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HIGH-ENERGY NUCLEON AND PION SPECTRA IN COSMIC RAYS AT A DEPTH OF 60 g/cm^2

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The paper presents a comparison between the differential intensities of the cosmic ray muon flux at sea level and the stratospheric γ -quantum and nucleon fluxes as measured with multi-layer X-ray emulsion chambers.

Some 3000 bremsstrahlung γ -quanta with energies above 2 Tev were detected within the entire range of zenith angles when studying the sea level muon flux with X-ray emulsion chambers of 500 ton.year exposure [1] . The resultant muon energy spectrum is in a good agreement, up to energies E_μ = 7 Tev, with the global data and the assumption that the pion generation spectrum up to 30 Tev nucleon energies exhibits the same slope as the primary cosmic ray spectrum. This means that the concept of the scale invariance is valid up to at least 30 Tev. At higher energies, however, the muon spectrum becomes steeper (see Fig.2). The question arises as to whether this increase in the spectrum slope is real. An unambiguous answer could have been obtained in case of absolute calibration of the method for determining the energy on the basis of measurements of the mass of a neutral pion decayed in the target above the installation. This calibration, however, is still not realized for the $E_\gamma > 6$ Tev energy range. An attempt may be made to answer this question by comparing the energy spectrum to the curve of muon absorption in ground. With this purpose, the spectrum was transformed into an absorption curve. The calculations, including the fluctuations in the muon energy loss [2] were used. It was assumed that the muons with energies of up to 10 Tev show no additional energy loss apart from that established reliably at $E_\mu \leq 1$ Tev. Fig.1 presents the results of

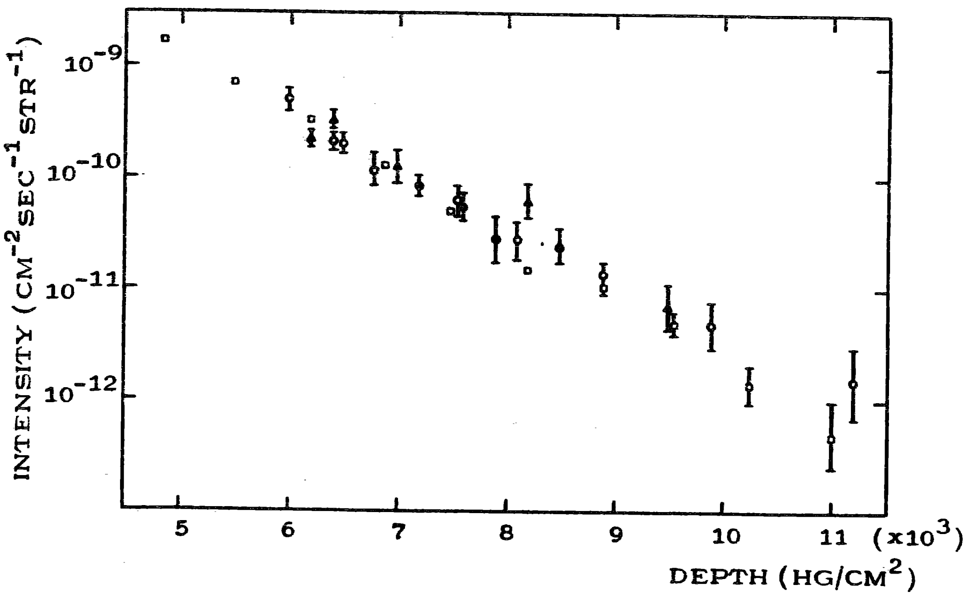

Fig.1. The depth intensity relation for muons underground. ▲ , ϕ , ● -[3], ☐ present data.

the comparison. It can be seen that our data are in a good agreement with the results on muon absorption in ground [3]. At great depths underground, however, the experimental data on absorption exhibit considerable errors both due to scanty statistical substantiation and due to inaccuracy in determining the density and composition of ground.Thus the above formulated question cannot be answered in such a way.

The change in the muon spectrum inclination (if real) might be understood in terms of one of the following hypotheses:(i) Scaling is violated in primary nucleon energy range $\geqslant 30$ Tev. (ii) In the $\geqslant 30$ Tev/nucleon energy range the primary spectrum becomes steeper.A change combination of these factors is of low probability, though possible in principle.

