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Calibration of particle detectors for secondary cosmic rays using gamma-ray beams from thunderclouds

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ABSTRACT

After observation of hundreds of Thunderstorm Ground Enhancements (TGEs) we measure energy spectra of particles originated in clouds and directed towards Earth. We use these "beams" for calibration of cosmic ray detectors located beneath the clouds at an altitude of 3200 m at Mount Aragats in Armenia. The calibrations of particle detectors with fluxes of TGE gamma rays are in good agreement with simulation results and allow estimation of the energy thresholds and efficiencies of numerous particle detectors used for studying galactic and solar cosmic rays.

1. Introduction

Networks of particle detectors located on the Earth's surface continuously measure the incident flux of cosmic rays. These networks cover areas up to thousands of square kilometers and are investigating ultrahigh energy cosmic rays (UHECR) which have been accelerated during the most violent explosions in the Universe. Smaller surface arrays of a few square kilometers or less are detecting mostly galactic cosmic rays (GCR) to locate their sources and identify the acceleration mechanisms. Worldwide networks of particle detectors of several square meters area detect solar cosmic rays (SCR) with the aim of understanding solar accelerators and solar terrestrial connections, in particular space weather phenomena. Last but not least, small size spectrometers at atomic power stations monitor radioactive isotopes escaping to the atmosphere. Interestingly, all these four types of detectors are used for research in the emerging field of high-energy physics in the atmosphere, measuring particle fluxes from thunderclouds [9,10].

The Aragats Space Environmental Center (ASEC, [2]) consists of different particle detectors registering almost all types of the secondary cosmic rays. ASEC is operated by the Cosmic Ray Division (CRD) of the Yerevan Physics Institute and is located at altitudes of 2000 and 3200 m, respectively, on the slopes of Mt. Aragats in Armenia. Research at ASEC includes registration of Extensive Air Showers (EAS) with large particle detector arrays, investigation of solar acceleration mechanisms, monitoring of space weather and observations of high-energy particles from thunderclouds. Nearly 500 particle detectors (mostly plastic scintillators read out with photomultipliers) are sending data every minute (or second) to the CRD headquarters in Yerevan. In addition to particle detectors, ASEC includes facilities measuring electric and geomagnetic fields, lightning occurrences and locations, broadband radio emission, a variety of meteorological parameters, and optical images of clouds and lightnings.

Dealing with ultra-high energy, galactic and solar cosmic rays, one of the most important tasks is the determination of the detector response. Usually it is estimated with the help of the GEANT detector simulation package [1], a standard tool in high-energy and astroparticle physics. However, it is important to perform calibration experiments with particle beams, too, with the aim to validate the calculated energy threshold, the response to different types of particles and the efficiency of their detection. While calibration with artificial particle beams is standard practice in accelerator experiments, there are only few attempts to calibrate cosmic ray surface detectors with particle beams. These attempts are related to the calibration of fluorescence detectors with lidars or linear accelerators. For instance, the Telescope Array has used an electron linac with beam pulses of one microsecond length and 10^9 electrons of 40 MeV, injected vertically upwards into the atmosphere to calibrate its fluorescence detectors. The calculated energy deposit of the beam in the atmosphere together with the fluorescence yield per deposited energy gives the number of photons expected at the telescope, which can be compared with the measured number of photons [12].

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At Mt. Aragats, Thunderstorm Ground Enhancements (fluxes of electrons, gamma rays and neutrons from thunderclouds, [3,4]) are usual phenomena, due to frequent storms, especially in spring and autumn. Large fluxes of the registered gamma rays allow precise recovery of the shape (usually a power law) and the slope of the gamma-ray spectrum. A network of large NaI crystals recently installed at ASEC opens new opportunities to use the measured beams of gamma rays *a posteriori* for the determination of the detector response. On a very small energy scale (the energies of electrons accelerated in thunderclouds do not exceed 50 MeV and gamma rays are below 100 MeV), this can be seen as the realization of an old vision of cosmic ray physicists: to arrange a particle accelerator in the atmosphere just above the EAS detectors. The proposed methodology allows estimation and monitoring of one of the important parameters of particle detectors, their energy threshold. We use the gamma ray "beams" to calculate the detector response of various particle detectors located beneath the thundercloud. We demonstrate, how the energy threshold of plastic scintillation counters to MeV gamma rays from the atmosphere can be calibrated with the help of neighboring NaI counters. The basic steps are the following:

(a) We perform a continuous monitoring of the secondary cosmic ray fluxes with the ASEC particle detectors and spectrometers.
(b) We select a data sample of ionizing atmospheric radiation from the thunderclouds (TGE events) where we know that gamma rays contribute a significant part.
(c) We measure the energy spectrum of the TGE events with the help of the network of large NaI spectrometers.
(d) We observe a power law spectrum between 4 and 100 MeV, which we assume to extend below the threshold for the NaI configuration.
(e) We select TGE events for which the electron/gamma ratio in the plastic scintillators should be no larger than 1–2%.
(f) We compare the count rates of plastic scintillators of various types and sizes to the integral energy spectrum recovered by the network of NaI crystal. Assuming a pure power law between 0.5 and 10 MeV and normalizing the scintillator apertures to the NaI aperture, the counting rate can be translated to an integral energy spectrum J_E (with $E > E_{threshold}$).

