# High-multiplicity events in the interaction of nucleons with photoemulsion nuclei at energies $\gtrsim 1$ TeV

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Experimentally measured counting frequency of events with $n_s \geq 100$ which occur at high altitudes in emulsion stacks due to cosmic ray nucleons is compared with calculations. The measured frequency of events with high multiplicity is approximately 10-fold greater than expected.

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Track scanning of optical cascades in two emulsion stacks with a volume of 80 l, exposed at high altitudes,[1,2] yielded nearly 150 nucleon interactions with $E \gtrsim 1$ TeV[1)] The average number of charged relativistic particles in these interactions $\langle n_s \rangle \approx 25$. In each flight at least one event with $n_s \geqslant 100$ was recorded. Two interactions of protons with the emulsion nuclei with $n_s \geqslant 100$ were also identified during the scanning of a $\sim$45-l stack exposed on board the Intercosmos-6 satellite.[3] The probability of occurrence of events with $n/\langle n_s \rangle \gtrsim 4$, on the basis of data obtained from particle accelerators, is $\lesssim 10^{-3}$. In this connection we compared experimental data for events with $n_s \geqslant 100$ with the expected frequency of these events.

Stack sizes are given in the aforementioned references. When calculating the geo-

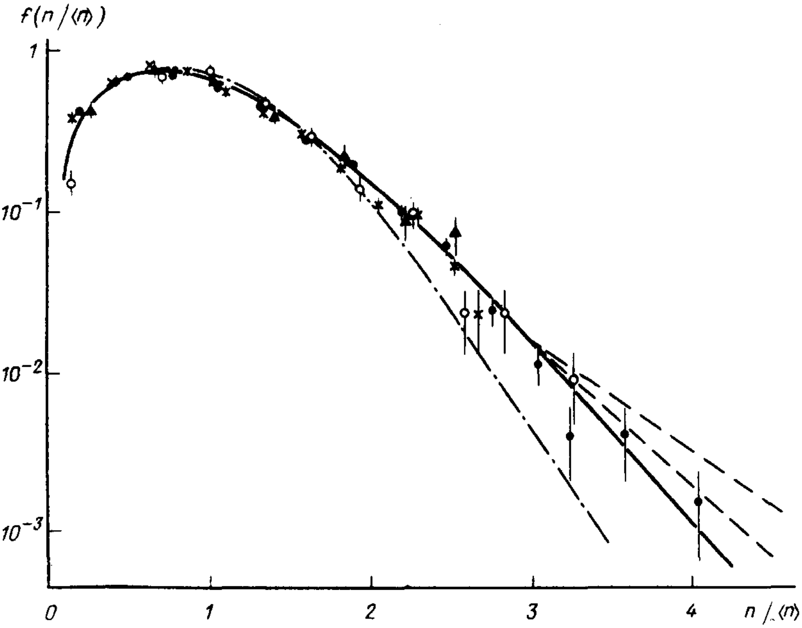

FIG. 1. Function $f(n/\langle n\rangle)$ of proton interactions in photoemulsion: ○—25 GeV; ▲—67 GeV; ●—200 GeV; ×—400 GeV. Solid and dashed lines—different approximations. Dot-dash line—$f(n/\langle n\rangle)$ for *p-p* interactions at 50–300 GeV.

metrical parameters for cascade counting, the angular distribution of nucleons incident on a stack was assumed to be isotropic and the nucleon interaction length in the emulsion was 35 cm. The average distance from the interaction point to where the casade is visible to the naked eye was taken to be ~10 cm. Also taken into consideration was the fact that only those cascades were used in the subsequent processing in Refs. 1 and 2, whose projections onto the emulsion plane were not less than 2 mm, and in Ref. 3–not less than 1.5 mm. As a result it was established that the geometrical factors for the counting of cascades due to nucleon-nuclear interactions by means of stacks exposed in Refs. 1–3 were 0.22, 0.22, and 0.19 $\mathrm{m}^2$ sterad. The exposure times were 32, 36, and 100 hours, respectively. Thus, counting frequency of events with $n_s \geqslant 100$ were $\nu_1 = 0.14 \pm 0.14$, $\nu_2 = 0.13 \pm 0.13$, and $\nu_3 = 0.11 \pm 0.07\ \mathrm{m}^{-2}\,\mathrm{hr}^{-1}\,\mathrm{sterad}^{-1}$. The mean value was $\nu_{\rm exp}(n_s \geqslant 100) = 0.12 \pm 0.06\ \mathrm{m}^{-2}\,\mathrm{hr}^{-1}\,\mathrm{sterad}^{-1}$.

