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# Spectra of hadrons at mountain altitude (600 g/sq.cm) and their relation with primary cosmic ray in CORSIKA simulations

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**Abstract.** Simulations of nuclear electromagnetic cascade development in the atmosphere initiated by primary cosmic ray particles have been calculated using CORSIKA program with QGSJET model. Spectra of hadrons at mountain altitude (4370 m a.s.l. - 600 g/cm$^2$), corresponding with Pamir experiment registration level, have been analysed.

Efficiencies of production of secondary hadrons at the registration level have been estimated for different primary cosmic ray nuclei.

Analysis has been conducted, what range of $E_o$ energy of primary particles gives hadron spectra observed at mountain altitude.

## 1 Introduction

The Pamir experiment, similar to other EAS experiments, records among others hadrons. Received hadron energy distributions have been published in (Malinowski, 2001). Hadrons registered at mountain altitude have energies of tens and hundreds TeV.

We want to connect received energy spectrum with spectrum of primary cosmic ray (PCR). It can be made by comparing experimental results with the results of simulations of nuclear electromagnetic cascade development in the atmosphere. Various assumptions about PCR were made.

Presented paper shows what PCR particles (i.e. having what energies $E_o$) produce hadrons registered at mountain altitude. Distributions of energy of hadrons coming from different PCR nuclei have been also presented.

## 2 Calculations

Calculations have been made using CORSIKA v. 5.62 program with QGSJET model (Heck et al., 1998). QGSJET model uses cross sections according to experimental data and their extrapolations are far from extreme. Assumptions about cross sections for interactions of h-A nuclei of air are important by the study of changes of hadron flux in the atmosphere.

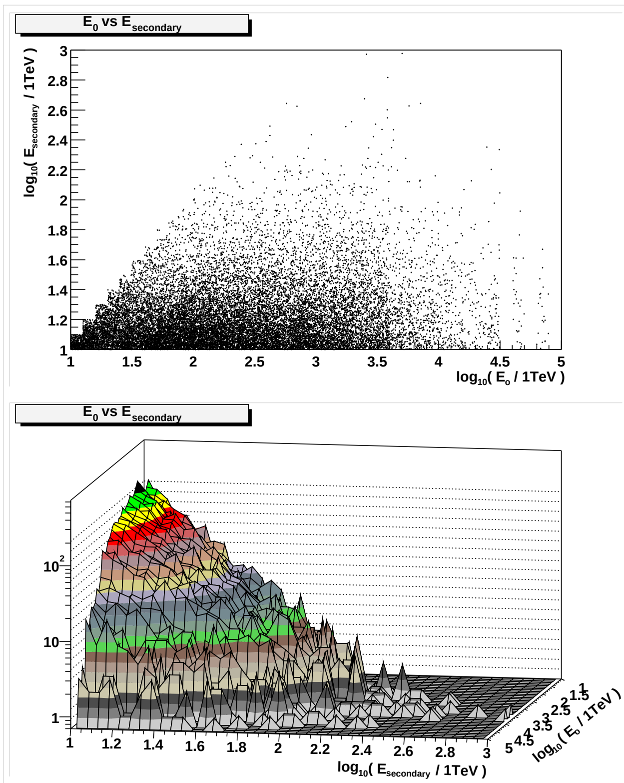


**Fig. 1.** Relations between energies of primary and secondary particles.

Primary cosmic ray particles have been sampled from power law distributions. The type of particles and exponents of spectrum, which the particles were sampled from, have been presented in Table 1.

Moreover, PCR spectrum according to Nikolski composition (Nikolski, 1987) has been used for simulations. Nikolski composition assumes: 40% protons, 21% He, 14% CNO,