2. Short description of some of the particle detectors

The NaI network consists of five NaI crystal scintillators, each in a sealed 1-mm-thick aluminum housing. The hygroscopic NaI crystal is protected against humidity by 0.5 cm thick sheets of magnesium, with a transparent window directed to the photo-cathode of the photomultiplier tube PM-49; see Fig. 1. The large photocathode of PM-49 (15-cm diameter) provides good light collection. The range of spectral sensitivity of PM-49 is 300–850 nm, which covers the emission spectrum of NaI(Tl). The sensitive area of each NaI crystal is $\sim$0.032 m^2; the total area of the five crystals is $\sim$0.16 m^2; the efficiency to detect a gamma ray is $\sim$80%.

SEVAN (Space Environmental Viewing and Analysis Network) is a network of particle detectors aimed to improve research of particle acceleration in the vicinity of the Sun as well as solar terrestrial relations. The modules of the SEVAN network (Fig. 2) simultaneously measure the flux and variations of three species of secondary cosmic rays to explore solar modulation effects. Two identical assemblies of $100 \times 100 \times 5$ cm^3 plastic scintillators and lead absorbers sandwich a smaller scintillator assembly of $50 \times 50 \times 20$ cm^3.

The new generation of ASEC detectors comprises 1 and 3 cm thick molded plastic scintillators arranged in stacks (STAND1 detector, Fig. 3) and in cubical structures (CUBE detector, Fig. 4), light from the scintillators is re-radiated by wavelength shifting optical fibers at larger wavelengths and propagates to photomultipliers of the type PM-115M. The DAQ electronics stores all configurations of the signals in the detector channels. If a signal is detected only in the upper scintillator, we register the code "100". The code "010" corresponds to a signal only in the middle scintillator, and so on.

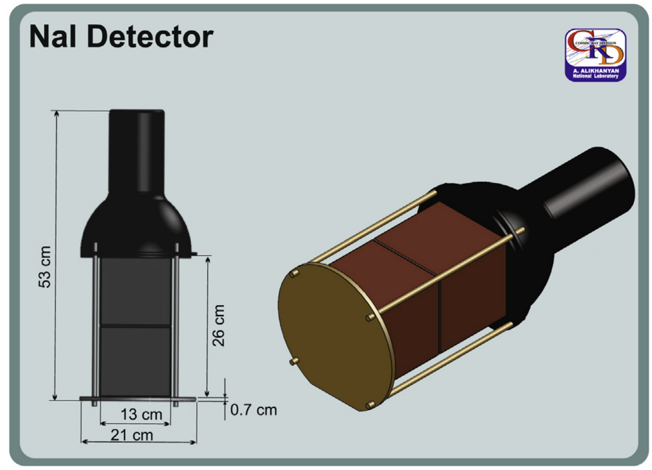

Fig. 1. Configuration of the NaI(Tl) spectrometer.

The Cube detector (Fig. 4) consists of six 1-cm thick plastic scintillators of the same type as used in the STAND1 detector. They surround two stacked 20 cm thick scintillators and can veto charged particles crossing the thick inner scintillators. They allow enrichment of the data sample with neutral particles and in particular estimating the fraction of electrons in the mixed electron and gamma ray flux. Furthermore, there other detectors used which are not described here. The detailed detector charts with all sizes are available from the WEB site of the Cosmic Ray Division of Yerevan Physics Institute: http://crd.yerphi.am/.

3. Recovering gamma ray spectra: the TGE detected on 27 May 2014

The electron flux in the atmosphere is much more attenuated than the gamma ray flux. Therefore, most of the particles registered by the surface detectors are gamma rays. However, sometimes, when a thundercloud is very low above the Earth's surface, the fraction of electrons in the total flux can be sizeable (see details in [6]). For calibration purposes we select from the observed TGEs those with a fraction of electrons not exceeding 1–2% of the total flux. We demonstrate the techniques to select approximately "pure gamma ray" TGEs with the help of a double peaked TGE detected on May 27, 2014.

On May 27, 8:40 UTC, the electric mill located at the Aragats research station recorded a large disturbance in the near-surface electric field related to the arrival of a large thundercloud, see Fig. 5. Ten minutes after a positive boost of the electric field (reaching a maximal value of +15 kV/m), at 8:50 the electric field abruptly changed the polarity to a field strength of -15 kV/m. The decrease of the solar radiation from 1200 to 100 W/m^2 during the TGE confirms the presence of the dense cloud just above the detectors. The high humidity of 88–97% allows the development of a Lower Positively Charged Region (LPCR) formed by the polarized micro-droplets of water [11]. Two oppositely charged layers – the positively charged LPCR and the negatively charged layer above – in the thundercloud formed a lower dipole accelerating electrons downward (see for details [8]).