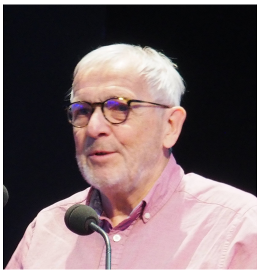
What Do We Learn from the Past for Neutrino Physics in the Future?

Francis Halzen
Department of Physics, University of Wisconsin–Madison,
Madison, WI USA



This conference celebrated the great breakthroughs achieved in neutrino physics since the neutrino was first proposed by Wolfgang Pauli in 1930 as a "desperate remedy" for the apparent violation of energy conservation in radioactive decays [1]. A gradual increase in the scope and sensitivity of our instruments made them possible, and nothing else. Let me illustrate this by contrasting the historical development of particle physics and neutrino physics.

In the prehistory of particle physics, up to about 1977, experiment drove theory, with some notable exceptions. Nature generously supplied the experimentalists with serendipitous discoveries, beginning with radioactivity and including the neutrino, the muon, strange particles, P and CP violation, the J/Ψ particle, the Υ, and more. This era ended with the emergence of the Standard Model, the most successful theory ever constructed and the subject of textbook physics by the early 1980's. Particle physics entered an era where we found what we looked for, and no more. Interesting fluctuations that were left to chase after were fewer over time, with g-2 and lepton flavor violation in b-decays leading the lineup at this point.

In neutrino physics, the era of serendipitous discovery never happened [2]. We chased the neutrino with purposely targeted experiments, which revealed neutrinos from a nuclear reactor [3], the second neutrino using a dedicated accelerator beam [4], atmospheric neutrinos in deep-mine experiments [5], oscillations [6] starting with the Super-Kamiokande detector [7] and followed by solar neutrinos [8], a supernova with the Kamioka and IMB experiments [9], geoneutrinos [10] ... and, most recently, cosmic neutrinos with IceCube [11]. The neutrino is a coy mistress [12] and its feeble interactions with the experiment make it unlikely that you will stumble on anything that you have not been specifically looking for. The nature of the neutrino is such that it is unlikely to generously and serendipitously reveal its mysteries in the future. (In case you had any doubt about supernova 1987A, the IMB proposal clearly identified supernova neutrinos as a target of the proposed experiment.)

We have no choice but to keep building dedicated exploratory and precision experiments on all fronts, and where prohibitively expensive, we should gamble on ingenuity and risk. What we must avoid is endless debate, which leads to conservatism. We know that the future is promising; unlike previous generations of physicists, we cannot live under the illusion that all physics has already been discovered. We have dark matter, dark energy, and, in this context, the nonvanishing neutrino mass itself, to remind us of this [13].

With dark matter and dark energy, astronomers have raised physics questions that seem as daunting now as the problem of the Sun's lifetime was when presented over one century ago. At the time, evolution and geology required a Sun that was older than several tens of millions of years. Chemistry established its lifetime at 3,000 years. Neither chemistry nor astronomy solved the puzzle; Becquerel did with the discovery of a new source of energy in his desk drawer, radioactivity. History may repeat itself with heavenly problems revealed by Earth-bound experiments, or vice versa, of course. Cosmic accelerators are what deliver the highest energy protons, photons, and neutrinos that we have observed. With the operation of a generation of totally novel detectors, they may, as was once the case in the pioneering days of cosmic ray physics, even yield particle physics results.

Before proceeding, I must emphasize that my argument in no way minimizes the role of theorists. Already in 1933, Fermi provided a phenomenological framework to address the question of why the neutrino's interactions were weak [14]. His proposal laid the groundwork for building the Standard Model. Fermi's theory prescribed a quantitative relation between the fine-structure constant and the weak coupling: $G \sim \alpha/M_W^2$. Fermi adjusted M_W to accommodate the observed relative strength and range of nuclear radioactive decays; one can, for instance, readily obtain a value of M_W of 40 GeV from the observed decay rate of the muon for which the proportionality factor is $\pi\sqrt{2}$. The answer is off by a factor of 2 because the discoveries of parity violation and neutral currents were in Fermi's future and these introduce an additional factor of $1 - M_W^2/M_Z^2$.

