The time structure of neutron emission during atmospheric discharge

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Abstract

The time structure of neutron count rate enhancement during thunderstorm is studied. The enhancements take place during the time of atmospheric discharge. Main part of neutrons are emitted in short bursts (200-400 μs). Sometimes the emission is well correlated over the space scale 1 km. Short burst width allows to suppose that neutrons are generated mainly in a dense medium (probably soil).

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1. Introduction

The neutron flux intensification during thunderstorm was discussed beginning from Shaha et al. (1985). The enhancements of neutron monitor (NM, 6NM64 type) count rate were identified by Dorman et al. (1985) at Emilio Segre' Observatory on Mt. Hermon (2025 m a.s.l.). Later the research group from Aragats Space Environmental Center (3250 m a.s.l.) has observed simultaneously the neutron count rate enhancement in one-minute time series of NM (18NM64 type) data and the high-energy gamma-ray emission (up to 50 MeV) (Chilingaryan et al. (2010)). It allowed to claim that the high-energy gamma-ray flux generates neutrons in atmosphere in photo-nuclear reactions with air atoms.

A new important step was done by Tsuchiya et al. (2012) at Yangbajing Cosmic Ray Observatory (Tibet, altitude 4300 m a.s.l.). The simultaneous measurements in five-minute time series of neutron count enhancements in NM (28NM64 type) and of high-energy (up to 160 MeV) gamma-ray emission flux during an intensive thunderstorm were fulfilled. Combining the results of measurements with numerical calculations the authors have stated that additional neutrons forming neutron count enhancements are born mainly not in atmosphere but inside the NM. In other words it was supposed that the environmental neutron enhancement does not play any essential role, and the observed additional neutrons are generated by energetic gamma quanta in the NM directly. Gamma quanta themselves are supposed to be generated by electrons accelerated in quasi-stable thunderstorm electric field. Aragats group afterwards reconsidered the previous statement and confirmed the Tibet group result (Chilingaryan et al. (2012)).

Gurevich et al. (2012) have reported the results of neutron flux measurements at Tian-Shan Cosmic Ray Station (altitude 3340 m a.s.l.) during summer 2010 thunderstorms. The NM (18NM64 type) and three low-energy neutron detectors were used simultaneously. For the first time the intensive fluxes of low-energy neutrons generated during thunderstorms have been registered. The correlation of the neutron count rate enhancements in one-minute time series with simultaneously measured electric field variations allowed to claim that the neutron flux enhancements are connected with atmospheric discharges.

It should be noted, that the enhancements of neutron flux were registered not only in mountaines but also at the low ground level (Kozlov et al. (2013)) and even in laboratory high-voltage atmospheric discharge (Agafonov et al. (2013)).

The time structure of the neutron flux enhancement in high resolution (200 μs) time series was studied during the summer 2013 thunderstorms using the modified installation at the Tien-Shan Station. We are reporting here the results of these observations. It is established that the neutrons are generated during thunderstorm atmospheric discharges. Mainly the neutrons are emitted in short bursts; the burst width is 200-400 μs. Besides, the bursts with longer width (up to 3-10 ms) were observed as well. Neutron count bursts are observed simultaneously by six independent detectors situated at the distance about 1 km from each other; often the bursts of distant detectors are well time-correlated. Mainly the observed neutrons had low energies, less than 1 keV, though in a part of the bursts the energy is higher.

2. Instrumentation

Measurements were fulfilled on the installation "Thunderstorm" of Tien-Shan Station (Gurevich et al. (2009)). The detectors used in summer 2013 investigation of thunderstorm neutron flux enhancements were located in two points: the Station itself – *Station point*, and on the top of a neighboring hill – *Hill point*. The Hill point is situated 160 m above the common level of the Station; the distance between Hill point and the Station point is about 1 km. At the Station point we used the neutron monitor (NM) as well as three low-energy ^{3}He neutron detectors. Two ^{3}He detectors were used at the Hill point.

The Tien Shan neutron monitor 18NM64 is sensitive mainly to the high-energy hadronic flux of the cosmic ray origin (above some hundreds of MeV) but is capable also to register the neutrons having energies ∼1 MeV and below with a small, 0.05-1%, probability (Gurevich et al. (2012); Chubenko et al. (2003)).

The low-energy neutron detectors are the 1.2×0.84 m^2 boxes of 2 mm thick aluminum each containing six 1 m long, 3 cm in diameter proportional ^{3}He neutron counters. These counters are not surrounded by any moderator material, and thus they are mostly sensitive to the low energy range (about and less than 1 keV) neutrons. The placement of three ^{3}He detectors situated at the Station point (*external*, *internal* and *underfloor*) is shown in Fig. 1.

Two neutron detectors were installed at the Hill point. The *Hill-free* detector is of the same type as those at the Station point. The *Hill-shielded* detector is surrounded with moderator polyethylene tubes of 0.5 cm wall thickness what leads to the increasing of efficiency for energetic neutrons.

