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Energy distribution of cosmic rays in the Earth's atmosphere and avionic area using Monte Carlo codes

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Abstract. Cosmic rays cause significant damage to the electronic equipments of the aircrafts. In this paper, we have investigated the accumulation of the deposited energy of cosmic rays on the Earth's atmosphere, especially in the aircraft area. In fact, if a high-energy neutron or proton interacts with a nanodevice having only a few atoms, this neutron or proton particle can change the nature of this device and destroy it. Our simulation based on Monte Carlo using Geant4 code shows that the deposited energy of neutron particles ranging between 200 MeV and 5 GeV are strongly concentrated in the region between 10 and 15 km from the sea level which is exactly the avionic area. However, the Bragg peak energy of proton particle is slightly localized above the avionic area.

Keywords. Earth's atmosphere; cosmic rays; avionic area; Geant4.

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1. Introduction

Earth's atmosphere is frequently bombarded by cosmic rays, most of them are solar energetic particles and come from other sources in our galaxy and beyond [1]. We notice here, that F_s, the solar energy flux reaching the Earth's orbit is 1.36×10^3 W m^{-2}, whereas F_{CR}, the cosmic ray energy flux (particles with energy $\geq$0.1 GeV) is 10^{-5} W m^{-2} [2]. In high altitude, cosmic rays have a significant influence on the atmosphere ionization. Devendraa Singh and R P Singh [3] have described some of the atmospheric processes affected by cosmic rays, such as atmospheric electric current, lightning production, cloud and thundercloud formation, etc.

Earth is largely protected from the solar wind by its magnetic field, which deflects most of the charged particles; however, some of the charged particles are trapped in the Van Allen radiation belt. A smaller number of particles from the solar wind manage to travel to the Earth's upper atmosphere and ionosphere in the auroral zones.

The existence of high-energy cosmic ray flux confined to Earth's magnetosphere has been considered in several experimental and theoretical works. Events with >100 MeV protons with intensity above 1 cm^2 s^{-1} were recorded during 1958–2006 [4]. About 95% of the cosmic ray particles has energy in the range 0.1–15 GeV, which contains more than 60% of all cosmic ray particle energy [5,6].

Cosmic rays interact with atoms of the atmosphere and produce secondary particles.

In this paper, we focussed our investigation on the behaviour of solar neutrons and protons in the Earth's atmosphere, specially in the energy interval of 20 MeV–5 GeV because the energy of a majority of solar cosmic rays lies in this range [11,12]. Indeed, these cosmic rays can cause significant damage to the electronic equipments of the aircrafts and spacecrafts [7–10]. Among the cosmic particles, protons and neutrons are the most interesting to study, because of their significant effects on the atoms in an electronic device. In fact, high-energy hadron particles have a very large range and are able to cross throughout the Earth's atmosphere. Therefore, it is interesting to see in which region in the Earth's atmosphere these particles will deposit the maximum of their energy.

2. Method and geometry

2.1 *Materials and geometry*

The atmosphere is assumed to have a spherical shape with a thickness of 150 km. This atmosphere is composed of 37 layers [13]. The chemical composition of the atmospheric air is 75.521% nitrogen, 23.143% oxygen, 1.288% argon and 0.048% carbon (figure 1).

The temperature T, the pressure P and the atmosphere mass density ρ were calculated using the NRLMSISE standard atmosphere model (see figure 2) [13,14]. The Earth's magnetic field varies between 30 and 60 μT depending on the location on Earth [15].

2.2 *Monte Carlo simulations*

Our simulation is based on Monte Carlo codes, Geant4 [16,17]. Geant4 is a software toolkit for the simulation of the passage of particles through matter. It is used in various application domains, including high-energy physics, astrophysics and space science, and medical physics. The simulation of hadronic shower requires simulation of particles interacting over a wide range of energy, from a few TeV down to thermal energies [18]. Physical processes used in this study are given in table 1. Three processes were executed in the simulation. They are the decay model, electro-magnetic physics model and hadronic physics model. Essentially, the standard model is valid in the energy range from 20 MeV to more than 10 TeV [19,20]. As can be seen in table 1, in our simulation, the binary cascade process for protons and neutrons has been taken into consideration. Indeed, binary cascade processes generate the final state for hadron inelastic scattering by simulating the intranuclear cascade (Geant4 Physics Reference Manual). The maximum step size was set to be 1 m by default in the Earth's atmosphere region.

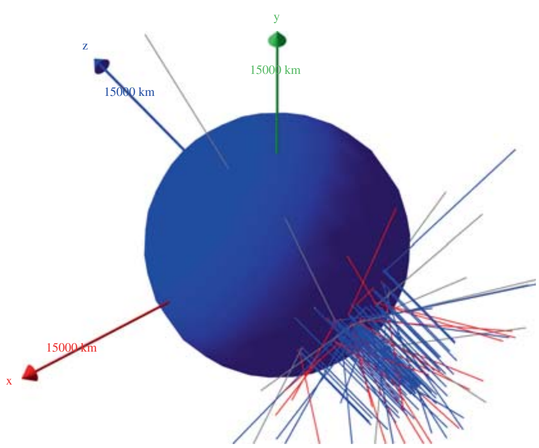


Figure 1. Simulation and geometry of the Earth's atmosphere using Geant4 codes.

