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Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons

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The Aragats Space Environmental Center facilities continuously measure fluxes of neutral and charged secondary cosmic ray incidents on the Earth's surface. Since 2003 in the 1-minute time series we have detected more than 100 enhancements in the electron, gamma ray, and neutron fluxes correlated with thunderstorm activities. During the periods of the count rate enhancements, lasting tens of minutes, millions of additional particles were detected. Based on the largest particle event of September 19, 2009, we show that our measurements support the existence of long-lasting particle multiplication and acceleration mechanisms in the thunderstorm atmosphere. For the first time we present the energy spectra of electrons and gamma rays from the particle avalanches produced in the thunderstorm atmosphere, reaching the Earth's surface.

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I. INTRODUCTION

Charles Thompson Rees Wilson in 1924 [1] realized that a "particle started with suitable velocity in the electrical field of the thundercloud may be expected to continue to acquire kinetic energy at the rate of many thousand volts per cm." In 1992 Alexander Gurevich, Gennady Milikh, and Robert Roussel-Dupre [2] introduced the theory of the generation of fast "runaway" electrons from the MeV electrons of the extensive air showers (EAS) initiated by the energetic proton or nuclei incident on the top of the atmosphere. However, the nature of seed particles is still under debate; an alternative source of the seed particles is connected with the lightning leaders [3,4]. Although there is no exact measurements yet of the possible strength of the electric field, in [5] it was suggested that streamer heads can produce fields up to several tens of millions volts per meter. The electrical fields in the thunderstorm atmosphere gave the cosmic ray shower and/or electrons from the lightning leaders a boost by increasing the number of energetic particles through a multiplication process initially called runaway breakdown (RB), and now referred to as relativistic runaway electron avalanche (RREA) [6–8]. The RREA mechanism can create large amounts of high-energy electrons and subsequently the gamma rays, as well as x rays and neutrons. Unfortunately, this model has not yet been able to demonstrate the creation of the hot plasma channel and lightning itself.

Astonishingly, the physical processes in the low atmosphere were observed by the orbiting gamma observatories at 400–600 km above the Earth's surface. Terrestrial gamma flashes (TGF), very short (tens of μ sec) bursts of high-energy gamma rays, have been routinely observed by satellite gamma ray detectors during the last 20 years (see Ref. [9]). Recently the TGF have been observed in correlation with strong thunderstorms in the equatorial regions [10]. The spectra of the flashes are roughly expressed by a power-law function with an exponential decaying term; some of them extending up to several tens of MeV. In Ref. [7] these events were interpreted as byproducts of the massive number of runaway electrons being generated within thunderclouds.

Surface detections of the RREA process, although having a long history, are discrepant and rare. Early measurements [11,12] discovered the existence of electron flux simultaneously, or earlier, than lightning located 30 kms apart. Atop Mt. Lemmon (altitude 2800 m) at the lightning research facility of the University of Arizona, the simultaneous detection of the cosmic ray flux (by the 10-cm diameter and 10-cm length plastic scintillator) and electrical field (by an electrical field mill) demonstrate $\sim$10% enhancement of the 1-minute count [13]. The average excess duration was $\sim$10 minutes; the threshold energy of the particle detector $\sim$100 keV. The Italian EAS-TOP surface array [14] measures significant excesses in the air shower counting rate lasting 10–20 minutes. The enhancements with maximum amplitude of 10%–15% were attributed mostly to highest energy EAS (large shower sizes, $>10^6$ electrons), and to zenith angles of incidence smaller than 20°; "thickness" (time distribution of the EAS particles arrival) of shower was slightly larger than in normal conditions [15].

A radiation monitoring post in a nuclear power plant in Japan reports on a comprehensive observation of a gamma ray burst emission lasting less than 1 min—correlated with snow and lightning activity. Enhancements were detected only during winter time, when thunderclouds are as low as several hundred meters [16]. The summer thunderstorm was observed by the same group at the top of Mt. Fuji (3776 m high). The flux of high-energy gamma rays had a

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continuous energy spectrum up to 10 MeV, prolonged up to 20 min. The authors of [17] claim that the bremsstrahlung photons generated by the energetic electrons were produced continuously due to an intense electric field in the thundercloud rather than having originated in the process of lightning discharge.

A Japanese group on another Japanese power plant also detected short (less than 1 min) gamma bursts during winter thunderstorms [18]. The same authors reported a simultaneous detection of gamma rays and electrons at a mountain observatory Norikura located 2770 m above sea level [19]. Two emissions, lasting 90 sec, were associated with thunderclouds. At the same research station, Norikura in the Japanese Alps operates a large multilayered particle detector, primarily intended to register solar neutron events. In August 2000 on account of thunderstorms, particle flux enhancement was detected in 3 layers of a 64 m^2 area detecting system [20].

In experiments at the Baksan Neutrino Observatory of the Institute for Nuclear Research, the time series of cosmic rays are continuously measured along with precise measurements being taken of the electric field and monitoring of thunderstorms [8]. Intensity changes of the soft cosmic rays (below 30 MeV) and hard cosmic rays (> 100 MeV) were studied [21]. It was shown that the critical field and particle energy for this process are $\sim$300 kV/m and $\sim$10 MeV, respectively [8].

The network of the NaI detectors along with EAS triggering system is located at Tien-Shan Cosmic Ray station of the Lebedev Physics Institute, at altitude 3340 m. The goal of the research is to detect runaway breakdown initiated by EAS with energy above 1000 TeV—so-called RB-EAS discharge. Based on short gamma flashes (less that 200 μ sec) detected by the network of gamma detectors, the authors of [22] claim that RB-EAS is a rather rare event ($\sim 1\%$ of all EAS registered during thunderstorms) requiring coincidence of several conditions, the most important of them being that the strong electrical field should be located not higher than 400–500 m above the detector.

The neutron production was claimed to correlate with the lightning process [23]; however, the mechanism by which neutrons can be generated by the lightning plasma are not well understood or even formulated [24]. The photonuclear reactions caused by gamma rays originated by bremstrahlung of the RREA electrons can be the origin of the neutron enhancements. On the other hand, absorption of neutrons in the dense lower atmosphere is so strong that the photonuclear neutron yield seems to be insufficient to account for the increase of neutron flux observed on the Earth's surface [25].