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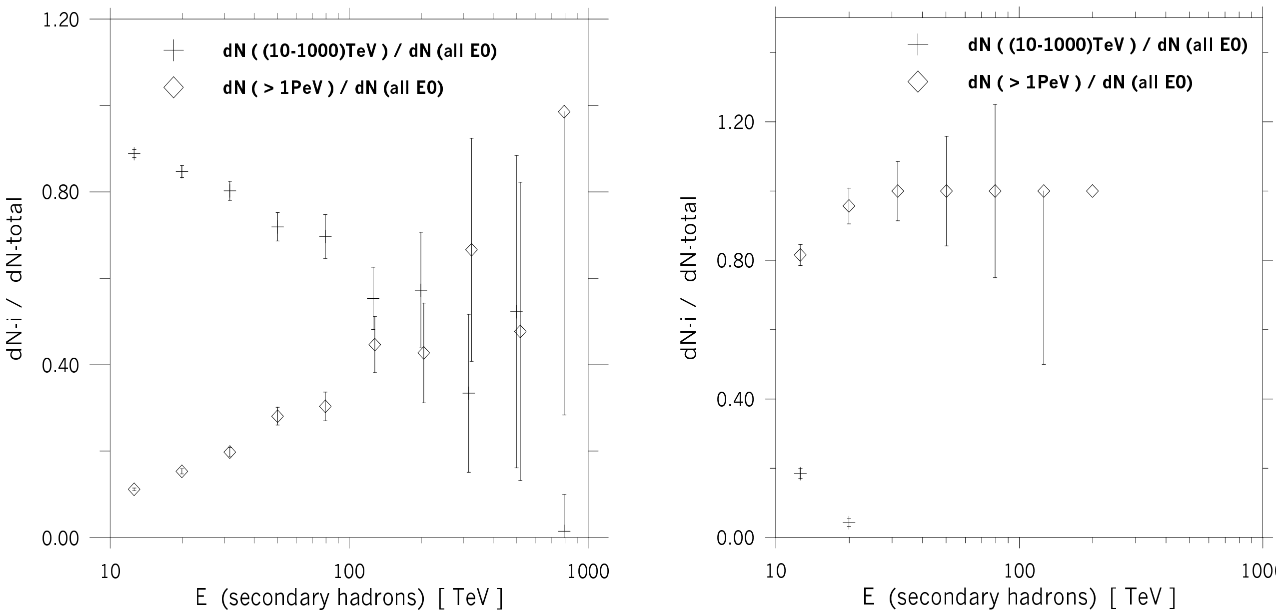


**Fig. 2.** Eff for primary protons (left) and for primary Fe nuclei (right).

13% heavy nuclei and 12% very heavy nuclei. Nuclei were sampled according to assumptions in Table 1.

**Table 1.** The type of particles and exponents of spectrum taken to calculations

| type of particle | ΔE [TeV] | $\gamma$ | ΔE [TeV] | $\gamma$ |
|---|---|---|---|---|
| p | 10 - $3\cdot10^3$ | 2.68 | $3\cdot10^3$ - $1\cdot10^5$ | 3.2 |
| He | 10 - $4\cdot10^3$ | 2.62 | $4\cdot10^3$ - $1\cdot10^5$ | 3.2 |
| N | 10 - $4\cdot10^3$ | 2.60 | $4\cdot10^3$ - $1\cdot10^5$ | 3.2 |
| Si | 10 - $5\cdot10^3$ | 2.60 | $5\cdot10^3$ - $1\cdot10^5$ | 3.2 |
| Fe | 10 - $6\cdot10^3$ | 2.60 | $6\cdot10^3$ - $1\cdot10^5$ | 3.2 |

**Table 2.** What part of secondary hadrons comes from PCR particles with selected $E_o$ range for chosen $E_{sec}$ (Eff); $dN_i$ - the number of secondary hadrons in differential distribution.

| $E_{sec}$ / Eff with cond. | 50 | 125 | 316 | 501 |
|---|---|---|---|---|
| <1 PeV | 0.61 | 0.45 | 0.24 | 0.34 |
| >1 PeV | 0.39 | 0.55 | 0.76 | 0.66 |
| <3 PeV | 0.83 | 0.76 | 0.59 | 0.48 |
| >3 PeV | 0.17 | 0.24 | 0.41 | 0.52 |
| $dN_i$ | 1362 | 209 | 21 | 9 |
| $N(> E_{sec})$ | 2214 | 309 | 35 | 14 |

## 3 Relation of secondary hadrons with primary cosmic ray particles

The distribution of energy of hadrons $E_{sec}$ registered at Pamir level received from simulations vs energy of primary particles $E_o$, from which secondary particles were created has been shown in Figure 1. It can be seen that even for very high energy $E_o$ (>1 PeV), the great majority of secondary hadrons have energies of tens and hundreds TeV.

