TASS Paper: Neutrinos

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Introduction

Neutrinos are leptons that are produced by the decay of radioactive elements. Being electrically neutral and having very little mass even compared to other subatomic particles, they are affected only by gravity and the weak interaction. Since gravity is very weak on the subatomic scale and the weak interaction is quite limited in its range, neutrinos pass through most matter without being obstructed or detected. This property implies that they travel immense distances with practically no interference and thus that they can be traced back to their origins, some of which are believed to be mysterious phenomena such as supernovae. Although the very property also implies that detecting them is extremely difficult and requires massive instruments, detecting their origins is likely to help with the research of such phenomena so is surely in our interest.

Hypothesis and Confirmation

In 1930, Wolfgang Pauli originally hypothesized the existence of neutrinos to account for a continuous energy spectrum for the particles detected from beta decay. At the time, beta decay was thought to produce only a proton and an electron, but the electron's energy would not be discrete if this were the case. Pauli showed that the energy spectrum of the electron could be modelled if a small uncharged particle was also created from the decay (Library.ethz.ch, 2015). In 1950's, a pair of experimentalists, Cowan and Reines, set out to detect the expected neutrinos from the core of nuclear reactors. They measured the interaction of an electron neutrino with a proton by detecting the resulting gamma rays and neutron (Hyperphysics.phy-astr.gsu.edu, 2015). The Cowan-Reines experiment provided the first confirmation that neutrinos were more than just a mathematical object. For their work, the pair of physicists earned a Nobel Prize in 1995.

Neutral Leptons

Neutrinos fall under a category of particles called leptons. Leptons are a group of elementary particles that, together with quarks and bosons, make up the standard model. Leptons are fermions (spin:$\frac{1}{2}$particles) that are grouped together because they do not interact with the strong nuclear force like quarks do.

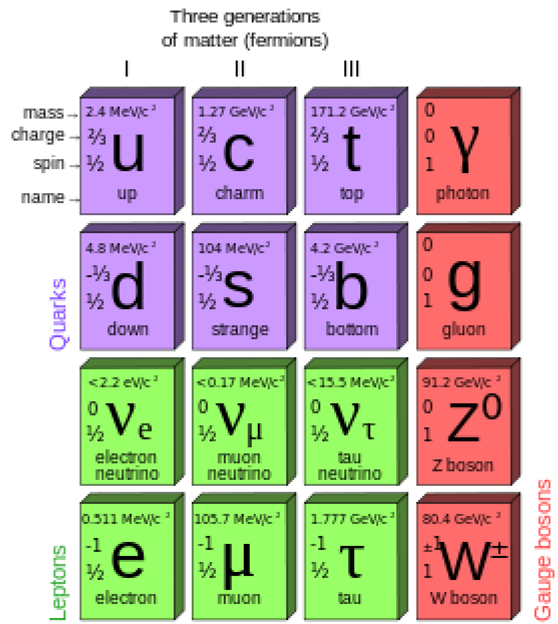


Image from: phys.org

This group is further divided into charged leptons and neutral leptons (Hyperphysics.phy-astr.gsu.edu, 2015). The charged leptons are the electron, muon, and tau. The neutral leptons are their respective neutrinos.

Since they are leptons, each neutrino is given its own lepton number specific to its respective charged lepton. e.g. the electron neutrino has an electron lepton number of +1, but muon lepton number of 0; a muon anti-neutrino has a muon lepton number of -1, but a tau lepton number of 0. Every single reaction must conserve lepton number which is why charged leptons and neutrinos often come in pairs.

