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On the origin of particle flux enhancements during winter months at Aragats

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A B S T R A C T

We consider the particle flux enhancement occurring during the Winter months on Aragats. We demonstrate that these enhancements originate from ^{222}Radon chain isotopes gamma radiation only. The relativistic runaway electron avalanche is possible on Aragats only in Spring-Autumn seasons. We measure with NaI ORTEC spectrometer the gamma ray radiation of the Radon progeny and use multidetector measurements to confirm the origin of the enhanced particle flux.

1. Introduction

The monitoring of the fluxes of gamma rays, electrons, and neutrons started at Aragats high-altitude station in 2000 [1]. The main field of the research were Solar physics and Space Weather. However, after an intense solar flare in January 2005, by which we determined the maximum energy of the solar proton accelerator [2], the activity of the sun has gradually declined and not a single ground level enhancement (GLE) has been recorded on Aragats since then. Therefore, our research shifted mostly to the modulation effects that the atmospheric electric field poses on the traversing elementary particles. The study of the relationship between the fluxes of elementary particles, lightning discharges of various types, and disturbances of the atmospheric electric field led to the discovery of a number of physical phenomena of both fundamental and applied nature. Using networks of detectors, along with electric field sensors, lightning locators, automatic weather stations, and panoramic cameras, we develop a new scientific direction, namely the high-energy physics in the atmosphere. The location of our station on the plateau under the southern summit of Mount Aragats is preferable for the observation of numerous thunderstorm ground enhancements (TGEs [3]) especially during spring when thunderclouds descend to the station. TGEs origin is the most powerful natural electron accelerator operated in thunderclouds. In 1961 Alex Gurevich [4] recognized that if an electron gains more energy from the electric field than it losses on ionization, the continuous acceleration and multiplication will lead to relativistic runaway electron avalanches (RREAs) that can reach the earth's surface and significantly enhance the background radiation. Background radiation is formed by numerous extensive air showers (EASs), the particle cascades originated from interactions of primary protons and nuclei with atoms of the terrestrial atmosphere. These "primary" cosmic rays are accelerated to ultra-high energies by galactic and extragalactic accelerators at exotic sites, like supernova remnants, neutron stars, and black holes. The RREAs started by an EAS electron (avalanche seed) in the atmospheric electric field are not so large and energetic, however, numerous avalanches from abundant seed electrons also cover a few square kilometers area on the earth's surface, lasting for several minutes, and electron energy can reach 50-60 MeV [5].

Another source of enhanced gamma radiation are the gamma emitters from the ^{222}Rn chain. Due to the continuous emanation and migration of ^{222}Rn from rocks, the concentration of short-lived daughter isotopes is constantly high near the earth's surface and in basements. Recently discovered at Aragats the radon circulation effect [6], the uplift of charged aerosols with attached isotopes by the near-surface electric field with following return with precipitation, leads to enhancement of the low energy (< 3 MeV) gamma radiation by tens of percent.

Thus, a comprehensive model which accounts for the enhancement of natural gamma radiation describes the bursts of particles

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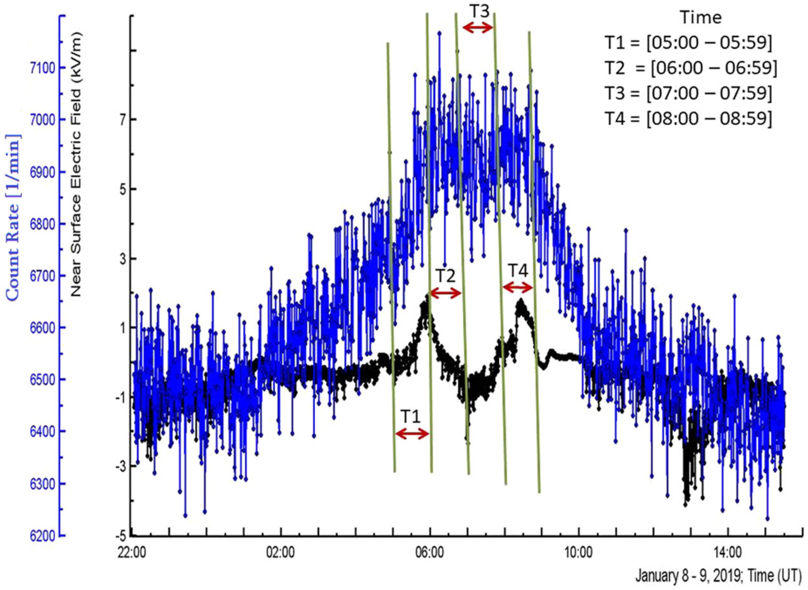

