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UPPER BORDER OF IRON NUCLEI FRACTION IN PRIMARY COSMIC RAYS AT $E_0=5\cdot10^3-5\cdot10^4$ TeV INFERRED IN PAMIR EXPERIMENT DATA

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Abstract

By an multidimensional analysis of energy, lateral and azimuthal symmetry characteristics of Pamir experiment gamma-families the upper boundary of the flux and fraction of primary iron nuclei at $E_0 > 10^{16}$ eV is estimated. The derived flux $I_{Fe}(>10^{16}) < 5.9\cdot10^{-9}$ m^{-2}sec^{-1}st^{-1} and fraction $p_{Fe}(>10^{16}) < 22$-27% show that iron nuclei do not dominate in primary cosmic rays above the break of the total energy spectrum.

1. Introduction. It has been shown in paper /1/ that the statistical decisions give one the opportunity for the estimation of the fraction of experimental gamma-families produced by primary iron nuclei. The description of the Monte-Carlo simulations as well as the other details one can also find in paper /1/. Here we shall classify the experimental families (the control sample) in L- and Fe-classes two times: firstly by use of the families simulated with N-model (the L- and Fe-class training samples consist of the N-model families) and, secondly, by the use of the F-model families. The estimated fraction p_{Fe}^{fam} of families produced by iron nuclei will be used for the estimation of the upper boundary of primary iron nuclear flux $I_{Fe}(>10^{16}$ eV) and fraction $p_{Fe}(>10^{16}$ eV).

2. The maximum flux of Fe-class gamma-families. The classification in two-dimensional space of pairs of variables leads to the following p_{Fe}^{fam} values (max $p_{Fe}^{fam} = p_{Fe}^{fam} + \Delta p_{Fe}^{fam}$ are shown in brackets):

	N-model	F-model
$\overline{ER}$, b'	0.01 ± 0.04 (0.05)	0.02 ± 0.04 (0.06)
Σ'ER, b'	-0.01 ± 0.04 (0.03)	0.02 ± 0.05 (0.07)
Σ'ER, n'	-0.001 ± 0.04 (0.04)	0.05 ± 0.05 (0.10)
b', n'	-0.07 ± 0.09 (0.02)	-0.02 ± 0.09 (0.07)

The average p_{Fe}^{fam} is negative in some cases, the statistical error is rather great, therefore we can only consider max p_{Fe}^{fam}, but not p_{Fe}^{fam}. It means that we can maintain only, that the true p_{Fe}^{fam} is smaller than the estimated max p_{Fe}^{fam} with probability ~0.67.

Let us consider the change of the results if one takes into account the possible change of the strong interaction model and experimental biases. It follows from $\langle n' \rangle$ data (see ref./1/) that:

1) the simulated $\langle n' \rangle$ values are smaller than the experimental ones, the difference is rather small, but it is statistically significant;

2) $\langle n' \rangle$ does not depend practically on the composition: the N- and F-model values are within the small statistical errors.

If one takes into account the overlapping of the γ-ray spots in X-ray films and the aggregation of the spots which spaced closely then the simulated $\langle n' \rangle$ value decreases /2/, so the use of n' in classification leads to the overestimated max p_{Fe}^{fam}. In contrast with n' the sensitivity of b' is the greatest to including of inelastic change-exchange process $\pi^{\pm} \rightarrow \pi^{o}$. The probability of the process is equal to 0.3 and does not decrease with increase of energy in the models. Therefore, the probability is near to the maximum one and $\langle b' \rangle$ of simulated families seems to be near the minimum value and N-model $\langle b' \rangle$ coincide with the experimental data (see ref./1/). It means that b'-variable being used in classification leads to the estimation of maximum fraction p_{Fe}^{fam}.

So, we take max p_{Fe}^{fam}=0.05 in the N-model case. In the F-model case the discrepancy between simulation and experiment is the greatest for n' variable (see ref./1/), the use of n' in classification leads to the overestimated p_{Fe}^{fam}. So, we shall not consider the greatest max p_{Fe}^{fam} value and take max p_{Fe}^{fam}=0.07 in the F-model case. We shall show in Sect.3 that the result is not changed in the case of max p_{Fe}^{fam}=0.1.