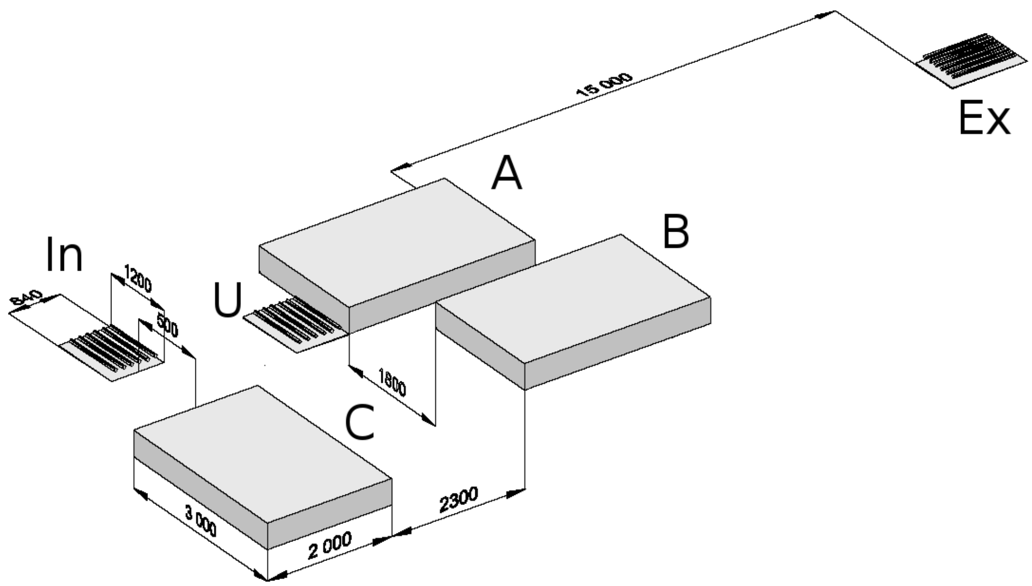

Figure 1: Placement of ^{3}He detectors and NM at the Station point. Ex, In and U – the external, the internal and the underfloor detectors correspondigly. A, B, C – three standart 6-counter units of the NM64 type supermonitor. An external detector is placed in the open air inside a plywood housing at the distance 15 m from other detectors. The internal detector is placed in the same room with the NM. The underfloor detector is placed under the wooden (4 cm) floor of the same room and is additionally shielded from the top by a 9 cm thick layer of rubber. Dimensions are shown in mm.

Efficiencies of detectors situated at the Station and Hill points are presented in Fig. 2.

Neutron counting rates are measured as follows. After an amplification and shaping, the electric signals from each neutron counter separately are connected to the multichannel pulse intensity measurement system which counts the number of pulses in 10000 succeeding 200 μs long time intervals. Each moment of time, this system keeps in its internal memory the temporal history of the counting rate on its inputs for the last 2 s, and can write it down with arrival of a special control signal — the trigger. In these records the arrival moment of trigger signal coincides always with the median time interval so both the pre-history of signal intensity during 1 s before the trigger and its behavior in succeeding second are available with resolution of 200 μs in each registered event.

The NM registration system was supplied by an additional fast registration system (besides the one described above) which had a temporal resolution of 72 μs in a limited time space of 4000 μs, and was synchronized by the trigger. In favorable cases when a single peak of neutron intensity falls on the first four milliseconds after the trigger the fast registration system permit to resolve the temporal development of neutron signal more distinctly.

Simultaneously, the signals from all neutron detectors are connected to another set of digital counters which continuously measure the number of pulses with a raw time resolution of 10 s, without binding to any external trigger. In this monitoring mode we aslo have used two field-mill type detectors to measure the electric field and two NaI scintillation detectors to register the gamma-ray flux. One electric field detector and one NaI detector were placed at the Station point, another pair of these detectors – at the Hill point.

The trigger signal is generated with a local electric field derivative detector (capacitor). This is a 0.25 m^2 capacitor sensor installed outdoors in NM vicinity with one of its plates being grounded. The short ($\leq$100 μs) electric pulses induced on the other plate of this capacitor in the moment of a fast change in local electric field are connected to a threshold discriminator scheme which generates trigger pulse if the signal on its input exceeds a predefined value. After its shaping the trigger is transmitted over the shielded cable simultaneously both to detector system at the Station and Hill points through the powerful amplifier which is stable against the influence of strong electromagnetic interferences from lightning.

A special attention was paid to reliability of signals registration in thunderstorm conditions. All the detectors were grounded and electromagnetically shielded. The absence of electromagnetic interference on the registration system was controlled by using a "dummy" information channels – additional ^{3}He counters placed inside the detector boxes which are switched to the data registration system but the high voltage in the feeding main is strongly diminished to exclude the neutron registration. All the signals from neutron detectors including the "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. Additional isolation against electromagnetic influence has been constructed at the Hill point. The plywood cabin at the Hill point containing detectors was shielded by a grounded outer aluminum upholstery, and every time with storm approach its whole powering is switched to internal accumulator battery. So, the neutron flux measurements at the Hill were fulfilled in the absence of the outer electromagnetic influence (Faraday cage).

3. Observational data

Thunderstorm neutron enhancement observations were fulfilled in 2013 on the Tien-Shan Station from 12.06 till 24.07. Twenty thunderstorms were observed during 11 days. Both the monitoring of neutron flux with 10 s accumulating time and the triggered 2 s long (1 s before and 1 s after the trigger) registration was used.