Fig. 1. Long-lasting flux enhancement measured by ORTEC spectrometer (1-minute time series of count rate, blue curve); near-surface electric field measured by the electric mill EFM-100 located on the roof of the MAKET experimental hall (black curve). The time spans corresponding to the frames a-d in Fig. 2 are shown by red arrows. (For interpretation of the colors in the figures, the reader is referred to the web version of this article.)

as a mixture of two separate processes, both having roots in the electric fields emerging during thunderstorms [7]. The particle flux enhancement in winter months when no thunderstorms are observed on Aragats, and the atmospheric electric field do not exceed the runaway initiation threshold, sure, comprise only enhanced natural gamma radiation of Radon isotopes.

In this letter, by analyzing a typical example of the flux enhancement observed in winter, we demonstrate that it originates only from the ^{222}Radon progeny radiation, and exclude the possibility of electron-gamma ray avalanches in the wintertime. We present the monthly distribution of TGEs in 2017-2020 showing that the most frequent months of RREA occurrence above Aragats are May and June and demonstrating that in winter months no RREA, and consequently no TGE took place.

2. Multidetector experiment on Aragats

Analyzing the condition leading to winter flux enhancements authors of [8] absolutely correct mention that "The relatively small amplitude of the disturbance of the surface electric field during the event 2019-01-09 (2 kV/m as compared to 10–30 kV/m at summer TGE) indirectly indicates that the charge of cloud layers during the considered event was significantly less than the characteristic charge of the cloud layer during summer thunderstorms." However, afterward, they formulate the wrong conclusion: "Thus, similar to the summer events of surface thunderstorm increases, the increase in the flux of energetic electrons and photons in the cold season occurs as a result of the acceleration and multiplication of electrons in the upward-directed electric field created by the cloud".

The main cause of this mistake was using data from a few particle detectors only. Incorporating information from spectrometers that measure the energy spectra of low energy gamma rays gives comprehensive information and allows to understand physical mechanisms responsible for the flux enhancement in winter months. To monitor the natural gamma radiation, we use a NaI (Tl) spectrometer, Model 905-4 ORTEC. The spectrometer uses a 3″ × 3″ diameter and length crystal, has 1024 channels, and provides relative energy resolution (FWHM ∼7.7%) [9]. The modernization of ORTEC spectrometer electronics allows to measure continuously 1-minute time series of count rates, and histograms of energy releases stored each minute. The network of large NaI crystal scintillators, overviewed by a PM-49 photomultiplier with a large photocathode (15-cm diameter) also monitored particle flux on Aragats. The sensitive area of each NaI crystal is ≈0.032 m^2; gamma ray detection efficiency is ≈60%. The energy threshold of two spectrometers is 300 KeV, of 3 other - 3 MeV. Numerous 1 and 3 cm thick molded plastic scintillators arranged in stacks (a network of STAND1 detectors and STAND3 detector) and in cubical structures (CUBE detector) also monitor particle fluxes. Light from the scintillators is re-radiated by wavelength shifting optical fibers at larger wavelengths and is detected by PM-115M photomultipliers. The DAQ electronics stores all configurations of the signals in the detector channels, details of detector operation can be found in [11]. All particle detectors and spectrometers operate 24/7; time series of detector count rates are available via the ADEI data analysis platform [10] from databases of cosmic ray division (CRD) of Yerevan physics institute.

In Fig. 1 we show a flux enhancement of ≈10 hours duration, that corresponds to the disturbed near-surface electric field [8]. Four episodes (T1-T4) were selected for the spectral analyses shown in Fig. 2.