3. <u>The upper boundary of flux and fraction of primary iron nuclei</u>. The direct calculation of the maximum fraction max p_{Fe} of primary iron nuclei is not possible by the following reason. The energies of primary particles belonging to L- and Fe-classes are different in simulation (the halfwidth is shown in brackets in PeV)

	N-model	F-model
L-class	6.2 (7.5)	8.5 (10.1)
Fe-class	29.6 (13.1)	29.5 (13.1)

For example, only 8% primary L-class nuclei in N-model have the energy greater than 16.5 PeV, while the iron nuclei energy is mainly greater than the value.

The vertical flux I_{Fe}^{fam} of experimental gamma-families produced by iron

$$I_{Fe}^{fam} = p_{Fe}^{fam} \frac{I^{fam}{}_{\Delta\Omega}}{\Delta\Omega_{Fe}}, \qquad (1)$$

where the total flux $I^{fam}{}_{\Delta\Omega}$ =$(1.08 \pm 0.06) \cdot 10^{-8} m^{-2} sec^{-1}$ for experimental families with ΣE_{γ}=100-400 TeV. The flux $I_{Fe}(>10^{16} eV)$ of iron nuclei is connected with I_{Fe}^{fam}:

$$I_{Fe}(>10^{16}\ eV) = I_{Fe}^{fam}/K_{Fe}, \qquad (2)$$

where K_{Fe} is the efficiency of production of gamma-families by iron nucleus at $E > 10^{16}$ eV. In simulation the values are following:

	λ_{Fe}, g/cm^2	$\Delta\Omega_{Fe}$	K_{Fe}
N-model	102	0.75	0.25
F-model	100	0.75	0.26

where λ_{Fe} is the absorption length of gamma-families induced by

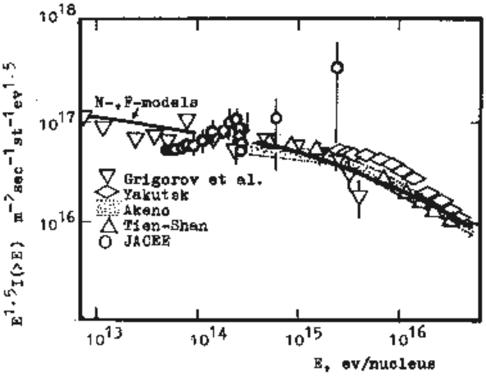

Fig. 1. The primary total energy spectrum. The experimental data are taken in ref./5/. The model spectrum is the approximation /4/

iron nuclei. The cross-section $\sigma^{prod} \sim 1+\alpha \ln E$ in the simulation, $\alpha=0.04$. σ^{prod} is apparently overestimated at $\alpha=0.06$. It is obviously that $\lambda_{Fe} \sim 1/\sigma^{prod}$; $K_{Fe} \sim \exp(-x_o/\lambda_{Fe})$, where $x_o=596$ g/cm^2. The average energy of nucleon contained in iron nucleus is about 600 TeV. The simple estimation at $\alpha=0.06$ gives min $\Delta\Omega_{Fe}=0.7$, min $K_{Fe}=0.14$ for both models.

λ_{Fe} decreases also when σ^{prod}_{FeN} increases. However, the decrease seems to be rather small at great depth in atmosphere. The accurate calculations will be made elsewhere.

The use of eq.(1) and (2) gives max $I_{Fe}(>10^{16}eV)=5.9\cdot10^{-9}$ $m^{-2}sec^{-1}st^{-1}$ and $7.9\cdot10^{-9}$ $m^{-2}sec^{-1}st^{-1}$ in the N- and F-model case at $\alpha=0.06$. The spectra of primary cosmic rays are identical to ones in both models (Fig.1). In the case max $p_{Fe}=0.22$ and 0.29 in N- and F-model. The greatest decrease of the adopted total energy spectrum that does not contradict to the experimental data at $E>10^{16}$eV is about 1.2 times. max $p_{Fe}=0.27$ and 0.35 even in the case. So, the F-model estimation of p_{Fe} is not selfconsistent one: the input (model) iron nuclei fraction (0.63 at $E>10^{16}$eV) is greater than the output (estimated) max p_{Fe}. Even the most suitable case (for F-model) when (1) max $p^{fam}_{Fe}=0.1$ instead of 0.07 (adopted in Sect.2, and (2) the smallest primary energy spectrum leads to $p_{Fe}=0.50$ and the selfconsistency is not achieved. In the N-model case the result is selfconsistent one.

