Future Developments at SuperKamiokande
on Atmospheric Neutrino Oscillations

1 R

The double ratio

$$R = \frac{(\nu_\mu/\nu_e)_{\rm data}}{(\nu_\mu/\nu_e)_{\rm MC}}, \tag{1}$$

which used to be the most important signature of neutrino oscillation, is already systematics limited: $R = 0.63 \pm 0.03 \pm 0.05$ for sub-GeV and $R = 0.65 \pm 0.05 \pm 0.08$ for multi-GeV data. The dominant systematic uncertainties, such as that in the calculated flux ratio, the uncertainty from single-ring multi-ring separation, and the uncertainty in the nuclear cross section, are unlikely to be improved. There will be no dramatic improvements in the measurement.

2 Zenith Angle Dependence

The distortion in the zenith angle dependence is another important signal of neutrino oscillation. This is still statistics limited. For instance, the up/down ratio in the multi-GeV μ-like data is $0.54^{+0.06}_{-0.05} \pm 0.01$ compared to the Monte Carlo expectation $0.98 \pm 0.03 \pm 0.02$. The statistical uncertainty in the MC can obviously be reduced, but the systematic uncertainty in the MC, mainly the effect of 1 km rock above Kamiokande in calculated ν_μ flux and the possible contamination of the cosmic ray background, cannot be improved. Still, overall determination of up/down ratio at 3% level appears feasible after 8 years.

3 Δm^2, $\sin^2 2\theta$

Even with the current data, they can try to combine information from the contained data, which gives the best signal, the zenith-angle distribution of the up-going muon data, and the ratio of stopping to through-going up-going muon data. However, the combined fit probably does not improve Δm^2 determination much, judging from their plot of the allowed regions from each analysis. Especially the up-going muon sample has a history of bad systematics and background issues (recall by-now-defunt IMB exclusion plot). The stopping/through-going ratio is already systematics limited: $0.22 \pm 0.023 \pm 0.014$ (data) compared to 0.39 ± 0.05 (MC), and the sensitivity is limited by the theoretical uncertainty 0.05 in the calculation.

The improvement in the statistics in the contained data would probably result in a better study of the distortion in the zenigh angle dependence. The main problem here is that SuperK does not measure the direction of the neutrino, but rather measures the direction of the lepton, which has a correlation only of order 15–20° even for multi-GeV data. Because the preferred Δm^2 range happened to correspond to the near-horizontal bin in the zenith angle, a small error in the angle result in a large uncertainty in the oscillation length, and hence a large uncertainty in Δm^2. I doubt it can be improved drastically using the contained data sample. On the other hand, $\sin^2\theta$ determination is improved purely by statistics from up-down ratio in multi-GeV μ-like sample.

4 Neutral-current π^0 Production

One known method to distinguish $\nu_\mu \to \nu_\tau$ oscillation from $\nu_\mu \to \nu_s$ case is to look at the rate of NC π^0 production. Their "single π^0" sample is roughly 80% NC, 15% ν_e CC, 5% ν_μ CC, according to John Learned's talk at SUSY 98.[1] Currently, $(\pi^0/e)_{\rm data}/(\pi^0/e)_{\rm MC} = 0.93 \pm 0.07 \pm 0.19$ (preliminary). The dominant systematic uncertainty is coming from our lack of knowledge on the π^0 production cross section from neutrinos. The claim is that the near detector of K2K experiment can measure this cross section and the systematic uncertainty will be reduced to 5%. On the other hand, the expected π^0/e ratio is about 98% for ν_τ case and about $100-(80*(2/3)+5)*(1-0.65) = 80\%$ for ν_s. Total of 5 years running would distinguish two cases at roughly 3 sigma level.

Another method, again using the NC π^0 production is to look at possible zenith angle dependence in π^0 direction after selecting events with high π^0 momentum. The momentum cut is necessary to improve the correlation between neutrino and π^0 directions. The current (535 days) size of their π^0 sample is 210 events. The expected up-down ratio for ν_s case and *perfect*

[1] Actually, the breakdown he gave doesn't sum up to 100%. But the mismatch is only of order 5% and I ignored it.

angular correlation is $1-(0.80*2/3+0.05)*0.55=0.68$. To distinguish it from 1 at 3 sigma level, we need 200 up-going and 200 down-going events, and total is 500 events including the horizontal bin. But the momentum cut probably has an efficiency as low as 1/3 (judging from a plot by Diwan–Goldhaber) and hence 1500 π^0, or 10 years of running, is needed.

5 Inclusive Multi-Ring Analysis

This is what Lawrence Hall and myself proposed. The up/down ratio of the inclusive multi-GeV sample already shows 2.5 σ deviation from 1 according to their preliminary data. The value is consistent with expectation based on $\nu_\mu \to \nu_\mu$ or ν_s oscillation. This would make the case for oscillation much more convincing.

In principle, the combination of multi-GeV and sub-GeV samples would distinguish ν_τ and ν_s because the sub-GeV multi-ring sample has the NC fraction of about 1/3. The true reach is somewhat uncertain because I don't know how good the angular correlation is for sub-GeV multi-ring data. 3 σ differentiation would take at least 5 years, possibly more.

6 NC-like event

The multi-ring sample is dominated by ν_μ CC and hence is sensitive to the ν_μ disappearance but is not ideal for distinguishing ν_τ from ν_s. Kajita was talking to me personally about selecting "NC-like" events; here is what I guessed. In principle, one can try something very similar to NuTeV: defining events with "long tracks" as CC-like, and those without "long tracks" as NC-like. Problems: (1) Water Čerenkov detector does not see tracks. However, they can in principle use the maximum timing difference from hits at the edge of the cone and inside the cone. How well this can be done is unknown. (2) ν_e events produce e which shower, and appear NC-like with this definition. But this may be useful in distinguishing ν_τ from ν_s, if up/down ratio can be studied. If this kind of selection can be done, the sensitivity should be better than the inclusive sample because one can enrich ν_e and NC in the multi-ring samples. The rate of "NC-like" event would probably suffer from systematic uncertainty in the selection criteria.

7 τ appearance

If the oscillation is $\nu_\mu \to \nu_\tau$, they must already have 10–20 τ events. The best hope to see them is in $\tau \to \nu_\tau \rho$ mode in QE production of τ. The rate is down to 1 event per year. Even with 50% efficiency and low background (whose estimate is quite uncertain), the best one can hope is something like: 5 rho's going up and 1 rho going down (background) after 10 years. Not impossible, but obviously hard. See Hall, HM.

8 Conclusion

There will be many more cross checks of the oscillation hypothesis: inclusive multi-ring, statistically improved sample of zenith angle dependence, etc. The "evidence" may be elevated to "observation" in a year or two. Combining different techniques, the distinction between ν_τ and ν_s case is probably possible after 5 years of running. But the result may not be too convincing.

The objective of other experiments had better not be the test of oscillation itself, but rather in precise measurement of parameters or detection of τ appearance.

I haven't summarized the capability of K2K experiment yet.