# Numerical analysis of 2010 high-mountain (Tien-Shan) experiment on observations of thunderstorm-related low-energy neutron emissions

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[1] The high-mountain experiment in a thunderstorm atmosphere, in which "extraordinary high flux of low-energy neutrons" was detected, is analyzed. Due to the lack of data on the radiation source, we do not analyze directly measured absolute count rates. Instead, we address the experimental configuration, namely, simultaneous measurements by shielded and unshielded helium counters, which allow a comparison of relative count rates and, thus, verifying the species of the detected radiation. Results of Monte Carlo simulations of neutron transport executed without aprioristic assumptions, using only data on the experimental configuration, have raised strong doubts as to whether the detected increases of the count rates can be attributed to neutrons. Results of simulations allowing for the neutron transport in atmosphere from distant (100–500 m) photoneutron source with spectrum in the range 0–20.1 MeV produced by relativistic runaway electron avalanche bremsstrahlung demonstrate that ratios $R$ of the count rates of shielded and unshielded counters below 1 keV are manyfold higher than the ratios $R_{\mathrm{exp}} \approx 0.34$–1.06 of the measured count rates. In the total range 0–20.1 MeV, the $R$ magnitudes vary from 0.14 to 0.84 depending on the distance to the neutron source. Results of simulations of γ rays transport executed without aprioristic assumptions demonstrate that, most likely, hard γ rays with energies $\varepsilon_\gamma > 1$ MeV were detected. We note that in thunderstorm environment, a selection is required of neutrons and γ rays, for which the time-of-flight technique is the most adequate.

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## 1. Introduction

[2] A possibility of nuclear reactions in thundercloud fields [*Wilson*, 1924] can be proved by detecting neutron emissions from thunderclouds. *Fleisher* [1975] carried out the first direct search of neutron flux enhancements in thunderstorm atmosphere with null results. *Shah et al.* [1985] were the first to communicate a detecting statistically significant neutron flux enhancements correlated with preceding lightning electromagnetic pulses (EMPs). Of 11,200 EMP events during the high-mountain experiment (Himalayas; 2743 m), 124 were associated with yields from 3 to 60 neutrons in 320 μs after EMPs. One and two neutron events were eliminated as, at least partially, originating from cosmic rays; the possible interference of EMPs and cosmic ray showers was excluded. Later, *Shyam and Kaushik* [1999], *Kuzhewskiĭ* [2004], *Bratolyubova-Tsulukidze et al.* [2004], *Martin et al.* [2009], *Martin and Alves* [2009, 2010], *Chilingarian et al.* [2010, 2012a, 2012b], *Gurevich et al.* [2012], and *Starodubtsev et al.* [2012] reported a detection of bursts of penetrating radiation associated with thunderstorms, which they identified as neutrons.

[3] The initial idea that the thunderstorm-correlated emissions of neutrons are stemmed from the $^2$H($^2$H, n)$^3$He reaction in the lightning channel [*Libby and Lukens*, 1973; *Fleisher et al.*, 1974; *Fleisher*, 1975; *Shah et al.*, 1985; *Shyam and Kaushik*, 1999; *Kuzhewskiĭ*, 2004] did not sustain careful analysis [*Babich*, 2006, 2007]. In view of reliably detected emissions of hard γ rays of atmospheric origin [*Fishman et al.*, 1994; *Eack et al.*, 2000; *Smith et al.*, 2005; *Khaerdinov et al.*, 2005; *Tsuchiya et al.*, 2007, 2009, 2012; *Torii et al.*, 2009, 2011; *Chilingarian et al.*, 2010; *Briggs et al.*, 2010], the enhancements of neutron flux in thunderstorm atmosphere can be connected with photonuclear (*γ*, *n*) reactions [*Babich*, 2006, 2007; *Babich and Roussel-Dupré*, 2007; *Babich et al.*, 2007, 2008, 2010; *Carlson et al.*, 2010].

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[4] However, because neutrons accompany emissions of high-energy electrons, X-rays, and γ rays, and even can be produced by electrons and γ rays, and in view of these emissions, are capable of producing the same effects in detectors as the neutron reaction daughter products, reliable selecting of neutrons is required. There are two well-known approaches: time-of-flight technique and neutron-activated reactions with long-living daughter products. Though both techniques are widely used in nuclear weapons testing, research with pulsed nuclear reactors, evacuated neutron tubes, etc., only the former allows receiving in situ information on neutrons. The latter allows obtaining information by comparing count rates as the detector is moved away from the radiation field. As the γ ray flux is significantly higher than the flux of daughter photonuclear neutrons and energies of γ photons $\varepsilon_\gamma$ are significantly above the photoneutron energies $\varepsilon_n = \varepsilon_\gamma - \varepsilon\text{th}(\gamma, 1n)$, the assertions of *Tsuchiya et al.* [2012] based on results of Monte Carlo simulations of their own high mountainous (4300 m) experiment that "…not neutrons but γ rays may possibly dominate enhancements detected by the Aragats neutron monitor…" [*Chilingarian et al.*, 2010] and their conclusion that "…worldwide networks of neutron monitors … and solar neutron telescopes … are useful for observations thunderstorm-related γ ray emissions", are fully justified. Here $\varepsilon\text{th}(\gamma, 1n)$ is the $(\gamma, 1n)$ threshold equal to 10.55 MeV for nitrogen nuclei [*Dietrich and Berman*, 1988].

[5] If neutrons are produced in lightning channels or lightning discharges trigger secondary processes accounting for the neutron production, arrival of neutrons at the detector is preceded by the lightning EMP and, possibly, by the γ rays because both propagate with the speed of light. EMPs and γ ray pulses are more or less time coinciding if both are emitted directly by the lightning plasma or the lightning-triggered processes, capable of producing other possible sources of penetrating emissions, develop sufficiently fast. The work [*Shah et al.*, 1985] is the only one, in which neutrons have been selected using the time-of-flight technique: Shah et al. have measured time delays between the EMPs and, therefore, possibly, but not for sure, between the γ ray pulses and arrival of the first neutron at the monitor.