Each episode covered 1-hour time; in all episodes, the spectral line of ^{214}Bi isotope (609 keV) is most abundant; other Bismuth isotopes ^{214}Bi (1.12 MeV) and ^{214}Bi (1.76 MeV) also produces smaller peaks. The low-intensity peaks like ^{214}Bi (2.21 MeV) are very difficult to identify with the ORTEC spectrometer. Nonetheless, we detect small enhancement above the background around the spectral line of this isotope as well. Fig. 2 illustrates the method of background subtraction for the enumeration of the gamma ray flux enhancement. Due to changes in the Radon emanation and migration from the surrounding rocks we detect diurnal variations of the isotope intensity, see Figs. 3 and 4 of [12]. The most stable isotope as we see from these figures is the K40 potassium isotope. We detect also a shift of the spectrometer channels relative to the genuine energy of isotopes due to the temperature dependence of the light output from the NaI crystal. As we use the one-and-the-same measurement of background for obtaining the enhancement of isotope radiation during 4 successive hours, we need to make for each hour calibration of ADC channels, to avoid

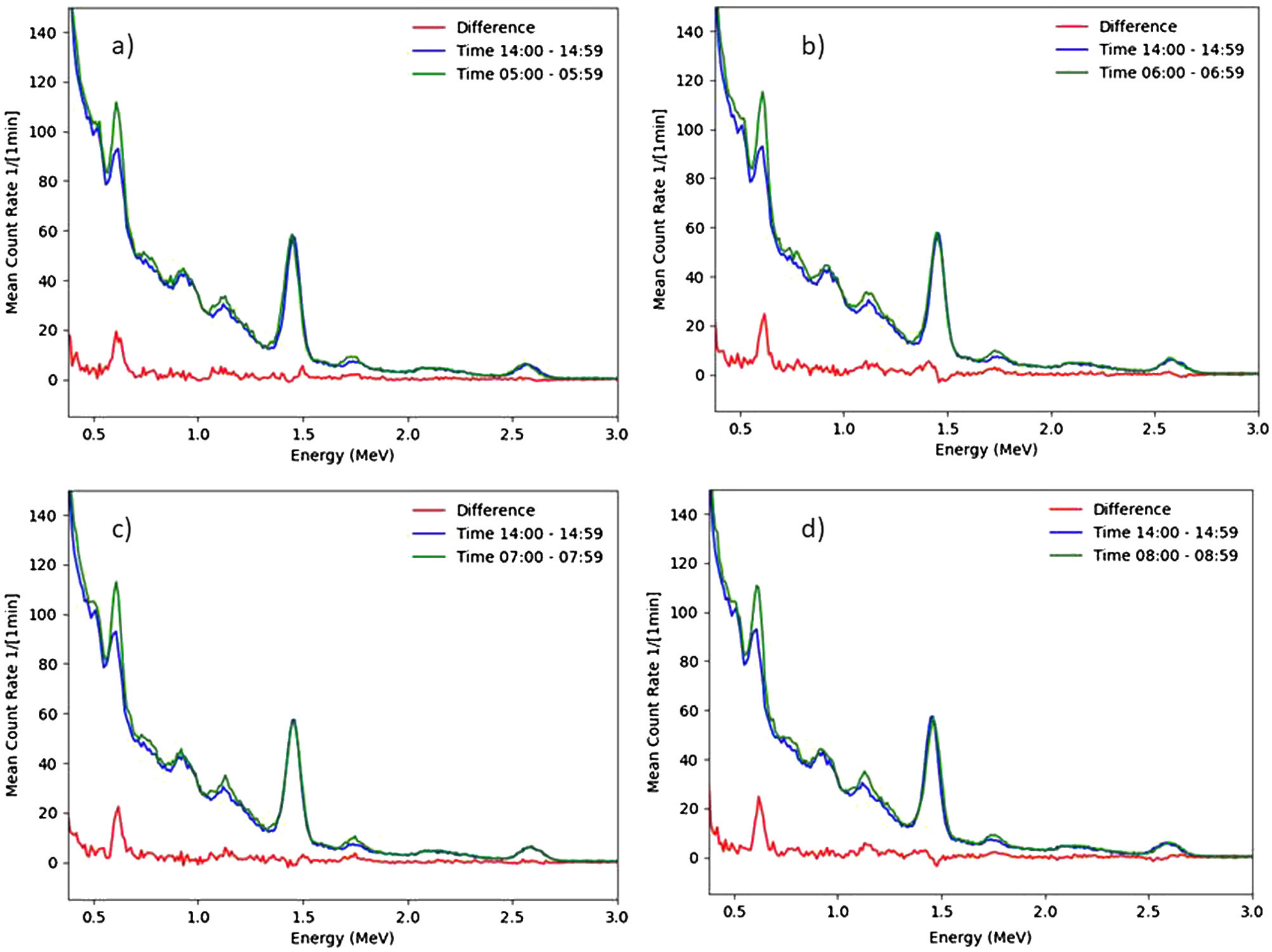

Fig. 2. Spectrograms of natural gamma radiation responsible for the enhancement of the count rate at low energies. The spectrograms are observed by an ORTEC spectrometer with resolution (FWHH ~7.7%). The red spectrogram is the residual obtained by subtracting the "fair-weather" spectrogram from the measured one. In the upper right corner, the times when spectrograms were measured are shown.

Table 1
Summary table of the enhanced radiation observed at 9 January 2019.

Time span	Sum of radionuclides	CR + Compton continuum
T1	58.3	41.7
T2	56.5	42.6
T3	51.5	48.5
T4	51.9	46.9
Mean±SE	55±1.7	44.98±1.7

the bias in the estimation of isotope energy. Therefore, we select a peak of 1.46 MeV (K40) for the calibration, positioning it in the same channels of ADC in each of successive hourly measurements (T1-T4, see Figs. 1 and 2). Thus, for each hour a relation between the ADC channels and isotope energies is tuned depending on the shift in the position of the K40 peak.

