IMPLICATIONS OF THE JHF-KAMIOKA NEUTRINO OSCILLATION EXPERIMENT

R. R. VOLKAS
School of Physics
Research Centre for High Energy Physics
The University of Melbourne
Victoria 3010 Australia

After quickly reviewing the existing evidence for neutrino oscillations, I summarise the goals and capabilities of the JHF-Kamioka long baseline superbeam experiment. Theoretical implications of what this experiment could potentially discover are then discussed.

1. Introduction

Neutrino oscillations arise when there is a mismatch between the neutrino states produced in weak interaction processes (“weak eigenstates”) and the Hamiltonian eigenstates (“mass eigenstates”). The three known weak eigenstates are the familiar $\nu_e, \mu, \tau$ flavours. If neutrinos have non-degenerate masses, then the neutrino mixing matrix $U$ defined through

$$\nu_{\alpha} = \sum_{i=1,2,3} U_{\alpha i} \nu_i,$$  

(1)

gives rise to non-trivial effects including oscillations. In this equation, $\alpha = e, \mu, \tau$ and $\nu_i$ is the state of definite mass $m_i$. The complex numbers $U_{\alpha i}$ constitute the mixing matrix. Additional light neutral fermions usually known as “sterile neutrinos $\nu_s$” may also exist. If so, then Eq. (1) must be generalised in the obvious way. For the three flavour case, the mixing matrix can be parameterised in terms of three physical mixing angles and some CP violating phases (the precise number of which depends on whether the neutrino masses are of Dirac or Majorana form). If light sterile neutrinos exist, then there are additional mass and mixing parameters.

Oscillations arise due to relative phases between the $\nu_i$ induced by time evolution. Considering two flavours only for simplicity, the mixing pattern

$$\nu_{\alpha} = \cos \theta \nu_1 + \sin \theta \nu_2,$$

$$\nu_{\beta} = -\sin \theta \nu_1 + \cos \theta \nu_2$$  

(2)
implies the transition probability

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}, \]  

(3)

after the state which begins life as a \( \nu_\alpha \) propagates through a distance \( L \). The mixing angle sets the magnitude of the oscillations, and \( \Delta m^2 / E \) determines the oscillation length, where \( E \) is energy and \( \Delta m^2 = m_2^2 - m_1^2 \). It is straightforward to generalise this formula to multflavour cases. Nature chooses the \( \Delta m^2 \) and \( \theta \) parameters, while experimentalists have some control over \( E \) and \( L \). This partial freedom is utilised in the design of the JHF-Kamioka experiment that is the focus of this talk.  

Extremely convincing evidence for the disappearance of muon-neutrinos has been provided by SuperKamiokande and other experiments through observations of atmospheric neutrinos. 2 The upper atmosphere acts as a beam dump for cosmic rays, with \( \nu_e,\mu \) and their antiparticles produced as byproducts. The zenith angle pattern of the contained \( \mu \)-like events reveals a clear deficit of up-going relative to down-going progenitor \( \nu_\mu \)'s, while the \( e \)-like events show no anomalous angular dependence. These data are consistent with \( \nu_\mu \rightarrow \nu_\tau \) oscillation, where \( x \neq e \). Doing a detailed fit assuming either \( \nu_\mu \rightarrow \nu_\tau \) or \( \nu_\mu \rightarrow \nu_s \) produces allowed regions which can be roughly described as \( \sin^2 2\theta \gtrsim 0.85 \) and \( 10^{-3} \gtrsim \Delta m^2 / eV^2 \gtrsim 8 \times 10^{-3} \). Other aspects of the atmospheric neutrino data show a preference for \( \nu_\mu \rightarrow \nu_\tau \) over \( \nu_\mu \rightarrow \nu_s \), the statistical significance of which has been under dispute. 4 JHF-Kamioka and the other long baseline experiments have been designed to reproduce the atmospheric neutrino effect in a terrestrial context where the neutrino source as well as the detector are under experimental control. Indeed, the pioneering K2K long baseline experiment has already reported a \( \nu_\mu \) deficit roughly consistent with the atmospheric effect. 3