[6] *Gurevich et al.* [2012] communicated new observations of multiple events with extremely high yields, (0.03–0.05)/(cm$^2$ s), of low-energy neutrons "connected with thunderstorm discharges" (Tien-Shan, 3340 m). Helium-3 counters have been used, which "register the neutrons having the energies less than few keV" [*Gurevich et al.*, 2012]. However, numerical simulations carried out by *Tsuchiya et al.* [2012] demonstrated that "…arriving neutron flux at > 1 keV is expected to be lower than that of arriving γ rays at > 10 MeV by more than 2 orders of magnitude." Results of numerical simulations, carried out by *Chilingarian et al.* [2012a] using Monte Carlo GEANT4 code, of absolute readings of counters in the communication by *Gurevich et al.* [2012] raised strong doubts that neutrons have been detected. Because in the experiment [*Gurevich et al.*, 2012], the count rates have been read in situ such that the γ ray interference cannot be excluded; careful analysis of results of this experiment is required. Therefore, a goal of our paper is to verify a validity of the following assertions [*Gurevich et al.*, 2012]:

[7] 1. The $^3$He "…counter registers both thermal neutrons having energies from 0.01 up to 0.1 eV and neutrons having energies from 0.1 up to 1 eV with the equal efficiency."

[8] 2. "Extraordinary high flux" (0.03–0.05)/(cm$^2$ s) of thunderstorm-related low-energy neutrons was detected.

[9] 3. Too high flux of low-energy neutrons "constitutes a serious difficulty for the photonuclear model of neutron generation in thunderstorm;" to this opinion, *Starodubtsev et al.* [2012] joined who reported "first (? *our question*) experimental observations of neutron splashes under thunderclouds near the sea level."

[10] 4. "As for the high energies 10–30 MeV, the only work where the flux of the γ ray emission during thunderstorms was measured from the ground is the paper" of *Chilingarian et al.* [2010].

[11] 5. The flux of γ rays, 0.04/(cm$^2$ s), measured by *Chilingarian et al.* [2010], is "3 orders of magnitude less than the value" needed for the photonuclear reactions to be capable of accounting for the neutron flux of (0.03–0.05)/(cm$^2$ s).

[12] More general goal of this paper is to attract attention of researchers developing experimental configurations for searching the thunderstorm-correlated neutrons, to difficulties arising from that neutron detectors, as a rule, are sensitive to any penetrating emissions of electromagnetic origin.

## 2. Experimental Data to be Compared With Results of Numerical Simulations

[13] A direct checking of absolute count rates and prescribing them to neutrons or γ rays and electrons is complicated because of uncertainties of the source location, their dimensions and power, emitted species, their energy, and angular distributions. Fortunately, comparative analysis is possible because in the experiment by *Gurevich et al.* [2012], two different $^3$He counters were used: the external unshielded counter and internal counter, located in a building, shielded by 2 mm iron roof and additionally covered by 20 cm carbon plate [*Gurevich et al.*, 2012]. Actually, the external counter was located inside light plywood housing [*Gurevich et al.*, 2012]. However, the neutron moderation and absorption in thin plywood layer is insignificant in comparison with those in thick carbon plate and iron roof; therefore, we consider the external counter as unshielded. Analysis of the relative count rates of the unshielded and shielded counters allows deducing reasonable conclusions as to the origin of the detected radiation. With this goal, we calculated ratios $R_{\text{exp}}$ of the internal-to-external counter count rates. The obtained values of $R_{\text{exp}}$ are presented in Table 1 for the rates measured during the storm 20 August 2010, given in *Gurevich et al.*

**Table 1.** Ratio $R_{\text{exp}}$ of Internal (Shielded)-to-External (Bare) Counters Count Rates

| Date | Time | $R_{\text{exp}}$ |
|---|---|---|
| 20 August 2010 | 12:54:00 | 641/1558 ≈ 0.41 |
| | 12:56:00 | 418/720 ≈ 0.58 |
| | 12:58:00 | 323/758 ≈ 0.43 |
| | 13:00:00 | 716/2055 ≈ 0.34 |
| 10 August 2010 | 08:06 | ~1200/2500 ≈ 0.48 |
| | 08:08 | ~1000/1600 ≈ 0.63 |
| | 12:50 | ~1250/2200 ≈ 0.57 |
| | 12:57 | ~1900/1800 ≈ 1.06 |
| Average $R_{\text{exp}}$ magnitude | | ~0.43 |

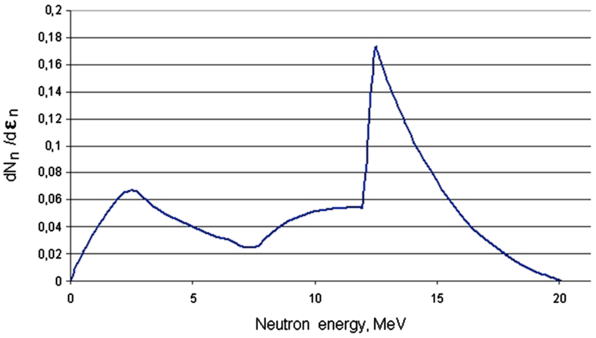


**Figure 1.** Energy distribution of photonuclear neutrons in the source.

[2012], and for the rates with extracted background, which we estimated from Figure 1 [*Gurevich et al.*, 2012] for the storm 10 August 2010. Initially, we carried out analysis, assuming that neutrons were being detected, without aprioristic assumptions of the origin of neutrons and location of their source. Then we carried out an analysis assuming a photoneutron source located at different distances from the counter. And, at last, we explored whether γ rays and electrons could account for the observed magnitudes of $R_{exp}$.