From the brief review above, it is apparent that many major problems connected with particle multiplication and acceleration in the thunderstorm atmosphere remains unsolved. Usually only one of the secondary cosmic ray species is measured; the additional particle flux is not too large and the number of detected "thunderstorm particle events" is very modest. Available experimental data cannot yet provide sufficient information to confirm the RREA theory. The energy spectra of RREA electrons and gamma rays are derived from a number of simulations; however, the experimental evidence is lacking till now.

Ground-based observations by a variety of the surface particle detectors systematically and repeatedly measuring the gamma rays, electrons, muons, and neutrons from atmospheric sources are necessary for answering these and other questions concerning high-energy phenomena in the atmosphere. Energy spectra and correlations between different particle fluxes, measured on the Earth's surface, address the important issues of where this radiation and particles come from and what kind of role they play in the lightning initiation.

The particle detectors of the Aragats Space Environment Center (ASEC) [26,27] observe charged and neutral fluxes of secondary cosmic rays by the variety of particle detectors located in Yerevan (1000 m a.s.l.) and on slopes of Mt. Aragats at altitudes 2000 and 3200 m. ASEC detectors measure particle fluxes with different energy thresholds and angles of incidence as well as EAS initiated by primary proton or stripped nuclei with energies greater than 50–100 TeV. Numerous thunderstorm-correlated events, detected by the ASEC facilities, constitute a rich experimental set to investigate the high-energy phenomena in the thunderstorm atmosphere. In this paper we will discuss the largest ever measured enhancement of cosmic ray fluxes on the Earth's surface, which occurred on September 19, 2009, at Mt. Aragats in Armenia.

II. PARTICLE DETECTORS OF THE ARAGATS SPACE ENVIRONMENTAL CENTER

The Aragats Space Environmental Center [26,27] of the Yerevan Physics Institute is located on the highland 3250 m above sea level, 5 km from the southern peak of Aragats (3750 m), near a large lake. The thunderstorm activity on Aragats is extremely strong in May–June. Sometimes, lightning continuously hits the ground in the vicinity of the station during an hour or longer. Thunderstorm clouds are usually below the southern peak (i.e., not higher than 500 m above) and sometimes 100–200 m above the station.

Along with solar modulation effects, ASEC detectors register several coherent enhancements associated with thunderstorm activity. Nearly 50 such events detected in 2007–2009, at solar cycle minimum, unambiguously pointed on the thunderstorm-correlated particle acceleration and multiplication. The experimental techniques used allowed for the first time to simultaneously measure fluxes of the electrons, muons, gamma rays, and neutrons correlated with thunderstorm activity[28].

Most of particle detectors are located in the MAKET building (see Fig. 1) and nearby. Along with 16 plastic

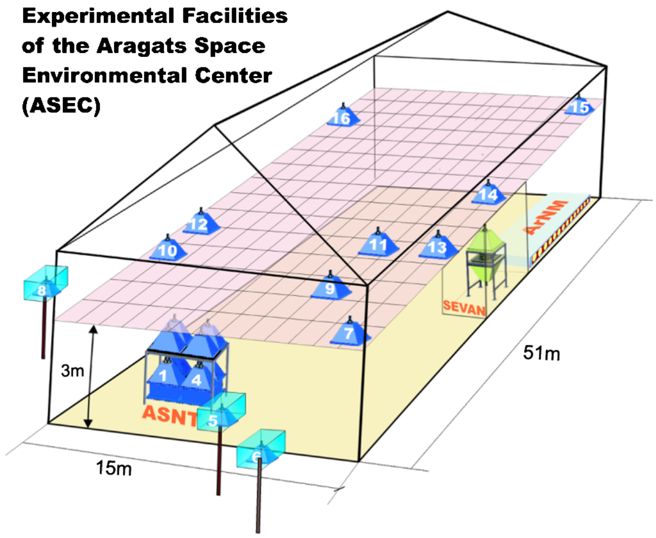

FIG. 1 (color online). The MAKET building at Aragats station, now hosting also ASNT, SEVAN, ArNM detectors, 3250 m above sea level.

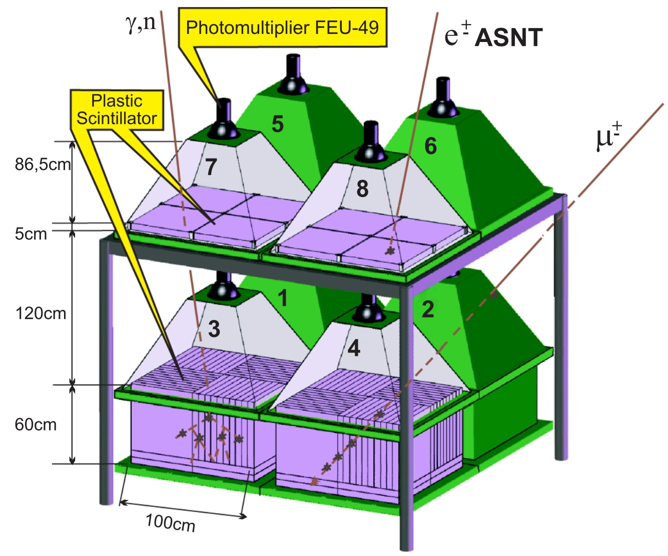

FIG. 2 (color online). Aragats Solar Neutron Telescope (ASNT).

scintillators belonging to the already finished MAKET-ANI surface array, in operation are Aragats Solar Neutron Telescope (ASNT); Aragats Neutron Monitor (ArNM) of 18NM64 type; and SEVAN (Space Environmental Viewing and Analysis Network) particle detectors. ArNM is detecting neutrons and ASNT and SEVAN are both neutral and charged species of the fallen secondary cosmic ray flux. Detailed descriptions of these particle detectors and appropriate references are presented in the following subsections.