All solar neutrino experiments have revealed a deficit by a factor of \( 2 \to 3 \) in the \( \nu_e \) flux relative to standard solar model expectations. 5,6 The new data from SNO provide strong evidence that solar \( \nu_e \)'s oscillate into other active flavours en route to the Earth. 6 The spectrally undistorted nature of the \( ^8B \) neutrino flux, when combined with the strong deficit factor, limits the oscillation parameter space to \( \sin^2 2\theta \sim 0.7 \). It is interesting that both the solar and atmospheric mixing angles are large, quite unlike their quark analogues. The solar \( \Delta m^2 \) is constrained to be at least an order of magnitude smaller than its atmospheric counterpart.

The LSND experiment has provided fully terrestrial evidence for \( \nu_\mu \rightarrow \nu_e \) oscillations, with a small mixing angle and a relatively large \( \Delta m^2 \) of about 1 eV\(^2\). 7 This as yet uncorroborated but fascinating result will soon be checked by MiniBooNE. Following a common practice that I do not condone, I will
sometimes “bury my head in the sand” during this talk by assuming that the LSND anomaly is not due to oscillations. If all three anomalies are due to oscillations, then the incommensurate $\Delta m^2$ values imply that at least one additional flavour, necessarily sterile, must exist.

So, in summary, with head in the sand: the atmospheric and solar anomalies imply that two out of the three mixing angles in $U$ are large (and at least the atmospheric one can even be maximal). These two angles are usually denoted $\theta_{12}$ and $\theta_{23}$. The third mixing angle, $\theta_{13}$, is constrained to be small through neutrino disappearance bounds, and we have no constraints on the CP violating phase $\delta$. Coming clean with LSND forces us to also confront the possible existence of $\nu_s$ flavours and additional parameters.

In light of the above, the scientific goals of JHF-Kamioka are well motivated. The main ones are:

- precision measurement of the atmospheric neutrino oscillation parameters;
- discrimination between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$;
- search for $\nu_\mu \rightarrow \nu_e$;
- search for CP violation in the lepton sector.

The first three of these goals can happen during phase 1 of the project, while the fourth will have to wait for phase 2.

2. The capabilities of JHF-Kamioka

The JHF-Kamioka project envisages a high flux, narrow band $\nu_\mu$ or $\bar{\nu}_\mu$ beam with peak energy in the few-GeV regime being directed from the Japan Hadron Facility to the Kamioka laboratory located about 295 km away. Contamination due to $\nu_e$ will be reduced by having a relatively short decay volume for the muons produced by pion decay. Various types of beams will be possible, depending on momentum selection of the parent pions and the choice of beam direction (off axis or well-directed). The peak energy will be tunable and the beam spectrum well known, enhancing sensitivity to oscillation effects. The far detector in phase 1 will be the existing Super-Kamiokande 50 kt water Čerenkov detector. Phase 2 envisages an increase in beam power and the construction of a 1 Mt water Čerenkov “Hyper-Kamiokande” as a second far detector. Plots of typical beam spectra including flavour composition are available from the collaboration’s Letter of Intent. 1

Note that the additional phases of the Majorana case do not affect oscillation probabilities.
2.1. **Precision measurement of “atmospheric” oscillation parameters.**

Figure 1 depicts the expected precision for measurements of the oscillation parameters relevant for solving the atmospheric neutrino problem.\(^{b}\) The sensitivity depends on the type of beam used and on the actual values of the parameters. Precision measurements down to about 0.01 in \(\sin^2 2\theta\) and few \(\times 10^{-5}\) in \(\Delta m^2/\text{eV}^2\) are envisaged.