<u>4. Gamma-family flux</u>. The total flux I_{fam}, of gamma-families with $\Sigma E_\gamma=100$-400 TeV is equal to $7.0\cdot10^{-8}$ $m^{-2}sec^{-1}$ in the N-model case, while the experimental flux is equal to $(1.08\pm0.06)\cdot10^{-8}$ $m^{-2}sec^{-1}$. If one takes $\alpha=0.06$, then the simple calculations give the smallest flux of the N-model simulated families $2.6\cdot10^{-8}$ $m^{-2}sec^{-1}$. The only way exists for the agreement between the N-model flux and experimental one: (1) the greater size of scaling violation, and (2) the rather great energy has to go into secondary kaons and η-(η'-) mesons in hN-interactions at 10^{15}-10^{16}eV. Both factors lead to decrease of the simulated flux.

<u>5. Conclusion</u>. Pamir experiment gamma-families show that the flux of primary iron nuclei

$$I_{Fe}(>10^{16}\ eV)<5.9\cdot10^{-9}\ m^{-2}sec^{-1}st^{-1}$$

with probability ~0.67, because the estimated upper boundary is equal to average plus one standard deviation. The corresponded fraction of iron nuclei: $p_{Fe}(>10^{16}eV)<22\%-27\%$. The estimated upper boundary of iron nuclei flux is consistent with the indirect Tien-Shan data and with the simple extrapolation of low energy direct results (Fig.2). On the other hand, the estimation contradicts to the assumption on the heavy enriched composition at $E_0>10^{15}$eV. The estimation has been made by use of the various pair combinations of energy, lateral and azimuthal symmetry characteristics of gamma-families.

The gamma-family flux has not been used in the analysis. The flux of the simulated families 2.4 times greater at least than the experimental flux. The fact is the additional independent confirmation of the more strong scaling violation size conclusion /7/. The additional decrease of the simulated families flux can be obtained if the rather great energy goes into secondary kaons and η-mesons in hN-interactions at $E>10^{15}$ eV.

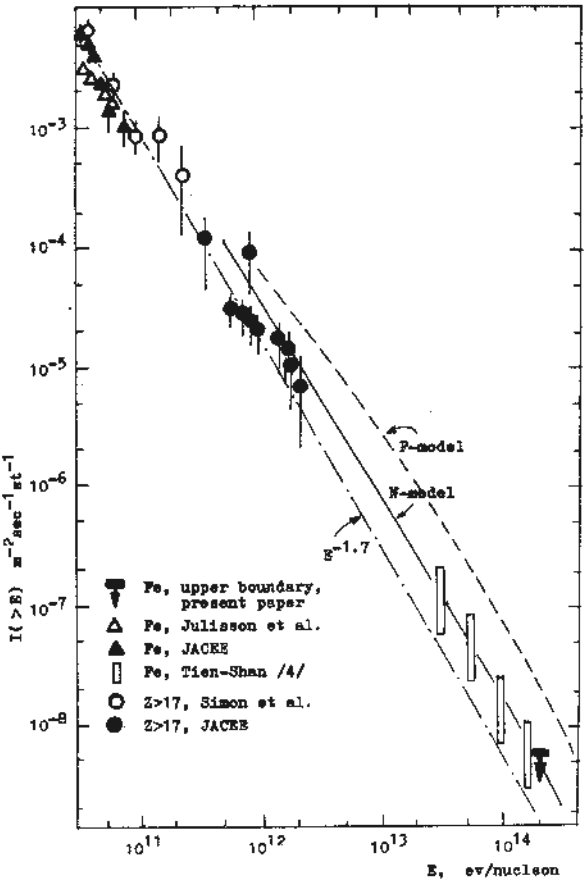

Fig. 2. The experimental data (except Tien-Shan ones) are taken in Ref./6/

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