The influence of low energy hadron interaction models in CORSIKA code on atmospheric ionization due to heavy nuclei

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Abstract. The largest uncertainties in a numerical simulation of cosmic ray induced atmospheric cascade are due to hadron interaction models. The influence of low energy hadron interaction models in CORSIKA code on longitudinal cascade development is important. It results longitudinal cascade development, respectively energy deposit and atmospheric ionization by secondary particles. In this work are presented simulations with CORSIKA 6.990 code using GHEISHA 2000, FLUKA 2011 and QGSJET II hadron generators. The energy deposit in the atmosphere by various nuclei, namely Helium, Oxygen and Iron is calculated. The ion pair production in the atmosphere and the impact of the different shower components, precisely the electromagnetic, muon and hadron is estimated according the used hadron generators. The yield function Y for total ionization is compared for various cases. The observed differences and applications are discussed.

1. Introduction
The planet Earth is constantly bombarded by high energy particles, most of them being protons. The galactic cosmic ray (GCR) are the main ionization source in the troposphere [1, 2]. The detailed study of ion production in the ionosphere and atmosphere is important, because it is related to various atmospheric processes. The cosmic ray induced electron-ion production rate could be estimated from the particle flux using the basic physics of ionization in air, an appropriate atmospheric model and realistic description of cascade process in the atmosphere [3, 4]. While the contribution of proton nuclei in a recent modelling of cosmic ray induced ionization is highlighted, the Helium, Light, Middle, Heavy and Very Heavy nuclei are also important. The largest uncertainties in a numerical simulation of atmospheric cascades are due to the assumed models for hadron interactions. Therefore the influence of low energy hadron interaction models in CORSIKA code on the energy deposit, respectively atmospheric ionization is very important to study.
2. Model and simulations
The estimation of cosmic ray induced ionization is carried out with full Monte Carlo simulation of the atmospheric cascade according Oulu model [5] on the basis of ionization yield function formalism $Y$:

$$Y(x, E) = \frac{\Delta E(x, E) \Omega}{\Delta x E_{\text{ion}}}$$  

where $\Delta E$ is the deposited energy in a atmospheric layer $\Delta x$, $\Omega$ is the geometry factor - a solid angle, $x$ in $g/cm^2$ is a residual atmospheric depth i.e. the amount of air overburden and $E_{\text{ion}} = 35$ eV is the ionization potential in air [1].

Hence the atmospheric ionization is obtained on the basis of equation (2) following the procedure [4, 6]

$$Q(x, \lambda_m) = \int_E^{\infty} D(E) Y(E, x) \rho(x) dE$$

where $D(E)$ is the differential cosmic ray spectrum for a given component of primary cosmic ray, $Y$ is the ionization yield function defined according to (1), $\rho$ is the atmospheric density, $\lambda_m$ is the geomagnetic latitude, $E$ is the initial energy of the incoming primary nuclei on the top of the atmosphere. The geomagnetic latitude $\lambda_m$ is related to the integration (above $E$).

In this study the evolution of atmospheric cascade is carried out with CORSIKA 6.990 code [7] with corresponding hadron generators FLUKA 2011 [8] or GHEISHA 2000 [9] for low energy hadron interactions (below 80 GeV/nucleon), respectively QGSJET II [10] above 80 GeV/nucleon. It is known that GEANT-GHEISHA suffers from deficiencies in handling the reaction kinematics properly. GHEISHA and FLUKA predict different momentum distributions of secondary $\pi$ mesons, which results on secondary particle distribution, energy deposition and atmospheric ionization.

In this connection atmospheric cascades induced by various nuclei are simulated. A pre-selection of the events (only events with large multiplicity are considered for analysis) is performed. This allows to reduce the shower to shower fluctuations and obtain flatter distributions for final analysis. During the simulations an isotropic flux of primary particles is assumed with realistic curved atmospheric model. The energy of the primary nuclei is 1 GeV/nucleon, 10 GeV/nucleon, 100 GeV/nucleon and 1 TeV/nucleon. The results are presented in figure 1 (Helium nuclei), figure 2 (Oxygen nuclei) and figure 3 (Iron nuclei).

3. Summary and discussion
As was recently demonstrated [11, 12] a difference on ionization capacity estimated with FLUKA and GHEISHA is observed, specifically in the region of a Pfotzer maximum. In general, this difference is significant in the low energy region and diminish with increasing the energy of the incident nuclei. The difference is small in the upper atmosphere and increase below some 11 km above sea level (a. s. l) for 1 GeV/nucleon Helium induced cascade (figure 1A). The difference is due the to equal contribution of all components (electromagnetic EM, hadron HA and muon MU). When the energy of the primary Helium nuclei is 10 GeV/nucleon (figure 1B) a significant difference in the region of the Pfotzer maximum is observed, which disappears below 11.5 km. It is due mainly to EM component. When the energy of the primary Helium nuclei is 100 GeV/nucleon (figure 1C) and 1 TeV/nucleon (figure 1D) a small difference is observed only in the region of a Pfotzer maximum. It is due to the muon component contribution. While the contribution of muon component to the total ionization in this energy region is not significant [5, 13], we observe smaller difference between various hadron generators.

