Chapter 1

Introduction: Particle Physics with Cosmic Accelerators

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At the close of the 19th century, many physicists believed that the laws of physics had been essentially settled — we do not live under that illusion today. We are blessed with an abundance of puzzles covering all aspects of particle physics, including the incompleteness of the standard model, the origin of neutrino mass, and the perplexing nature of dark matter and dark energy. Over the last half century, the focus of particle physics has shifted from cosmic rays to accelerators, returning in the disguise of particle astrophysics with the discovery of neutrino mass in the oscillating atmospheric neutrino beam, the first chink in the armor of the standard model. This book anticipates strategies for exploiting natural neutrino beams, which now include very high-energy neutrinos from the cosmos. In the Preface, we introduce the cosmic accelerators that produce them in heavenly beam dumps, including in the Earth's atmosphere.

Considering the size of the Sun and the rate at which it must be contracting in order to transform gravitational energy into its radiation, Lord Kelvin concluded that the Sun could not be more than 20–40 million years old. His estimate, published in the March 1862 issue of Macmillan's Magazine,[1] was indeed correct but in direct conflict with known geology. Moreover, it did not leave sufficient time for Darwins evolution to run its course. The puzzle was resolved after Becquerel accidentally discovered radioactivity, and in a lecture at the Royal Institution in 1904, Rutherford[2] eventually used the measured relative abundances of radioactive and stable isotopes of heavy elements such as uranium to establish a lower limit of 700 million years on the solar system's lifetime. The puzzling gap between Kelvin's tens of millions and the actual age of 4.5 billion years provided the hint of spectacularly new physics to be discovered at a time when many thought that all physics had left to do was dot the i's and cross the t's. Today, we are blessed with an abundance of puzzles covering all aspects of particle physics, including the question of how to stabilize the Higgs mass in the standard model, the origin of neutrino mass, and the nature of dark matter and dark energy.

A century ago, neither chemistry nor astronomy had solved the puzzle of what powers the Sun; Becquerel did so by accidentally discovering a new source of energy in his desk drawer, radioactivity. In this book, the authors speculate that history may repeat itself, with heavenly problems resolved by earthbound experiments, and vice versa. Actually, cosmic beams deliver the highest energy protons, photons, and neutrinos for probing new physics. In the tradition of the pioneering days of cosmic-ray physics, a generation of novel detectors such as ANTARES in the Mediterranean, GVD in Lake Baikal and IceCube at the South Pole has already yielded new results covering particle physics.[3] The key is that the very large volume/area of the recently constructed detectors compensates for the very low luminosity (flux) of the natural beams.

Along with the origin of cosmic rays, neutrino physics beyond the standard model tops our list of the big questions to be explored by neutrino "telescopes." 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 a non-vanishing neutrino mass that cannot be tailored into the standard model symmetries. If the neutrino mass itself represents a new energy scale, it comes with its own hierarchy problem with the ratio of the neutrino and electron masses at one million. Modifying the properties of the neutrino is challenging because its couplings to the charged leptons have been shown to be consistent with the standard model with exquisite precision. The introduction of right-handed neutrinos that do not couple to matter — sterile neutrinos — finesse this constraint. Despite multiple claims, compelling evidence for their existence has been elusive.

Every neutrino experiment is launched with the hope of stumbling on aspects of neutrino physics beyond the standard model, which we already know exist. Precision may be the gateway, with intense proton beams delivering neutrinos to next-generation neutrino detectors. The landscape of neutrino oscillation experiments reaches beyond Fermilab, though, with the IceCube Upgrade, ORCA, and Hyper-Kamiokande exploiting the atmospheric neutrino beam instead, as ANTARES, IceCube, and Super-Kamiokande are doing today.[4] Specifically, these experiments have the unique capability of performing precision tests of the standard model with tau neutrinos, which are scarce in the lower energy Fermilab beam. Already, IceCube is measuring the oscillation parameters with neutrinos in the energy range of 5–55 GeV, an order of magnitude above the energy of all present experiments.[5] The primary goal is to detect variations with energy of the oscillation parameters, signaling new physics. Additionally, neutrino detectors can be used to target other science goals such as the search for dark matter and proton decay and, in the case of DUNE detector at Fermilab, 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.

