Thesis Title
Second Line if Necessary

by

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Abstract

This is my abstract.

Acknowledgments

Blah blah blah.

Statement of Originality

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Chapter 1

Introduction

The cosmic sky has entranced humans for as far as recorded history can trace. As technology evolved, so too did the observation of the universe around us; from the naked eye to primitive telescopes, and eventually to present day space telescopes, like the Hubble Space Telescope and the upcoming James Web Space Telescope **(NEED TO CITE THESE)**. These growing technological leaps have also resulted in the exploration of the incredibly small and eventually resulted in the discovery of the neutrino [14]. It was perhaps inevitable that these two seemingly separate areas of physics would eventually meet.

1.1 Neutrinos

The neutrino is a fundemental particle first proposed by Wolfgang Pauli [3], and then later discovered in 1956 using the byproducts of β^- decay [14]. As research continued into the elusive neutrino, another flavour of neutrino was discovered in 1962 called the muon neutrino (ν_μ) [5] and eventually the final flavour of the tau neutrino (ν_τ) [11].

1.1.1 Oscillations

Alongside the discovery of the neutrino and their flavours, another problem arose in the field of neutrino physics: the solar neutrino problem [12]. During the 1960's, an experiment was proposed by Bahcall and Davis to measure the solar neutrino flux, referred to as the Homestake experiment [6, 1]. This was a tank of ^{37}Cl, built underground to avoid cosmic backgrounds, and used the simple reaction[6, 1]

$$\nu_e +^{37} \mathrm{Cl} \rightarrow e^- +^{37} \mathrm{Ar} \tag{1.1}$$

to measure the expected solar neutrino flux from the sun.

Solar neutrinos originate from nuclear processes that occur in the sun, such as the PP chain, or the CNO cycle, and can be detected in experiments on Earth [9]. Depending on the energy and process in producing the neutrino, we can expect to detect particlar flavours of neutrinos in experiments like the Homestake experiment. In particular, using the predicted distribution of the internal electron density of the Sun, and a spectrum of the produced electron flavours, one could predict the expected flux of solar neutrinos [9]. In particular, one could predict the influx of electron neutrinos, as was exactly done for the Homestake experiment. It was found that the measured flux was consistently around 30% the theoretical amount [6, 1, 9], and hence was coined the solar neutrino problem.

Neutrino detectors continued to be constructed to research and understand these fundemental particles, such as Super-Kamiokande [16], the collaboration of Kamiokande [10] and the IMB [4] experiments. Another class of solar neutrino detectors were those that used the Gallium chain

$$\nu_e +^{71}\mathrm{Ga} \to e^- +^{71}\mathrm{Ge}\,, \tag{1.2}$$

such as GALLEX [15]. Regardless, the same issue persisted as there continued to be a distinct dissonance between the theoretical expectations of solar neutrinos and the observed experimental results. That was, until the Sudbury Neutrino Observatory (SNO) made a distinct change in their approach to solar neutrino detection compared to predecessors by using heavy water [2]. This allowed for the following interactions [2],

$$\nu_e + d \to p + p + e^- \tag{1.3}$$

$$\nu_l + d \to p + n + \nu_l \tag{1.4}$$

where we have the Charged Current (CC) interaction in equation 1.3 and the Neutral Current (NC) interaction in equation 1.4. This meant that all flavours of neutrinos could be detected, and using it to detect solar neutrinos showed the theoretical flux originally predicted [2].

This result had an astounding implication; the neutrinos were changing on their journey from the Sun [2]. In the Standard Model, all the neutrino flavours have masses that are identically zero, and this would mean that there is no possible way for the neutrinos to somehow change flavour on their journey to the detectors [9]. Clearly there was a change in flavour, and thus the Standard Model must be incorrect about the masses of the neutrinos.

The classic demonstrative method to see this is to consider the mixing of two neutrino flavours (like ν_μ and ν_e) [9]. In analogy to quark flavour mixing [7], we know the mixing of the flavours occurs in the transformation from the mass to the flavour basis. In particular, for two mass and flavour states one can find [9],

$$P(\nu_e \to \nu_\mu, ct) = \sin^2 2\theta \sin^2\left(\frac{\pi ct}{L}\right) \tag{1.5}$$

where θ is the mixing between the two flavour states, $L = \frac{4\pi E}{\Delta m^2}$ is the vacuum oscillation length, and $\Delta m^2 = m_2^2 - m_1^2$. Here it is easy enough to see that the oscillation probability vanishes if the masses are identical, and this naturally extends into the three flavour case. The vacuum oscillation length, L, is an important and useful quantity as it describes the distance a neutrino must travel before an oscillation is expected [9]. Experiments like the long-baseline neutrino oscillation experiment Tokai-to-Kamioka (T2K) attempt to use this length to probe the mixing angles of the three neutrino flavours.

Similar to the CKM matrix for quark mixing [7], the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [13] gives a relation between the mass and flavour states:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \tag{1.6}$$

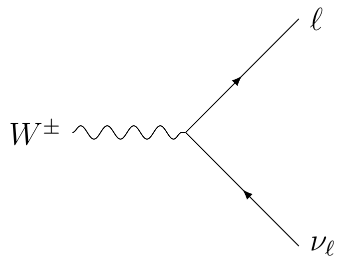

Figure 1.1: The Feynmann diagrams for the vertices that would be included in neutrino interactions using the charged $W^{\pm}$ boson on the left and the neutral Z^0 boson on the right.

and we see that

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{1.7}$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, δ_{CP} is the Charge-Parity violation phase [13], and η_i are the Majorana phases.

1.1.2 Interactions

Neutrinos are neutral and interact only through the Weak interaction. The Weak interaction is a force that is mediated by the $W^{\pm}$ and Z^0 massive bosons, and is the force responsible for decays. The main vertices involved in neutrino interactions are shown in Figure 1.1, where the interacting lepton corresponds with the interacting neutrino flavour.

All interaction involving neutrino production or detection utilize these vertices in some shape or form. We refer to interactions that use the $W^{\pm}$ boson as the Charged Current (CC) interaction [8], and those that use the Z^0 boson as being Neutral

Current (NC) interactions [8].

1.1.3 Production & Sources

Solar: Neutrinos produced from the fusion process inside the sun. Go into detail about the process.

Atmospheric: Cosmic rays that interact with the atmosphere produce neutrinos that then shower the earth. Go into detail about process

Geo: Rare decays in the crust eject neutrinos which can be detected.

Active Galactic Nucleus: Active centres of galaxies that are hubs for producing high energy neutrinos

Supernova: Massive Explosions of dying stars that eject high energy neutrinos.

Chapter 2

Background

2.1 Detection Techniques

Literature dive into different types of neutrino detection techniques.

Cherenkov indirect, ect..?

2.2 Neutrino Telescopes

Generally use Cherenkov radiation as a method of detecting high energy neutrinos from cosmic sources.

2.2.1 IceCube

2.2.2 ANTARES

2.2.3 KM3NET

Chapter 3

The Pacific Ocean Neutrino Explorer

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Results

6.1 Likelihood

Chapter 7

Summary and Conclusions

7.1 Summary

7.2 Future Work

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