A. Aragats Solar Neutron Telescope

Aragats Solar Neutron Telescope (ASNT, see Fig. 2) is part of the worldwide network coordinated by the Nagoya University (see details in [29]) aiming primarily to measure the fluxes of the neutrons born in the violent solar flares. In 2006, after setting up new data acquisition electronics [30], ASNT measures stopping particle energy in the range 7–120 MeV.

Histograms of the energy releases in the thick scintillators are measured and stored each minute, providing the exact pattern of the energy releases during solar transient events and during thunderstorms. The ASNT consists of 4 up and 4 bottom scintillators, each having the area of 1 m^2. The distance between layers is ~1.2 m. The data acquisition system can register all coincidences of detector signals from the upper and lower layers, thus, enabling measurements of the arrival of the particles from different directions. The signals ranging from 0.5 mV to 5 V, from each of 8 photomultipliers, are passed to the programmable threshold discriminators. The output signals are fed in parallel to the 8-channel logical OR gate triggering device and to a buffer. If there is a signal in the channel we will denote it by 1 and the channels that were not fired within the "opening" of the gate (~ 1 μ sec) by 0. The ASNT trigger condition is defined by detecting at least one signal in the 8 data channels. The trigger rate of the entire detector system does not exceed 10 kHz. The duration of the entire data readout and signal processing procedure is less than 10 μ sec . There are 23 different possibilities of so-called "basic states." Sixteen of them carry information about the direction of the incident particle. For example, the state configuration 0010 for the upper layer and 0010 for the lower layer corresponds to the charged particle traversal through the third upper and third lower scintillators (zenith angle between 0° and 30°). Combination 0010 and 1000 corresponds to the traversal through the third upper and the first lower scintillator (zenith angle between 20° and 40°). The other 7 possibilities give additional valuable information on the particle flux incident on the detector. For instance, the combination 01, i.e., no signal in the upper and the signal in the lower layer can be attributed to the traversal of a neutral particle. However, due to small sizes of the anticoincidence shielding (see Fig. 2), several charged particles can hit the detector from the side. Nonetheless, if the particle beam is near vertical (it is just the case of electron-gamma avalanche hitting ASNT), we can measure the energy release spectrum of the thunderstorm-correlated gamma rays. The combination 01 selects neutral particles, and viceversa the combination 10 selects low-energy charged particles (due to energy losses in the roof the threshold energy is ~15–17 MeV). The top scintillators have the thickness of 5 cm (energy release for the vertical electrons and muons is ~10 MeV) the combination 11 will select charged particles with energy greater that 25–27 MeV. The advanced data analysis system (ADAS) provides registration and storage of all logical combinations of the detector signals for further

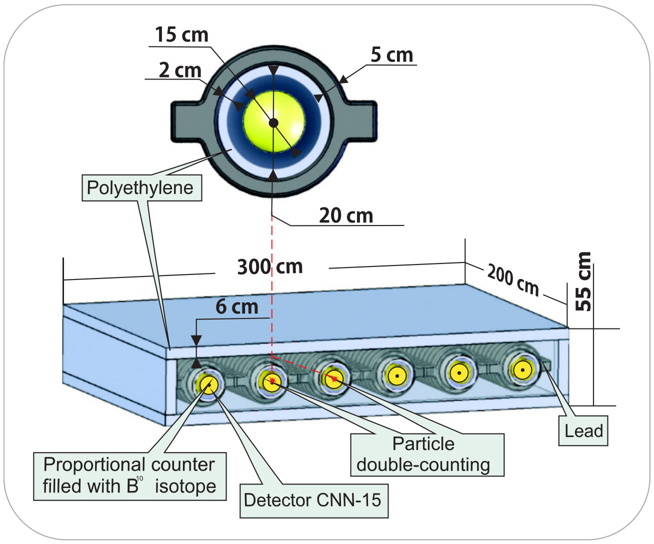

FIG. 3 (color online). Section of Aragats Neutron Monitor 18NM64 type; ArNM consists of 3 separate sections with 6 proportional chambers in each.

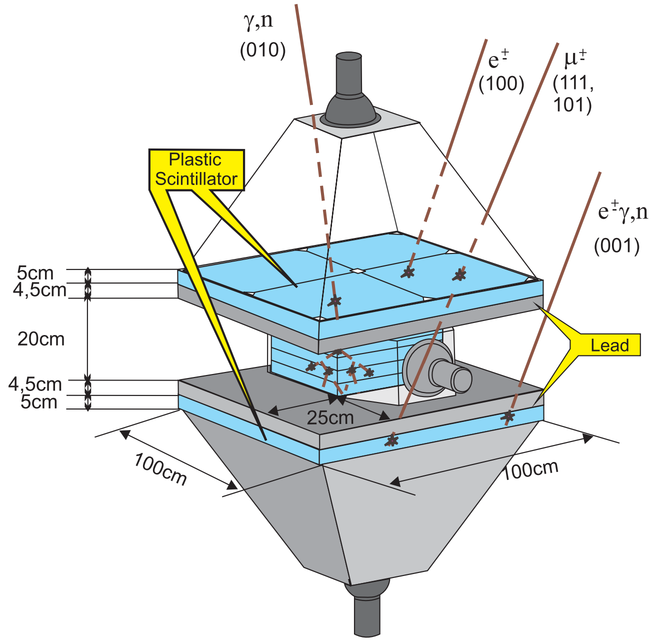

FIG. 4 (color online). SEVAN detector measuring charged and neutral secondary cosmic rays.

offline analysis and for issuing warnings and alerts on the dangerous space weather conditions [31].

B. Aragats Neutron Monitor (ArNM)

The standard neutron monitor (NM) of 18NM-64 type, see Fig. 3, consists of 18 boron-filled proportional chambers, located below 5 cm of lead (producer) and 10 cm of polyethylene (moderator).

