

Lateral distribution cosmic ray muon coincidences up to 36 m

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ABSTRACT

Primary cosmic ray particles comprise about 85 % protons, 12 % helium, 3 % iron, and heavier elements. These particles interact with the Earth's atmosphere, generating the Extensive Air Showers (EAS). Among the particles produced are pions and kaons, which decay into cosmic ray muons. In this research, the lateral distribution of cosmic ray muons was measured using two-fold coincidences. Four NaI (Tl) detectors and the associated electronics were used in the measurements of cosmic ray muons. The detectors were positioned from 0 to 36 m at regular intervals. The muon count rate was observed to decrease as the distance between the detectors increased. The measurements were fitted to the Nishimura–Kamata–Greisen (NKG) function to analyze the lateral distribution. Monte Carlo (MC) simulations of EAS were performed using the Cosmic Ray Simulations for the KASCADE Grande (CORSIKA) program. The simulations made use of EPOS and GHEISHA models for high and lower energies respectively.

- The measurements for the two-fold coincidence are consistent with the NKG function.
- The simulated and measured data were found to be in agreement.
- The knowledge gained from the lateral distribution of cosmic ray muons is essential for the understanding of the development of extensive air showers.

Specifications table

Subject area:	<i>Physics and Astronomy</i>
More specific subject area:	Lateral distribution of cosmic ray muons
Name of your method:	Two-fold coincidence technique
Name and reference of the original method:	<i>MEASUREMENT OF LATERAL DISTRIBUTION OF COSMIC RAY MUONS USING TWO-FOLD COINCIDENCE TECHNIQUE.</i>
Resource availability:	The data is available in this article

Method details

Introduction

Galactic and extragalactic sources of cosmic radiation include supernova explosions, the sun, active galactic nuclei (AGN), pulsars, and others. The origin of primordial cosmic radiation can be seen in its sources [1]. Primary cosmic radiations are cosmic rays that arrive at the Earth's atmosphere unmodified. This includes photons with high energy, alpha particles, protons, and heavier nuclei.

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Secondary cosmic radiation results from the interaction of primary cosmic radiation, which produces electromagnetic, hadron, muon, and neutrino components. These elements combine to generate Extended Air Showers (EAS).

When a primary cosmic ray proton (p) or nucleus collides with nuclei in the atmosphere, secondary particles such as the pions (π) and kaons (K) are produced [2]. The proton loses energy as a result of these collisions. The produced pions and kaons can be charged or neutral. Charged pions and kaons decay to muons (μ) which further decay into electrons (e^-) and positrons (e^+). Muons of sufficient energy can reach the earth’s surface and beyond. Cosmic ray muons serve as penetrating probes to explore the cosmos [3].

Muons lose energy as they travel through the atmosphere. Muons are about 200 times more massive than electrons and they have a mean life of 2.2 μ s. These muons continuously hit the Earth’s surface at a rate of around 10,000 muons per minute per square meter [4]. Muons are measured by the use of particle detectors. In a previous study, three detectors were used for measurements in coincidence. The data showed that the coincidence technique improves on the measured values of the muon flux [5].

This study used four detectors in two-fold coincidence to measure the lateral distribution of cosmic ray muons. We have also determined the variation of cosmic ray muon count rate on an hourly basis in order to understand the flux variations during the day. The Cosmic Ray Simulation for KASCADE Grande (CORSIKA) program was used to carry out Monte Carlo simulations of the Extensive Air Showers. The EPOS LHC and GHEISHA models were used in this study for the high and low energies respectively.

Cosmic ray muons can penetrate significant depths in the atmosphere, making them valuable tools for studying the particle interactions in the atmosphere [6]. The studies of the lateral distribution of cosmic ray muon coincidences (decoherence curve) provides a means to understand the interaction of particles in the earth’s atmosphere and hence the Extensive Air Showers (EAS) [7]. The knowledge of the lateral distribution of cosmic ray muons enables one to understand the interactions of cosmic ray particles in the atmosphere and the formation of EAS.

Material and methods

The following equipment’s were used for the measurements of cosmic ray muons in this work:

Four thallium-activated sodium iodide (NaI (TI)) detectors, high voltage power supply, Nuclear Instrument Module (NIM) with the following components: LeCroy model 612 AM (Amplifier), LeCroy model 622 (Quad Coincidence) Model 620 BL 8- channel discriminator, coincidence counter, ORTEC 771-timer counter and a personal computer for Monte Carlo simulations.

