Neutrinos
A First Year Vacation Essay

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At the subatomic level, our world is made up of different particles. There is one type of particle however passing by with almost no attention. A neutrino has a tiny mass and carries no electrical charge [1]. Therefore, it doesn't feel the electromagnetic force, that dominates at atomic scales, and will pass through most matter with no effect. This creates an almost undetectable particle, despite the fact trillions pass through the Earth every second [1].

1 Pauli's solution

During the early 1900's, particle physics and radiation were recent discoveries and being thoroughly investigated. The three types of radioactivity had been discovered: alpha particles, beta particles and gamma rays. Emitted alpha particle and gamma ray energies were seen to occur at discrete values. Conversely, the energy of emitted beta particles (electrons) were observed as following a continuous spectrum, varying between zero and a maximum value [2]. This discovery seemed to violate the fundamental law of energy conservation and open up a gap in the understanding of nature's building blocks.

Wolfgang Pauli proposed the idea of a new particle, by letter to a physics meeting, as a bold[1] solution to the problem in 1930. Pauli named his theoretical particle the neutron. This new particle solved the energy problem, as only the combination of electron and neutron energies had a constant value. The lack of a charge and mass meant confirmation of the new particle seemed extremely remote; Pauli even apologised for predicting a particle that he thought impossible to detect [3].

Figure 1: Wolfgang Pauli, the theoretical physicist behind the neutrino [9]

1 The concept of particle physics is well established now but in 1930 only two particles had been discovered, protons and electrons.

Two years later, an electrically neutral particle was discovered. The new particle was given the name neutron, yet it wasn't Pauli's "neutron". The neutron was discovered with a mass that was far from negligible. The theory behind beta decay was finally formulated in 1933 by Enrico Fermi. As well as incorporating the neutron, Pauli's theoretical particle, now dubbed the neutrino[2], was a crucial piece of the formula. Fermi's work remains a crucial part of particle physics today and introduced the weak interaction to the list of fundamental forces. [2]

2 Discovery of the neutrino

Pauli would wait around 20 years until he finally saw his prediction confirmed. Frederik Reines and Clyde L. Cowan Jr. designed an experiment to detect neutrinos. The basis of the experiment was the large neutrino flux from nuclear reactors (of the order 10^{13} per second per cm^2). Beta decay and neutron decay in the reactor produce anti neutrinos. They will then interact with protons as follows,

$$\bar{\nu}_e + p \rightarrow n + e^+$$

producing a neutron and positron. The emitted positron will quickly collide with an electron, annihilate and produce two gamma rays. The positron can therefore be detected by two gamma rays, of the correct energy, travelling in opposite directions.

Detecting a positron alone isn't sufficient evidence for neutrinos, the emitted neutron must also be detected. Cadmium chloride, a strong neutron absorber, was added to the detector's liquid tank. When cadmium absorbs a neutron it excites and subsequently de-excites as below,

$$n + {}^{108}Cd \rightarrow {}^{109}Cd + \gamma$$

emitting a gamma ray. Detecting this extra gamma ray soon enough after the first two provides evidence of a neutron, consequently proving the existence of neutrinos. Cowan and Reines detected about 3 neutrino events per hour. In 1956 they published their results; the proof of neutrino existence. [4]

3 Theoretical refinements

Although neutrinos had been discovered there were still some important properties that had not yet been identified. At the time of the neutrino being theorised, the electron was the only lepton discovered, although the particle category of lepton had not yet been proposed. In 1936, the muon was discovered [5]. Along with the muon, an associated neutrino was discovered and Pauli's neutrino was once again renamed, to the electron neutrino. The last generation of lepton, the tau, was discovered in 1975. The associated tau neutrino was eventually detected in 2000 [3]. This completed the set of all three types (flavours) of neutrino. It has also been discovered that the neutrinos can switch between their flavours and this switching could help explain the imbalance of matter and antimatter in the early universe [1].

Pauli's original solution assumes that the neutrino is massless. However, the theory behind the aforementioed flavour switching required neutrinos to have some mass. In 1998, the Super-Kamiokande experiment discovered that neutrinos had a small mass, with the different flavours having varying masses [6]. This provided clues for the answer to the question of where mass comes from and the unification of nature's forces and particles.