We can probably agree that neutrino physics beyond the Standard Model tops our list of the big questions to be probed by future experiments. As with the Large Hadron Collider, there are compelling reasons to expect physics beyond the Standard Model in the neutrino sector. In fact, physics beyond the Standard Model is guaranteed by the observation of nonvanishing neutrino mass that cannot be tailored into the Standard Model symmetries. Furthermore, the observed neutrino masses come with their own hierarchy problem, with the ratio of the neutrino and electron mass at one million. Theoretical speculations are challenging because the couplings between the neutrino and the charged leptons have been shown to be consistent with the Standard Model with exquisite precision. This makes it challenging to modify the properties of the neutrino. Right-handed neutrinos can finesse the problem, but compelling evidence for their existence has been elusive [15]. Encouraged by the fact that deliberately planned experiments have delivered most of the outstanding results in neutrino physics to date, we will discuss future experiments and methods with an opportunity for success. In a sense, every neutrino experiment is launched with the hope of stumbling on aspects of neutrino physics beyond the Standard Model that we already know to exist.

1 Neutrino Oscillation Experiments: Precision and Exploration

Two decades ago, a string of fundamental experimental measurements established the three-flavor framework of oscillating massive neutrinos. At the time, it could be elegantly summarized by simple relations between the neutrino states produced by the weak interactions in electron, muon and tau flavors and propagating as mixed states ν_1, ν_2 and ν_3:

$$\begin{aligned}
\nu_1 &= -\cos\theta\nu_e + \sin\theta\left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right), \\
\nu_2 &= \sin\theta\nu_e + \cos\theta\left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right), \\
\nu_3 &= \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right). \qquad (1)
\end{aligned}$$

Here, θ is the solar mixing angle. Discovery of neutrino oscillations in the atmospheric [7] and solar [8] neutrino beams has been confirmed by supporting evidence from reactor and accelerator neutrino beams [16]. Their status can be elegantly captured by the so-called global analyses [17].

A new generation of reactor experiments has falsified this elegant approximation for the oscillation scheme by measuring a large value of the θ_{13} angle with impressive precision [18]. In Eq. (1), one assumes that the mixing of muon and tau neutrinos is maximal and that there is no mixing that connects the solar and atmospheric oscillations. The measurement of a large value for θ_{13} made another dramatic impact on the field: where before long-baseline experiments were a second choice to a neutrino factory or a beta beam for pursuing precision measurements of neutrino properties, because of the large value of θ_{13}, some outstanding "known-unknowns" of neutrino physics, the hierarchy and the CP-violating phase, came within reach of long-baseline experiments. A high-intensity neutrino beam, from Fermilab to the South Dakota mine that once housed the Davis solar neutrino experiment, has emerged as a unified effort to deliver a precision PMNS matrix. It will be exposed to a 40-kiloton liquid argon detector, DUNE [19]. In the process, the possibility of building a future neutrino factory has unfortunately been eliminated, but could eventually reappear as the first stage of a muon collider that has recently reemerged as a very attractive tool for precision Higgs physics.

Why a precision measurement of another matrix? Indeed, despite continued efforts to measure the CKM matrix with increased precision, we are not closer to understanding the Cabibbo angle. What is the alternative? Stop doing oscillation experiments? Precision may be the gateway to new neutrino physics. Additionally, the instrumentation can be used to target other science goals such as proton decay and the search for dark matter and, in the case of DUNE, the observation of the next Galactic supernova explosion with capabilities that are complementary to those of the large Cherenkov detectors that are mostly sensitive to electron antineutrinos, such as Super-Kamiokande, IceCube, and their next-generation extensions. New insights may emerge with a possible connection of leptonic CP-violation to baryogenesis or to the origin of flavor.

The landscape of neutrino oscillation experiments reaches beyond Fermilab with Hyper-Kamiokande [20], ORCA [21], and IceCube-Phase1 all exploiting the atmospheric neutrino beam instead. These experiments have a unique capability to perform precision tests of the Standard Model via atmospheric tau-neutrino appearance measurements, realistically to better than 10%. Already, IceCube is measuring the oscillation parameters with neutrinos in the energy range of 5 to 55 GeV, an order of magnitude above the energy of present experiments, with the primary goal of detecting variations in the oscillation parameters, signaling new physics.

This landscape is even more diversified with JUNO [22], the Fermilab short-baseline program, the multiple very-short-baseline oscillation experiments positioned near research reactors, and experiments exploiting the intense neutrino beams associated with neutron factories.

Oscillations only reveal mass differences; probing the neutrino's absolute mass is a lot more challenging. The KATRIN spectrometer is taking data probing neutrino mass to 0.02 eV by studying the kinematics of tritium decay [23]. Information on neutrino mass has emerged from a new direction: cosmology [24]. The structure of the Universe is dictated by the physics of cold dark matter, and the galaxies we see today are the remnants of relatively small overdensities in the nearly uniform distribution of matter in the very early Universe. Overdensity means overpressure that drives an acoustic wave into the other components making up the Universe: the hot gas of nuclei, photons, and neutrinos. These acoustic waves are seen today in the temperature fluctuations of the microwave background as well as in the distribution of galaxies in the sky. With a contribution to the Universe's matter balance similar to that of light, neutrinos play a secondary role. The role is however identifiable — neutrinos, because of their small cross sections and large mean-free paths, prevent the smaller structures in the cold dark matter from fully developing, and this is visible in the observed distribution of galaxies. Simulations of structure formation with varying amounts of matter in the neutrino component, i.e., varying neutrino mass, can be matched to a variety of observations of today's sky, including measurements of galaxy-galaxy correlations and temperature fluctuations on the surface of last scattering. Necessarily, results can only be obtained in the framework of a specific model for the cosmology.

