Study of XREC response to measured variables of γ-ray families

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***Abstract*. Results of analysis of influence of X-ray emulsion chamber (XREC) response on characteristics of γ-ray families detected by the *Pamir* experiment are considered. Atmospheric nuclear-electromagnetic cascades with primary energies of $2 \cdot 10^{14} - 10^{18}$ eV are simulated with QGSM-based MC0 and FANSY 1.0 models developed in the *Pamir* experiment. Simulation of observation in XREC of γ-ray families with detected energy higher than 100 TeV is carried out by GEANT 3.21-based code (*ECSim* 2.0 package) especially adapted for accurate consideration of measuring procedures and experimental technique accepted in the *Pamir* experiment.**

***Keywords*: simulation, emulsion chamber, detector response**

I. Introduction

The *ECSim* 2.0 package version is intended for detailed 3D-simulation of development of electromagnetic showers and nuclear-electromagnetic cascades (NEC) initiated by various hadrons and nuclei in X-ray emulsion chambers (XREC) on the basis of GEANT 3.21 code. It is based on the *ECSim* 1.0 package [1] used by RUNJOB experiment, which, however, cannot be directly applied to simulation of ground-based experiments detecting secondary particles (π, K etc.). The *ECSim* 2.0 package can be used in a broader field of problems for simulations of NECs in complex and multi-layer media in a wide range of energies from 10 keV to ~ 100 PeV accounting for specific measuring procedures exploited in XREC experiments. This paper is devoted to the simulation of the *Pamir* experiment XREC response.

II. Simulation of emulsion chamber responce

In particular, the *ECSim* v. 2.0 package incorporates:
- the LPM effect for electromagnetic processes;
- generation of hadron-hadron and hadron-nucleus interactions at $E > 80$ GeV using the QGSJET model [2];
- simulation of NECs initiated in the chamber by hadrons of various types ($p/\bar{p}$, $n/\bar{n}$, π, $K/\bar{K}$ and so on), $e^{\pm}, \gamma$-rays at different incident angles;
- tracking of correlated groups of particles ($\gamma, e^{\pm}$, h) of high energies ($E \gtrsim 1$ TeV), the so-called γ-h families, passing through XREC that requires substantial changes in the logic of processing of these events;
- simulation of the passage of superhigh-energy muons with appropriate cross sections for bremsstrahlung, $e^{+}e^{-}$ pair production, knock-on electron production and nuclear interaction similar to those used in GEANT4;
- accounting for the LPM effect which appreciably decreases the pair production cross section at high energies ($E \gtrsim 70$ TeV) in the case of high-Z lead absorber, the most frequently used one in XREC structures; respectively, the muon cross section is reduced by a factor proportional to the γ-ray cross section decrease at the

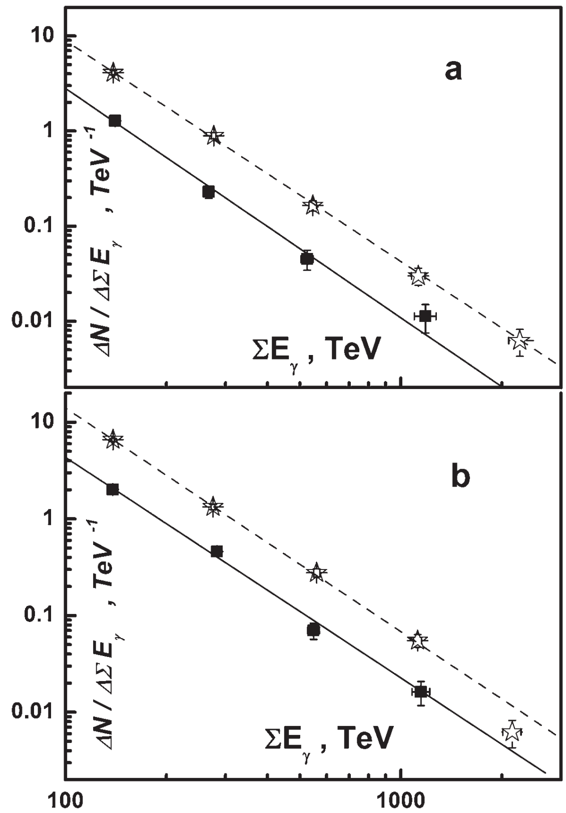

Fig. 1: Dependence of number of γ-ray families on $\sum E_\gamma$. Notations are the same as in Fig. 3. Broken and solid lines denote fits obtained for MC0 and FANSY 1.0 data, respectively.

