The impact of low energy hadron interaction models in CORSIKA code on cosmic ray induced ionization simulation in the Earth atmosphere

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***Abstract*. In this work are presented simulations with CORSIKA 6.52 code using GHEISHA, FLUKA 2006 and QGSJET II hadronic interaction subroutines. The energy deposit of proton induced air showers is calculated. The ion pair production in the atmosphere and the impact of the different shower components, precisely the electromagnetic, muon and hadronic is estimated according the used different hadronic interaction models. The yield function Y for total ionization, respectively for the different components is compared. The observed differences are discussed. The obtained ionization rates are compared with experimental results.**

***Keywords*: cosmic rays, ionization model, hadronic models**

I. Introduction

Presently the nature of primary cosmic ray radiation is clarified. The Earth is hit by elementary particles and atomic nuclei of very large energies and in wide energy range. The majority of these particles are protons, especially in low energy region. The primary cosmic rays extend over twelve decades of energy with the corresponding decline in the intensity. The flux goes down from 10^4 m^{-2} s^{-1} at energies 10^9 eV to 10^{-2} km^{-2} yr^{-1} at energies 10^{20} eV.

When a particle from primary cosmic ray flux penetrates the Earth's atmosphere the results is cascade process in the atmosphere. The cascade consists of billions of secondary particles, the majority electrons and muons. They arrive at ground level over large areas of several square kilometers. The predominant interactions are electromagnetic.

The cross sections for the production of hadron and muon pairs are several orders of magnitude smaller than that for electron-pair production. In the electromagnetic shower, protons produce electron-positron pairs, and electrons and positrons produce photons via Bremsstrahlung (stopping radiation). Generally in such type of cascade process only a small fraction of the initial primary particle energy can reach the ground (observation level) as high energy secondary particles. In fact the most of the primary energy is released in the atmosphere by ionization and excitation of the air molecules. In fact the cosmic rays are the dominant source of ionization of the troposphere.

In this connection the study of cosmic ray induced ionization is very important, because it is possibly connected with cloud formation [1], [2] and atmospheric chemistry [3]. Thus a recent model for cosmic ray induced ionization is necessary for investigation of similar problems. One possible tool is based on Monte Carlo simulations of the cascade process in the atmosphere, precisely the energy deposit and afterwards the estimation of ion pair production.

Cosmic Ray Simulations for KASKADE (CORSIKA) code [4]is one of the most widely used in the last years atmospheric cascade simulation tool in cosmic ray and astroparticle physics. This is a Monte Carlo program for detailed study of EAS evolution and properties in the atmosphere. The code simulates the interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to extreme energies. The result of the simulations is detailed information about the type, energy, direction, location and arrival time of the produced secondary particles at given selected observation level. Moreover it exist possibility to obtain the energy deposit by different shower components and particles at given observation levels.

Therefore it is possible to follow the evolution of cascade processes induced by different primaries in the atmosphere. In then general case the largest uncertainties in numerical simulation of EAS with primary energies above some TeV are due to assumed models for hadronic interactions. Obviously an extrapolation to the highest energies is necessary, when the collision energies exceed those attainable with accelerators experiments. In the case when the kinematic ranges are not accessible with collider experiments one has to rely on theoretical guidelines and assumptions to describe the interactions. As a result the essential uncertainties are related with those interaction products emitted at small angles into the extreme forward direction carrying away the largest energy fraction.

In collider experiments those particles disappear in the beam pipe without being observable. Contrarily, during the development of EAS such particles are responsible for transporting the energy down into the atmosphere. The dependence of EAS simulations on high-energy hadronic interaction models is widely discussed in [7], [8]. In this work we compare the influence of low energy hadronic interaction models in CORSIKA code on the energy deposit, respectively ionization yield function Y including the contribution of the different shower components.

