Reconstruction of high energy thunderstorm radiation effects on soil matrix using Monte Carlo simulations

Yuliia Ruban[1,2], *Ondrej* Ploc[1], *Jakub.* Šlegl[1,3] *David.* Chvátil[1], *Ivo* Světlík[1], *Lenka* Tomášková[1], and *Lembit* Sihver[1,4]

[1]Nuclear Physics Institute of the Czech Academy of Science, Czech Republic
[2]Institute of Safety Problems of Nuclear Power Plants of the National Academy of Science, Ukraine
[3]Czech Technical University in Prague, Czech Republic
[4]Technische Universität Wien, Atominstitut, Vienna, Austria

Abstract. Due to their electromagnetic properties, thunderclouds can act as natural particle accelerators. Electrons accelerated in the thunderclouds can reach energies up to tens of MeV. Large populations of high energetic electrons formed by avalanche growth driven by electric fields in the Earth atmosphere called Relativistic Runaway Electron Avalanches (RREA) propagate through matter. They are decelerated and deflected in the course of collisions with particles in the atmosphere and emit gamma rays known as bremsstrahlung. The produced gamma rays can further trigger photonuclear reactions in the air and soil. This article reports on the work of project CRREAT (Research Centre of Cosmic Rays and Radiation Events in the Atmosphere), studying various lightning-related phenomena in various ways, both *in situ* and in the laboratory. This paper focuses on the simulation of the laboratory experiments at the Microtron accelerator in Prague and the neutron generator in Ostrava, where we irradiated various soil samples with 20 MeV electron beams. Experiments showed which radionuclides can be formed during the reactions of high-energy electrons with various soils and can be as targeted products in the thunderstorm radiation effect analysis. Radionuclides produced in exposed samples were measured using a high-purity germanium (HPGe) detector. A computer simulation was done with a simple source and sample geometry using the general-purpose 3D Monte Carlo code PHITS.

1 Introduction

In the 20s of the last century, C. Wilson [1] proposed that thunderclouds could be the most significant natural electron accelerators on Earth. Subsequently, observations from satellites, balloons, aircraft, and ground-based facilities have confirmed the occurrence of gamma-ray flashes during thunderstorms worldwide over the last two decades. The electrons accelerated in the thunderclouds can reach energies up to tens of MeV and create several different phenomena: Terrestrial gamma-ray flashes (TGFs), Terrestrial Neutron Flashes (TNFs), Terrestrial Ground Enhancements (TGEs), and Relativistic Runaway Electron Avalanches (RREA). RREAs are large populations of highly energetic electrons formed by avalanche growth driven by electric fields in Earth atmosphere propagating through the air matter and emitting gamma rays known as

bremsstrahlung. The interaction of these gamma rays with nuclei can lead to photonuclear reactions [2,3,4].
Even if the effects of thunderstorm radiation on the atmosphere and other materials have been investigated to some extent [9], understanding the interactions with the Earth soil and its inhabitants needs more detailed consideration as discussed below. Therefore, it is crucial to study the effect of lightning strikes and the increase in gamma background radiation on photonuclear reactions in the soil.
Considering that finding the locations of thunderbolt impact is difficult and that only a limited amount of experimental data may be acquired, simulations are obviously a valuable approach for providing a dose evaluation and possible processes per event. Also, the application of Monte Carlo code, simulations, and calculations help solve the data gap problem using radiation-matter interaction and evaluated nuclear data libraries. Similar approaches are used for the calculation of cosmic radiation particle events on aircraft crew [6,7].
The main objective of this research is to reconstruct and estimate the impact of thunderstorm radiation on the soil and other exposed materials. To achieve this, we measured gamma and neutron-induced reactions produced by electron accelerator and neutron generator (discussed in Section 2.1) to estimate photonuclear reactions occurring in soil components with energies of up to 20 MeV. In addition, a comparative assessment of the impact of RREAs was performed for two penetration depths.