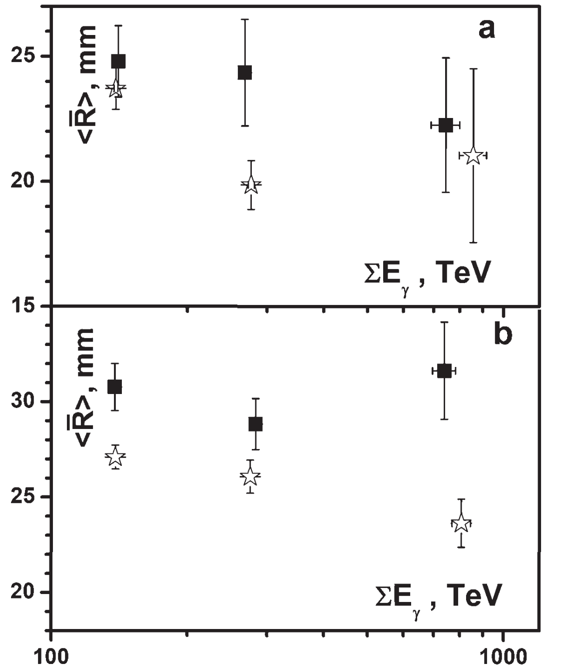

Fig. 2: Dependence of doubly averaged γ-rays' radius, $\langle\overline{R}\rangle$, on total family energy $\sum E_\gamma$. Notations are the same as in Fig. 3.

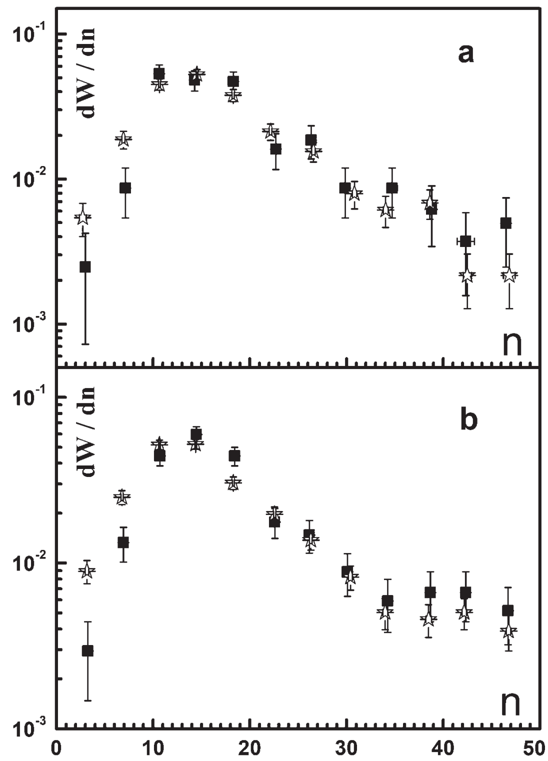

Fig. 3: Distributions of number of γ-ray families' particles: a) above XREC; b) "measured" at the observation layer. Family selection criteria: $\sum E_\gamma > 100$ TeV at $E_{\gamma\, min} = 4$ TeV, at distances $R_\gamma \leq 15$ cm. Data are simulated by MC0 ($\star$) and FANSY 1.0 (■) codes.

same energy;

• LPM-corrected cross sections for bremsstrahlung by electrons and pair production by γ-rays are extended up to 10^{19} eV.

