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Wind-induced natural gamma radiation

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Abstract – During extreme weather conditions in the fall of 2024 at Mount Aragats, Natural Gamma Radiation (NGR) levels surged by more than 1000%, with a total fluence of 2×10^7 gamma/cm^2 recorded over 10 hours. The corresponding dose reached 3.26 mSv —approximately 120 times higher than the seasonal background level. This unprecedented enhancement occurred during strong, dry snowstorms under subzero temperatures, in the absence of thunderstorm-related electric fields. The observed gamma-ray intensities significantly exceed those explainable by known atmospheric mechanisms such as relativistic electron avalanches or radon exhalation alone. We propose that these enhancements, which we call Wind-induced Gamma-ray Enhancements (WiGERs), are caused by dense radioactive clouds formed when electrified snow and aerosols mobilize radon progeny and keep them suspended near sensitive detectors. These findings indicate that similar radiation surges may occur in high-altitude and polar environments, such as the Arctic and Antarctic, where strong winds and extended snowstorms are common. Understanding the origin and persistence of WiGERs is crucial for enhancing radiation background models, refining atmospheric ionization forecasts, and assessing environmental and climatic impacts during extreme winter weather events.

Introduction. – Natural Gamma Radiation (NGR) is crucial to the Earth's near-surface radiation environment. It is essential in radiation safety, geological exploration, atmospheric chemistry, and space weather studies. Scientific efforts to monitor and comprehend the sources and variability of NGR are vital for both environmental protection and fundamental research.

Among the known contributors to NGR are radioactive decay chains in the Earth's crust, atmospheric radon and its progeny, and energetic processes in thunderclouds. During thunderstorms, strong atmospheric electric fields can exceed the critical breakdown threshold for air, initiating relativistic runaway electron avalanches (RREAs) that generate bursts of high-energy electrons and gamma rays [1]. When such avalanches develop above ground-based detectors, the resulting particle flux is observed as a Thunderstorm Ground Enhancement (TGE) —a well-documented phenomenon in spring and autumn over highland regions [2–5].

In addition to thunderstorm processes, radon exhalation from the ground and subsequent redistribution by the near-surface electric field (NSEF) can also significantly influence gamma-ray fluxes. This radon circulation effect [6] highlights the role of meteorological and electric conditions in modulating background radiation levels.

However, during winter, especially at temperatures below $-10\,^{\circ}$C, TGEs are rare, and radon exhalation is typically suppressed by frozen or snow-covered soil. Surprisingly, in December 2024, at Mount Aragats (3200 m altitude), we recorded strong, long-lasting enhancements in gamma-ray flux under winter snowstorm conditions. These enhancements were closely correlated with intense wind events and the presence of dry, electrified snow.

At high elevations and in polar regions, strong horizontal winds often sweep over large expanses of dry snow, mobilizing and charging snow particles. We observed that such charged snowstorms can loft radon progeny into the air, forming compact, electrified radioactive clouds. These clouds penetrate buildings and detector housings, sustaining elevated gamma-ray fluxes for extended periods —a behavior markedly different from the short, impulsive TGEs triggered by thunderstorms.

We refer to this newly observed class of events as Wind-induced Gamma-ray Enhancements (WiGERs). They represent a previously unrecognized atmospheric source of NGR, driven by mechanical and electrostatic processes in snow-laden winter winds, rather than by strong electric fields in thunderclouds.

