

# **Measuring charged current neutrino interactions in the Electromagnetic Calorimeters in near detector of T2K**

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TODO

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# Abstract

To write



## Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

Dominic Brailsford



## Acknowledgements

Something about my supervisor ...





## Preface

This thesis describes my analysis of the  $\nu_\mu$  charged-current cross-section on lead using the T2K near detector electromagnetic calorimeters.



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*“These chickens jackin’ my style. ”*

— Fergie



# Chapter 1

## Introduction

The field of neutrino physics is currently undergoing a revolution. With its tenuous postulation [1] acting as a future omen, the neutrino's mark on history would not become apparent from its discovery [2–4], but rather from a spate of surprising discoveries at the end of the 20th century [5–7] which conclusively proved that the Standard Model, while very successful, was incomplete. This revelation was experimental proof of Maki, Nagakawa and Sakata's extension [8] to Pontecorvo's theory of neutrino oscillation [9] with the inclusion of the Mikheyev-Smirnov-Wolfenstein (MSW) effect [10, 11]. The findings were groundbreaking as the underlying theory requires massive neutrinos, which is in direct contradiction to the Standard Model. The, now, standard theory of neutrino oscillation defines three neutrino flavours and three neutrino masses. However, the map between flavour and mass is not one-to-one, but rather a rotation of mass space onto flavour space. The main consequence of this rotation is that the flavour eigenstates are a superposition of mass eigenstates, namely

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad (1.1)$$

where  $\alpha \in \{e, \mu, \tau\}$ ,  $\nu_i$  are the neutrino mass eigenstates and  $U_{\alpha i}^*$  is an element of a unitary rotation matrix which is known as the PMNS mixing matrix. As there are 3 mass and flavour eigenstates, the PMNS matrix is a  $3 \times 3$  matrix and is often

parameterised as

$$U \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 3 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1.2)$$

where  $c_{ij} \equiv \cos \theta_{ij}$  and  $s_{ij} \equiv \sin \theta_{ij}$ .  $\theta_{ij}$  are known as the mixing angles which parameterise how strong mixings between the flavour and mass eigenstates are and  $\delta$  is a CP violating phase. The most surprising observable feature of this mechanism is the non-zero probability to detect a neutrino of specific flavour which was created at source in a different flavour state. By propagating the mass eigenstates through time, one can arrive at this probability which has the following form

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = |U_{\beta k} e^{-iE_k t} U_{\alpha k}^*|^2, \quad (1.3)$$

where  $\nu(t)$  is the time-dependent neutrino mass eigenstate and  $E_k$  is the energy of the  $\nu_k$ . For an accelerator-based neutrino oscillation experiment, the beam will be  $\nu_\mu$  dominated. So, the  $\nu_\mu$  survival probability,  $P(\nu_\mu \rightarrow \nu_\mu)$ , and  $\nu_e$  appearance probability,  $P(\nu_\mu \rightarrow \nu_e)$ , have are typically of interest and can be approximated in the following forms

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( 1.27 \frac{\Delta m_{23}^2}{(\text{eV}^2)} \frac{L}{(\text{km})} \frac{(\text{GeV})}{E} \right) \quad (1.4)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( 1.27 \frac{\Delta m_{23}^2}{(\text{eV}^2)} \frac{L}{(\text{km})} \frac{(\text{GeV})}{E} \right), \quad (1.5)$$

where  $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ ,  $L$  is the distance the neutrino propagates and  $E$  is the energy of the neutrino.