These hypotheses may be verified only by simultaneously measuring the stratospheric nucleon and pion spectra in the same energy range of the primary spectrum using the same methods to decrease as possible the effects of the methodical factors.

We started such measurements in the summer of 1973. By now, a multi-layer X-ray emulsion chamber has been flown three times in stratosphere on high-altitude automatic balloons. In the two first flights, the chamber was exposed at altitudes of 18-21 km for 86 and I12 hours respectively. In the third flight the chamber was exposed for 30 hours at altitudes of 19-30 km. The chamber area was 0.5 m^2, the total thickness of lead was 8 cm. In the first flight there were 8 detecting layers (spaced with 1 cm Pb), and in the second and third flights 16 layers (spaced with 0.5 cm Pb). The detecting layers consisted of three X-ray films or of two X-ray films and one nuclear emulsion layer of a 50 micron thickness. In the first flight the nuclear emulsion was in three layers and in the second and third flights in ten layers.

The method for analysing the experimental data permitting the energy and angles of the electron-photon cascades (EPC) to be determined, is described in details in our earlier papers [4].

By now, the results, of two exposures have been completely processed. In these exposures, 684 EPC with zenith angles $\leq 60^0$ and $E_\gamma \geq 2.0$ Tev were detected. In cases a shower becomes to develop at a depth exceeding 4 cascade units from the chamber surface. These events are EPC produced by hadrons in the chamber (Pb-jets). Among the remainder 478 EPC, 162 events should be due to hadron interaction in the upper part of the chamber. The rest 316 events are initiated by single γ -quanta (including the correlated pairs) and γ -quanta from 10 families with $n_\gamma \geq 3$ and $\sum E_\gamma \geq 7$ Tev. The resultant spectra are displayed in Fig.2 (B,C). The differential energy spectrum of the Pb-jets initiated by hadrons, which consist mainly of nucleons at a depth of 60 g/cm^2 in atmosphere, may be represented by the simple power law of the form

$$I_h(E) = (6{,}4 \pm 1{,}3)\left(\frac{E}{2}\right)^{-2{,}56 \pm 0{,}17} \; Tev^{-1}\, m^{-1}\, hour^{-1}\, str^{-1} .$$

The electron-photon component spectrum may be represented as

$$P_{e\gamma}(E) = (1{,}7 \pm 0{,}3)\left(\frac{E}{2}\right)^{-3{,}2 \pm 0{,}2} \text{Tev}^{-1}\,\text{m}^{-1}\,\text{hours}^{-1}\,\text{str}^{-1}.$$

To reduce the effects of the scanty known factors, the experimental material will be presented as the ratio of γ-quantum to nucleon intensities in air above the chamber (see Fig.3). This ratio should be independent of the value of the absolute nucleon flux at $\sim 10^{13}$ ev, but should depend on the elementary interaction model and may be used to verify the available models, first of all the scaling model. If the scaling is valid in the high-energy range, the ratio $P_{e\gamma}/P_h$ will be energy independent. Appearance of an energy dependence might have been interpreted as scaling violation, had the primary spectrum ranges determining the $P_{e\gamma}$ and P_h spectra been the same. The differential γ-quantum intensity is, however, formed by a region of somewhat higher (by a factor of $\sim$ 1.5) energies of the primary spectrum than the differential Pb-jets intensity. This circumstance makes the ratio $P_{e\gamma}/P_h$ sensitive not only to interaction model but also to, strictly speaking, the change in the nucleon spectrum slope. These two possibilities can be separated only by a several times increase of the upper energy boundary in the Pb-jets spectrum, which can be made using a vast experimental material.

The conclusion was drawn in [1] from the analyses of the 2-7 Tev muon angular distribution about the composition of particles generating the muons. At a 99% reliability level, the direct generation contribution to the observed muon intensity was found to be below 10^{2} of the pion generation cross-section. This is equivalent to the assertion that the effective cross-section of muon generation through fast channels (Ψ-particle generation, etc.) at (10-30) Tev nucleon energies is smaller than $3\times10^{-28}\,\text{cm}^2$. The kaon portion, α_K, is 0.15 ± 0.11. The acceleration data in the (0.2-1.5)Tev range make it possible to calculate the kaon portion in cosmic rays in this energy range. Such estimate was made in [1] and gave a value of 0.12 ± 0.02. Thus, increase in the kaon portion with energy in the fragmentation region is not very pronounced, if any.