3. The spectrum of primary neutron and proton particles

In this paper, based on the geometry cited previously (see figure 1), we carried out a simulation of the interaction of cosmic rays with the Earth's atmosphere, especially neutrons and protons with energy ranging between 200 MeV and 5 GeV. We should mention here that several experimental works show that the majority of cosmic rays have an energy around 2 GeV [5,6]. We plotted in figures 3a and 3b, the energy spectrum of primary neutron and proton in the Earth's atmosphere for different energy fluxes ranging between 200 MeV and 5 GeV. These particles are accumulated in a specific region in the atmosphere called Bragg peak energy. As can be seen, the Bragg peak energy is located in an area between 15 and 10 km for neutron and between 16 and 30 km for proton (see figure 3c). We should notice here, that for neutron energy below 2 GeV, the deposited energy stabilizes around 13 and 14 km

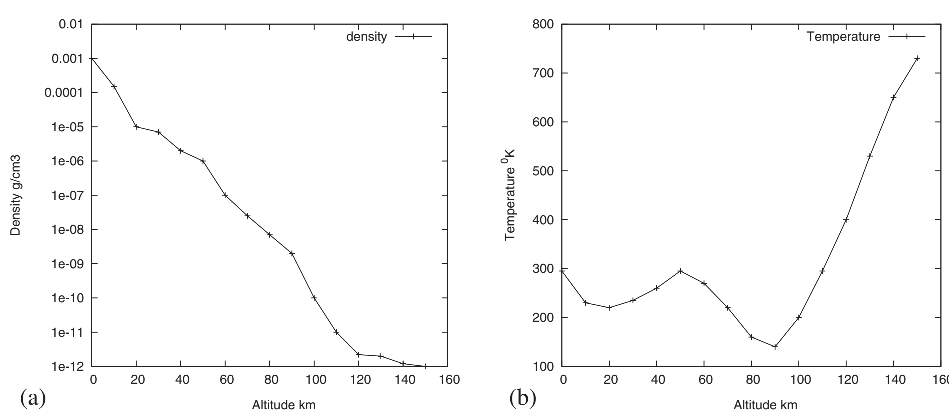
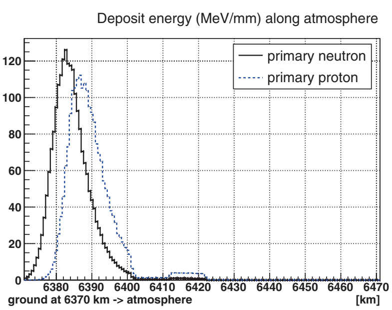


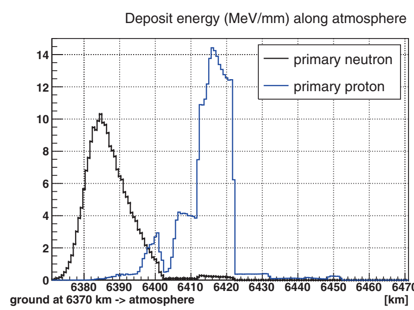
Figure 2. (**a**) Atmosphere mass density and (**b**) temperature using the NRLMSISE standard atmosphere model.

Table 1. Physical processes used in Geant4 code simulation.

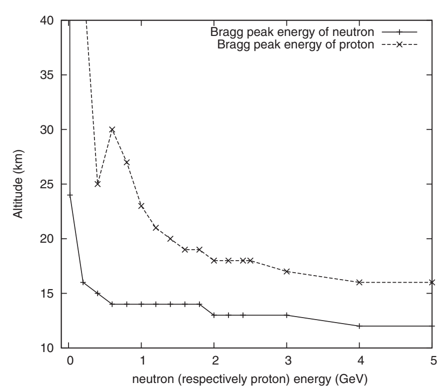
Particles	Physical processes (Standard Model)
Photon processes	Photoelectric effect
	Gamma conversion (also called pair production)
	Compton scattering
	Rayleigh scattering
Electron and positron processes	Ionization and δ-ray production
	Multiple scattering
	Positron annihilation (into two gammas, into two muons, into hadrons)
	Bremsstrahlung
Hadron/ion processes	Binary and Bertini cascade processes (both elastic and inelastic models)
	Binary light cascade process
	Ionization for ions
	Multiple scattering
	Bremsstrahlung
Coulomb scattering processes	All charged particles
Decay model	