The expected frequency of interactions with $n_s \geqslant n$.

$$\nu_{\rm calc}(n_s \geqslant n) = \int_{E_{\rm opt}}^{\infty} F(E)\, W\left(E; E_k \geqslant E_{\rm opt}\right) f\left(\geqslant \frac{n}{\langle n(E)\rangle}\right) dE,$$

where $F(E)dE$ is the differential energy spectrum of nucleons; $W(E;\, E_k \geqslant E_{\rm opt})$ is the probability that as a result of interaction of a nucleon with energy $E$, energy $E_k$ is transferred to the electromagnetic cascade which is greater than the energy $E_{\rm opt}$ at which cascades are seen with the naked eye; $f(\geqslant n/\langle n(E)\rangle)$ designates a probability that an interaction with $n_s \geqslant n$ will be observed when recording interactions of nucleons with energies $E$ and average multiplicity of charged relativistic particles $\langle n(E)\rangle$.

Calculations carried out at several laboratories yield $E_{\text{opt}} \approx 0.5$ TeV. We determined the function $W(E;\ E_k \geqslant 0.5\ \text{TeV})$ on the basis of our measurement of distribution of that portion of energy which the hadrons with $E \gtrsim 1$ TeV transfer to $\pi^0$-mesons in a layer of iron with a thickness 0.6 times the interaction length.[4] To determine function $f(\geqslant n/\langle n\rangle)$ we used the accelerator data on the interaction of protons with photoemulsion nuclei. The scaling topological function $f(n/\langle n\rangle)$ shown in Fig. 1 was constructed. The solid line represents an approximation. In the region $n/\langle n\rangle \geqslant 3$ the function is exponential $f(n/\langle n\rangle) \sim \exp(-2.5n/\langle n\rangle)$. We calculated that the average multiplicity associated with interactions in the photoemulsion was 1.7-fold greater than in the $p$-$p$ interactions for which $\langle n(E)\rangle_{pp}$ was taken from Ref. 5. Thus, $\langle n(E)\rangle_{p\,\text{emul}} = 1.7\ (1.65 \times \ln S - 1.84)$, where $S$ is in GeV$^2$.

Three possibilities were considered when analyzing the nucleon spectrum. First, total flux of primary nucleons with $E = 1$ TeV was considered (both protons and nucleons packed in the nuclei) and subsequently extended in the high-energy region with $\gamma = 2.6$. In the second case, the nucleon flux which comprises the primary nucleus flux with the spectrum $F(E) \sim E^{-2.6}$ primary nucleons were added with the spectra recorded on the Proton satellite.[6] Finally, we selected the proton spectrum measured in Ref. 6 to be the nucleon spectrum.

TABLE I.

| Nucleon spectrum | $f(n/\langle n\rangle)$ at $n/\langle n\rangle \geqslant 3$ | | | What required |
|---|---|---|---|---|
| | $\sim \exp\left(-\frac{2.5n}{\langle n\rangle}\right)$ | $\sim \exp\left(-\frac{2.0n}{\langle n\rangle}\right)$ | $\sim \exp\left(-\frac{1.5n}{\langle n\rangle}\right)$ | |
| 1 | 0.016 | 0.036 | 0.096 | 1.4 |
| 2 | 0.007 | 0.018 | 0.053 | 1.1 |
| 3 | 0.003 | 0.007 | 0.026 | 0.6 |

Results of calculations of the expected frequency of interactions with $n_s \geqslant 100$ are tabulated above. Calculations were made for three nucleon spectra analyzed which are designated by numbers 1–3. Approximating the function $f(n/\langle n(E)\rangle)$ by a function shown in Fig. 1 we get $\nu_{\text{exper}}/\nu_{\text{calc}} \gtrsim 10$. Calculations were also made to plot the function $f(n/\langle n(E)\rangle)$ in the region $n/\langle n\rangle \geqslant 3$; some of these plots are shown in Fig. 1, and the results are tabulated above. The last column in Table I indicates a value of the exponent $\nu_{\text{calc}} = \nu_{\text{exper}}$. Table I shows that the probability of interactions with high multiplicity should be greater than the probability shown in Fig. 1 (solid line).

Another explanation of the observed frequency of events with high multiplicity is also possible. It requires that we assume a much faster growth of $n(E)$. Thus, in the case of $\langle n\rangle = 0.88 + 0.44 \ln S + 0.12(\ln S)^2$ [7] and spectrum 1, $\nu_{\text{calc}}$ is only half as large as $\nu_{\text{exper}}$, and for spectrum 3 the difference is 10-fold. Cosmic rays indicate that at superhigh energies $n \sim E^{1/4}$. If this is so, transition from the relationship in Ref. 5 to this law for spectrum 1 should occur at energies $E' \approx 10$ TeV and from the relationship in Ref. 7 at $E' \approx 50$ TeV. In the case of spectrum 3, $\nu_{\text{calc}} = \nu_{\text{exper}}$ is unattainable even at $E' \approx 1$ TeV. However, we are unable within the framework of the current analysis to choose between the aforementioned possibilities.

1) The authors wish to thank the Polish physicists for leaving at our disposal certain data obtained in the processing of the stack.

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