Energies of primary particles $E_o$ and created by them secondary particles at registration level $E_{sec}$ are known from calculations. Energy distribution of particles which come from primary particles from selected $E_o$ interval has been made. The energy $E_{sec}$ distribution for all primary particles has been also made. Ratio of the number of particles from distribution for chosen $E_o$ interval to the number from distribution for all $E_o$ (later as 'Eff') has been estimated for particular $E_{sec}$ intervals.

The value of Eff ratio estimated in such way informs what part of secondary particles at registration level comes from primary spectrum from taken $E_o$ interval.

Dependence of Eff values from energies of secondary hadrons $E_{sec}$ coming only from primary protons and Fe nuclei has been shown in Figure 2. Figure 3 show Eff values for primary spectrum with assumption of Nikolski mass composition. Chosen data for these figures are presented in Table 2.

It can be seen that hadrons observed at mountain altitude come from PCR particles with energies $E_o$ 10 TeV - 3 PeV. Protons and light nuclei from PCR contribute to observed hadrons for energies $E_o > 10TeV$. Hadrons coming from heavy nuclei - Fe come from particles with $E_o > 1PeV$. For secondary hadrons with $E_{sec} < 50TeV$, contribution of primary particles with $E_o$ smaller than hundreds of TeV (300 - 500) dominates. At energy $E_{sec} \sim 50TeV$, 39% of hadrons comes from primary particles with $E_o > 1PeV$; for

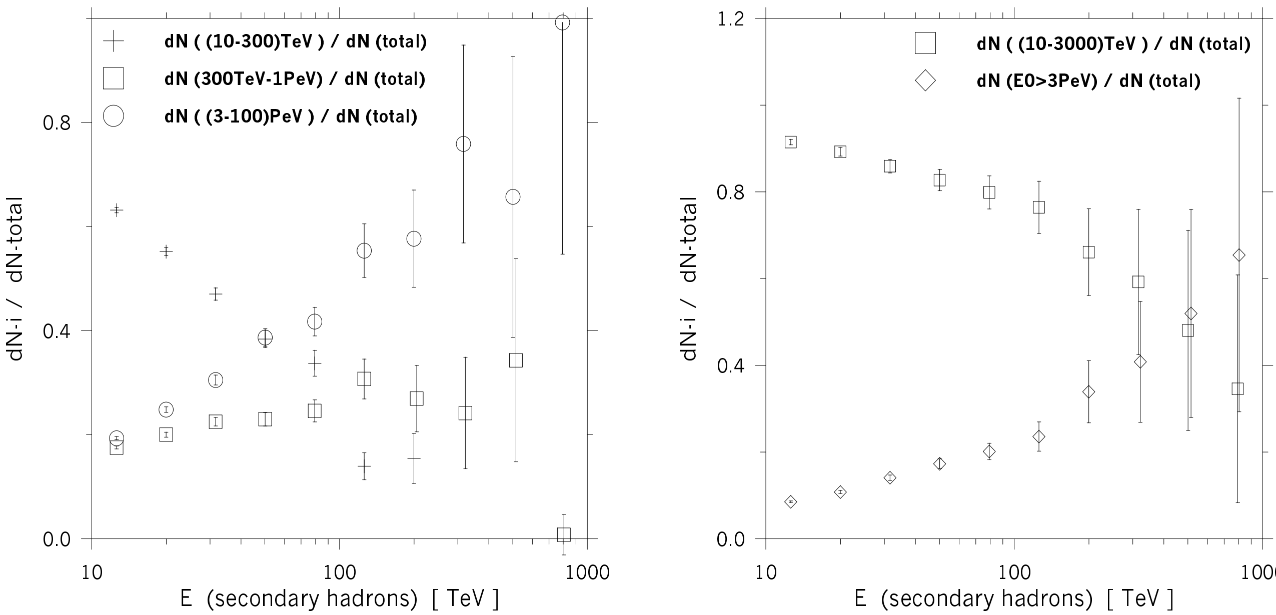


**Fig. 3.** Eff for primary particles from Nikolski spectrum for various $E_o$ intervals selected.

$E_{sec} \sim 100TeV$, over 45% hadrons comes from particles with $E_o > 1PeV$.