The main result of the monitoring is that the neutron enhancements are observed in the periods of thunderstorm activity only. It is illustrated in Figs. 4-5. In Fig. 3 the monitoring data obtained during July 13 and July 21, 2013 are presented. It is clearly seen from the figure that neutron enchancements were observed whithin the period of electric field variations and gamma-ray emission enhancement. In Fig.4 the monitoring data obtained during the storms on the same days are presented. The prominent count rate enhancements in some of neutron detectors are seen during the thunderstorm wich lasted for 30 min from 13:40 to 14:10. The prominent neutron count rate enhancemnet on July, 21 is clearly seen at the beginning of the thunderstorm which lasted from 6:30 till 13:00. Two enhancements are presented in Fig.5 with a time scale zoomed in relative to that of Fig. 4. It is seen that the duration of enhancements is not longer that 10 s. This statement is right for all registered neutron count rate enhancements.

Triggered registration was used to study the fine time structure of neutron flux during thunderstorms. The overall number of triggered records containing count rate enhancements was 39 through the 20 thunderstorms, it makes 20% of all triggered records. Durations of enhancements and main characteristics of neutron bursts observed during all the events are presented in Table 1. The enhancement duration is less than 100 ms in most cases. For example, the neutron signal during the discharge 13.07.2013 (13:56:02, see left panel of Fig. 6 and Fig. 7) lasted 100 ms, and during the discharge 21.07.2013 (06:37:52, see right panel of Fig. 6 and Fig. 7) – 10 ms. But some neutron signals are longer. The longest one (23.07.2013, 09:55:56) lasted 550 ms, the other enhancements of this long-term events lasted 460, 400, 350, 350 and 230 ms.

The main striking the eye characteristic of the enhancements registered by ^{3}He detectors and often by NM is its burst time structure (Fig. 6). The burst width is usually about 1-2 registration time intervals (200 μs). Occasionally the 3-4 registration intervals duration of bursts is also observed. Such a time structure is observed both in the main part of events and in the long-term ones.

In 13 records the count rate enhancements in neutron detectors start at the trigger moment. Six of these near-trigger enhancements are short (less than 2 ms), and seven are relatively long (3-6 ms, see left panel of Fig.7 for an example). Significant and often even the main part of neutrons is generated during this initial milliseconds of atmospheric discharges. Sometimes these initial events are accompanied by a tail of solitary bursts.

The count rate enhancements are registered by NM in all cases. A number of long (up to 10 ms) time-correlated enhancements are observed both in NM and in Hill-shielded detector. In these cases the enhancements in non-shielded ^{3}He counters are not very prominent what indicate that neutrons observed both in NM and shielded detector are energetic ($E > 1$ keV). For example, in the event 08.07.2013 (07:54:45) sum number of surplus neutron

Table 1: Neutron event characteristics. All columns except column NM (neutron monitor) and column C present data obtained by one of non-moderated ^{3}He detectors. The presented parameter value is the maximal registered at the Station point (S) or at the Hill point (H). Duration – time from the beginning of the first neutron burst to the end of the last one. Short and Long – numbers of neutron bursts shorter and greater than 400 μs correspondingly. N – the maximal neutron count in a 200 μs interval registered by a ^{3}He detector. C - coincidence number, i.e. a number of bursts registered simultaneously by all detectors and NM.

Event		Duration, ms			Short		Long		N		C
Date	Time	S	H	NM	S	H	S	H	S	H	
12:06:13	12:31:39	0.6	180	330	1	8	0	1	4	8	1
13:06:13	12:42:55	0.4	120	240	1	6	0	0	9	20	1
13:06:13	12:44:28	1	1.6	6.2	0	0	1	1	8	14	1
03:07:13	11:27:44	0.2	8	133	1	2	0	0	11	47	1
03:07:13	11:29:42	0.4	0.4	420	1	1	0	0	12	43	1
07:07:13	15:02:28	0.4	24	24	1	5	0	0	34	32	1
07:07:13	15:05:12	0	0.2	81	0	1	0	0	0	6	0
07:07:13	15:18:03	0.2	0	192	1	0	0	0	3	0	0
08:07:13	07:54:45	6	22	27	2	2	0	1	4	5	1
11:07:13	11:46:21	0	0.4	1.2	0	1	0	0	0	8	0
11:07:13	12:41:08	0.4	0.4	98	1	1	0	0	3	9	1
13:07:13	13:56:02	54	54	92	7	6	0	1	20	19	3
13:07:13	14:01:03	12	51	186	3	9	0	1	8	23	1
14:07:13	09:00:13	8	22	51	12	8	3	4	31	17	5
15:07:13	05:13:58	26	43	121	2	4	0	1	22	36	2
15:07:13	15:18:20	0.2	1.4	158	1	1	0	1	3	15	0
17:07:13	07:50:14	0.2	0.2	410	1	1	0	0	3	9	1
17:07:13	09:55:11	0.2	0.2	19	1	1	0	0	3	21	1
20:07:13	18:05:38	0	1.6	2.1	0	0	1	1	14	28	0
21:07:13	06:37:51	6	6.2	11	0	0	1	1	42	44	1
21:07:13	07:02:18	0.2	0.2	225	1	1	0	0	9	37	1
21:07:13	07:05:40	0.2	0.2	254	1	2	0	0	3	18	1
21:07:13	07:49:47	0.2	180	462	1	3	0	0	3	4	0
21:07:13	07:54:34	0.4	0.4	163	1	1	0	0	5	22	1
23:07:13	06:32:44	0.2	47	52	1	6	0	1	4	10	1
23:07:13	06:38:45	18	24	88	4	5	0	1	3	9	1
23:07:13	06:42:25	0.4	33	47	1	3	0	1	25	8	1
23:07:13	09:55:56	221	533	542	2	6	0	0	22	21	2
23:07:13	09:57:24	0.4	0.4	113	1	1	0	0	6	5	0
23:07:13	12:52:08	33	41	214	2	5	0	0	11	22	2
23:07:13	12:52:57	0	0.4	67	0	1	0	0	0	5	0
23:07:13	12:55:15	77	77	362	2	2	0	0	4	11	2
23:07:13	12:57:08	8	8	213	2	2	0	1	10	9	2
23:07:13	12:58:20	0.6	0.6	3.8	0	0	1	1	7	6	1
23:07:13	13:00:23	0	28	28	0	7	0	1	0	19	0
23:07:13	13:05:43	0	46	205	0	2	0	4	0	7	0
23:07:13	13:02:01	0.4	0.4	24	1	2	0	0	10	16	1
24:07:13	05:01:51	0.4	0.4	4	1	1	0	0	13	17	1
24:07:13	05:11:34	1.6	1.6	161	2	1	0	0	4	5	1