Secondary protons and neutrons interacting with the lead producer give birth to numerous neutrons of smaller energies which release energy in polyethylene (thermalized) and enter the proportional counter filled with gaseous boron. A small fraction of these neutrons ($\sim 5\%$), are absorbed by ^{10}B isotope and generate alpha-particles detected by the proportional chamber. The neutron monitors are equipped with DAQ electronics, providing 3 different values of the detector dead time—0.4, 250, and 1250 μs. Only incident hadrons can be detected by the neutron monitor; the sensitivity of ArNM to electrons, muons, and gamma rays is vanishingly small.

C. SEVAN particle detectors

The new particle detector system, named SEVAN (Space Environmental Viewing and Analysis Network [32,33]), simultaneously measures fluxes of most species of secondary cosmic rays, thus representing an integrated device used for the exploration of the solar modulation effects.

The basic detecting unit of the SEVAN module (see Fig. 4) is assembled from standard slabs of $50 \times 50 \times 5$ cm^3 plastic scintillators. Between two identical assemblies of $100 \times 100 \times 5$ cm^3 scintillators (4 standard slabs) are located two $100 \times 100 \times 5$ cm^3 lead absorbers and thick $50 \times 50 \times 20$ cm^3 scintillator stacks (4 standard slabs). A scintillator light capture cone and photomultiplier tubes (PMTs) are located on the top, bottom, and intermediate layers of the detector. Incoming neutral particles undergo nuclear reactions in the thick 20 cm plastic scintillator and produce protons and other charged particles. In the upper 5-cm thick scintillator, charged particles are registered very effectively; however, for the nuclear or photonuclear interactions of neutral particles there is not enough substance. When a neutral particle traverses the top thin (5 cm) scintillator, usually no signal is produced. The absence of the signal in the upper scintillators, coinciding with the signal in the middle scintillator, points to neutral particle detection (gamma ray or neutron). The coincidence of signals from the top and bottom scintillators indicates the traversal of high-energy muons, traversing 10 cm of lead (minimal energy ~250 MeV).

D. Surface arrays: Aragats Multichannel Muon Monitor and MAKET ANI

Two detector assemblies measuring the extensive air showers operate on the Aragats research station. The main goal of the GAMMA [34] and MAKET-ANI [35] detectors is to measure the energy spectra of cosmic rays to understand their origin and particle acceleration mechanisms. Both detectors use the plastic scintillators overviewed by photomultipliers to determine the number of electrons in the shower and infer the energy and type of the primary particle. About 300 detecting channels formed from 5-cm thick plastic scintillators with area 1 m^2 each are located at the highland of Mt. Aragats at altitudes

3200–3250 m. EAS detectors are triggered arrays; however, each detector counts all incident particles measuring the time series of the changing fluxes of cosmic rays. High count rate ($\sim 30,000$ counts per m^2 per minute), combined with the large area of the detector assembly makes surface arrays ideal detectors for measuring additional electron flux correlated with thunderstorms. We select several detectors from both surface arrays and implement special trigger conditions for detecting additional fluxes of cosmic rays and large particle bursts in correlation with thunderstorm activity. Twenty-six of 1 m^2, 5-cm thick scintillators, located in iron boxes, comprise the surface array of the Aragats Multichannel Muon Monitor (AMMM). Another 16 same type scintillators comprise a surface array named MAKET, located inside and in the vicinity of the building where most of the other particle detectors are located, see Fig. 1. AMMM and MAKET detectors measure the charged species of secondary cosmic rays with very high accuracy: the relative error of the mean 1-minute count rates are 0.13% and 0.18% correspondingly. Each of MAKET standalone detectors provide measurements of the incident particles and the array on the whole also provides count of, so-called, EAS triggers (''firing'' of more than 8 detectors of array within the time window of 400 nsec). From the collected triggered events we can select other firing combinations of detector channels (for instance, events with all 16 channels firing). These 2 selections (> 8 and all 16 firing channels) routinely collect EAS with sizes $\sim 10^4$ and $\sim 2^* 10^4$ electrons correspondingly. However, when thunderstorm clouds are ''sitting'' on Mt. Aragats, the RREA process triggers the array and the stable count rate of EAS events goes up abruptly.

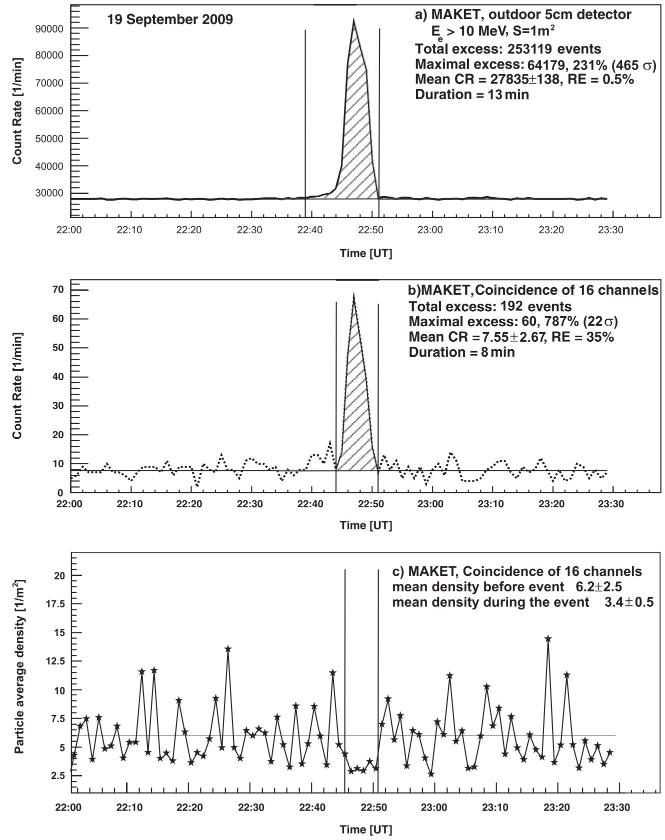

FIG. 5. One-minute time series detected by the MAKET array. (a) Count rate of the standalone outer detector. (b) Count rates of the ''EAS triggers''—all 16 scintillators give signal within 400 nsecs. (c) The mean density of the particles generating the MAKET trigger conditions.

