Translation from Near to Far at K2K

Takashi Kobayashi§

Institute for Particle and Nuclear Studies, KEK, 1-1 Oho, Tsukuba, 305-0801, Japan

Abstract. In the K2K experiments, the expected observations at the far site are estimated by extrapolating the observations at the near site. In the extrapolation, the ratio of the neutrino energy spectrum at far site to that at the near site is used. The detail of the near-to-far extrapolation is described.

K2K is the first long baseline neutrino oscillation experiment [1, 2] to explore the neutrino oscillation found in atmospheric neutrinos [3]. The neutrino beam is produced by the 12-GeV proton synchrotron at KEK and detected by Super-Kamiokande (SK) at 250 km from KEK. The primary purpose of K2K is to look for $\nu_\mu \to \nu_x$ disappearance. Since the disappearance signature is a distortion of the energy spectrum after propagation through a long distance, it is of crucial importance to predict the absolute energy spectrum at the far site as precisely as possible.

In K2K, the absolute flux and spectrum just after production is measured by the near neutrino detector (ND) system located at 300 m from the production target. The neutrino spectrum at the far site is different from the one at the near site even without neutrino oscillations. This originates from the finite length of the decay volume and acceptance difference between ND and SK. The absolute spectrum at SK is calculated from the near spectrum by multiplying by a far to near (F/N) spectrum ratio which is estimated by the beam simulation. The simulation is based on GEANT [4] with a detailed description of the materials and magnetic fields in the target region and decay volume. Primary proton interactions on an aluminum target are modeled with a parameterization of hadron production data [5]. The beam simulation is validated *in-situ* by measurements of pion distributions just after production by a gas-Cherenkov detector (PIMON) as described later. The errors including correlations at neutrino energies E_ν above 1 GeV, where the PIMON is sensitive, are estimated based on the PIMON measurements. The errors on the ratio for E_ν below 1 GeV are estimated based on the uncertainties in the hadron production models.

Downstream of the horn system, before the 200 m long decay volume, PIMON [6] is occasionally put in the beam to measure the kinematics of the pions after their production and subsequent focusing. Cherenkov photons generated by pions in the detector are focused by a pie-shaped spherical mirror to an array of PMTs of 8 mm effective diameter in its focal plane. Measurements are made at seven indices of refraction, controlled by gas pressure, to give additional information on the velocity distribution of the particles. To avoid background from 12 GeV primary protons, the index of refraction is adjusted below the Cherenkov threshold of 12 GeV protons ($1-\beta \approx 2.6 \times 10^{-3}$). As a consequence, analysis is done for pion momentum $p_\pi \geq 2\mathrm{GeV/c}$, giving the ν_μ energy spectral shape above 1 GeV.

§ To whom correspondence should be addressed (takashi.kobayashi@kek.jp)

The pion momentum and angular distribution in the p_π-θ_π plane is estimated by fitting the expected light distributions to the observed ones at the 7 refractive indices. The fitting parameters are the relative pion populations, W_i ($i = 1, 50$), in the p_π-θ_π plane (5 bins in p_π above 2 GeV/c $\times$ 10 bins in θ_π from -50 to 50 mrad). The fitted results for the W_i's are plotted in Fig. 1 (a). The contribution of the j-th p_π-θ_π

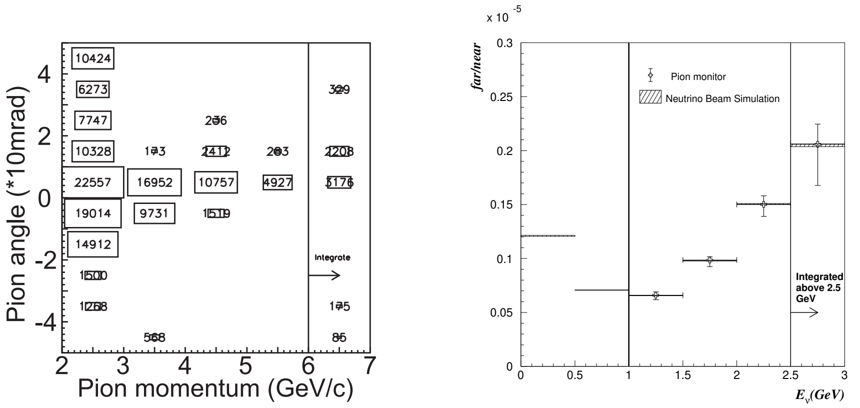

Figure 1. PIMON results. (a) Pion distribution (W_i) in arbitrary unit . (b) Far/near spectrum ratio. Points with error bars are experimental data and boxes are beam simulation.

bin to the i-th bin of neutrino flux at ND(SK), $\phi_{ij}^{ND(SK)}$, is calculated numerically by using the beam simulation, which essentially relies only on decay kinematics and geometry but not on a hadron production model. Then the neutrino spectrum at the FD(SK) is calculated as $\Phi_i^{ND(SK)}(W) = \sum_{j=1}^{50} W_j \cdot \phi_{ij}^{ND(SK)}$ and the F/N ratio as $R_i(W) = \Phi_i^{SK}(W)/\Phi_i^{FD}(W)$, where W represents the 50 W_i. The F/N ratio thus calculated from the PIMON observation and the beam MC prediction are plotted in Fig. 1 (b). The PIMON results agree with the beam MC very well.