More than 50 years ago, pioneering experiments in deep underground mines in India and South Africa discovered atmospheric neutrinos.[6] The atmospheric neutrino beam was later exploited by a new generation of underground detectors to demonstrate that neutrinos have a tiny mass. In contrast, the search for cosmic neutrino beams reaching us from sources beyond the Sun, anticipated since the 1960s, came up empty. They established an upper limit on a cosmic flux of

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

assuming an E^{-2} energy spectrum of the cosmic neutrino beam. At a level that is more than a factor of one hundred below this, the IceCube experiment discovered in 2013 a flux of cosmic neutrinos of extragalactic origin.[7,8] Thus, neutrinos became a tool for astronomy.

Two principal methods are used to identify cosmic neutrinos in the presence of a large background of atmospheric muons and neutrinos. Traditionally, neutrino searches have focused on the observation of muon neutrinos that interact primarily outside the detector to produce kilometer-long muon tracks passing through the instrumented volume. Although this allows identifying neutrinos that interact outside the detector, it is necessary to use the Earth as a filter in order to remove the background of cosmic-ray muons. This limits the neutrino view to a single flavor and half the sky. IceCube measured the atmospheric muon neutrino flux over three orders of magnitude in energy with a result that is consistent with theoretical calculations. However, with 8 years of data, an excess of events was observed at energies beyond 100 TeV[9] that could not be accommodated by the atmospheric flux. Allowing for large uncertainties in the extrapolation of the atmospheric component to higher energy, the statistical significance of the excess astrophysical flux is 6.7σ.

An alternative method exclusively identifies high-energy neutrinos interacting inside the detector, so-called high-energy starting events. It divides the instrumented volume of ice into an outer veto shield and an inner fiducial volume. The advantage of focusing on neutrinos interacting inside the instrumented volume of ice is that the detector functions as a total absorption calorimeter providing an excellent energy measurement. Furthermore, with this method, neutrinos from all directions in the sky can be identified, including both muon tracks and secondary showers, produced either by charged-current interactions of electron and tau neutrinos or by neutral-current interactions of neutrinos of all flavors. Neutrinos of atmospheric and cosmic origin can be separated, not only by their well-measured energy but also by exploiting the fact that background atmospheric neutrinos can be removed because they are accompanied by particles produced in the same air shower from which they originate. Using this method, IceCube designed a veto that leaves an approximately 500-megaton fiducial volume for detecting cosmic neutrinos. The analysis provided the first evidence for a cosmic component of the neutrino flux.[10]

The observation of neutrinos of cosmic origin has also been confirmed by the appearance of very high-energy tau neutrinos in the cosmic beam, including one event where a tau traveled 17 m through the ice before decaying. IceCube also identified a first Glashow-resonance event where an intermediate boson was produced in the interaction of a 6300-TeV antielectron neutrino with an atomic electron.[11]

In summary, IceCube has observed cosmic neutrinos using multiple methods for rejecting atmospheric background. The results of these methods agree, pointing to extragalactic sources whose flux has equilibrated in the three neutrino flavors after propagation over cosmic distances. The diffuse flux of cosmic neutrinos observed is large; it corresponds to an energy density in the extreme Universe that is similar to that in photons, guaranteeing a bright future for neutrino as well as multi-messenger astronomy.

At the time that Rutherford solved the puzzle of energy generation in the Sun, a new one emerged with the discovery of cosmic rays. Their origin is the oldest unsolved problem in astronomy, and building kilometer-scale neutrino detectors represents the latest desperate attempt to solve it. Cosmic rays are the highest energy messengers reaching us from the Universe. They are not "rays" at all but mostly protons and some heavier nuclei. Since they were first detected over one hundred years ago, cosmic rays have posed an enduring mystery: What creates and launches these particles across such vast distances? Where do they come from, and how do their cosmic accelerators achieve the huge energies and luminosities observed? Cosmic rays fascinate particle physicists because their energy is routinely observed to be more than a million times greater than that of the Large Hadron Collider beams. IceCube recently identified the first extragalactic cosmic-ray accelerator: a rotating supermassive black hole in an active galaxy at a surprising distance of four billion light-years.[12]