II. Model and simulations

The cosmic ray induced ionization could be estimated using the Oulu model formalism [5] on the basis of ionization yield function Y (1).

$$Y(x,E) = \triangle E(x,E)\Omega/\triangle x E_{ion} \quad (1)$$

where $\triangle E$ is the deposited energy in a atmospheric layer $\triangle x$, Ω is the geometry factor integration over solid angle and E_{ion}=35 eV is the ionization potential [6].The atmospheric ionization is obtained on the basis of equation (2)

$$q(x,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(E,x)\rho(x)dE \quad (2)$$

where D(E) is the differential CR spectrum, Y defined according (1) and ρ is the atmospheric density. The recent version CORSIKA 6.52 code [4] with corresponding hadronic interaction models FLUKA 2006 [9] and QGSJET II [10] is used for the simulations. The FLUKA 2006 is used for simulation of hadronic interactions below 80 GeV/nucleon and QGSJET II for hadronic interactions above 80 GeV/nucleon, respectively. Additionally simulations with GHEISHA 2002 [11] hadronic model (hadronic interactions below 80 GeV/nucleon) are carried out, aiming comparison between different generators. Usually the hadronic event generator FLUKA 2006 is used only for the description of inelastic interactions below energy of several 100 GeV [12].

Within FLUKA 2006 these collisions are handled by different hadronic interaction models above, around and below the nuclear resonance energy range. We simulate 5000 events (proton nuclei) per energy point and per spectrum.

First we compare the ionization yield function Y (1) for proton incoming showers in wide energy range between 1 GeV and 1 TeV kinetic energy of the primary particle.

The standard version of the CORSIKA code is designed for simulations of EAS with practically vertical incidence. In the energy range around the "knee" and for EAS with very inclined zenith angle (more than 60 degrees) the majority of the shower particles are absorbed in the atmosphere. Generally the longitudinal shower development can be followed by CORSIKA in vertical bins by counting all particles crossing horizontal layers (particle distribution) and summing the deposited energy between two consecutive horizontal layers. In fact at the beginning the layer altitude table is established according to the equal increment in mass overlay. For each particle track the starting and ending altitudes are compared with the height of the vertical binning and for all passed layers the corresponding particle numbers are incremented. The energy deposited between the layers is added up in the energy deposit tables.

In the SLANT option these horizontal layers are replaced by skew planes perpendicular to the shower axis and arranged in a spacing, which corresponds to a regular increment in the penetrated atmospheric mass thickness along the shower axis. Each time a shower particle crosses such a skew plane it is counted for the longitudinal particle distribution, and the energy deposited between two adjacent skew planes is added up to obtain the longitudinal energy deposit distribution. As a result the calculation of the energy deposit is more precise comparing to the standard option. During the simulations the SLANT version of the code is used with realistic curved atmospheric model according the Standard US Atmosphere . This permits to simulate precisely the longitudinal development of the shower and thus cosmic ray induced ionization in the atmosphere.

III. Results and Discussion

In the past mostly GHEISHA routines have been used for simulations of EAS and the detector response of the majority of the experiments in preparation. However is known [13] that GEANT-GHEISHA suffers from deficiencies in handling the reaction kinematics properly.

For example, in EAS simulations using GHEISHA the sum of the energy of the secondary particles and the deposited energy is often larger than the primary energy by several percents. This depens on the primary energy and the low-energy threshold (typically 300 MeV) above which, hadronic particles are followed. In fact GHEISHA and FLUKA predict different momentum distributions of secondary $\pi - mesons$. Therefore spectra of muons with E_{lab} less than 30 GeV, which result mainly from the decay of pions produced in low-energy interactions, depend on the used low-energy model. The largest differences are observed between the energy spectra amount to 15 percent at E_μ about 0.8 GeV and they are clearly correlated with the differences in the predicted distributions of mesons.