## 1.1 The state of the field

Data provided from a wide range of experiments show excellent agreement with the theory of neutrino oscillation and with a 3 flavour neutrino picture. Global fits applied to the data provided by these experiments gives best fit values for the oscil-



Parameter	best-fit ( $\pm 1\sigma$ )
$\Delta m_{12}^2$ [ $10^{-5}\text{eV}^2$ ]	$7.54^{+0.26}_{-0.22}$
$ \Delta m^2 $ [ $10^{-3}\text{eV}^2$ ]	$2.43 \pm 0.06$ ( $2.36 \pm 0.06$ )
$\sin^2 \theta_{12}$	$0.308 \pm 0.017$
$\sin^2 \theta_{23}, \Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2 \theta_{23}, \Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$
$\sin^2 \theta_{13}, \Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2 \theta_{13}, \Delta m^2 < 0$	$0.0240^{+0.019}_{-0.022}$
$\sin^2 \theta_{13}, \Delta m^2 < 0$	$0.0240^{+0.019}_{-0.022}$
$\delta/\pi$ ( $2\sigma$ range quoted)	$1.39^{+0.38}_{-0.27}$ ( $1.31^{+0.29}_{-0.33}$ )

**Table 1.1:** The best-fit values of the 3-neutrino oscillation parameters.  $\Delta m^2 \equiv m_3^2 - (m_2^2 - m_1^2)/2$ . The values (values in brackets) correspond to  $m_1 < m_2 < m_3$  ( $m_3 < m_1 < m_2$ ) [12].

lation parameters, which are summarised in table 1.1 [12]. The experiments which provided the data inputs to the global fit generally fall into one of four categories, with each category sensitive to a different subset of the neutrino oscillation parameters.

Solar neutrino experiments detect neutrinos generated in the core of the Sun as a result of nuclear reaction chains. Such experiments are primarily sensitive to  $\theta_{12}$  and  $\Delta m_{12}^2$  which are often referred to as the solar mixing parameters. The final state neutrinos created in the Sun's core are MeV-scale  $\nu_e$  but, because of propagation through the core's surrounding matter, the MSW effect results in a highly pure state of  $\nu_2$  at the Sun's surface. As  $\nu_2$  is a mass eigenstate, no oscillation occurs between the surface of the Sun and the Earth. Homestake [13], SAGE [14] and SNO [6] are examples of such experiments.

Reactor neutrino experiments measure  $\bar{\nu}_e$  disappearance provided by inverse  $\beta$  decay in nuclear reactors with an average neutrino energy of 3 MeV. The baseline for oscillations varies between experiments, but a baseline of around 1 km provides excellent sensitivity to  $\theta_{13}$ . Examples of reactor experiments are CHOOZ [15], Double CHOOZ [16], Daya Bay [17] and RENO [18].

Atmospheric neutrino experiments detect neutrinos which are produced from  $\pi$  and  $K$  mesons, created by cosmic rays interactions with the upper atmosphere of the Earth,

decay. The neutrinos produced are a mixture of  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_e$  and  $\bar{\nu}_e$ . Because the cosmic ray flux is fairly uniform, atmospheric neutrino experiments are exposed to neutrinos from all directions, which results in a very wide range of oscillation baselines. The oscillation parameters that such experiments are sensitive to are  $\theta_{23}$  and  $\Delta m_{13}^2$ . Super-Kamiokande [5] is an example of an atmospheric neutrino experiment.

Accelerator neutrino experiments produce beams of high purity  $\nu_\mu$  (or  $\bar{\nu}_\mu$ ) at GeV-scale energy with wide ranging baselines which are generally  $\mathcal{O}(100 \text{ km})$ . The highly man-made nature of such experiments allows almost complete control over  $L/E$  allowing careful tuning of parameter sensitivity. Accelerator neutrino experiments are generally sensitive to  $\theta_{13}$ ,  $\theta_{23}$ ,  $\Delta m_{13}^2$  and  $\delta$ . K2K [19], MINOS [20], T2K [21] and NO $\nu$ A [22] are examples of such experiments.

## 1.2 The future

It should be clear that an immense amount of progress has been made in the field, with remarkable contributions to the picture coming only in the last 20 years. However, there are several key questions which remain unanswered.

By far the most sought after answer is whether CP violation occurs in the lepton sector. The magnitude of CP violation is encapsulated in the CP violating phase  $\delta$  and so it is this parameter which current and future long-baseline experiments are aiming towards. Currently, T2K and NO $\nu$ A can provide the strongest constraints on  $\delta$ . The future long-baseline experiments, Hypker-Kamiokande [23] and DUNE (formerly LBNE) [24] are being designed with a possible measurement of  $\delta$  as a primary goal.