Uncertainties on R_i above $E_\nu = 1$ GeV are estimated from the results of PIMON measurements. A 50 $\times$ 50 error matrix M_W for the fitting parameters W_i is given as a result of the fitting. A transformation matrix $U_{ij} = dR_j/dW_i$ is numerically calculated using the beam simulation. Using these two matrices, the error matrix on R_i is calculated as $M_R = U^T \cdot M_W \cdot U$. Contributions to the errors on R_i from the uncertainties which are not incorporated as an error on Cherenkov light distributions are numerically evaluated one by one and added to the matrix.

The estimation of errors on R_i below $E_\nu = 1$ GeV relies on a hadron production model [5]. The parameters in the model and their errors are estimated by fitting the model to the previous hadron production data [5]. There are many more data points above $p_\pi = 2$ GeV/c than below 2 GeV/c. If all the data points are used in the fit, pion production below 2 GeV/c is mostly constrained by the data points above 2 GeV/c through the momentum dependence assumed in the model. In order to minimize the effect of data points in the non-relevant momentum region and model assumption on the momentum dependence, only the data points below 2 GeV/c are used in the fit. The fit parameters are put in the K2K beam simulation and the F/N ratio is calculated. Changes in R_i when the model parameters are varied within their errors are taken as the error of R_i.

The error matrix on R_i for all energy regions, thus estimated, is,

$$\left(\begin{array}{rr|rrrr} 2.6 & -1.6 & 0.0 & 0.0 & 0.0 & 0.0 \\ -1.6 & 4.3 & 0.0 & 0.0 & 0.0 & 0.0 \\ \hline 0.0 & 0.0 & 6.5 & 2.4 & -1.8 & -4.0 \\ 0.0 & 0.0 & 2.4 & 10.4 & 9.5 & 5.0 \\ 0.0 & 0.0 & -1.8 & 9.5 & 11.1 & 7.2 \\ 0.0 & 0.0 & -4.0 & 5.0 & 7.2 & 12.2 \end{array}\right), \tag{1}$$

where the numerical values are $\mathrm{sign}(M_{Rij})\sqrt{|M_{Rij}|}$ in the unit %. The 6 columns or rows correspond to 6 bins in neutrino energy (measured in GeV) of $[0, 0.5]$, $[0.5, 1.0]$, $[1.0, 1.5]$, $[1.5, 2.0]$, $[2.0, 2.5]$, $[2.5, \infty]$. As indicated in the matrix, the F/N ratio below and above $E_\nu = 1$ GeV are treated as non-correlated, since those sub-components of the matrix are derived with independent data and by an independent method.

Finally, the effects of the error on the F/N ratio on the K2K results is briefly mentioned. In the latest K2K analysis [2], the expected total number of events in the absence of oscillations is estimated to be $80.1^{+6.2}_{-5.4}$, while 54 events are observed. The systematic error on the expectation $(^{+7.7\%}_{-6.7\%})$ is dominated by contributions from uncertainties of normalization ($\pm 5\%$) and on the F/N ratio $^{+4.9\%}_{-5.0\%}$. As for the spectral shape analysis, since the number of events used in the analysis, 29 single-ring μ-like events, is still small, the effect of the error on the F/N ratio is negligible compared to the statistical error.

Currently, the significance of the K2K results is mostly determined by the deficit of the total number of events. Therefore, a reduction of the uncertainty in R_i, which is the dominant contribution to the systematic error on the number of events, will enable K2K to probe ν_μ disappearance with much higher sensitivity. For that purpose, the hadron production data was taken with the K2K Al target at K2K proton beam energy in the HARP experiment at CERN this summer [7]. Analysis of the data is currently underway.

In summary, the method of near to far extrapolation in the K2K experiment is described. The F/N spectrum ratio which is estimated by a beam simulation is used. The simulation is validated by *in-situ* measurements of the pion momentum and angular distributions. The error on the ratio is estimated with PIMON data and beam MC. The ratio is one of major sources of systematic errors in the K2K analysis. Analysis of hadron production data taken at the HARP experiment is ongoing and will result in an improved precision on the F/N extrapolation.

[1] S.H. Ahn *et al* (K2K collaboration), Phys. Lett. **B511**, 178 (2001).
[2] M.H. Ahn *et al* (K2K collaboration), hep-ex/0212007, submitted for publication, M. Yoshida, in these proceedings.
[3] Y.Fukuda *et al* , Phys. Rev. Lett. **81**, 1562 (1998), Phys. Rev. Lett. **85**, 3999 (2000) T. Kajita, in these proceedings.
[4] R. Brun *et al* , CERN DD/EE/84-1 (1987).
[5] J.R.Sanford and C.L.Wang, BNL AGS internal reports No.BNL11299 and No.BNL11479 (1967); C.L.Wang, Phys. Rev. Lett. **25**, 1068 (1970); Y.Cho *et al* , Phys. Rev. **D4**, 1967 (1971); J.G.Asbury *et al* , Phys. Rev. **178**, 2086 (1969); G.J.Marmer *et al* , Phys. Rev. **179**, 1294 (1969); G.J.Marmer and D.E.Lundquist, Phys. Rev. **D3**, 1089 (1971); J.V.Allaby *et al* , CERN-TH-70-12 (1970).
[6] T.Maruyama, Ph.D. Thesis, Tohoku University (2000); K2K Beam Monitor Group, in preparation.
[7] http://harp.web.cern.ch/harp/