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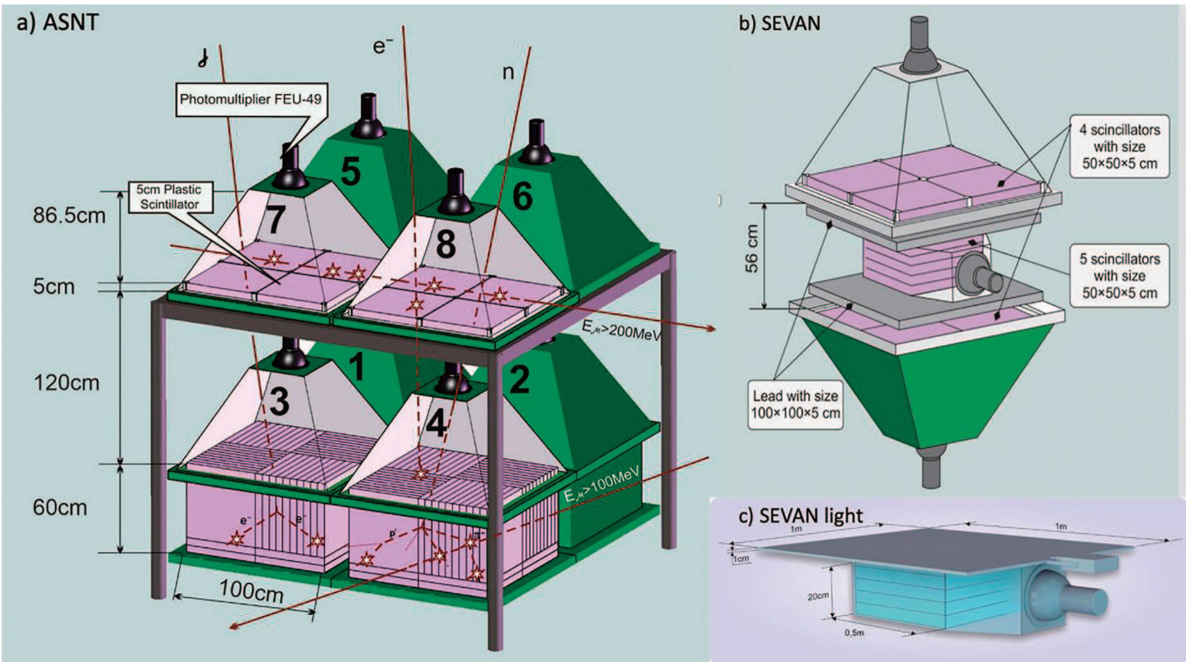

Fig. 1: Particle detectors of the Aragats research station (3200 m).

This study presents observational evidence and a conceptual model for WiGERs. We analyze their characteristics, distinguish them from TGEs, and explore their implications for background radiation monitoring, atmospheric ionization, and high-latitude environmental effects.

Instrumentation. – In [7], we present a detailed description of the experimental facilities on Aragats. The Aragats Solar Neutron Telescope (ASNT, fig. 1(a)), located in the MAKET experimental hall of 20000 m^3 volume, measures the flux of electrons and gamma rays in the energy range of 10–100 MeV. The Aragats Neutron Monitor (ArNM), type 18HM64, and the SEVAN (fig. 1(b)) detectors are in the same hall. A network of three STAND1 detectors (three stacked scintillators with a thickness of 1 cm and an area of 1 m^2 and one stand-alone with a thickness of 3 cm) is located at Aragats station premises, covering a ≈ 50000 m^2 area. DAQ electronics based on the National Instruments MyRIO board (see details in [8]) continuously measure and send to servers a 50 ms time series of count rates of all 12 scintillators.