signals during the 10 ms long burst in NM is 430, in Hill-shielded detector – 177, in Hill-free detector – 12, in external detector – 5, in internal detector – 7, and in underfloor detector - 2.

A number of bursts (40 during all thunderstorms) are time-correlated in NM and in all ^{3}He detectors independently on where they are placed, at the Station or at the Hill registration points. These bursts are short – 1-2 registration intervals. Sometimes there are two time synchronized events during the same discharge. For example on July, 15 (05:13:58) there were two synchronized bursts in all detectors at 12 ms and 44 ms after the trigger time.

The strong neutron enhancement at the electric field jump moment is seen clearly in Fig.6-7. We emphasize, that the neutron signal enhancements occure in the after-trigger time only. During the pre-trigger second any neutron enhancements are absent. So, our observations demonstrate definitely that the neutron enhancements are deeply connected with the lightning discharge.

4. Discussion

Comparing the 2013 results with the 2010 results Gurevich et al. (2012) we see that the neutron amount was somewhat larger in 2010. Note, that this difference is more visible in the low-energy ^{3}He detectors than in NM. The one minute integral amount of neutron enhancements observed by NM are quite comparable: 900-1200 in 2013, and 600-2800 in 2010. Related to a single NM unit the amplitude of neutron enhancement in 2010 reaches 140 per minute for strong thunderstorms, and is about 50 for a weak one, in 2013 the enhancement is about 60±40. These results are in accordance with the results of Tibet and Aragatz groups: 140 per minute for a one NM unit for the strong thunderstorm analyzed by Tibet group, and 60 for the Aragatz group. Thus, one can state that the integral enhancement of neutrons during thunderstorm in the averaged one minute NM data are analogous in all three groups.

The detailed time structure of the neutron signal is shown in Fig.6. It is seen that the neutrons are often observed in multiple short bursts as it was mentioned above. Each burst as registered by ^{3}He detector lasts only 1-2 time intervals (200-400 μs).

Note, that the simultaneous bursts in NM signal seem to be wider – about 1 ms (see Fig.6). The following consideration shows that it is an apparent effect. It is well known that after a momentary generation of neutrons inside NM by a high- energy cosmic ray hadron the neutron intensity grows up in a microsecond time scale and after that falls down due to neutron diffusion in NM. The fall is in accordance with exponential law $I(t) \sim 0.72exp(-t/\tau_1) + 0.28exp(-t/\tau_2)$ with lifetimes τ_1 ∼240 μs and τ_2 ∼650 μs (for the NM64 type supermonitor configuration) Hatton and Carmichael (1964); Antonova et al. (2002). If to draw the corresponding distribution curves on the plots of Fig. 8 one can see that the experimentally measured signal intensity agrees with the expected exponential behavior. This is an evidence that we observe neutrons and that the initial neutron signal lasts in NM the same short time as in ^{3}He detectors.

The definite time delay (about 2-3 ms) between the initiation of neutron emission at two registration points is seen in left panel of Fig.7. This time delay could be interpreted as the result of the atmospheric discharge front motion between the points. This motion has the velocity $(3-5)\cdot 10^7$ cm s^{-1} which is just the characteristic lightning velocity.

The mean neutron free path time in a dense medium (soil, Si) is 50 μs and the thermalization time is about 500 μs, while in the air at the height of the Station the neutron free path time is about 20 ms, and thermalization time is 90 ms – hundreds times larger. Thermalized neutrons have the diffusion length in soil about 17 cm, the thermalization length from energies about 10 MeV up to the thermal energy is 115 cm. Thus, the observed width of the bursts shows that neutrons are generated and propagate in soil or in other dense medium but not in the air. It should be noted, that the discussion of neutron registration results in Chilingaryan et al. (2012), Babich et al. (2013), and Tsuchiya (2014) is based on the assumption that the neutrons are generated in the air or directly in the detectors, their generation and propagation in soil or other environmental dense medium are not considered at all.