In Table 1 we show the summary numerical results obtained from Fig. 2. The count rate excess we divide into the Radon progeny radiation (counts integrated around isotope spectral lines, first column) and continuum radiation (second column). Energies of most of the gamma ray emitters are below 1.5 MeV. Thus, all enhancements can be explained by isotope radiation only and no other gamma emitters are necessary to consider. Differences of the isotope shares from episode to episode can be explained by the changing meteorological conditions during the day that influence isotope emanation and distribution in the atmosphere, as well as to the temperature dependence of the light output of NaI crystal of ORTEC spectrometer.

In Fig. 3 we show the 1-minute time series of plastic scintillator and NaI spectrometer both with energy threshold above 3 MeV for the same day 9 January analyzed above and for a thunderstorm in the May same year when THEs are abundant.

As we can see in Figs. 3a and 3b, the time series of particle detector count rates with an energy threshold above 3 MeV do not show any flux enhancement during disturbances of the near-surface electric field. The intensity enhancement measured with ORTEC spectrometer with energy threshold 300 keV was originated only from isotope radiation, no electron acceleration in the atmosphere above detectors took place. In Figs. 3c and 3d, we can see count rate enhancements lasting several minutes during large disturbances of the near-surface electric field than in May. The peak heights were 7.6 and 12% for NaI spectrometer and plastic scintillator consequently and we can conclude that the RREA process in the thundercloud above detectors generates enough avalanche particle to reach the earth's surface and be registered by the detectors with a high energy threshold.

In Fig. 4 we demonstrate the monthly distribution of TGE events originated by the RREA process in the atmosphere above detectors. The energy threshold of the used detector is higher than 3 MeV; in this way, we exclude the flux enhancement episodes originated by the isotope radiation only. As we can see in Fig. 4 no RREA occurred in 2017-2020 in the winter months. Also, as we can see in Fig. 4 that in the last 2 years the number of TGEs in April-May months abruptly diminished and the total number of TGEs reduced ≈3 times in 2019-2020 compared with 2017.