1.1 Theoretical approaches

The theoretical studies were divided into three parts: an assessment within the selected energy range, products that can be formed in exposed material, and computer simulation using the general-purpose Monte Carlo particle transport simulation code PHITS version 3.280 [12]. Initially, an attempt was made to accurately characterize the source term in our simulation based on the available experimental data. According to data obtained from satellites and simulations during a thunderstorm [8], about 10^{18} particles, mainly photons of different energies, are generated. In addition, neutrons are produced during photonuclear reactions [3, 5, 9]. Obtained source parameters were used for computer simulation as described below.
In addition to Monte Carlo simulations, this work focused on which reactions and products occur under thunderstorm radiation. Therefore, for the analysis of possible reactions and products, the Experimental Nuclear Reaction Data (EXFOR) Database Version of 2023-05-31/Evaluated Nuclear Data File (ENDF) Database Version of 2022-10-07 [10] was used.
The computer simulation method tested the effect on small patches of soil using a simple model. A monotonous photon source with an energy of approximately 20 MeV is located at a height of 1 m from the ground, which irradiates the soil with a relative composition and density of 2.1 g/cm^3. The simplified geometry was used, consisting of a 1 m high cylinder. The following simulations estimate three physical observables: dose, fluence, and interactions.

1.2 Experimental approaches

Since lightning in natural conditions differs significantly from the existing laboratory conditions, reproducing the natural conditions is challenging. Therefore, to solve this issue, we reviewed the existing literature concerning the particle flux and energy

density, and this information was analyzed for further reproduction in irradiation experiments. According to available research, a lightning discharge generates about 10^{18} particles per event. In this work, particle accelerators were used to achieve similar parameters.
Based on the obtained data, the possibility of a photonuclear reaction was assessed in soil, sand, and other materials.
Unfortunately, it is not possible to replicate lightning impact conditions in an experiment, due to incomplete knowledge in timing, current, voltage, etc. To reach particle production similar to that of a thunderstorm, it is necessary to irradiate the sample for at least 10 minutes instead of just a couple of milliseconds.

2 Material and methods

To study which radionuclides are generated in soil from thunderstorm radiation, we used the following radiation sources: (1) Microtron MT 25 as a source of electrons and gamma radiation up to 20 MeV, and (2) Neutron generator as a source of 14 MeV neutrons.
To replicate thunderstorm conditions in the laboratory is difficult because of the complex nature of this phenomenon. In nature, electron acceleration by thunderstorms involves a large number of unclear sources and phenomena. Therefore, an experiment was conducted to irradiate soil, wood, and sand samples to study radionuclide production and material activation in conditions similar to those of lightning.

2.1 Samples preparation

Three types of environmental materials were collected: topsoil, sand, and tree (sapwood and cambium cell layer with inner bark). The samples weren't cleaned for measurements to reach artificial conditions for lightning events. In total, six environmental samples were collected.
The background was measured after and before irradiation by a digital Geiger counter Thermo Scientific™. The activation products were detected by HPGe measurement in the laboratory of the Department of Radiation Dosimetry, Nuclear Physics Institute of the Czech Academy of Sciences.

2.2 Neutron generator

The neutron irradiation was performed in Vysoká škola báňská — Technical University of Ostrava, using MP-320 Neutron Generator (NG) produced by Thermo Fisher Scientific Inc. The generator is portable, with a cylindrical shape (diameter of 12 cm, length of 57 cm), and has 14 MeV neutrons from the deuterium-tritium fusion reaction, yielding 10^8 n/s. The NG is located below the ground in the laboratory, shielded by concrete and YTONG blocks.
The HPGe detector (GWD-3023, Baltic Scientific Instruments Inc.) with a relative counting efficiency of about 30% was utilised to measure the neutron-induced delayed γ-ray radioactivity. The detector was positioned inside a massive shielding (Pb – 100 mm; Cu – 8 mm).

