Numerical calculations of cosmic ray cascade in the Earth’s atmosphere using different particle interaction models

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Abstract. The interaction of primary cosmic rays with the Earth’s atmosphere is investigated using the simulation toolkit GEANT4. Two reference lists of physical processes – QGSP_BIC_HP and FTFP_BERT_HP – are used in the simulations of cosmic ray cascade in the atmosphere. The cosmic ray neutron fluxes are calculated for mean level of solar activity, high geomagnetic latitudes and sea level. The calculated fluxes are compared with the published results of other analogous simulations and with experimental data.

1. Introduction
The Earth’s atmosphere is permanently bombarded by energetic particles of cosmic rays. The cosmic ray particles interact by electromagnetic and nuclear processes with the atoms of the Earth’s atmosphere and produce secondary particles. Some of the particles produced in the cascade can reach the Earth’s surface and induce nuclear reactions there. It is essential to know the temporal and spatial variation of cosmic ray particle fluxes in the atmosphere for many geophysical and engineering problems such as production of cosmogenic nuclides, radiation dosimetry and single event upsets in the microelectronics.

To quantify the effect of cosmic rays on the Earth’s environment it is important to know precisely the flux of cosmic ray shower particles in function of position, atmospheric depth, and time. A number of studies have been devoted to the calculation of cosmic ray particle spectra in the atmosphere [1-5]. A common approach to the treatment of atmospheric particle cascade is the Monte Carlo calculations. In this method, the trajectories of all the particles in the cascade are simulated until they are absorbed by nuclei, stopped or escape from the atmosphere. Monte Carlo calculations are needed to account accurately for decay and energy loss processes, and for the energy dependence of the cross sections. Several simulation codes such as CORSIKA, PHARMA, FLUKA and GEANT4, were developed or used for the calculation of particle fluxes in the atmosphere [1, 2, 6, 7]. The simulation codes give an opportunity to employ different particle interaction models and cross sections in the simulations. The simulation toolkit GEANT4 was used in the numerical calculations of cosmic ray cascade in the Ref. [3]. The interaction models and cross sections were chosen in the code in the Ref. [3] to match available experimental data on particle fluxes. The aim of this study is to do simulations using the same model of the atmosphere and the ground as in the Ref. [3] but with different list of particle interaction models and cross sections.

2. The calculational model
Particle fluxes in matter were calculated using simulation toolkit Geant4 version 10.0 [7]. The model of the target (the Earth’s atmosphere and the ground), the energy and type of incident particles and
particle interaction models are set by special commands in the code. A detailed description of the physical model and calculation of particle fluxes is given in the Ref. [3]. Here, a brief overview is given.

2.1. The simulation of particle interactions

Two reference lists of physical processes were used in the calculations – QGSP_BIC_HP and FTFP_BERT_HP – that differ in description of hadron-nucleus interactions [8]. In the FTFP_BERT_HP list, the fritiof precompound model is employed for describing inelastic scattering of hadrons and mesons with nuclei at high energies \( > 4 \text{ GeV} \), and the Bertini intranuclear cascade model is employed at energies below this energy limit. In the QGSP_BIC_HP list, the quark-gluon string precompound model is used to describe inelastic scattering of nucleons and mesons with nuclei at high energies, the binary cascade is used for describing nucleon-nucleus interactions at medium energies. High precision neutron models are used for simulating neutron-nucleus interactions at neutron energies below 20 MeV in both physics lists. These models are based on the G4NDL data library that comes largely from the ENDF-B VII and JENDL libraries.

The list of physical processes used in the numerical calculations in the Ref. [3] was similar to the FTFP_BERT_HP reference list, but the JENDL/HE cross section data were employed in the simulation of neutron-nucleus interactions at neutron energies \( > 20 \text{ MeV} \).