![Figure 1. Sensitivity of the atmospheric oscillation parameters for the case \(\sin^2 2\theta = 0.9\) (dashed line) compared to the case \(\sin^2 2\theta = 1\) (solid line), as a function of the true \(\Delta m^2\). The beam choice has been optimised for a true \(\Delta m^2\) of \(3 \times 10^{-3}\) eV\(^2\) in this illustration. See the LOI for further details.](image)

2.2. **Discrimination of \(\nu_\mu \rightarrow \nu_\tau\) and \(\nu_\mu \rightarrow \nu_s\).**

This relies on the observation of neutral current (NC) induced single pion production in the far detector. The \(\pi^0\) events will be the most useful, because of the relatively clean nature of the \(\gamma\gamma\) decay mode. Figure 2 compares the expected rates for the \(\nu_\tau\) and \(\nu_s\) cases, with a clear suppression evident in the latter for \(\Delta m^2 > 1 - 2 \times 10^{-3}\) eV\(^2\).

![Figure 2.](image)

2.3. **Search for \(\nu_\mu \rightarrow \nu_e\) and CP violation.**

MiniBooNE will confirm or disconfirm the \(\overline{\nu}_\mu \rightarrow \overline{\nu}_e\) interpretation of the LSND anomaly. Assuming disconfirmation, the existence of such an oscillation mode

\(^{b}\)These and all subsequent figures come from the LOI.\(^1\)
again becomes an open question. In the three neutrino picture, the $\nu_\mu \rightarrow \nu_e$ transition probability is proportional to the small parameter $\sin^2 2\theta_{13}$. Figure 3 displays the expected sensitivity for $\nu_e$ appearance in JHF-Kamioka, with the region already excluded by CHOOZ and Palo Verde superimposed. The angle $\theta_{13}$ must be sufficiently large for CP violation effects to be observable in oscillation experiments.

3. Theoretical implications

I will now briefly discuss possible theoretical ramifications of the type of information JHF-Kamioka could provide.

3.1. $\nu_s$ or no $\nu_s$

Particles, arranged into multiplets, form the raw ingredients for spontaneously broken gauge theories such as the standard model. A very basic activity in theoretical particle physics is to understand how the standard model Lagrangian might emerge in an effective sense out of a more fundamental theory. To pursue these studies, we really need to know what the fundamental low-mass degrees of freedom are. The possible existence of light sterile neutrinos is therefore a very interesting loose end from the theoretical perspective as well as the phenomenological.

One of the famous issues arising from the standard model is the flavour problem: can the values of the quark and lepton mass and mixing angle parameters, and the family structure, be understood through a standard model extension? Neutrinos could well provide very important clues, because of the
contrast they provide to the other fermions. Neutrinos are unusually light, and the large vacuum mixing angles required look qualitatively very different to the small Kobayashi-Maskawa mixing angles of the quark sector. But before we can properly reflect on how they might help resolve (or deepen!) the flavour puzzle, we need to know exactly how many neutrino-like degrees of freedom exist. The discovery of sterile neutrinos would be roughly as important as the discoveries of $c$, $\tau$ and $b$ in the 1970’s.

In the near future, we await results from MiniBooNE. While this experiment is very important for sterile neutrino research, it can only provide indirect evidence for their existence. Irrespective of what is found by MiniBooNE, the ability of experiments such as JHF-Kamioka to perform neutral current measurements and thus potentially discover sterile neutrinos directly is very welcome. SNO has of course recently provided strong constraints on the sterile neutrino component of the solar neutrino flux.

A famous theoretical problem posed by light sterile neutrinos is: Why are they light? The most sterile of possible sterile neutrino candidates are fermions with the gauge quantum numbers of the vacuum. Such states obviously have gauge invariant Majorana mass terms, and there is no a priori reason to expect them to be of similar magnitude to the active neutrino masses. In fact they can

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3}
\caption{Expected reach of the $\nu_\mu \to \nu_e$ oscillation search via $\nu_e$ appearance after 5 years of running. The three contours correspond to different beam choices.}
\end{figure}
be arbitrarily large. Mirror symmetry has been proposed to explain both why apparently sterile states exist and why they are light.\textsuperscript{11,12} If the mirror matter idea is correct, then sterile neutrinos would be just the tip of iceberg, because mirror partners would be expected for all known particles. The ramifications of this would obviously be enormous.

