Secondary Cosmic Rays - Summary

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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:

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

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

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.

4 Cosmic rays underground

Remnants of extensive air showers, which developed in the atmosphere, are measured underground. Electrons, positrons, photons, and hadrons are completely absorbed already in relatively shallow layers of rock. Therefore, **only muons and neutrinos of extensive air showers penetrate to larger depths.**

From depths of 10km water equivalent ($\approx$ 4000m rock) onwards muons induced by atmospheric neutrinos dominate the muon rate.

Muons suffer energy losses by ionization, direct electron-positron pair production, bremsstrahlung, and nuclear interactions. Energy-loss processes increase linearly with the energy of the muon. The energy loss equation allows to work out the range R of muons (how far they can reach underground) by integration:

$$R = \int \frac{dE}{-dE/dx}$$

at not too large energies (E ¡ 100GeV) the ionization energy loss dominates.
The **sea-level muon spectrum** and the **energy-loss processes** of muons allow one to determine the depth-intensity relation for muons. This relation also depends on the **inclination of the direction of propagation.**

The low energy muons can get absorbed easier $\to$ the average muon energy of the muon spectrum increases with increasing depth.

The multiplicity of produced secondary particles increases with energy of the initiating particle. Since the secondaries produced in these interactions decay predominantly into muons, one observes **bundles of nearly parallel muons underground** in the cores of **extensive air showers.**

Examples for Underground muon detectors:
- the ALEPH experiment
- ICECUBE

4.1 They are a background to neutrino astronomy

Experiments in neutrino astronomy are usually set up at large depths underground to provide a sufficient shielding against the other particles from cosmic rays (e.g. muons). Because of the rarity of neutrino events even low fluxes of residual cosmic rays constitute a background.

The neutrino-induced muon rate does not depend on the depth. For large zenith angles the μ flux decreases steeply. $\rightarrow$ At large depths and from inclined directions neutrino- induced muons dominate.

5 Extensive air showers

Extensive air showers are cascades initiated by energetic primary particles, which develop in the atmosphere. An extensive air shower (EAS) has an electromagnetic, a muonic, a hadronic, and a neutrino component. The air shower develops a shower nucleus consisting of energetic hadrons, which permanently inject energy into the electromagnetic and the other shower components via interactions and decays. Neutral pions, which are produced in nuclear interactions and whose decay photons produce electrons and positrons via pair production, supply the electron, positron, and photon component. Photons, electrons, and positrons initiate electromagnetic cascades through alternating processes of pair production and bremsstrahlung. The muon and neutrino components are formed by the decay of charged pions and kaons.

Since most of the charged hadrons produced also undergo multiple interactions, the largest fraction of the primary energy is eventually transferred into the electromagnetic cascade. Therefore, in terms of the number of particles, electrons and positrons constitute the main shower component.

The particle number increases with shower depth t until absorptive processes start to dominate and cause the shower to die out. The particle intensity increases initially in a parabolic fashion and decays exponentially after the maximum. The position of the shower maximum varies only logarithmically with the primary energy, while the total number of shower particles increases linearly with the energy. The latter can therefore be used for the energy determination of the primary particle. The **minimum energy** for a primary particle to be reasonably well measured at sea level via the particles produced in the air shower is about 10^{14} **eV**. The chemical composition up to the TeV range can be determined with balloons or satellites in direct measurements, but beyond that one has to resort to extensive air-showers

Only about 10% of the charged particles in an extensive air shower are muons. They reach a maximum number relatively high in the atmosphere and retain similar numbers until sea-level (not much energy loss or decay).

The different components of the air-shower have different longitudinal/lateral spread with the heaviest particles (hadrons) in the centre and the lighter particles in a more broad distribution.

Showers with energies **below 100TeV does not reach sea level**, it can nevertheless be recorded via the Cherenkov light.

Particles on the ground can be detected with scintillators or water-Cherenkov detectors.

It is also helpful to measure the total longitudinal development of the cascade, this can be done with Fly's Eye detectors (detect scintillation light or air-Cherenkov light). Examples for observatories:

- Fly's Eye detector in Utah $\rightarrow$ Telescope Array (new telescope in Utah)
- Piere Auger observatory in Argentina

The **shower maximum** happens at different atmospheric depths **depending on the energy** of the primary particles. e.g. higher energy particles produce shower maxima at lower altitudes in the atmosphere. In addition, photomultipliers allow to reconstruct the longitudinal profile of the air shower. **The total recorded light intensity is used to determine the shower energy.** However, the disadvantage is that air scintillation light detectors can only be operated in clear moonless nights.

