Primary energy distribution among components of extensive air shower initiated by UHECR

A.A. Ivanov, S.P. Knurenko and I.Ye. Sleptsov
Yu.G. Shafer Institute for Cosmophysical Research and Aeronomy
Lenin ave., 31, Yakutsk 677980, Russia
E-mail: ivanov@ikfia.ysn.ru

***Abstract*— Model calculations are performed of extensive air shower (EAS) component energies using a variety of particle interaction parameters. The main objective is a confidence region of unobservable characteristics which are essential for the shower primary particle energy estimation algorithm in ultra-high energy cosmic ray (UHECR) physics.**

I. Introduction

UHECR particles hitting Earth atmosphere produce the cascade of secondary particles, the small part of which are detected on the ground by EAS arrays. The energy of the primary particle is distributed among the shower components. The most of the energy deposit is due to ionization and excitation of the air molecules caused by electromagnetic component.

The primary energy estimation algorithms are based mainly on the measurement of the shower parameters connected to electromagnetic component energy. Such an approach is realized in HiRes, Auger (air fluorescence technique) and the Yakutsk array (air Cherenkov light measurement) experiments. Future applications are planned in the Telescope Array and satellite projects.

In all these experiments a fraction of the primary energy cannot be detected because it is carried away by hadrons, muons and neutrinos (muons are detected at the Yakutsk array). This 'missing energy' can be estimated only basing on the simulations of the cascade in atmosphere.

II. Basic experimental data

Measurements of the shower maximum position in atmosphere, x_{max}, as a function of the primary particle energy and the number of muons at the sea level (usually as a ratio to the number of electrons) are the basic parameters to be guided by performing the cascade simulations in UHE region. We have revealed that almost any model of the shower particle interactions results in congruent values if x_{max} and N_μ/N_e meet experimental data.

The only measurement results available in the region are those given by the HiRes, AGASA and Yakutsk experiments [1], [2], [3]. The HiRes detector (Fly's Eye successor) is measuring air fluorescence light induced by EAS electrons along the shower track. The position of the shower maximum is located by the stereo system of two Eyes. On the contrary, the Yakutsk array detectors are measuring the Cherenkov light generated by relativistic electrons of the shower in air. The lateral distribution form of the light spot on the ground is used to derive the shower maximum position in atmosphere in this case (Fig. 1).

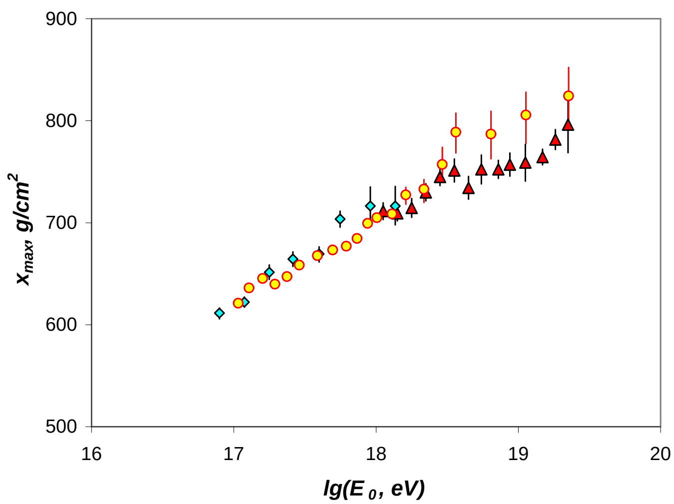

Fig. 1. Shower maximum depth in atmosphere as a function of EAS primary particle energy. HiRes [1] (triangles) and HiRes/MIA [4] (rhombuses) results are shown in comparison with the Yakutsk array data (circles).

The number of electrons and muons on the ground is measured by scintillation detectors/proportional counters (shielded with Fe/concrete and ground to detect muons) of the Yakutsk and AGASA arrays (Fig. 2).

Experimental errors in x_{max} measurement are $\sim$ 30 to $\sim$ 50 g/cm^2 in the whole energy range; N_μ/N_e ratio differs up to $\sim$ 2 times between Yakutsk and AGASA data while the difference in N_μ itself is around 25% [2]. The main source of the discrepancy is the total number of charged particles on the ground which is estimated using the particle density measured at the shower periphery in both experiments.