3.2. \textit{Precision measurements of the atmospheric parameters.}

As well as performing a degree of freedom audit, we of course also need as much information as possible on the precise values of mass and mixing angle parameters. We can dream that one day a predictive theory for flavour will emerge, and an important test will be a direct comparison of those predictions with measured neutrino parameters. In the meantime, we should try to at least correlate aspects of the neutrino flavour problem with new theoretical principles.

The existence of large neutrino mixing angles is thought provoking. The mirror symmetry idea allows two-flavour active-sterile \textit{maximal} mixing to be understood on the basis of a simple theoretical principle. We had hoped that the solar and atmospheric neutrino problems could be solved in a unified way through the maximal oscillations of $\nu_e$’s and $\nu_\mu$’s into their respective mirror (sterile) partners.\textsuperscript{11} Alas, the SNO results appear to have ruled out the solar neutrino part of this hypothesis (they imply an upper bound on the $\nu_e$–mirror-$\nu_e$ $\Delta m^2$ parameter). As discussed above, it is important for experiments such as JHF-Kamioka to check the claim from Super-Kamiokande that the atmospheric mode is predominantly into $\nu_\tau$.\textsuperscript{13}

But there is also the question of the atmospheric mixing angle: is it maximal or merely large? A precision measurement of $\sin^2 2\theta$ at the 0.01 level has the potential to rule out exact maximal mixing, or point more strongly towards it. This is important theoretically, because exact maximal mixing is a special point in parameter space. The atmospheric neutrino data have always preferred true maximal mixing, though it is possible that the actual value is, say, $\sin^2 2\theta = 0.93$. If so, then JHF-Kamioka should be able to rule out maximal mixing to a high level of statistical significance.

Maximal mixing would point to an underlying new symmetry of nature. If the mode is $\nu_\mu \rightarrow \nu_s$, then mirror symmetry would be the prime candidate. But we should in general endeavour to discover new symmetry principles through neutrino oscillation physics. It is perhaps useful to categorise such attempts according to whether the symmetry is exact (e.g. the Melbourne version of mirror symmetry), spontaneously broken (e.g. broken mirror symmetry, horizontal symmetry) or approximate (e.g. $L_e \pm L_\mu - L_\tau$). There is historical precedent for the first and third possibilities (e.g. colour and electromagnetic gauge invari-
ance, and Gell-Mann–Neeman SU(3), respectively), while the second awaits discovery of the Higgs boson.

3.3. $\nu_\mu \to \nu_e$ search and CP violation.

Let us assume that LSND has not already discovered the anti-particle version of this oscillation mode. Then the connection between $\theta_{13}$ and the existence of CP violation indicates that the former in a sense quantifies the extent to which the neutrino mixing is “truly three-flavour”. This is an important part of the flavour puzzle.

Observing CP violation in the lepton sector would allow comparison with similar effects in the quark sector, with information about the latter on the rise because of the $B$-factory experiments. The neutrino sector already displays a difference from the quark sector through its large mixing angles. How will CP violation compare, and what implications will that have on theories of quark-lepton symmetry?

CP violation is of course important in theories of baryogenesis. While its establishment in neutrino oscillations would have no direct consequence for baryogenesis, it would show that matter-antimatter asymmetry is not confined to strongly interacting particles. Baryogenesis can proceed through the sphaleron reprocessing of a lepton asymmetry created, for example, from out-of-equilibrium and CP violating decays of “heavy neutral leptons”. The latter (hypothetical) species are neutrino-like, but very massive (perhaps they are the heavy gauge singlets needed for the see-saw mechanism). Unfortunately, the CP violating parameters in the heavy neutral fermion sector need not be related to those in the light neutral fermion (i.e. neutrino) sector. While these interconnections are not mandatory, one can hope for relations within specific and predictive standard model extensions. We are a long way from having such a theory, but all the experimental information we can get will help. Switching perspective, plausible theoretical proposals for connecting the neutrino sector parameters to baryogenesis would be welcomed by experimentalists as a spur to their leptonic ambitions. The possible existence of Majorana phases in addition to Dirac phase(s) is an important consideration.