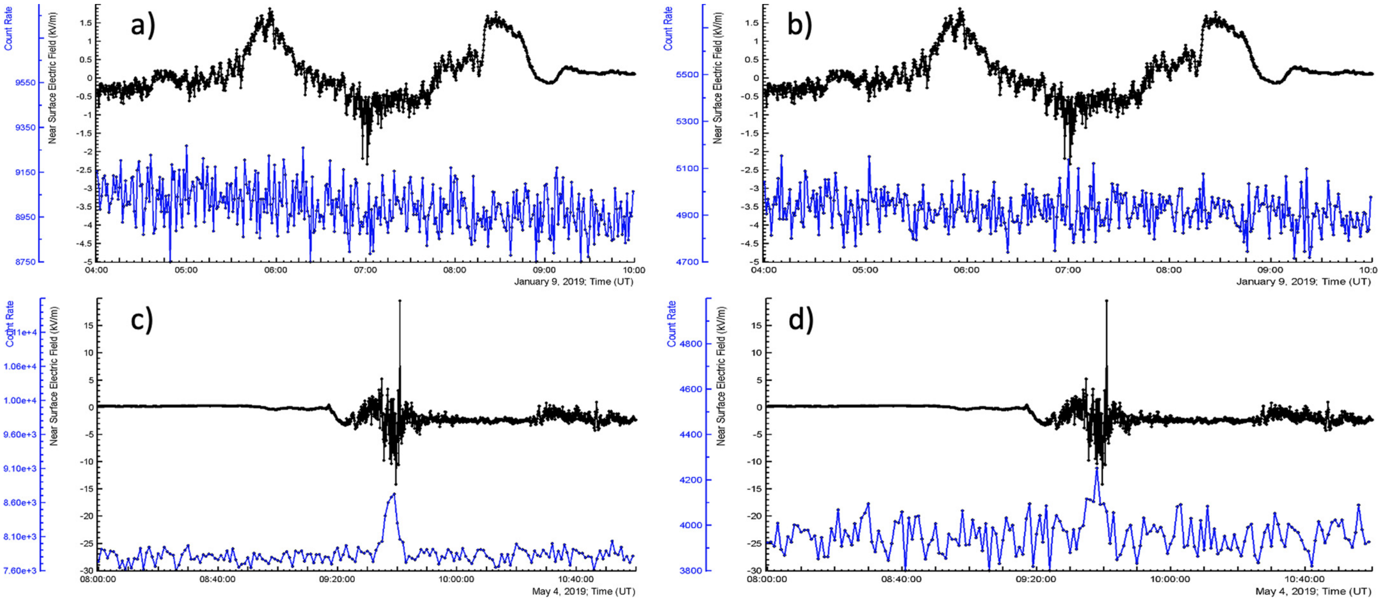

Fig. 3. a) – time-series of 1-minute count rates of 3 cm thick and 1 m^2 area upper plastic scintillator of STAND3 array (combination "1000", the signal only in the upper layer of the stacked plastic scintillators, energy threshold ≈3 MeV; b) of NaI spectrometer with energy threshold ≈4 MeV; c) and d) time-series of count rates of the same detectors, but measured at May 4, when particle avalanche originates in the thundercloud. By the black curve, we show disturbances of the near-surface electric field.

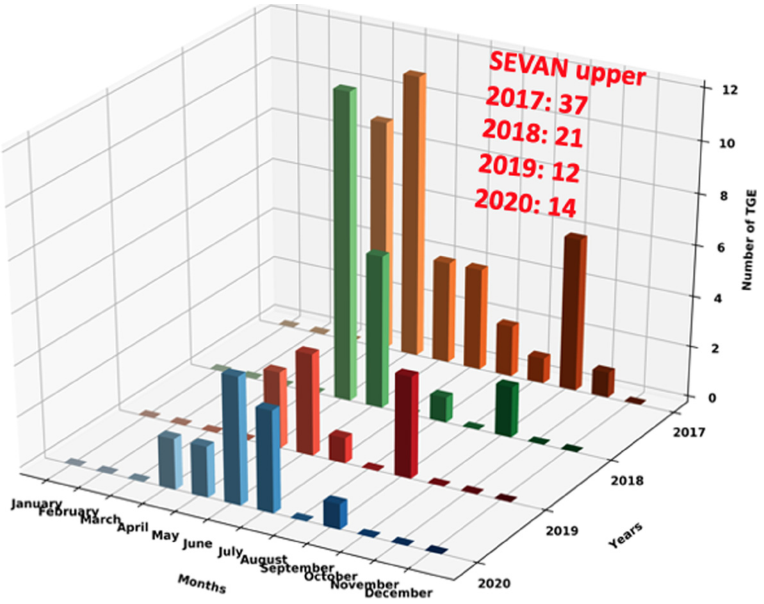

Fig. 4. Monthly distribution of TGEs in 2017–2020 measured by the SEVAN detectors upper scintillator (energy threshold ≈5 MeV).