III. Modeling the cascade in atmosphere

Let us forget all nuclear interaction parameter predictions (concerning cross sections, multiplicities etc.) in very high energy region based on extrapolation of accelerator data. Instead, we can verify model predictions using air shower observables shown in the preceding section.

Our previous calculation of the energy balance of EAS components insists [6] that the energy of the primary particle

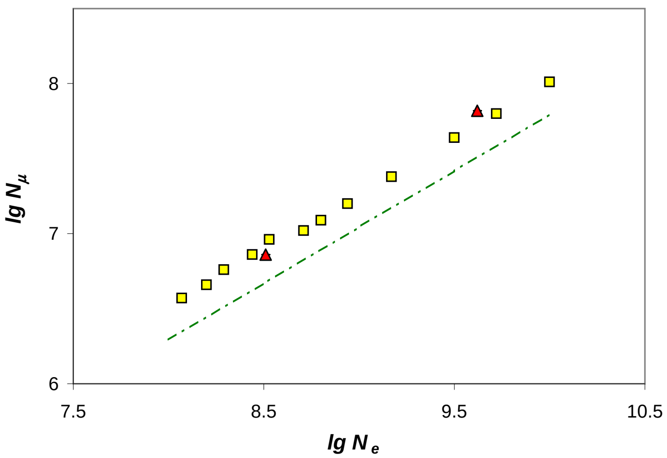

Fig. 2. The number of muons ($E_\mu > 1$ GeV) vs number of electrons at the sea level. Current and previous [3] Yakutsk array data are shown by squares and triangles. AGASA data approximation [2] is given at $x = 1020$ g/cm^2 by dash-and-dot line.

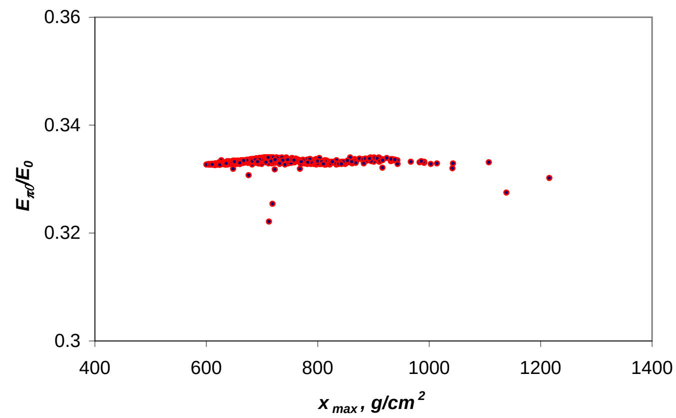

Fig. 3. Event-by-event fluctuations in a leading fragment approximation.

deposited as ionization energy in atmosphere depends mainly on inelasticity coefficients and cross sections of particle interactions. All other model parameters - such as the multiplicity of secondaries, their production spectrum form and others, are less relevant and can be parameterized via resultant x_{max} and N_μ/N_e of the shower.

In this paper we are using three models of hadronic interactions which are characterized by extremely different forms of the rapidity, y, distribution of the 'sea' secondaries in pionization region: i) Gauss model with normal rapidity distribution; ii) Delta model with equal rapidities of n_s secondaries and iii) Flat distribution model with $f(y) = const$. All other parameters of the models are flexible in order to get x_{max} and N_μ/N_e of the shower fitting experimental data within errors. In the Flat distribution model, for instance, the pionization region width and the fraction of secondary pions, kaons and nucleons in multiple production processes have been adjusted in addition to cross sections and fragmentation coefficients to get the output EAS observables desired.

It is well-known that x_{max} is strongly fluctuating parameter of the shower. Monte Carlo simulations using CORSIKA code give RMS deviation ~ 70 and ~ 40 g/cm^2 for proton and Fe initiated showers of the same E_0, correspondingly [5]. On the contrary, the primary energy fraction deposited as ionization energy in the atmosphere is fluctuating much lesser because it is proportional to integral of the electron number along the slant depth, ionization integral.

