Energy dependence of the average multiplicity in hadron–hadron interactions up to ~10^{16} eV

R. A. Antonov, I. P. Ivanenko, and T. M. Roganova
M. V. Lomonosov Moscow State University

(Submitted 5 February 1982; resubmitted 8 April 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 10, 446–449 (20 May 1982)

The energy dependence is found for the multiplicity of the charged particles produced in hadron–hadron interactions at energies up to ~10^{16} eV, from an analysis of extensive experimental data on the cosmic radiation in the atmosphere.

PACS numbers: 13.85.Tp, 94.40.Rc

Calculations have been carried out to determine the behavior of the many cosmic-ray components at various depths in the atmosphere: the intensities and spectra of single γ rays and hadrons, the characteristics of their families, the altitude profile of extensive air showers, and the characteristics of their electron, hadron, and muon components and their Čerenkov radiation. Use was made of the accelerator data on the inclusive cross sections.[1-5] The results show that it is possible to develop a common description of the characteristics of many types of experimental data with the conventional characteristics of the primary cosmic rays[6] or with a spectrum assumed rich in heavy nuclei.[7] The energy dependence of the inelastic cross section is adopted in the form

$$\sigma_{hA}^{in}(E)=\sigma_{hA}^{0,in}(E_0)[1+a_h\cdot\ln(E/E_0)], \tag{1}$$

where

$$h-N,\ \pi^{\pm};E\cong 0.1\,\text{TeV};\ a_N\cong 0.03-0.05;\ a_{\pi^{\pm}}/a_N=\sigma_{NA}^{0,in}/\sigma_{\pi^{\pm}A}^{0,in};$$

and $a_h=0$ corresponds to scaling with a constant interaction cross section. The dependence of the multiplicity of the particles produced in the pionization region on the square of the total energy in the c.m. frame (S) was varied from $\ln^2 S$ to S^{β}, where $\beta\leqslant 0.5$. It was assumed that $n=n^{sc}+n^{N\,sc}$, where

$$n_{\pi^{\pm}}^{sc}(S)=2.4\ln(S/S_1)/(1+a_h\ln(S/S_0)),\ S_1\cong 10\,\text{GeV}^2,\ S_0\cong 160\,\text{GeV}^2, \tag{2}$$

$$n_{\pi^{\pm}}^{Nsc}(S)=4\eta\frac{\pi}{2}\frac{S^{\beta}}{2<m_{\perp}>}\Big/(1+a_h\ln(S/S_0)),\ <m_{\perp}>=0.4\,\text{GeV};\ \eta=\frac{2}{3}a_h \quad \text{for } \beta=0.5, \tag{3}$$

or

$$n_{\pi^{\pm}}^{Nsc}(S) = 4\eta \frac{\ln(S/S_0)}{1 + a_h \ln(S/S_0)} \frac{S^{\beta}}{(2<m_{\perp}>)^{2\beta}} \frac{1}{2} \frac{\Gamma(1/2)\Gamma(\beta)}{\Gamma(1/2+\beta)}, \tag{4}$$

where $\eta \cong \alpha_h(1 - 2\beta)/3x_0^{1-2\beta}$, $x_0 \cong 0.1$, and Γ is the gamma function, for $\beta \lesssim 0.4$.

Analysis of the experimental data showed that the characteristics of the extensive air showers in the early stage of their development are the most sensitive to the particular energy dependence of the multiplicity (the degree of energy division). A series of experiments carried out with some unique apparatus carried on aircraft[8] and high-altitude balloons[9-11] has yielded some detailed data for altitudes up to ~12 km on the altitude profile of showers, the position of maximum shower development in the atmosphere, the shape of the spatial distribution of the particles, and the shape of the shower spectra in the number of particles.

To analyze the spatial distribution function of the particles and to take the effect of fluctuations into account more accurately, we carried out calculations on the three-dimensional evolution of extensive air showers in the atmosphere by the Monte Carlo method.[12]

Here are the basic conclusions which we drew from a comparison of the calculated results with experiment.

1—The flux density of extensive air showers with more than 10^6 particles measured at depths of 210-230 g/cm^2 is about six orders of magnitude higher than that calculated under the assumption of scaling with a constant cross section and under the assumption of the primary spectrum of Ref. 6; it is about ten times that calculated with scaling with a constant cross section under the assumption that the primary radiation consists of iron nuclei exclusively; and it agrees with that calculated under the assumption $\alpha_N \cong 0.05$ and $\beta \cong 0.4$-0.5 with the primary spectrum of Ref. 6.