Detection techniques for air-showers:

- scintillation light

- water-Cherenkov
- Radio detection
- Acoustic detection
- underground muon detectors

Goals:
- measuring the chemical composition
- measuring the energy of the primary
- identifying the acceleration sites

The position of the shower maximum or the muon content of an air shower provides some evidence of the nature of the primary particle that has initiated the shower. The masses of the primary cosmic rays get heavier beyond the knee (≈ several PeV). At the highest energies lighter particles seem to be dominant. It is obviously not easy to determine the mass of a particle whose energy is more than a million times heavier than its rest mass.

Origin: a tentative evidence of a clustering along the supergalactic plane, and Centaurus A as a potential source → indicating AGN as the origin.

There is a correlations between arrival times of air showers over distances of more than 100km exist. → The primary cosmic particles undergo interactions or fragmentations at large distances from Earth. The secondary particles produced in these interactions would initiate separate air showers in the atmosphere. Variations in arrival times of these showers could be explained by unequal energies of the fragments.

5.1 Radio detection

A primary proton of 1018 eV creates about 108 secondary charged particles at ground level. At these primary energies mainly electrons and positrons are produced → interactions in the atmosphere.

Electromagnetic radiation emitted in the radio band → this radio signal is caused by shower electrons deflected in the Earth's magnetic field thereby creating **synchrotron radiation → geosynchrotron emission**. Radio waves are mostly detected in the radio band from 40 to 80 MHz. At higher frequencies one would have to live with a considerable background from man-made radio waves. At lower frequencies the radio noise from the Milky Way.

Another mechanism for radio emission is the **Askaryan effect.** In the course of the shower development a negative charge excess of 10-20% is generated. This is a consequence of the ionisation of the air by the air-shower particles. The ionisation electrons essentially follow the cascade, while the much heavier ions stay behind. In the course of shower development this negative charge excess increases up to the shower maximum and decreases later on. This **time-dependent negative charge anisotropy creates the emission of radio waves**.
A third mechanism is Cherenkov radiation in the radio regime and leads to Cherenkov rings with typical radii of about 150 m at ground level for vertical showers.

The radio signal is proportional to the energy of the primary particle. On top of that the complete longitudinal development of the cascade in the atmosphere is recorded. This also supplies the measurement of the position of the shower maximum, which is sensitive to the mass of the primary particle.

Radio arrays are operated jointly with classical air-shower detectors, which can also provide a trigger for the readout of the radio antennas. A trigger is needed otherwise there is too much noise to notice faint air shower signals.

Example telescope arrays:
- LOPES experiment as part of the KASCADE-Grande air-shower array
- LOFAR radio telescope

Advantages:
- can operate any time (24/7)
- easy to simulate/ calculate expectations
- good energy resolution

- we can determin the shower maximum → determine energy of the primary

Disadvantage:
- needs trigger

5.2 Acoustic detection

Large showers with energies in excess of, 10^{18} eV will produce a **thermoacoustic shock wave** in water or ice that could be detected by appropriate hydrophones. The signals are supposed to be created by the sudden energy deposit of relativistic particles. In the case of air showers such signals would be generated by relativistic electrons and positrons, which are absorbed over a relatively short distance in water or ice, which leads to a local heating and a subsequent characteristic pressure pulse that propagates in the surrounding medium.

The advantage of acoustic detectors is the very long attenuation length of acoustic signals in water or ice, which would allow large effective volumes to be instrumented. **The pressure amplitude** of such air showers or neutrino events is expected to be **proportional to the shower energy** and inversely proportional to the distance of the hydrophones from the shower core. The shower electrons will deposit their energy over a short distance, which is about 20m in water or ice.

One of the problems of acoustic detection is the noise level. → needs trigger

Presently there is a large number of prototype experiments
- ICECUBE
- Lake Baikal
- ANTARES
- NEMO
- KM3NeT

6 The most energetic particles

The most extreme energy cosmic rays - ultra-high-energy cosmic ray (UHECR, $> 10^{18}$ eV):
- OMG - 3.20 $\times 10^{20}$ eV
- Amaterashu - 2.44 $\times 10^{20}$ eV