In the SKL experimental hall (Solar Cosmic-ray Laboratory, K letter remains historically from the Russian) with a volume of 4000 m^3, the STAND3 stacked detector [9] is located. STAND3 incorporates four 3 cm thick and 1 m^2 area plastic scintillators, and it measures vertical electron fluxes with energy thresholds of 20, 30, and 40 MeV by identifying coincidences across 4 layers of the detector. The energy releases of gamma rays and electrons are measured using the SEVAN-light spectrometer (fig. 1(c)), which consists of a 20 cm thick and 0.25 m^2 spectrometric scintillator and a 1 cm thick, 1 m^2 area "veto" scintillator positioned above it. The SEVAN-light detector records energy-release histograms continuously each minute. The efficiency of the upper 1 cm thick veto scintillator in registering charged particles exceeds 95%, while its efficiency for neutral particles is around 2%. Thus, an "11" coincidence, the signal in both scintillators indicates passage of charged particles, while a "01" coincidence selects the neutral ones. Therefore, using a SEVAN-light detector, we can disentangle neutral and charged fluxes and measure the energy releases of each separately. The SEVAN-light detector is located on the first floor of the SKL hall. The Logarithmic amplitude-to-digit converter (LADC), used in SEVAN-light electronics, allows for the acquisition of spectra ranging from 0.3 to 300 MeV at the cost of low-energy resolution in the lowest-energy band ($\approx 70\%$). For recovering the energy spectra from energy release histograms, the detector response function was calculated using the GEANT 4 code by transporting particles through the building and detector media, considering various sources of randomness and uncertainty in the measurement process. The response matrix will account for the smearing effects due to the finite resolution of the detector and the asymmetry in the bin-to-bin migration due to very steep cosmic ray spectra. The energy spectra recovery procedure is detailed in [10]. As the atmospheric electric field (AEF) is vertical, we use the inverse matrix obtained by vertical transport of TGE electrons and gamma rays from the roof of the building through the veto scintillator down to the bottom of the 20 cm thick spectroscopic scintillator. However, when the radioactive cloud blows into the building, the gamma rays enter the scintillator from all sides without interacting with additional material. Thus, new simulations and a new inverse matrix for recovering energy

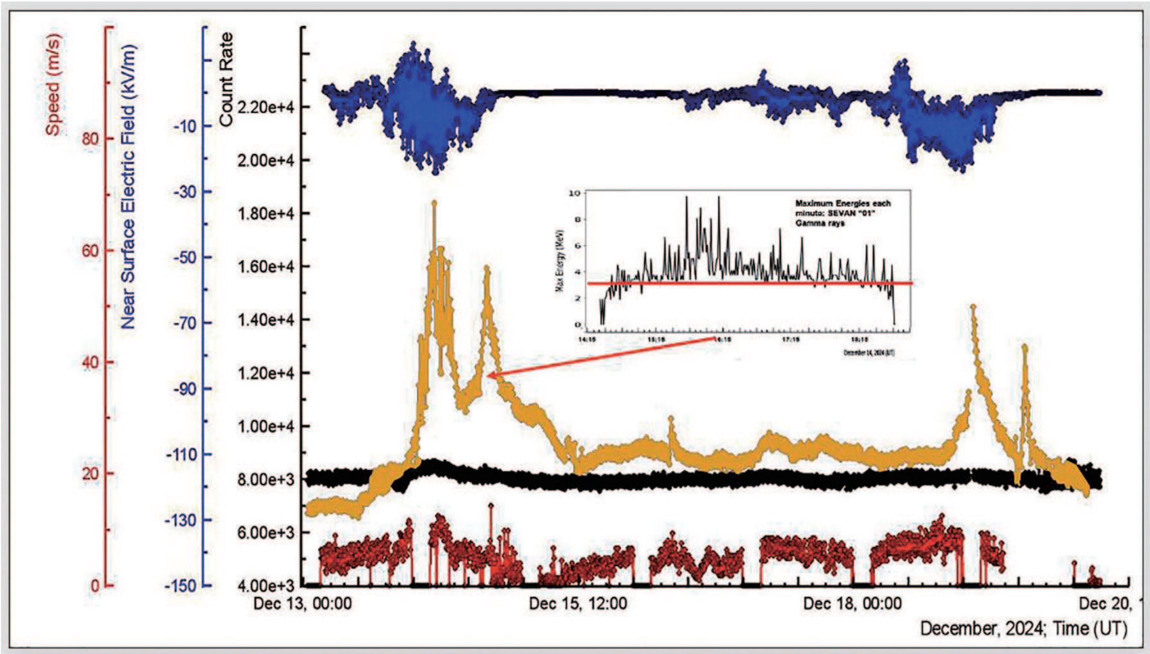

Fig. 2: One-minute time series of "11" coincidence (electrons, black) and "01" coincidence (gamma rays, brown) measured by the SEVAN-light detector; disturbances of NSEF (blue); and wind speed (red). In the inset, we display the minute-by-minute maximum energies of gamma rays; the red arrow indicates when energy spectra were selected. The red line in the inset demonstrates that the maximum energy during this period exceeds 3 MeV. Due to severe weather conditions, there are several gaps in wind measurement.

