Decrease of Atmospheric Neutron Counts Observed during Thunderstorms

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We report here, in brief, some results of the observation and analysis of sporadic variations of atmospheric thermal neutron flux during thunderstorms. The results obtained with unshielded scintillation neutron detectors show a prominent flux decrease correlated with meteorological precipitations after a long dry period. No observations of neutron production during thunderstorms were reported during the three-year period of data recording.

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Introduction.—The production of MeV neutrons during thunderstorms has been the subject of several papers. The first suggestion, to our knowledge, of the existence of this phenomenon appeared in Ref. [1]. More recently, some experimental papers have been published regarding neutron detection during thunderstorms at Mt. Aragats [2], at Tien-Shan [3], at Yakutsk [4], and Yangbajing (Tibet) [5]. All these experiments utilize standard neutron monitor (NM) detectors plus ^{3}He counters in the case of Ref. [3]. In Ref. [6], simulations are presented that support the idea of neutron generation in (γ, n) reactions taking place in the lead surrounding the NM detectors, as suggested also in the Yangbajing paper [5]. A similar conclusion was also made in theoretical works such as Refs. [7], [8] and in Ref. [9]. A possibility of ion runaway in lightning events in thunderstorms and its connection to neutron production as well as overview of existent experimental data can be found in Ref. [10]. Satellite observations of the terrestrial γ-ray flashes associated with strong thunderstorms and an estimation of the possible associated neutron production can be found in Ref. [11].

We report here results obtained with a network of thermal neutron detectors that do not make use of lead or any other heavy shielding. During the last decade, our joint international group studied environmental thermal neutron flux variations, e.g., Refs. [12–15], using a network of electron-neutron detectors (ENs in the following). The network is comprised of five arrays of detectors, located at the following four geographical points: (1) Moscow [Russia, 56°N, 38°E, 200 meters above sea level (MASL), with detectors both in National Nuclear Research University (MEPhI) and in Moscow State University (MSU)], (2) Obninsk (Russia, 55°N, 37°E, 175 MASL), (3) Baksan (Russia, North Caucasus, 43°N, 43°E, 1700 MASL), (4) Laboratori Nazionali del Gran Sasso (LNGS, Italy, 42°N, 13°E, 1000 MASL) In Table I we report the full list of the detectors that are in use as of today in our network of EN-detector arrays.

In this Letter we used detectors with a minimal shielding—outdoor or under a thin roof or with walls as the most sensitive to thermal neutrons: two A1 detectors (EN-4 and EN-5), A2 (HE) detector, and A5 (EN-14) detector. Detectors under a concrete absorber, EN-1, EN-2, and EN-3, were used for comparison.

Neutron recording methods.—A specialized granulated alloy scintillator $^6\mathrm{LiF} + \mathrm{ZnS(Ag)}$ is used to detect neutrons. The scintillator layer has a thickness of $\sim 30\ \mathrm{mg/cm^2}$ with a sensitive area of $0.75\ \mathrm{m^2}$. A schematic view of the detector is shown in Fig. 1. At some points, we use similar but smaller detectors of $0.36\ \mathrm{m^2}$ area. The detection efficiency of the EN detector for thermal neutrons is equal to 20%. The efficiency curve follows the usual behavior for thin detectors showing an inverse dependence on neutron velocity. Because of the thin scintillator layer, the ionization losses of relativistic charged particles, such as electrons or muons, produce very tiny signals that can be easily kept below the detection threshold level and thus be excluded. The detector is operated in scaler mode to study low flux variations of thermal neutron. The barometric coefficient for our data was found to be close to $-0.9\%/\mathrm{mm\,Hg}$ and the data correction for this coefficient has been applied to correct the data.

A distinctive feature of our data acquisition is that all the pulses from the photomultiplier tube (PMT) (for EN detectors) are digitized by a FADC (flash analog-to-digital converter) and on-line pulse shape analysis and selection are used to discriminate real neutron pulses from the background, induced by a cascade of charged particles, PMT or electromagnetic noise of any origin.

TABLE I. Summary of detectors forming the global network of EN detectors equipped with ^{6}LiF + ZnS(Ag) scintillator, as well as other detectors involved in this work.