Two-fold coincidences

Measurements of cosmic ray muons were carried out from 6th to 29th June 2023 from 0900 h to 1700 h using a two-fold coincidences technique as illustrated in Fig. 1. Counts were taken at different times of the day at varied distances. The distance between each pair of two detectors has been increased to a maximum of 35.5 m. The output from the detectors was fed to the

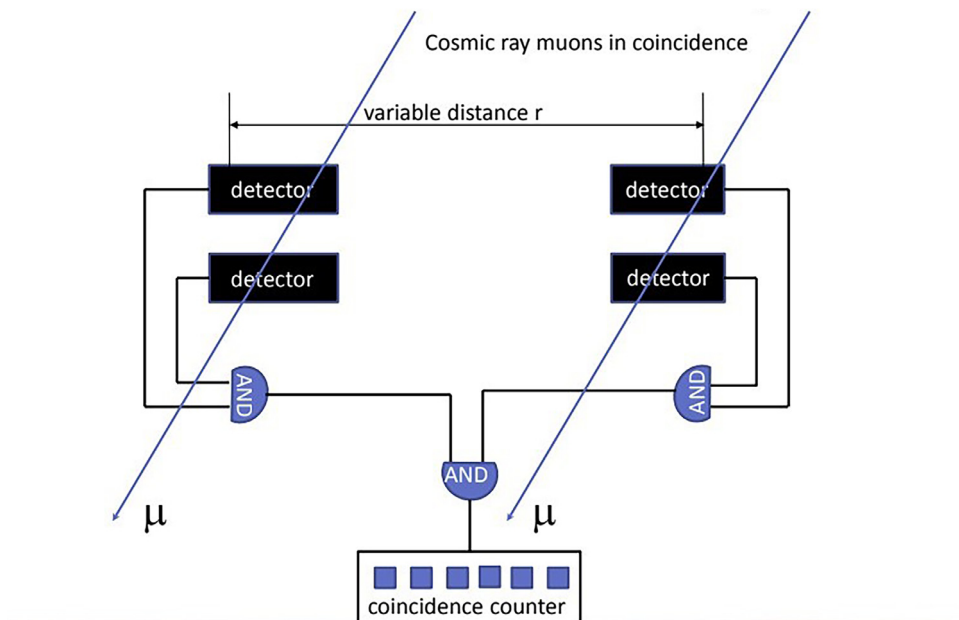


Fig. 1. Experimental setup for the detection of cosmic ray muons in two-fold coincidence.

amplifier and then to the discriminator. This is to filter out the noise from the signal. The output from the discriminator was fed to the quad coincidence unit. The coincidence rate was calculated for each distance between the detectors. The statistical uncertainties were considered and data was recorded in counts/minute. The data was converted to coincidence flux (counts/min /m²/sr) taking into account the detector acceptance.

Measurements at the AND GATE section

This work below shows how the two-fold coincidences appear for the 3-AND gates. For there to be coincidences detectors 1 and 2 have to detect muons for both detectors within a few nanoseconds same as detectors 3 and 4. For there to be a two-fold coincidence the set Detector 1 and 2 with the set of Detector 3 and 4 have to be in coincidence. This technique ensures that false coincidences of either gamma or K⁴⁰ from the ground or walls are filtered giving quality data.

Detector acceptance

Considering two detectors 1 and 2 with surface areas A1 and A2, the solid angle of acceptance for muons arriving at the element of area δA_2 on detector 2 is estimated as follows:

$$\Delta\Omega_2 = \frac{A_1}{d^2} \quad (1)$$

where d is the distance between the detectors 1 and 2.

The coincidence flux in (counts/min /m²/sr) is estimated as follows:

$$\delta NC = N \delta A_2 \Delta\Omega_2 \quad (2)$$

$$\approx N \delta A_2 \cdot A_1 / d^2 \quad (3)$$

where N is the count rate in counts/minute

This work involves four detectors set in two-fold coincidence to determine the flux. Each of the four detectors has a surface area of $A_1 = A_2 = 20 \text{ cm}^2$. Each pair of detectors is separated by a distance of $d = 8 \text{ cm}$. The solid angle of acceptance for one pair of detectors is therefore $\Delta\Omega_2 = 6.25 \text{ sr}$. This value was multiplied by 2 to get the overall solid angle of acceptance for the four detectors operated in coincidence. From Eq. (3) the muon flux is estimated by $N \times 0.1$. The factor of 0.1 converts the measured count rates in the units of (count/minute) to coincidence flux in the units of (counts/min /m²/sr).

