Week 9
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Neutrino Physics: Where We Are & Where We're Going

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Neutrinos have been puzzling physicists since they were first proposed in 1930. Through experimental findings and theoretical developments over the past decades, we have learned a great deal about these wily fundamental particles, but many mysteries remain. Meanwhile, we know enough about neutrinos to use them as a unique tool for studying previously inaccessible systems such as the interiors of stars.

This week, we will review the progress we have made in understanding neutrinos, and highlight the important open questions in the field.

I. Where We Are

Neutrinos were first proposed in 1930 by Wolfgang Pauli to explain the energy apparently missing from nuclear decays, but only in 1956 were they first observed by Cowan and Reines. Subsequent experiments revealed the existence of three *flavors* of neutrinos, each associated with a charged lepton (electron, muon, and tau) that accompanies them in interactions. An interesting property of neutrinos is that they can switch flavor over time, or "oscillate" — a neutrino born as the electron type can later be detected as the muon type, for example. This quantum mechanical phenomenon is a result of neutrinos having a small but non-zero mass. The oscillations were first observed as a deficit in the expected number of neutrinos arriving from the Sun (the Solar Neutrino Problem) and from cosmic ray interactions in the atmosphere (Atmospheric Neutrino Anomaly). This effect has now been studied in detail by many experiments, using neutrinos from the Sun, atmosphere, nuclear reactors, radioactive isotopes, and particle accelerators.

II. Puzzles

There remain many open questions of fundamental significance to our understanding of the universe, including:

- What are the masses of the neutrinos, and why are they so small?
- What is the ordering of the neutrino masses?
- Is the neutrino its own antiparticle (a *Majorana* neutrino)?
- Could CP violation in neutrino interactions explain the matter/antimatter asymmetry that gives rise to our matter-filled universe?
- Are there additional neutrino types (*sterile* neutrinos) beyond the known three?

A broad range of experimental efforts are underway to address these important questions, and among these are SNO+ (neutrino mass, Majorana neutrinos), the Short-Baseline Neutrino Program at Fermilab (sterile neutrinos), and DUNE (CP violation, mass ordering, new interactions).

III. Neutrinos As Tools

Despite the mysteries, neutrinos provide an invaluable tool for studying otherwise inaccessible physical systems, thanks to their weak interactions with matter. Here on Earth, neutrinos can be used to monitor nuclear reactor operation and the production of dangerous fissile materials. They also come to us directly from the core of the Sun and deep inside supernovae, carrying information of the dynamics therein. Neutrinos can also teach us about the furthest reaches of space and time: efforts are in process to detect the *relic* neutrinos left over from the Big Bang (PTOLEMY), and the IceCube experiment is studying ultra high-energy neutrinos coming from phenomenally powerful, naturally occurring particle accelerators in distant space. Neutrinos have become a powerful tool of multi-messenger astronomy, where we build an understanding of astrophysical events by looking at many signals together.

IV. Learning More

It is a very exciting time in neutrino physics! Here are a few ways to keep up to date:

- **Visit Fermilab:** Fermi National Accelerator Laboratory, located near Batavia, IL, offers many programs for the public and students, including lectures and tours. Details can be found at https://www.fnal.gov/pub/visiting.
- **Web & Social Media:** Many physics laboratories and experiments post updates on social media platforms like Twitter and Facebook, and you can follow them to get the latest news. Their websites will offer an overview of the projects and scientific goals, and links to more information. A few examples:
  - Fermilab's "All Things Neutrino": https://neutrinos.fnal.gov
  - Fermilab on Twitter: https://twitter.com/Fermilab
  - Website for SNO+: https://snoplus.phy.queensu.ca/
- **Science Journalism:** There are several great science-focused publications with articles about new research. Scientific American (scientificamerican.com) and Science News (sciencenews.org) cover a broad range of science topics, and Symmetry Magazine (symmetrymagazine.org) is focused on particle physics.