Array	Location	Detector ID	Detectors in the array	Type of installation	Start year
A1	MEPhI-Moscow	EN-1	EN detector of 0.75 m^2	Indoors, concrete absorber (basement)	2011
A1	MEPhI-Moscow	EN-2	EN detector of 0.75 m^2	Indoors, concrete absorber	2011
A1	MEPhI-Moscow	EN-3	EN detector of 0.75 m^2	Indoors, concrete absorber	2011
A1	MEPhI-Moscow	EN-4	EN detector of 0.75 m^2	Almost outdoors (glass walls)	2011
A1	MEPhI-Moscow	EN-5	EN detectors of 0.36 m^2	On the roof	2011
A2	MSU-Moscow	EN-6	EN detectors of 0.75 m^2	Underground (25 MW_e)	2011
A2	MSU-Moscow	HE	20 ^{3}He gas count. of 0.5 m^2	Indoors under a thin roof	2011
A3	Baksan	EN-7	EN detector of 0.36 m^2	Indoors, 5 cm polyethylene shielding	2013
A3	Baksan	EN-8	EN detector of 0.36 m^2	Indoors	2013
A3	Baksan	EN-9	EN detector of 0.36 m^2	Indoors	2013
A3	Baksan	EN-10	EN detector of 0.36 m^2	Outdoors	2013
A3	Baksan	EN-11	EN detector of 0.36 m^2	Underground (5 MW_e)	2008
A3	Baksan	EN-12	EN detector of 0.36 m^2	Underground (800 MW_e)	2009
A4	Obninsk, Russia	EN-13	EN detector of 0.36 m^2	Indoors	2010
A5	LNGS, Assergi, Italy	EN-14	EN detector of 0.36 m^2	Indoors inside a light hangar	2009

Three typical signal families can be recognized: "neutron," "sharp," and "very slow." Typical "neutron" and "sharp" pulse shapes after integration over $\tau = 5\ \mu$s are presented in Fig. 2. "Very slow" pulses appear due to any electromagnetic noise (including lightning discharges). An example of a pulse shape produced by lightning is shown in Fig. 3. This pulse is much longer (tens of μs) than the typical neutron pulse, and it exhibits higher frequency components. The full signal digitization allows for an easy rejection of such signals.

ZnS(Ag) has several scintillation time constants (from 40 ns to microseconds and even hours) and heavy non-relativistic particles, namely, α particles and tritium arising from the neutron capture by ^{6}Li, excite slow scintillations as well, resulting in a long tail. "Sharp" pulses should be of different origins: PMT noise, synchronous passage of several charged particles (cosmic ray induced showers, muon bundles, etc.).

Therefore an on-line pulse shape discrimination allows us to separate neutron signals from the background: neutron-only counting rates are presented in the figures of the following sections.

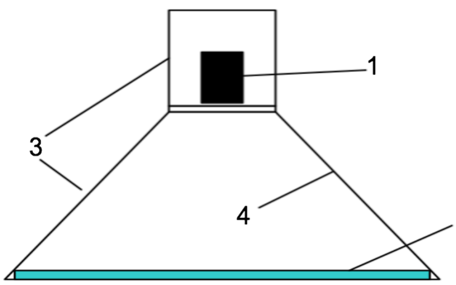

FIG. 1 (color online). Schematic layout of an EN detector. Item 1, 6 in. photomultiplier tube (PMT); item 2, scintillator layer; item 3, light proof boxes; item 4, white light reflector.

To validate the pulse shape discrimination, a standard calibration based on the use of a neutron source has been performed. Data taking runs of 1 minute or 5 minutes have been used in the data acquisition process. Statistical accuracy for 0.75 m^2 detectors at sea level is equal to $\sim$12% and $\sim$5.4% for 1 and 5 minute data points, respectively. It is essential to point out the procedures of extracting neutron capture signals from those generated by other particles (muons, electrons, γ's) which interact in the neutron detectors (EN detectors and He tube). For "EN-detectors", we use the on-line pulse shape analysis (results are reported in Figs. 4–7), while for He-tube detectors, we use an off-line filtering procedure, which ignores the pulses within a time difference of less than 0.1 ms (result is reported Fig. 8). Details of the filtering procedure are in the text of the following section.