2—The index (κ) of the integrated spectrum of extensive air showers in the number of particles which has been measured by various methods with several different instruments remains essentially constant over observation altitude and is $\kappa \cong 1.6 \pm 0.1$ down to a depth ~200 g/cm^2. This value of κ agrees with that calculated for $\alpha_N \cong 0.05$ and $\beta \cong 0.4$-0.5 for primary protons. The calculated value of κ for $\alpha = 0$ is $\kappa = 4.0$ for primary protons and $\kappa = 3.0$ for primary iron nuclei.

3—The spatial distribution of the particles measured at a depth ~250 g/cm^2 at distances $\lesssim 15$ m from the axis of the extensive air showers is approximated by the function r^{-n} with $n = 0.73 \pm 0.05$. The spatial distribution calculated for primary protons with $\alpha_h = 0$ corresponds to $n = 1.3$. For primary iron nuclei, $n = 1.0$. Calculations are currently being carried out for primary protons with $\alpha_N \cong 0.05$ for various distributions in the transverse and longitudinal momenta of the particles produced. The agreement of the measured spatial distribution with that calculated in Ref. 16 for primary protons interacting in accordance with a high-multiplicity model with an average transverse momentum $\langle p_{\perp} \rangle = 0.4$ GeV/c shows that $\langle p_{\perp} \rangle$ must be assumed to increase severalfold with increasing energy of the interacting particles according to the model under consideration here (in which the multiplicity of the particles produced at energies $\gtrsim 10^{15}$ eV is several times lower than in the high-multiplicity model).

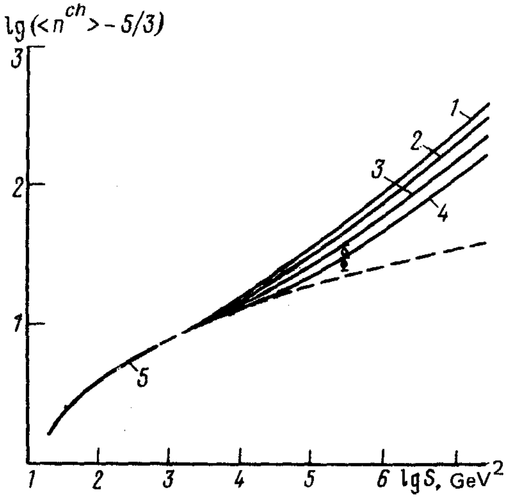

FIG. 1. Dependence of the charged-secondary multiplicity on the energy of the interacting nucleons. Curves 1-5 are calculated. $1-\alpha_N = 0.05, \beta = 0.4; 4-\alpha_N = 0.03, \beta = 0.4$. Curve 5–Accelerator data of Ref. 15 and their extrapolation (dashed part of the curve). ●–Experimental data of Ref. 19; ○–from the experimental data of Ref. 20.

4–The experimental depth of the maximum development of extensive air showers with $N = 10^6$ particles is 450 ± 30 g/cm^2, in agreement with the value found recently from measurements of the shape of the Čerenkov flash with various types of apparatus. This value is inconsistent with that calculated for a primary proton and $\alpha_h = 0$, and consistent with the values calculated for $\alpha_N \cong 0.05$ and $\beta \cong 0.5$ and also with $\alpha_h = 0$ for primary iron nuclei, as are certain other characteristics of extensive air showers.[13]

The combined experimental results on the characteristics of extensive air showers in the upper half of the atmosphere are at odds with the results calculated from this model under the assumption that the primary radiation in the energy range 10^{15}-10^{16} eV consists primarily of heavy nuclei ($A \cong 50$) and under the assumption that the nucleus-nucleus interaction can be described by the independent-collision model, as at lower energies.

The experimental results agree with the results calculated for the primary cosmic ray spectrum of Ref. 6 with $\alpha_h = 0.04$-0.05 and $\beta \cong 0.4$-0.5. Figure 1 shows the dependence of $\log n^{ch}$ on $\log S$ recalculated from Eqs. (2)-(4) for a nucleon-nucleon collision.