Monte Carlo simulations

Monte Carlo the simulations of EAS were carried out using CORSIKA [8]. The following hadronic interaction models—EPOS LHC and GHEISHA for the high and low energies respectively were selected. The primary particles used in the simulations were proton, helium, and iron. The energy range of the primary particle was from 10⁴ GeV to 10⁵ GeV.

The slope of the energy spectrum used in the simulations was a constant value of -2.7 . The horizontal flat orientation for the detector was selected during the simulations. The trajectory of the primary particles used in the simulations was specified by zenith angle from 0 to 69° and the azimuthal angle from -180° to 180° . The values of the earth's magnetic field used in the MC simulations were as follows: -12.7973 T vertically and 30.89 T horizontally corresponding to the magnetic field of Nairobi. The energy cuts for the simulations in this work were as follows: 9 GeV for hadrons and muons; 10⁶ GeV for electrons and photons. The electron and photon component of the EAS was of no interest in this work, hence the high values of their energy cut-off used in the simulations. This reduced on the computational requirements (space/memory) during the simulations.

Method validation

Results and discussions

The dataset presented in Table 1 comprises measurements of cosmic ray muons at various times of day, as well as the relevant distance, average count rate (c/min), coincidence flux (counts/min /m²/sr), and statistical uncertainty. The data was collected during the day, from 0900 h to 1700 h, and is indicated in (Table 1).

Differences in the coincidence rates at various distances are observed. The coincidence rate decreases as the distance between the detectors increases. The lateral spread of the coincidences depends on the primary particle initiating the shower. The heavier the primary particle the larger the spread of the EAS [9].

As muons travel through matter, they have a higher probability of undergoing decay as they cover more distance. The longer their path through a material, the greater the likelihood that they will decay into other particles. This leads to a reduction in the number of muons that can be detected as they traverse greater distances [5,10,11].

Table 1
AND gate truth tables representing the 3 AND gate.

INPUT		OUTPUT
D1	D2	O12
0	0	0
0	1	0
1	0	0
1	1	1

INPUT		OUTPUT
D3	D4	O34
0	0	0
0	1	0
1	0	0
1	1	1

OUTPUT		AND
O12	O34	01234 02FC
0	0	0
0	1	0
1	0	0
1	1	1

D1 – DETECTOR 1.
 D2 – DETECTOR 2, 02FC – OUTPUT TWO-FOLD COINCIDENCE.
 D3 – DETECTOR 3.
 D4 – DETECTOR 4.
 O12 – OUTPUT 12.
 O34 – OUTPUT 34.

NKG function

The lateral distribution of cosmic ray muons was analyzed using the NKG function. The NKG function was fitted to the two-fold coincidence measurements for the cosmic ray muon.

$$F(R) = a \cdot \left(\frac{R}{R_0}\right)^b + \left(1 + \frac{R}{R_0}\right)^c \tag{4}$$

where *a* is the normalization factor

*R*₀ is the Moliere radius
b and *c* are the shower age

The following values were obtained after fitting the NKG function to the two-fold coincidence in (Table 2), and the following parameters were obtained the normalization factor was 4.37 ± 1.62, the Moliere radius was 0.35 ± 0.13, and shower ages were 5.77 ± 0.47 and 7.60 ± 0.24 respectively.

Monte Carlo simulations of extensive air showers

Extensive Air Shower (EAS) simulations were performed using the CORSIKA program version 76,900. The simulations were conducted using the EPOS LHC model for the hadronic interactions at high energies (>80 GeV) and GHEISHA for the lower energies. The total number of primary particles for the EAS was about one hundred thousand in the proportion of 85:12:3 for proton, helium, and iron respectively. The simulated coincidence rates as a function of the distance between the detectors were analyzed (Fig. 2).

