Versuchsbericht zu

V9 – Mössbauer-Effekt

Gruppe Ma-A-06

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1 Introduction

Earth is permanently bombarded with cosmic rays. Primary cosmic rays consist of protons (90 %), α-particles (12,5 %) and heavier nuclei (2,5 %) [1]. Through interaction of primary rays with the Earth's atmosphere, secondary rays are produced. Further nuclear processes, which will be discussed in detail later on, lead to the production of muons (amongst others). These muons are supposed to be detected within the following experiments.

In particular, the mean lifetime of muons stopped in the used detector module is measured, as well as the dependency of cosmic rays' spectrum and count rate on zenith angle. This way, not only the existence of cosmic rays and correctness of nuclear processes to produce muons is proven, but also the characteristics of cosmic rays detected at sea level can be quantified.

2 Basic theory of cosmic rays and their detection

Before going into actual detection of cosmic rays, some basic theory is to be discussed. The presented theory is based on the instruction manual for this experiment [1].

2.1 Cosmic rays and production of muons

High-energetic primary cosmic rays cover an energy range from 10^5 eV to 10^{20} eV. They consist of protons (90 %), α-particles (12,5 %) and heavier nuclei (2,5 %), while electrons and protons are almost completely suppressed.

When hitting the Earth's atmosphere, almost every particle within the primary rays causes an hadronic or electromagnetic shower by interacting with oxygen or nitrogen atoms in the atmosphere. These cascade reactions primarily lead to the production of many pions and photons. Neutral pions then mainly decay into two photons themselves. However, charged pions with a mean lifetime of $2{,}6 \cdot 10^{-8}$ s decay into muons and muon neutrinos in 99,99 % of all cases:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \tag{2.1}$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \tag{2.2}$$

At sea level, the majority of all detected charged particles are muons (almost 80 %) and electrons (20 %, rest roughly makes up 1 %). Also, muons almost entirely make up the so called *hard component* of cosmic rays detected at sea level, which is per definition the component that can pass through 10 cm of lead. Furthermore, muons have a mass of $105{,}7\,\mathrm{MeV} \approx 207 \cdot m_e$. In Münster, the detected rate of muons is approximately 200 muons per square meter and second.

2.2 Characteristics of muons detected at sea level

2.2.1 MIP peak and energy loss distribution

Particles that are able to pass the detector are minimally ionizing, i. e. their energy loss ΔE inside the detector module only depends on the travelled distance and follows a Landau distribution. The latter one looks similar to a Gaussian but introduces an asymmetry. As it cannot be represented by a closed analytical expression, the following approximation [2] will be used:

$$\rho(\Delta E) \approx \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left((\Delta E - \Delta E_{\max}) + e^{-(\Delta E - \Delta E_{\max})}\right)\right], \tag{2.3}$$

where $\Delta E_{\max}$ is the most probable energy loss referred to as MIP (minimum ionizing particle) peak.

2.2.2 Dependency of the detected spectrum on zenith angle

The measured flux I_μ of low-energy muons with energies $\leq 5\,\mathrm{TeV}$ depends on zenith angle θ as follows:

$$I_\mu \sim \cos^2\theta \tag{2.4}$$

For greater angles muons need to travel a longer distance through the Earth's atmosphere, thus they are more likely to be absorbed before reaching sea level. On the other hand, it becomes more probable that a high-energy pion or kaon decays into a muon with energies $> 5\,\mathrm{TeV}$. Hence, their measured flux follows:

$$I_\mu \sim \frac{1}{\cos\theta} \tag{2.5}$$

In comparison, the flux of low-energy muons is dominant.

2.2.3 Mean lifetime of muons

Muons decay by almost 100 % probability within the following processes:

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e \tag{2.6}$$

$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e \tag{2.7}$$

Their decay follows an exponential law:

$$N(t) = N(0)\exp(-t/\tau) \tag{2.8}$$

It can be derived from the differential equation

$$\dot{N}(t) = -\frac{1}{\tau}N(t) \tag{2.9}$$

using separation of variables. Hence, the more muons the more decays. Furthermore, τ is the so-called mean lifetime. For free muons, positive or negative, it is:

$$\tau_{\text{free}} = (2{,}19703 \pm 0{,}00004)\,\mu\text{s} \tag{2.10}$$

Negatively charged muons can also be captured by a proton inside the detector via

$$\mu^- + p \longrightarrow n + \nu_\mu\,. \tag{2.11}$$

It is

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\text{free}}} + \frac{1}{\tau_{\text{captured}}} \tag{2.12}$$

and thus

$$\tau_{\text{total}} < \tau_{\text{free}}\,. \tag{2.13}$$

Literatur

[1] Author unknown. „Ein Detektor für kosmische Strahlung“. Instruction manual, handed out at WWU Münster.

[2] C. Niebuhr. *Vorlesung 5*. URL: http://www.desy.de/~niebuhr/Vorlesung/Hannover/Vorlesung5.pdf (besucht am 27. 11. 2019).