spectra were performed. The count rate of the spectrometer significantly increased due to an enhanced detection surface (0.9 m^2 compared to 0.25 m^2 for vertical TGE particle transport) and a larger path in the scintillator for half of the incidences (0.5 m instead of 0.2 m for vertical transport).

An additional SEVAN-type detector is installed in a 25 m^3 hut on four 5 meter long pipes near the SKL hall (see inset to fig. 3). This hut, known as "Cuckoo's Nest," is fully exposed to the wind. The 1 second time series of count rates is recorded using analog discriminator inputs for the photomultiplier signals. Light from particles entering the sensitive volume of scintillators during $\approx 1\ \mu s$ is summed to produce a PMT impulse fed to the comparator [11].

A network of commercially available field mills (Model EFM-100 [12]) continuously monitors the near-surface electric field (NSEF). The EFM-100's sensitivity range for lightning location is 33 km, and the instrument's response time is 100 ms. Changes in the electrostatic field are recorded at a sampling interval of 50 ms.

The lightning activity from 30 km to 480 km is monitored by Boltek's Storm Tracker (lightning detection system [13]). Storm tracker defines four types of lightning (CG−, CG+ cloud-to-ground negative and positive, IC−, IC+ intracloud positive and negative) in radii up to 480 km around the location of its antenna. On 14 December, multiple discharges in Boltek instruments caused by dry, electrified snow encounters resulted in a whole area around the station, spanning a hundred kilometers, being detected by lightning detections. However, the worldwide lightning location network (WWLLN), one of the nodes located in Yerevan, did not register any lightning discharges from December 14 to 28 within a 200 km radius.

Davis Instruments' Vantage Pro2 Plus automatic weather stations monitor meteorological conditions, including a wind speed sensor, rain collector, atmospheric pressure sensor, temperature and humidity sensors, anemometer, solar radiation sensor, and UV sensor. When wind fills buildings with air enriched by radon progeny, gamma radiation enters detectors not only from the top (as with RREA avalanches accelerated in the vertically oriented AEF) but also from all sides of the detectors, reaching 3.6 m^2 for ASNT and 0.9 m^2 for the SEVAN light.

Winter NGR enhancements. – According to the Armenian Meteorological Service, the strongest winds of 2024 occurred between December 14 and 16, achieving speeds of up to 30 m/s. On Aragats, winds reached 20 m/s, while the outside temperature ranged from −10 to −20 degrees Celsius, and atmospheric pressure fluctuated from 678 to 690 mbar. Simultaneously, we observe unusual patterns of NSEF (blue curve in fig. 2). The dense blue curves, which appear only during Winter's strong winds, highlight the high-frequency fluctuations in the EFM 100 sensor readings, indicating continuous discharges from the

