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Physics

Monte Carlo Studies of the Muon Decay Detection at Cherenkov Neutrino Telescopes

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Muon decay is a thorougly studied process in particle physics, offering insights into the weak interaction. Muons, heavier counterparts of electrons, are unstable and decay into electron (or positron) and two neutrinos ($\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$). The ability to observe this decay in new-generation Cherenkov neutrino telescopes presents an exciting opportunity for advancing their research program. These telescopes operate by detecting the Cherenkov radiation emitted when high-energy particles travel faster than light through a transparent medium like water. In this study, we conducted Monte Carlo simulations to evaluate the response of these telescopes to muon decay events. Our results indicate that the detection capabilities of these new telescopes, exemplified by KM3NeT, offer a promising avenue for observations of muon decay, which could be applied for detector calibration, the estimation of the muon charge ratio and other topics. *© 2025 Bull. Georg. Natl. Acad. Sci.*

neutrino telescope, Cherenkov radiation, muon decay, Michel electron, digital optical module

Muon decay. Muon (μ) is an elementary particle with a unitary electric charge of -1 (+1 for the antimuon) and a spin of ½. On Earth, most of the naturally occurring muons are created by decay of pions ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$; $\pi^+ \rightarrow \mu^+ + \nu_\mu$) produced in interaction of cosmic rays with atmosphere. According to the Standard Model, muon decays (almost 100%) through weak interactions mediated by the W boson into an electron (or a positron) and two neutrinos ($\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$; $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$), as shown on Feynman diagram in Fig. 1. This decay is often referred to as the Michel decay [1].

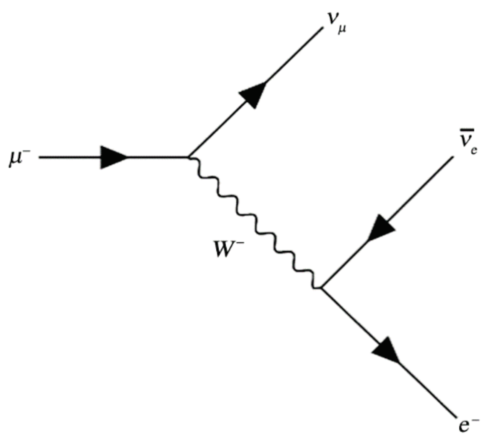

Fig. 1. Feynman diagram of the Michel muon.

The muon lifetime is equal to τ_μ=2.1969811±0.0000022 μs and its mass is m_μ = 105.7 MeV/c^2 [2]. Michel electron energy spectrum reaches its maximum and has a sharp edge at the energy value of E_e = 52.8 MeV, as shown in Fig.2.

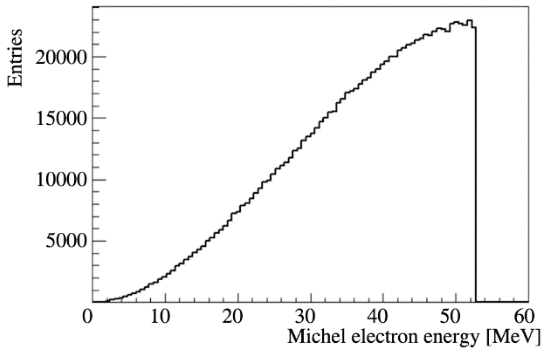

Fig. 2. Michel electron energy distribution obtained with simple ROOT simulations of the decay of 10^6 muons.

Cherenkov neutrino detectors are optimized for the detection of neutrino events [3-5], but they might have additional feature, such as reconstructing muon decays. New-generation detectors, such as KM3NeT consist of thousands of digital optical modules (DOMs) arranged on vertical strings anchored to the seafloor. These optical modules, with a proven effective background suppression, signal recognition and sensitivity to the incoming direction of photons, offer a promising platform for detecting muon decay events. Each DOM contains multiple photomultiplier tubes (PMTs) that detect the Cherenkov light [6]. By analyzing the timing and spatial distribution of the detected Cherenkov light across many DOMs, the trajectory and energy of the secondary particle (mostly muon) can be reconstructed. This information is used to infer the direction and energy of the original neutrino. There are two event classes that can be identified: track-like events and cascade-like events. The track-like events are generated by muons that are produced inside or near the detector through charged current (CC) interactions of muons and tau neutrinos, while cascade-like events are produced through CC interactions of electrons and tau-neutrinos and in neutral current (NC) interactions. A track-like event is characterized by the Cherenkov light from the emerging muon that can travel large distances through Earth rock and sea water. Muons might stop inside detector volume and decay. The reconstruction of muon decay can be used for detector calibration and for studying the muon charge ratio. To check this possibility, Monte Carlo simulated events were used. In this paper, we present results of the study of muon decay using optical modules which includes muon decay simulations and optical modules response.

