New ideas about measurements of cosmic ray energy spectrum and composition around the knee

A.A. Petrukhin

National Research Nuclear University MEPhI, Moscow, Russia

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Introduction

Energy spectrum and composition – the main characteristics of primary cosmic rays.

EAS parameters measurements – the only possibility of their investigations above $10^{15}$ eV.

All “experimental data” about energy spectrum and composition are results of interpretation of these measurements.

Therefore the question about energy spectrum and composition above the knee is discussed more 50 years.
Standard approach to EAS analysis

Energy spectrum

Composition

Interaction model

EAS

$N_{ei}$  $\Delta E_n$  C. C.  $x_{max}$  $N_{\mu\nu}$
Basic ideas of standard approach

EAS energy is equal to energy of primary particle.

Measured EAS parameters depend on type of primary particle only.

All changes of EAS characteristics in dependence on energy are results of energy spectrum or/and composition changes only.

And the following results were obtained:
Results of energy spectrum “measurements”

Really, in the best case, EAS energy can be evaluated.
Really, $N_\mu / N_e$ – ratio and $X_{\text{max}}$ are measured.
Primary cosmic rays have galactic origin.

Their acceleration and keeping in Galaxy are determined by their charge $Z$ or/and mass $A$.

Of course numerical results depend on interaction models, which are differed each other but quantatively only.
acceleration of CR in supernova remnants:

Fermi acceleration
finite lifetime of shock front:
$E_{\text{max}} \sim Z \cdot 10^{15} \text{ eV}$

rigidity dependent cut-off
$E_k(Z) \sim Z$

propagation through galaxy:

Leakage from Galaxy:
escape probability $\sim 1/Z$

$B = 3 \mu G$

Jörg R. Hörandel, 2003
A.P. Garyaka et al., 2007
An alternative approach.
Qualitative change of interaction model.

Evidences for change of interaction model at very high energies (above the knee) are the following:

The absence of the good description of “measured” energy spectrum and composition. In particular, it is not clear how to explain a quick transition to iron and the appearance of proton component at energies where iron nuclei must dominate.

But the most serious argument is the observation in various experiments different unusual events, which cannot be explained in frame of existing models.
List of unusual events

In hadron experiments:
- halos, alignment, penetrating cascades, Centauros (Pamir-Chacaltaya);
- long-flying component, Anti-Centauros (Tien-Shan).

In muon experiments:
- excess of VHE (~ 100 TeV) single (MSU) and multiple (LVD) muons;
- observation of VHE muons (Japan, NUSEX), the probability to detect which is very small.

In EAS investigations (in this approach we can consider):
- change of EAS energy spectrum in the atmosphere, which now is interpreted as a change of primary energy spectrum.
- changes of behavior of $N_{\mu}(N_e)$ and $X_{\text{max}}(N_e)$ dependences, which now are explained as the heaving of composition.

**Important:** Unusual events appear at PeV energies of primary particles.
Halo and alignment

- a) no. 108, no. 383
- b) no. 539, no. 386
- c) no. 586, no. 295, no. 403, no. 420
Penetrating cascades

\[ \text{Total Energy} = 257.79 \, \text{TeV} \]

\[ \tan \theta = 1.0 \]

<table>
<thead>
<tr>
<th>Depth [cmPb]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
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<tbody>
<tr>
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<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Graph showing the relationship between depth in cmPb and darkness for different energies. Labels include:
- 66.4[TeV]
- 45.4[TeV]
- 27.5[TeV]
- 40.3[TeV]
- 23.0[TeV]
- 39.6[TeV]
- 5.2[TeV]
- 10.4[TeV]
Muon flux excess

vertical intensity $\times E_{\mu}$ (cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$)

- LVD data
- ASD data
- MSU data

muon energy at sea level (GeV)

LVD best fit
MACRO best fit
Excess of muon bundles
The knee as result of new interaction

In this case a difference between primary and EAS energies, so-called missing energy appears.
What we need to explain all unusual data?

Model of hadron interactions which gives:

1. Threshold behaviour (unusual events appear at several PeV only).
2. Large cross section (to change EAS spectrum slope).
3. Large yield of leptons (excess of VHE muons, missing energy and penetrating cascades).
4. Large orbital (or rotational) momentum (alignment).
5. More quick development of EAS (for increasing the $N_\mu / N_e$ ratio and decreasing $X_{max}$ elongation rate).
Possible variants

Since muons and neutrons cannot be produced in hadron interactions directly, it is necessary to suppose that at the knee energy (about 3 TeV in the centre-of-mass system) some new states of matter (or short-lived particles) with effective mass ~ TeV appear and then decay through t-quarks or W, Z – bosons into leptons.