Similar results are obtained for Oxygen nuclei. The difference is significant below 11 km, in the case of 1 GeV/nucleon (figure 2A). In this case all components differ. In the case of 10
Figure 1. Ionization yield function for primary Helium nuclei obtained with FLUKA/GHEISHA hadron generators.

Figure 2. Ionization yield function for primary Oxygen nuclei obtained with FLUKA/GHEISHA hadron generators.

GeV/nucleon Oxygen nuclei significant difference is observed for all components (figure 2B) in a whole atmosphere. The difference in the case of 100 GeV/nucleon (figure 2C) and 1 TeV/nucleon (figure 2D) is observed only for muon component. The contribution of muon component to the total ionization in this case is not significant, the impact on total ion rate is not important.

In the case of 1 GeV/nucleon Iron nuclei induced cascade, the ionization capacity is different at altitudes below 11.5 km (figure 3A) with contribution of all components. The difference increases as an inverse function of altitude, as in a previous case. Contrary to the previous case, for 10 GeV/nucleon a significant difference of ionization yield function is observed at the upper atmosphere and in the region of a Pfotzer maximum (figure 3B), which is due to hadron and muon component. In the case of 100 GeV/nucleon (figure 3C) and 1 TeV/nucleon (figure 3D) for Iron induced cascade, a small difference is observed only in the region of the Pfotzer maximum. In this case the muon component differ with not significant contribution to the total ionization.

In all cases, the ion pairs produced using FLUKA 2006b as hadron generator, are greater
Figure 3. Ionization yield function for primary Iron nuclei obtained with FLUKA/GHEISHA hadron generators

then those produced by GHEISHA 2000. The obtained results are important for recent studies of cosmic ray induced ionization. While the significant difference is observed in the energy range 1 GeV/nucleon-10 GeV/nucleon, we have to pay attention on the used hadron generator for analysis of solar energetic particles events such as GLE69 on 20 January 2005 [14, 15, 16], specifically considering Helium and heavy nuclei contribution [17].

References
[1] Velinov P I Y, Nestorov G and Dorman L 1974 Cosmic Ray Influence on the Ionosphere and on the Radio-Wave Propagation (Bulgarian Academy of Sciences Publ. House, Sofia)
[2] Usoskin I G, Desorgher L, Velinov P, Storini M, Flueckiger E O, Buetikofer R and Kovaltsov G A 2009 Acta Geophys. B 57 88
[3] Usoskin I G, Gladysheva O G and Kovaltsov G A 2004 J. Atm. Solar-Terr. Phys. 66 1791
[4] Mishev A and Velinov P I Y 2007 Comptes Rendus de l’Academie Bulgare des Sciences 60 225
[5] Usoskin I and Kovaltsov G 2006 Journal of Geophysical Research 111 D21206
[6] Velinov P I Y, Mishev A and Mateev L 2009 Advances in Space Research 44 1002
[7] Heck D, Knapp J, Capdevielle J N, Schatz G and Thow T. 1998 CORSIKA: A Monte Carlo code to simulate extensive air showers Report FZKA 6019, Institut für Kernphysik Forschungszentrum und Universität Karlsruhe
[8] Battistoni G, Muraro S., Sala P, Cerutti F , Ferrari A, Roesler S, Fasso A and Ranft J 2007 Proc. of the Hadronic Shower Simulation Workshop 2006,Fermilab 6-8 September 2006, M. Albrow, R. Raja eds. AIP Conference Proceeding 896 31
[9] Fesefeldt H C 1985 GHEISHA program Report PITHA 85-02, Physikalisches Institut, RWTH Aachen Physikzentrum
[10] Ostapchuenko S 2006 Nuclear Physics B Proc. Suppl. 151 143
[11] Mishev A and Velinov P I Y 2007 Comptes Rendus de l’Academie Bulgare des Sciences 60 511
[12] Mishev A and Velinov P I Y 2010 Journal of Atmospheric and Solar-Terrestrial Physics 72 476
[13] Mishev A and Velinov P I Y 2007 Comptes Rendus de l’Academie Bulgare des Sciences 60 725
[14] Mishev A, Velinov P I Y and Mateev L. 2010 Comptes Rendus de l’Academie Bulgare des Sciences 63 1635
[15] Usoskin I, Kovaltsov G, Mironova I, Tyulk A and Dietrich W 2011 Atmos. Chem. Phys. 11 1979
[16] Mishev A, Velinov P I Y, Mateev L and Tassev Y 2011 Advances in Space Research 48 1232
[17] Mishev A and Velinov P I Y 2012 Comptes Rendus de l’Academie Bulgare des Sciences 65 373