Strong Flux of Low-Energy Neutrons Produced by Thunderstorms

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We report here for the first time about the registration of an extraordinary high flux of low-energy neutrons generated during thunderstorms. The measured neutron count rate enhancements are directly connected with thunderstorm discharges. The low-energy neutron flux value obtained in our work is a challenge for the photonuclear channel of neutron generation in thunderstorm: the estimated value of the needed high-energy γ-ray flux is about 3 orders of magnitude higher than that one observed.

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Introduction.—First observations of neutron flux enhancement in thunderstorms were reported in [1]. The authors have studied the multiplicity in the neutron monitor (NM) data during thunderstorm in the correlation with lightning events. To interpret the results it was supposed *a priori* that the NM registers only solitary neutrons. Later it was found that the multiplicity in NM data is strictly connected with extensive air showers [2,3]. So the observed multiplicity events were not determined by thunderstorms itself. Authors interpret the observed neutrons as a result of the thermonuclear process in lightning channel. Recent analysis [4] calls in question this interpretation. Analogous observational results were reported later in [5,6].

The statistical analysis performed in [7] revealed a correlation between the excess in NM data and the thunderstorm electric field. The correlation was explained as the affect of the thunderstorm electric field on the cosmic ray muons, which generate a part of the neutron flux in NM.

Quite a new type of observations of neutron flux during thunderstorms was reported recently in [8]. The neutron count rate enhancement was observed in 1-min time series of NM data. The enhancement lasted for 9 min and had maximum flux value of 5.1 standard deviations (σ) from the mean background level. It allowed to claim that the flux of neutrons born in the atmosphere during the thunderstorm was observed. Unfortunately, the thunderstorm itself was fixed using the rough information from the meteorological service only. Neither electric-field sensors nor radio sensors were used.

The neutrons if generated in atmospheric discharge processes are expected to have low energies. For example being born in photonuclear channel near the threshold they would have energies of a few MeV and less due to collisional losses. The NM sensitivity in this energy range is very low. So, it is more appropriate to use the low-energy neutron detectors simultaneously with NM. We inform here for the first time about the registration of the extremely intensive fluxes of low-energy neutrons generated during thunderstorms. We also claim that these fluxes are connected with atmospheric discharges. Observations were performed at the Tien-Shan Mountain Cosmic Ray Station, Kazakhstan (altitude 3340 m) during 17 thunderstorms in the summer 2010.

Experimental setup.—Low-energy environmental neutron flux around the Tien-Shan Station was measured by a set of three thermal neutron detectors (TND) based on the "Helium-2"-type proportional neutron counters [9]. These detectors are 1.2×0.84 m^2 aluminum boxes each containing six 1 m long, 3 cm in diameter neutron counters. The counters are filled with the gaseous ^{3}He under the pressure of 2 atmospheres, so the neutron registration in the low-energy range succeeds due to the reaction $^3\mathrm{He}(n, p)t$ with an efficiency of about 60%.

According to the specification the 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. At the higher energies the efficiency falls down and become three orders lower at the neutron energy 10 keV. TNDs register the neutrons having the energies less than few keV and they are fully insensitive to the high-energy hadrons flux of the cosmic ray origin.

One of TNDs—an "external" one, is placed in the open air inside a light plywood housing at the distamce 15 m from other two detectors. An "internal" detector is placed in the room screened from the top by a thin (2 mm) roofing iron ceiling and a 20 cm carbon layer. The third one, an "underfloor" is placed under wooden 4 cm floor of the same room and is additionally shielded from the top by a 3-cm-thick layer of rubber.

Registration of the hadronic cosmic ray component, including the high-energy neutrons was performed by a standard 18NM64 type neutron supermonitor [10] placed in the same room as the internal detector. The NM consists of three separate units. Each unit contains six SNM15 type proportional neutron counters, 150 mm in diameter and 2 m in the length. The energy response of the NM64 neutron supermonitor was studied both experimentally [11] and with the use of simulation approach (e.g., [12]). It was found, that the typical energy threshold is about some hundreds of MeV, at which interaction energy the mean number of registered secondary neutrons exceeds 1 which ensures an efficient registration of primary hadron. At the few MeV the registration efficiency of NM falls down from 10% at 3 MeV to 2% at 0.5 MeV. In the energy range less than 100 keV the efficiency remains at the level of 1% diminishing to 0.5% at the thermal energies.