The second question still to be answered is the ordering of the mass eigenstates. Specifically is  $m_3 \gg m_2 > m_1$  (the normal mass hierarchy) or  $m_2 > m_1 \gg m_3$  (the inverted mass hierarchy)? The matter effects introduced by the MSW effect are mass hierarchy dependent. So, for very long-baseline experiments, there is mass hierarchy sensitivity. Currently NO $\nu$ A is set to resolve the mass hierarchy problem. However, both Hyper-Kamiokande (via atmospheric measurements) and DUNE have measurement of the hierarchy as a primary goal.

Oscillation experiments only have the capability to measure the square of the mass

splitting differences. This means that all oscillation experiments have no sensitivity to the absolute neutrino mass scale. This means an entirely different type of neutrino experiment is required. Neutrinos are one of the final states associated with  $\beta$  decay and the mass of the neutrino should appear as a cut off in the  $\beta$  spectrum. The visibility of the cut-off entirely depends on the mass scale. So, the KATRIN experiment [25] will attempt to utilise the  $\beta$  decay feature, with a neutrino mass sensitivity of 0.2 eV.

It is not currently known whether neutrinos are their own anti-particle, otherwise known as Majorana neutrinos. A number of experiments are currently investigating this, all by searching for neutrinoless double  $\beta$  decay. A large neutrinoless double  $\beta$  decay experiment effort is ongoing, including EXO [26], SuperNEMO [27] and SNO+ [28].

While the long-baseline neutrino oscillation programme has been very successful, the short-baseline programme has seen several anomalies [29]. The LSND experiment found evidence of  $\bar{\nu}_e$  in a  $\bar{\nu}_\mu$  beam, which was consistent with neutrino oscillations [30]. However the data suggested a mass-squared splitting of 0.2-10 eV<sup>2</sup>. This large splitting is consistent with a fourth species of neutrino. Because the data suggesting 3 flavours of weakly-interacting neutrino is strong, this postulated fourth species must be sterile. More recently, the Mini-BooNE experiment observed a similar short baseline excess of  $\bar{\nu}_e$  in a  $\bar{\nu}_\mu$  beam with a mass-squared splitting of 0.01-1.0 eV<sup>2</sup> [31], further suggesting the sterile hypothesis. New experiments are now under development which aim to test this hypothesis, which include MicroBooNE [32] and SBND (formally LAr1-ND) [33].



## Chapter 2

# Neutrino interactions with atomic nuclei

The neutrino is a strictly weakly interacting particle. This has difficult implications for any experiment aiming to study neutrinos as particle detectors generally rely on the electromagnetic force. In fact, the only proven method of neutrino detection is to utilise a high mass target in which the neutrinos can interact with. Generally speaking, charged particles are produced by this interaction which can be detected by the usual means. The collected information from these charged final states can then be used to infer information about the incident neutrino. All neutrino experiments rely on this method and so any attempted measurements (e.g.  $\delta$ ) rely on our understanding on neutrino interactions with atomic nuclei. Our understanding of such processes is encompassed in the models we use to simulate the interactions.

### 2.1 Neutrino interactions at the GeV-scale

For neutrino energies below  $\sim 2$  GeV, the neutrino-hadron interactions are largely Quasi-Elastic (QE) [INSERT ZELLER REFERENCE]. In such an interaction, the incident neutrino scatters off the nucleon as if it were a single particle, rather than with one of the nucleon's constituent partons. As the neutrino is weakly interacting, there are two channels available: the Charge Current (CC) interaction in which a W boson is exchanged and the Neutral Current (NC) interaction in which a Z boson is exchanged. In the case of a CCQE interaction, the neutrino is converted into its charged lepton equivalent and the target neutron converted to a proton. In the specific case of an

