Exercises for Neutrino Physics: Theory and Experiment

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Sheet 11: Experiment

1. **Reactor neutrino detection [6 Points]**

   In nuclear reactors, electron anti-neutrinos are produced in β^- decays of fission fragments created in nuclear fission processes. Nuclear reactors thus provide a convenient artificial neutrino source for studying neutrino properties such as their oscillations between different flavours.

   (a) Which neutrino interaction process is used for the detection of electron anti-neutrinos produced in reactors? Draw the Feynman diagram for this process and calculate its energy threshold.

   (b) How large is this energy threshold in comparison to the energy spectrum of reactor electron anti-neutrinos? Comment on why there are no oscillation appearance experiments using reactor neutrinos.

   (c) While some reactor neutrino experiments employ a pure organic liquid scintillator as target, others have cadmium (Cd) or gadolinium (Gd) added to the scintillator (loading). Explain the advantages and disadvantages of using pure vs. loaded scintillator targets.

2. **The KamLAND Reactor Neutrino Experiment [10 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) What is the main signature of a neutrino signal event in KamLAND?

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

3. The θ_{13} Mixing Angle and the Neutrino Mass Hierarchy [4 Points]

(a) Why is the precise determination of θ_{13} particularly interesting? 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 θ_{13}.

(b) For a precise measurement of θ_{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?

4. Bonus: Electron Anti-Neutrino Survival Probability [5 Bonus-Points]

In the three-flavour treatment of neutrino oscillations, the weak eigenstates of the neutrinos and their mass eigenstates are related by the PMNS matrix. Using the PMNS matrix entries (and assuming that $\Delta m_{31} \approx \Delta m_{32}$), the electron anti-neutrino survival probability can be expressed as

$$P(\overline{\nu}_{\mathrm{e}} \to \overline{\nu}_{\mathrm{e}}) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 \cdot L}{4E_{\overline{\nu}}}\right) - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{32}^2 \cdot L}{4E_{\overline{\nu}}}\right) \quad (1)$$

where θ_{ij} are the mixing angles and $\Delta m_{ji}^2 = m_j^2 - m_i^2$ are the squared mass differences between the mass eigenstates i and j. $E_{\overline{\nu}}$ is the neutrino energy and L is the distance traveled by the neutrino.

(a) Plot the survival probability (preferably using a computer program, e.g. python) as a function of the neutrino travel distance L in the range of $L = 0.1 - 200\,\mathrm{km}$. Use a reactor neutrino energy of $E_{\overline{\nu}} = 3\,\mathrm{MeV}$, the mixing angles $\theta_{12} = 35^\circ$ and $\theta_{13} = 10^\circ$, and the neutrino mass differences $\Delta m_{21}^2 = 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\Delta m_{32}^2 = 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$.
Indicate in the plot how to extract the mixing angles and mass differences (you can do that by hand). Where do you need to have a detector placed to be sensitive to Δm_{21}^2 or Δm_{32}^2?
(Hints: Use the relation $\frac{\Delta m^2 L}{4E} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$ and you may want to make the scale of your x-axis logarithmic.)