An integral number of neutrons generated in one burst could be estimated for those events when the enhancement is observed simultaneously in all detectors both at the Station and the Hill points. Taking into account that the distance between the location points is $R \approx 1000$ m the number of neutrons generated in one short burst could be estimated as $N_b \sim R^2 \cdot I_b$, were I_b is the neutron fluence in the burst. As it follows from the Fig. 6 about 10-20 neutrons are registered in one short burst. Taking into account that the efficiency of the low-energy neutron registration is about 10%, and that the effective area of the counter is about 0.5 m^2 the fluence I_b could be estimated as 10^2 m^{-2}. Thus, we obtain $N_b \approx 10^8$. The full number of neutrons in a long burst could be about 10^9. The total neutron number generated during one discharge can reach $3 \cdot 10^9 - 10^{10}$.

5. Conclusions

Previously, the neutron enhancements in thunderstorm were studied only with a long-scale time resolution (1-5 min). In this work the time structure of the neutron count rate enhancement was studied more precisely with resolution of 200 μs. It is demonstrated that the enhancements take place during the time of atmospheric discharge. Neutrons are emitted mainly in short bursts lasting 200-400 μs. Sometimes the emission is well correlated over the wide space - up to 1 km scale. The full number of neutrons generated in a burst is about 10^8. Short burst width allows to suppose that neutrons are generated mainly in a dense medium near the detector, probably in soil or partly in the neutron monitor.

It should be noted also, that the time structure of the neutron signal is observed by three types of detectors: ^{3}He counters, polyethylene moderated ^{3}He counter and the NM. All the detectors sometimes demonstrate the highly correlated short pulses of neutrons. Sometimes correlated bursts are observed around one point only – Station point or Hill point which are divided by a large distance. In a number of events only detectors of a type sensitive to energetic neutrons demonstrate an intensive neutron burst while other detectors are silent. All this indicates that the neutrons of different energies correlated in time and space are generated during thunderstorm discharge.

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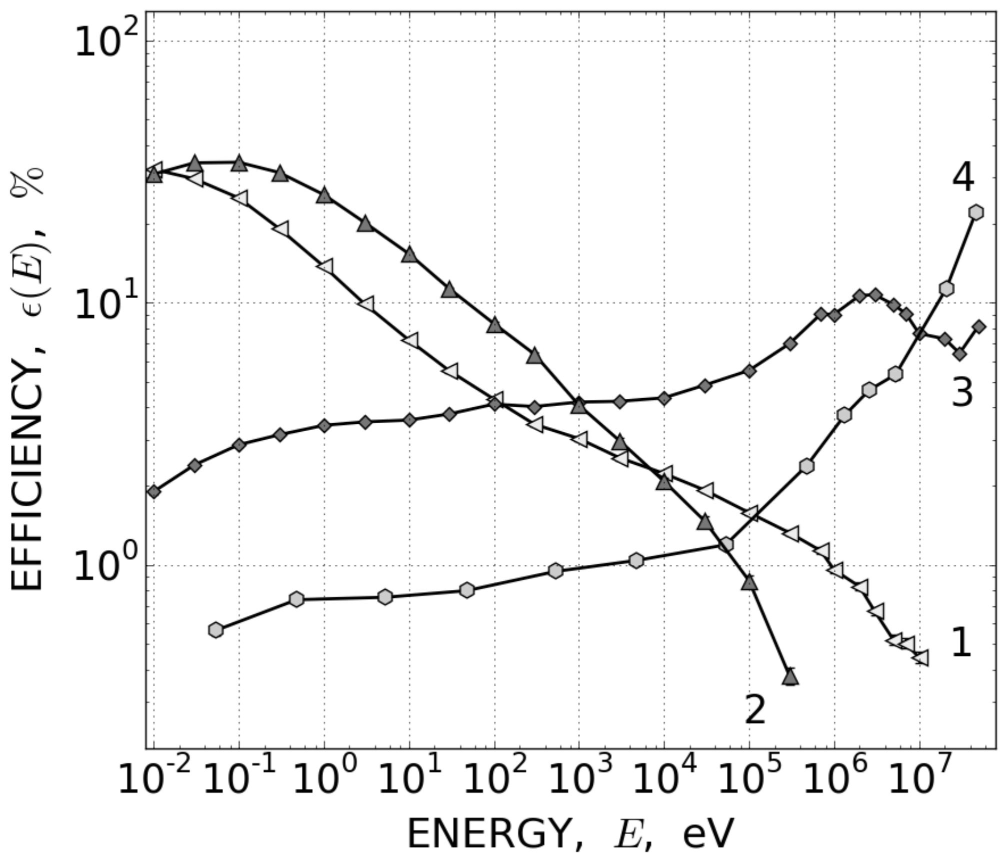

Figure 2: Efficiencies of neutron detectors calculated with the use of GEANT4 toolkit (GEANT4 collaboration (2003)). ^{3}He counters: *1* – without moderator (external and internal detectors), *2* – the counters with polyethylene moderator tubes at the Hill point; *3* – underfloor detector; *4* – the neutron monitor.

