Exercises for Experimental methods in Astroparticle Physics

Universität Heidelberg | 20. November 2019 | **Hand in:** 4. December 2019

Sheet 5

Note: Please scan your solutions and send them to tim.wolf (@) mpi-hd.mpg.de

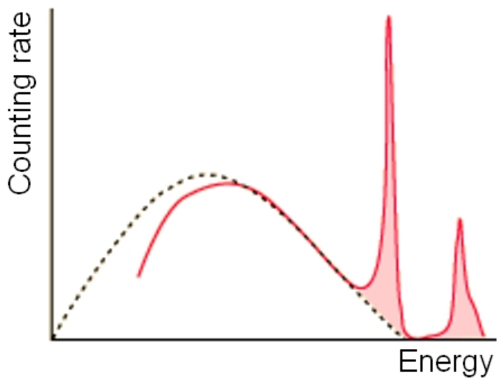
1. **Postulate of the neutrino**

   The neutrino was proposed for the first time by Pauli in 1930 to explain the experimental measurement of the beta decay.

   (a) Calculate the visible energy of the beta decay of ${}^{203}_{80}\text{Hg} \rightarrow {}^{203}_{81}\text{Tl}$ if neutrinos would not exist. The binding energy of Hg is $E = 1601.2\text{MeV}$. The respective value for Tl is $E = 1600.9\text{MeV}$.

   (b) Give another reason apart from the shape of the mass spectrum that points towards the existence of the neutrino. (Bonus)

   (c) Actually, there are lines in the beta decay spectrum of heavy nuclei. Look at the picture where the solid line represent the measured spectrum of ${}^{203}_{80}\text{Hg}$ and try to find an explanation to these lines. (Bonus)



2. **Detection of the ν_τ**

   The ν_τ was detected directly for the first time at Fermilab by an experiment called DONUT. Read thoroughly the reference to this experiment: DONUT Collaboration, Phys. Lett. B 504 (2001) 218, hep-ex/0012035 and answer the next questions.

   (a) What is the source of the ν_τ's?

   (b) What is the signature of ν_τ events?

   (c) The ν_τ interacts in the detector producing a τ lepton, what is the maximal length of flight of this particle? What spatial resolution do you need in your detector to see it?

   (d) What are in this experiment the main sources of background and why?

Please turn the page!

3. Neutrino oscillations in matter

Analog to many different physics problems (optics, solid state physics ...), when particles, in this case neutrinos, move in matter their masses are replaced by an effective mass. This is usually done through an effective potential corresponding to the effect of interactions of the particles with the medium. Due to the different reactions of ν_μ, ν_τ and ν_e with ordinary matter, the flavour oscillation of neutrinos is also modified.

(a) Write the Feynman diagram of neutrino scattering on electrons common for all neutrino flavours. Which additional diagrams are possible for ν_e? Why is only this diagram important concerning the modifications of neutrino oscillation?

(b) The effective potential for electron neutrinos is finally written as $A = 2\sqrt{2}G_F N_e p$, where $p \approx E$ neutrino energy, $N_e = Y_e \rho / m_N$ is the density of electrons, Y_e the number of electron per nucleon, m_N the nucleon mass and ρ the matter density. Considering the easier oscillation case $\nu_e \to \nu_\mu$, a new mixing angle can be defined:

$$\tan 2\Theta_m = \frac{\sin 2\Theta}{\cos 2\Theta - \frac{A}{D}} \tag{1}$$

where $D = \delta m^2 = {m_2}^2 - {m_1}^2$. For the solar neutrinos $D = 8 \cdot 10^{-5}$ eV^2 and $\Theta = 33.9°$. Calculate the minimal energy that solar neutrinos should have to see a resonance in matter ($\Theta_m = 45°$) taking the value for the density of the Sun in the center: $\rho = 150$ g/cm^3.

(c) Is the sign of D important?

(d) To proof the parameters of D and Θ from the solar oscillation problem a laboratory experiment can be performed. The two possibilities are accelerator and reactor experiments (typical energies: $\sim$ GeV for accelerator ν's and ~ 4 MeV for reactor ν's), what is the optimal distance between neutrino source and detector, in these two experiment types, to confirm the solar parameters?
You can start by deriving the oscillation length in vacuum and quantify matter effects based on your result. Do you need to take matter effects into account for both types of experiment?
Note: The density of the earth is $\rho = 3.0$ g/cm^3.