Results on the neutron flux measurements during thunderstorms.—Figure 4 shows the data of the A1 array (except EN-5) during a very strong thunderstorm

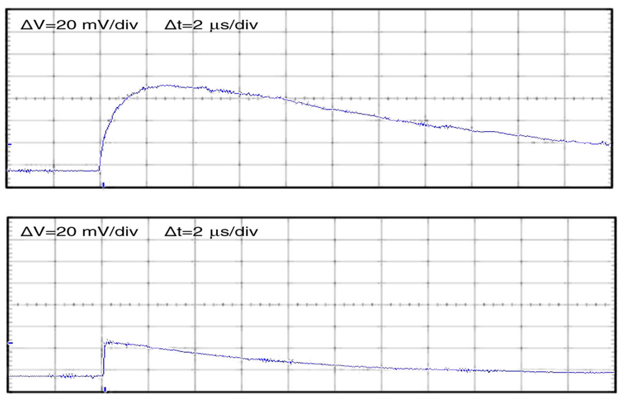

FIG. 2 (color online). Pulse induced by neutron capture ("neutrons," top panel) and background "sharp" pulse (bottom panel).

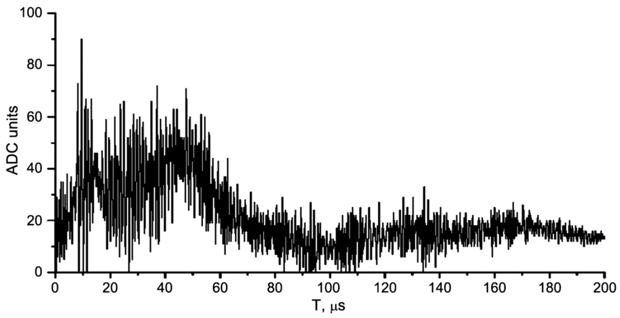

FIG. 3. Noise pulse shape produced by lightning.

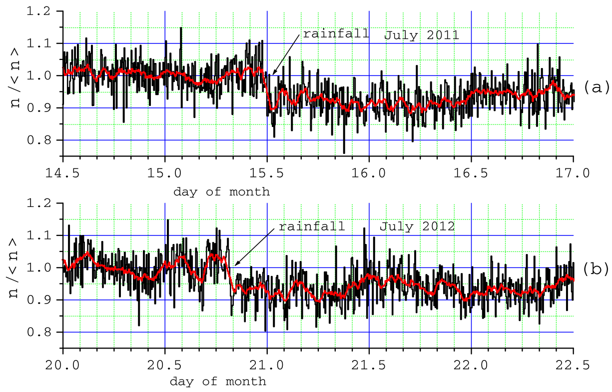

FIG. 5 (color online). Neutron counting rate as a function of the time for two different rainfalls [panels (a) and (b)]. Pressure corrected data.

accompanied with rainfall which occurred in Moscow on 20 July 2012. None of 4 detectors showed any enhancement in thermal neutron flux. Moreover, the outdoor detector EN-4 showed a counting rate decrease lasting many hours. Note that the array detectors EN-1 through EN-4 have a common high voltage power supply and a common 4-channel FADC. The only difference between the detectors is the different absorber thicknesses. EN-4, with a very thin absorber of 3 mm of glass, is sensitive to the atmospheric thermal neutron flux, which is in turn sensitive to water in air and in soil. Note that water, as any hydrogenous media, is a very effective neutron moderator and a good absorber.

During the three-year period of data recording, our detectors integrated no less than 15 thunderstorms. No increase of the neutron rate was ever recorded. On the contrary, we did observe a decrease of the neutron counting rate during some events, as described below.

An environmental thermal neutron flux decrease during and after the rainfalls associated with two different thunderstorms registered on 15 July 2011 and 20 July 2012 in Moscow region after a long period of dry weather and can be seen in Fig. 5. The corresponding counting rate as a function of time (detector EN-4) is shown. The first rainfall began on 15 July 2011 in the afternoon [panel (a)] while the second in the evening of 20 July 2012 [panel (b)]. A 10% decrease in counting rate is clearly visible at the same time of the two rainfalls. Bold lines are one-hour averaged curves. A remarkable feature of panel (b) is that one of the lightning strikes hit the MEPhI building (at ∼10 m from EN-4), causing some electrical damage. However, our data acquisition was not affected and even in this case not one of the A1 detectors showed any counting rate enhancement.