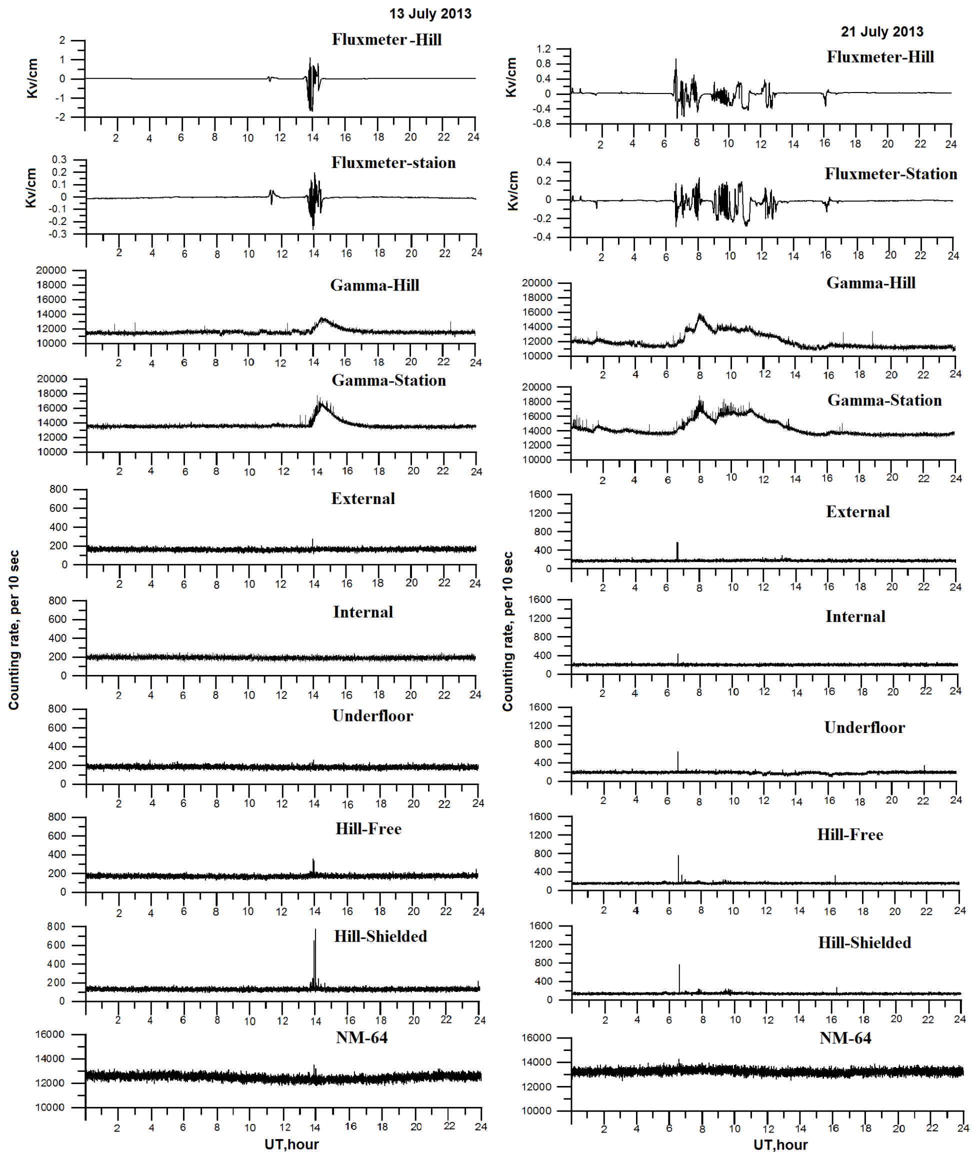

Figure 3: Monitoring mode results during July 13 and 21, 2013. Detectors are marked in the panels.

