# Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 9

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**Deadline for this sheet**: Thu, 25.06.2020

## Reactor Neutrino Experiments

### 9.1 The KamLAND reactor neutrino experiment *6.5 Points*

The KamLAND ('Kamioka Liquid Scintillator Antineutrino Detector') experiment is a reactor neutrino experiment located in Kamioka in Japan. It started data taking in early 2002, and within about a year reported its first results: `https://arxiv.org/abs/hep-ex/0212021`. Read the paper and answer the following questions.

**a)** What is the connection between the 'solar neutrino problem' and the KamLAND experiment? What mixing angle and mass difference is the KamLAND experiment sensitive to and why?

**b)** Describe the processes that are used to detect neutrino scattering events in the KamLAND experiment. What is the main signature of a neutrino signal event?

**c)** Name three of the event selection criteria (also called cuts) that are employed in the data analysis and describe shortly what kind of non-valid events are removed from the selection by them.

**d)** Name three of the background sources of the KamLAND experiment and explain their origin shortly.

**e)** Figure 3 in the paper displays the distribution of prompt and delayed energies of possible neutrino events. Explain the (most likely) origins of the different event populations.

**f)** What is the conclusion drawn from the results presented in this paper regarding the 'solar neutrino problem'?

### 9.2 The $\theta_{13}$ mixing angle and the neutrino mass hierarchy *3.5 Points*

**a)** Why is the precise determination of $\theta_{13}$ particularly interesting in regard of finding new physics? Name and shortly explain three experimental features of reactor neutrino detectors that are needed in order to be sensitive to the small angle fluctuations of $\theta_{13}$.

**b)** For a precise measurement of $\theta_{13}$, the determination of the neutrino mass hierarchy is of great importance as well. Sketch the two possible hierarchies of the neutrino masses and indicate the mass differences. How can the two hierarchies be distinguished experimentally? What would be another way to determine the mass hierarchy that does not involve neutrino oscillations?

### 9.3 Measurement of oscillation parameters *2 Bonus Points*

In the figure below you can find another experimental result from KamLAND, published in 2008[1]. Here the electron anti-neutrino survival probability is determined by the ratio of measured events vs. expected events assuming no oscillations. The x-axis is given in units of $L_0/E_{\bar{\nu}}$, where $L_0$ is the flux-weighted average distance of the KamLAND experiment to its various reactor sources, and $E_{\bar{\nu}}$ is the measured anti-neutrino energy. The solid line histogram represents the expected event distribution for the best fit oscillation parameters extracted from the data.

**a)** Use the equation for the electron anti-neutrino survival probability (equation (2) from the previous exercise sheet) to extract the value of $\Delta m_{12}^2$ from the best fit to the data shown in the plot.
(*Hint: Use the second visible minimum.*)

**b)** Extract the value of $\sin^2(2\theta_{12})$ from the data as well. Note, however, that according to the oscillation equation the maximum of the peak at $L/E = \pi$ should correspond to $\cos^4(\theta_{13}) \approx 0.95$, which is the value provided by short-baseline reactor neutrino experiments. This is not the case here since due to the variance in reactor distances $L$ to the detector, the oscillation structure is smeared out, so this effect needs to be accounted for.

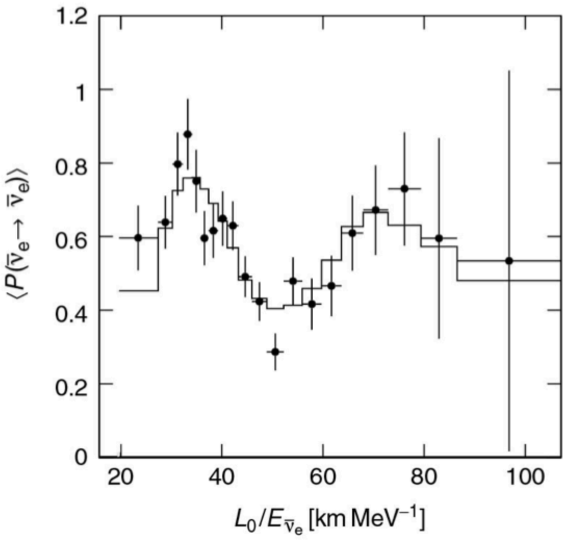


Figure 1: Data from the KamLAND experiment, showing the measured survival probability as a function of measured neutrino energy divided by the flux-weighted mean distance to the reactors $L_0$. [2]

[1] `https://arxiv.org/abs/0801.4589`

[2] Figure from Thomson, M. (2013). Neutrinos and neutrino oscillations. In Modern Particle Physics (pp. 329-363). Cambridge: Cambridge University Press