ECSim 2.0 makes it possible to analyze the NEC development in any stratified medium. Test results show good agreement with other authors' data. For instance, the n_{ch} transition curves in Pb in cascades initiated by γ-rays of energy $E_0 = 1$ PeV and traced down to $E_{min} = 1$ TeV agree with results [4].

Study of detector response is considered in [5] as well, for single particles only. However, one of the most important points of XREC techniques is the measurement of darkness of nearby spots produced on X-ray films by electron-photon cascades (EPC) (produced in the upper part of XREC by γ-rays, $e^\pm$ and hadrons, all named below γ-rays for simplicity) and corresponding reconstruction of EPC energies. The problem is especially difficult and complicated in the case of analysis of high-energy γ-ray families due to overlapping of spots and appearance of high background darkness in the family area. This techniques is described in detail in [3]. This work considers a solution of this problem and some results on simulation of γ-ray families.

III. Simulation of γ-ray families

Atmospheric nuclear-electromagnetic cascades with primary energies of $2 \cdot 10^{14} - 10^{18}$ eV are simulated by QGSM-based MC0 [6] and FANSY 1.0 [7] models developed in the *Pamir* experiment. The most important difference between these models in proton-nucleus is as follows. 1) Spectrum of most energetic baryon is harder in FANSY 1.0; 2) Spectra of secondary particles are more soft in FANSY 1.0; 3) Values of $\langle p_t\rangle(X_F)$ are higher in FANSY 1.0 in the most important hadron-nucleus kinematics fragmentation region $X_F \simeq 0.05 - 0.5$ by $\simeq 20\%$ which is responsible for formation of so-called γ-ray families, i.e. groups of $e^\pm, \gamma$-rays and hadrons, which produce darkness spots in X-ray films in upper part of XREC.

IV. Results

Fig. 3 demonstrates distributions of number of γ-ray families' particles: a) above XREC; b) "measured" at the observation layer. Family selection criteria are as follows: $\sum E_\gamma > 100$ TeV at $E_{\gamma\, min} = 4$ TeV, at distances $R_\gamma \leq 15$ cm. Data shown in Fig. 3 are simulated by MC0 (stars) and FANSY 1.0 (black squares) models.

Fig. 4 demonstrates energy distributions of single electrons/positrons and γ-rays in families.

Fig. 1 demonstrates dependence of number of γ-ray families on $\sum E_\gamma$. Broken and solid lines denote fits obtained in the form $\Delta N/\Delta \sum E_\gamma \sim (\sum E_\gamma)^{-\chi}$ for MC0 and FANSY 1.0 data, respectively. a) $\chi_{\rm MC0} = 2.32 \pm 0.07$, $\chi_{\rm FANSY} = 2.41 \pm 0.14$; b) $\chi_{\rm MC0} = 2.31 \pm 0.05$, $\chi_{\rm FANSY} = 2.28 \pm 0.11$.

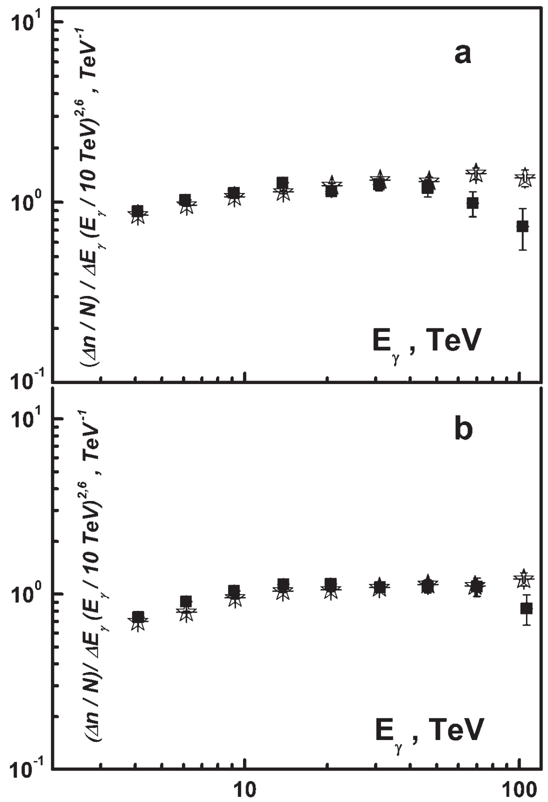

Fig. 4: Energy distributions of single $e^{\pm}$ and γ-rays in families. Notations are the same as in Fig. 3.