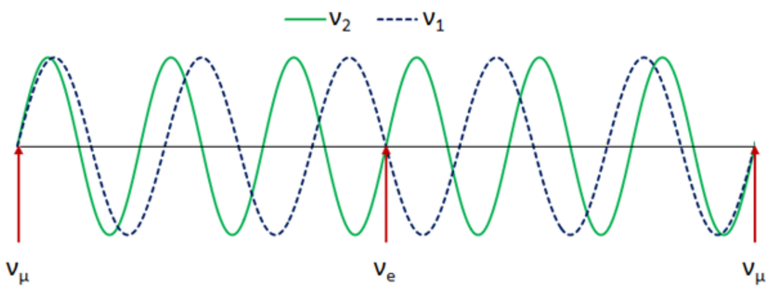
Classification

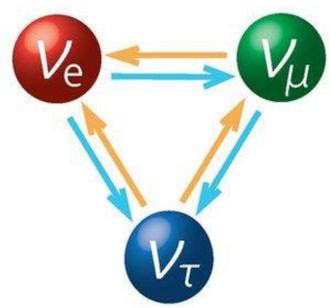
Neutrinos can be classified in two different ways: weak-type and mass-type. Weak-type names, such as electron neutrinos or muon neutrinos, are given when W-bosons decay. This decay produces a charged lepton/anti-neutrino or anti-charged lepton/neutrino pair. For example, when a W-boson decays, it may produce a positron and the associated electron neutrino. Mass-type neutrinos are given the numbers 1, 2, or 3 based off of increasing order of mass. They are the building blocks of weak-type neutrinos. Each weak-type neutrino has a different average composition of neutrino-1, 2, and 3, which leads to neutrino oscillations (Of Particular Significance, 2011).

Neutrino Oscillations

When scientists were first trying to detect neutrinos from the sun, they only detected a third of the expected number of electron neutrinos. Eventually, scientists at SNO and Super-Kamiokande discovered that neutrinos were changing flavors mid-flight from the sun to the

Earth (Hyperphysics.phy-astr.gsu.edu, 2015). This project is discussed in further detail in the *Neutrino Detection* section. This led to the notion of neutrino mass which is explained by mass-type classification. Since the neutrinos are made up of smaller neutrinos with different masses, their parts move at slightly different speeds. Because of this, as they travel, the "parts" become separated ever so slightly and the composition changes. For strange quantum mechanical reasons, the neutrino becomes a superposition of the three different weak-type neutrinos (electron, muon, tau) and can change form completely (Of Particular Significance, 2011). In fact, the probability of a neutrino being discovered as an electron, muon, or tau neutrino varies sinusoidally with distance; thus, these changes are called oscillations because they happen regularly. Below on the left is a visual describing the sinusoidal behavior governing oscillations given that there are two smaller neutrinos. These two sinusoidal functions can collapse to muon or electron neutrino depending on the time at which the neutrino is detected. This type of behavior can be extrapolated to three smaller neutrinos and three sinusoidal functions, which explain neutrino oscillations as we see them in the real world.





Images from: www.lppp.lancs.ac.uk

Once the neutrinos are detected on Earth, the superposition must collapse into one of the three weak-type neutrinos so detectors will view them as either electron neutrino, muon neutrino, or tau neutrino but nothing else. On the way to Earth, neutrinos from the Sun have sufficient time to change flavor, which is why the electron neutrinos are equally likely to become muon or tau neutrinos on Earth.

Fundamental Forces

As mentioned, neutrinos are uncharged leptons. Since neutrinos are uncharged fundamental particles and leptons, they neither experience electromagnetic interactions nor strong nuclear interactions. Because they ignore these two forces, they can easily pass through most objects. As a result they are extremely difficult to capture. However, they do interact with the other two fundamental forces: gravity and the weak force (Physics.rutgers.edu, 2015).

Gravity: In the creation of the standard model, it was originally accepted that neutrinos were massless and therefore did not interact with other particles through gravity. However, in 1998, at the Super-Kamiokande detector in Japan, a group of scientists discovered neutrinos oscillating in flavor, providing experimental evidence towards massive neutrinos (Nobelprize.org, 2015). Although this was very exciting and led to interesting discussions of neutrino oscillations, the mass of a neutrino is too small to be significantly affected by gravity.