2 A natural name for the Italian Fermi, utilising the suffix -ino, literally translating as little neutron.

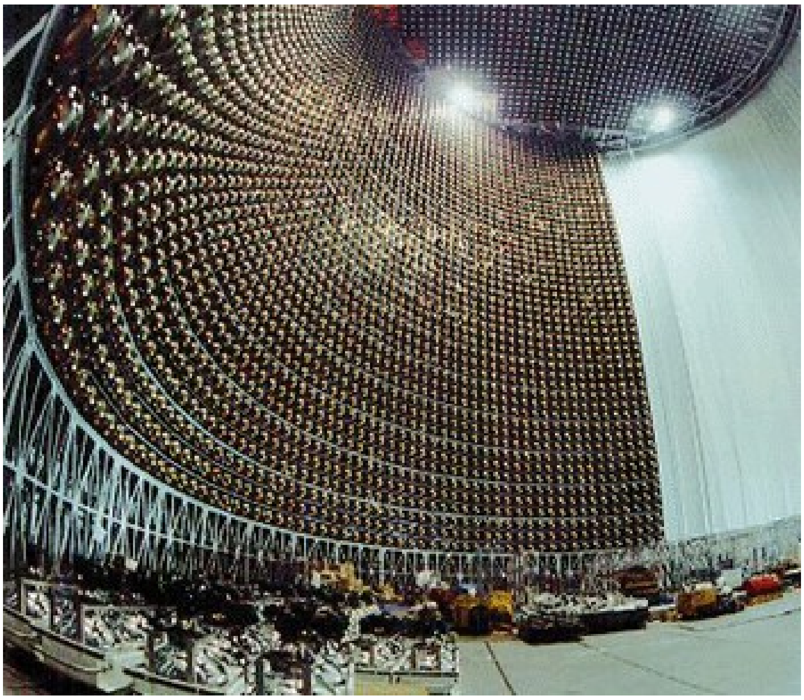

Figure 2: The Super-Kamiokande experiment [10]

4 Neutrino applications

A ghostly particle that is almost impossible to detect may not seem to offer any useful benefits for society but some scientists are working on practical applications for neutrinos. There is one obvious use of neutrinos that harks back to their discovery. Detection of neutrinos could help to locate hidden nuclear reactors, due to the increased neutrino flux in the proximity of a reactor. This would assist in monitoring of rogue states and ensuring nuclear treaties are obeyed. However, the major problem would be detecting these fluctuations from a distance [7]. In the Cowan and Reines experiment the detector was placed 11m from the reactor as well as being 12m underground, to shield it from cosmic rays [4]. Significant improvements in detector sensitivity would be required before this could be deployed in the field.

The most interesting use of neutrinos is high-speed communication [7]. Beams of neutrinos could be sent, at close to light speeds, straight through the earth instead of around the earth, as in conventional communication methods. This would allow extremely fast communication, especially useful for applications such as financial trading. Communication with neutrino beams would also be a great asset to submariners. Current communication is impossible at large depths of seawater and submarines have to risk detection by surfacing or floating an antenna to the surface. Of course, weakly interacting neutrinos would have no problem penetrating any depth of seawater. In fact, the feasibility of communication has been demonstrated already by scientists at Fermilab. They encoded the word 'neutrino' into binary and then transmitted this signal using the NuMI neutrino beam, where 1 is a group of neutrinos and 0 is an absence of neutrinos. This signal was then successfully decoded by the MINERvA detector. [8]

However, the problem of detecting the neutrinos still remains a large barrier to overcome before this technology will be incorporated into real world projects. For this feat an intense source of neutrinos is required, as to produce large groups of neutrinos, ensuring that enough can be detected to recognise a 1. A large, technologically advanced detector is also required to ensure that the neutrinos are detected correctly. The MINERvA detector weighs several tonnes. These factors ensure that neutrino communication is a technology for the future rather than the present. [8]

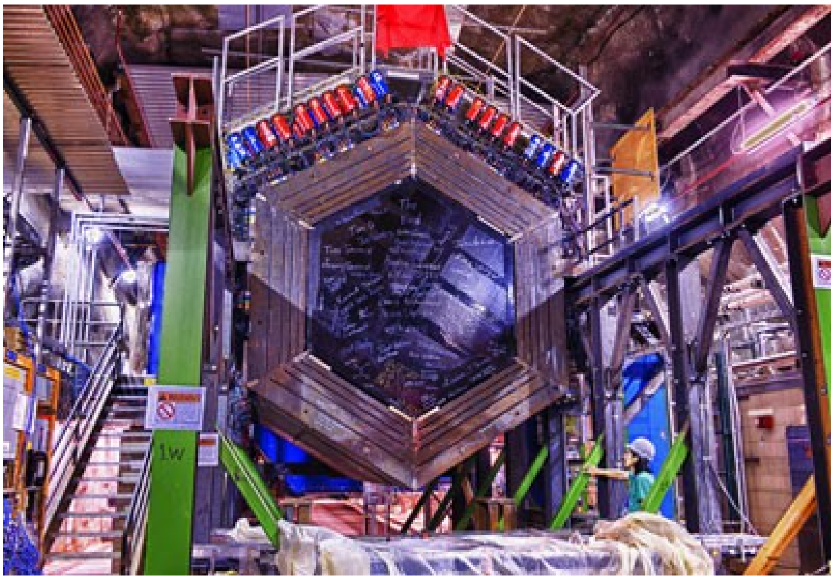
Figure 3: The MINERvA detector at Fermilab [11]

The boldest suggestion for neutrino use is that they could be a method of communication with extra terrestrial beings, owing to the incredible range they could travel. There is currently no equipment to beam neutrinos into space and whether the aliens would be able to decode our message is a different question entirely. [7]

5 Conclusion

The neutrino started as an extreme hypothetical solution to a problem threatening the validity of the standard model and ended the decade as an essential part of that model, which is still the accepted basis of particle physics. They still remain as the most elusive particles. In spite of this, neutrinos are now an important field of study that could hold the key behind unveiling secrets of not only our sun, the origins of our universe and further intricacies of the standard model. Someday in the future, neutrinos may even be used for practical applications, such as communication. Usually in the shadow of other particles, neutrinos may come to the forefront for future physics breakthroughs.

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[10] **Figure 2 –** Super-Kmaiokande experiment, Image source: http://physicsworld.com

[11] **Figure 3 –** MINERvA detector, Image source: http://physicsworld.com

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