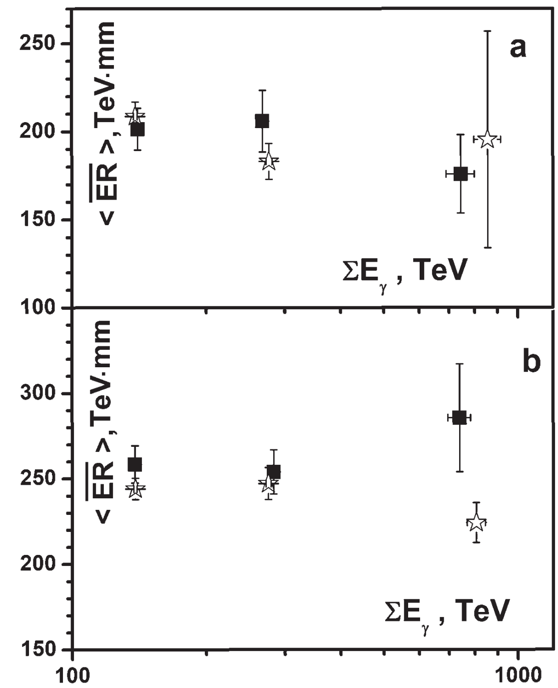

Fig. 5: Dependence of doubly averaged product of γ-rays' radius and energy, $\langle \overline{ER} \rangle$, on total family energy $\sum E_\gamma$. Notations are the same as in Fig. 3.

Fig. 2 demonstrates dependence of doubly averaged[1] γ-rays' radius, $\langle \overline{R} \rangle$, on total family energy $\sum E_\gamma$. Consideration of response of XREC results in growth of the doubly averaged γ-rays' radius value by $15 - 20\%$. This is caused by the fact that subthreshold electrons/positrons and γ-rays become visible due to fluctuations.

Fig. 5 demonstrates dependence of doubly averaged product of γ-rays' radius and energy, $\langle \overline{ER} \rangle$, on total family energy $\sum E_\gamma$.

Fig. 6 demonstrates zenithal angular distributions of γ-ray families calculated by the use of MC0 code. Solid and broken lines denote fits obtained in the form $dN/d\cos^2\vartheta \sim \exp(-x/\lambda_{att})$ for data found before and after simulation of chamber response ("measured" data), respectively. Here λ_{att} is the attenuation length value. For solid and broken lines $\lambda_{att} = 85.4 \pm 5.4$ and $\lambda_{att} = 74.8 \pm 3.4$, respectively. Probably difference in λ_{att} is caused by techniques used in the *Pamir* experiment.

Table I demonstrates average values of some parameters of γ-ray families with energies $\sum E_\gamma = 100 - 400$ TeV before and after simulation of chamber response, namely, multiplicity of particles ($e^{\pm}$, γ), $\langle n_\gamma \rangle$, doubly averaged particles' radius, $\langle \overline{R} \rangle$, and doubly averaged product of particles' radius and energy, $\langle \overline{ER} \rangle$.

[1]Double averaging of a parameter means that at first stage the averaging is made over particles of one event, after that over particles of another event, and so on. At the second stage, the found values are averaged once again (over all events).

V. Conclusion

1. Consideration of response of emulsion chambers and experimental procedures of energy measurement is very important as characteristics of γ-ray families before and after such consideration are mainly different.

2. Emulsion chamber experiments are sensitive even to close models and can be a good techniques for model testing and tuning.

