08/01/94

FPRINT-94-43

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ICHEP94 Ref. 0034
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ON THE NATURE OF THE "KNEE" IN OBSERVED HIGH ENERGY COSMIC RAYS SPECTRA.

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Abstract

A simulation of extended air showers (EAS) initiated by primary nuclei with A = 1, 4, 14, 28 and 56 for different fixed energies in the range $10^{13} - 10^{17}$ eV has been made using our string-decay cascade interaction model that extrapolates accelerator data.

Obtained cascade curves were used for electron number spectra calculation assuming primary cosmic rays spectrum and chemical composition that are consistent with JACEE and recent Fly's Eye data.

We have got a good quantitative description of experimental spectra for $N_e = 10^5 - 10^8$ and altitudes 500-900 g/sm^2. The "knee" near $N_e = 10^6$ can be regarded as a joint effect of the power dependence between N_e and E violation for primary protons and of the primary nuclei spectra slopes growth that is necessary for JACEE and Fly's Eye data consistency.

The nature of Extended Air Showers (EAS) spectra slope change near $N_e = 10^6$ is essential for solution of high energy cosmic rays origin problem as well as for interpretation of cosmic rays data in terms of interactions properties. The usual approach to the primary energies spectrum investigation is recalculation of N_e at definite altitude to primary E using model-dependent function:

$$N_e = \alpha E^{\beta} \tag{1}$$

But this approach is not taking into account the primary cosmic rays chemical composition and N_e fluctuations at the fixed E. In the present paper we are calculating N_e spectra for different altitudes directly from assumptions on interaction properties and primary spectrum considering EAS fluctuations and the chemical composition.

1 The interaction model and simulation procedure

The hadron-hadron interactions model [1] was used for the simulation. This model is based on the picture of cascade fragmentation of hadron strings, which is simulated by chains of unisotropic decays of heavy objects. The model well reproduces inclusive data (including P_t data) of accelerator experiments on PP - interactions at $\sqrt{S}$ from 30 to 1800 GeV in the central region as well as existing data in the fragmentation region of secondary particles spectra. It gives unessential Fainman scaling violation in the fragmentation region for secondary particles. The model simulates pions, nucleons and strange particles generation. The KNO - scaling violation and correlations between multiplicity and transversal momenta at the energy over ISR region are not reproduced. The model has a reasonable "logarithmical" extrapolation to super high energies.

The experimental data extrapolations [2] for hadron - hadron total, elastic and diffraction cross sections were used. All cross sections were recalculated to the hadron - nucleus case considering experimental rates at lower energies. The difference between hA and hP collisions was accounted by the simulation of secondary collisions inside the nucleus for the increased multiplicity in hA - collisions reproducing.

It was assumed that the primary particles of cosmic rays are protons and nuclei flying into the atmosphere from the vertical direction. The three - dimensional simulation for electron - photon cascade component was fulfilled for particles with energies more than 10^{-5} of primary energy. If an electron or photon with the energy lower than this threshold was generated, the contribution of electron - photon cascade initiated by this particle into N_e was analytically calculated considering the particle energy, depth of generation and individual fly angle. The threshold for hadron component simulation was lower - 10^{-6} of primary energy. Hadrons with energies lower than the threshold was rejected, but their energies in every cascade were summarized for energy leakage control. During the calculation the total control of energy and momenta conservation for every cascade as

a whole was fulfilled. There was simulated 100 cascades for each of the following fixed primary energies E : $10^{13}, 10^{14}, 10^{15}, 10^{16}$ and 10^{17} eV and for atomic weight of primary nuclei A = 1, 4, 14, 28 and 56. The N_e was calculated for atmosphere depths Z from 500 to 1030 g/sm^2.