Weak Interaction: The weak-interaction is responsible for most of the neutrino-related activities. For example, beta-decay (a result of the weak-force) produces neutrinos and charged leptons.

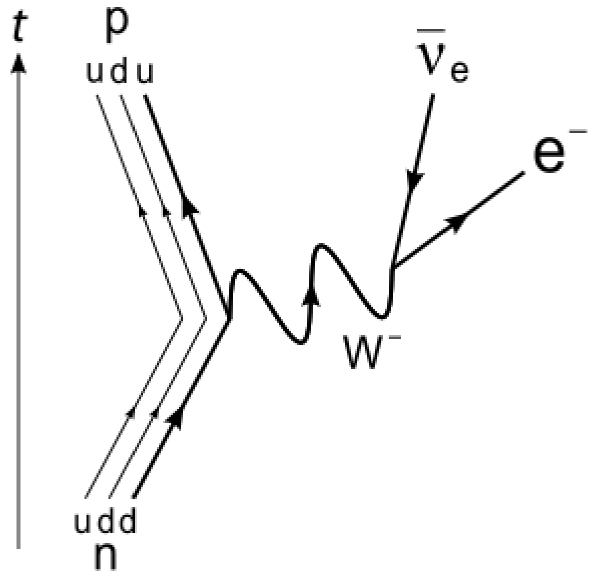


Image from: newworldencyclopedia.org

Displayed in the Feynman diagram above, a neutron decays into a proton, electron, and electron antineutrino through the weak interaction mediated by the W- bosons.

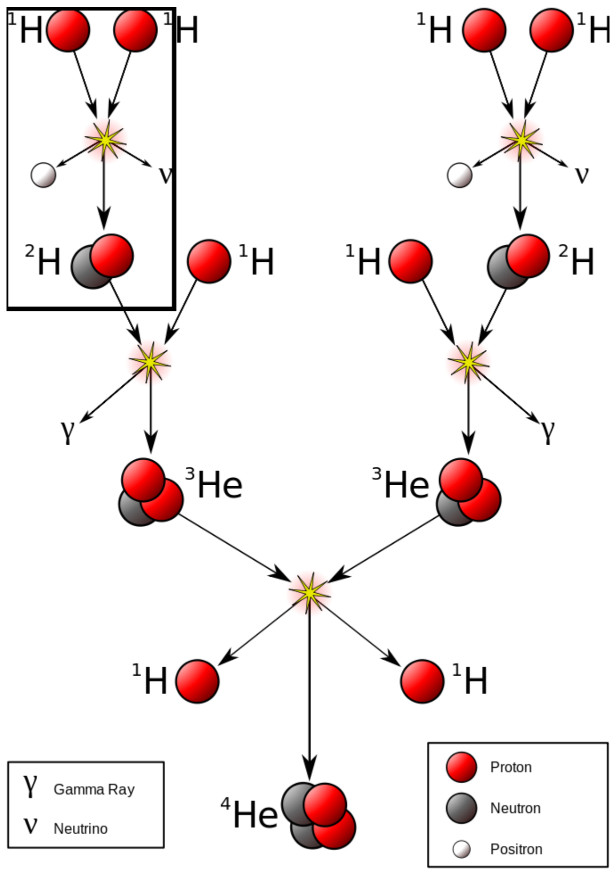
Sources of Neutrinos

Neutrinos, although hard to detect, are abundant almost everywhere. In fact, about 10^14 neutrinos pass through the human body every second. Given their abundance, there are numerous processes by which they are produced, some of which will be mentioned in the following sections.