We study the influence of shower fluctuations on the ionization integral using leading fragment approximation in the simplest case of the primary nucleon - only fluctuations in inelasticity and interaction points of the EAS primary particle are considered as it was proposed in [7]. The electromagnetic component energy originates predominantly in neutral pions decaying into two photons. Bearing in mind the isotopic invariance of multiple production processes and multiplicity distribution we derive the ionization integral event-by-event distribution, $f(E_{e+\gamma})$ with fixed E_0, as a ($n = x_0/\lambda \sim 10$ - fold) convolution of inelasticity fluctuations. Resultant distribution is a Gaussian with average energy fraction

$$\frac{E_{\pi^0}}{E_0} = \frac{1-\bar{K}^n}{1-\bar{K}}\overline{K_{\pi^0}},$$

where K is elasticity in nucleon interactions; K_{π^0} is projectile energy fraction carried out by neutral secondary pions. RMS deviation is $\approx\ 0.001$ as illustrated in Fig. 3. We neglect fluctuations in the rest of E_0 distributed among the shower components because of averaging over a huge number of secondaries.

IV. Results

We are interesting in the total ionization integral of electrons (i.e. electromagnetic component energy, $E_{e+\gamma}$) and the energy deposited to muons+neutrinos in a shower. These values are calculated in our models as the energy of decaying neutral pions ($E_{e+\gamma}$) and charged pions+kaons decay, respectively (Fig. 4). Hadronic component energy is less than $0.01E_0$ at the sea level, x_0.

Ionization loss of electrons in atmosphere, E_i, is closely related to the total air Cherenkov light flux on the ground [3], [6] and is measured with Cherenkov light detectors of the Yakutsk array. A point in Fig. 4 is given with experimental error in the aggregate of calibration, atmospheric extinction of light uncertainty, etc.

The energy of muons and neutrinos at the sea level is estimated as a sum of E_μ measured on the ground and model calculation results giving energy of neutrinos, ionization loss and decay of muons [8]. Absolute experimental $E_{\mu+\nu}$ uncertainty ($\sim\ 2\%$) is estimated basing on the difference between Yakutsk and AGASA N_μ measurements.

Electromagnetic component energy is $E_{e+\gamma} = E_i + E_l$, where E_l is energy of electrons and photons dissipated in ground for the vertical showers. To estimate this we need the total number of electrons at the sea level and its attenuation length: $E_l \simeq \varepsilon_0 \lambda_{N_e} N_e(x_0)/t_0$. The result based on the

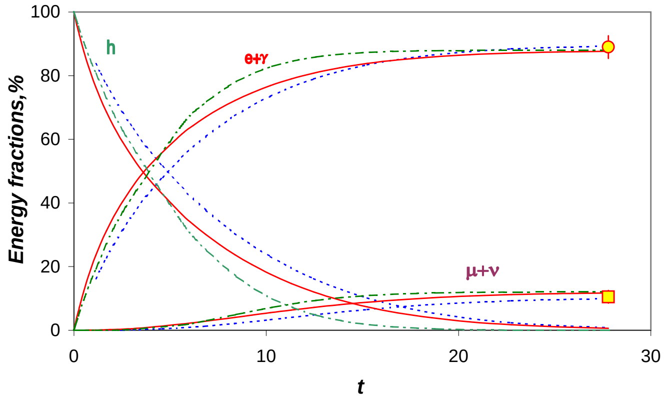

Fig. 4. Energy fractions of EAS components as a function of the depth in atmosphere. Model calculation results are given for hadronic (h), electromagnetic ($e+\gamma$) components and muons and neutrinos ($\mu+\nu$). Solid line refers to Gauss model, dotted line to Delta model and dash-dotted line to the Flat rapidity distribution model. Experimental data of the Yakutsk array are shown at $x = 1020$ g/cm^2: ionization loss of the shower in atmosphere (circle) and energy of muons+neutrinos (square) [9].