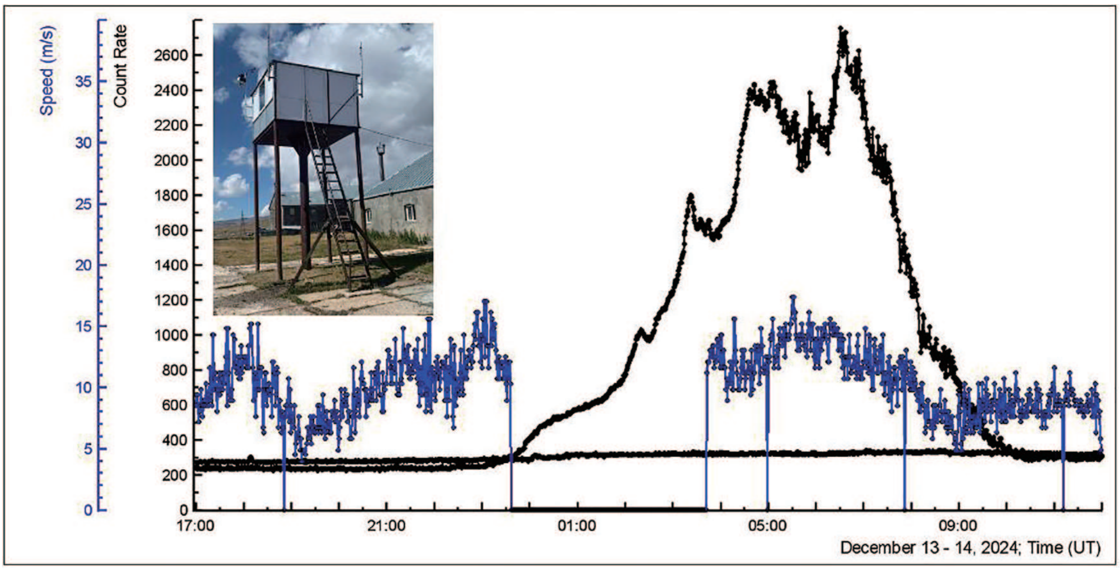

Fig. 3: 1 second time series of electrons and gamma rays and 1 minute time series of wind speed. Due to severe weather conditions, there is a gap in wind measurement for ≈4 hours.

device. These episodes can last up to 10 hours as the wind blows.

Concurrently, we note a significant increase in the gamma-ray flux (yellow curve) measured by the 20 cm thick scintillator of the SEVAN-light detector located in the SKL experimental hall at 14:24–18:42 (258 minutes, fig. 2), when the count rate enhancement r reaches 35% (35σ).

There was no increase in the coincidence of 1 cm thick and 20 cm thick scintillators ("11" coincidence, black curve in fig. 2) that selects charged particles. No muon flux enhancement was registered by the Aragats muon detectors as well. Low-energy gamma rays from radon progeny emission, predominantly undergoing photoelectric absorption or low-energy Compton scattering, result in electrons with insufficient energy to penetrate the 1 cm plastic scintillator and generate detectable light pulses. Therefore, such radiation cannot produce signals in the SEVAN-light detector. However, the situation changes if radioactive snow accumulates on or near the detector. Decay chains involving ^{214}Bi emit beta particles and high-energy gamma rays (up to 1.7 MeV), which can produce pair production events in the scintillator, potentially triggering "11" coincidences. Thus, the detector may register enhanced activity if exposed directly to contaminated snow. During strong winds, electrified snow containing radon progeny can be transported into the building through micro-openings in the roof and walls. Although the SEVAN-light detector is located securely on the bottom floor of the SKL building and is well protected from direct snowfall, it remains sensitive to enhanced gamma-ray background caused by radioactive particles deposited in the building. Thus, wind-driven infiltration of radioactive aerosols leads to transient gamma-ray enhancements detectable by SEVAN light. To gain insight into gamma-ray flux enhancement and determine its origin, we recover energy spectra on a minute-by-minute basis for 258 minutes of flux enhancement. The maximum energy was determined each minute on 14 December from 14:24 to 18:42 (pointed by the red arrow). The time series of maximum energies is shown in the inset to fig. 2. The principal contributor to gamma radiation from ^{222}Rn progeny is the isotope ^{214}Pb, with a half-life of 26.8 minutes and emitting prominent gamma lines at 295 keV and 352 keV with emission probabilities of 18.5% and 35.8%, respectively. ^{214}Bi with a half-life of 19.9 minutes, produces a broad spectrum of gamma rays, including a strong line at 609 keV ($\sim$ 45%) and several higher-energy emissions: 1120 keV ($\sim$ 15%), 1238 keV ($\sim$ 5.8%), 1378 keV ($\sim$ 4.0%), 1764 keV ($\sim$ 15%), and a maximum-energy gamma ray at 2204 keV ($\sim$ 5%) However, most of 1 minute maximum energies exceed 3 MeV, and a few reach 9 MeV. These large maximum energies of gamma rays significantly exceeding radon progeny energies require clarification and confirmation to be presented in the next section.