Another difference of 10 percent is observed at E_μ about to 10 GeV, probably related to the distribution of charged pions in pion atmospheric Nitrogen collisions. The uncorrected GHEISHA 600 shows a flatter muon energy spectrum below 1 GeV than the corrected version. This difference has to be attributed to secondaries of protons emitted with too high energy in preceding collisions that do not conserve energy. In addition it is known that the codes have similar behavior for kaons as for pions. The dominance of K^+ mesons over the K^- mesons caused by the associated production of K and Λ in proton initiated interactions is in practice reproduced in all codes [14].

Generally FLUKA produces small deficit of $K^\pm$ at x_{lab} less then ¡0.3. While the electron densities of

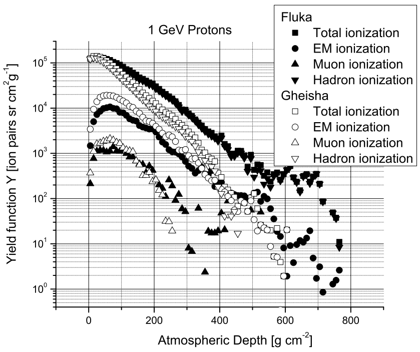

Fig. 1: Ionization yield function Y for primary proton induced showers with 1 GeV energy simulated with FLUKA and GHEISHA models

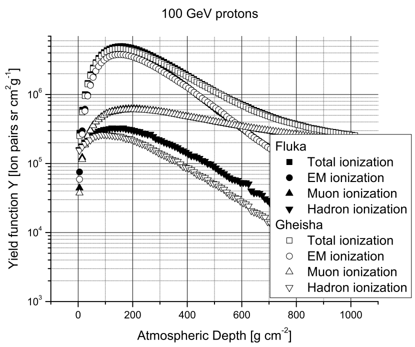

Fig. 2: Ionization yield function Y for primary proton induced showers with 10 GeV energy simulated with FLUKA and GHEISHA models

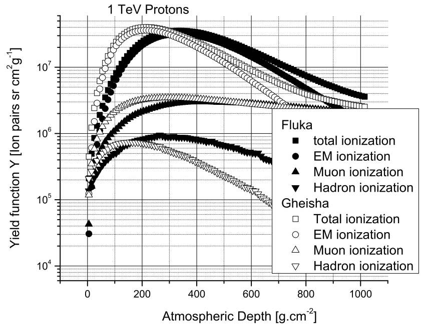

Fig. 3: Ionization yield function Y for primary proton induced showers with 1 TeV energy simulated with FLUKA and GHEISHA models

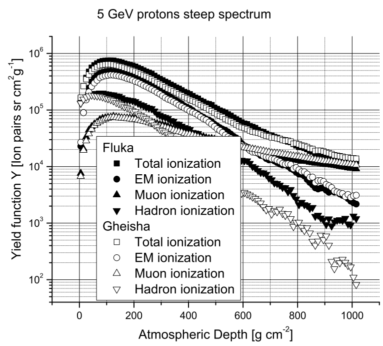

Fig. 4: Ionization yield function Y for primary proton with 5 GeV energy simulated with FLUKA and GHEISHA models following steep spectrum

simulated EAS show no significant dependence on the used low-energy model, its influence on the hadronic and muonic component is obvious. Whit this in mind we study the impact on low energy interaction models in CORSIKA code for cosmic ray induced ionization. We simulate proton induced EAS with FLUKA 2006 and GHEISHA 2002 , respectively for low energy hadronic interactions. For high energy we used QGJET II subroutine in both cases. The used statistics is 5000 events per energy point.

We compare the ion production yield function Y . The results for 1GeV- 1 TeV proton incoming particles are presented in Fig. 1-3. With solid figures are shown the yield functions Y obtained with FLUKA and with open symbols with GHEISHA. In all cases the squares are used for total ionization, the circles for EM component contribution, with up triangles are presented the muon contribution and with down triangles the hadron component contribution. One can see difference in all cases except for 100 GeV EAS. The observed difference is significant for 1 TeV showers. This is due essentially on pion distribution momenta differences. The observed difference between two models for muon component is in practice negligible.