2.2. Model of the Earth’s atmosphere and surface

The Earth was modelled as a sphere of a radius of 6371 km. The elemental composition of the surface was assumed to be an average composition of the upper continental crust – in weight percents, 48.3% O, 31.1% Si, 8.2% Al, 3.6% Fe, 2.6% Ca, 2.4% Na, 2.3% K, 1.5% Mg [9]. The surface density was taken to be 2.65 g/cm\(^2\). The atmosphere was considered as a spherical shell of 100 km thickness. The chemical composition of the air (by mass) is nitrogen 75.5%, oxygen 23.2% and argon 1.3%. The total thickness of the atmosphere was taken to be equal to the atmospheric depth of 1034 g/cm\(^2\) at sea level. The atmosphere was divided into concentric subshells with a thickness of 15 g/cm\(^2\) and constant air density within one subshell. Additional division was done near air-ground interface. The dependences of air density and temperature on altitude were taken from the COSPAR reference atmosphere data CIRA-86 (http://ccmc.gsfc.nasa.gov/modelweb/atmos/cospar1.html). The data were averaged over the latitude.

2.3. Calculation of particle fluxes

The energy range of the spectrum of primary particles was split into intervals. The number of energy intervals was taken to be 16 in the energy ranges 1–10, 10–10\(^2\) GeV/nucleon and was taken to be 8 in the energy ranges 0.1–1, 10\(^3\)–10\(^4\), 10\(^3\)–10\(^4\) GeV/nucleon. Within each interval the primary energy was sampled at random for energies up to 10 GeV/nucleon and was sampled according to power spectrum with the exponent -2.7 for higher energies. The primary particle distribution over the nadir angle \( \theta \) was adopted to be proportional to \( \cos \theta \sin \theta \) with the nadir angle being sampled in the range 0–90°. The simulation of particle cascade in matter initiated by the primary particle of a given type was performed with results being stored separately for each energy interval of the primary. Thus, the yield functions of secondary particle fluxes corresponding to the primary of a given type and energy were computed. We considered two most abundant species of galactic cosmic rays – protons and \( \alpha \)-particles. We considered primary particles with energies up to 10 TeV for protons and up to 3 TeV/nucleon for \( \alpha \)-particles.

The contribution of all \( Z > 2 \) nuclei to particle cascade in matter was determined by applying a scaling factor \( f \) to the results, obtained for \( \alpha \)-particles. This scaling factor is the ratio of nucleon number densities of all \( Z > 2 \) nuclei to \( \alpha \)-particles in the galactic cosmic rays. The value of \( f = 1.4 \) was used [3].

The total number of primary particles for which the cascade simulations were performed is about 7 million for protons and 2 million for \( \alpha \)-particles. Simulations were performed on the supercomputer at
2.4. The spectra of primary cosmic rays near the Earth’s orbit

Primary cosmic rays at energies above several hundred MeV per nucleon are mostly of galactic origin, about 90% of particles being protons and 10% helium nuclei. The particle fraction of heavier nuclei does not exceed 1%. At energies below few GeV per nucleon the flux of galactic cosmic rays in space at the Earth’s orbit significantly depends on the level of solar activity. In the force field model the level of the solar modulation of particle spectra is described by the modulation potential, which characterizes the energy losses of cosmic rays in the heliosphere. The differential energy spectrum of cosmic ray nuclei of type \(i\) in the force field approximation is given by [10]:

\[
J_{\text{diff}}(E) = J_{\text{LIS},i}(E + \Phi_i) \frac{E(E + 2m_p c^2)}{(E + \Phi_i)(E + \Phi_i + 2m_p c^2)},
\]

where \(J_{\text{LIS},i}(E)\) gives the local interstellar spectrum of nuclei \(i\), \(E\) is nucleus kinetic energy per nucleon, \(m_p c^2\) is proton’s rest-mass energy, \(\Phi_i = (eZ_i/A_i)\varphi\), \(Z_i\) and \(A_i\) are nucleus charge and mass numbers, respectively, \(e\) is the elementary charge, and \(\varphi\) is the modulation potential which is related to solar activity. We took the parameterization of the local interstellar spectrum from the Ref. [11]:

\[
J_{\text{LIS},i}(E) = C_i \frac{p(E)^{-2.78}}{1 + 0.487 p(E)^{-2.51}}, \quad p(E) = \bigg[ E \bigg( E + 2m_p c^2 \bigg) \bigg]^{3/2},
\]

