Results of the measurements of the cosmic ray penetrating component in the Moscow State University underground laboratory and the COSMOLEP program

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After the first indication of the "knee" in the size spectrum of EAS observed at the sea level in the EAS array of the Lebedev Institute (Kulikov and Khristiansen, [1], 1958) in the Moscow State University (MSU) a larger EAS array started to be constructed [2] (Figs. 1, 2). The array comprised the underground laboratory with the room of 100 m^2 at the depth of 40 m.w.e. and the room of 20 m^2—at the depth of 20 m.w.e. underground (Fig. 3). The EAS array on the ground surface allowed to locate the EAS core (the core position in the observation plane and the core direction), to measure the electro-magnetic (e-m) component size of the shower and to measure the lateral distribution of e-m component (the shower "age" parameter). For a given shower size and a core distance R the muon density at the depth 20 and 40 m.w.e. underground was measured and the lateral distribution of muons of the corresponding energy thresholds 5 and 10 GeV was derived [3]. The knee in the e-m size spectrum was confirmed with a high statistics and the knee in the muon size spectrum was observed for the same primary energy [4]. The energy flux in the e-m, muon and hadron components (the hadron detector [5] was the part of the EAS array) near the shower core was measured ($R < 100$ m) in the range of primary energies E_0 before the knee ($E_0 = 5\times10^{14}$–3×10^{15} eV) and after the knee ($E_0 = 3\times10^{15}$–10^{17} eV). It was shown that the main parameters of the inelastic hadron interactions do not change in this energy range. The change of the exponent in the size spectra of the EAS e-m and muon components was attributed to the change of the exponent of the primary energy spectrum (Vernov, Khristiansen, Kulikov, Solovieva, Abrosimov and Khrenov, 1970, diploma of the USSR discoveries, #84).

For more detailed study of the muon component the magnetic spectrometer and the muon interaction detector along with the muon density detector of 37 m^2 area were installed in the room at the depth of 40 m.w.e. underground (Fig. 4). The muon magnetic spectrometer had the maximum detectable momentum 500 GeV/c and the aperture 0.13 m^2 sr. In the EAS size range 5×10^4–10^7 the momentum spectra of muons at various core distances $R = 5$–100 m were measured (Fig. 5). It was shown that the average muon energy $\langle E_\mu \rangle$ decreases with core distance so that at $R = 10$ m $\langle E_\mu \rangle = 100$ GeV and at $R = 100$ m $\langle E_\mu \rangle = 10$ GeV (at the ground surface). The lateral distribution of muons becomes "narrower" with muon threshold energy E_μ (Figs. 6, 7). The experimental data for the fixed EAS size N_e and the average zenith angle of 20° were approximated by the following formula:

$$\rho(E_\mu, N_e, R) = (N_e/10^6)^{0.78} 1.4 \times 10^4 (E_\mu + 250)^{-1.4} R^{-0.55 q^{0.1}} \exp(-R q^{0.62}/80),$$

where $q = (E_\mu + 2)/12$, R in m, E_μ in GeV.

The integrated over core distances muon energy spectrum was approximated as:

$$N(E_\mu, N_e) = (N_e/10^6)^{0.78} 3.9 \times 10^6 (E_\mu + 250)^{-0.4} (E_\mu + 2)^{-1.25}.$$

The energy flux in all muons in EAS of the size 10^6 (Fig. 8) was equal to $9.4 \pm 1.5 \times 10^5$ GeV, the energy flux in muons of energies higher than 500 GeV was less than 1.2×10^5 GeV. The average muon energy in EAS of size 10^6 is 10.6 ± 1.5 GeV and changing very slowly with the EAS size. Estimates of the average primary energy of cosmic ray particles generated EAS of the size 10^6 in the QGS model is equal to 8.6×10^6 GeV so the primary particles release to the EAS muons only $13 \pm 3\%$ of their energy.

The obtained parameters of the EAS muon component added strong arguments against the scaling model of the hadron interaction [6] (Fig. 9). The modern QGS model developed by Kalmykov and Khristiansen [7] (its last version is the QGSJET model [8]) was approved in comparison with the EAS data of the MSU array [9] (Figs. 8, 9, 10, 11).

Presented above experimental results could be used in discussion of the muon multiplicity spectra measured by the LEP instruments. The triggering of the LEP muon detectors is different from the MSU array triggering. The MSU results were obtained for a fixed EAS size in near vertical direction of the EAS cores. The LEP results are being measured for a given muon numbers in the detector for any muon (EAS) directions. The EAS model explaining the LEP results should be checked also in comparison with the MSU results.

