Radboud Universiteit Nijmegen
Afdeling Sterrenkunde
Jörg R. Hörandel
Antonio Bonardi

Astroparticle Physics – 2016/17

Werkcollege 7 – 20.10.2016

Problem 26 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 $\tau_0 = 2.2$ μs. 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: $m_{\pi^{\pm}} = 140$ MeV/c^2, $m_{\pi^0} = 135$ MeV/c^2, and $m_{\mu^{\pm}} = 106$ MeV/c^2.

Problem 27 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 28 Extensive air showers

When a cosmic-ray particle impinges on the Earth's atmosphere, an Extensive Air Shower 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 26). All electromagnetic cascades combined together contain by far the largest fraction of the number of particles in the shower, 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 13). 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 air shower reaches its maximum extension, respectively.
In case of purely electromagnetic cascade, the X_{max} and N_{max} values are correlated with the primary particle energy E_0 through the equations

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

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} and a purely electromagnetic cascade, compute the energy of a cosmic ray initiating a vertical air shower (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 air shower started by a particle with an energy $E_0 = 10^{18}$ eV.

Problem 29 Primary particle reconstruction from air-shower observations

The atmospheric depth X_{max} where an extensive air shower reaches its maximum extension depends on the primary particle energy E and on the atmospheric depth of the first interaction X_0 (see Problem 28). Since the value of X_0 is dominated by the cross section of the primary particle (which is strictly related to the mass of the primary particle), X_{max} measurements are often used to infer the mass 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 air shower initiated by a proton with $E = 10^{18}$ eV with the X_{max} value for an air shower 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 is given by $r_A = r_{proton}\ A^{1/3}$.

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 showers with $E = 10^{18}$ eV.

The solutions will be discussed during the werkcollege on 20.10.2015 in HG01.029.
Student assistant: Antonio Bonardi a.bonardi@astro.ru.nl
Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1516