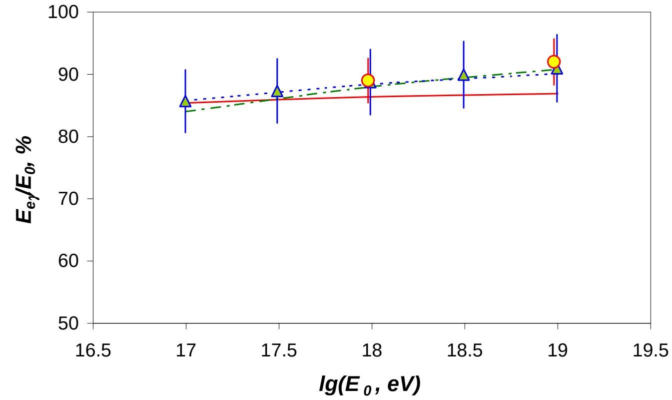

Fig. 5. Electromagnetic component energy fraction vs EAS primary energy. The hadronic interaction model results are shown by the same signs as in Fig. 4. A HiRes estimation based on air-fluorescence measurement + CORSIKA/QGSjet simulations is shown by triangles [1]. Simulation uncertainty 6% due to unknown primary nuclei mass is assigned to points. Two circles at 10^{18} and 10^{19} eV illustrate $E_{e+\gamma}$ evaluation based on the Yakutsk array data [6]. Experimental errors (4%) of ionization loss ratio to E_0 are shown by vertical bars.

Yakutsk array data is shown in Fig. 5 at $E_0 = 10^{18}, 10^{19}$ eV by circles.

Another approach is realized by the HiRes group. Fluorescence light intensity is proportional to the number of electrons in a shower. Integrating it along the axis of inclined shower one can estimate electromagnetic component energy $E_{e+\gamma}$ (ionization integral, Fig. 5). Energy remainder deposited to muons, hadrons and neutrinos undetectable in the HiRes case is estimated using the cascade modeling.

The main feature of results given in Fig. 5 is that different models lead to the very similar fraction of the primary energy assigned to electromagnetic component, $E_{e+\gamma}/E_0$, if x_{max} and N_μ/N_e are coincident. The model uncertainty is less than 3% in energy interval $(10^{17}, 10^{19})$ eV where the experimental data are available. Additionally, the ionization integral and $E_{\mu+\nu}$ is varying with the primary particle mass, even x_{max} is fixed for different nuclei. We estimated the variance to be less than 6% if the primary mass is $1 \leq A \leq 56$. The sum of two uncertainties (coming from the model and primary mass) is $\delta E_{e+\gamma}/E_0 < 7\%$. We have not considered here showers initiated by other primaries, such as photons, neutrinos or mini black holes, because their muon content is not confident enough.

Due to the negligible fraction of hadronic component energy on the sea level, the remainder of E_0 is transferred to muons and neutrinos. As a consequence, $E_{\mu+\nu}/E_0$ is nearly model independent, too. But the muon component energy measurable on the ground is more variable in different models.

V. Experimental uncertainties

The experimental errors in the shower maximum detection and the muon number at the sea level lead to the uncertainty of calculated $E_{e+\gamma}/E_0$ ratio (we will pass over $\delta E_{\mu+\nu}/E_0$ considering it congruous). We have modeled this varying the multiplicity of secondaries and cross sections which result in the changes of x_{max} and $N_\mu(E > 1GeV)$ comparable to experimental uncertainties. Resultant $\delta E_{e+\gamma}/E_0$ turned out to be below 0.05 in the case of x_{max} variation within 50 g/cm^2 and 0.03 for $\delta N_\mu/N_\mu \in (0.75, 1.25)$. And so we have assumed the aggregate experimental uncertainty due to x_{max} and N_μ measurement errors to be $\delta E_{e+\gamma}/E_0 = 0.06$.

The greater uncertainty source is the ionization integral measurement itself. For the Yakutsk array data it comprises of errors due to Cherenkov light measurement and the number of charged particles on the ground [6], [10]: uncertainty in atmospheric transparency (15%); detector calibration (21%) and the total light flux measurement (15%) errors; an uncertainty in the number of electrons at the sea level reaches $30-60\%$ because the only measurable parameter is the particle density beyond hundred meters from the shower core. Resultant $E_{e+\gamma}/E_0$ estimation uncertainty ($\sim 30\%$) is the sum of all these errors weighed with the shower component energies.

The HiRes group claims a systematic uncertainty $\sim 20\%$ [11] aggregated of errors in the absolute calibration of the photo-tubes (10%), the yield of the fluorescence process (10%), the modeling of the atmosphere and so on.