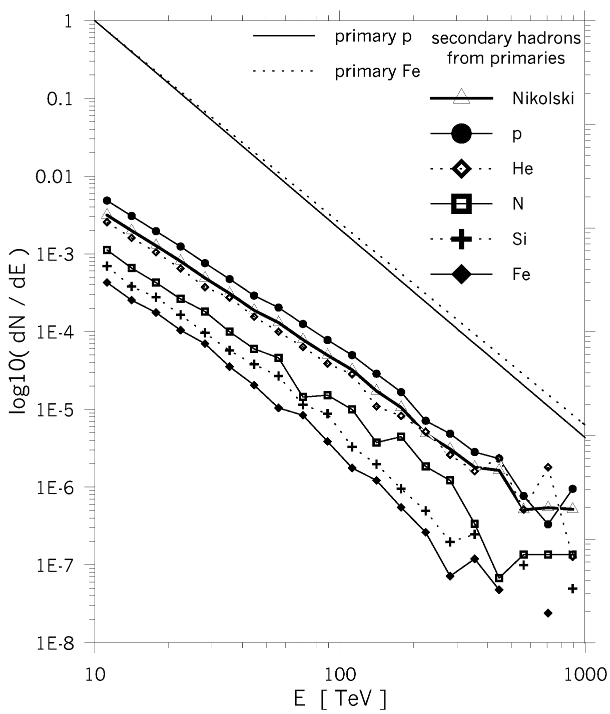


**Fig. 4.** Spectra from various primary particles.

## 4 Distributions of secondary hadrons from various components

For various primary particles with exponential spectrum presented in Table 1 nuclear electromagnetic cascade has been sampled and spectra of hadrons have been made. Intensity value of secondary hadrons was divided by the number of primary particles with energy $E_o = 10TeV$. Received results have been shown in Figure 4 and in Table 3.

**Table 3.** Ratio of the number of secondary hadrons to the number of particles of primary spectrum for $E_o = 10TeV$; composition of primary spectra as description of column.

| | $\frac{dN_{sec}}{N_o(E=10TeV)}$ | | | |
|---|---|---|---|---|
| E [TeV] | Nikolski | p | N | Fe |
| 11 | $3.17 \cdot 10^{-3}$ | $4.86 \cdot 10^{-3}$ | $1.12 \cdot 10^{-3}$ | $4.29 \cdot 10^{-4}$ |
| 56 | $1.31 \cdot 10^{-4}$ | $2.05 \cdot 10^{-4}$ | $4.59 \cdot 10^{-5}$ | $1.04 \cdot 10^{-5}$ |
| 112 | $3.22 \cdot 10^{-5}$ | $5.01 \cdot 10^{-5}$ | $9.96 \cdot 10^{-6}$ | $1.77 \cdot 10^{-6}$ |
| 354 | $1.81 \cdot 10^{-6}$ | $2.83 \cdot 10^{-6}$ | $3.39 \cdot 10^{-7}$ | $1.20 \cdot 10^{-7}$ |
| 562 | $5.12 \cdot 10^{-7}$ | $7.72 \cdot 10^{-7}$ | $1.36 \cdot 10^{-7}$ | |

Observed flux of hadrons coming from Fe is about 12 times smaller than the one for particles coming from primary protons. Calculated values can be interpreted analogously to attenuation length as absorption length of hadrons in the atmosphere. Values of absorption length of hadrons for energy E = 10 TeV calculated from presented data have been shown in table 4.

**Table 4.** Mean absorption length (in g/cm$^2$) for hadrons in the atmosphere (for $E_o = 10 TeV$) for different primary particles shown in column.

| Nikolski | p | He | N | Si | Fe |
|---|---|---|---|---|---|
| 104.3 | 112.6 | 100.6 | 88.3 | 82.6 | 77.4 |

## 5 Summary

Analysis of energy distributions of hadrons registered in the Pamir experiment can give information about primary cosmic ray with energy 10 TeV - 3 PeV, i.e. up to knee.

Protons and light nuclei give substantial contribution to observed hadrons. Contribution of hadrons, which come from primary Fe nuclei, to observed spectrum should be significantly smaller than the one of hadrons coming from protons. This fact should be observed in the experiment if Fe nuclei dominated in primary spectrum for $E_o \sim 1 PeV$.

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