Figure 6 shows a decrease of neutron flux (30-minute smoothed curve) measured by EN-14 in correlation with

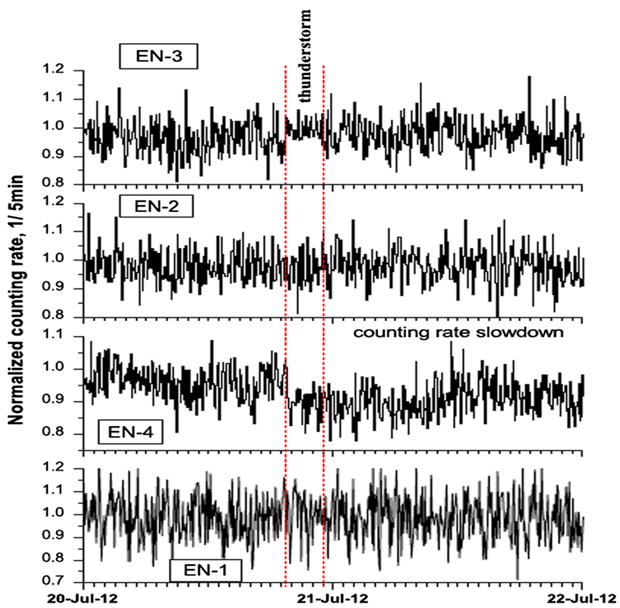

FIG. 4 (color online). Normalized neutron counting rate as a function of the time recorded by the A1 detectors installed at MEPhI-Moscow. The two vertical dashed lines define the duration of the thunderstorm that occurred on 20 July 2012. Pressure corrected data.

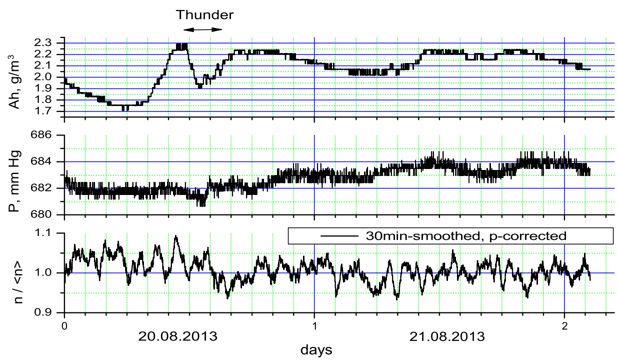

FIG. 6 (color online). Neutron counting rate as a function of time registered by the EN-14 detector at Gran Sasso National Laboratory (LNGS) after a rainfall on 20 August 2013. Pressure corrected data.

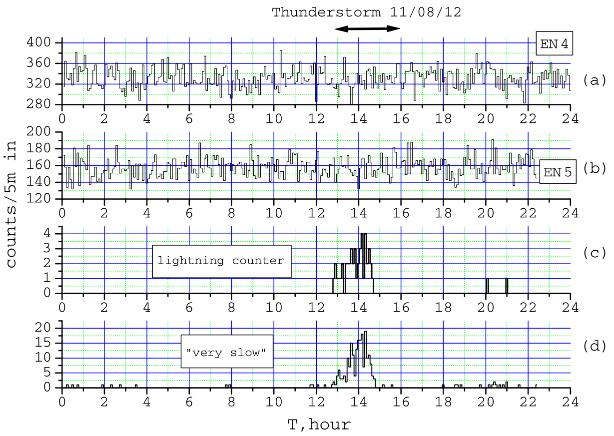

FIG. 7 (color online). Example of false neutron flux enhancement during a thunderstorm on 11 August 2012. (a) Outdoor EN-4 detector counting rate vs time; (b) roof EN-5 detector counting rate vs time; (c) electromagnetic noise vs time; (d) very slow pulses vs time from EN-5.