Analysis of the prolonged gamma-ray enhancements during strong winds. – From the previous section, it is apparent that there is a contradiction: the climatic conditions do not support runaway avalanches in the atmosphere that can produce particles with energies exceeding 10 MeV (no thunderstorm, no expected RREA in the atmosphere that can produce relativistic particle avalanches). Yet, the energy spectra are significantly above the radon progeny gamma radiation levels. First, we check the flux enhancements recorded by thick and thin scintillators in the Cuckoo's Nest hut (see inset to fig. 3), showing a huge enhancement at 0:0–9:30 the same day, 14 December 2024. Horizontally placed 1 cm thick detectors register all TGEs at Aragats (see the TGE catalog [14]).

However, as shown in fig. 3, the 1 cm thick scintillator of the Cuckoo's Nest detector (lower black line), as well as the 1 cm thick scintillator of the SEVAN-light detector, does not register the count rate enhancement observed by the 20 cm thick scintillators just below them (upper black line in fig. 3). The detector in Cuckoo's Nest is a SEVAN-light detector (fig. 1(c)); however, it uses different DAQ electronics, which do not include an ADC, only scalers that measure count rate each second [11]. The 1 cm thick detectors of the STAND1 network also do not register any enhancement. Consequently, we conclude that the radiation comes not from a vertical but a horizontal direction. When strong wind blows into buildings, detectors are exposed to radon progeny from all 6 sides, with a sensitive surface of ≈ 1 m^2.

At the maximum flux, the enhancement count rate measured by the Cuckoo's Nest detector reaches 1150% (590σ), much higher than registered by SEVAN light. This difference is attributed to varying exposure to strong winds carrying isotopes and electrified snow; the hut has a large hole in the bottom, and wind directly blows electrified snow inside.

Over the 258 minute event registered by SEVAN light, the total fluence was 2.58×10^3 gamma rays per square centimeter. Assuming a mean gamma-ray energy of 1 MeV and using the ICRP [15] dose conversion factor of 5.7×10^{-14} Sv per gamma, the corresponding effective dose is estimated to be 1.47 mSv. This dose significantly exceeds the natural background over the same interval and confirms measurable exposure from wind-transported radon progeny. The detector located in Cuckoo's Nest observes an intensity at least ten times greater; thus, the effective dose can reach 15 mSv or more during windy days in winter.

Let us consider now the large (3–9 MeV) maximum recovered energies of gamma rays. These are not the energies of individual gamma rays, but rather the sum of the energies of several gamma rays entering the detector. Because the SEVAN-light spectrometer integrates deposited energy over a short time window, it accurately sums the energy of multiple gamma rays that arrive simultaneously. This does not constitute a pile-up in the electronic sense, since the detector is not saturated, but it does lead to high total energy depositions.

The mean gamma-ray flux during the windstorm (14:24–18:42) reaches 100000 gamma rays per minute per square meter. The observation time was 258 minutes, and the digitally controlled fixed integration window defined by the acquisition logic of the SEVAN-light spectrometer was 1 microsecond. Gamma rays entered the 20 cm thick and 0.25 m^2 area scintillator from six sides.

The detector energy resolution was approximately 70% FWHM at 1.6 MeV, corresponding to a standard deviation $\sigma \approx 0.475$ MeV.

We initially estimated the probability of two gamma rays arriving within a 1 μs detection window using a Poisson model with an average rate of $\lambda = 1.67 \times 10^3$ gamma per window. This results in a small probability of coincident arrivals: $P(2) \approx 1.39 \times 10^{-6}$, leading to approximately 83 double coincidences per minute across 60 million windows.