2.3 Microtron

The Prague microtron MT25 is a cyclic electron accelerator with a Kapitza resonator. Soil samples were placed into an 80 ml Marinelli beaker and irradiated on an MT 25 microtron. Samples were placed on an aluminium stand 20 cm from the emitter. The electron beam was delivered at 22 MeV with a current ranging from 7 to 10 μA for a duration of 30 minutes. A tungsten plate was installed to generate gamma photons by bremsstrahlung and direct inner-shell ionization by e- impact.
The HPGe detector with relative counting efficiency of about 20% and an energy resolution of 1,9 keV for line 1173 keV (^{60}Co). The detector was positioned inside a massive shielding (Pb – 100 mm; Cu – 1 mm; Cd – 1 mm.) [13, 14]

3 Results and Discussions

As stated above, the goal of this work was to reconstruct the effect based on theoretical observations and experimental data. The irradiation of the samples was aimed at obtaining a list of potential radionuclides that could be formed during exposure to RREA on the material. Simulation using Monte Carlo code was used to evaluate the potential of electron avalanches, the number of interactions and the absorbed energy. The simulations further aimed at comparing and searching for matches in samples exposed to thunderstorm radiation. Measuring the irradiated soil background after 20 minutes showed peaks identified as ^{28}Al, ^{29}Al, ^{24}Na, ^{56}Mn, ^{57}Ni, ^{74}As, ^{122}Sb, ^{46}Sc but their presence disappeared in seconds and hours due to the nature of these isotopes.
Repeated measurements after two weeks showed no excess, but the gamma spectrum showed the presence of activation products. The presence of the following radionuclides was identified in the soil: ^{139}Ce, ^{74}As,^{51}Cr, ^{58}Co,^{65}Zn, ^{22}Na, ^{88}Y.
The identified radionuclides are activation products that are of interest to the presented research. It was trace elements in the soil that showed activation and not the major (Al, Si, Ca, Mg, Na, K, Ti, Fe, Mn, P) ones of the soil.
When conducting similar studies in the future, it could be worth paying attention to the change in the ratio of the presented radionuclides or even rare earth metals. Based on these changes, it will be possible to make a conclusion about the presumed location of the impact.
The track tally information of the PHITS simulation shows that particles penetrate only a few centimetres into the soil (see Fig. 1). An assessment of depth difference showed that even a slight change (of more than 2 cm) increases not only the area but also the probability of the occurrence of photonuclear reactions.

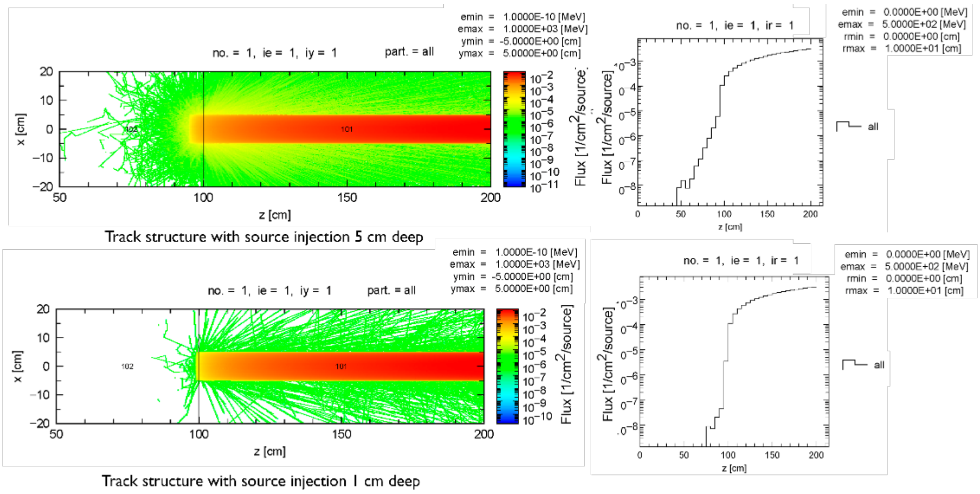

Fig. 1. Track tally information with different source injection

The deposited energy tally shows similar results (see Fig. 2). The main part of energy deposits on the surface part of the soil and terminates at 1-2 cm. However, dose evaluation was observed in depths of over 2 cm as a result of secondary particle production.

