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Astroparticle Physics – 2015/16

Werkcollege 7 – 19.10.2015

Problem 28 Particle decay

In an Extensive Air Shower many secondary particles are pions ($\pi^\pm$ and π^0) and muons ($\mu^\pm$), which are short-living particles. Write down the decay reaction for pions and muons.

In their own system of reference, charged pions ($\pi^\pm$) have a mean lifetime $\tau_0 = 26$ ns, neutral pions (π^0) have a lifetime $\tau_0 = 8.4 \cdot 10^{-17}$ s, and the muons ($\mu^\pm$) have a lifetime $\tau_0 = 2.2\ \mu$s. By neglecting all possible energy losses, compute how far (on average) charged pions, neutral pions, and muons travel in the atmosphere before decaying. Consider particles with energies of 10 TeV, 100 GeV, and 1 GeV. Compare the found values with the atmospheric thickness (~ 20 km).

Hint: use as mass at rest the following values: $m_{\pi^\pm} = 135$ MeV/c^2, $m_{\pi^0} = 139$ MeV/c^2, and $m_{\mu^\pm} = 106$ MeV/c^2.

Problem 29 Interaction of pions

Charged pions in an air shower can decay into muons or interact hadronically. By assuming their interaction length $\lambda_I = 120$ g/cm^2 being independent of the pion energy, calculate the energy E' for which the probability to decay is equal to the probability to have a hadronic interaction as function of the density ρ of the crossed material.

The density of air as function of height is given through the barometric formula $\rho(h) = \rho_0 \cdot \exp(-h/H)$, with $H = 8005$ m and $\rho_0 = 1.3$ g/l. Calculate the energy E' for sea level, as well as for altitudes of 1 km, 10 km, and 30 km.
For the 4 considered cases, which process dominates the energy losses for $E_\pi < E'$?

Problem 30 Extensive air showers

When a cosmic-ray particle impinges on the Earth's atmosphere, an Extensive Air Shower (EAS) is started by the interaction of the cosmic ray with an atmospheric nucleus. During the first interaction (hadronic interaction), the target nucleus is fragmented and many pions are produced. While charged pions and the primary particle (if surviving the interaction) will produce secondary hadronic interactions, neutral pions will start electromagnetic cascades (the characteristics of this process is part of Problem 28). All electromagnetic cascades combined together contain by far the largest fraction of the number of particles in the EAS, while the most energetic ones will be produced in hadronic cascades.

Hadronic cascades in the atmosphere behave similarly as cascades in an electromagnetic calorimeter (see Problem 9). The number of secondary particles can be described by the Gaisser–Hillas function

$$N(X) = N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\frac{X_{max}-X_0}{\lambda}} \exp\left(\frac{X_{max} - X}{\lambda} \right),$$

where X_0 is the atmospheric depth at which the first interaction takes place, $\lambda = 70$ g/cm^2 is the mean free path, N_{max} and X_{max} are the number of particles and the atmospheric depth at which the EAS reaches its maximum extension, respectively. The X_{max} and N_{max} values are correlated with the primary particle energy E_0 through the equations

$$\begin{aligned} X_{max} &= \ln\left(\frac{E_0}{86\ MeV} \right) \cdot \lambda_{e/m} + X_0 \\ N_{max} &= 2^{\frac{X_{max}-X_0}{\lambda_{e/m}}}, \end{aligned}$$

where $\lambda_{e/m} = 36.6$ g/cm^2 is the radiation length of electrons in air. By assuming $X_0 = 80$ g cm^{-2}, compute the energy of a cosmic ray initiating a vertical EAS (i.e. perpendicular to the ground) which reaches X_{max} at sea level ($X_{sea\ level} = 1035$ g cm^{-2}) and the corresponding N_{max} value.

Under the same assumptions, compute the number of particles at sea level for an EAS started by a particle with an energy $E_0 = 10^{18}$ eV.

Problem 31 Primary particle reconstruction from air-shower observations

The atmospheric depth X_{max} where an EAS reaches its maximum extension depends on the primary particle energy E and on the atmospheric depth of the first interaction X_0 (see Problem 30). Since the value of X_0 is dominated by the cross section of the primary particle (which is strictly related to the primary particle mass composition), X_{max} measurements are often used for reconstructing the mass composition of the primary particle.

By assuming that primary particles have always the first interaction on Nitrogen nuclei and that the cross section is given by the geometrical one, compare the X_{max} value for an EAS initiated by a proton with $E = 10^{18}$ eV with the X_{max} value for an EAS initiated by an iron nucleus with the same energy.
Hint: $X_0 = 80$ g cm^{-2} for a proton and assume the radius of a generic nucleus equal to $r_A = r_{proton}\ A^{1/3}$.

Ground-based particle detector arrays reconstruct the energy of the primary particle by measuring the number of particles $N(X)$ hitting the detectors. By assuming a particle detector array at the sea level ($X_{sea\ level} = 1035$ g cm^{-2}), evaluate the maximum allowed uncertainties on reconstructing the primary particle energy in order to be able to disentangle proton-initiated from iron-initiated EAS with $E = 10^{18}$ eV.

The solutions will be discussed during the werkcollege on 19.10.2015 in HG03.082.
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Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1516