

## INTRODUCTION TO THREE-NEUTRINO MIXING PARAMETERS LISTINGS

Updated October 2007 by M. Goodman (ANL).

**Introduction and Notation:** With the exception of the LSND anomaly, current accelerator, reactor, solar and atmospheric neutrino data can be described within the framework of a  $3 \times 3$  mixing matrix between the flavor eigenstates  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  and mass eigenstates  $\nu_1$ ,  $\nu_2$  and  $\nu_3$ . (See Eq. (13.32) of the Review “Neutrino Mass, Mixing, and Flavor Change,” by B. Kayser.) Whether or not this is the ultimately correct framework, it is currently widely used to parameterize neutrino mixing data and to plan new experiments.

The mass differences are called  $\Delta m_{21}^2$  and  $\Delta m_{32}^2$  following Eq. (13.30) in the review. In these Listings, we assume that  $\Delta m_{32}^2 \sim \Delta m_{31}^2$ , although in the future, experiments may be precise enough to measure these separately. The angles, as specified in Eq. (13.31) of the review, are labeled  $\theta_{12}$ ,  $\theta_{23}$ , and  $\theta_{13}$ . The  $CP$  violating phase is called  $\delta$ , but that does not yet appear in the Listings. The familiar two-neutrino form for oscillations is given in Eqs. (13.18) and (13.19). Despite the fact that the mixing angles have been measured to be much larger than in the quark sector, the two-neutrino form is often a very good approximation and is used in many situations.

The angles appear in the equations below in many forms. They most often appear as  $\sin^2(2\theta)$ . The Listings currently use this convention.

**Accelerator neutrino experiments:** Ignoring the small  $dmsq$  scale,  $CP$  violation, and matter effects, the equations for the probability of appearance in an accelerator oscillation experiment are:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E) \quad (1)$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(\Delta m_{32}^2 L/4E) \quad (2)$$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(\Delta m_{32}^2 L/4E) \quad (3)$$

$$P(\nu_e \rightarrow \nu_\tau) = \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2(\Delta m_{32}^2 L/4E) . \quad (4)$$

For the case of negligible  $\theta_{13}$ , these probabilities vanish except for  $P(\nu_\mu \rightarrow \nu_\tau)$ , which then takes the familiar two-neutrino form.

New long-baseline experiments are being planned to search for non-zero  $\theta_{13}$  through  $P(\nu_\mu \rightarrow \nu_e)$ . Including the  $CP$  violating terms and low mass scale, the equation for neutrino oscillation in vacuum is:

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) &= P1 + P2 + P3 + P4 \\
 P1 &= \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E) \\
 P2 &= \cos^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{21}^2 L/4E) \\
 P3 &= -/ + J \sin(\delta) \sin(\Delta m_{32}^2 L/4E) \\
 P4 &= J \cos(\delta) \cos(\Delta m_{32}^2 L/4E) \tag{5}
 \end{aligned}$$

where

$$\begin{aligned}
 J &= \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times \\
 &\quad \sin(\Delta m_{32}^2 L/4E) \sin(\Delta m_{21}^2 L/4E) \tag{6}
 \end{aligned}$$

and the sign in P3 is negative for neutrinos and positive for anti-neutrinos. For most new proposed long-baseline accelerator experiments, P2 can safely be neglected, but depending on the values of  $\theta_{13}$  and  $\delta$ , the other three terms could be comparable. Also, depending on the distance and the mass hierarchy, matter effects will need to be included.

**Reactor neutrino experiments:** Nuclear reactors are prolific sources of  $\bar{\nu}_e$  with an energy near 4 MeV. The oscillation probability can be expressed

$$\begin{aligned}
 P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &= 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta m_{21}^2 L/4E) \\
 &\quad - \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E) . \tag{7}
 \end{aligned}$$

For short distances ( $L < 5$  km), it is a good approximation to ignore the second term on the right, and this takes the familiar two-neutrino form with  $\theta_{13}$  and  $\Delta m_{32}^2$ . For long distances and small  $\theta_{13}$ , the second term oscillates rapidly and averages to zero for an experiment with finite energy resolution, leading to the familiar two-neutrino form with  $\theta_{12}$  and  $\Delta m_{21}^2$ .

**Solar and Atmospheric neutrino experiments:** Solar neutrino experiments are sensitive to  $\nu_e$  disappearance and have allowed the measurement of  $\theta_{12}$  and  $\Delta m_{21}^2$ . They are also sensitive to  $\theta_{13}$ . In the discussion after Eq. (13.21), we identify  $\Delta m_{\odot}^2 = \Delta m_{21}^2$  and  $\theta_{\odot} = \theta_{12}$ .

Atmospheric neutrino experiments are primarily sensitive to  $\nu_{\mu}$  disappearance through  $\nu_{\mu} \rightarrow \nu_{\tau}$  oscillations, and have allowed the measurement of  $\theta_{23}$  and  $\Delta m_{32}^2$ . In Eqs. (13.24) and (13.25), we identify  $\Delta m_{atm}^2 = \Delta m_{32}^2$  and  $\theta_{atm} = \theta_{23}$ . Despite the large  $\nu_e$  component of the atmospheric neutrino flux, it is difficult to measure  $\Delta m_{21}^2$  effects. This is because of a cancellation between  $\nu_{\mu} \rightarrow \nu_e$  and  $\nu_e \rightarrow \nu_{\mu}$  together, with the fact that the ratio of  $\nu_{\mu}$  and  $\nu_e$  atmospheric fluxes, which arise from sequential  $\pi$  and  $\mu$  decay, is near 2.