III. DETECTION OF THE THUNDERSTORM-CORRELATED COSMIC RAY FLUXES

On September 19, 2009 all ASEC detectors measured large enhancements, seen as huge peaks in the 1-minute count rates (see Figs. 5, 6, and 8). According to the staff report and information from the Armenian meteorological service, the thunderstorm clouds height was 100–200 m and lightning accompanied with snow and rain were seen at $\sim$21–22 UT, a half an hour before the particle event.

In the legends of Figs. 5, 6, and 8, we depict a total enhancement during the event, the maximal enhancement occurred during 1 min, and statistical significance of the detected peaks in percents and numbers of standard deviations (σ). The mean count rate and variance of the count rate and the relative error were estimated by the 1-hour data before the start of enhancement when the mean and variance of the count rate corresponds to the detector typical operation.

In Fig. 5(a) one can see the enhancement of the count rate measured by the outdoor 5-cm thick scintillator of MAKET array (energy threshold 7–8 MeV, scintillator N 5 in Fig. 1. The observed enhancement above the background is really huge—10 times more than any reported ''thunderstorm particle'' flux by the other groups. The count rates of ''triggered'' events (signals in all 16 plastic scintillators within a time window of 400 nsec) although is only 0.1% of the 1-minute total count rate, enhanced $\sim$8 times compared with the background value. The background for the triggered events is EAS generated by the primary proton or stripped nucleolus entering terrestrial atmosphere. From the mean background count rate we can estimated the threshold energy of the primary proton to be 50–100 TeV. During the ''thunderstorm event'' the nature of the additional triggers is completely different from the EAS events. The mean value of the particle density is considerably lower as we can see in Fig. 5(c). A huge number of particles born in a very short time covering large surfaces on the ground possibly pointed on the new source of seed particles, different from the ambient population of the MeV secondary cosmic rays. Possibly seed particles come from the electrons accelerated by very large electrical fields in the plasma of intracloud lightning [4,36].

Also in Fig. 5 we can see that the duration of the particle enhancement measured by the standalone scintillator is much larger than the duration of the "short flashes" of particles—13 and 7 min correspondingly. The duration of the event was determined by visually examining the time series; the enhancement is demonstrating itself as a characteristic peak in the time series. Usually we do not need a more formal definition for very large events. However, the peak searching algorithm defines the start as the initial point in the time series starting from which 3 consequent enhancements are greater than 2.5σ. Nonetheless, the big variety of the peaks requires visual check as a final procedure.

IV. ELECTRONS AND GAMMAS DETECTED BY ASNT

In Fig. 6 we present the excess measured by the ASNT detector at the same time, on September 19, 2009. The statistical significances of the peaks are extremely high. We assume that additional flux was due to the RREA process and additional particles are mostly electrons and gamma rays. Plastic scintillators can register both electrons and gammas and first of all we performed GEANT4 [37] simulations of the detector response to estimate the probability of detection of particles of different types by selecting various ASNT operation options (namely, 01, 10, and 11 combinations).

For each combination we calculate the efficiencies of the registration of the particle of a definite type and contaminations of its counterparts. Gamma rays can be registered by a 5-cm scintillator, with efficiency less than 10% (imitating electron) and in a 60-cm scintillator with efficiency ~20%.[1] The electron can be registered in the top scintillator with efficiency above 95% or miss detection in the top scintillator and be detected in the lower one (imitating gamma ray) with efficiency less than 5%. Taking into account the energy of the minimal ionizing particle, giving a signal in the scincillator, and amount of the matter above the scintillator (roof, scintillator housing), we estimate the threshold energy to detect electron or gamma ray by the top layer of the ASNT to be equal ~15–17 MeV. Several indoor MAKET detectors located near walls of the building have energy thresholds of 11–13 MeV. The energy of electrons detected in both layers of ASNT (11 combination) is above 25 MeV).

The start of the enhancement of gamma rays (energy above 7 MeV) is 4 min earlier compared to the start of the enhancement of electrons with energy above 15 MeV; see Figs. 6(a) and 6(b).

[1]Neutrons also are detected by the thick scintillator with considerable efficiency. However, the cross section of the neutron photoproduction is not large and additional neutrons can comprise only very few percents of the gamma rays.

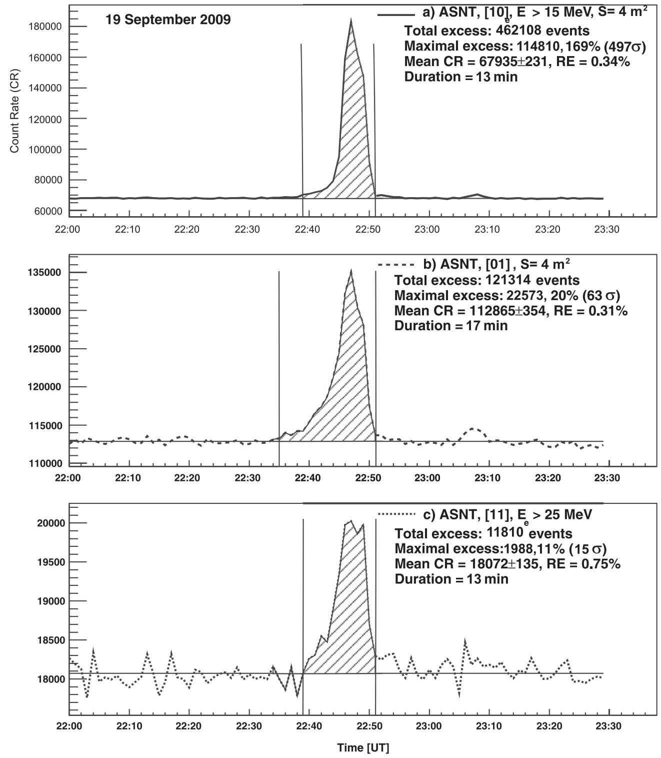

FIG. 6. One-minute time series of the particle fluxes measured by ASNT. (a) 10 combination, signal only in top layer, mostly electrons with energy greater than 15 MeV. (b) 01 combination—mostly gamma rays with contamination of neutrons and electrons. (c) 11 combination—electrons and/or gamma rays with energy above 25 MeV. Additional particles are demonstrated by the dashed areas.