2 Primary cosmic rays spectrum and composition

Recent new data from JACEE [3] and Fly's Eye [4] experiments gives us the possibility to propose new chemical composition and E spectrum approximation. The JACEE data near $E = 10^{14}eV$ shows a growth of nuclei contribution in the cosmic rays composition whereas Fly's Eye data on cascade maximum depth leads to conclusion that at $E = 10^{18}eV$ heavy components of cosmic rays are vanishing. We are assuming here the following nuclei primary differential spectra that are in concordance with new data (see fig. 2 and 3):

$$\lg(E^{2.8}I_P) = 20.55 \tag{2}$$

$$\lg(E^{2.8}I_{He}) = 20.65 + 0.2(\lg E - 13) - 0.07(\lg E - 13)^2 \tag{3}$$

$$\lg(E^{2.8}I_{CO}) = 19.20 + 0.27(\lg E - 13)(18.5 - \lg E) \tag{4}$$

$$\lg(E^{2.8}I_{NeS}) = 18.90 + 0.27(\lg E - 13)(18.5 - \lg E) \tag{5}$$

$$\lg(E^{2.8}I_{Fe}) = 19.20 + 0.27(\lg E - 13)(18.5 - \lg E) \tag{6}$$

Where E is in eV, and I are in $m^{-2}s^{-1}sr^{-1}eV^{-1}$.

So here primary E spectrum of protons have not slope change and nuclei are dominating at definite energies region.

3 Calculation of N_e spectra

As a result of the Monte-Carlo simulation the cascade curves for different fixed E and A was obtained. At the Fig.1 cascade curves for A=1 and A=56 are plotted. For our

further calculations we have made approximations of average N_e logarithm and square root from dispersion of N_e logarithm σ - both versus primary energy E:

$$< \lg N_e >= P + Q \lg E + R \lg E^2; \tag{7}$$

$$\sigma = a + b \exp(-c(\lg E - 13)). \tag{8}$$

Approximations of $< \lg N_e >$ considers a small violation of power dependence between N_e and E.

We have adopted that $\lg N_e$ distribution at fixed primary energy has a shape of normal distribution:

$$\frac{dW}{dy} = \frac{1}{\sigma(x)\sqrt{2\pi}} \exp - \frac{(y - < \lg N_e > (x))^2}{2\sigma^2(x)} \tag{9}$$

where $y = \lg N_e$; $x = \lg E$; $\sigma(x)$ - square root from dispersion of $\lg N_e$, depending on $\lg E$ according to (8), and $< \lg N_e >$(x) is (7).

We can calculate $\lg N_e$ spectra for observation level by the following way:

$$\frac{dI}{dy} = \int_{-\infty}^{\infty} \frac{dI}{dx} \frac{dW}{dy}(x) dx \quad , \tag{10}$$

where x = lgE, and

$$\frac{dI}{dx} = \frac{dI}{dE} \frac{dE}{dx} = \frac{dI}{dE} E \ln 10$$

We will get after necessary transformations:

$$\frac{dI}{dN_e} = \frac{1}{N_e\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{dI}{dx} \exp\left(-\frac{(\lg N_e - < \lg N_e > (x))^2}{2\sigma^2(x)}\right) \frac{dx}{\sigma(x)} \tag{11}$$

Then we have taken into account the experimental errors of N_e measurements. The reported errors [5] was approximated by the following way:

$$\sigma_{exp} = 0.096 + 0.4 \exp(-0.94(\lg E - 13)) \tag{12}$$

And in the integral (11) calculation there was used $\sqrt{\sigma^2 + \sigma_{exp}^2}$ instead of σ. The integral (11) was calculated numerically in limits providing necessary precision.

4 Results

Results of the N_e spectrum calculation for $Z = 690 g/sm^2$ (Tien-Shan station level [6]) are plotted at Fig.4. We can see that experimental spectrum can be well described by sum of the calculated spectra for all primary nuclei. Violation of power dependence between E and N_e for primary proton leads to the growth of spectrum slope near $N_e = 10^6$, but the "knee" phenomenon looks like a joint effect of this violation for light nuclei and of heavy nuclei E spectra shape.

Fig.5 shows vertical N_e spectra for different altitudes. We can see that our calculation is describing the character of mountains spectra and the area near $N_e = 10^{7.5}$ where the lines are crossed because of cascades maximum passing under the observation level (see also Fig.1).