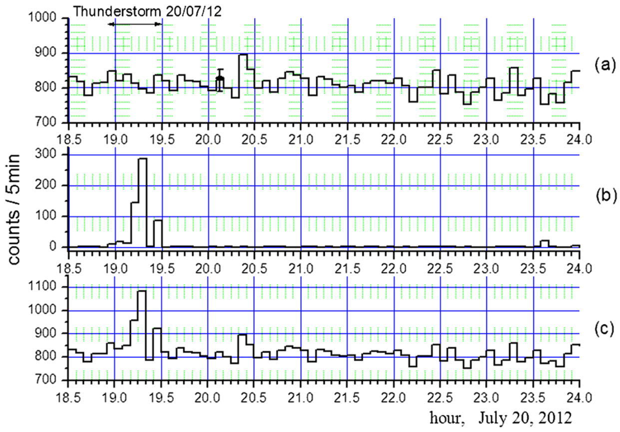

FIG. 8 (color online). An example of a 35% possible false increase in the neutron counting rate during the 20 July 2012 thunderstorm measured through ^{3}He counters without a pulse shape selection technique. (a) neutron counting rate vs time; (b) pulses with time intervals between the neighbors less than 0.1 ms vs time; (c) overall counting rate (neutrons + noise) vs time.

rainfall in Gran Sasso on 20 August 2013. The upper panel shows absolute humidity in g/m^3.

The LNGS detector measured, after the event, a decrease in neutron flux of about 5%. The difference between the measured flux decreases at the different sites could be explained by the difference in rainfall intensity as well as a different absorber thickness above the detectors, and even by the precipitation prehistory. Neutron environmental flux decrease during and after rainfalls was observed with unshielded neutron counters many years ago (see Refs. [16,17]).

Figure 7 shows a typical effect that could be mistaken as neutron emission during a thunderstorm. During a rainstorm that occurred on 11 August 2012 in Moscow, the discrimination performance was tested. It is worthwhile to note that this thunderstorm was not accompanied by strong precipitation. Panel (a) of Fig. 7 shows a neutron counting rate of the EN-4 detector. Panel (b) of Fig. 7 shows the counting rate of EN-5 (on the roof, see Table I) after pulse shape discrimination. To take into account the effect of the atmospheric electromagnetic noise during a thunderstorm, a simple device (antenna + amplifier + ADC) acting as a lightning counter has been designed. Panel (c) of Fig. 7 shows its response in terms of lightning counts, while panel (d) of Fig. 7 shows the rate of the "very slow" pulses described above.

Had we included these signals in our total neutron counting rate, we would have observed a 10% increase. Note that the different counting rate in panels (c) and (d) is explained by different thresholds for electromagnetic noise of the two methods. The "very slow" channel is more sensitive and records not only the nearby lightning but also distant lightning and other electromagnetic noise as well.

Figure 8 shows a further example of a false thunderstorm neutron effect obtained with an alternative technique based on the use of ^{3}He proportional counters (HE) of the A2 array located at Moscow State University. The array consists of many unshielded HE counters 3 cm in diameter with 0.5 m^2 of total recording area. The array is very simple: all counter pulses are summed and discriminated without any digitization nor pulse shape selection. The recording system stores the absolute time of each pulse with an accuracy of 5 ns allowing us to check the arrival time of each pulse precisely.

Thermal neutrons cannot form a burst of pulses with a duration of less than $\sim$1 ms: fast evaporation neutrons, produced in nuclear disintegration processes [say through (γ,n) reactions], have to be thermalized before detection (it takes about 0.5 ms in soil) and they have a rather long lifetime (order of 1 ms) in concrete or soil and much longer in air. Under this constraint, the pulses with time intervals among the neighbors less than 0.1 ms have been selected [panel (b) of Fig. 8] from the total counting rate [panel (c) of Fig. 8]. Subtraction of these pulses from a total counting rate is shown in panel (a) of Fig. 8. This filtering procedure, capable of distinguishing the different sorts of pulses, removes false "neutron excesses" produced by electromagnetic noise caused by lightning.

Without using this algorithm, an approximately 35% enhancement of neutron flux in a case of 5-minute data points would be found. The effect would be worse with 1-minute data points.

Discussion and conclusion.—The results obtained with unshielded scintillation neutron detectors showed prominent flux decreasing correlated with powerful rainfalls after a long dry period. No evidence of lightning neutron production was observed during three summer time periods of data recording.

The method includes full pulse shape digitization and selection allowing an effective rejection system: no excess of thermal neutrons during thunderstorms has been recorded.

A new variation array of four EN detectors (EN-7–EN-10) is now deployed at the Baksan site and we plan to install a similar array at LNGS to improve the study of the above discussed effects as well as other geophysical phenomena.

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