V. RREA ELECTRON AND GAMMA-RAY ENERGY SPECTRA

By the 60-cm thick scintillator of the ASNT we measure not only count rates but also spectra of energy releases [the distribution of the PMT amplitude heights enumerated as ADC (amplitude-to-digital converter) codes]. However, we are interested not in the energy release spectrum, which is dependent on the detector response, but in the flux of gamma rays before entering the roof and detector. Thus, we have to solve the inverse problem of cosmic ray physics—reconstruct by the measured spectrum of energy releases the spectrum that is fallen on the detector or on the roof of the building where the detector is located. We solve the inverse problem and "unfold" the gamma ray energy spectrum by multiple solutions of the direct problem: assuming the analytic form of the RREA gamma ray spectra (power, exponential, or power with cutoff), we tune free parameters (normalizing coefficients, spectral indexes) by minimizing the "quality" function describing the closeness of simulated with GEANT4 energy releases histogram to an experimentally measured one. As a quality function we use the sum of the square differences between bin values of 2 histograms. The electrons and gamma rays were traced through the material of the roof above the detector and through the substance of the detector. Light absorption in the plastic scintillators was also taken into account in GEANT 4 simulation. Light attenuation coefficients were taken from [29]. We use the random search procedure for selecting the parameters of the energy spectra (see, for example, [38]).

The RREA electron spectrum was obtained using count rates measured by 5-cm thick scintillators of MAKET, ASNT, and SEVAN detectors. From Fig. 1 you can see that the MAKET 5th, 6th, and 8th scintillators are located outdoors and ASNT, SEVAN, and other 13 MAKET scintillators are located indoors. These detectors are of the same type; however, their energy thresholds are different due to different electronics thresholds and a various amount of substance above. Using enhancements (peaks) detected in these 18 5-cm thick scintillators, we select groups corresponding to 4 diverse energy thresholds. The energy thresholds were determined by comparing the mean count rates of scintillators with ''theoretical'' values, obtained from simulations of the EAS propagation in the atmosphere.

The electron integral spectrum is shown in Fig. 7 along with a gamma ray spectrum. The electron spectrum in the energy range 7–20 MeV is fitted by exponential function—$A \bullet e^{b \bullet E}$. The spectral index is -0.18 ± 0.06; corresponding fit quality—$\chi^2/\mathrm{ndf} = 0.34$. The horizontal error bars in the electron energy spectrum reflect uncertainties in determination of the energy thresholds, due to the complicated structure of the roof substance. The electron spectrum abruptly ended at ~30 MeV, as there is no evidence of additional electrons detected by 11 coincidence of ASNT. The peak seen in Fig. 6(c) was found to be caused by the gamma rays giving signals both in the top 5-cm and bottom 60-cm thick scintillators.

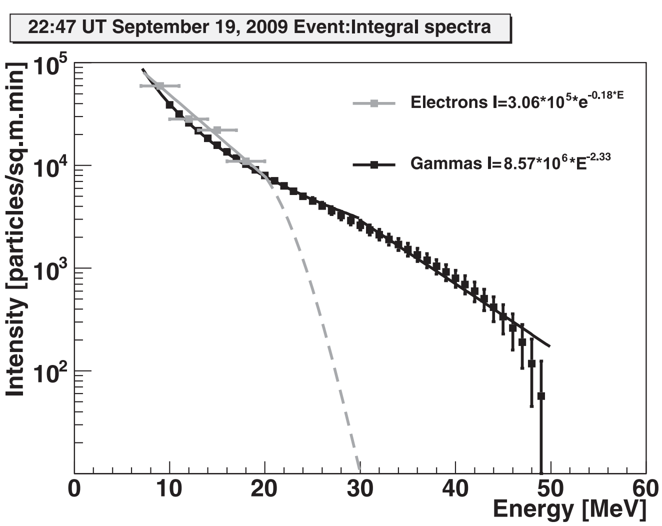

FIG. 7. Unfolded electron and gamma ray spectra fitted by exponential and power functions.

Using obtained electron spectrum, we estimate the number of electrons contaminating the energy release spectrum measured by the 60-cm thick scintillator and afterward correct the gamma ray energy spectrum. In turn, after reconstructing the gamma ray spectrum we correct the electron spectrum. The efficiency of gamma ray detection was checked by GEANT4 simulation; the probabilities of gamma rays to be detected in outer MAKET and ASNT 5-cm detectors are ~3.5% and ~10%, respectively. There is significant roof substance (metallic tilts, wood) above ASNT in which gamma rays create additional electron-positron pairs, increasing the probability of gamma rays to be detected in the 5-cm thick detector under the roof. The reconstructed energy spectrum of the incident gamma rays described by power function is continued till ~50 MeV. The gamma ray energy spectrum is fitted by power function—$A \bullet E^b$ in the range 7–30 MeV ($\chi^2/\mathrm{ndf} \sim 2.4$); in the energy range 30–45 MeV, the gamma ray spectrum is rather well described by the exponential function with slope equal to -0.14 and afterwards abruptly vanished near 50 MeV; see Fig. 7. Error bars of the gamma ray energy spectrum are statistical ones.

Details of the electron and gamma ray energy spectra at 3250 m are posted in Table I.