[14] As mentioned in section 1, *Chilingarian et al.* [2012a] have analyzed the communication of Gurevich et al., using the above advantage of the experimental configuration in *Gurevich et al.* [2012]. Proceeding from the efficiency and size of the external $^3$He counter and recorded count rates, Chilingarian et al. recovered a flux (1/m$^2$ min) of thermal neutrons (0.01–1 eV) incident the external counter. Than with the corresponding values of the flux, they, using the GEANT4 Monte Carlo code, simulated transport of thermal neutrons through the iron and carbon layers and calculated the flux of neutrons incident the internal $^3$He counter, which appeared to be 5–11 times less than the flux following from count rates of the internal counter in *Gurevich et al.* [2012]. Chilingarian et al. calculated that the neutron flux at the internal $^{10}B(n;{}^4He,\gamma)^7Li$ monitor [*Gurevich et al.*, 2012] appeared to be 44–117 times less than the flux following from the count rates reported by Gurevich et al.

[15] We believe that the above results of comparative analysis of absolute neutron flux by Chilingarian et al. already proved that count rates reported by *Gurevich et al.* [2012] are not due to neutrons. However, in view of importance of the problem of thunderstorm-correlated neutron emissions and foreseeing that a scale will be increased of the discussion already started by *Chilingarian et al.* [2012a] and *Tsuchiya et al.* [2012] on the validity of the communications on the neutron flux enhancements in thunderstorm atmosphere, we present results of our work. Its advantage is that it contains comparative analysis of relative count rates of internal and external counters without addressing to absolute neutron flux. Such approach seems to be more persuasive than comparing absolute quantities of neutron flux recovered from count rates. Besides, we did not limit the analysis to the thermal neutrons.

[16] The simulations were executed using VNIIEF Monte Carlo code C-007 [*Zhitnik et al.*, 2011] with the ENDF/BVII.0 library of neutron elementary cross sections [*Chadwick et al.*, 2006] and Los Alamos National Laboratory (LANL) MCNP-4C code with LANL library of cross sections [*Briesmeister*, 2000]. The difference in results is insignificant.

## 3. Analysis Without Aprioristic Assumptions (Transport of Neutrons in the Matter Covering the Internal Counter)

[17] To check if the $R_{exp}$ magnitudes can be treated as testifying to detecting of low-energy neutrons, we carried out numerical simulations of neutron transport through plane layers of iron (2 mm) and carbon (20 cm). The other layers (walls of the counters and aluminum containers) were not taken into account as they are the same for both internal and external counters; the layers were thin and did not disturb significantly the neuron flux and spectrum. The effect of interactions with atmosphere was not taken into account. The simulations were executed for the range energy from 0.01 eV to 100 keV of neutrons irradiating the iron layer for normal incident upon the iron surface and, more real, Lambert's angular distribution. The temperature of the matter was let to be 270 K ≈ 0.025 eV. We calculated portions of neutrons per one neutron incident the counters and neutron spectra reflected backward into the atmosphere and at the outlet of the carbon plate and entering the shielded counter. As a matter of fact, values of the portions are related to one neutron detected by the unshielded external counter. From 0.71 for $\varepsilon_{inc} = 0.01$ eV to 0.87 for $\varepsilon_{inc} = 100$ keV of neutrons incident the iron roof and then carbon plate are reflected backward, and in these, simulations are lost from being detected by the internal counter. The portions Δ and average energies $\varepsilon_{ent}$ of neutrons entering the internal counter are presented in Table 2. It is seen that the neutron spectrum at the outlet of the carbon plate is strongly shifted

**Table 2.** Portions of Neutrons Per One Incident Neutron Δ and Energies $\varepsilon_{ent}$ of Neutrons Entering the Internal Counter

| | Angular Distribution of Incident Neutrons | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Normal to the Iron Surface | | | | Lambert | | | |
| Energy $\varepsilon_{inc}$ of Incident Neutrons (eV) | Δ | Error (%) | $\varepsilon_{ent}$ (eV) | Error (%) | Δ | Error (%) | $\varepsilon_{ent}$ (eV) | Error (%) |
| 0.01 | 0.115 | 0.09 | 0.025 | 0.12 | 0.087 | 0.10 | 0.025 | 0.12 |
| 0.1 | 0.131 | 0.09 | 0.051 | 0.11 | 0.102 | 0.09 | 0.051 | 0.12 |
| 1 | 0.136 | 0.09 | 0.064 | 0.13 | 0.107 | 0.08 | 0.062 | 0.11 |
| 10 | 0.138 | 0.09 | 0.195 | 0.29 | 0.109 | 0.09 | 0.169 | 0.29 |
| 100 | 0.140 | 0.09 | 1.50 | 0.36 | 0.110 | 0.09 | 1.26 | 0.37 |
| 1,000 | 0.148 | 0.08 | 14.64 | 0.37 | 0.114 | 0.09 | 12.00 | 0.38 |
| 10,000 | 0.150 | 0.08 | 150.0 | 0.36 | 0.120 | 0.09 | 123.0 | 0.37 |
| 100,000 | 0.156 | 0.08 | 1899 | 0.36 | 0.124 | 0.09 | 1513 | 0.36 |