Comparison between experimental data and simulated data

The experimental data and simulated data were compared. Comparing the graph for the combined lateral distribution of cosmic ray (CR) muons for 100,000 showers using EPOS LHC to data using the two-fold coincidence technique yielded the result (shown in Fig. 3). The experimental data indicated a consistent trend with the EPOS LHC simulation. This facilitates the accurate application of physics for the lateral distribution of cosmic ray muons in this technique. The combination of experimental data and model comparisons provides an understanding of EAS formations and estimates primary composition. However, there is a bit of variation in data points of cosmic ray muons from 0 to 8 m followed by consistency beyond 8 m. The variation of muon coincidence rates at distances below 8 m, followed by an agreement for lateral distribution, can be attributed to the nature of muon propagation

Table 2
Measurement of cosmic ray muons using the two-fold coincidence.

Time of the day	Date	Distance (m)	Coincidence flux (counts/min /m ² /sr)
1500 h	6th June 2023	1	0.0643 ± 0.0001
1600 h	6th June 2023	2	0.0633 ± 0.0003
1700 h	6th June 2023	3	0.0170 ± 0.0000
1600 h	7th June 2023	4	0.0353 ± 0.0027
1500 h	7th June 2023	5	0.0253 ± 0.0046
1400 h	7th June 2023	6	0.0298 ± 0.0002
1100 h	7th June 2023	7	0.0100 ± 0.0010
1000 h	7th June 2023	8	0.0115 ± 0.0006
1100 h	8th June 2023	9	0.0043 ± 0.0003
1400 h	8th June 2023	10	0.0032 ± 0.0007
1100 h	9th June 2023	11	0.0112 ± 0.0005
1300 h	23rd June 2023	12	0.0038 ± 0.0022
1430 h	23rd June 2023	13	0.0032 ± 0.0009
1200 h	29th June 2023	14	0.0023 ± 0.0001
1100 h	27th June 2023	15	0.0020 ± 0.0000
1400 h	23rd June 2023	16	0.0024 ± 0.0001
0900 h	14th June 2023	17	0.0023 ± 0.0001
1400 h	14th June 2023	18	0.0022 ± 0.0002
1100 h	15th June 2023	19	0.0019 ± 0.0001
1500 h	16th June 2023	20	0.0022 ± 0.0001
1200 h	29th June 2023	21	0.0016 ± 0.0004
1620 h	17th June 2023	23	0.0022 ± 0.0003
1420 h	17th June 2023	24	0.0015 ± 0.0002
1150 h	22nd June 2023	25	0.0014 ± 0.0003
1300 h	19th June 2023	27	0.0013 ± 0.0000
1600 h	19th June 2023	28	0.0012 ± 0.0001
1400 h	21st June 2023	30	0.0011 ± 0.0001
1030 h	24th June 2023	35.5	0.0005 ± 0.0001

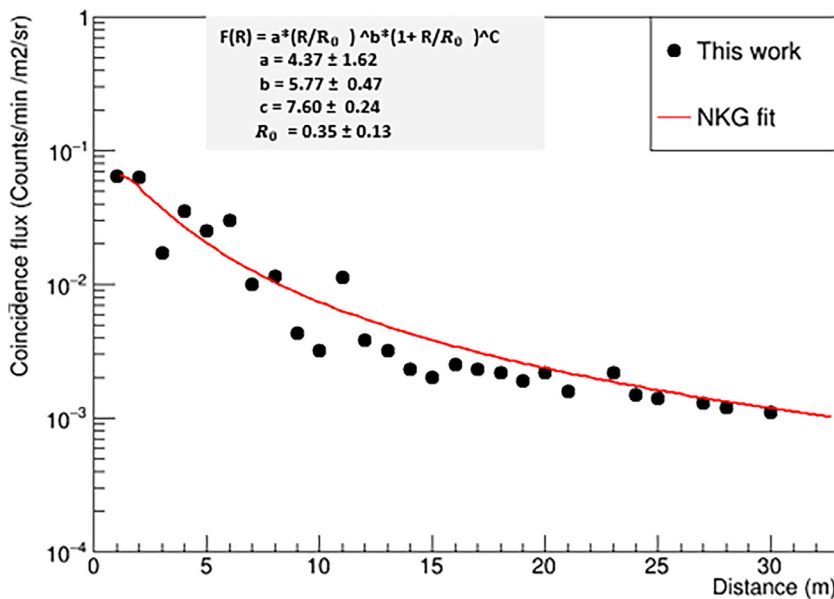


Fig. 2. Graph for the NKG fit for the two-fold coincidences measurements for cosmic ray muons.

and interactions in matter. This phenomenon has been observed in this experiment for the two-fold coincidence technique. Muons undergo multiple events as they traverse matter, such as the Earth’s crust or shielding material. These varying events can cause fluctuations in the number of muons detected at short distances, leading to variations in the count rates [12]. This variation in data points is a result of the Coulomb interactions between muons and atomic nuclei in the material.