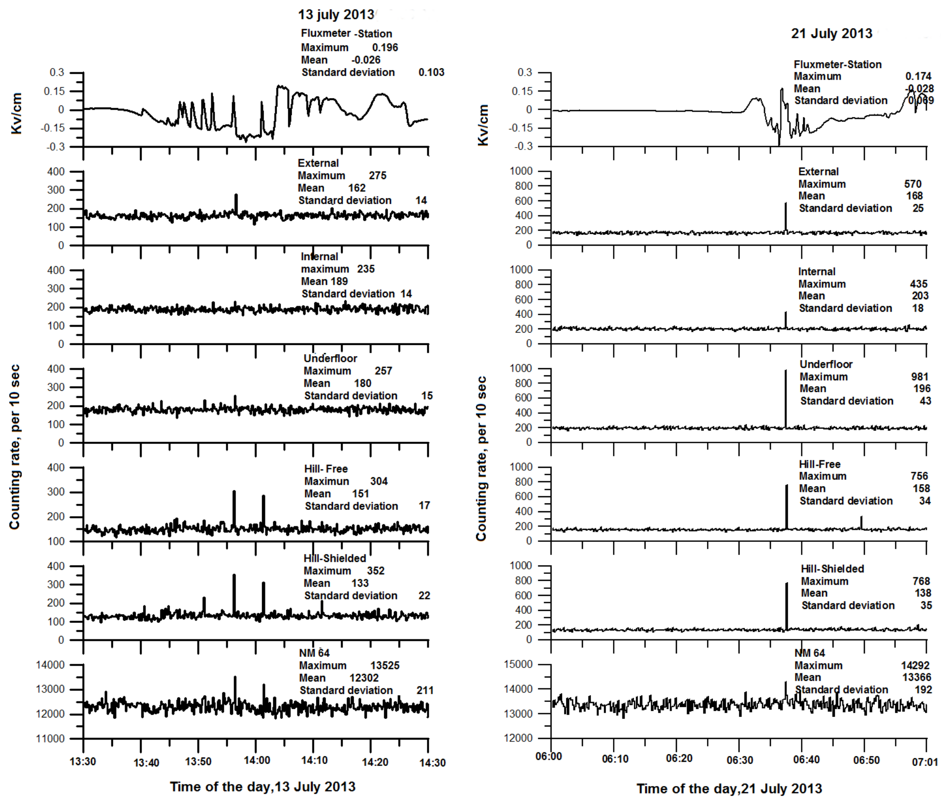

Figure 4: Monitoring mode results during thunderstorms on July 13 and 21, 2013. Upper panel - electric field as measured by the field-mill detector placed at the Station point, lower panels - count rates in different neutron detectors marked in the panels.

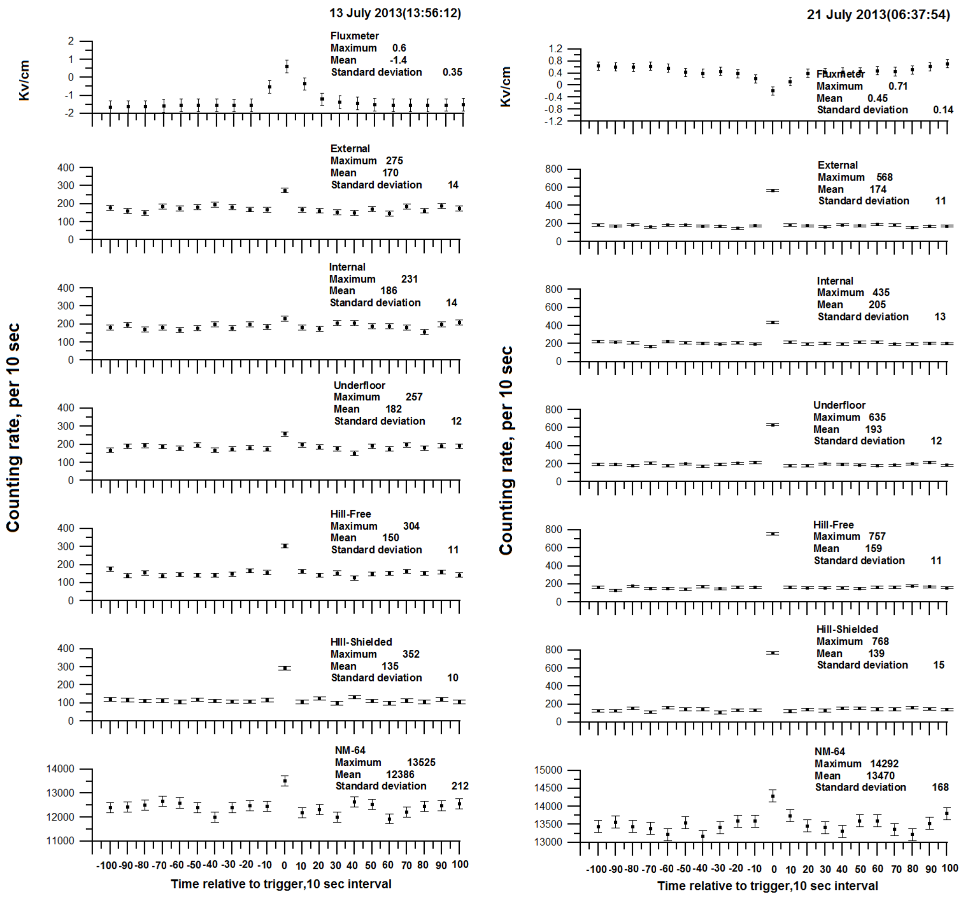

Figure 5: Examples of neutron count rate enhancements registered in the monitoring mode on July, 13 and 21, 2013, presented with a time scale zoomed in. Panels are the same as in Fig. 4. Zero points marks the middle of a 10-s intervals containing the trigger moments presented in Figs. 6, 7.

