Week 1
March 31, 2018

Little, Neutral, Mysterious: An Introduction to Neutrino Physics

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Neutrinos are subatomic particles that are all around us, yet very difficult to detect. Since they very rarely interact with other matter, observing them requires very sensitive experiments. By studying in detail the properties of neutrinos, we hope to learn deeper truths about the most fundamental building blocks of matter. We can also study the processes that create neutrinos, taking advantage of the fact that the neutrinos arrive from their sources largely unaltered by interactions. In this way, neutrinos can help us understand the interiors of stars, the history and evolution of the universe, and even monitor for nuclear tests on Earth.

This week, we will cover the key discoveries through which we came to know these particles, and how they fit into our broader understanding of particle physics.

I. Discovery

Trouble with Beta Decay, 1927: James Chadwick's experiments with so-called beta radiation (where an atomic nucleus emits an electron) were producing strange results: the electrons came out with too little energy, as if it had vanished. It had long been understood that energy is conserved, changing form but never disappearing.

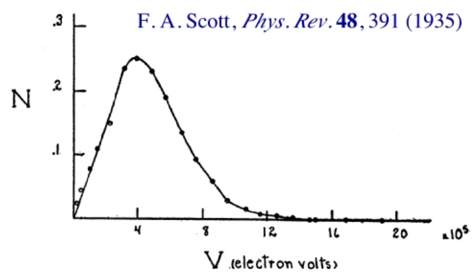


FIG. 5. Energy distribution curve of the beta-rays.

Pauli's Proposal, 1930: Wolfgang Pauli suggests a new, very light, electrically neutral particle could also be produced in beta decays, carrying off some energy unseen.

Fermi's Theory, 1934: Enrico Fermi develops a new theory of beta decay, where a neutron (n) converts into a proton (p) while emitting an electron (e) and Pauli's invisible "neutrino" (ν), which better agrees with the experiments:

$$n \rightarrow p + e^{-} + \nu$$

Hans Bethe and Rudolf Peierls use this theory to calculate the chance of observing a neutrino interacting with matter, and conclude there is no hope.

Project Poltergeist, 1956: Fred Reines and Clyde Cowan devise an experiment using a huge number of neutrinos to increase the chance of seeing an interaction. Initially planning to deploy a detector near a nuclear bomb test, they instead set up next to a nuclear reactor. In 1956, they reported the first successful detection of the "undetectable" neutrino. Fred Reines is awarded the 1995 Nobel Prize in physics.

II. The Plot Thickens

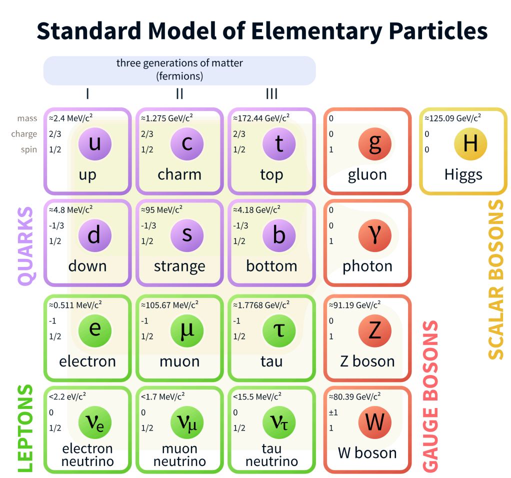
Neutrinos and Antineutrinos, 1955: Raymond Davis, Jr. performs an experiment to test whether the neutrinos from nuclear reactors interact with electrons, or only positrons (the electron's antiparticle) as seen in Cowan & Reines' experiments. With no interactions detected, we conclude there is a distinct neutrino (which interacts with electrons) and *anti*-neutrino (which interacts with positrons). Now we have two of these light, electrically neutral particles!

Muon Neutrinos, 1962: Two new particles are revealed by studies of cosmic rays in the 1930s and 1940s, the muon μ (which is like a very heavy electron) and the pion π, which also undergo decays where energy goes missing. The hypothesis is that the neutrino is responsible, and there is a question of whether it is the same type, or if there are different neutrinos that interact with electrons and muons. In 1962, Leon Lederman, Melvin Schwartz, and Jack Steinberger conduct an experimental test using a particle accelerator, and demonstrate that there are indeed two distinct neutrinos (and antineutrinos), bringing our total to four.

Tau Neutrinos, 2000: The discovery of the tau particle τ in 1975 (which is like an even heavier electron) raises the question: Does this get its own neutrino, too? The DONUT experiment at Fermilab proved in 2000 that it does indeed.

III. Neutrinos in the Standard Model

The Standard Model is a mathematical description of all known elementary particles and how they interact. Matter consists of six *quarks* (plus *antiquarks*) — which can combine to form protons, e.g. — and six *leptons* (e, μ, τ, and their neutrinos). They interact by exchanging messenger particles called *bosons*, and these interactions define the fundamental forces in nature (excluding gravity). Today, beta decay is understood to be an interaction through the "weak" force, which takes place via the exchange of a so-called *W* boson within the nucleus.



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