Solar Neutrinos

Stars are a common source of neutrinos. In stars, the process of fussion converts hydrogen to helium using a proton-proton chain reaction. In such a reaction, protons are converted into neutrons in order to complete the intermediate process of creating deuterium. As mentioned before, beta-decay produces electron antineutrinos through the transformation of neutrons into protons. However, in this case, the opposite reaction (positron emission) occurs. A positron is emitted along with an electron neutrino and energy. Written out, the equation for the reaction is:

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + e^{+} + \nu_e + 0.42\ \text{MeV}$$



Images from: odec.ca

A diagram of the overall process of converting hydrogen into helium is shown above, with the intermediate reaction enclosed in the black box on the top left. Given the frequency of fusion reactions within the cores of young and small stars, it is easy to imagine that neutrinos are produced at a rapid pace. Unlike other particles, neutrinos can easily escape the sun even when they are produced in the core due to their unreactive nature. In fact, the flux of solar neutrinos at the Earth's surface is on the order of 10^{11} $cm^{-2}s^{-1}$ (Sns.ias.edu, 2015). The number of these electron neutrinos are about a third of the amount predicted, but this is explained in the *Neutrino Oscillations* section.

Particle Accelerators

Neutrinos may also be produced from particle accelerators, which collide particles at relativistic speeds. In particular, this occurs when hadrons such as protons collide with each other. Below is a diagram of the entire process.

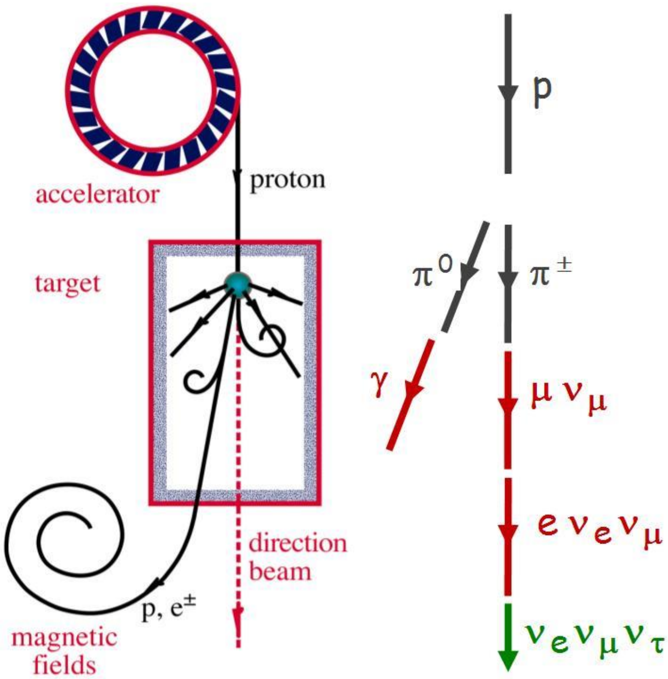


Image from: astro.wisc.edu

When protons collide, they produce particles known as pions, which are mesons that are composed of a quark-antiquark pair. These pions can be charged or uncharged. The neutral pions decay into photons while the charged pions decay to form a muon and muon neutrino. The muon then turns into an electron, muon neutrino, and electron neutrino (astro.wisc.edu). Depending on the neutrino oscillations that occur, the resultant neutrinos can change flavors to form tau neutrinos as well (these oscillations are represented by the final arrow).

Decay of Unstable Particles

One of the most obvious sources of antineutrinos would be nuclear reactors that depend on beta decay for energy. The decay of certain nuclei to form more positively charged and stable nuclei can result in the emission of electrons and antineutrinos. Examples of this production are the decay chains of U-238, Th-232, and K-40. These decay processes occur within the Earth and the resultant antineutrinos are called geoneutrinos. Geoneutrinos provide more information to scientists about the Earth's interior.

Certain interactions between the atoms in the Earth's upper atmosphere and cosmic rays can also result in unstable particles. These unstable particles can also decay, resulting in the production of neutrinos.

Supernovae are also known to form neutrinos. Sometimes when a star collapses, the densities become high enough that protons and electrons are crunched together to form neutrons and electron neutrinos. The thermal energy of the neutron core can also be dissipated through the release of neutrino-antineutrino pairs of all flavors.

Finally, it is thought that neutrinos have been left over from the Big Bang. Some believe that neutrinos also explain the existence of dark matter and the difficulty of detecting it (see *Dark Matter* section).