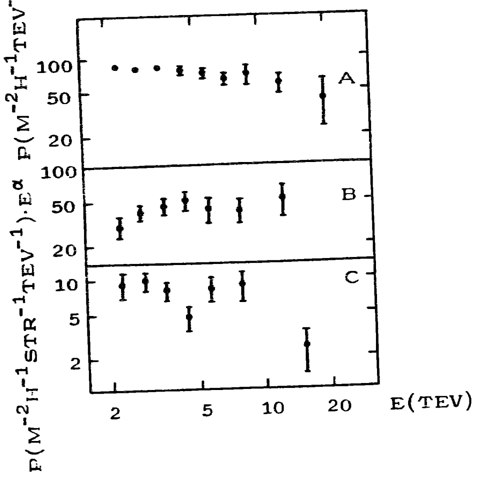

Fig.2. A) Differential muon spectrum (zenith angle range 0-90^0) $\beta = 3,6$ ($\gamma_\pi + 1 = 2,7$ respectively B) and C) differential vertical spectrum at atmospheric depth 60 g/cm^2 for hadron ($E_h = \sum E_\gamma$) and photon respectively $\alpha = 2,7$

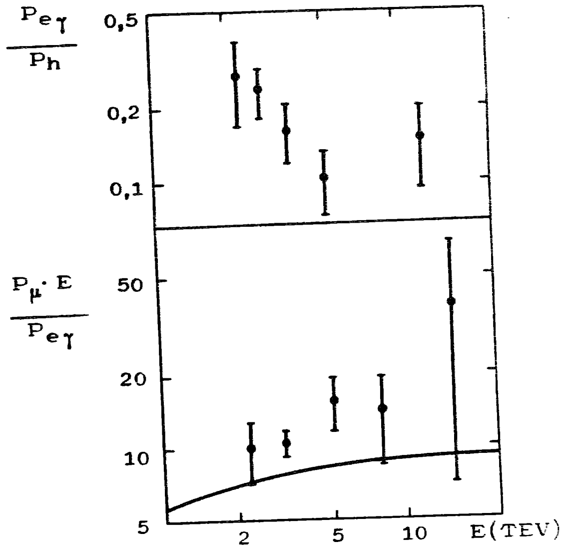

Fig.3. Differential intensity ratio

a) $P_{e\gamma}/P_h$, b) $P_\mu E/P_{e\gamma}$

Solid curve-calculation for $\gamma_\pi = 1,8$; $K/\pi^\pm = 0.1$; $\pi^0/\pi^\pm = 0.5$

At $E_\mu > 7$ Tev muon energies, a somewhat more gradual angular distribution was observed; high statistical errors however made it impossible to draw a conclusion about α_K variations or about increase in the contribution from the direct generation channel.

Information about the secondary particle nature may be also obtained from the comparison of the stratosphere γ-quantum spectrum to the sea-level muon spectrum measured using the same methods. With this purpose, Fig.3 (B) presents the energy dependence of $P_\mu E/P_{e\gamma}$, where P_μ and $P_{e\gamma}$ are the differential intensities of muons and γ-quantum respectively.. This ratio is worth noting because it (i) is independent of the absolute primary cosmic ray flux and is a weak function of the slope of primary cosmic ray spectrum, (ii) is a weak function of the spectrum of pion generation in an interaction, (iii) is a strong function of the secondary particle composition. For example, in the high-energy range this ratio is a rapidly increasing function of energy if the channel of the direct muon production exists.

As a result, the conclusion may be drawn that the applied method for comparising between the results of measurements of the stratospheric photon energy spectrum, the Pb-jets spectrum and the sea-level muon spectrum is promising in obtaining the data on the nucleon spectrum, the nucleon interaction dynamics, and the secondary particle composition. The improvement of the statistical substantiation of the experimental data, which we expect to achieve soon, will permit more definite estimate to be made.

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