For other experiments chasing the "known-unknowns" in neutrino physics, the observation of neutrinoless double beta decay would be especially rewarding [25]. Its observation can confirm the theoretical bias that neutrinos are Majorana particles, yield critical information on the absolute mass scale, and, possibly, resolve the hierarchy problem. In the meantime, we will keep wondering whether small neutrino masses are our first glimpse at grand unified theories via the see-saw mechanism or represent a new Yukawa scale tantalizingly connected to lepton conservation.

It is not a secret that many of the experiments have been inspired, partially or completely, by the possibility of revealing sterile neutrinos. I have already mentioned that sterile right-handed neutrinos provide us with a compelling way to naturally endow neutrinos with a small mass. It has been argued that they may have been sighted in the eV mass range, but they could exist with masses ranging all the way to those typical of Grand Unified Theories (GUT) particles.

2 Neutrinos Branch out into Astronomy

More than fifty years ago, pioneering experiments in deep underground mines in India and South Africa discovered atmospheric neutrinos [5]. The atmospheric neutrino beam was later exploited by a new generation of underground detectors to demonstrate that neutrinos have a tiny mass, representing the first chink in the armor of the Standard Model [7]. In contrast, the same detectors' search for cosmic neutrinos reaching us from sources beyond the Sun came up empty, establishing an upper limit on their flux, assuming an E^{-2} energy dependence:

$$E_\nu^2 \frac{dN}{dE_\nu} \leq 5 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}. \tag{2}$$

At a level more than a factor of one hundred below this, the IceCube experiment discovered in 2013 a flux of cosmic neutrinos of extragalactic origin [28]. An IceCube high-energy muon-neutrino detected on September 22, 2017 (IC-170922A) launched a broadband multiwavelength follow-up program identifying the flaring, rotating supermassive black hole TXS 0505+056 as the source [29]. Inspection of the archival IceCube data from this same direction identified a spectacular 150-day flare of 19 high-energy neutrinos on a background of less than 6 occurring in December 2014. After 106 years following their discovery, IceCube thus identified a source of cosmic rays, the particles that represent the highest energy radiation reaching us from the Universe. These measurements were made possible only via the rapidly evolving global effort in multimessenger astronomy, for which neutrinos represent a crucial new window on our universe.

Thus, neutrinos became a tool to do astronomy. Additionally, for neutrino physics, cosmic neutrinos provide a new beam reaching energies exceeding by five orders of magnitude those of the highest energy neutrinos produced in the laboratory and ten million times those that reached us from supernova 1987A. IceCube performed the first oscillation measurement over cosmic distances and found evidence for the appearance of tau neutrinos, including one event where a tau travels 17 meters through the ice before decaying. IceCube also identified a first Glashow-resonance [26] event where an intermediate boson is produced in the interaction of a 6300-TeV anti-electron neutrino with an atomic electron [27]. These observations clearly illustrate the possibility of using neutrino telescopes for exploring the physics of neutrinos themselves.

For astronomy to flourish, we will need more and much larger neutrino detectors, and these are already in their first stages of construction with ARCA in Italy, GVD in Lake Baikal, and IceCube-Gen2 at the South Pole [11]. Neutrino energies will soon be extended from the PeV into the EeV range by radio detectors observing the electric spark made by secondary particles produced in neutrino interactions and by air shower detectors looking down from mountain tops for the showers produced by the decay of tau neutrinos produced in neutrino interactions near the surface of the Earth.

3 Outlook

I would like to underscore two points raised in the introduction. The search for new physics is not only the province of accelerator experiments. This is especially true because we have very little guidance from theory at this point; supersymmetry at the natural scale has not shown up so far. And, there is ample evidence in the past of great synergy between particle and astroparticle experiments: the discovery of helium in the Sun, the formation of carbon by three alpha particles in stars, and the discovery of neutrino mass with natural neutrino beams. The road to future success is to keep up the impressive build-up of instrumentation that we have witnessed over the last decade on all fronts and not get depressed over whether we should, or should not, have discovered anything new by this time.

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