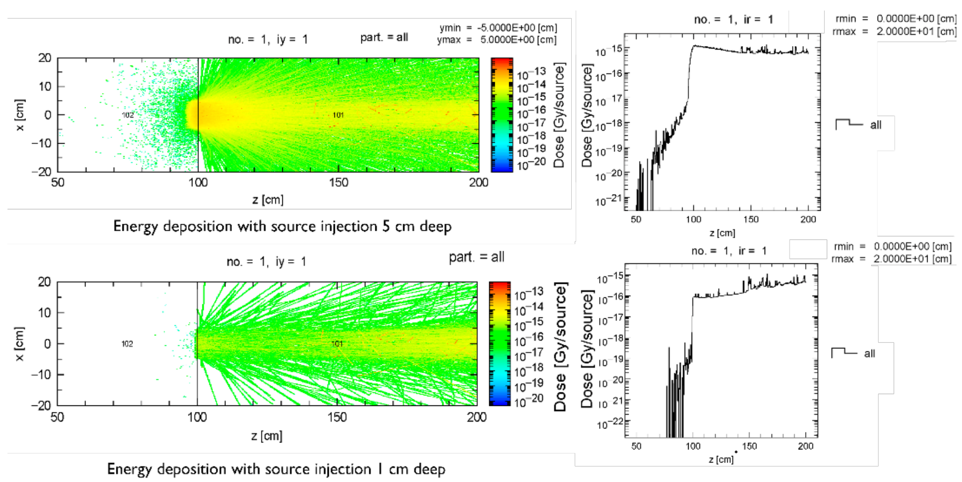

Fig. 2. Deposited energy tally information with different source injection

The interaction tally confirmed information that was discussed before. The data show that a 5 cm source injection increases the amount of interaction and produces more secondary particles.

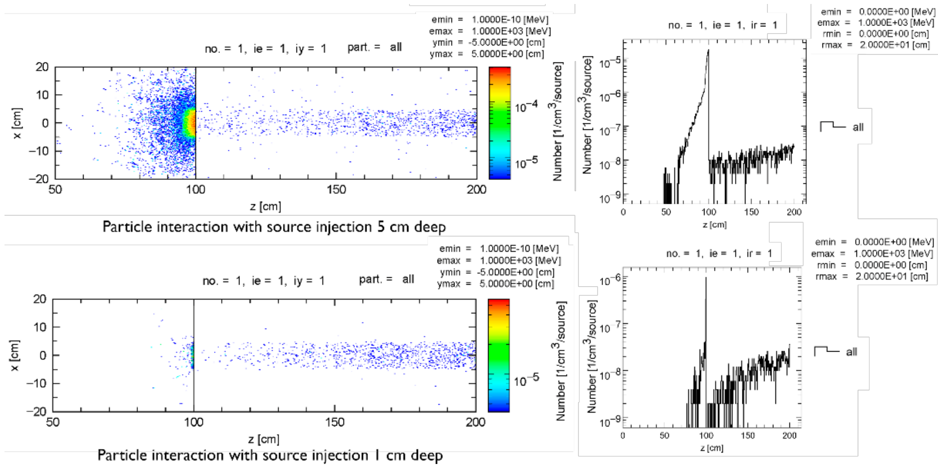

Fig. 3. Particle interaction tally information with different source injection.

4 Conclusion

Experiments with photon irradiation have shown which radionuclides can be formed during the reactions of high-energy electrons with various soils and can be target products and elements in assessing the effects of electron avalanche radiation. Analysing the data of the soil irradiation experiment, radionuclides were identified, which can be targeted in assessing the thunderstorm radiation effects in natural samples. These were ^{39}Ce, ^{74}As,^{51}Cr, ^{58}Co,^{65}Zn, ^{22}Na, ^{88}Y. Additionally, neutron irradiation has shown that only radionuclides that have a life time of more than one day are formed. That makes us conclude the radionuclides mainly formed by gamma photon exposure will be markers. The measured radionuclides can play a role in dose delivered to soil biota and could be used for further research with natural samples.

The Monte Carlo simulation showed dose evaluation in the area of impact; a major part of interactions lies in the first 1cm of soil depth. Also, it has been shown that in case of deeper penetration, the number of nuclear reactions increases, and therefore also the number of radionuclides produced in the soil samples.

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