**Table 3.** Ratio of Internal to External Counter Count Rates With Allowing for the Counter Sensitivity[a]

| External (Unshielded) Counter | | Internal (Shielded) Counter | | | | |
|---|---|---|---|---|---|---|
| Energy $\varepsilon_{inc}$ of incident neutrons (eV) | $\sigma(\varepsilon_{inc}) \times 1$ | $\Delta$ | $\varepsilon_{ent}$ (eV) | $\sigma(\varepsilon_{ent})$ | $\sigma(\varepsilon_{ent}) \times \Delta$ | $\frac{\sigma(\varepsilon_{ent}) \times \Delta}{\sigma(\varepsilon_{inc}) \times 1}$ |
| 0.01 | 8670 | 0.087 | 0.025 | 5300 | 465 | 0.054 |
| 0.025 | 5328 | | | | | |
| 0.1 | 2766 | 0.102 | 0.05 | 4070 | 415 | 0.15 |
| 1 | 870 | 0.107 | 0.06 | 3690 | 395 | 0.45 |
| 10 | 260 | 0.109 | 0.17 | 2000 | 218 | 0.84 |
| 100 | 85 | 0.110 | 1.26 | 750 | 83 | 0.97 |
| 1,000 | 26.6 | 0.114 | 12.0 | 240 | 27 | 1.01 |
| 10,000 | 7.5 | 0.120 | 123.0 | 74 | 9 | 1.20 |
| 100,000 | 2.05 | 0.124 | 1510.0 | 21 | 2.6 | 1.26 |

[a]The $^3He(n, p)^3H$ reaction cross section $\sigma$ is in barn ($10^{-24}$ cm$^2$) units.

to the low-energy range and ratios of the measured internal-to-external counter count rates $R_{exp} = 034–1.06$ in Table 1 are much larger than $\Delta = 0.087–0.156$. In the range, $\varepsilon_{inc} =$ 0.01–1 eV $\Delta = 0.087–0.107$ for the Lambert's distribution. This discrepancy between $R_{exp}$ and $\Delta$ is consistent with results of simulations by *Chilingarian et al*. [2012a].

[18] To allow for the energy sensitivity of the counters, we multiplied $\Delta$ for Lambert's distribution from Table 2 by $^3$He $(n, p)^3$H reaction cross section $\sigma(\varepsilon_{ent})$ [*Chadwick et al*., 2006]. From Table 3, it is seen that in the range of incident neutron energies $\varepsilon_{inc} = 0.01–0.1$ eV, the ratio $\frac{\sigma(\varepsilon_{ent}) \times \Delta}{\sigma(\varepsilon_{inc}) \times 1} \approx$ 0.05–0.15 is significantly less than $R_{exp} \approx 0.34–1.06$. Only in the vicinity of $\varepsilon_{inc} = 1$ eV ($\varepsilon_{ent} \approx 0.06$ eV), the ratio is close to $R_{exp}$. Beginning with $\varepsilon_{inc}$ of few eV, it exceeds 2–3 times the most of the $R_{exp}$ values, 0.34–0.63, in Table 1. It is expedient to note that only neutrons with energies $\varepsilon_{ent}$ less than 1 eV ($\varepsilon_{inc}$ less than 100 eV for the internal counter) are directly detected by the counters. The neutrons with higher energies pass through the counters (3 cm diameter, 2 atm) without being detected. For instance, the range of 1 eV neutron in helium for the reaction $^3He(n, p)^3H$ (cf. Table 2 for the cross section) is of 21 cm > > 3 cm.

[19] Simulations, results of which are described in this section, were executed for monoenergetic neutrons with a few chosen initial energies $\varepsilon_{inc}$ of neutrons incident the counters. Events of multiple neutron reflections into atmosphere and backward to counters were ignored. The goal of these preliminary simulations was to demonstrate the effect of carbon moderator shifting the neutron spectrum to the domain of the highest sensitivity of the counter. It would be possible to expect that due to this shift, the count rates of the internal counter are significantly higher than those of the external counter. However, this is the case in the range of high energies above 1 keV. If combined with neutron flux attenuation, the net result is that only in the range of the lowest energies the count rates of the internal counter are lower than those of the external counter; in the range of energies between approximately 100 eV and 1 keV, the rates are almost the same. In the next section, results are presented of simulations more adequate to the real experiment. In particular, a transport of neutrons is simulated in atmosphere from a distant source; the energy distribution in the source was used of photonuclear neutrons produced by bremsstrahlung of relativistic runaway electron avalanche (RREA) in atmosphere, as illustrated in Figure 1.

## 4. Simulations Allowing for the Transport of Photonuclear Neutrons in Air

[20] According to *Gurevich et al*. [2012], the "…extraordinary high flux of low-energy neutrons…," the authors believed, they measured, "…is a challenge for the photonuclear channel of neutron generation in thunderstorm." As another origin is not proposed, we are forced to remain in the framework of the photonuclear one. To proceed the analysis, we carried out Monte Carlo simulations of transport of neutrons produced by $(\gamma, n)$ reactions in air. With this goal, we preliminarily calculated initial energy distribution of photonuclear neutrons in air (Figure 1) using the spectrum of RREA bremsstrahlung $f_\gamma(\varepsilon_\gamma)$ [*Babich et al*., 2004] and the photonuclear reaction cross section $\sigma_{\gamma n}(\varepsilon_\gamma, n)$ from [*Dietrich and Berman*, 1988]

$$\mathrm{d}N_n/\mathrm{d}\varepsilon_n = A^{-1}\int_0^\infty f_\gamma(\varepsilon_\gamma)\sigma_{\gamma n}(\varepsilon_\gamma, 1n)\delta(\varepsilon_\gamma - \varepsilon_n - \varepsilon\mathrm{th})\mathrm{d}\varepsilon_\gamma = f_\gamma(\varepsilon_n + \varepsilon\mathrm{th}) \times \sigma_{\gamma n}(\varepsilon_n + \varepsilon\mathrm{th}, 1n)/A, \quad (1)$$

where

$$A = \int_0^\infty f_\gamma(\varepsilon_\gamma)\sigma(\varepsilon_\gamma)\mathrm{d}\varepsilon_\gamma,$$
$$\sigma(\varepsilon_\gamma) = \begin{cases} \sigma_{\gamma n}(\varepsilon_\gamma, n), & \varepsilon_\gamma \geq \varepsilon\mathrm{th}(\varepsilon_\gamma, n), \\ 0, & \varepsilon_\gamma \leq \varepsilon\mathrm{th}(\varepsilon_\gamma, n). \end{cases} \quad (2)$$