Neutrino Detection

There are many different ways to detect neutrinos, but neutrinos have miniscule volume and mass, and as a result difficult to detect. They can travel through space without interfering with magnetic fields or matter, which is why they are also difficult to find their origin. As a result, most neutrino detectors are massive in order to detect as many neutrinos as possible. Neutrinos can interact in two different ways: through neutral current or charged current. In neutral current interactions, the neutrino doesn't effectively change, but instead transfers energy. In charged current interactions, a neutrino changes into an electron, muon, or tau, and the detector will often detect the lepton. (Neutrino, n.d.)

The charged current interactions generally give more information, because electrons and muons are easy to detect, and they also give information about the flavor of the neutrino.

Scintillators

The neutrino was discovered through a scintillator detector in the Cowan-Reines neutrino experiment. Scintillators produce light when a particle passes through the material. Scintillators are often used with photomultiplier tubes, which absorb the scintillator's light and re-emit these in electrons through the photoelectric effect. This is useful because the electrons yield an electrical pulse which can give information about the original particle.

Radiochemical Methods

Radiochemical methods of neutrino detection often seek to have a low energy threshold in order to detect low energy neutrinos. This is particularly useful for solar neutrinos. Most radiochemical neutrino detection experiments use a target element for the neutrino to react with. Once the element decays into the daughter isotope, the daughter isotope is extracted, and the radioactive decay is counted/calculated to determine the number of neutrinos.

In a chlorine neutrino detector, the neutrino reacts with the chlorine and converts it into argon. A tank of carbon tetrachloride and helium gas is released into the chamber in order to take out the argon. The argon is removed by cooling the helium gas. (All, n.d.)

The gallium to germanium transformation, known as the Alsace-Lorraine technique, has a lower threshold of 0.233 MeV. The neutrino reacts with gallium-71 and changes it to germanium-71, an unstable isotope. $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$. The detection of neutrinos occurs through measuring the amount of germanium radioactive decay. Although gallium has a lower detection threshold, is an expensive material. A few notable experiments involve SAGE and GALLEX/GNO which used 50 and 30 tons of gallium. The GALLEX experiment, a collaboration between many different European scientists, was one of the first neutrino experiments to detect nuclear fusion's initial reaction. The low threshold of the gallium to germanium made the neutrinos detectable.

Radiochemical experiments only give information on the number of neutrinos. No information about energy levels or direction is yielded. (Neutrino, n.d.)

Cherenkov Detectors

When charged particles travel faster than the speed of light in the medium, they create a phenomenon called Cherenkov radiation. Electromagnetic radiation is thus emitted due to an optical shockwave, creating a blue glow. A Cherenkov detector contains a large amount of water or ice (essentially clear material) that is surrounded by photomultiplier tubes. If a neutrino produces a charged lepton, Cherenkov light is created, which affects the photomultiplier tubes in a ring like fashion. Cherenkov detectors can often determine the direction, energy, and flavor of the neutrino.

Some prominent examples of Cherenkov neutrino detectors today are IceCube and the Super-Kamiokande. IceCube is located in the South Pole and uses one cubic kilometer of ice. There are Digital Optical Modules (DOMs), which contain photomultiplier tubes and minicomputers that send data back to the surface. The DOMS are connected by cable and go deep into the ice. (All, n.d.)