3. Systematic errors in small peaks identification

The ability to discriminate among photo-peaks that are relatively closely spaced in energy depends heavily on the detector type used. First of all, a large count rate required to resolve small peaks. The photopeak counting efficiency of a relatively low-energy resolution spectrometer ORTEC NaI (Tl) is significantly better comparing with a greatly higher resolution of the germanium spectrometer. Also, a very important characteristic is the magnitude of the Compton continuum under the photopeak and the degree of interference with other closely lying peaks in the pulse height distribution. The Compton continuum arises because of primary gamma rays undergoing Compton scattering within the crystal. Depending on the scattering angle, the Compton electrons have different energies and hence produce pulses in different energy channels. When a gamma ray undergoes a Compton interaction and a portion of the energy escapes from the detector volume without being absorbed, the corresponding count will appear in a channel below the channel that corresponds to the full energy of the gamma ray. Depending on the scattering angle, the Compton electrons have different energies and hence produce pulses in different energy channels. The highest energy that can be deposited, corresponding to full back-scatter (the Compton edge). Both the Compton continuum and Compton edge effects smear the spectrogram and make the small spectral lines identification troublesome.

Another source of uncertainty is the diurnal variations of the ^{222}Rn emanation. The data collection time is rather large and background fluctuations can introduce additional errors in the estimated signal spectrograms. The temperature dependence of the NaI crystal used in the ORTEC spectrometer led to a shift of ADC channels relative to the genuine energy of spectral lines. Nonetheless, the relatively large size of the crystal used in the ORTEC spectrometer ($3'' \times 3''$) and large data collection time allow us to show that majority of count rate enhancement comes from the ^{222}Rn progeny gamma radiation around the known spectral lines and from the Compton continuum. An additional demonstration of the absence of the gamma rays from a runaway avalanche are time series measured by detectors with energy thresholds exceeding the energies of ^{222}Rn daughter gamma-emitters shown in frames a) and b) of Fig. 3. For comparison, we present the typical time series with flux enhancement due to electron-gamma avalanches measured on May 4 2019, frames c) and d) of Fig. 3.

4. Conclusions

We analyzed a typical example of winter flux enhancement and its relation to RREA and radon progeny radiation. We demonstrate that the observed flux enhancement is due to ^{222}Rn progeny radiation mostly, and no RREA process occurred in the atmosphere. 55% of the enhanced radiation comes from the ^{222}Rn progeny isotope radiation (integrated around known spectral lines); and 45% – is the continuum radiation of Compton scattered gamma photons and secondary cosmic ray radiation, and from the positron annihilation, see Table 1. The large peaks and large energies of TGE particles (above 3 MeV) originating from the electron-gamma avalanches in the thundercloud are observed only in Spring-Autumn months when the electric field inside the cloud exceeds the runaway threshold strength, see Fig. 3c and 3d and Fig. 4. In winter the shape of the flux enhancement is a Gaussian-like type with a long, exponentially decaying tail. The count rate of NaI spectrometer with energy threshold ≈4 MeV and STAND3 detector with energy threshold ≈3 MeV show no enhancement at the time when NaI spectrometer with energy threshold 300 KeV demonstrates large peaks. We conclude that no RREA has been observed on Aragats in winter, all observed flux enhancements are due to the isotope enhanced radiation only.

CRediT authorship contribution statement

A. Chilingarian designed experiment, formulated research goals and wrote the paper.

D. Aslanyan made data analysis, made a monthly distribution of the TGE events, made Fig. 4.

B. Sargsyan performed experiment, made data analysis, and Figs. 1-3 and Table 1.

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.

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