Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 8

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Reactor Neutrinos

8.1 Reactor neutrino detection *4 Points*

In nuclear reactors, electron anti-neutrinos are produced in the β^- decays of fission fragments created in the 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 (called 'loading'). Explain the advantages and disadvantages of using pure vs. loaded scintillator targets.

8.2 Electron anti-neutrino survival probability *6 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 $\Delta m^2_{31} \approx \Delta m^2_{32}$), the electron anti-neutrino survival probability can be expressed as

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E_{\bar{\nu}}}\right) - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32} L}{4E_{\bar{\nu}}}\right), \quad (1)$$

where θ_{ij} are the mixing angles and $\Delta m^2_{ji} = m^2_j - m^2_i$ are the squared mass differences between the mass eigenstates i and j. $E_{\bar{\nu}}$ is the neutrino energy and L is the distance travelled 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 $L = (0.1 - 200)$ km. Use a reactor neutrino energy of $E_{\bar{\nu}} = 3\,\mathrm{MeV}$, the mixing angles $\theta_{12} = 35°$and $\theta_{13} = 10°$, and the neutrino mass differences $\Delta m^2_{21} = 8 \times 10^{-5}\,\mathrm{eV}^2$ and $\Delta m^2_{32} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$.
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^2_{21} or Δm^2_{32}?

(*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.*)

b) Why is it not possible to resolve the fast oscillations due to the Δm^2_{32} term in eq. 1 in detectors that are more than a few km away from the reactor?
Show that in this case, the survival probability can be approximated like

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx \cos^4(\theta_{13}) \left[1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E_{\bar{\nu}}}\right)\right] \tag{2}$$

by taking only the average value of the $\sin^2(\Delta m^2_{32})$ term into account. Plot this function on top of your plot from a).