QGP model is very suitable for that.
1. Better to speak about quark-gluon matter, since:
   - usual plasma is a gas;
   - quark-gluon plasma is a liquid.

2. Production of QGP (QGM) provides main conditions:
   - threshold behavior, since for that large temperature and density are required;
   - large cross section, since the transition from quark-quark interaction to some collective interaction of many quarks occurs $\sigma \left( \frac{\lambda}{\pi R} \right)^2$ or $\left( \frac{R_1 + R_2}{2} \right)^2$.

3. But for explanation of other observed phenomena a large value of orbital angular momentum is required.
Orbital angular momentum in non-central ion-ion collisions

Zuo-Tang Liang and Xin-Nian Wang, Prerpint LBNL-56383
Centrifugal barrier

1. As was shown by Zuo-Tang Liang and Xin-Nian Vang, in non-central collisions a globally polarized QGP with large orbital angular momentum which increases with energy \( L \sqrt{s} \) appears.

2. In this case, such state of quark-gluon matter can be considered as usual resonance with large centrifugal barrier.

3. Centrifugal barrier \( V(L) = \frac{L^2}{2mr^2} \) will be large for light quarks but less for top-quarks or other heavy particles, which are necessary for production of leptons.
Centrifugal barrier for different masses
Results of EAS simulations in new approach

Simulations were made by standard method with CORSIkA.

To introduce correctly top-anti-top quark production the well known CERN program PYPHIA was used.

Unfortunately PYPHIA describes p-p interaction only, but even in this case obtained results are very impressive.

Two types of simulations were done:

Change of muon spectrum after introducing of top quarks.

Comparison of cascades from nuclei without top quarks and cascades from protons with taking into account top quarks.
PYTHIA, pp, $E = 10^{17}$ eV

The plot shows the differential yield $dN/d\lg E$ as a function of $\lg(E, \text{GeV})$ for various particles, including electrons ($e$), neutrinos ($\nu_e$, $\nu_{\mu}$, $\nu_\tau$), pions ($\pi$), kaons ($K$, $K^0$), and nucleons ($n$, $p$). The graph indicates the distribution of particle yields at different energy levels.
PYTHIA, pp $\rightarrow$ tt, $E = 17\ \text{GeV}$
\( \frac{dN}{d\log E} \) vs. \( \log(E, \text{GeV}) \)

- **p, CORSIKA**
- **pp, PYTHIA+CORSIKA**
- **pp->tt, PYTHIA+CORSIKA**

E = \( 10^6 \) eV, H1int = 23.5 km
CORSIKA, $E = 10^{16}$ eV
$E = 10^6 \text{ eV}$

$H1\text{int} = 24.3 \text{ km}$
What results of EAS measurements can explain new model?

Slope change of energy spectrum, since EAS energy will be less than energy of primary particle (missing energy).

Mass composition change, since new channel for primary nuclei interaction appears and EAS arrays will detect more showers from nuclei than from protons.

Both these effects will imitate decreasing of proton flux.

But really measured EAS energy spectrum from nuclei will decrease with energy more quickly than from protons.
How to check new approach?

Of course it is possible to wait for results of LHC experiments in which new state of matter (if it exists) will be observed.

But may be this will be not soon, since in the frame of considered approach, for production of QGP in p-p collisions more large energy than 14 TeV (in the centre-of-mass system) can be required.

When ion-ion collisions in LHC appear nobody knows.

Therefore we can consider possibilities to check new approach in cosmic ray experiments.
How to check new approach in cosmic ray experiments?

There are two possibilities to check new approach in investigations of cosmic ray muons:

1. Measurements of muon energy spectrum above 100 TeV.
2. Measurements of energy deposit of EAS muon component below and above the knee.

For that existing muon and neutrino detectors can be used: BUST, NEVOD-DÉCOR, Baikal, ANTARES, IceCube etc.
Results of VHE muon measurements
Preliminary results of muon energy spectrum investigation in Baksan Underground Scintillation Telescope (BUST)

http://arxiv.org/pdf/0911.1692
Expected results of muon energy deposit measurements
Standard approach to EAS analysis

Energy spectrum → Interaction model → Composition

$N_{ei}$ ← $\Delta E_{h}$ ← C. C. ← $x_{\text{max}}$ ← $N_{\mu \nu}$
New approach to EAS analysis
Considered approach to interpretation of results of EAS characteristics measurements allows to solve some problems connected with primary cosmic ray energy spectrum and composition investigations.

To check this approach muon energy spectrum above 100 TeV or/and energy deposit of muon component of EAS below and above the knee have to be measured.

For these purposes existing muon and neutrino detectors (BUST, NEVOD-DÉCOR, Baikal, ANTARES and IceCube (InIce and IceTop) can be used.
Thank you!