence of sterile neutrinos that do not couple to SM fields [110]. Sterile neutrinos have also been invoked in explanations of astrophysical phenomena, such as neutron star "kicks" [111]. Although considerable efforts have been devoted to theoretical studies of sterile neutrinos, evidence for their existence is inconclusive.

Neutrino astrophysics is the newest frontier of the field. The advent of the large neutrino telescopes IceCube [112] and ANTARES [113] makes possible the search for neutrinos from astrophysical sources [114], which produce distinctive flavor mixes at the sources that can be inferred from the ratios observed at the earth where their oscillations have averaged [115]. Dark matter capture by the sun followed by annihilations in the solar core could yield neutrinos that may be observed in the DeepCore detector of IceCube and provide an important diagnostic about the nature of dark matter.

Neutrinos were pivotal in testing the Standard Model of particle physics. The SM is a fully renormalizable theory where the charged-current interaction occurs due to the exchange of a W-boson, replacing the effective field theory approach of Fermi's four-fermion description of beta decay. Another new ingredient of the SM was the neutral current mediated by the Z-boson. Accelerator measurements of neutrino scattering cross sections provided many of the tests to show the validity of the SM. Neutrinos are also of unique importance at colliders, since they give rise to missing energy. The discovery of the predicted W-boson of the SM [116] utilized a transverse mass variable [117, 118] constructed from the transverse energy of the charged lepton and the transverse missing energy of neutrinos in leptonic W-decays, $W \to \ell\nu$. The transverse mass has an upper endpoint of M_W, smeared by the W-width, by which the W-mass and W-width have been measured. In high energy collisions, the decays to neutrinos of produced Z-bosons is a source of missing transverse energy that is a background to new physics models that give missing energy through the emission of a stable particle. Many decay processes include transitions to final states with neutrinos, including the decays of the muon, tau lepton, charged pions, charged kaons, etc. Thus, neutrinos are ubiquitous in their presence in high energy physics.

The field of neutrino physics has progressed dramatically over the last decade and a half, and this fruitful era of neutrino exploration continues at a high rate. Our goal is to summarize the present status of the field and to discuss ways that progress will be made in answering the outstanding questions. Anticipating the future is a fragile enterprise and neutrino physics has a long history of unexpected surprises. We can look forward with anticipation to the surprises.