However, a comparison of our model predictions with the HiRes/MIA measurement of the average cascade curve in the interval $(10^{17}, 10^{18})$ eV (Fig. 6) suggests that there may be an additional uncertainty up to 40% in $E_{e+\gamma}/E_0$ assignment due to inadequate fitting of the longitudinal shower profile. This may be the result of increased measurement error of the faint fluorescence light far from the shower maximum, and/or the direct and scattered Cherenkov light contamination to the signal.

VI. Conclusion

A ratio of ionization integral to EAS primary particle energy is practically independent of the model parameters under the

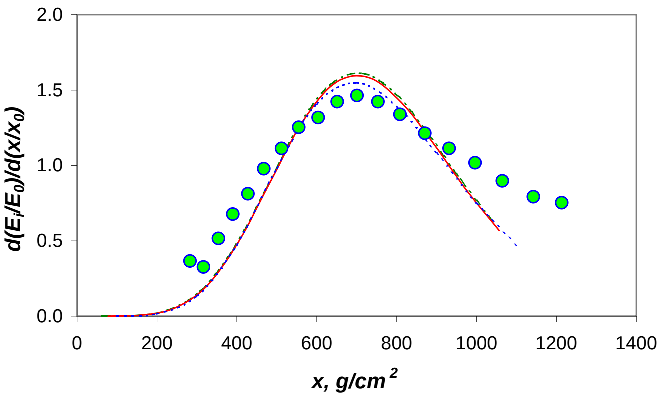

Fig. 6. The average longitudinal profile of EAS ionization loss (circles, $E_0 \in (10^{17}, 10^{18})$ eV) measured in the HiRes/MIA hybrid experiment [4] and shower cascade curve computation results. Signs for models are the same as in previous Figures. Data are shifted to coincide with models at $E_0 = 10^{18}$ eV, $x_{max} = 700$ g/cm^2.

necessary condition of given x_{max} and N_μ/N_e values in a shower. Extremely different models of hadronic interactions lead to the resultant $E_{e+\gamma}/E_0$ values which are consistent within 7% if the model parameters/primary mass guarantee the same EAS maximum position and muon ratio:

$$\frac{E_{e+\gamma}}{E_0} = (0.87 \pm 0.01) + (0.02 \pm 0.01)\lg\frac{E_0}{10^{18}},$$

$10^{17} < E_0 < 10^{19} eV$.

The primary energy estimation algorithms based on ionization integral measurement rely on this ratio and we conclude that its main uncertainty originates from experimental errors ($\leq 45\%$); model dependent one is minor in the presence of contemporary measurements of the main air shower parameters.

Acknowledgment

This work is partially supported by RFBR (grants #06-02-16973, #05-08-50045) and INTAS (grant #03-51-5112).

References

[1] P. Sokolsky, J. Belz and the HiRes Collaboration, *Proc. 29th ICRC, Pune*, vol. 7, 2005, p. 381.
[2] M. Nagano and A. A. Watson, *Rev. Mod. Phys.*, vol. 72, p. 689, 2000.
[3] M. N. Dyakonov et al., *Cosmic Rays of Extremely High Energy* Nauka, Novosibirsk, 1991 (in Russian).
[4] T. Abu-Zayyad et al., *Astropart. Phys.*, vol. 16, p. 1, 2001.
[5] S. S. Ostapchenko, Thesis, Moscow State University, 1994 (in Russian).
[6] V. P. Egorova et al., *Nucl. Phys. B (Proc. Suppl.)*, vol. 136, p. 3, 2004.
[7] L. G. Dedenko, Thesis, FIAN, 1968 (in Russian).
[8] A. D. Erlykin and A. W. Wolfendale, *Astropart.Phys.*, vol. 18, p. 151, 2002.
[9] S. P. Knurenko et al., *JETP Lett.*, vol. 83, p. 473, 2006.
[10] A.A. Ivanov et al., *Nucl.Phys. B (Proc. Suppl.)*, vol. 122, p. 226, 2003.
[11] R.U. Abbasi et al., *Phys. Rev. Lett.*, vol. 92, p. 151101, 2004.