HE.1.2.14

Characteristics of gamma-hadron families against heavy chemical composition of primary cosmic rays in the energy region around 10^{16} eV.

M.Kalmakhelidze[1],R.Mukhamedshin[2], N.Roinishvili[1], S.Slavatinski[3],M.Svanidze[1]
[1]*Institute of Physics, Academy of Sciences of the Georgian Republic, Tamarashvili 6, Tbilisi, Georgian Republic, SU-380077.*
[2]*Institute for nuclear Physics, Russian Academy of Sciences, 117312 Moscow, Russia*
[3]*Lebedev Physical Institute, Russian Academy of Sciences, 117924 Moscow, Russia*

Abstract

Various parameters of gamma-hadron families observed by Pamir and Pamir-Chacaltaya Collaborations are analyzed to study primary cosmic rays chemical composition in the energy region around 10^{16} eV. It is shown that all characteristics of families, including their intensity, are in a very good agreement with properties of families simulated by means of a quasi-scaling model at the normal chemical composition and are in sharp disagreement with heavy dominant compositions.

1 Introduction:

At energies more than 10^{15}eV information about Chemical Composition (CC) of PCR comes either from Extensive Air Showers or families of γ-quanta and hadrons registered by X-ray emulsion chambers. Despite of long-term researches results are very contradictory. Statements concerning CC swing from the normal (Nikolski,1984; Fedorova, Mukhamedshin, 1994) and even with proton dominant (Tamada, 1997) to heavy (Ren, 1988) and superheavy (Shibata, 1981) compositions. The appropriate data are brought in Table 1, where fractions, C_A, of various components are given at different CC.

Table 1. Various chemical compositions of PCR at $E_0=10^{15}$eV, C_A %.

Composition	**P**	**He**	**CNO**	**Si, Mg**	**Fe**	**<lnA>**
Normal	40	20	10	10	20	1.7
Heavy	15	10	17	0	58	3.0
Superheavy	7	5	12	6	70	3.4

Efficiency, ε_A, of families production by a nucleus strongly depends on its atomic number decreasing with increase of A. Therefore fractions, f_A, of various components in family's chemical composition differs from CC of PCR:

$$f_A = \varepsilon_A \times C_A / \sum (\varepsilon_A \times C_A) \quad (1)$$

The present work is a research of PCR CC in the energy region directly after the knee of its energy spectrum. Characteristics of γ-hadron families registered by Pamir and Pamir-Chacaltaya Collaborations are used for this task. We analysed families satisfying the following conditions:

$$100\text{TeV} < \Sigma E_\gamma < 1000 \text{ TeV}, \quad n_\gamma > 10, \quad E^\gamma_h, E_\gamma > 4 \text{ TeV}, \quad \overline{<R_\gamma>} > 1\text{cm} \quad (2)$$

In (2) E^γ_h, E_γ is visible energy of a hadron and a γ-quantum, $<R_\gamma>$ - an average radius only γ-quanta seated at distance less than 15cm from the energy-weighted centre of a family are included in it.

Total number of families satisfying condition (2) and studied in the present work is 174.

MC0 model (Fedorova, Mukhamedshin, 1994)] is used for analyse of the data. The model is based on the theory of quark-gluon strings. Diffraction processes, generation of jets with large transverse momentum, production of strange and charm particles are included in it. The important peculiarity of MC0 is an increase of an inelasticity coefficient with energy. It was shown (Biolobrzeska et al, 1997; Bielawska et al 1997) that MC0 predicts faster absorption of hadron component than DPM and VENUS variants of CORSIKA (Knapp J adn Heck D 1993). Fast absorption of hadron component provides the agreement of MC0 model with the observed intensity of γ-families.

With the help of MC0 model nuclear-electromagnetic cascades in the Atmosphere generated by various nuclei were simulated at power like energy spectrum. Index of integral energy spectra of PCR, γ, for all nuclei was taken equal to –1.7. For protons an additional set of events with a bend in energy spectra was also simulated. $\gamma = -1.7$ for energies less than 3×10^{15}eV and $\gamma = -2.2$ below the "knee" were input in this case.

2 Characteristics of γ-hadron families, Pamir experiment:

γ-hadron families are characterised by a number of measured parameters. Conditionally they can be divided into 4 classes:

1. Characteristics of γ-quanta related to energy: n_γ, $\sum E_\gamma$, $\sum E_\gamma / n_\gamma$.
2. Spatial characteristics of γ-quanta: R_γ, $E_\gamma R_\gamma$, $R_\gamma^E=\sum E_\gamma R_\gamma/\sum E_\gamma$, d

Parameter $d = n_{ini} / n_{obs}$ is defined as the ratio of the number of initial γ-quanta, n_{ini}, to the number of observed γ-quanta, $n_{obs}= n_\gamma$. An initial γ-quantum is responsible for a narrow group of spots on an X-ray film, which are the result of an electromagnetic cascade induced by it in the Atmosphere. Observed dark spots being on a small distance, R_{ij}, from each other are combined into one initial γ-quantum, if $R_{ij} / (1/E_i + 1/E_j) < 10$ TeV mm. Using this algorithm the number of initial γ-quanta was determined.