[21] The simulations were carried separately for the external (transport in atmosphere) and internal (transport in atmosphere, iron roof, and carbon plate) counters assuming a point source of neutrons with Lambert's angular distribution in the lower semispace for a few distances $L$ between the source and counter. In dependence on the $L$ magnitude, the numbers of the initial simulated neutrons were being varied from 30,261,411,000 to 9,804,634,000 for the external counter and from 3,821,949,000 to 3,496,720,000 for the internal. The following values of the air (composition $N_2 : O_2 : Ar = 75.52 : 23.20 : 1.28$), iron and carbon densities were used: $\rho_{air} = 0.81$ mg/cm$^3$ at the altitude 3340 m [*Gurevich et al*., 2012], $\rho_{Fe} = 7.8$ g/cm$^3$, $\rho_C = 2.26$ g/cm$^3$. The computed spectra of neutrons entering the external (bare) and internal (shielded) counters are given in Table 4 as portions $P_{ext}$ and $P_{int}$ of neutrons entering the detectors per one emitted neutron. It is seen that the range of high

**Table 4.** Photonuclear Neutron Energy Spectra at External (Unshielded) $P_{ext}$ and Internal (Shielded) $P_{int}$ Counter[a]

| | | Ranges of Neutron Energies Entering the Counters | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\Delta\varepsilon_n$ | 0–0.01 | 0.01–0.1 | 0.1–1.0 | 1.0–10 | 10–100 | 100–1000 | 1–10 | 10–100 | 100–1000 | 1–10 | 10–20.1 |
| | $\sigma$ | $1.4 \cdot 10^5$ | 5700 | 1800 | 565 | 172 | 56 | 17 | 4.8 | 1.45 | 0.53 | 0.13 |
| $L$ (m) | | (eV) | | | | | | (keV) | | | (MeV) | |
| 100 | $P_{ext}$ | 0 | 0 | 0 | $8.1^{-9}$ | $1.2^{-7}$ | $1.7^{-6}$ | $3.0^{-5}$ | $6.7^{-4}$ | $\mathbf{2.4^{-2}}$ | $\mathbf{3.2^{-1}}$ | $\mathbf{3.6^{-1}}$ |
| | $P_{int}$ | $1.0^{-3}$ | $1.8^{-2}$ | $9.6^{-3}$ | $8.4^{-3}$ | $1.0^{-2}$ | $1.3^{-2}$ | $1.6^{-2}$ | $2.0^{-2}$ | $\mathbf{3.9^{-2}}$ | $\mathbf{9.3^{-2}}$ | $\mathbf{3.5^{-2}}$ |
| 200 | $P_{ext}$ | $1.5^{-9}$ | $1.3^{-7}$ | $1.5^{-6}$ | $6.5^{-6}$ | $2.2^{-5}$ | $7.3^{-5}$ | $3.1^{-4}$ | $2.1^{-3}$ | $\mathbf{3.1^{-2}}$ | $\mathbf{2.6^{-1}}$ | $\mathbf{2.3^{-1}}$ |
| | $P_{int}$ | $1.1^{-3}$ | $2.0^{-2}$ | $1.0^{-2}$ | $8.3^{-3}$ | $9.8^{-3}$ | $1.2^{-2}$ | $1.4^{-2}$ | $1.7^{-2}$ | $\mathbf{3.0^{-2}}$ | $\mathbf{6.9^{-2}}$ | $\mathbf{2.4^{-2}}$ |
| 300 | $P_{ext}$ | $5.9^{-8}$ | $4.9^{-6}$ | $4.0^{-5}$ | $1.1^{-4}$ | $2.2^{-4}$ | $4.7^{-4}$ | $1.1^{-3}$ | $4.2^{-3}$ | $\mathbf{3.7^{-2}}$ | $\mathbf{2.1^{-1}}$ | $\mathbf{1.5^{-1}}$ |
| | $P_{int}$ | $1.1^{-3}$ | $1.9^{-2}$ | $9.4^{-3}$ | $7.4^{-3}$ | $8.5^{-3}$ | $9.9^{-3}$ | $1.1^{-2}$ | $1.3^{-2}$ | $\mathbf{2.3^{-2}}$ | $\mathbf{5.1^{-2}}$ | $\mathbf{1.6^{-2}}$ |
| 500 | $P_{ext}$ | $7.6^{-7}$ | $6.0^{-5}$ | $3.8^{-4}$ | $7.7^{-4}$ | $1.2^{-3}$ | $1.8^{-3}$ | $3.0^{-3}$ | $7.1^{-3}$ | $\mathbf{3.6^{-2}}$ | $\mathbf{1.3^{-1}}$ | $\mathbf{6.7^{-2}}$ |
| | $P_{int}$ | $8.4^{-4}$ | $1.5^{-2}$ | $6.9^{-3}$ | $5.2^{-3}$ | $5.8^{-3}$ | $6.5^{-3}$ | $7.1^{-3}$ | $7.9^{-3}$ | $\mathbf{1.3^{-2}}$ | $\mathbf{2.8^{-2}}$ | $\mathbf{7.3^{-3}}$ |

[a]The $^3He(n, p)^3H$ reaction cross section $\sigma$ is in barn ($10^{-24}$ cm$^2$) units. Entries in boldface indicate that the range of high energies above 100 keV dominates both in Pext and Pint magnitudes.

energies above 100 keV dominates both in $P_{ext}$ and $P_{int}$ magnitudes. What is important in the context of the analyzed problem, in disagreement with the ratios $R_{exp}$ of the measured count rates (the average $R_{exp} \approx 0.43$ in Table 1), the portions $P_{int}$ are significantly higher than $P_{ext}$ below 10–100 keV, especially in the range of the lowest energies, to which, as Gurevich et al. claimed, neutrons belong in their experiment. In this range, the ratios $P_{int}/P_{ext}$ also are much higher than $\Delta$ in Table 2. The reason is the effect of wide spectrum: neutrons of high energies feed the low-energy range due to the moderation in the layers covered the internal counter. The effect of the atmosphere also is pronounced: with increasing $L$ both $P_{int}$ and $P_{ext}$ increase in the range of low energies and the upper boundary of energies, below which $P_{int} > P_{ext}$ decreases. On the contrary, in the energy range above 100 keV, the $P_{int}$ magnitudes are less than $P_{ext}$. The reason of such $P_{int}$ behavior is mentioned above shift of the neutron spectrum to the low-energy domain due to the neutron moderation in iron roof and, mainly, in carbon plate.