3. The MC0 code describes *Pamir* experiment's data [8] better than FANSY 1.0 with respect to lateral characteristics. This indicates a need of decrease of the average transverse momentum of secondary particles realized by FANSY 1.0 in the hadron-nucleus kinematics fragmentation region ($x_F \gtrsim 0.05$) being responsible for formation of γ-ray families.

4. The influence of hadrons registered in XREC on characteristics of γ-ray families is first taken into account.

5. The inclusion of the XREC response shows that a) γ-ray multiplicity and energy spectrum of families are not changed; b) doubly averaged γ-rays' radius increases in 15-20%; c) attenuation length of families decreases in 10-15%.

VI. Acknowledgements

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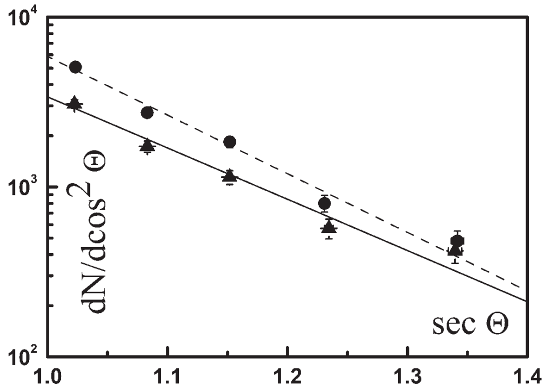

Fig. 6: Zenithal angular distribution of γ-ray families simulated by MC0 model. Family selection criteria: $\sum E_\gamma > 100$ TeV at $E_{\gamma\, min} = 4$ TeV, at distances $R_\gamma \leq 15$ cm. Data are found before (•) and after simulation of chamber response ("measured" data) (▲), respectively.

TABLE I: Average values of some parameters of γ-ray families with $\sum E_\gamma = 100 - 400$ TeV before and after simulation of chamber response.

	$\langle n_\gamma \rangle$	$\langle \overline{R} \rangle$, mm	$\langle \overline{ER} \rangle$, TeV·mm
	MC0		
before	17.0 ± 0.4	22.6 ± 0.9	201 ± 9
after	15.8 ± 0.3	26.8 ± 0.7	245 ± 8
	FANSY 1.0		
before	17.5 ± 0.6	24.7 ± 1.6	203 ± 14
after	17.5 ± 0.5	30.2 ± 1.3	257 ± 12

REFERENCES

[1] Galkin V.I., Nazarov S.N. *Simulation of cosmic ray passage through an emulsion chamber* Preprint SINP MSU (1999) 99-14/572

[2] Kalmykov N.N. and Ostapchenko S.S. *QGS model taking into account jets and EAS* Yad. Fiz. **58** (1994) 21.

[3] Borisov A.S., Denisova V.G., Galkin V.I., Kogan M.G., Kanevskaya E.A., Kotelnikov .., Mukhamedshin R.A., Nazarov S.I., Puchkov V.S. *et al. A GEANT-based package for determination of the PAMIR experiment X-ray emulsion chamber response*. Proc. 30th ICRC, Merida (2007) v.4, p. 593-59

[4] Okamoto M., Shibata T. *Nucl. Instrum. & Methods in Phys. Res.* A257 (1987) 155.

[5] Haungs A. *Nucl. Phys. B* (Proc. Suppl.), 2006. V. 151. P. 215-222.

[6] Fedorova G.F. and Mukhamedshin R.A., Bull. Soc. Sci. Lettr. Lodz, Ser. Rech. Def., **XVI** (1994) 137.

[7] Mukhamedshin R.A. *FANSY 1.0: a phenomenological model for simulation of coplanar particle generation in superhigh-energy hadron interactions*. Eur. Phys. J. C (2009) 60: 345-358; DOI 10.1149/epjc/s 10052-009-0945-y

[8] Borisov A.S. *et al.* Nucl. Phys. B (Proc. Suppl.) **175-176** (2008) 143