In the MSU underground laboratories the other approach to the cosmic ray high energy physics was in use. The "single" muon energy spectra was measured via size spectrum of secondary showers generated in lead by particles penetrating to the underground room. The highest measured sizes corresponded to the energies of muon of 10 TeV. The detector triggered by the size of secondary shower selects rare events of high transfers of energy from muon to gamma (bremmstrahlung) and high energy transfers from primary protons to muon parent particles. It was shown in many calculations that due to steep cosmic ray energy spectrum the average energy of protons responsible for the secondary shower of energy E' is only 10–20 times higher (Fig. 12), i.e., in measurements of spectrum of secondary showers underground the "hard" processes with energy transfers $X \approx 0.1$ are studied. The experimental result—the shape of the secondary shower size spectrum—depends on the cosmic ray energy spectrum per nucleon (protons are the main contributors) and on the inclusive spectra of muon parent particles (pions, kaons and charmed mesons).

In MSU underground laboratory at the depth of 40 m.w.e. three independent measurements of secondary shower spectrum in lead were performed: two with the ionization chambers [10,11] and one with the scintillation detectors and spark chambers [12] (Fig. 13). All three experiments gave the excess of showers with energies more than 1 TeV to compare with the expected shower spectrum generated by cosmic ray muons. The same result was obtained in the experiment with the ionization chambers at the depth of 20 m.w.e. in the Tian-Shan laboratory of the Lebedev Institute [13] (Fig. 14). At the same time the MSU X-ray lead chambers [14] placed at the depth of 15 m.w.e. underground did not show excess of the showers in the range of energies 1–10 TeV and only gave some excess at energies more than 10 TeV that was interpreted as the yield of charmed mesons to the muon spectrum.

In paper [15] the excess of secondary showers at shallow depths underground was related to the existence of an unknown stable (or long live) massive hadron (mass M_x = 10–30 GeV) that release energy in nuclear interaction with the interaction mean free path λ by small portions $\langle E'/E_x \rangle = m_u/M_x$ where m_u is the u,d quark mass. The absorption mean free path L of the primary cosmic ray X-hadrons having the power law energy spectrum with the exponent γ is large $L = M_x/m_u \gamma \lambda \approx 80$ m.w.e. The rare X-particle interactions with the high energy release to the secondary hadrons are responsible for the observed excess of the secondary showers at the depths 20–40 m.w.e. underground.

The difference in results with X-ray chambers and the scintillation detectors was related to the difference in the lateral distribution of electrons in hadron and gamma induced showers: the X-ray chambers have higher energy threshold for the hadrons showers. In the next decade (in 80s–90s) the experiments at the shallow depths underground were stopped and the problem of the excess of the secondary showers underground was not resolved. The LEP instruments being installed at the depths underground close to 20–40 m.w.e. have the opportunity to measure the spectrum of the secondary showers with better statistics and much better space resolution of the secondary particles. In the LEP calorimeters the hadronic and e-m showers could be distinguished.

Recently the problem of the existence of massive hadrons arises in the highest cosmic ray particle range—at energies 10^{20} eV where the expected Zatsepin–Greisen–Kuzmin cut off is not observed (Fig. 15). In papers [16–18] the massive SUSY hadrons are introduced as the primary cosmic ray component capable to come through the background black body radiation in the Universe. If this primary component exists in the wide range of energies—down to 10^{13} eV then the excess of the secondary showers underground will be also explained. For agreement with the underground experimental results the intensity of primary X-particles at energies 10^{13}–10^{14} eV should be only 10^{-3} of the intensity of primary protons of the same energies if the parameters of the X-hadron interaction are as in [18] for the mass $M_x = 50$ GeV (Figs. 16, 17). Two points in the primary energy spectrum of X-particles : at 10^{13}–10^{14} eV from the underground experiments and at 10^{20} eV from the gigantic EAS arrays experiments give the estimate of the X-particle energy spectrum exponent 1.6–1.7 (Fig. 18).

If the primary massive hadrons do exist they should make an essential yield to the phenomenology of the cosmic ray events at shallow depth of matter:

- not only the excess of high energy secondary showers at depths of tens of m.w.e. underground but also excess of horizontal air showers should be observed. Among the horizontal showers the percentage of the "hadronic" showers should be higher than in an usual case of muon induced showers,

- the percentage of "young" EAS showers at sea level at intermediate zenith angles should be higher. The lateral distribution of muons associated with "young" showers should be wider due to muon parent particle generation high in atmosphere by the X-hadron.

In experimental phenomenology of the cosmic rays there are indications of those effects (Fig. 19).

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