incident  $\nu_\mu$ , the interaction takes the following form

$$\nu_\mu n \rightarrow \mu^- p \quad (2.1)$$

For NCQE interactions, the incident neutrino remains after the interaction has occurred and no nucleon conversion takes place. Because of this fact, the target nucleon in a NCQE interaction need not be a neutron. So, for  $\nu_\mu$  NCQE interactions, there are two channels available

$$\nu_\mu n \rightarrow \nu_\mu n, \quad (2.2)$$

$$\nu_\mu p \rightarrow \nu_\mu p \quad (2.3)$$







# Bibliography

- [1] W. Pauli, Open letter to the Gauverein meeting in Tübingen, 1930.
- [2] C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire, *Science* **124**, 103 (1956).
- [3] G. Danby *et al.*, *Phys. Rev. Lett.* **9**, 36 (1962).
- [4] K. Kodama *et al.*, *Physics Letters B* **504**, 218 (2001).
- [5] Y. Fukuda *et al.*, *Phys. Rev. Lett.* **81**, 1562 (1998).
- [6] Q. R. Ahmad *et al.*, *Phys. Rev. Lett.* **87**, 071301 (2001).
- [7] K. Eguchi *et al.*, *Phys. Rev. Lett.* **90**, 021802 (2003).
- [8] Z. Maki, M. Nakagawa, and S. Sakata, *Progress of Theoretical Physics* **28**, 870 (1962).
- [9] B. Pontecorvo, *JETP Lett.* **33**, 549 (1957).
- [10] L. Wolfenstein, *Phys. Rev. D* **17**, 2369 (1978).
- [11] S. Mikheev and A. Y. Smirnov, *Sov.J.Nucl.Phys.* **42**, 913 (1985).
- [12] Particle Data Group, K. Olive *et al.*, *Chin.Phys.* **C38**, 090001 (2014).
- [13] B. T. Cleveland *et al.*, *The Astrophysical Journal* **496**, 505 (1998).
- [14] J. N. Abdurashitov *et al.*, *Phys. Rev. C* **80**, 015807 (2009).
- [15] M. Apollonio *et al.*, *The European Physical Journal C - Particles and Fields* **27**, 331 (2003).
- [16] Y. Abe *et al.*, *Physics Letters B* **723**, 66 (2013).
- [17] F. P. An *et al.*, *Phys. Rev. Lett.* **108**, 171803 (2012).

- [18] J. K. Ahn *et al.*, Phys. Rev. Lett. **108**, 191802 (2012).
- [19] M. H. Ahn *et al.*, Phys. Rev. D **74**, 072003 (2006).
- [20] D. G. Michael *et al.*, Phys. Rev. Lett. **97**, 191801 (2006).
- [21] (T2K Collaboration), K. Abe *et al.*, Phys. Rev. Lett. **112**, 061802 (2014).
- [22] NOvA, D. Ayres *et al.*, (2004), hep-ex/0503053.
- [23] Hyper-Kamiokande Working Group, K. Abe *et al.*, (2014), 1412.4673.
- [24] LBNE, C. Adams *et al.*, (2013), 1307.7335.
- [25] C. Weinheimer, Progress in Particle and Nuclear Physics **48**, 141 (2002).
- [26] M. Auger *et al.*, Phys. Rev. Lett. **109**, 032505 (2012).
- [27] A. Barabash and the SuperNemo Collaboration, Journal of Physics: Conference Series **375**, 042012 (2012).
- [28] SNO+, M. C. Chen, (2008), 0810.3694.
- [29] J. Fan and P. Langacker, Journal of High Energy Physics **2012** (2012).
- [30] LSND, A. Aguilar-Arevalo *et al.*, Phys.Rev. **D64**, 112007 (2001), hep-ex/0104049.
- [31] MiniBooNE, A. Aguilar-Arevalo *et al.*, Phys.Rev.Lett. **110**, 161801 (2013), 1207.4809.
- [32] C. M. Ignarra, ArXiv e-prints (2011), 1110.1604.
- [33] LArTPC, C. Adams *et al.*, (2013), 1309.7987.

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