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Time correlation of cosmic-ray-induced neutrons and gamma rays at sea level

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A B S T R A C T

The neutrons and gamma rays produced by cosmic ray interactions in spallation and evaporation processes of air nuclei are time-correlated. The occurrence of their counts in a fixed time interval is not a random (Poisson) distribution, but rather time-correlated bursts of counts. A computational model is developed to explore time correlations of cosmic-ray-induced background of neutrons and gammas at sea level. Their lifetimes in air showers, multiplicity distributions, coincidence count statistic, and excess variance are analyzed. The effects of latitude and area size on multiplicity and coincidence distributions are also studied. The coincidence count distributions and Feynman-Y statistic are used to reveal the duration of spallation processes and properties of multiplying media. It is found that the coincidence count distribution in fixed time intervals deviates from a Poisson distribution. The Feynman-Y is about an order of magnitude greater for gammas than that for neutrons. For both neutrons and gammas, the duration of time-correlated multiplying processes in air showers is ~250 μs.

1. Introduction

Primary cosmic rays incident upon the Earth's atmosphere mainly consist of protons (about 87 percent) [1]. After impacting the upper atmosphere, high-energy protons interact with air nuclei generating a cascade air shower. At the Earth's surface, the background radiation consists of neutrons and protons (nucleonic component), electrons and gammas (soft component), and muons (hard component) [2–6]. A vast amount of experimental and theoretical data is available on cosmic rays in the Earth's atmosphere, at sea level, and underground [3]. Many of the studies have been focused on nuclear interactions and spatial structure of air showers [7,8], their propagation [9], composition [10], energy and angular spectra of particles [11,12]. Several attempts have been made to study the longitudinal structure of the shower core by investigating the arrival-time distribution of shower particles. In pioneering work of Bassi et al. [13], the instantaneous spatial distributions of particles in extensive air showers at sea level have been studied by measuring their times of arrival. It was found that the electron–photon component is confined in a thin disk of thickness 1–2 m, slightly in advance of a thicker muon disk. Further experiments [14–17] have revealed more details in the structure of air-shower electrons both near and far from the core axis. The arrival time of muons have been studied using high-speed recordings in order to clarify their longitudinal development through the atmosphere [18–20]. Monte Carlo calculations on the arrival time distribution of particles in air showers have been also carried out [21,22]. These studies of individual extensive air showers have utilized the time distributions of air-shower particles in order to derive information concerning their longitudinal evolution, arrival direction, and shower composition.

Rather less attention has been paid to the analysis of arrival times of particles using statistical techniques for analyzing time correlations, mean values, dispersion and multivariate distributions, although some work has been done in this direction for both the individual air showers and the background radiation of particles at sea level. Theoretical methods of nonlinear analysis have been applied to study the bursts of the count rate of extensive air showers and the correlation of their time series that represent shower arrival times [23]. Large-scale correlations and coincidences in arrival time of extensive air showers have been investigated using ten independent stations scattered over a very large area [24]. The time correlation of cosmic-ray-induced background of neutrons and gammas at sea level has been also investigated to some degree [25–27]. However, the statistical aspects of time correlations such as multiplicities, coincidence count statistic, and excess variance of neutrons and gammas were not analyzed. The importance of statistical methods in the analysis of the temporal and spatial features in cosmic ray data was highlighted by Orford [28]. It is a well established fact that the majority of neutrons is produced in spallation and evaporation processes of air nuclei [2,3]. Since each shower is triggered by a

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single proton, all the secondary neutrons and gammas are, to some extent, time-correlated. Thus, neutrons and gammas produced by cosmic ray interactions with air nuclei are not Poisson distributed (not independent random events), but can be characterized by bursts of time-correlated counts [27].

The spread in arrival time and coincidence correlations of neutrons and gammas in the air shower are of fundamental and practical significance. From the point of view of fundamental science, these distributions can reveal the duration of spallation processes and excess variance compared to a random Poisson distribution. The properties of the multiplying medium can be deduced through a statistical distribution of counts. Practical importance is related to the detection of Special Nuclear Materials (SNM) [29–31]. These materials emit multiple neutrons and gammas simultaneously, very unique time-correlated signatures, via spontaneous or induced fission. The fact that SNM emits multiple neutrons simultaneously (time-correlated) is used in modern neutron detectors to detect fission events. These two features, multiplicity and time-correlation, are the way of distinguishing the different types of neutrons. However, the neutron detectors are unable to discriminate time-correlated neutrons induced by cosmic events from those emitted by a fission source. The neutron and gamma background produced by cosmic rays can be comparable or even more intense than that from fission of highly enriched uranium (HEU), making the detection of HEU extremely difficult [32,33]. If the SNM multiplicity and coincidence distribution can be uncoupled from cosmic-ray interferences, then the identity of a fission source can be determined. However, the arrival time, coincidence correlations, large-scale structure, angular, energy and area distributions of neutrons and gammas from atmospheric cascade showers at sea level are not understood. There is a need in analyzing the arrival time of cosmic-ray-induced neutrons and gammas and understanding their multiplicity, coincidence count and excess variance distributions.