Muons arriving from different directions can experience varying energy loss levels, leading to fluctuations in count rates. The angular distribution of muons can affect their detection rates at different distances from the source. The range of muons in matter depends on their energy. Due to ionization and energy loss processes, lower-energy muons may lose energy rapidly at short distances.

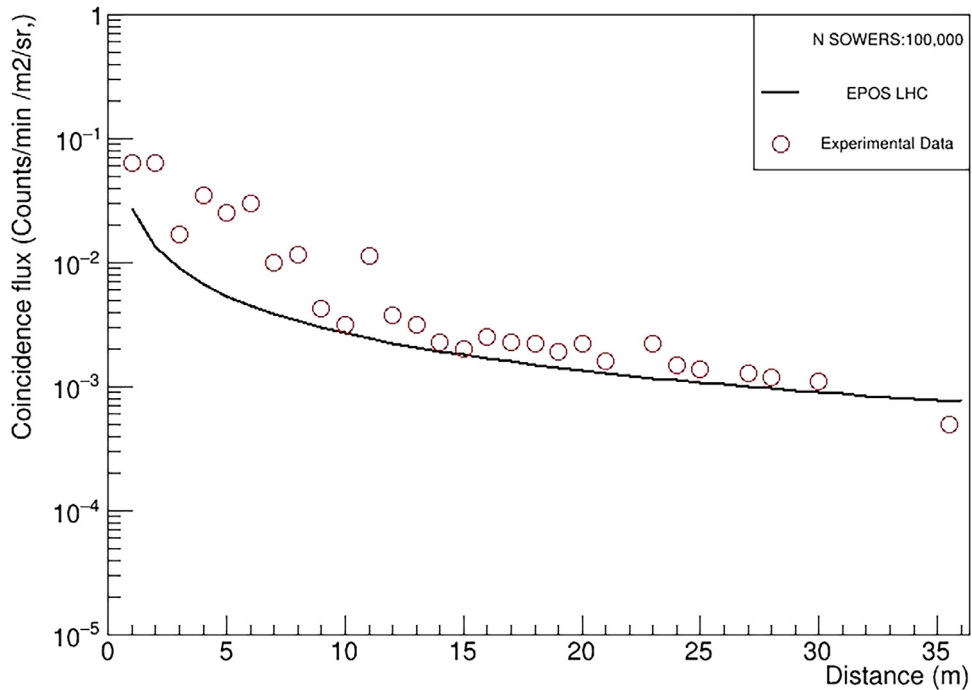


Fig. 3. Comparison of measurements of cosmic ray muons using the two-fold coincidence technique and the Monte Carlo simulations using EPOS LHC model in CORSIKA.

This energy loss can result in some muons not reaching the detectors, contributing to the muon coincidence rates. At larger distances, the variation effects become less pronounced, and the muon count rates tend to be more consistent [13].

Conclusion

The measured coincidence rates for cosmic ray muons using the two-fold coincidences technique are found to decrease with increasing distance between the detectors. The measured cosmic ray muon coincidence rate is in agreement with the Nishimura Kamata Greisen (NKG) function and the Monte Carlo simulations using the EPOS LHC model in the CORSIKA program. This indicates that the model predictions are suitable for the study of EAS.

Ethics of statements

N/A.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Veronica N. Kihagi: Conceptualization, Methodology, Data curation, Writing – original draft. **Samuel M. Chege:** Data curation, Formal analysis. **Nadir O. Hashim:** Data curation, Supervision, Writing – review & editing. **Naftali K. Kimani:** Data curation, Supervision, Writing – review & editing. **Claus Grupen:** Validation, Visualization, Resources.

Data availability

Data will be made available on request.

Acknowledgments

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