4. Conclusion.

Long baseline superbeam experiments such as JHF-Kamioka promise to supply very important new information about the neutrino sector, from precision measurements of parameters through to possible discovery of sterile neutrinos and/or CP violation. These are of great importance in the quest to understand the flavour problem.
While not discussed fully in this talk, these results will be of great relevance for astrophysics and cosmology as well as for particle physics, especially if light sterile neutrinos are discovered. The discovery of leptonic CP violation would also be (indirectly) important for the baryogenesis puzzle.

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References

1. Y. Itow et al., hep-ex/0106019.
2. Super-Kamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. 82, 1562 (1998); Phys. Lett. B436, 33 (1998); Phys. Lett. B433, 9 (1998); Soudan 2 Collaboration, W. W. Allison et al., Phys. Lett. B449, 137 (1999).
3. K2K Collaboration, S. H. Ahn et al., Phys. Lett. B511, 178 (2001).
4. Super-Kamiokande Collaboration, S. Fukuda et al., Phys. Rev. Lett. 85, 3999 (2000); R. Foot, Phys. Lett. B496, 169 (2000).
5. Homestake Collaboration, B. T. Cleveland et al., Astrophys. J. 496, 505 (1998); Kamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. 77, 1683 (1996); Super-Kamiokande Collaboration, Phys. Rev. Lett. 86, 5651 (2001); Sage Collaboration, J. N. Abdurashitov, et al., Phys. Rev. Lett. 83, 4686 (1999); Gallex Collaboration, W. Hampel et al., Phys. Lett. B447, 127 (1999); GNO Collaboration, M. Altann et al., Phys. Lett. B490, 16 (2000).
6. SNO Collaboration, Q. R. Ahmad et al., nucl-ex/0204008; nucl-ex/0204009; Phys. Rev. Lett. 87, 071301 (2001).
7. LSND Collaboration, C. Athanassapoulos et al., Phys. Rev. Lett. 81, 1774 (1998); Phys. Rev. C58, 2489 (1998).
8. As far as I know, this terminology was proposed by A. de Rujula.
9. CHOOZ Collaboration, M. Apollonio et al., Phys. Lett. B466 415 (1999); Palo Verde Collaboration, F. Boehm et al., Nucl. Phys. Proc. Suppl. 91 91 (2001).
10. For a pedagogical introduction to sterile neutrino theories see R. Volkas, hep-ph/011326, Prog. Part. Nucl. Phys. (in press).
11. R. Foot, H. Lew and R. R. Volkas, Mod. Phys. Lett. A7, 2567 (1992); R. Foot, Mod. Phys. Lett. A9, 169 (1994); R. Foot and R. R. Volkas, Phys. Rev. D52, 6595 (1995).
12. Z. G. Berezhiani and R. N. Mohapatra, Phys. Rev. D52 6607 (1995).
13. R. Foot and R. R. Volkas, hep-ph/0204265.
14. M. Fukugita and T. Yanagida, Phys. Lett. B174, 45 (1986).
15. For reviews on neutrino cosmology see, M. Prakash, J. M. Lattimer, R. F. Sawyer and R. R. Volkas, Ann. Rev. Nucl. Part. Sci. 51, 295 (2001); A. D. Dolgov, hep-
ph/0202122; for recent interesting work on neutrino oscillations and cosmology see A. D. Dolgov et al., hep-ph/0201287; Y. Y. Y. Wong, hep-ph/0203180; K. N. Abazajian, J. F. Beacom and N. F. Bell, astro-ph/0203442.