Exercises Astroparticle Physics – ICTP-SAIFR School 2019

Johannes Knapp[1], Astroparticle Physics, DESY Zeuthen

Try to do all problems by yourself. Some can be solved with basic school/university physics, others require some reading, web searching or educated guesses.

1. **Wavelength, frequency, energy and interactions of photons:** What are the frequency and wavelength of a photon of 1 TeV?
   How does it (most likely) interact when impinging on matter?

2. **Relativistic energies and momentum:** A proton (rest mass $m_p = 938$ MeV/c^2) moves with a velocity $v = 0.7c$.
   Calculate its relativistic mass, momentum, kinetic and total energy. Show that for $v \ll c$ the relativistic momentum and kinetic energy approach the classical values.

3. **Energy and directional reconstruction:** In a satellite detector like Fermi, photons are detected via the measurement of the e^+e^- pairs they produce. A pair is observed with the following direction unit vectors $\vec{d_i}$ and energies E_i. What are the energy and direction of the incident photon?
   $\vec{d_1}$(x,y,z) = (-0.65, 0.14, -0.75) E_1 = 2.93 GeV and
   $\vec{d_2}$(x,y,z) = (0.66, -0.04, -0.75) E_2 = 2.27 GeV.

4. **Energy thresholds:** What is the energy threshold for a high energy photon (γ) to produce an e^+e^- pair when colliding with an infrared photon of 1100 nm wavelength?

   What are the threshold energies for a high energy protons (p) colliding with a CMB photon of energy 10^{-5} eV the following reactions:

   a) p + $\gamma_{\rm CMB} \rightarrow$ e$^+$ + e$^-$ + p

   b) p + $\gamma_{\rm CMB} \rightarrow \pi^0$+ p

5. **First interaction of photons:** What is the average amount of air (in g/cm^2) traversed by a TeV photon to its first interaction in the atmosphere? What is the distribution of first interaction points? To what height (in km) does this roughly correspond for a vertical primary photon?

6. **Telescopes and time spreads:** What are the characteristics of a Davies-Cotton Telescope? What is the maximum time spread of a parabolic telescope and of a Davies-Cotton telescope of 12 m diameter and f = 14.4 m?

7. **Gamma hadron separation:** How can astrophysical photons in satellite and ground-based Cherenkov experiments be separated from the overwhelming background of charged cosmic rays?

8. **Transients and size of gamma ray emission region:** In 2007 the gamma-ray source PKS 2155-304 was observed to double its output within 5 min. Estimate the size of the emission region.
   What if the emission region is moving towards us with a Lorentz γ factor of 15?

9. **Energy spectrum:** The energy spectrum of the Crab nebula (the strongest steady TeV gamma ray source) is about J = 3.2 $\times 10^{-7}$ (E/TeV)$^{-2.5}$ $\frac{1}{\rm m^2\ s\ TeV}$. Can you explain the units?
   Estimate roughly how many photons above 500 GeV a single Cherenkov telescope would detect per minute from the Crab. (assume the detection efficiency ε_γ is 100%.)

10. **Fermi vs CTA:** How does CTA achieve better performance than existing Cherenkov experiments?
    In what sense (and why) is it superior to the Fermi LAT observatory?

11. **Gamma Rays and Neutrinos:** How are the fluxes of gamma rays and neutrinos from an astrophysical source linked?

[1]e-mail: johannes.knapp@desy.de

12. **Shower Detection:** How do detect showers? Why did Victor Hess not detect showers? What is needed to detect showers? What is the time duration of the signals produced by a shower in a single detector? How to know that signals in different detectors are hit by a shower? Origin and rate of random noise in a detector? How to reduce noise through coincidence? Chance coincidence rate? Twofold, threefold coincidences?

    Direction distribution of shower particles at ground? How to reconstruct the direction of an air shower from arrival times? Coincidences with multiple detectors on top of each other? Coincidences with multiple detectors at distances from each other (the original experiment by Pierre Auger)? Estimate of energy of a shower from coincidence with detectors at 300 m distance?

13. **Decay point and interaction length distributions:** What is the decay law of radioactive decays? Where does it come from? What are "decay constant", "life time", "half life" and "activity" of a decaying particle and how do they relate? What are their units? How can they be measured?

    Why does the interaction point distribution follow an exponential distribution? What is the average value of an exponential distribution? What is the interaction length? What is the decay probability per unit time? What is the Interaction probability per unit path length?

14. **Bethe-Heitler shower model for electromagnetic showers:** Understand qualitative features of a shower with the Bethe-Heitler model. How do high-energy electrons and photons interact? Typical interaction length of photons? Radiation length of electrons? Units of interaction length and of path length? Relation of path length and density profile in atmosphere? Respective definitions for electrons and for photons? Definition of the critical energy? What is the critical energy in air?

    Particle number and particle energies as function of depth in the atmosphere? N_{max}, X_{max} as function of energy? For what energies do vertical shower particles reach the ground? For what energies do vertical shower particle have their shower maximum at ground level?

15. **Neutrino cross sections and neutrino interactions:** What is a "cross section"? How to interpret it as an interaction probability?

    In the Chlorine solar neutrino experiment, 15 neutrino reactions are detected per month.
    What is approximately the neutrino interaction probability?
    (610 t of C_2Cl_4 ; only 25% of natural Chlorine is ${}^{37}_{17}Cl$; total solar ν flux at Earth is $6.3 \times 10^{10}/(cm^2 s)$)

    The absorption cross-section of neutrinos ($\sim$ 10 MeV) on a nucleon (proton or neutron) is about $\sigma_{\nu n} = 6 \times 10^{-44}$ cm^2. What is the probability that such a neutrino is absorbed when traversing the full diameter of the Earth?
    (r_{Earth} = 6370 km, ρ_{Earth} = 5.5 g/cm^3)

16. **Relativistic kinematics:** A π^0 at rest decays mostly in 2 photons. What are the photon energies? What is the angular distribution of the photons? What if the π^0 has an energy of 10 GeV and decays in flight?

17. **Nuclear masses:** Explain the terms: mass defect, strong interaction, fusion, fission.

18. **Cherenkov effect:** Explain the following expressions: Cherenkov threshold, angle, number of Ch. photons, Energy loss, ring image Cherenkov, Cherenkov footprint of shower

19. **Fermi satellite:** Explain the following: gamma detection principle, gamma hadron separation, what sources seen, diffuse gamma emission, Fermi bubbles, Crab variability

20. **Fermi acceleration:** Explain 1st and 2nd order Fermi acceleration, containment time, power law, slope of energy spectrum.