(a) 2 GeV



(b) 200 MeV



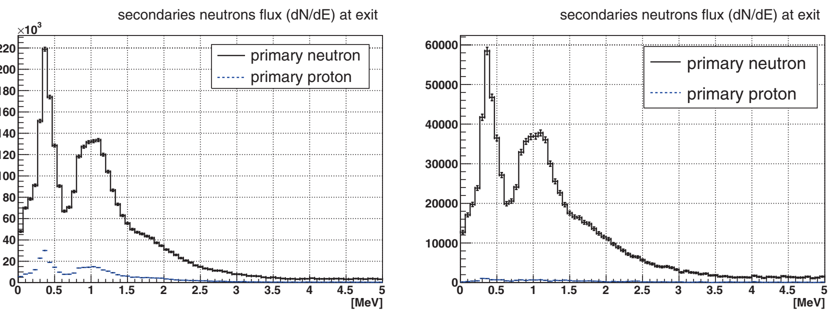
(c) Brag peak energy of both neutron and proton

Figure 3. Plot of the differential deposit energy of protons vs. the depth in the Earth's atmosphere. The Earth's magnetic field is assumed to be $47\mu T$.

from the ground, except for very low energies below 400 MeV. When the neutron energy is above 2 GeV, the Bragg peak slightly shifted around 12 and 13 km from the ground. Neutron energies between 200 MeV and 5 GeV are strongly localized between 12 and 15 km from the ground. However, for protons, our results show that the energy of the Bragg peak is largely located in an area between 16 and 30 km from the Earth's surface.

3.1 *Spectrum of secondary particles*

The energy loss of the ionizing radiation during its travel through the Earth's atmosphere leads to secondary



(a) 2 GeV (b) 200 MeV

Figure 4. Spectrum of secondary neutrons in the atmosphere.

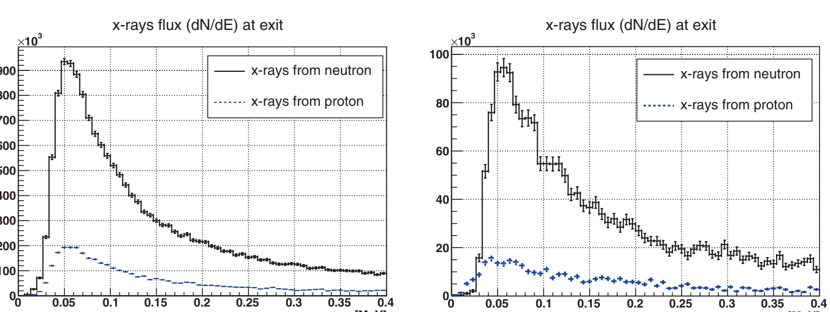
particles formed by the interaction between neutron or proton and atmospheric atoms. These secondary particles can be γ-particles, X-rays, neutrons, protons or others. Most of these secondary particles are formed at the Bragg peak region.

3.1.1 *Spectrum of secondary neutron particles*. The energy spectrum for the secondary neutrons is shown in figure 4. In this figure, the existence of two energy peaks around 0.5 and 1 MeV is observed. Also, the energies corresponding to these two peaks are the same for both protons and neutrons. Majority of secondary neutrons are produced from primary neutrons. We should mention here, that these two energies are not high enough to cause damage to aircraft devices.

3.1.2 *Yield of X-rays from neutron and proton*. X-rays are produced from charged particles such as electrons and positrons formed in the Earth's atmosphere, especially in the area corresponding to the Bragg peak. The spectrum energy of X-rays produced from primary neutron and primary proton are represented in figure 5. Both figures (figures 5a and 5b) show the existence of an energy peak around 50 keV. Generally, X-rays of 50 keV energy is not high enough to cause direct damage to aircraft devices.

4. Results and discussion

Cosmic rays penetrate the Earth's atmosphere and may affect electronic devices, especially in aircrafts flying above 10 km. In fact, electronic devices may behave strangely under the influence. Nowadays, electronic devises are made using nanotechnology. A small number of high-energy particles may damage these sensitive electronic devices, and cause serious problems to an airplane. The most important thing is to know where this cosmic high-energy particle can be localized in the Earth's atmosphere. The first step of our simulation is to study the deposited energy of cosmic rays on the Earth's atmosphere. Indeed, for particle energies ranging between 200 MeV and 5 GeV, we have plotted the deposited energy of cosmic ray particles, especially solar neutrons and protons, across the Earth's atmosphere. We found that the solar neutrons deposit most of their energy in a very narrow area, exactly between 12 and 14 km from the sea level which corresponds to the avionic area. But, solar protons are populated in a wider region between 30 and 16 km altitude from the sea level. Moreover, we study the energetic spectrum of secondary particles formed in the Earth's atmosphere from the solar particles colliding with the atmospheric atoms. Our results show that



(a) 2 GeV (b) 200 MeV

Figure 5. Yield of X-rays from neutron and proton in the atmosphere.

secondary particles can be neutrons, protons and X-rays with low energy that cannot cause significant damage to an electronic device.

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