The description for sea level is worse. But in this calculation there was not considered any methodical effects that can distort the measured vertical spectra. At the mountains level the cascades with $N_e = 10^5 - 10^8$ are investigated near cascade maximum so results can be less sensitive to measurement technique than for sea level.

Figure captions

Fig. 1. Cascade curves - $< \lg N_e >$ for primary protons (solid lines) and iron (dashed). The average squared deviations of $\lg N_e$ are shown.

Fig. 2. Spectra of primary nuclei Ne-S (filled squares, line 1) and C-O (opened squares, line 2). Data from [3], lines - our extrapolations for A=28 and 14.

Fig. 3. Spectra of primary protons (small filled squares, line 1), helium (opened squares, line 2), iron (large crosses, line 3) and total cosmic rays spectrum (large filled squares and small crosses, line 4). Data at $E < 10^{15}$ from [3], at $E > 10^{16}$ - from [4], lines - our extrapolations.

Fig. 4. Vertical N_e differential spectrum for observation level at $Z = 690 g/sm^2$. Data from [6]. Results of calculation: 1 - only protons, power dependence $N_e(E)$ (1) is used; 2 - only protons, calculation with approximation (7); 3 - only proton, fluctuations are taken into account; 4 - helium contribution is added; 5 - CO contribution is added; 6 - NeS contribution is added; 7 - all contributions including iron are considered.

Fig. 5. Vertical N_e differential spectra for different altitudes. Lines - present calculation. Data from appropriate observation levels: (from up to down) [7], [8], [6], [5], [9].