Output pulses from the NM counters are registered continuously with a 1-minute time resolution (this is a standard in the worldwide net of the cosmic ray intensity variation database which the Tien-Shan supermonitor belongs to). Handling of the output signals from all TNDs is quite the same as for NM: accumulated intensity values are recorded with a 1-min time resolution, separately for each counter.

Because our installation is destined for operation under a very intensive electromagnetic and acoustic interference on the part of lightning discharges, a special attention was paid to the control of the reliability of its signals. Besides the usual grounding and electromagnetic shielding of the all electric circuits this control includes using of the special ‘‘dummy’’ information channels. These are additional neutron counters placed inside the boxes of low-energy detectors which are switched to the data registration system but the high voltage in the feeding main is diminished strongly to exclude the registration of neutrons. All the signals from neutron detectors including dummy ones pass through the discriminators having the same thresholds for all channels. The threshold value is arranged in such a way that it is higher than the electronic circuit noise. The registration system counts pulses of the discriminator output signal. The number of pulses in dummy channels is found to be zero both in the nonthunderstorm and in the thunderstorm time.

The quasistatic electric field during the thunderstorm passages is measured with the use of an electrostatic flux meter of the ‘‘field-mill’’ type which operates with sampling frequency of 1000 Hz, while the fast variation of the electric field in lightning discharges is detected using the capacitor-type sensor. Both the ‘‘field-mill’’ and the capacitor sensor are installed in the vicinity of the neutron detector complex. Additionally, atmospheric discharges were registered using two radio-antenna setups which operate in the frequency range of 0.1–30 MHz.

*Results of experiment.—*Firstly, we discuss one typical thunderstorm event observed on 10 August 2010, when the thunderclouds were moving directly at the height of Tien-Shan station. Temporal dependencies of the neutron counting rate and the strength of the local electrostatic field

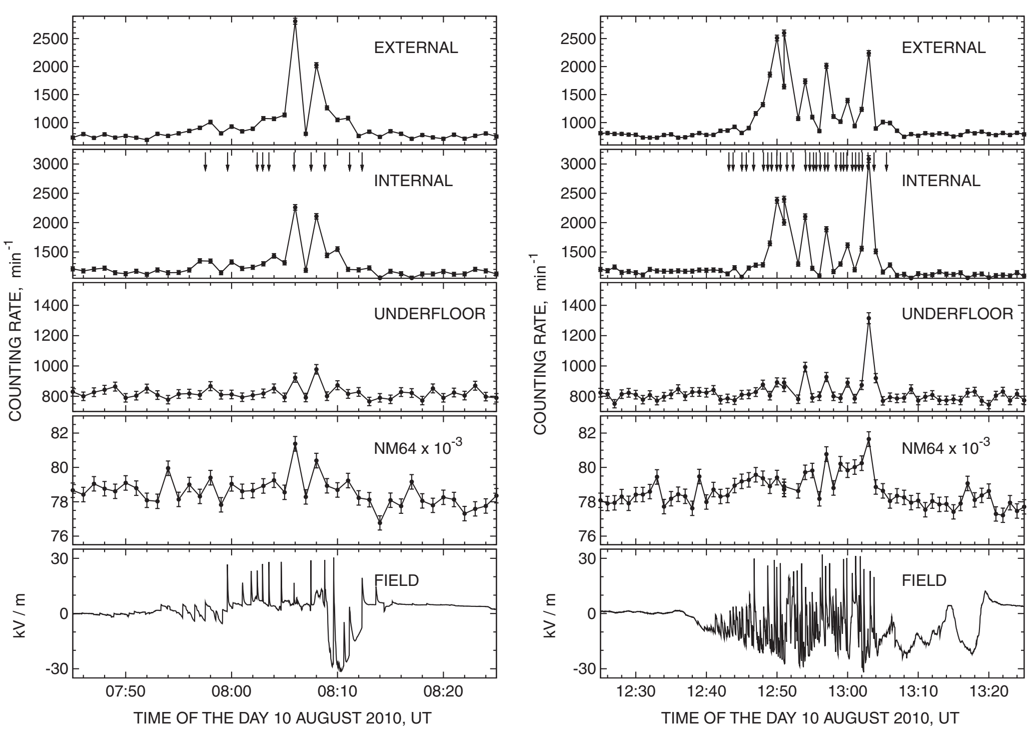

FIG. 1. Two typical thunderstorm events observed on 10 August 2010. On the panels from top to bottom: the minutely pulse numbers counted in external, internal, and underfloor thermal neutron detectors; the multiplied by 0.001 minutely pulse numbers in the supermonitor NM64; the strength of the local electric field in kV/m.