In addition simulation of proton EAS is carried out following steep spectrum with different starting energies. The results are presented in Fig. 4-6. The contribution of the hadronic component in all cases is different using different hadronic interaction models. However the impact on total ionization is not significant, especially in the low atmosphere. In the region of the Pfotzer maximum a small difference of about 10-15 percent is observed with systematical increase of the ionization simulated with GHEISHA [12]. This is due as was mentioned above on the different contribution of the hadron component and additionally on the different ionization due to muon component around the Pfotzer maximum. In conclusion the application of the FLUKA 2006 [10] hadronic interaction model with CORSIKA code [7] for simulation of the cosmic ray induced ionization seems to be more reasonable comparing to the version with GHEISHA 2002 [12]. However for ionization estimation in low atmosphere it is possible to use both of the proposed models.

Finally for proton induced showers with 1.5 GeV corresponding to polar regions the simulatred ion rates with FLUKA and GEISHA arte compared with experimental data. We observe in one hand the difference between mentioned hadronic interaction models and on the other hand the agreement with experimental data.

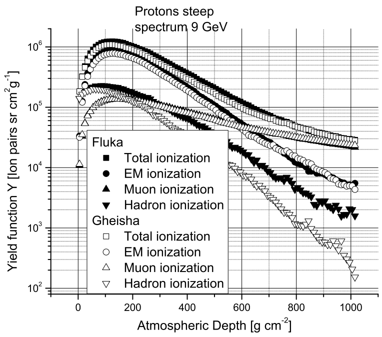

Fig. 5: Ionization yield function Y for primary proton with 9 GeV energy simulated with FLUKA and GHEISHA models following steep spectrum

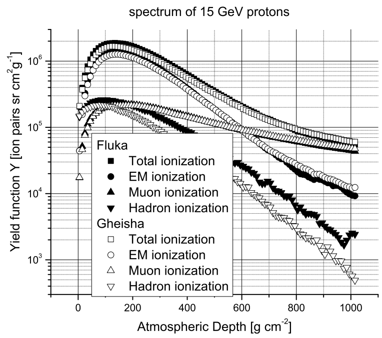

Fig. 6: Ionization yield function Y for primary proton with 15 GeV energy simulated with FLUKA and GHEISHA models following steep spectrum

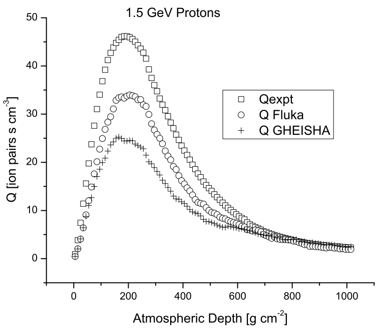

Fig. 7: Ionization rate due to 1.5 GeV protons simulated with FLUKA and GHEISHA compared with experimental data

IV. CONCLUSION

Generally in CORSIKA simulations, an (adjustable) energy threshold Ethr is adopted for the shower calculation, i.e. particles are followed explicitly above some threshold and discarded for smaller energies. This is due to the fact that a detailed calculation down to smallest energies, for instance to the eV-range, seems both hardly possible (because the large excess of CPU time) and hardly necessary for classical air shower experiments measuring surviving particles on ground. In fact low-energy particles also contribute to the ionization and excitation of air molecules. Therefore, two categories of shower particles are distinguished for calculating the energy release. Particles above the simulation threshold which are tracked in details, and particles below the simulation threshold which are discarded. Obviously the energy deposit is sum of these two contributions. The continuous ionization energy loss of a single charged hadron or muon traversing matter of thickness dx along its track is calculated by the BetheBloch stopping power formula. The obtained results for ionization yield function Y and ionization rates assuming different low energy hadron interaction models within CORSIKA code permit to use them for different aims. Both mentioned above low energy hadron interaction models are fully applicable, however we suggest to use FLUKA.

V. ACKNOWLEDGEMENT

We thank Dr. Usoskin from Oulu university Finland and our colleagues from IT division of INRNE-BAS.

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