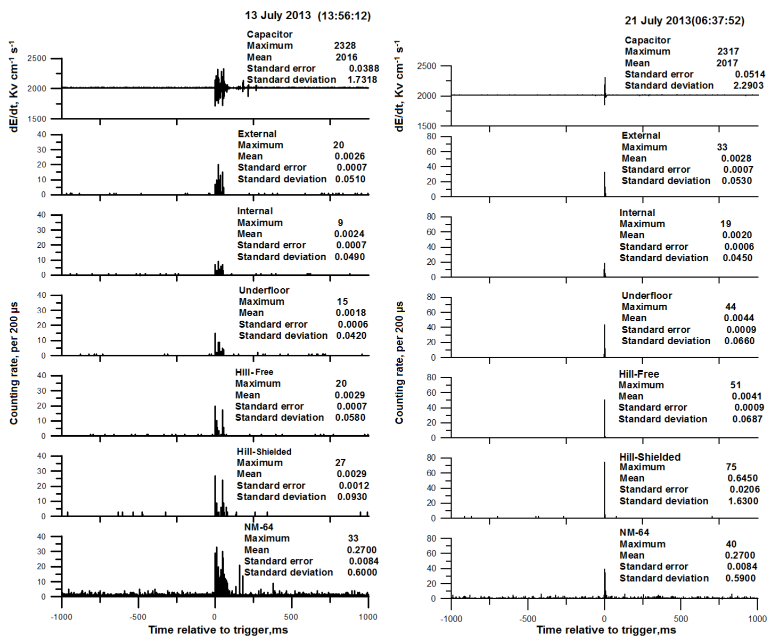

Figure 6: Time structure of neutron count rate of the discharge 13 July 2013 (13:56:02) and of the discherge 21.07.2013 (06:37:52).

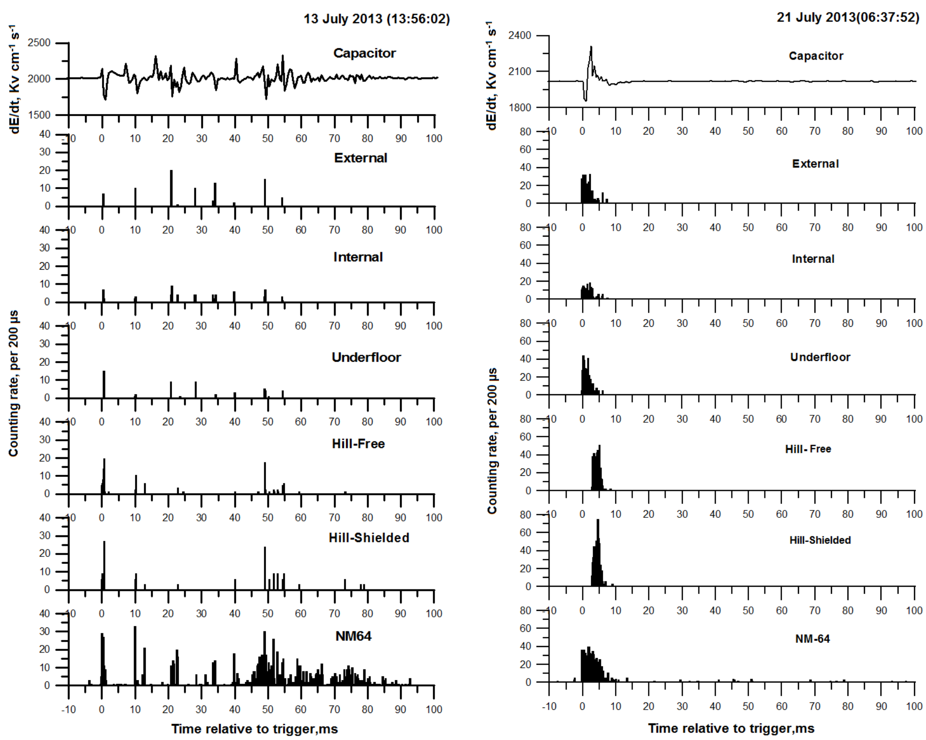

Figure 7: Fine time structures of neutron count rate of the discharge 13 July 2013 (13:56:02) and of the discherge 21.07.2013 (06:37:52). Left: burst type time structure, right: long-term type time structure.

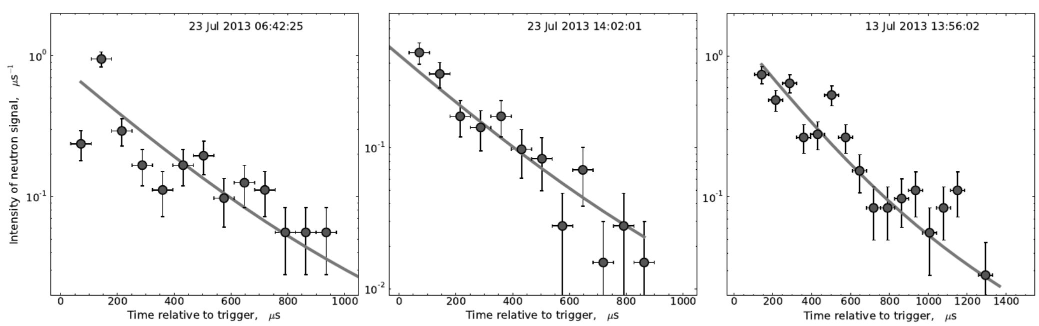

Figure 8: The example of the neutron signal time dependencies as registered by the NM fast registration system (circles with error bars). Every plot corresponds to a neutron signal peak registered just at the moment of trigger arrival. The smooth continuous lines represent the usual exponential distribution anticipated for the neutrons momentary born in the monitor and diffusing inside it afterwards (see text).