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Surrounding material effect on measurement of thunderstorm-related neutrons

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ABSTRACT

Observations of strong flux of low-energy neutrons were made by ^{3}He counters during thunderstorms (Gurevich et al., 2012) [11]. How the unprecedented enhancements were produced remains elusive. To better elucidate the mechanism, a simulation study of surrounding material impacts on measurement by ^{3}He counters was performed with GEANT4. It was found that unlike previously thought, a ^{3}He counter had a small sensitivity to high-energy gamma rays because of inelastic interaction with its cathode-tube materials (Al or stainless steel). A ^{3}He counter with the intrinsic small sensitivity, if surrounded by thick materials, would largely detect thunderstorm-related gamma rays rather than those neutrons produced via photonuclear reaction in the atmosphere. On the other hand, the counter, if surrounded by thin materials and located away from a gamma-ray source, would observe neutron signals with little gamma-ray contamination. Compared with the Gurevich measurement, the present work allows us to deduce that the enhancements are attributable to gamma rays, if their observatory was very close to or inside a gamma-ray emitting region in thunderclouds.

1. Introduction

Like the Sun and supernova remnants, thunderclouds as well as lightning are powerful particle accelerators in which electrons are accelerated by electric fields to a few tens of MeV or higher energies. Then, they in turn produce high-energy gamma rays extending from a few hundred keV to a few tens of MeV or 100 MeV on rare occasions.

In addition to gamma rays and electrons, some observations [1–4] showed that neutrons were probably produced in association with lightning and thunderclouds. To explain such neutron generations, two mechanism have been investigated theoretically and experimentally since the first positive neutron detection [1]. One is fusion mechanism via $^2\mathrm{H} + {}^2\mathrm{H} \rightarrow \mathrm{n} + {}^3\mathrm{He}$, and the other is photonuclear reaction or the Giant Resonance Reaction (GDR), mainly via $^{14}\mathrm{N} + \gamma(> 10.6\ \mathrm{MeV}) \rightarrow \mathrm{n} + {}^{13}\mathrm{N}$ in the atmosphere. Conducting numerical calculations, Bahich and Roussel-Dupré [5] presented that only the latter was feasible in an usual thunderstorm environment. However, a recent calculation considering ion runaway in a lightning discharge suggested a possibility of neutron production via the former [6]. Thus, a neutron generation process in thunderstorms remains elusive.

Experimentally, a BF_3 and ^{3}He counters were frequently employed in order to detect neutrons associated with thunderstorms. As well known, the two detectors have high sensitivity to neutrons thanks to high total cross-section in thermal to epithermal energy region; 3840 b for ^{10}B and 5330 b for ^{3}He at 0.025 eV [7]. Especially, a set of neutron monitors (NMs), installed at high mountains with an altitude of >3000 m, detected remarkable count increases during thunderstorms [2,3]. Generally, a NM consists of a BF_3 counter and its thick shields of lead and polyethylene $[(C_2H_4)_n]$ [8,9]. Thus, it was naturally considered that the detected count increases by NMs were attributable to neutrons, not gamma rays. However, Tsuchiya et al. [3], using GEANT4 simulations [10], demonstrated that such a NM had a low but innegligible sensitivity to gamma rays with their energy higher than 7 MeV because they can produce neutrons in the surrounding lead blocks via photonuclear reaction. Consequently, they pointed out that count enhancements of NMs associated with thunderstorms were dominated by gamma rays rather than neutrons. This claim was favored shortly afterward by Chilingalian et al. [4].

As shown in Fig. 1, Gurevich et al. [11] recently reported detections of strong flux of low-energy (< a few keV) neutrons during thunderstorms. They observed the enhancements by several

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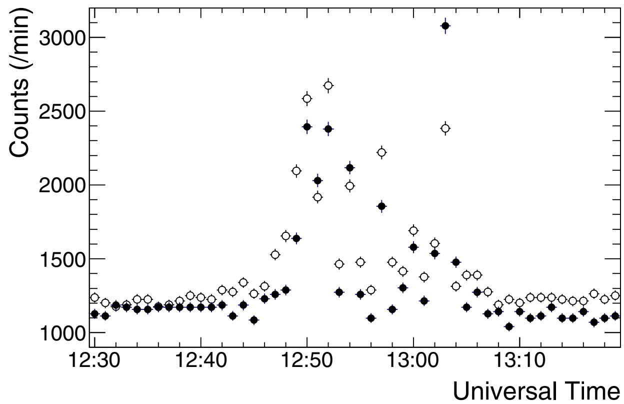

Fig. 1. A thunderstorm event obtained by Gurevich et al. [11] on 2010 August 10. Plotted data are taken from Fig. 1 in the Gurevich paper. Open and filled circles denote one minute count histories of external and internal counters. As mentioned later, external and internal counters are called in this paper plywood and Fe + C ones, respectively.

independent detectors for 1 min or longer, in coincidence with high electric field changes ($< \pm 30$ kV/m). Such a long duration, together with the simultaneous detections, may exclude the increases being due to electrical noise, and is similar to prolonged ones observed by other groups [2,3]. Unlike the other observations, the Gurevich's events were done with a set of ^{3}He counters that were installed at a high mountain with an altitude of 3340 m. They argued that the detected neutron flux of 0.03–0.05 cm^{-2} s^{-1} were not able to be explained by the photonuclear reaction, requiring at least three orders of magnitude higher flux of gamma rays emission than previously measured. However, such an increase obtained by ^{3}He counters may originate from gamma rays, not neutrons, if we consider inelastic interaction between high-energy gamma rays and their cathode wall made by aluminum or stainless steel. For example, a threshold energy of ^{27}Al$(\gamma, n)^{26}$Al and ^{27}Al$(\gamma, p)^{26}$Mg is 13.1 MeV and 8.3 MeV, respectively [12]. Actually, gamma rays at enrages of 10 MeV or higher have been measured by sea-level experiments [13–17], high-mountain ones [2,3,18–20], and space missions [21–23]. In addition, it is well known that neutron measurement by a ^{3}He counter is disturbed by gamma rays in a mixed field of gamma rays and neutrons [24,25]. Such a mixture environment is similar to observations of gamma rays and neutrons during thunderstorms.