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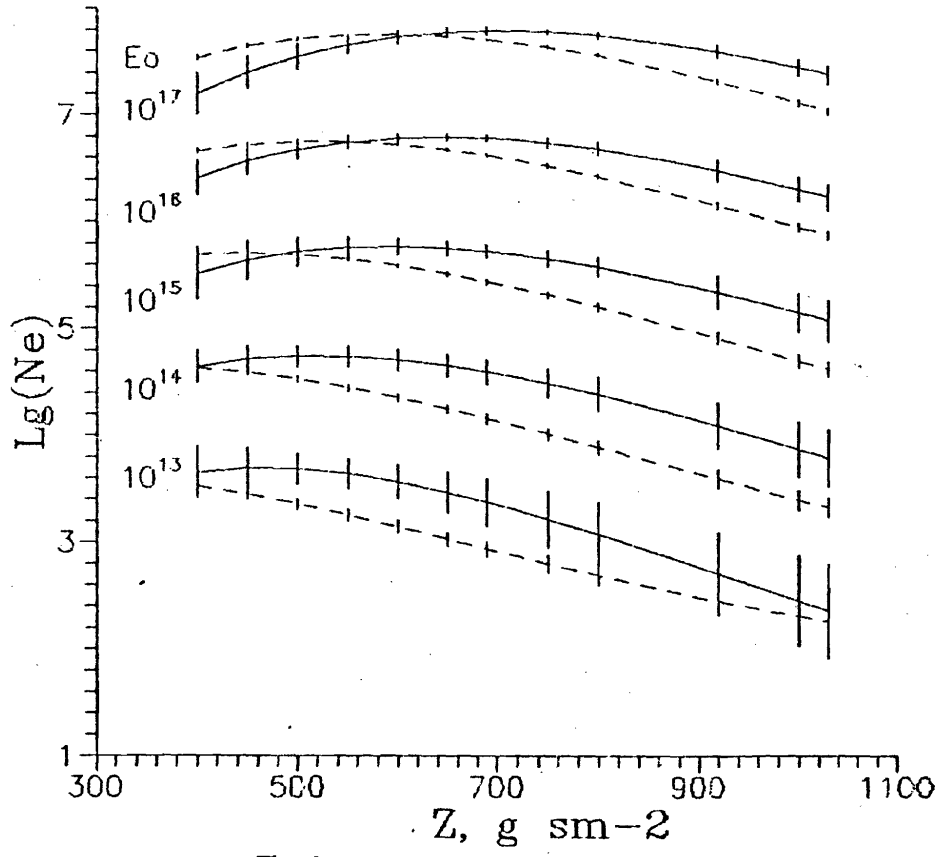
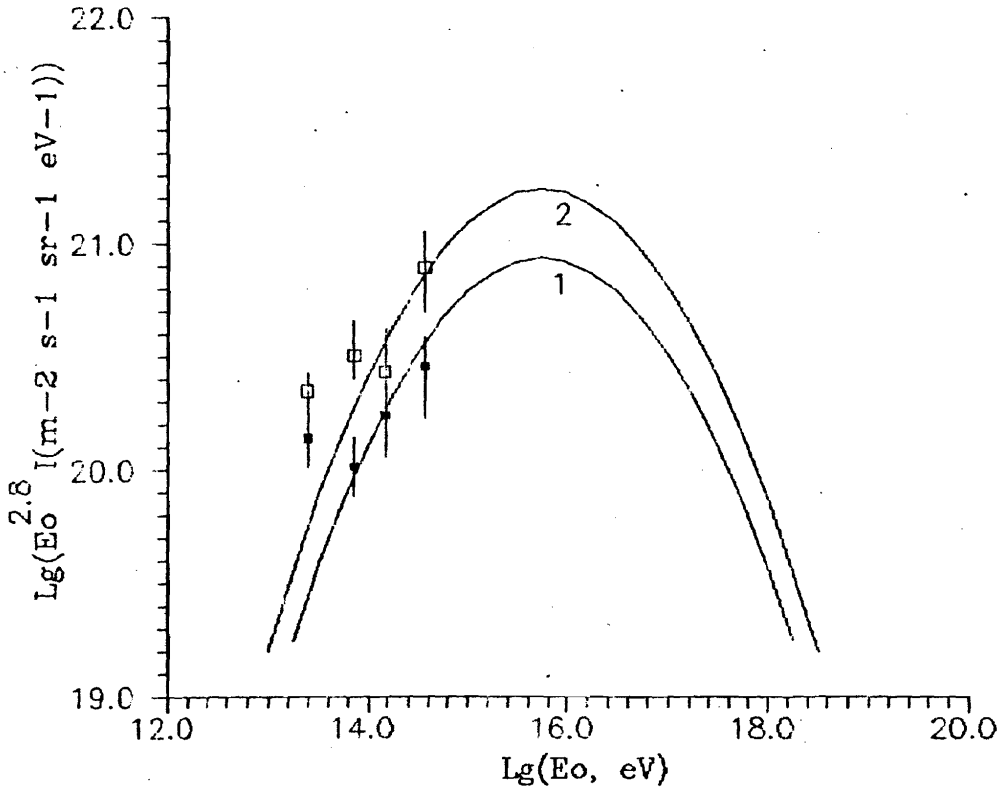

Eo
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
Lg(Ne)
1
3
5
7
300
500
700
900
1100
Z, g sm−2