[22] To compare the total count rates of the internal and external counters with allowing for the counter sensitivity, we calculated a ratio $R$ of integrated portions $P_{int}^{(i)}$ and $P_{ext(i)}$ preliminarily multiplied by $^3He(n, p)^3H$ cross section $\sigma_i$ (index $i$ corresponds to the energy ranges $\Delta\varepsilon_n$ in Table 4):

$$R = \sum_i P_{int}^{(i)} \times \sigma_i \Delta\varepsilon_i / \sum_i P_{ext}^{(i)} \times \sigma_i \Delta\varepsilon_i \qquad (3)$$

[23] The results are presented in Table 5. It is seen that computed ratios $R$ disagree with the ratios of the measured count rates in Table 1. In the energy range below 1 keV, the $R$ magnitudes (~4–$10^4$) being manyfold higher than $R_{exp}$ means that not low-energy neutrons were detected. In the total range of energies 0–20.1 MeV of photonuclear neutrons produced by RREA bremsstruhlung in atmosphere, the $R$ magnitudes, varying from 0.14 to 0.84 depending on the distance $L$ to the neutron source, though are less than unit similar to the most $R_{exp}$ values; nevertheless, they significantly differ from the average $R_{exp} \approx 0.43$ in Table 1. With increasing distances $L$, the $R$ magnitudes become much smaller than $R_{exp}$.

**Table 5.** Ratio of Internal (Shielded) to External (Unshielded) Counters Count Rates Allowing for the Counter Sensitivity

| $L$ (m) | 100 | 200 | 300 | 500 |
|---|---|---|---|---|
| $R$ ($\varepsilon_n = 0$–1 keV) | 10034 | 204 | 25.1 | 4.1 |
| $R$ ($\varepsilon_n = 0$–20.1 MeV) | 0.84 | 0.26 | 0.24 | 0.14 |

## 5. Analysis Without Aprioristic Assumptions (γ Ray Transport in the Matter Covering the Internal Counter)

[24] To verify whether γ rays could account for the observed ratios $R_{exp}$, we carried out numerical simulations of transport of γ rays of different energies in the iron ($l_{Fe} = 2$ mm) and carbon ($l_C = 20$ cm) layers covering the internal counter [*Gurevich et al.*, 2012]. Even simple estimations, basing on the γ ray attenuation coefficient $\mu(\varepsilon_\gamma)$, demonstrate that γ ray attenuation $\exp(-\mu(\varepsilon_\gamma) \cdot (l_{Fe} + l_C))$ in the energy range above approximately $\varepsilon_\gamma \approx 1$ MeV is not too far from the most values of $R_{exp} \approx 0.34$–0.63 in Table 1. So $\exp(-\mu(\varepsilon_\gamma = 5 m_e c^2) \cdot (l_{Fe} + l_C)) \approx 0.25$. Consistent Monte Carlo simulations were carried out using Lambert's angular distribution of incident photons. Portions of γ photons $\Delta_\gamma$, electrons $\Delta_e$, and positrons $\Delta_p$ per one photon incident the counters with the energies in the range $\varepsilon_{\gamma,inc} = 0.5$–10 MeV, and spectra of photons, electrons, and positrons entering the internal counter are the results of the simulations. The numbers of initial γ photons were from 23,286,500,000 for

**Table 6.** Portions Per One Incident Photon and Mean Energies of $\gamma$ Photons ($\Delta_\gamma$, $\varepsilon_{\gamma,ent}$), Electrons ($\Delta_e$ $\varepsilon_{e,ent}$), and Positrons ($\Delta_p$ $\varepsilon_{p,ent}$) Entering the Internal (Shielded) Counter[a]

| Energy $\varepsilon_{\gamma,inc}$ of Photons Incident the Detectors (MeV) | $\Delta_\gamma$ | $\varepsilon_{\gamma,ent}$ (MeV) | $\Delta_e$ | $\varepsilon_{e,ent}$ (MeV) | $\Delta_p$ | $\varepsilon_{p,ent}$ (MeV) |
|---|---|---|---|---|---|---|
| 0.5 | 0.11 | 0.18 | $5 \cdot 10^{-5}$ | 0.13 | 0.0 | |
| 1 | 0.19 | 0.38 | $3.6 \cdot 10^{-4}$ | 0.32 | 0.0 | |
| 2 | 0.30 | 0.87 | $1.8 \cdot 10^{-3}$ | 0.72 | $1.8 \cdot 10^{-6}$ | 0.45 |
| 4 | 0.43 | 1.97 | $6 \cdot 10^{-3}$ | 1.53 | $1.2 \cdot 10^{-4}$ | 0.84 |
| 5 | 0.47 | 2.60 | $8.2 \cdot 10^{-3}$ | 1.92 | $2.8 \cdot 10^{-4}$ | 1.18 |
| 6 | 0.50 | 3.15 | $1.0 \cdot 10^{-2}$ | 2.32 | $5.2 \cdot 10^{-4}$ | 1.91 |
| 7 | 0.52 | 3.74 | $1.3 \cdot 10^{-2}$ | 2.7 | $8.7 \cdot 10^{-4}$ | 2.30 |
| 8 | 0.54 | 4.34 | $1.5 \cdot 10^{-2}$ | 3.08 | $1.3 \cdot 10^{-3}$ | 2.61 |
| 9 | 0.55 | 4.94 | $1.7 \cdot 10^{-2}$ | 3.44 | $1.7 \cdot 10^{-3}$ | 2.93 |
| 10 | 0.57 | 5.53 | $1.9 \cdot 10^{-2}$ | 3.80 | $2.2 \cdot 10^{-3}$ | 3.30 |

[a]Lambert angular distribution of incident photons.

