Exercise to the Lecture Astroparticle Physics
KIT, Wintersemester 2022/23

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Lectures	Thur. 11:30 + Wed 14:00 (every 14 days), Phys-HS Nr. 3
Exercises	Wed 14:00 (alternating with lecture), Phys-HS Nr. 3
ILIAS	`https://ilias.studium.kit.edu/goto.php?target=crs_1902412&client_id=produktiv`

Sheet 3 – Due 30.11.2022

1) The IceCube Neutrino Obervatory

The IceCube Neutrino Observatory was built at the South Pole to detect high-energy neutrinos with $E_\nu > 100\,\text{GeV}$ For this purpose, a cubic kilometer of ice is instrumented with photomultipliers and neutrinos are detected via the Cherenkov radiation of charged leptons with the same flavor.

(a) For muon neutrinos, this charged-current (CC) interaction looks like this:

$$\nu_\mu + \text{N} \rightarrow \mu^- + \text{M}\,. \tag{1}$$

Here N denotes a resting nucleon before and M one after the interaction, where $m_\text{N} \approx m_\text{M} \approx 939\,\text{MeV}$ should hold. Calculate the minimum energy $E_{\nu,\text{min}}$ required by the muon neutrino for the CC interaction to occur.

(b) Calculate the mean free path of muon neutrinos with $E = 100\,\text{TeV}$ in ice ($\rho_\text{Eis} = 934\,\text{kg}\,\text{m}^{-3}$) if the effective cross section σ for the CC interaction at this energy is $6{,}7 \cdot 10^{-38}\,\text{m}^2$.

(c) The photomultiplier tubes (PMTs) are located at a depth of 1500 to 2500 m below the ice surface. The neutrino flux Φ of muon neutrinos is for $E_\nu \geq 100\,\text{TeV}$ integrated $1 \cdot 10^{-12}\,\text{cm}^{-2}\,\text{s}^{-1}$. Calculate the event rate of muon neutrinos in IceCube per year for the CC interaction in the instrumented volume crossing the detector from top to bottom. *Note:* The event rate is calculated using $R = \Phi \cdot W \cdot A$, where A is the cross-sectional area of the detector and W is the interaction probability. To calculate W, assume a mean free path length of $\lambda = 2{,}5 \cdot 10^7\,\text{m}$ or your result from the previous subtask. You can assume the shape of the instrumented volume of IceCube to be cube-shaped.

(d) How long does a muon travel through ice before it has lost so much energy that the energy falls below the Cherenkov threshold? The muon's energy loss is described by

$$-\frac{\text{d}E}{\text{d}x} = A + B \cdot E,$$

where $A = 2\,\text{MeV}\,\text{cm}^{-1}$ and $B = 4{,}2 \cdot 10^{-6}\,\text{cm}^{-1}$ are quantities already corrected for the density of the ice. Assume a muon with energy $E_\mu = 5\,\text{TeV}$. Comment on the result from task part c) on the basis of this result.

(e) According to calculations (e.g. as you did them on the last problem sheet) muons above a minimum energy of 160 MeV produce Cherenkov radiation in ice. Why can IceCube only detect muons above an energy of 100 GeV? Briefly describe the planned expansion stages of IceCube, PINGU, and IceCube-Gen2, and address the scientific goals and energy ranges covered in each case.

2) IceCube as part of multimessenger-observations

Read the article "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A" (link: `http://science.sciencemag.org/content/sci/361/6398/eaat1378.full.pdf`)[1]. Then answer the following questions (usually one sentence per bullet point is sufficient):

(a) Background knowledge

- Which two sources could be proven beyond doubt as the origin of non-terrestrial neutrinos before the article was published? Can these two sources explain the complete neutrino flux?
- How do active galactic nuclei (AGNs) produce cosmic rays?
- What is a blazar?
- What would a measured neutrino from a blazar tell us about the energies of protons/atomic nuclei produced in the blazar?

(b) Detection and reconstruction of the neutrino IceCube-170922A

- When was the neutrino of interest to this article discovered and what was its flavor at the time of the interaction? How long did the initial analysis of the direction and energy of the neutrino take?
- What is the reconstructed direction of origin of the neutrino? What is the name and direction of the blazar that is believed to have produced the neutrino?
- What is the reconstructed energy of the neutrino? What is the probability (considering IceCube as the only possible source of information) that the neutrino has an astrophysical origin?

(c) observations of TXS 0506+056 from gamma-ray observatories

- Where is the Fermi-LAT located and for which energy range is it sensitive?
- How did the measured light curve of the blazar behave in the period April - October 2017 compared to the previous records?
- Were VERITAS and HESS also able to detect gamma rays from the blazar? At what time interval did these two IACTs study the blazar?
- What are the results of MAGIC regarding the blazar?
- Do the results of the three IACTs (HESS, VERITAS and MAGIC) contradict each other? Consider fig. 4 in the article.

(d) Analysis and discussion of the results

- With what significance level can it be excluded that the neutrino is not causally related to blazar TXS 0506+056?
- Can the neutrino IceCube-170922A be used to test models of neutrino production in blazars?
- Can blazars explain the complete astrophysical neutrino flux? If not, why not?
- Is the VHE gamma flux of blazar TXS 0506+056 constant over the period of several weeks?
- How many neutrino events has IceCube detected since 2010 that would have triggered an "alert"? Was there another one among them from the direction of blazar TXS 0506+056?

[1] You have to be in the KIT network to get access to the article (either by being logged in to the kit-network on campus or via vpn). If you have trouble getting access, please contact Anton Huber.