In this paper, we investigate how materials surrounding ^{3}He counters affect their measurement during thunderstorms. For this aim, we derived in Section 2, with GEANT4, detection efficiency of a ^{3}He counter for >10 MeV gamma rays as well as neutrons in 0.01 eV–20 MeV energy range. Some authors [4,26] argued against an interpretation given by Gurevich et al. [11], but did not clearly gave detection efficiency of a ^{3}He counter for gamma rays. Then, to examine how neutrons and gamma rays contributes to a ^{3}He counter surrounded by a thick or thin material, we utilized two roof configurations according to Gurevich et al. [11] in Section 3. Considering the derived efficiency and roof effects on neutron detection during thunderstorms, we argue the Gurevich observations.

2. Detection efficiency of a ^{3}He counter

As described in [25], a reason why a ^{3}He counter has a sensitivity to gamma rays is believed that they occasionally supply either neutrons or protons in the counter via inelastic interaction with a cathode wall. As a consequence, such a gamma-ray induced nucleon would produce a large energy deposit in the counter. Table 1 lists properties of several photonuclear reactions to be considered in this paper. From this table, gamma rays at energies of >10 MeV are found to probably give a contribution to a ^{3}He counter during thunderstorms, because its cathode usually consists of either Al or stainless steel.

Table 1
Characteristics of several photonuclear reactions to be considered.

Nuclide[a]	E_n (MeV)[b]	E_p (MeV)[c]	E_{peak} (MeV)[d]	σ_{peak}(mb)[e]
^{12}C	18.7	16.0	23	20
^{14}N	10.6	7.6	23	27
^{16}O	15.7	12.1	22	31
^{27}Al	13.1	8.3	21	42
^{52}Cr	12.0	10.5	20	95
^{56}Fe	11.2	10.2	20	80

[a] These values were gathered from [12].
[b] Threshold energy of (γ, n) reaction.
[c] Threshold energy of (γ, p) reaction.
[d] Peak energy of total photonuclear reaction.
[e] Cross-section at peak energy.

For the purpose of calculating detection efficiencies of ^{3}He counters for neutrons and gamma rays in the relevant energy range, we adopted in the GEANT4 simulation a hadronic model of QGSP_BERT_HP and GEANT4 standard electromagnetic physics package to simulate neutron reactions and electromagnetic interactions including GDR, respectively. Then, we constructed a set of three ^{3}He counters confined in an Al box with an area of 1.2×0.84 m^2 based on "Experimental setup" of [11] and a reference given by Gurevich group [27]. The setup is shown in Fig. 2. Each counter has a diameter of 3 cm and a length of 100 cm, containing 100% ^{3}He gas with a pressure of 2 atm. Because the thickness and cathode material were not shown in [11,27], we employed in our GEANT4 simulation 2-mm thick stainless steel (74%Fe + 8%Ni + 18%Cr) that is generally used by a commercial ^{3}He counter. Then, 10^6 neutrons or 10^7 gamma rays with mono energy were illuminated on the same area of a set of three ^{3}He counters, isotropically injected to the counters from the vertical to 60°.

According to Gurevich et al. [11], an efficiency of their ^{3}He counters for neutrons in a low energy range is about 60%, and the efficiency at ~10 keV becomes three orders of magnitude lower. As shown in Fig. 3, this trend is found to be consistent with that of neutron detection efficiency derived here. In addition, it is found that the whole structure of the detection efficiency for neutrons in a wide energy range of 0.01 eV–20 MeV completely follows the total cross-section of ^{3}He atom[1] mainly a neutron capture reaction of ^{3}He(n, p)T in energy below 0.1 MeV and an elastic scattering above 0.1 MeV. These consistencies validate the simulation.

Due to the smaller cross-section, gamma rays are detected with a relatively low sensitivity of at most $(1.47 \pm 0.12) \times 10^{-3}$% at 20 MeV (the error is statistical one only). This is consistent with that each peak energy of photonuclear reaction for ^{52}Cr and ^{56}Fe is around 20 MeV (Table 1). From this simulation, it was found that gamma-ray induced protons or neutrons (alpha on rare occasions) had a typical kinetic energy of nearly 10 MeV. Then, such a proton (or alpha) deposits via ionization loss an amount of a hundred keV or higher energies in a ^{3}He counter, while the gamma-ray induced neutron mainly causes an elastic scattering with ^{3}He nucleus to produce a large energy deposit of >1 MeV. Changing a cathode material of stainless steel to Al, we found that gamma-ray detection efficiency for Al was the same with the derived values (Fig. 3), within statistical uncertainty.

[1] The total cross-section can be seen at e.g. http://wwwndc.jaea.go.jp/j40fig/jpeg/he003_f1.jpg.