Fig.1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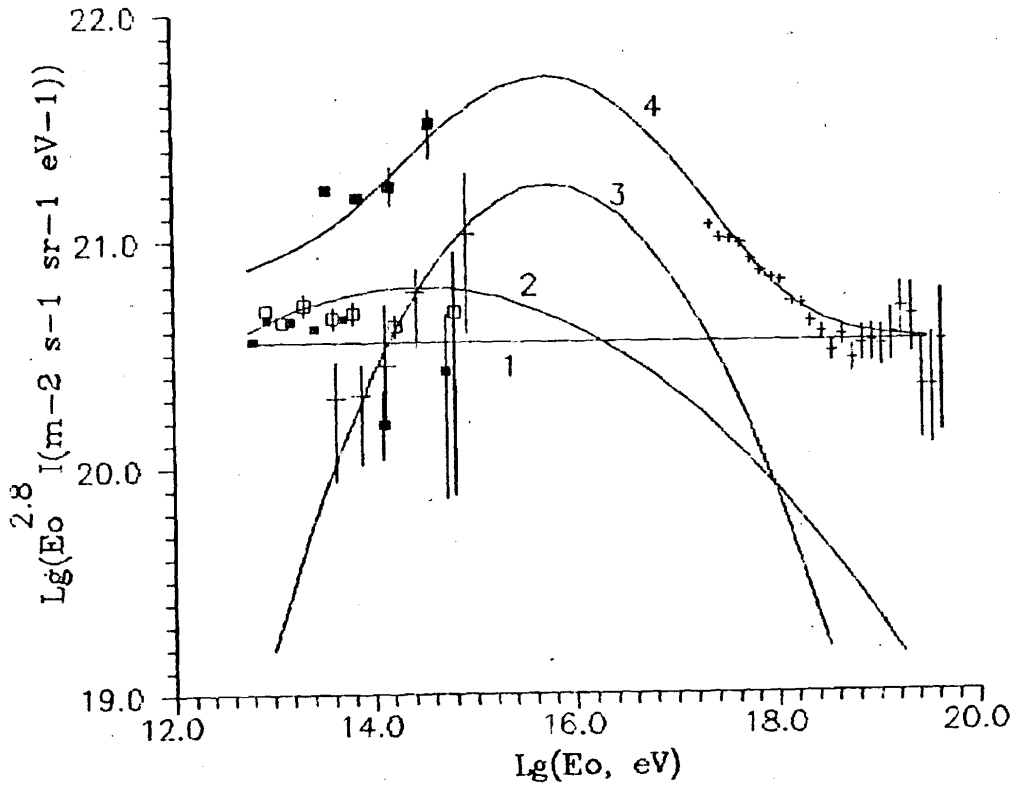
1
2

Fig.2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Lg(Eo^2.8 I(m-2 s-1 sr-1 eV-1))
1
2
3
4