Computing at Tbilisi State University. For our analysis, we used Monte Carlo events simulated on the local server at High Energy Physics Institute of Tbilisi State University. TSU hosts a Linux based computing infrastructure. It is mainly used as KM3NeT Tier-2 Tbilisi (Tier-2 TSU) hub for local members of the collaboration. It is also used as hub for members of the Institute. Local server software resources consist of KM3NeT software developed in the framework of collaboration and widely used software packages for high-energy physics computing as well. This includes data analysis and simulations software. To make the hub more accessible, the python-based user-friendly web environment – JupyterHub is installed [7].

Monte Carlo Simulated Data

The analysis presented here is based on Monte Carlo (MC) simulations of muon decay and Cherenkov detector's response. According to the simulations, all particles emerging from muon decay are propagated with the GEANT4-based software [8]. GEANT4 generates Cherenkov photons from primary and secondary particles, tracks them through the medium (in this case – sea water) taking into account absorption and scattering. These Cherenkov photons and detected by the PMTs. Cherenkov radiation occurs when a charged particle travels through a dielectric (non-conducting) medium at a speed greater than the phase velocity of light in that medium.

$$v > \frac{c}{n}. \tag{1}$$

In other words when a particle has a kinetic energy:

$$E_k > \left(\frac{n}{\sqrt{n^2 - 1}} - 1 \right) m, \tag{2}$$

where v is the speed of the charged particle; c is the speed of light in a vacuum; n is the refractive index of the medium through which the particle is traveling (for sea water n = 1.33-1.35), m is the mass of a particle. For muon this energy equals to $E_k = 52$MeV, for electron $E_k = 0.25$ MeV.

To study the detector response KM3NeT digital optical module or DOM was chosen as an example of new generation Cherenkov detector. The KM3NeT Digital Optical Module is a transparent 17-inch diameter glass sphere comprising two separate hemispheres, housing 31 photo-multiplier tubes (PMT) and their associated readout electronics. The design of the DOM has several advantages over traditional optical modules using single large PMTs, as it houses three to four times the photo-cathode area in a single sphere and has an almost uniform angular coverage. As the photo-cathode is segmented, the identification of more than one photon arriving at the DOM can be done with high efficiency and purity. In addition, the directional information provides improved rejection of optical background.

In this study, 10^6 muons with kinetic energy equal to zero were simulated. This means the only particle causing Cherenkov radiation is a Michel electron. Simulations also take into account muon capture by a nucleus in the water, leading to different decay time for muons and antimuons [9]. Muons were randomly (uniformly in x,y,z) distributed around with a maximum distance of 20 m from the DOM surface.

Results

Figure 3 shows distributions of number of hits (signals) for different distance from DOM, for different PMT multiplicity Efficiency to get at least one hit from 1 meter distance roughly equals to 0.5 and it drops quickly to 0.1 at 5 meters distance and its value is less for greater PMT multiplicity. Because of such low efficiency at greater distances, it was decided to do further analysis in the 5-meter range from DOM.

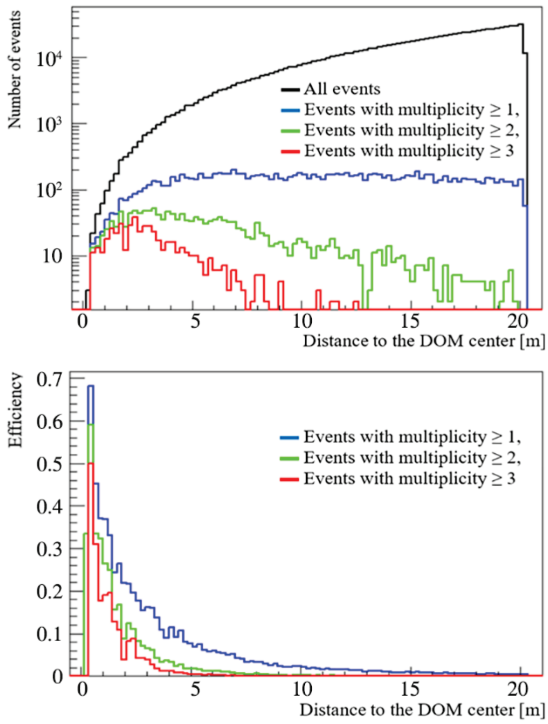

Fig. 3. Number of events distribution (top) and expected efficiency of getting a hit (bottom), respect to the distance from the DOM.