$\varepsilon_{\gamma,\mathrm{inc}} = 0.5$ MeV to 24,637,900,000 for $\varepsilon_{\gamma,\mathrm{inc}} = 10$ MeV. The portions $\Delta_\gamma$, $\Delta_e$, $\Delta_p$, and average energies of photons $\varepsilon_{\gamma,\mathrm{ent}}$, electrons $\varepsilon_{e,\mathrm{ent}}$, and positrons $\varepsilon_{p,\mathrm{ent}}$ entering the internal counter are presented in Table 6. It is seen that $\Delta_\gamma$, varying from 0.11 for $\varepsilon_{\gamma,\mathrm{inc}} = 0.5$ MeV to 0.57 for $\varepsilon_{\gamma,\mathrm{inc}} = 10$ MeV, fit rather well the $R_{\mathrm{exp}}$ magnitudes in Table 1. Especially impressive is proximity of $\Delta_\gamma$ to $R_{\mathrm{exp}}$ for $\varepsilon_{\gamma,\mathrm{inc}} > 2$ MeV. Though $\Delta_e$, $\Delta_p << \Delta_\gamma$, electrons and at less degree positrons could significantly deposit the count rates in view of their penetrating capability is significantly less than that of photons of the same energy. Further simulations are required allowing for the γ ray photon, electron, and positron interactions with the counter matter (aluminum box and helium).

## 6. Conclusions

[25] 1. The opinion of *Gurevich et al.* [2012] that in their experiment neutrons were detected is based simply on that $^3$He counters are intended for detecting neutrons. The claim that low-energy neutrons were detected is based on that the counter efficiency ($^3$He($n$, $p$)$^3$H cross section) is the highest in the low-energy domain.

[26] 2. From the fifth column in Table 3 follows that $^3$He counter efficiency in the ranges 0.01–0.1 eV and 0.1–1 eV is almost the same provided that the counter is shielded by sufficiently thick neutron moderator. For the bare counter, the efficiency varies on the order of magnitude in these energy ranges (Table 3, first two columns). Consequently, *the assertion number 1 in section* 1 *is not valid*. Note also that it is very improbable that neutrons were detected with energies less than 0.025 eV ≈ 270 K.

[27] 3. The analysis carried out only using available data on the experimental configuration in *Gurevich et al.* [2012] demonstrated a disagreement between portions of neutrons entering the internal (shielded) counter relative to one incident neutron (calculated both without and with allowing for the counter sensitivity) and ratios of the measured internal-to-external counter count rates $R_{\mathrm{exp}}$. This analysis confirms the results by *Chilingarian et al.* [2012a] and *makes extremely doubtful the assertion number 2* that low-energy neutrons really were detected in *Gurevich et al.* [2012], if neutrons at all, in view of inevitable interference of X and γ emissions.

[28] 4. Numerical simulations, allowing for the counter sensitivity and the neutron transport in atmosphere from distant ($L$ = 100–500 m) photoneutron source with spectrum in the energy range 0–20.1 MeV, produced by RREA bremsstrahlung in atmosphere, demonstrated that computed ratios $R$ of the internal-to-external counter total count rates in the energy range below 1 keV are up to $10^4$ times or more, higher than the ratios $R_{\mathrm{exp}}$ of the measured count rates. Hence, not low-energy neutrons were detected in *Gurevich et al.* [2012]. The computed total $R$ magnitudes in the range 0–20.1 MeV, varying from 0.14 to 0.26 for $L$ = 500–200 m, are significantly less than the average ratio $R_{\mathrm{exp}} \approx 0.43$ of the measured count rates. Hence, not neutrons have been detected in *Gurevich et al.* [2012] but, most likely, γ rays. Results of consistent Monte Carlo simulations of γ rays transport in the iron and carbon layers covering the internal counter proved that this is the case. Portions of photons entering the internal counter $\Delta_\gamma = 0.30$–0.57 in the energy range of photons incident the detectors $\varepsilon_{\gamma,\mathrm{inc}} = 2$–10 MeV are very close to the most values of observed $R_{\mathrm{exp}} = 0.34$–0.63 (Table 1). *Therefore, the assertion numbers 2 and 3 are not valid*.

[29] 5. The skepticism of Gurevich et al. regarding the photonuclear origin of the thunderstorm-related neutrons is based on that, according to them, the γ ray flux, 10–30/(cm$^2$ s), required to account for the neutron flux of (0.03–0.05)/(cm$^2$ s), as they believed, they measured, is unreal and on that, according to their opinion, thunderstorm-related X-rays and γ rays have been observed at the ground with photon energies much below the threshold εth(γ, *1n*) = 10.5 MeV. They underlined that only *Chilingarian et al.* [2010] have detected at the ground γ rays with photon energies above εth(γ, *1n*) (assertion number 4), missing, however, other observations of γ ray bursts with spectra extending to energies close or high above εth(γ, *1n*): 40–50 MeV [*Chilingarian et al.*, 2010], more than 40 MeV [*Tsuchiya et al.*, 2012], 10 MeV [*Tsuchiya et al.*, 2009, 2011], and more than 10 MeV [*Khaerdinov et al.*, 2005] correspondingly at altitudes 3250 m, 4300 m, 2770 m, and 1700 m; more than 20 MeV [*Smith et al.*, 2005] and 30–38 MeV [*Briggs et al.*, 2010] in near space; up to ~35 MeV with small and up to ~70 MeV with large error bars at the sea level [*Tsuchiya et al.*, 2007, 2011]. *We believe that the assertion number 4 is not valid, and photonuclear reactions are capable of accounting for neutron generation in thunderstorm atmosphere*.