We know that cosmic rays originate in galactic and extra-galactic accelerators and that the arrival directions of the highest energy cosmic rays show a small asymmetry in the sky that points in the general direction of the highest density of nearby extragalactic astronomical sources.[13] Neither a precise picture has emerged nor is one actually expected, because the directions of the electrically charged cosmic rays are made isotropic by magnetic fields in our Galaxy and beyond. Neutrinos track cosmic rays that, once accelerated, interact with the radiation fields (or, possibly, hydrogen or molecular clouds) ubiquitous in the extreme environments where large gravitational energy is converted into the acceleration of particles. The neutral and charged pions produced in these interactions decay into electrically neutral gamma rays and neutrinos that do point back to their sources.[14] For neutrino physics, however, the subtleties of the astrophysics are not critical; cosmic neutrinos provide a new beam for neutrino physics reaching energies over five orders of magnitude higher than those of the highest energy neutrinos produced in the laboratory. Unique opportunities include precision tests of fundamental symmetries, most prominently Lorentz invariance, and the search for new physics covering magnetic monopoles, TeV-scale gravity and, in general, the search for any hints of deviations from standard model physics using a neutrino beam in a new energy regime.

Neutrino energies cover more than six orders of magnitude, from a few GeV at threshold to a record event initiated by a cosmic neutrino with energy beyond 10 PeV. Both ANTARES and IceCube have demonstrated the capability of measuring atmospheric neutrino oscillation parameters at levels competitive with dedicated long-baseline experiments. The next-generation atmospheric neutrino detectors, ORCA and the IceCube Upgrade, will provide high statistics measurements of the appearance of tau neutrinos, constraining elements of the PNMS matrix that are not accessible to long-baseline experiments. They will contribute to the identification of the neutrino mass ordering, search for sterile neutrinos, and other new neutrino physics in novel ways. Neutrino telescopes have set world-leading limits in the search for dark matter searches and magnetic monopoles and on the violation of fundamental symmetries, such as the violation of Lorenz invariance.

In this context, the many opportunities for neutrino telescopes to search for dark matter stand out.[15] One way is by looking for neutrinos from concentrations of weakly interacting massive particles (WIMPs) that have accumulated over time in the Sun, the Milky Way, and nearby external galaxies. The neutrinos are secondary products of the annihilation of pairs of WIMPs into standard model particles, which subsequently decay into neutrinos. Along with Super-Kamiokande, neutrino telescopes have produced the world's best sensitivity to WIMPs, with significant spin-dependent cross-sections for interactions with protons. The WIMPs are efficiently trapped by protons in the Sun, resulting in a dense concentration of dark matter in a nearby and readily identifiable source. The signal would simply be an excess of neutrinos from the direction of the Sun over the atmospheric neutrino background in the same angular window. There is no alternative astrophysical explanation of such a signal — detection would be a smoking gun for the discovery of dark matter.

Finally, a Galactic supernova explosion would not only be the astronomical event of the century, it would also provide an extraordinary opportunity to do neutrino physics, as was the case with SN 1987A. A sudden increase in the total summed counting rate of the IceCube optical sensors would signify a potential supernova explosion in the Galaxy.[16] Supernova neutrinos of $\sim$15 MeV interacting within a few meters of a DOM would generate enough hits to cause a sharp increase in the summed counting rate followed by a characteristic decline.[17] For the most likely distance of 10 kpc, IceCube records a DC current that tracks the time evolution of the supernova in two-nanosecond time bins. The current sums up the Cherenkov light from one million neutrino interactions inside the detector that result from the passage of the supernova burst. The detector records the time of every photoelectron hit with two-nanosecond precision. The additional measurement of the rate of two-photon correlations is sensitive to the energy of the supernova neutrinos. If it comes on time, the event is expected to reveal the mass ordering in less than 10 s!

It is likely that the most exciting science to be done with these unusual instruments has not yet been identified at this early stage.

Acknowledgments

This research was supported in part by the US National Science Foundation under Grants No. OPP-0236449 and PHY-0969061 and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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