However, this estimate assumes statistically independent gamma emissions. In reality, radon progeny such as ^{214}Bi undergo cascade decays, emitting multiple gamma rays (*e.g.*, 609, 1120, 1764 keV) within nanoseconds. These are not random coincidences but correlated emissions from a single nuclear transition, inherently increasing the rate of multi-gamma detection events. Additionally, the detector's finite energy resolution smears these summed signals. For instance, the combination of two 1.6 MeV photons may deposit 3.2 MeV, and with a 3σ upward fluctuation ($\sigma \approx 0.475$ MeV), the observed energy can reach 4.63 MeV. A triple event (4.8 MeV) can appear as 6.23 MeV or more. Such resolution broadening allows low-energy gamma cascades to mimic much higher energies in the spectrum.

Assuming a gamma-ray flux of 100000 per minute and a 1 μs sintegration window, more than 80 double events and one triple event every ~ 25 minutes are expected. Therefore, the high-energy tail observed during wind-enhanced gamma-ray episodes (up to 10 MeV in SEVAN data) can be plausibly explained by correlated gamma-ray cascades from radon progeny and resolution-induced upward fluctuations.

Discussion and conclusions. – In fall 2024 at Aragats, NGR levels increased by more than 1000% during electrified snowstorms driven by intense winds. The observed radiation intensities far exceed those explainable by known atmospheric processes, indicating the presence of a previously unrecognized mechanism of particle transport and radiation amplification under winter storm conditions.

We propose a novel mechanism, distinct from both relativistic runaway electron avalanche (RREA) and radon progeny radiation models. Our scenario involves the following key processes:

- Radon trapping: cold near-surface air traps radon gas near the ground, while snow-covered soil suppresses its exhalation, reducing radon release compared to warmer seasons.
- Aerosol uplift: strong winds lift radon progeny and associated aerosols, overcoming gravitational settling and distributing radioactive material over wide areas.
- Electrified snow transport: charged snow particles are efficient carriers for radon daughters, enhancing attachment rates and sustaining elevated airborne radioactivity.
- Radioactive cloud formation: a dense, electrified radioactive cloud forms, significantly amplifying ambient gamma-ray flux through sustained interactions among radon progeny, dry snow, and charged aerosols.

– Indoor penetration: these radioactive clouds infiltrate buildings and detector housings, maintaining elevated detector count rates and high NGR levels for several hours.

Unlike Thunderstorm Ground Enhancements (TGEs), which are typically short-lived and driven by transient atmospheric electric fields, the enhancements observed during windstorms are sustained over long periods. This suggests a continuous input of radon progeny and a mechanical transport process rather than a singular release event. The prolonged gamma-ray enhancement confirms that strong winds are critical in modulating radiation exposure during winter snowstorms.

The Aragats observations point to a previously overlooked mechanism of radiation enhancement in high-altitude snowy environments. Analogous conditions may exist in polar regions such as the Arctic and Antarctic, where katabatic winds, frequent snowstorms, and charged aerosols favor the formation of radioactive clouds.

In other natural systems, there may be parallels where energetic radiation emerges from complex interactions between plasma, surface charging, and radioactive material. For instance, the lunar surface exhibits high-energy emissions due to electrostatic charge buildup on dielectric regolith surfaces exposed to the solar wind and micrometeorite bombardment. The Kaguya mission recorded gamma rays from 200 keV to 13 MeV, attributed to interactions between charged dust, solar plasma, and surface electric fields [16].

This proposed mechanism has significant implications:

– Radiation monitoring: radioactive cloud events may bias background gamma-ray measurements, leading to misinterpretation of long-term trends or anomaly thresholds.

– Aviation and operational safety: prolonged near-surface radiation exposure in extreme weather conditions could necessitate revised safety guidelines for ground-based and low-altitude activities.

– Atmospheric and climate modeling: charged aerosols interacting with radon progeny may impact ionization rates, cloud microphysics, and large-scale charge distributions in storm systems.

* * *

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Data availability statement: The data that support the findings of this study are openly available at the following URL/DOI: http://adei.crd.yerphi.am.

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