VI. NEUTRONS IN THE RREA: ARNM EVIDENCE

In Figs. 8(a) and 8(b) we compare the enhancements of the neutrons detected by the ArNM and all neutral particles in the SEVAN detector (signal only in the middle scintillator, combination 010). Placed in a few meters from SEVAN, ArNM's enhancement is consistent with neutral

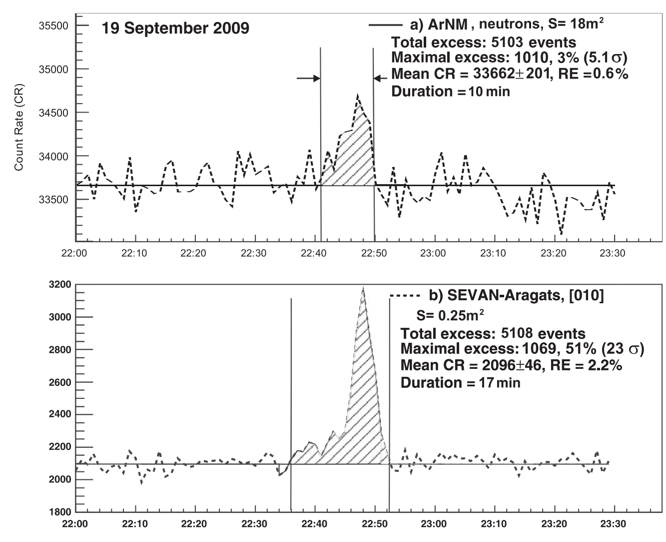

FIG. 8. One-minute time series of the particle flux detected by the SEVAN and ArNM detectors (a) 1-minute time series of ArNM. (b) 1-minute time series of SEVAN (010 combination). The additional particles are demonstrated by the dashed areas.

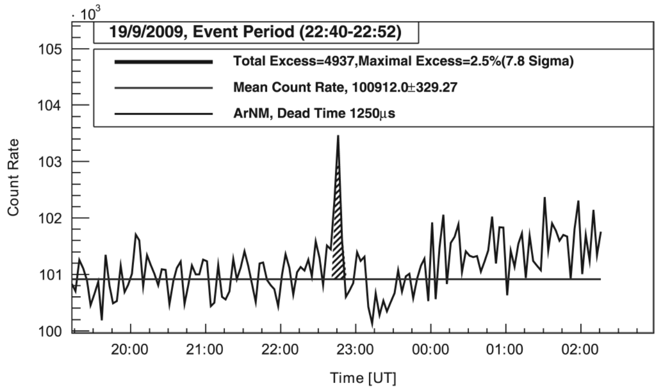

FIG. 9. 3-minute time series of ArNM on September 19, 2009.

fluxes registered by ASNT and SEVAN detectors. ASNT and SEVAN measure all neutral particles; there is no possibility of distinguishing between gamma rays and neutrons. The neutron monitor is a device with suppressed efficiency to measure leptons (see [39,40]).

Additional protons of the cosmic ray flux can also generate an enhancement in NM; however, the conditions of interplanetary magnetic fields were very stable on September 19 and there is absolutely no reason to expect extra proton flux. Therefore, although the enhancement of neutrons in ArNM is not so significant as detection of neutral particles by ASNT and SEVAN (5.1σ against 63σ and 23σ), nonetheless, the peak in ArNM time series proves the detection of neutrons. The source of additional neutrons is located in the atmosphere; the high-energy gamma ray flux generates neutrons in photonuclear reactions with air atoms (see details in [41]). A simultaneous measurement of electrons and gammas on September 19 provides unambiguous confirmation of the photonuclear mechanism for neutron production and is another demonstration that RREA was developing very close to the ASEC detectors on September 19, 2009.[2] The duration of a neutron event is 7 min shorter as compared with the duration of a gamma enhancement. The start time and duration of the gamma ray enhancement detected by the SEVAN detector coincide with the ones detected by the ASNT detector, located 30 m from SEVAN in the same building.

Taking into account the importance of proving neutron production, we form 3-minute time series from initial 1-minute ones, summing counts of the 3 succeeding minutes (a standard practice in time series statistical analysis; see Fig. 9). Obtained significance of the 3-minute neutron peak, equal $\sim 7.8\sigma$, is overwhelming. Calculating the chance probability of obtaining a peak in the 3-minute time series, we take into account the number of attempts we made to obtain the maximal peak significance. Three-minute time series can be obtained by 1-minute time series in 3 ways. Taking only one time series from 3 possible ones, we alter the statistical distribution used for calculation of chance probability (see details of statistical techniques used in [42,43]; see Web calculator in [44]). Final obtained chance probabilities of order $\sim 10^{-14}$ leave absolutely no doubts of the neutron detection on September 19, 2009.

VII. DISCUSSION

For the quantitative description of the RREA process in the thunderstorm atmosphere the most difficult problem is to determine the height of the cloud and structure and value of the electrical field in it. Nonetheless, despite the fact that we do not measure the height of the thundercloud and the structure of the electrical field in it, we can make rough estimates of some phenomenological parameters of the RREA process based on the measured particle energy spectra and neutrons. The energy spectra of the RREA electrons and gamma rays, as well as the measured flux of the neutrons, contain information on the strength and elongation of the electrical field in the thunderstorm cloud and on the height of the cloud above the detector.

To estimate the multiplication rate of the electrons in the thundercloud and overall number of electrons in it, we first have to estimate the height of the thundercloud on September 19, 2009, above the ASEC detectors. From the measured electron energy spectrum we can conclude that at least 20 MeV electrons reached ground level and were detected by the 5-cm scintillators inside the MAKET building. We can assume that maximal energy of the RREA electrons reached 40–50 MeV.[3] Therefore, assuming the average ionization losses of these electrons at $\sim$3500 m altitude equal to $\sim$200 KeV per meter, the most probable height of the cloud will be 100–150 m, well coinciding with the observations of the Armenian meteorological service. Taking for granted the height of 130 m, we estimate the RREA electrons spectrum just at the entrance from the thundercloud by selecting the trial electron spectrum at 3380 m and simulating with GEANT4 the electron-gamma avalanche till 3250 m. By trying different trial spectra (analogically to recovery of the gamma ray energy spectrum above the roof), evaluating the avalanche from 3380 till 3250 m and comparing each obtained spectrum with an experimental one (shown in Fig. 7 and Table I) we have found that the best approximation of the spectrum at 3380 m have again a exponential functional form; the spectral index is -0.15 ± 0.2. The number of electrons with energies greater than $\sim$30 MeV at 3380 m is $350,000/\mathrm{sq\,m\,min}$ only $90,000/\mathrm{sq\,m\,min}$ electrons with energy greater than 7 MeV (minimal ionizing particle energy of the 5-cm thick scintillators) survive traveling

[2]Neutrons attenuate very fast in dense atmosphere and survival probability of neutrons born high above the detector is very low.