The next step was to extract muon decay time from simulated data. For this task, the ROOT software was used. The decay process of 10^6 atmospheric muons was simulated within a 5-meter range from the DOM. Decay time extracted from the data can be seen in Figure 4 for muons and antimuons (1861 ± 15 ns for muons, 2205 ± 14 ns for antimuons). The results show us that decay is detectable in the DOM.

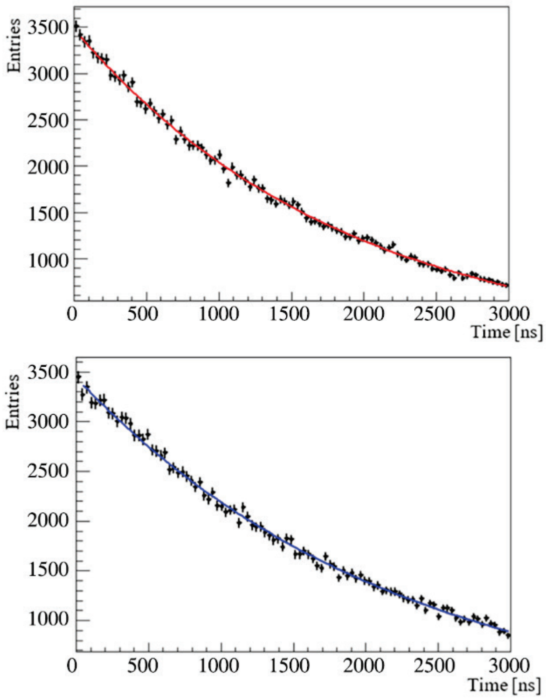

Fig. 4. Muon (top red) and antimuon (bottom blue) decay time reconstructed from MC hits.

This paper doesn't include the study of background processes, such as scattered muon Cherenkov light and K^{40} background, caused by radioactive potassium decay in the seawater ($^{40}K \rightarrow {}^{40}Ca + e + \nu_e$), being necessary to extract decay signals in real data.

Conclusion

This work studies muon decay detection within Cherenkov neutrino telescopes, using KM3NeT as an example of a new-generation Cherenkov neutrino detector. The analysis includes Monte Carlo simulations and detailed analysis of muon decay. The simulations demonstrate that KM3NeT's digital optical modules can successfully detect the Cherenkov light emitted by Michel electrons when a muon decays within a few meters. The expected difference in decay time between muons and antimuons was observed. Background processes still require further study to effectively extract decay signals from real data.

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ფიზიკა

მიუონის დაშლის დეტექტირების შესწავლა მონტე-კარლოს მეთოდის გამოყენებით ჩერენკოვის ნეიტრინულ ტელესკოპებზე

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(წარმოდგენილია აკადემიის წევრის ა. ხელაშვილის მიერ)

მიუონის დაშლა სუსტი დაშლების ერთ-ერთი ცნობილი მაგალითია და ნაწილაკების ფიზიკაში კარგადაა შესწავლილი. მიუონი არასტაბილური ელემენტარული ნაწილაკია, რომელიც ელექტრონად და ორ ნეიტრინოდ იშლება ($\mu^{\pm} \to e^{\pm} + \nu + \bar{\nu}$). ახალი თაობის ნეიტრინულ ტელესკოპებზე ამ დაშლის დამზერის შესაძლებლობა საშუალებას იძლევა მაღალენერგიული ნაწილაკები და მათი ურთიერთქმედება უკეთ შევისწავლოთ. ნეიტრინული ტელესკოპები აფიქსირებს ჩერენკოვის გამოსხივებას, რომელიც გამჭვირვალე გარემოში, მაგალითად, წყალში სინათლის სიჩქარეზე სწრაფად მოძრავი მაღალენერგიული ნაწილაკის გავლისას წარმოიქმნება. წარმოდგენილ ნაშრომში, მონტე კარლოს სიმულაციების საშუალებით, KM3NeT დეტექტორის მაგალითზე, შევისწავლეთ ამ ტიპის ნეიტრინული ტელესკოპების გამოძახილი მიუონური დაშლების მიმართ. შედეგები გვაჩვენებს მიუონის დაშლების დამზერის შესაძლებლობას, რითაც წარმოაჩენს ამ ტიპის ინოვაციური დეტექტორების განსაკუთრებულობას. აღნიშნული, შესაძლებელია მომავალში გამოყენებულ იქნეს დეტექტორის კალიბრაციაში, მიუონის მუხტური წილის შეფასებასა და სხვა ამოცანებში.

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