[30] 6. Gurevich et al. wrote that *Chilingarian et al.* [2010] have measured γ ray flux $\Phi_\gamma = 0.04/(\mathrm{cm}^2\,\mathrm{s})$, which, to their opinion, is 3 order of magnitude less than the value required for generation by (γ, $n$) reactions a neutron flux (0.03–0.05)/(cm$^2$ s) they communicated. Integrating the absolute spectrum in *Chilingarian et al.* [2010, Figure 7] above εth(γ, *1n*) = 10.55 MeV, we obtained tenfold larger flux: $\Phi_\gamma \approx 0.4/(\mathrm{cm}^2\,\mathrm{s})$. Possibly, Gurevich et al. received the estimation $\Phi_\gamma = 0.04/(\mathrm{cm}^2\,\mathrm{s})$ using count rate of γ channel and area of the counter in *Chilingarian et al.* [2010, Figure 6], ignoring the counter efficiency ~10% [*Chilingarian et al.*, 2010]. The comparing with *Chilingarian et al.* [2010] (the assertion number 5), however, is not correct at all, if lightning-correlated neutrons really were detected by Gurevich et al. because the Aragats neutron monitor [*Chilingarian et al.*, 2010, 2012a, 2012b] have measured 10–20 min enhancements; such long duration of which does not allow connecting them with lightning. However, more important is that in the communication of *Chilingarian et al.* [2010], as well as in the other communications, the count rates and spectra of photons at the counters are presented, not the flux and spectra in the γ source, which are required to calculate the yield of photonuclear neutrons produced in air and in the matter of counters and surrounding subjects.

[31] In the above communications reporting a detection of thunderstorm-related neutrons, $^3$He($n$, $p$)$^3$H or $^{10}$B($n$; $^4$He, γ)$^7$Li *gas-discharge* counters were used. In these counters, the current pulses can be initiated by any ionizing radiation, not obligatory by the daughter proton and triton ($^3$He($n$,$p$)$^3$H) or α particle and 478 keV γ photon ($^{10}$B($n$; $^4$He, γ)$^7$Li). Therefore, possibly, not neutrons, but X-rays, γ rays, and high-energy electrons of thunderstorm origin have been detected. In the experiment by *Shah et al.* [1985], the registration of neutrons, seems, is proved by that the delay times were measured of neutrons arrival at the neutron monitor relative to the lightning EMPs, and, therefore,

probably, relative to γ rays (time-of-flight technique?). However, though the detector was switched on by EMPs, actually, the assertion that count rate enhancements were caused by neutrons, not by *γ* photons, is not rigorously proved: Possibly, the monitor was irradiated by prolong γ ray flux as have been observed by *Khaerdinov et al.* [2005] and *Tsuchiya et al.* [2007, 2011, 2012]. At Aragats [*Chilingarian et al.*, 2010, 2012a, 2012b], the positive result is substantiated by the configuration of the observations, in which high-energy electrons, γ rays, and neutrons were simultaneously detected. In other available communications [*Shyam and Kaushik*, 1999; *Kuzhewskiĭ*, 2004; *Bratolyubova-Tsulukidze et al.*, 2004; *Martin et al.*, 2009; *Martin and Alves*, 2009, 2010; *Gurevich et al.*, 2012; *Starodubtsev et al.*, 2012], the observations of thunderstorm-related neutrons unfortunately are not substantiated at all, because observed increases of neutron detectors count rates could be caused by X-rays and γ rays [*Tsuchiya et al.*, 2012].

[32] It is worth noting that the thunderstorm-related neutrons were not obligatorily emitted from lighting channels, if neutrons really have been detected in the communications cited above, even if they somehow were related to, more or less, coincident lightning discharges. In this connection, the direct relation of count rate enhancements detected by Gurevich et al., to "thunderstorm discharges" unfortunately was not proved in view of 1 min time resolution in *Gurevich et al.* [2012], is longer than the lightning duration. Even if the γ ray sources were located in lightning channels [*Babich and Roussel-Dupré*, 2007], the photonuclear neutrons would be produced outside the channels, because the ranges of photons with the energies above the photonuclear threshold $\varepsilon$th($\gamma$, $1n$) = 10.5 MeV are much longer than transversal size of the channels. Possibly, the observations of prolong γ ray bursts with duration up to 10 min [*Khaerdinov et al.*, 2005; *Tsuchiya et al.*, 2007, 2011, 2012] are an argument in favor that photonuclear neutrons are generated not during the fast transitive process of lightning but in rather long-living large-scale electric fields of thunderclouds, for instance, during volumetric discharges developing in the mode of RREAs initiated by background cosmic rays. Such atmospheric discharges are similar to volumetric discharges initiated by external radiation intended for pumping gas lasers [*Mesyats and Korolev*, 1986].

[33] Overcoming inevitable difficulties and inconsistencies in explorations of lightning- and thunderstorm-correlated enhancements of neutron flux is extremely important because neutrons produced by lightning and thunderstorms could provide valuable information about the physics of atmospheric electricity and, maybe, about the lightning mechanism as *Fleischer et al.* [1974] assumed. This knowledge possibly would have impact on radiocarbon ($^{14}$C) dating [*Libby and Lukens*, 1973]. Thunderstorm-produced neutrons, as the other penetrating radiation of the thunderstorm origin [*Dwyer et al.*, 2010; *Kutsyk et al.*, 2011], are dangerous for electronic equipment of flying vehicles, for crews, and passengers of airliners; therefore, processes responsible for the generation of neutrons should be revealed and carefully studied.

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