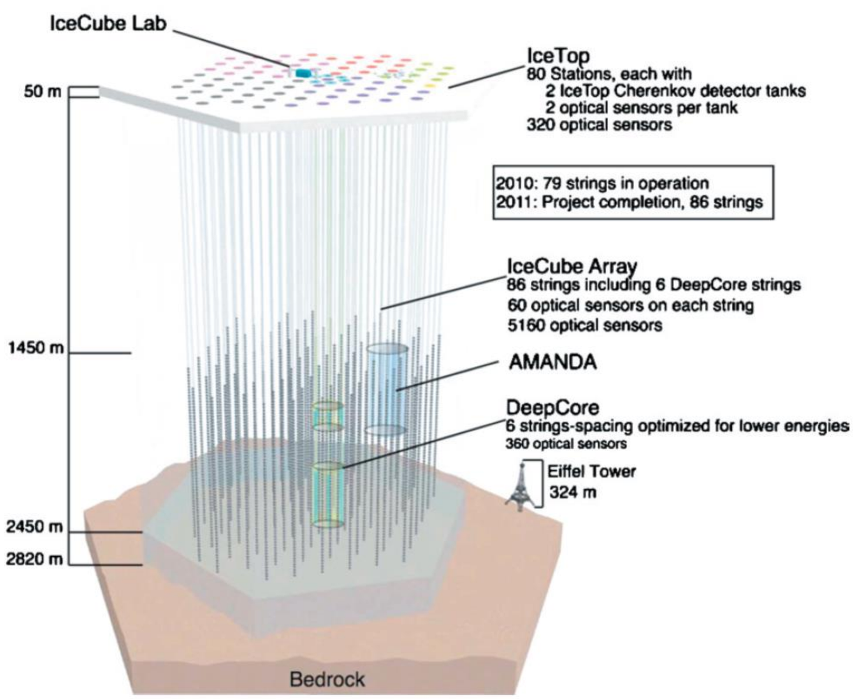


Image from: en.wikipedia.org

Astronomy with a Neutrino Telescope and Abyss environmental RESearch project

(ANTARES) is a neutrino detector which is the counterpart to IceCube. It is 2.5 kilometers underwater in the Mediterranean Sea. It observes cosmic neutrino fluxes from the Southern Hemisphere, while IceCube observes neutrinos from the Northern Hemisphere. Instead of using ice, ANTARES uses water, which is an advantage because light scatters less in water than in ice.

Super-Kamiokande, or Super-K, uses 50,000 tons of water and 11,000 photomultiplier tubes. It is a famous neutrino detector located in Japan one kilometer below ground level. Super-Kamiokande has a 39.3 meter cylindrical steel tank with photomultiplier tubes along the walls of the cylinder. The photomultiplier tubes detect the Cherenkov light. This detection can be used to calculate the charged particle's energy and direction. (Detector, n.d.)

