Secondary Cosmic Rays - Summary

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This summary is based on the book Chapters 7.1 and 7.2 from Klaus Grupen: Astroparticle Physics.

1 Secondary Cosmic Rays

The flux of low-energy primary cosmic-ray particles is anti-correlated to the solar activity. The influence of the Sun is limited to primary particles with energies below 10 GeV.

The solar wind, whose magnetic field modulates primary cosmic rays, is a particle stream in itself. The low energy (MeV region) solar wind particles are captured to a large extent by the Earth's magnetic field in the **Van Allen belts**. There are two main belts: The **proton belt** extends over altitudes from 2000 to 15 000 km and contains particles with energies up to 1 GeV. The electron belt consists of two parts: the inner electron belt at an altitude of approximately 3000 km, while the outer belt extends from about 15000 to 25000 km.

2 Propagation in the atmosphere

Primary cosmic rays are strongly modified by interactions with atomic nuclei in the atmospheric air. For the interaction behaviour of primary cosmic rays the thickness of the atmosphere in units of the characteristic interaction lengths for the relevant particles species is important. The radiation length for photons and electrons in air is $X_0 = 36.66$ g/cm^2. The atmosphere therefore corresponds to a depth of 27 radiation lengths.The relevant interaction length for hadrons in air is $\lambda = 90.0$ g/cm^2, corresponding to 11 interaction lengths per atmosphere. This means that practically not a single particle of original primary cosmic rays arrives at sea level. Already **at altitudes of 15-20 km primary cosmic rays interact with atomic nuclei of the air and initiate electromagnetic and/or hadronic cascades.**

Most common particles observed at the top of the atmosphere are hydrogen isotopes (h, d, t), muons and $\bar{p}$. The muons have been produced trough pion decays and the measured antiprotons are not of primordial origin, but are rather produced by interactions in interstellar or interplanetary space or even in the residual atmosphere above the balloon.

Protons with approximately 85% probability constitute the largest fraction of primary cosmic rays. Primary protons initiate a hadron cascade already in their first interaction. The secondary particles most copiously produced are pions. Kaons, on the other hand, are only produced with a probability of 10-15% compared to pions.

Neutral pions initiate via their decay ($\pi^0 \to \gamma + \gamma$) electromagnetic cascades, whose development is characterised by the shorter radiation length ($X_0 \approx 13\lambda$ in air). This shower component is absorbed relatively easily and is therefore also named a **soft component**.

Charged pions and kaons can either initiate further interactions or decay. The competition between decay and interaction probability is a function of energy. For the same Lorentz factor charged pions ($\tau = 26$ ns) have a smaller decay probability compared to charged kaons ($\tau = 12.4$ ns).

The leptonic decays of pions and kaons produce the penetrating muon and neutrino components:

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$K^+ \to \mu^+ + \nu_\mu$$

$$K^- \to \mu^- + \bar{\nu}_\mu$$

Muons can also decay and contribute via their decay electrons to the soft component and neutrinos to the neutrino component:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Relativistic muons constitute with 80% of all charged particles at sea level. Some secondary mesons and baryons can also survive down to sea level. Most of the low-energy charged hadrons observed at sea level are locally produced. The total fraction of hadrons at ground level, however, is very small. Apart from their longitudinal development electromagnetic and hadronic cascades also spread out laterally in the atmosphere. The lateral size of an electromagnetic cascade is caused by **multiple scattering of electrons** and positrons, while in hadronic cascades the **transverse momenta** at production of secondary particles are responsible for the lateral width of the cascade.

The electrons and positrons produced through π^0 decay with subsequent pair production reach a maximum intensity at an altitude of approximately 15km and soon after are relatively quickly absorbed while, in contrast, the flux of muons is attenuated only relatively weakly.

Because of the steepness of the energy spectra the particle intensities are of course dominated by low-energy particles.

Because of the low interaction probability of neutrinos these particles are practically not at all absorbed in the atmosphere. Their flux increases monotonically because additional neutrinos are produced by particle decays.

3 Secondary cosmic rays at sea level

Approximately 80% of the charged component of secondary cosmic rays at sea level are muons. These muons originate predominantly from pion decays, since pions as lightest mesons are produced in large numbers in hadron cascades.

For **large zenith angles** the parent particles of muons travel relatively long distances in rare parts of the atmosphere. Because of the low area density at large altitudes for inclined directions **the decay probability is increased compared to the interaction probability**. Therefore, for inclined directions pions will produce predominantly high-energy muons in their decay.

Since the energy losses of muons at very high energies are dominated by bremsstrahlung and direct electron pair production, which are proportional to the muon energy, these muon-induced showers allow to infer the muon energy.

The total intensity of muons, however, is dominated by low-energy particles. Because of the zenith angle dependance, the total muon intensity at sea level varies like

$$I_\nu(\theta) = I_\mu(\theta = 0) cos^n \theta$$

where θ is the zenith angle.

In addition to 'classical' production mechanisms of muons by pion and kaon decays, they can also be produced in semileptonic decays of charmed mesons:

$$D^0 \to K^- + \mu^+ + \nu_\mu$$

$$D^+ \to \bar{K}^0 + \mu^+ + \nu_\mu$$

$$D^- \to K^0 + \mu^- + \bar{\nu}_\mu$$

Since these charmed mesons are very short-lived ($\tau_{D^0} \approx 0.4$ ps, $\tau_{D^\pm} \approx 1.1$ ps), they decay practically immediately after production without undergoing interactions themselves $\to$ they are a source of high-energy muons. Since the production cross section of charmed mesons in proton-nucleon interactions is rather small, D decays contribute significantly only at very high energies. Correspondingly, this is also true for the semileptonic decays of B mesons.

Some **nucleons can be observed at sea level**. These nucleons are either remnants of primary cosmic rays or they are produced in atmospheric hadron cascades. About one third of the nucleons at sea level are neutrons. The proton/muon ratio varies with the momentum of the particles, with fewer protons at higher energies.

In addition to muons and protons, one also finds **electrons, positrons, and photons at sea level as a consequence of the electromagnetic cascades** in the atmosphere. A certain fraction of electrons and positrons originates from muon decays. Electrons can also be liberated by secondary interactions of muons **'knock-on electrons'.**

The **few pions and kaons observed at sea level** are predominantly produced in local interactions.

Electron and muon neutrinos are produced in pion, kaon, and muon decays. Altogether, muon neutrinos dominate, since the π and K decays are strongly suppressed due to **helicity conservation**. Only in muon decay equal numbers of electron and muon neutrinos are produced. At high energies also semileptonic decays of charmed mesons constitute a source for neutrinos.

3.0.1 charge ratio of muons at sea level

the possible charge exchange reactions:

$$p + N \rightarrow p' + N' + k\pi + +k\pi^- + r\pi^0$$

$$p + N \rightarrow n + N' + (k+1)\pi + +k\pi^- + r\pi^0$$

From this we can estimate the charge ratio of pions:

$$R = \frac{N(\pi^+)}{N(\pi^-)} = 1 + \frac{1}{2k}$$

Approximately 70% of the cases the incident proton stays a proton, which with other theorethical considerations gives an estimated R = 1.25. The measured values is R = 1.28.