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Observation of gamma ray bursts at ground level under the thunderclouds

Y. Kuroda [a], S. Oguri [b], Y. Kato [a], R. Nakata [a], Y. Inoue [c], C. Ito [d], M. Minowa [a,*]

[a] Department of Physics, School of Science, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[b] Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1, Oho, Tsukuba, Ibaraki 305-0801, Japan
[c] International Center for Elementary Particle Physics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[d] Oarai Research and Development Center, Japan Atomic Energy Agency, 4002, Naritacho, Oarai-machi, Higashiibaraki-gun, Ibaraki 311-1393, Japan

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ABSTRACT

We observed three γ-ray bursts related to thunderclouds in winter using the prototype of anti-neutrino detector PANDA made of 360-kg plastic scintillator deployed at Ohi Power Station at the coastal area of the Japan Sea. The maximum rate of the events which deposited the energy higher than 3 MeV was $(5.5 \pm 0.1) \times 10^2$ /s.

Monte Carlo simulation showed that electrons with approximately monochromatic energy falling downwards from altitudes of order 100 m roughly produced the observed total energy spectra of the bursts. It is supposed that secondary cosmic-ray electrons, which act as seed, were accelerated in electric field of thunderclouds and multiplied by relativistic runaway electron avalanche. We actually found that the γ-rays of the bursts entered into the detector from the direction close to the zenith. The direction stayed constant during the burst within the detector resolution.

In addition, taking advantage of the delayed coincidence detection of the detector, we found neutron events in one of the bursts at the maximum rate of $\sim 14 \pm 5$ /s.

1. Introduction

In the early 1920's, C.T.R. Wilson suggested that strong electric fields in thunderclouds might accelerate free electrons present in the atmosphere to high energies [1]. Since then, radiation associated with thunderstorms attracted the interest as natural particle-acceleration process and many experiments have been attempted to detect these radiations in various environments.

For instance, bursts of γ-rays were observed on orbiting satellites with energy up to tens of MeV and with duration of less than 1 ms. They are called Terrestrial Gamma-ray Flashes (TGF's) [2].

Recently, Dwyer et al. [3] reported unexpected observation of positron bursts, lasting about 0.2 s, by an airborne detector when the aeroplane flew into a thundercloud.

On the other hand, γ-ray flux enhancements of longer duration of order 100 s were reported in limited environments like high mountains [4–13] and sea level locations in the coastal area of the Japan Sea. They are also called Thunderstorm Ground Enhancements (TGE's) [13]. Japanese groups found that radiation monitoring posts or dedicated scintillation counters in and near nuclear power plants signaled an increase of γ-ray dose which seemed to originate from low altitude winter thunderclouds [14–19]. Especially, Torii et al. [20] found that area of γ-ray flux enhancements was moving as the associated thundercloud passed across the observation site.

Gurevich et al. [21,22] developed the runaway electron model to explain the electron acceleration in the electric field of the thunderclouds. The stopping power of air for electrons decreases with increasing electron energy and goes up again by relativistic effects. Therefore, electric field in the thundercloud may accelerate electrons if the electric force is larger than the minimum stopping power and the electron energy is in the region where the electric force exceeds the stopping power. Such electrons are called runaway electrons. By generating knock-on electrons successively, the runaway electrons can cause an avalanche multiplication process called relativistic runaway electron avalanche (RREA).

Numerical simulations [23–25] with models of thundercloud electric field suggested that the avalanche can be produced continuously if energetic seed electrons are provided, for example, by cosmic ray secondaries. A significant flux of relativistic runaway electrons in the lower parts of thunderclouds is capable of produc-

* Corresponding author.
E-mail address: minowa@phys.s.u-tokyo.ac.jp (M. Minowa).

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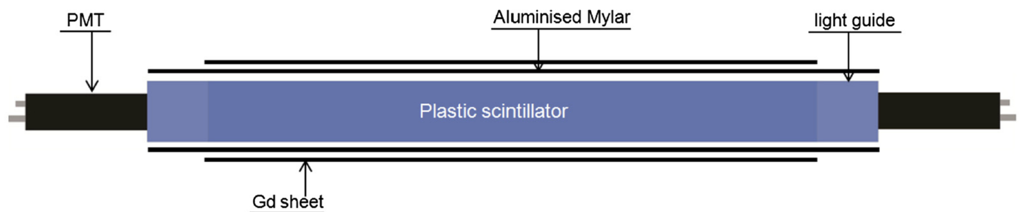

Fig. 1. Structure of the PANDA module.