The goal of this study is to gain a better understanding of time-correlation of cosmic-ray-induced background of neutrons and gammas at sea level. We have developed and implemented the statistical methods in order to analyze the stream of arrival times of neutrons and gammas, and investigated their lifetimes and multiplicity distributions in air showers, coincidence count statistic, and excess variance. The effects of latitude and the size of area on these distributions are studied. The paper is organized as follows: in Section 2 we describe the computational models; in Section 3 the results are presented; Section 4 contains discussion; and conclusions are provided in Section 5.

2. Computational models

Our specific goal is to analyze the arrival times of neutrons and gammas from multiple air showers (i.e. radiation background) within a specified area at sea level. Their times of arrival are sampled using the cosmic-ray shower library (CRY) [34] that is described below in this section. In order to register arrival times, distinct time axes are introduced for neutrons and gammas. Time points corresponding to arrival times of neutrons or gammas are stored in arrays. The arrival-time statistic is accumulated over several days accounting for billions of air showers. The huge stream of arrival times then serves as an input for the statistical models that are developed and implemented in our MONSOL code. The code calculates lifetime, multiplicity, coincidence count distributions and Feynman-Y statistic.

2.1. Calculation of neutron and gamma lifetimes in air showers

The lifetime distribution of neutrons and gammas in air showers is calculated as follows. For each individual air shower, a clock starts at $t=0$ with a proton impacting the top of the atmosphere. The clock continues to run, and proton-induced cascades of secondary particles are developed. The lifetime of particles in air shower is defined as the time between the particle being born in the atmosphere at some point and the time it is arrived at sea level. Some secondary particles are absorbed, before they can reach sea level. New particles generated in spallation reactions close to sea level may have very short lifetimes. Particles with long lifetimes are produced in evaporation decays of air nuclei. Therefore, lifetimes of neutrons and gammas can vary from microseconds to seconds. The clock stops when all neutrons and gammas are counted from a particular air shower at sea level within a specified area. The distribution of lifetimes is then calculated as an average of neutron and gamma lifetimes in individual air showers.

2.2. Calculation of neutron and gamma multiplicity

Multiplicity means the frequency of the occurrence of 0, 1, 2, etc. neutrons or gammas at sea level within a specified area for each of individual air showers. To calculate multiplicity distributions, the number of neutrons and gammas at sea level is counted for succeeding air showers. The multiplicity distribution is then constructed as an average of multiplicities of individual air showers.

2.3. Calculation of coincidence counting and Feynman variance-to-mean statistic

In order to calculate the coincidence count distribution and the excess variance-to-mean ratio (Feynman-Y statistic), each time axis is divided into time bins of a predetermined time period, the length of which can be different for each of particles [28]. The schematic is illustrated in Fig. 1 with particular time bin widths of $\tau=100$ µs and $\tau=10$ µs for neutrons and gammas, respectively. The arrival time data are then analyzed in fixed time bins with different width τ (400 time distributions were analyzed with widths of 5 µs, 10 µs,… 2000 µs) imposed on the stream of neutron and gamma counts. Let us focus on the stream of neutron counts. After the simulation is finished, there are n_0 time bins with 0 neutron counts, n_1 time bins with 1 neutron counts, etc. The time bins are then arranged in increasing order of the number of counts $k=0, 1, 2,\ldots$ For each of 400 time widths, the coincidence count distributions $\Omega(k,\tau)$ as a function of k is built by normalizing n_k to the total number of time bins K. Finally, there are 400 distributions $\Omega(k,\tau)$ with fixed bin widths of $\tau=5$ µs, 10 µs, 15 µs,… 2000 µs. The derived coincidence count distributions are further processed for estimates of mean and variance. The mean μ is calculated as the average number of counts $\mu=<k>$ in time bins with width τ. The variance is then determined as the mean of the

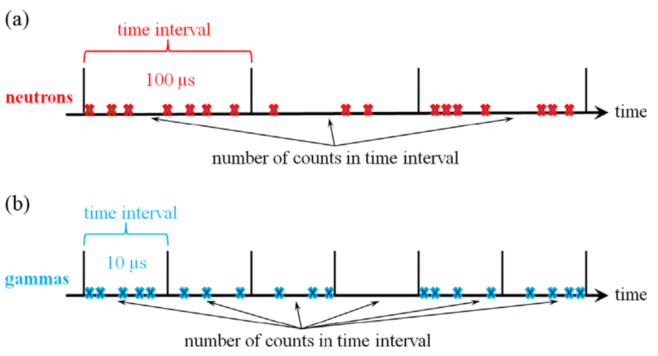

Fig. 1. Representative sketch illustrating the number of (a) neutron and (b) gamma counts within fixed time intervals with particular widths 100 µs and 10 µs, respectively. Particle counts are marked by cross symbols (x).