Exercises for Experimental methods in Astroparticle Physics

Universität Heidelberg 11. December 2019 **Hand in:** 18. December 2019

Sheet 7

1. **Water Cherenkov detectors and Superkamiokande**

   Charged particles that move in a medium with refractive index n and have a velocity v that exceeds the speed of light in the medium, $c_n = c/n$, emit electromagnetic radiation known as *Cherenkov radiation*.

   (a) Explain the physical principle of the Cherenkov effect and derive the formula for the opening angle θ_C from the Huygens principle.

   (b) How can the mass of a charged particle be inferred from the Cherenkov angle θ_C and its momentum p?

   (c) Calculate the energy threshold of e^- and μ^- to produce Cherenkov light in water. (Index refraction of water: $n = 1.344$, $m_e c^2 = 0.511\,\mathrm{MeV}$, $m_\mu c^2 = 105.659\,\mathrm{MeV}$)

   Super-Kamiokande is the large water Cherenkov detector. The construction was started in 1991 and the observation began on April 1st, 1996. The Super-Kamiokande detector consists of a stainless-steel tank, $39.3\,\mathrm{m}$ diameter and $41.4\,\mathrm{m}$ tall, filled with $50.000\,\mathrm{t}$ of ultra pure water ($\rho = 1\,\mathrm{g/cm^3}$ and $n = 1.33$). About 13000 photo-multipliers are installed on the tank wall. The detector is located at 1,000 meter underground in the Kamioka-mine, Hida-city, Gifu, Japan. Tracks of muons are measured through Cherenkov radiation in the water.

   (d) Describe which muon neutrino interaction in water could generate a muon. Are these neutral current or charged current interactions?

   Considering that in Superkamiokande only muon neutrinos with energy $E_\nu = 1\,\mathrm{GeV}$ are measured:

   (e) What is the mean free path of $1\,\mathrm{GeV}$ muons in water?

   (f) For which fraction of this path does the muon emit Cherenkov light?

   (g) An atmospheric muon neutrino moving downwards ($\Theta = 0$) in the SK detector interacts at a distance of $50\,\mathrm{m}$ from the bottom creating a muon which moves along the same direction. What is the radius of the circle that is illuminated at the bottom of the cylinder if the energy of the muon is $1\,\mathrm{GeV}$?

2. **Neutrinos in IceCube**

   Read the paper *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A* from the IceCube Collaboration (clickable link here) and work through the following tasks:

   (a) Describe which muon neutrino interaction in ice could generate muon. Are these neutral current or charged current interactions?

   (b) A muon neutrino interaction was discovered in IceCube with energy $290\,\mathrm{TeV}$ pointing towards the Blazar TXS 0506+056. Describe how the energy can be deduced from the measurement of the muon track and how the direction is extracted. Discuss which effect could reduce the precision of obtaining the direction from which the muon neutrino is coming.

(c) An electromagnetic counterpart for the neutrino emission was searched with several other observatories. Please list the experiments which have searched for the EM radiation from Blazar TXS 0506+056 and which energy range was covered by each experiment.

(d) Try to estimate the luminosity of the source of neutrino by knowing the information that one neutrino of energy $290\,\mathrm{TeV}$ was detected over a time period of 6 months in $1\,\mathrm{km}^3$ ice detector. Search for the cross-section of the interaction of muon neutrino of $E = 290\,\mathrm{TeV}$ in water and consider that the distance of TXS 0506+056 is about $1.7\,\mathrm{Gpc}$.