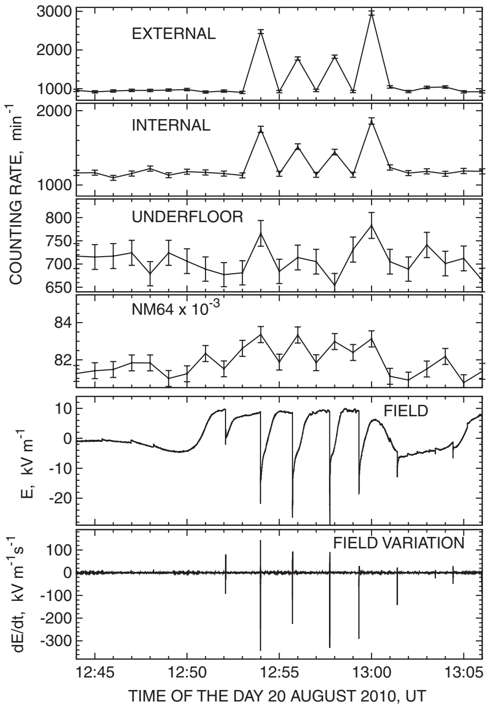

FIG. 2. Records of the neutron counting rate and the local electric field during the initial part of the event 13h, 20 August 2010.

written during two neutron enhancement events are plotted in Fig. 1. Vertical arrows in the panels of Fig. 1 mark the moments when a signal from the fast stepwise change of the nearby electric field has been generated by the capacitor-type field sensor due to a close atmospheric discharge. At the same time moments strong bursts of HF radio emission have been detected.

In the Fig. 1 it is seen an obvious correlation between the periods of electric discharge and considerable enhancement in the counting rate of low-energy neutrons: in those minutes which overlap with a discharge moment both the external and internal detectors demonstrate an excess of signal intensity up to 2–3 times above their mean background levels. The short-time intensity enhancements are also visible in the underfloor detector, thou their amplitude here is only about 0.2–0.5 above the background, and even in the NM, where the relative enhancement amplitude of 0.02–0.05 is noticeable due to its high counting rate. Statistically, the excesses observed during the storms of 10 August in neutron intensity are quite satisfied. For example in the 13 h event the relative peak amplitudes above the background levels are 63σ, 57σ, 18σ, and 11σ for external, internal, underfloor detectors, and for NM supermonitor correspondingly.

On 20 August 2010 a prolonged period of thunderstorm activity at the Tien-Shan Station lasted about 3.5 hours when a number of short-time intensity enhancements of the low-energy neutron signal have been registered. The data recorded during initial phase of thunderstorm are presented

TABLE I. List of all neutron enhancement events seen during thunderstorms in summer 2010 with corresponding amplitudes of the enhancements (in σ) in minutely neutron-number counts. Zeros indicate an absence of any noticeable excess (above 3σ) in the counting rate.

Date, 2010	External	Internal	Underfloor	18NM64
11.06	18	7	5	5
12.06	10	5	0	0
19.06	13	0	0	0
20.06, 5h	14	5	0	0
20.06, 22h	72	23	0	0
21.06, 5h	96	51	20	15
21.06, 6h	68	17	0	0
24.06	28	0	0	0
28.06, 14h	24	33	36	6
28.06, 15h	19	4	0	0
5.07	18	8	0	0
7.07	72	41	14	8
9.07	224	121	37	11
16.07	49	16	0	4
17.07	58	23	4	0
18.07, 10h	97	37	6	12
18.07, 11h	216	84	15	23
18.07, 12h	69	43	8	10
10.08, 8h	74	33	6	9
10.08, 13h	63	57	18	11
15.08	28	15	0	0
17.08	45	18	0	0
20.08, 13h	111	28	0	13
20.08, 14h	111	63	11	12
20.08, 16h	113	36	0	13