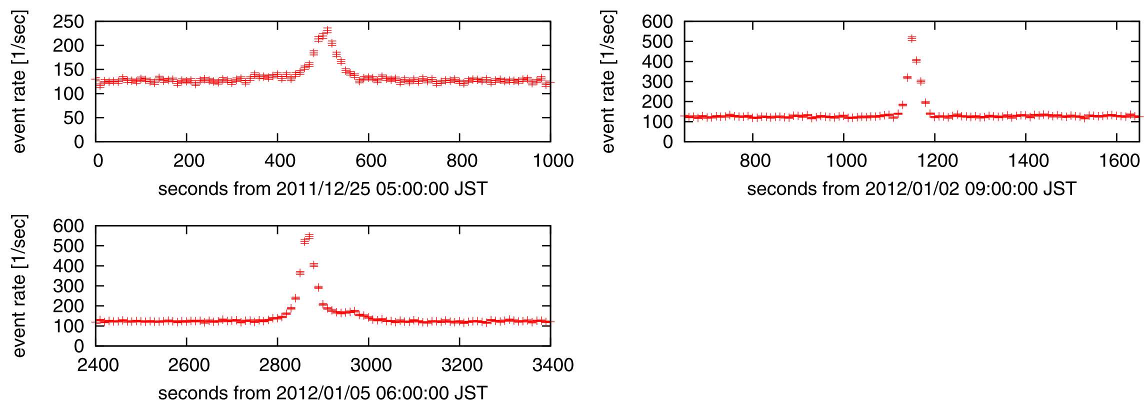

Fig. 2. Temporal variation of the event rates of three bursts.

ing intensive bremsstrahlung which can reach the Earth's surface or the mountain top to account for the observed flux enhancement.

Recently, the neutron bursts associated with thunderstorms were also observed in various experiments [26,12,27–29]. The generation of neutrons is most probably by photoproduction by γ-rays with air nuclei as the detected γ ray spectrum extends above the photonuclear reaction threshold for nitrogen ($\sim$ 10.5 MeV) [30]. It may have a significant effect on ^{14}C dating [31,32] through the neutron capture reaction $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$.

Our research group have developed prototypes of a reactor neutrino detector "PANDA", which stands for Plastic Anti-Neutrino Detector Array [33,34]. We have originally targeted PANDA at presenting the feasibility of reactor monitoring using neutrinos with a tonne-size detector. γ-Rays and neutrons can also be detected by PANDA by Compton scattering and the delayed coincidence of proton recoil and neutron captures. We installed the PANDA detector outside of the reactor building of Ohi power station, which stands near the Japan Sea in Fukui, and tried to watch the reactor operating status via detecting and analyzing the anti-electron neutrinos produced in the reactor core.

We accidentally found that there were intensive increases of γ-ray flux correlated with the winter thunder-storm activity during the measurement. In this paper, we report the investigated properties of these burst events taking advantages of the unprecedented features of the detector including high statistics, good energy response, direction sensitivity and neutron identification.

2. Experimental setup

Our prototype detector "PANDA36" consists of thirty-six (six by six) stacked modules [33,34].

The module was made of a plastic scintillator bar (10 cm × 10 cm × 100 cm) with effective mass of about 10 kg wrapped with aluminized Mylar films and gadolinium (Gd) coated Mylar films (4.9 mg of Gd per cm^2). Each bar was connected to acrylic light guides and photomultipliers on both ends (Fig. 1).

The light intensity ratio seen by each PMT pair allows one to estimate the position of the hit along the module [33]. Using the position of the hit and the charge outputs from each PMT, one can estimate the energy deposit of the hit. The position and energy resolutions were 16 cm and 300 keV for 4 MeV hit on the center, respectively.

Each PMT signal was divided into two: about 15% of the original charge was sent to CAEN V792 multi-event Charge-to-Digital-Converters (QDCs) and the other 85% was passed to CAEN V895 leading edge discriminators.

The discriminator outputs were sent to CAEN V1495 general purpose VME board, which has customizable FPGA unit (Altera Cyclone EP1C20). The logic counted the number of pairs of fired PMTs seeing the same scintillator. Whenever the number of the pairs was greater than or equal to two, the logic generated the gate pulses of 400 ns duration for the QDCs.

The timing of the gate pulses and busy signals from the QDCs were recorded by the same FPGA. We used these time stamps to select neutrino events by delayed coincidence method offline.

The PANDA36 detector was loaded on and transported by a 2-tonne dry van. The detector was deployed beside the Unit 2 of Ohi Power Station (35°32′32″N, 135°39′14″E and about 10 m above the sea level) of Kansai Electric Power Co., Inc on November 18th, 2011. We continued the measurement for 62 days.

Energy calibrations were carried out before the deployment using the Compton edge of ^{60}Co γ-rays. Time drifting of gains of each PMT and QDC was corrected using the peak of through-going cosmic muons in the spectrum of the events.

3. Event-rate increase

In the data acquired by the PANDA36 detector through the neutrino detection experiment, we found unexpected increases of event rate. The trigger rate got twice or higher for a few minutes for the events with total energy deposit larger than 3 MeV independently of the reactor operation.

Temporal variation of the event rate are shown in Fig. 2. Burst duration is defined as an interval whose event rates are 5σ greater