where \(E\) is expressed in GeV per nucleon, \(C_i\) is the normalization factor; \(C_p = 1.9 \times 10^4\) (m\(^2\) s sr GeV\(^{-1}\)) for protons, and \(C_{He} = 9.5 \times 10^2\) (m\(^2\) s sr GeV/nucleon\(^{-1}\)) for helium nuclei. The value of modulation potential of 0.65 GV was adopted in this study as an average value for the present epoch [11]. The power functions for the primary particle spectra were employed for energies higher than 100 GeV. The parameters of the spectra approximation for protons and helium nuclei were taken according to the results of ATIC2 experiment [12]. The calculated yield functions of secondary particle fluxes were convoluted with a given energy spectrum of the primary cosmic rays.

The geomagnetic field inhibits low energy charged primaries from penetrating the atmosphere for equatorial and mid-latitude positions. The cosmic ray fluxes in the atmosphere are unaffected by the geomagnetic field at high geomagnetic latitudes \(\lambda > 60^\circ\) [4].

3. Results and discussion

Figure 1 shows calculated neutron angle-integrated differential fluxes at the atmosphere-ground interface at sea level at high geomagnetic latitudes. The modulation potential value of 0.65 GV was taken in the calculations. For comparison, we present the calculated and measured neutron angle-integrated differential fluxes from the Refs. [2, 3, 13]. The data from the Ref. [2] are the results of Monte Carlo simulations using the PHITS code coupled with the nuclear data library JENDL/HE. The spectrum was calculated for semi-infinite atmosphere without considering air-ground interface. The data from the Ref. [3] are the results of numerical calculations using the simulation toolkit GEANT4. The atmosphere and the ground models in the Ref. [3] were the same as in the present calculations but the different particle interaction models and cross sections were used. The data from the Ref. [13] are the results of neutron spectrum measurements scaled to sea level high geomagnetic latitudes and mean level of solar modulation.

The high energy neutrons are the main carrier of the nuclear cascade and come predominantly from vertical direction [3]. At high neutron energies, there is disagreement between the neutron differential fluxes calculated in this work and the flux calculated in the Ref. [3] despite the fact, that the GEANT4...
code system was used in both simulations. The discrepancy in the spectra may be suggested as arising from different particle interaction models and cross section data used in the simulations. In particular, the JENDL/HE cross section data were used in the Ref. [3] that can be the main reason of disagreement between calculated fluxes. The discrepancy between the simulation data reaches the factor 2 and is much larger than the estimated error of neutron flux measurements using the neutron monitors – about 15% at energies above 150 MeV and lower at lower neutron energies [13]. There is a good agreement between calculated neutron fluxes from the Refs. [2, 3] and neutron spectrum measurements [13] at high neutron energies E > 10 MeV.

Through elastic and inelastic scattering the neutron energy is reduced and, after many collisions neutrons thermalize to energies corresponding to the ambient gas temperature. A significant fraction of high energy neutrons reaches epithermal and thermal energies [14]. The fluxes of low energy neutrons E < 1 MeV are isotropic [3]. The differences between calculated low energy neutron spectra in this work and in the Ref. [3] can be attributed to the difference between calculated high energy neutron fluxes.

Ground level low energy neutron flux depends strongly on the landscape geometry and the chemical composition of the ground [5]. The cross sections of scattering and capture of low energy neutrons differ substantially for different chemical elements. The different models of the atmosphere-ground interface were considered in the Refs. [2, 3], that can be the reason of discrepancy between calculated fluxes at low neutron energies.

![Figure 1](image.png)

**Figure 1.** The neutron angle-integrated differential flux in the atmosphere. The neutron flux values multiplied by neutron energy are plotted in the vertical axis with a logarithmic scale on the horizontal axis.
4. Conclusions
The cosmic ray particle cascade in the atmosphere was calculated using the GEANT4 simulation toolkit. Different particle interaction models and cross sections were used. A comparison is made between calculated neutron fluxes in this work and published results of analogous simulations. The results strongly depend on particle interaction models used in the simulations. The discrepancy between neutron fluxes calculated using the different physical models is much larger than the estimated error of neutron monitor measurements.

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