Fig.3

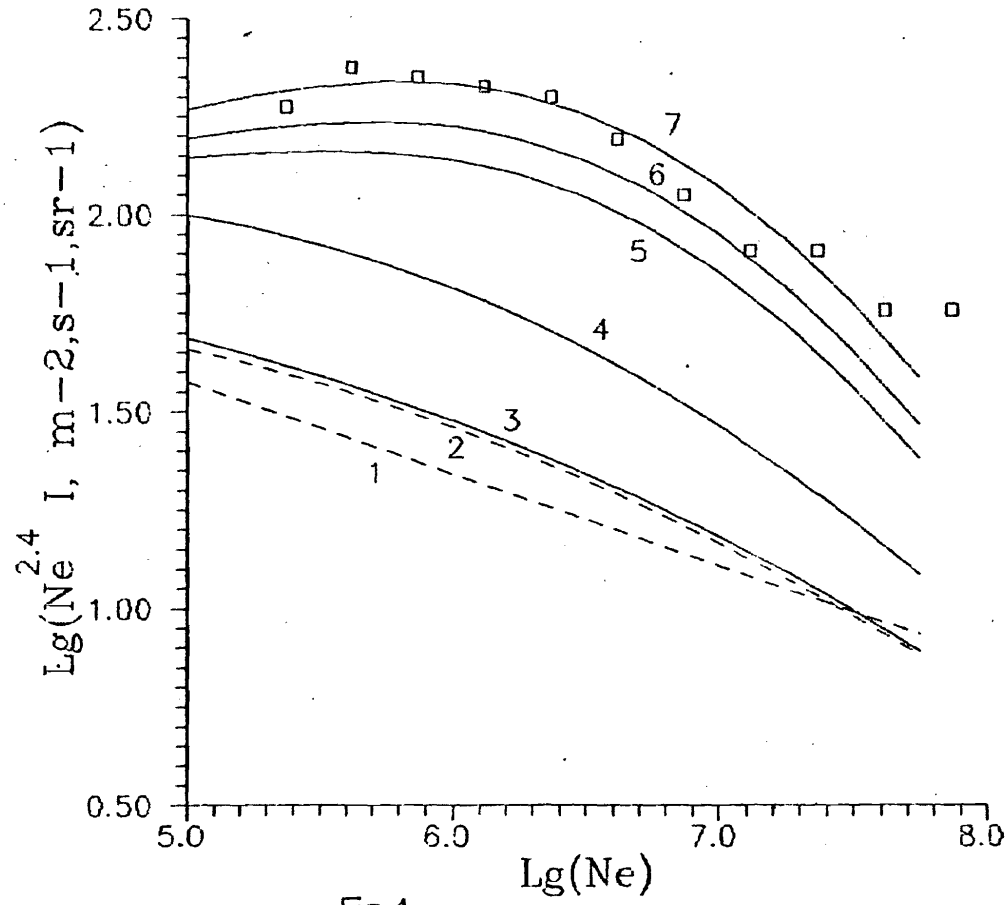

Fig.4

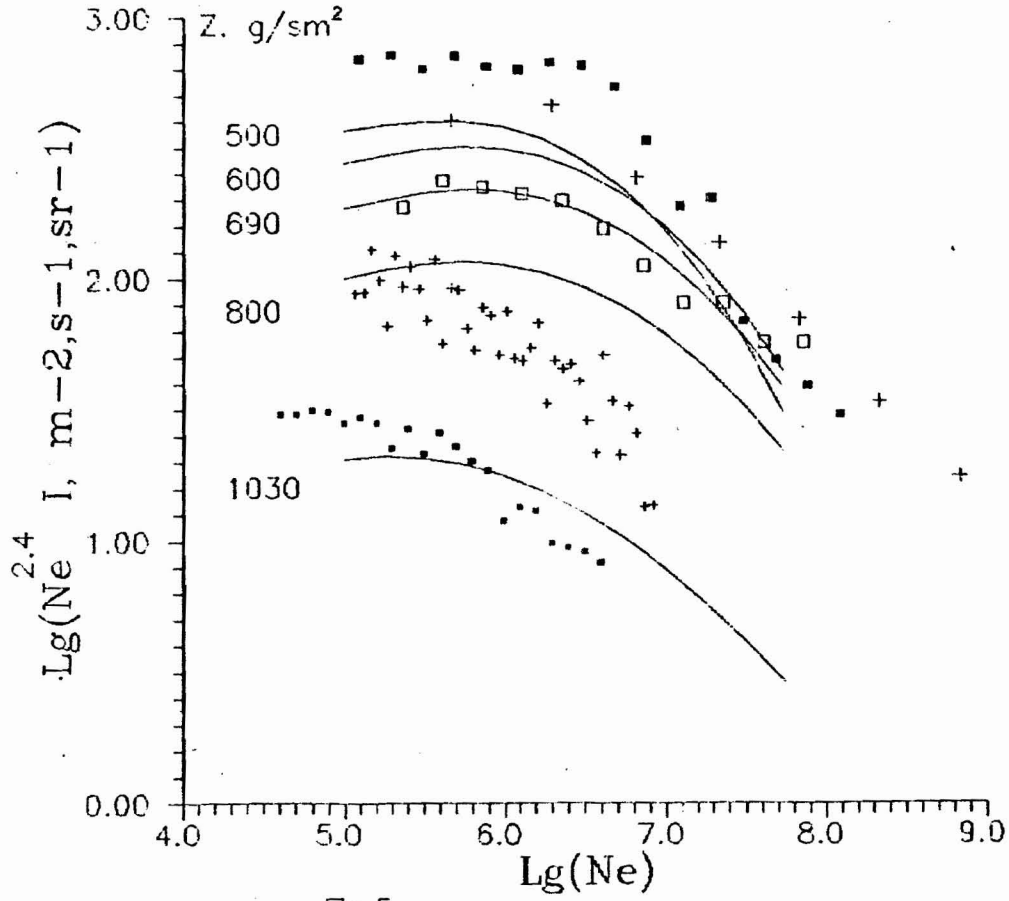
Z, g/sm²
500
600
690
800
1030
3.00
2.00
1.00
0.00
4.0
5.0
6.0
7.0
8.0
9.0
Lg(Ne)
Lg(Ne^2.4 I, m-2,s-1,sr-1)

Fig.5