Other cosmic-ray data which have appeared in recent years require a rapid increase in the secondary-particle multiplicity with the energy.[14] All these data are in qualitative agreement with the theoretical predictions of Logunov *et al.*[17] regarding a possible rapid increase in the multiplicity of particles produced in the pionization region, and they are also in agreement with some calculations based on quantum chromodynamics.[18]

An accelerator study of the inclusive cross sections and of the behavior of the inelasticity coefficients in the energy ($\sqrt{S}$) range 50-500 GeV would make it possible to determine a possible mechanism for the disruption of scaling, to refine the parameters of the model, and to make effective use of this model over a broad energy range to analyze the characteristics of hadron-nucleus interactions and the chemical composition and spectrum of the primary cosmic rays.

1. I. P. Ivanenko, B. L. Kanevskiĭ, and T. M. Roganova, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 704 (1978) [JETP Lett. **28**, 654 (1978)]; Yad. Fiz. **29**, 694 (1979) [Sov. J. Nucl. Phys. **29**, 358 (1979)]; Preprint No. 001, Lebedev Physics Institute, Moscow, 1979.
2. R. A. Antonov, L. G. Dedenko, I. P. Ivanenko, B. L. Kanevskiĭ, V. V. Makarov, and T. M. Roganova, Izv. Akad. Nauk SSSR, Ser. Fiz. **44**, 557 (1980).
3. R. A. Mukhamedshin, Proceedings of the Seventeenth International Cosmic Ray Conference, Vol. 5, 1981, pp. 343, 347.
4. V. V. Makarov, V. I. Galkin, L. A. Hein, I. P. Ivanenko, and B. L. Kanevsky, Proceedings of the Seventeenth International Cosmic Ray Conference, Vol. 6, 1981, p. 135.
5. A. A. Lagutin, V. V. Uchaikin, and G. V. Chernyaev, Proceedings of the Seventeenth International Cosmic Ray Conference, Vol. 6, 1981, p. 260.
6. S. I. Nikol'skiĭ, Izv. Akad. Nauk SSSR, Ser. Fiz. **39**, 1160 (1975).
7. E. Juliusson, Proceedings of the Fourteenth International Cosmic Ray Conference, Vol. 8, 1975, 2689.
8. R. A. Antonov and I. P. Ivanenko, Yad. Fiz. **19**, 869 (1974) [Sov. J. Nucl. Phys. **19**, 443 (1974)].
9. R. A. Antonov, V. A. Astafiev, I. P. Ivanenko, and T. M. Kopylova, Proceedings of the Fifteenth International Cosmic Ray Conference, Vol. 8, 1977, p. 137.
10. R. A. Antonov, I. P. Ivanenko, and V. A. Kuzmin, Proceedings of the Sixteenth International Cosmic Ray Conference, Vol. 9, 1979, p. 263.
11. R. A. Antonov, V. A. Kuzmin, and I. M. Fateeva, Proceedings of the Seventeenth International Cosmic Ray Conference, Vol. 6, 1981, p. 229.
12. R. A. Antonov, I. P. Ivanenko, and V. A. Kuzmin, Proceedings of the Seventeenth International Cosmic Ray Conference, Vol. 6, 1981, p. 225.
13. T. Gaisser *et al.*, Rev. Mod. Phys. **5**, 859 (1978).
14. M. Akashi, M. Amenomori, E. Konoshi *et al.*, ICR Report 91-81-12, Institute for Cosmic Ray Research, University of Tokyo, 1981.
15. W. Thome *et al.*, Nucl. Phys. **B129**, 365 (1977).
16. N. N. Kalmykov and G. B. Khristiansen, Yad. Fiz. **21**, 757 (1975) [Sov. J. Nucl. Phys. **21**, 391 (1975)].
17. V. V. Ezela, A. A. Logunov, and M. A. Mestverishvili, Preprint IHEP 72-1, Serpukhov, 1971.
18. L. V. Gribov, E. M. Levin, and M. G. Ryskin, Fizika vysokikh énergiĭ (materialy 16 zimneĭ shkoly LIYaF) (High-Energy Physics. Proceedings of the Sixteenth Winter School of the Leningrad Institute of Nuclear Physics), Leningrad, 1981, pp. 3–25.
19. K. Alpgard *et al.*, Phys. Lett. **B107**, 315 (1981).
20. G. Arnison *et al.*, Phys. Lett. **B107**, 320 (1981).

Translated by Dave Parsons
Edited by S. J. Amoretty