3. Characteristics of hadrons related to energy: n_h, $\sum E_h^\gamma$, $q_E=\sum E_h^\gamma/(\sum E_\gamma+\sum E_h^\gamma)$, $q_n=n_\gamma/(n_\gamma+n_h)$
4. Spatial characteristics of hadrons: R_h, $E_h^\gamma R_h$ and etc. The last characteristics are not examined in this work, since the number of hadrons is, as a rule, small and consequently their spatial characteristics have very wide fluctuations.

Parameters belonging to a given class are subject to common systematic errors. In the 1-st class they are determined by errors in energy measurement of γ-quanta. The effects of saturation of darkness and the overlapping of spots appeared for larger energies. Whenever possible these effects are taking into account during primary processes of families: γ-quanta being on distance $R_{ij} < 0.15$ mm are united in one; only families with $\Sigma E_\gamma < 1000$TeV and $R_\gamma > 1$cm are included into analysis. These restrictions eliminate the main part of systematic errors of the 1-st class parameters.

Aggregation of quanta with $R_{ij} < 0.15$ mm and exclusion of families with $R_\gamma < 1$ cm from analysis set aside most difficulties in determination of spatial characteristics (the 2-nd class).

Main uncertainties of the 3-rd class's parameters are connected with determination of visible energy of a hadron, E_h^γ, based on its darkness. This complexity will be discussed in next section.

Average values of parameters of the experimental families are given in Table 2.

Table 2. Average values of experimental parameters, P, their statistical errors, σ_P, and sensitivity, S.

	n_h	R_γ (cm)	R_γ^E	$E_\gamma R_\gamma$	d	q_n	q_E
P	3.1	2.8	2.4	27.	.63	.11	.14
σ_P	0.3	0.1	0.1	2.0	.01	.01	.01
S	1.38	1.33	1.26	1.04	0.96	0.65	0.60

Sensitivity of a parameter to atomic number of primary particle is defined as:

$$S=(\langle P_{Fe}\rangle - \langle P_P\rangle)/D_P \qquad (3)$$

$\langle P_{Fe}\rangle$ - is average value of the given parameter for families induced by Fe, $\langle P_P\rangle$ - the same for families induced by protons, D_P - dissipation of a parameter for primary proton. **S** is calculated by means of simulated families for primary protons and iron.

Let us note, that all parameters are defined in such a way that $\langle P_P\rangle$ is less than $\langle P_{Fe}\rangle$. For this purpose in two cases it was necessary to depart from initial definitions of parameters. Parameter **d** was introduced for the first time in work (Asimov, 1987) as the ratio $d = n_{obs} / n_{ini}$. We have redefined it by replacing $d \to 1/d$. Parameter q_E, was introduced in work (Bielawska, Tomashevski, 1980) as $q_E = \sum E_\gamma / (\sum E_\gamma + \sum E_h^\gamma)$. We transformed it as $q_E \to 1 - q_E$.

In Table 2 parameters are brought in order of decrease of their sensitivity. Characteristics of families with S<0.5 are not given there. At a research of chemical composition they can be only harmful. Not having sensitivity they are useless but the systematic errors in them can enter distortions into final results.

3 Characteristics of γ-hadron families, MC0-model:

The average value of a given parameter of families, P, at certain chemical composition can be expressed by a formula:

$$P = \sum (C_A \times \varepsilon_A \times P_A) / \sum (C_A \times \varepsilon_A) \qquad (4)$$

where P_A is an average value of the given parameter in families generated by a nucleus with atomic number A. The model determines values P_A and ε_A, whereas CC and the power index of energy spectra of nuclei A are set as an input of simulations.

Peculiarity of simulated events is a modelling of hadron registration in X-ray emulsion chamber and determination of energy transferred by it into the soft component, $E_h^\gamma = K_\gamma E_h$. For Pamir carbon chambers special investigations (Malinowski et al, 1980) have shown that the probability of interaction is about 0.7 and K_γ has a distribution, $f(K_\gamma)$, similar to incomplete γ-function

$$f(K_\gamma) = d\,f(K_\gamma)/d\,K_\gamma = A\,K_\gamma^\alpha \exp(-K_\gamma/\beta) \qquad \langle K_\gamma \rangle = (\alpha+1) \times \beta \qquad (5)$$

At $\alpha = 1.5$ and $\beta = 0.075$ average $\langle K_\gamma \rangle$ has quite reasonable values equal to 0.188.