in Fig. 2 together with the measurements of electric field. One can see an evident time correlation between the enhancements of neutron flux and atmospheric discharge fixed by the stepwise moments of the electric-field variation. Namely, the enhancements of the neutron counting rate in external and internal TNDs and in NM are in pulses per minute (p.p.m.): 1558, 641, and 804 p.p.m. at 12:54:00, 720, 418, and 1136 p.p.m. at 12:56, 758, 323, and 913 p.p.m. at 12:58 and 2055, 716, and 587 p.p.m. at 13:00. The corresponding atmospheric discharges were fixed at: 12:53:55, 12:55:38, 12:57:41, and 12:59:17. At the same time, any additional neutron flux at TND is absent both before and after the moments of the field change. Hence, one can declare that the neutrons in every enhancement are generated during the corresponding atmospheric discharge. Note, that the same effect is seen in the Fig. 1 as well. Two electric discharges at 08:05:57 and at 08:07:30 correspond to the neutron flux enhancement which is evidently revealed in all detectors. The counting rate growth in the external and internal TNDs and NM are 1673, 927, 2821 p.p.m., and 1225, 922, 2112 p.p.m. correspondingly, similar to the event presented in Fig. 2. Quite analogouse correlation of the neutron enhancements with electric discharges is seen in other events. Taking into account that the atmospheric discharge lasts for a few hundred milliseconds while the neutron detectors have a 1-min time resolution we see that the additional neutron flux generated in every discharge should be really giant!

The flux enhancements of environmental neutrons in the low-energy range similar to those on August 10 and 20 were met regularly in many thunderstorm events observed at the Tien-Shan station. A full statistics of these events for the year 2010 is presented in Table I. Practically all the events listed in this table demonstrate the presence of a considerable excess of the neutron counting rate in thunderstorm period, especially in the signals of the external and internal detectors of low-energy neutrons. The relative amplitude values shown in the table were calculated with account to background levels of signal intensity, which are about 800–900 p.p.m., 1100–1300 p.p.m., and 600–800 p.p.m. for the external, internal, and underfloor thermal neutron detectors correspondingly; for the neutron supermonitor due to its large sensitive surface the background intensity is about $(75–83) \times 10^3$ p.p.m. Hence, the characteristic values of standard deviation σ are about 30 p.p.m. for external and internal detectors, 20 p.p.m. for underfloor detector, and about 300–500 p.p.m. for supermonitor.

Discussion.—Taking into account the geometrical sizes of neutron counters used in our experiment one can conclude that the sum sensitive surface of the supermonitor neutron detectors is 30 times larger then that of the TND. The counting rate enhancement during neutron events is the same (within the 1.5–2 times limit) both in the external and the internal TNDs and the supermonitor. Because of the difference in sensitive areas, it follows that the additional neutron flux registered by the TND is 15–20 times higher then that of supermonitor. From that it follows that the main part of the observed neutron flux in thunderstorm events consists of the low-energy particles.

It should be stressed, that such relationship between the signal in the low and high ranges of neutron energy, when just the low-energy neutron flux resolutely prevails above the high-energy one, is quite unusual and directly opposite to determined domination of the high-energy neutron signal observed generally in interaction of the cosmic ray hadronic component [9].

The neutron background intensity at the internal TND is higher than at the external one. To the contrary according to the Table I the neutron count rate enhancements during thunderstorms are stronger at the external TND than at the internal TND and even more than at the underfloor TND. It means that neutrons observed during the enhancement event are generated in the air and in the upper layer of the ground, what may indicate the possibility for neutrons to be born in photonuclear process by γ rays generated in atmospheric discharge.

Taking into account the minute neutron counting rates registered in thunderstorm period and the effective sensitive surface of the TNDs, one can state, that the additional neutron fluxes during thunderstorm reach the extremely high values of the order of $(3 - 5) \times 10^{-2}$ neutrons $cm^{-2}\ s^{-1}$. This flux value constitutes a serious difficulty for the photonuclear model of neutron generation in thunderstorm. Simulations of low-energy neutron generation both in air and in the ground show that an extraordinary large intensity of γ radiation in the energy range 10–30 MeV, of the order of 10–30 quanta $cm^{-2}\ s^{-1}$ is needed to obtain the observed neutron flux. Quite the same high flux value was observed in thunderclouds in balloon experiment at the height 5 km [13] and in the highest point of the ground experiment at the height 4 km [14]. At lower heights the flux was an order of magnitude less. But in all these observations the γ-radiation intensity was observed at moderate energies 50–200 keV. 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 [8]. The obtained γ-ray emission flux was about 0.04 quanta $cm^{-2}\,s^{-1}$, 3 orders of magnitude less than the needed value.

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