[3]At least the AGILE gamma observatory detects one gamma ray with energy 40 MeV [10].

TABLE I. Parameters of the electron and gamma ray energy spectra fits measured on September 19, 2009, (maximal minute intensities) at altitude 3250 m above sea level.

Spectra fit function	A (coeff.)	b (slope)	Mean Energy (MeV)
Electron $A^*e^{-b^*E}$ (from 7 till 20 MeV)	$(3.1 \pm 0.3) \bullet 10^5$	-0.18 ± 0.06	5.6 ± 0.2
Gamma A^*E^{-b} (from 7 till 30 MeV)	$(8.57 \pm 0.53) \bullet 10^6$	-2.33 ± 0.02	4 ± 0.8 ($E_{min} = 1$ MeV)

till 3250 m. The mean electron energy is estimated to be $\sim$6.7 $\pm$ 0.8 MeV at the lower edge of the thundercloud at 3380 m. This value is in rather good agreement with that obtained from simulations of value 7.3 MeV [45]. From the measured RREA electron spectrum and spectrum of secondary cosmic ray electrons at 3380 m [46], we have calculated the multiplication rate (avalanche growth factor) in the thundercloud electric field. The obtained RREA energy spectrum on the 3380 m height (assumed end of the thundercloud and large electrical field in it) was extrapolated until 7 MeV; the number of electrons above 7 MeV was calculated and divided by the secondary cosmic ray electron number calculated according to [47]. Obtained multiplication factor equals $\sim$330, corresponding to $\sim$6 e-folding. Assuming a cross section area of electric field with radius 500 m (maximal distance between ASEC detectors measuring the thunderstorm-correlated particle enhancements), we will get a total number of electrons above 7 MeV $\sim 3.8^*10^{12}$.

The maximal energy gain of electrons per one avalanche length is approximately independent of the atmosphere density and electrical field value and equals $\sim$7 MeV [45]. Thus, based on the calculations of the multiplication rate we obtain maximal energy of electrons $\sim$40 MeV in good agreement with our assumptions and measurements.

To calculate the value of the e-folding length we need to know the elongation of the electrical field in the thundercloud. This length we estimate taking into consideration the neutron detection by the Aragats Neutron Monitor; see Figs. 8 and 9. The nuclear fusion origin of the thunderstorm-correlated neutrons was ruled out in [27]. Assuming the flux of the gamma rays with a spectrum stretching up till 50 MeV, well above the photonuclear reaction threshold for nitrogen ($\sim$ 10.5 MeV), the (γ, n) reaction becomes the best candidate for the neutron generation [25]. On September 19, 2009, ArNM detected $\sim$70 additional neutrons per square meter at a maximal intensity minute. In the GEANT4 simulation, after the passage of 1500 m, bremsstrahlung photons had generated $\sim$2250 neutrons. The number of gammas in simulation was taken to be 1×10^6, which corresponds to the 100 000 gammas after the passage of 1500 m (close to the experimental value). The obtained neutron energy spectrum can be fitted by the exponential function with slope -0.45; the maximal energy of neutrons was 14 MeV. The probability of the photonuclear reactions of gamma rays with atmosphere nucleus is rather low ($\sim$ 1%) in comparison with the probability of electromagnetic interactions. That is why the neutron flux is smaller in comparison with the gamma ray flux. Besides, the efficiency of the neutron monitor to register neutrons with energy below 15 MeV is much smaller than the efficiency of detecting neutral particles by ASNT and SEVAN. However, according to [48,49], even neutrons with energy less than 1 MeV still can be detected by the NM 64 neutron monitor. According to their estimates of the neutron detecting efficiency, we calculate the number of the neutrons expected to be registered by the ArNM to be $\sim$20. The discrepancy between experiment and simulation can be due to other sources of neutron production [24] not taken into account in simulation or by greater than assumed efficiency of the NM 64 to detect low-energy neutrons, or by a too simplified model used for simulation. From the multiple trials of simulations started at the different heights in the atmosphere, we found that the maximal neutron yield was obtained when the starting point was $\sim$1500 m above the detector. Therefore, from the estimate of the electrical field elongation of 1500 m, we can estimate the e-folding length as 250–300 m and the electrical field strength (if we assume its uniform distribution), according to equation (1) in [45] will be 180–200 kV/m.

A very long duration of the electron and gamma ray fluxes detected on the ground ($\sim$ 10 orders of magnitude greater than duration of the terrestrial gamma ray flashes) requires a permanent stable source of the seed particles, and secondary cosmic rays fulfill this condition. On the other hand, we do not decline that the intracloud lightning leader can provide another source of the seed particles. Detection of very short (within 400 nsec) flashes of the electrons detected by the MAKET air shower array is just a demonstration of this possibility. Existence of the alternative seed particle source did not put under question our calculations because a fraction of particles from this source does not exceed 0.1% of the total observed enhancement.

VIII. CONCLUSION

During the particle event on September 19, huge enhancements of the electrons, gamma rays, and neutrons, as well as short particle bursts, counting millions of the additional particles and distributed over a large area, were detected. The observations of ASEC monitors prove the existence of the long-lasting electron-photon avalanches developing in the atmosphere during thunderstorms.

Simultaneous measurements of the gamma rays and neutrons provide confirmation of the photonuclear mechanism for neutron production.[4]

For the first time we measured the electron and gamma ray energy spectra and made quantitative estimates of some phenomenological parameters of the RREA process based on detected particle fluxes. The exponential spectrum of the RREA electrons is in good agreement with simulations [45], and gamma ray power energy spectrum do not contradict recent observations of the TGF by orbiting gamma observatories [10]. However, we recognize that we measure only high-energy tails of the energy spectra of electrons and gamma rays; to measure bulk of particles of lower energies we need new particle detectors with much lower energy thresholds, under construction now.

[4]However, only ~20% of the detected neutrons can be explained by the photonuclear reaction according to our simulations

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