Average values of sensitive parameters of families, P_A, and their dispersions, D_P, for various primary nuclei were calculated at integral energy spectrum index $\gamma = -1.7$. Data for families generated by protons having power spectrum with bend in point $E_0 = 3 \times 10^{15}$eVwere also investigated. Calculations shown that the "knee" of the spectrum insignificantly influences on average characteristics of proton induced families.

Expected values of parameters for the given CC calculated with the help of expression (3) are given in Table 3.

Table 3. Expected values of family's characteristics at various chemical compositions.

	n_h	R_γ	R_γ^E	$E_\gamma R_\gamma$	d	q_n	q_E
Normal	3.2	3.0	2.6	26.	0.62	0.11	0.11
Heavy	3.6	3.3	2.9	29.	0.64	0.12	0.12
Supeheavy	4.2	3.7	3.3	32.	0.66	0.13	0.14

Comparison of Tables 2 and 3 shows that characteristics of families at normal composition are in good agreement with the experimental data whereas predictions for heavy and the more so for superheavy compositions differ much from the observations.

4 Comparison of the experimental data with the results of MC0 model:

Among seven parameters sensitive to chemical composition (Table 2) characteristics related to the energy of hadrons, n_h, q_n, q_E and spatial characteristics of γ-quanta, R_γ, R_γ^E, $E_\gamma R_\gamma$ strongly correlated. Apart stands parameter d, which does not correlate with both of the groups. Parameters belonging to the different classes do not correlate also. We have chosen three sensitive and not correlated parameters: n_h, R_γ, and **d.** Only they are used in the subsequent analysis.

For comparisons of the experimental and simulated families the following quantities were calculated:

$$\chi^2_p = [(P_{exp} - P_{mod}) / \sigma P_{exp}]^2 \qquad (6)$$

and sum of χ^2_p for the three parameters

$$\chi^2_3 = [((n_{h\,exp} - n_{h\,mod}) / \sigma n_{h\,exp})^2 + ((R_{\gamma\,exp} - R_{\gamma\,mod}) / \sigma R_{\gamma\,exp})^2 + ((d_{exp} - d_{mod}) / \sigma d_{exp})^2]/3 \qquad (7)$$

Here P_{exp} and P_{mod} are an average value of some parameter but σP_{exp} is an error of P_{exp}. The results are shown in Table 4.

Table 4. Values of χ^2_P for various parameters and χ^2_3.

	χ^2_{nh}	$\chi^2_{R\gamma}$	χ^2_d	χ^2_3
Normal	0.11	3.4	0.95	1.5
Heavy	2.7	20.	0.24	7.7
Superheavy	13.	54.	7.2	25.

Each χ^2 should be near one if the experiment and calculations are in a good agreement, since the number of degrees of freedom for separate parameter is 1 and χ^2_3 is an appropriate χ^2 with the 3 degrees of freedom divided on 3. This expectation is fulfilled only for the normal composition, but is not satisfied for the heavy and superheavy compositions. Rather large values of $\chi^2_{R\gamma}$ =3.4 for the normal composition can indicate on the presence of some systematic errors. Investigations show that 10% underestimation of energy near threshold (4.5TeV instead 4.TeV) is sufficient for decrees of $\chi^2_{R\gamma}$ up to suitable value.

5 Conclusions:

MC0 model at the normal chemical composition is in the complete agreement with the experimental data of γ-hadron families;

The chemical composition of Primary Cosmic Ray in the energy region near to 10^{16}eV just above the "knee" of its energy spectrum is close to the chemical composition at energy around 10^{14}eV;

Chemical compositions enriched by heavy elements contradict to the experimental data on families. They predict too low intensity of families and incorrect values of the characteristics of families

References

Asimov S A et el 1987 Proc. 20th ICRC v 5 p 304

Bielawska H et al 1997 Proc. 25th ICRC v 6 p 269

Bielawska H et al 1997 Proc.25th ICRC v 6 p 273

Bielawska H and Tomaszevski A 1980 UL Pamir Collaboration Workshup p 38

Biolobrzeska H et al 1997 Proc. 25th ICRC v 6 p 265

Fedorova G F and Mukhamedshin R A 1994 Bull Soc. Sci. Lettr. Lodz Ser. Rech. Def v XVI p 137.

Knapp J adn Heck D 1993 KfK 5196B

Malinowski A et al 1980 UL Pamir Collaboration Workshup p 49

Michalak W 1980 Zesz. Nauk. UL z 60 s 137

Nicolsky S I 1984 Pros.3rd Int. Sym. on Cosmic Ray and Particl Physics p 507

Ren J R et al. 1988 Phys. Rev. v D38 p 1404

Shibata M 1981 Phys. Rev. v D24 p 184

Tamada M 1997 J. Phys. G: Nucl. Phys. 23 p 497