Week 8
May 19, 2018

Neutrinos, the Universe, and CP Violation

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Why are we here? Neutrinos may be able to provide some insight into this age-old question. The laws of physics tend toward balance, so we would expect the matter and antimatter created after the Big Bang to cancel out and annihilate. Yet, we find a universe filled with structures made of matter. Neutrinos may have helped tip the scales toward matter, and extraordinary experimental efforts are getting underway to study this important question.

This week, we will discuss the universe's matter/antimatter asymmetry and its potential solution with neutrino physics, and experiments designed to study this possibility.

I. The Matter-Antimatter Asymmetry

Observationally, we see a universe filled predominantly with matter, not antimatter. In 1967, Anrdei Sakharov outlined three conditions required for this:

1. Non-conservation of baryon number (number of neutrons/protons is not constant)
2. Broken *C* and *CP* symmetries
3. Reactions occurring out of thermal equilibrium

C and CP: As operations one can do to Standard Model particles, *C* means to flip the charge, *P* means to invert its coordinates, and *CP* means to do both. *CP* changes the charge and handedness (whether the spin is aligned with the direction of motion), effectively turning a particle into an antiparticle. If a given reaction and the *CP*-ized version happen at equal rates, then *CP* symmetry is said to be *conserved*. If not, it is *violated*. Whether neutrino oscillations are *CP*-violating is an open question.

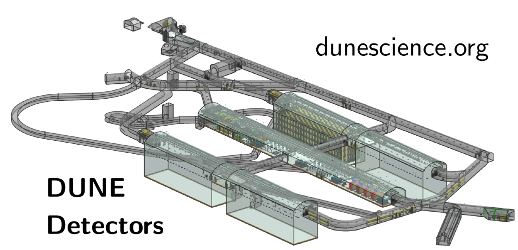
Heavy Majorana Neutrinos: A "Majorana neutrino" refers to a scenario where the neutrino is its own antiparticle (Lecture 6). Part of the theoretical allure of Majorana neutrinos is the so-called Seesaw Mechanism, where neutrinos come in two kinds, one very light and one very heavy. The masses balance out, and this provides an explanation for the unusually small neutrino masses. The heavy ones are too heavy to produce in particle accelerators, but would be created in abundance in the early universe. If *CP* is violated, they could decay at different rates to matter and antimatter, creating an imbalance.

The Baryon Asymmetry: The final step is to convert the lepton imbalance (produced by these decays) into an imbalance in the baryons that make up matter, like protons and neutrons. The current Standard Model already allows for an exotic "sphaleron process," which could accomplish this conversion — it allows the number of leptons and baryons to change, but preserves the difference between these two numbers.

II. Long-Baseline Neutrino Oscillations

The Standard Model permits CP violation in neutrino oscillations through a parameter called δ_{CP}, but whether Nature chooses to exercise this possibility is an open question. If it does, a non-zero δ_{CP} will lead to subtle differences in the flavor-changing oscillations of neutrinos and antineutrinos. Two major experimental efforts are pursuing this: Hyper-Kamiokande in Japan, and the Deep Underground Neutrino Experiment (DUNE) in the US.

Challenges: Searches for this effect will require unprecedented precision. The impact of the Earth's matter (through which the neutrinos propagate) will be different for neutrinos and antineutrinos, and this must be carefully accounted for. The existence of any sterile neutrinos (Lecture 7) will alter the predictions. Understanding in detail neutrinos' interactions with matter will require significant developments in nuclear physics and new, more sophisticated experimental measurements. In short, it will require a major community-wide effort to make these experiments successful.



DUNE and LBNF: In the US effort to search for neutrino *CP* violation, a beam of neutrinos is sent through the ground from Fermilab in Illinois to the DUNE detectors at the Sanford Underground Research Facility in South Dakota. It is an "international science mega-project" with over 1000 physicists from 32 nations and 175 institutions, among the largest-scale scientific projects ever devised. The experiment, situated deep underground in a former gold mine, consists of four very large Liquid Argon Time Projection Chambers (LArTPCs), each over 20 times the size of the largest one yet built (ICARUS). Using the fine-grained images of neutrino interactions provided by LArTPCs, physicists will study neutrinos and antineutrinos arriving at DUNE for differences that would indicate *CP* violation, and perhaps offer insight into the existence of the universe.