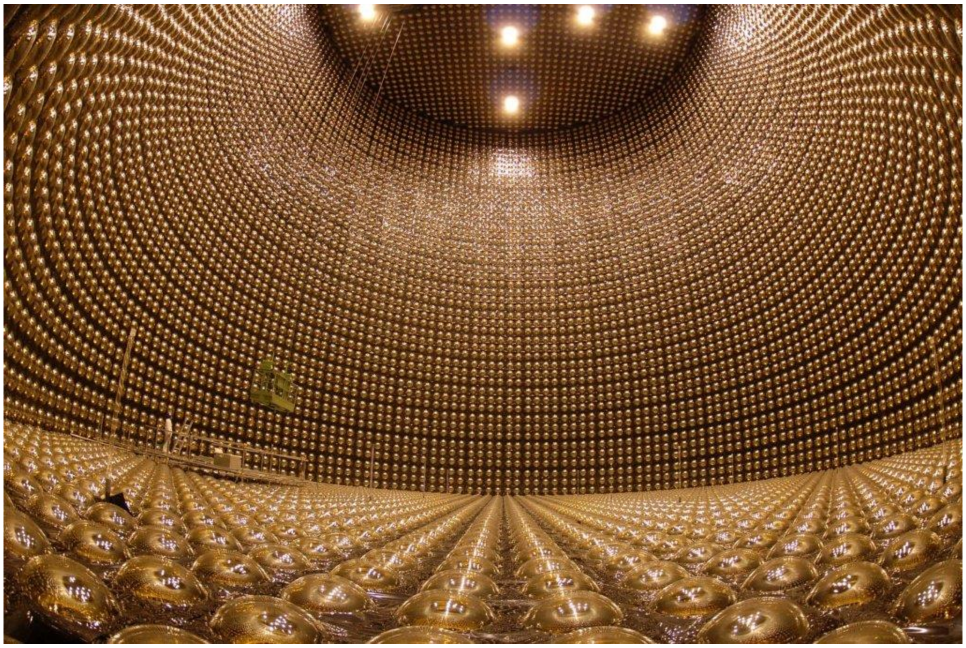


Image from: www.technology.org

Tracking Calorimeters

Tracking calorimeters track the path of charged leptons that are created during neutrino charged current interactions. Tracking calorimeters can only detect high energy neutrinos because the higher energy neutrinos travel further through the detector, which means that the path is easier to reconstruct. For example, when a muon is produced, a long and distinguishable track is created. The tracking calorimeters can use the length and curvature of the track to determine the energy and charge of the neutrino. (Neutrino, n.d.)

Dark Matter

One of the biggest mysteries of science lies in the unseen dark matter. Dark matter has never been directly observed, as it does not interact with electromagnetic radiation. However, there has been evidence to suggest that dark matter does exist. In fact, it is estimated that 85% of the matter in the universe is dark matter. In space, we observe that light is often subject to gravitational lensing (bending light due to a gravitational force), but there have been many instances where the actual lensing is greater than expected. Fritz Zwicky was one of the first to discover this in 1933, when he calculated the mass of galaxies to be much larger than expected. Zwicky made the guess that there must be some non-visible mass adding to the galaxy, this being dark matter.

Hot dark matter (HDM) is dark matter moving at relativistic speeds. It has been hypothesized that this hot dark matter may make up clouds of hot gas. One theory is that hot dark matter is composed of neutrinos, since it is weakly interactive. HDM theory is limited and questionable due to the speeds at which neutrinos move. If dark matter moved at relativistic speeds, it would diffuse throughout the universe. The would not be enough clumping of dark matter that would explain phenomena like the formation of galaxies and observed density fluctuations. Another theory is cold dark matter (CDM) which is slow moving dark matter instead. This would allow for possible clumping and fluctuations that are observed in the universe.

Although the above theories are valid and can explain certain properties of dark matter, neutrinos are not a good candidate for dark matter. It has been recently discovered that the mass of all of the neutrinos in the universe is nowhere near the mass of dark matter needed to explain the effects of dark matter we see today. As of now, the leading candidate for dark matter is the weakly interacting massive particle (WIMP). Currently, resources are being devoted to detect WIMP's. Describing such efforts is out of the scope of this paper.

Overview Future Projects and Goals Concerning Neutrinos

Over the past few decades, many discoveries have been crucial to our understanding of neutrinos. For instance, the fact that we know that neutrinos change their state implies that they has mass. Neutrinos sources and methods of detection have been identified and theories their interactions have been proposed. However, in order for more information to be obtained, empirical data needs to be collected concerning neutrinos. For this reason, the major goal moving forward is neutrino detection.

One future experiment involving neutrinos is the Accelerator Neutrino Neutron Interaction Experiment (ANNIE), a project originated at Fermilab. This project involves the use of a Cherenkov detector that looks at phenomena like proton decay. The goal of this experiment is to understand the nature of neutron-producing processes associated with neutrino interactions with water nuclei. Neutrinos are produced through proton decay in a particle accelerator. These neutrinos are then allowed to interact with water. The neutrons produced through these interactions are then captured using gadolinium-loaded water and analyzed to find out their final state. This will ultimately help scientists determine whether the state abundance in the neutrons produced depends on the momentum transfer that occurs during this experiment.

Another experiment from Fermilab is the Main Injector Neutrino Oscillation Search

(MINOS). This experiment is dedicated to investigating the neutrino oscillations discovered by the Super-K experiment. Neutrinos travel from Chicago to Minnesota, a 735 km journey. There are steel-scintillators on either side to compare the neutrino beam composition. The actual values compared are out of the scope of this paper.

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