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ON THE GENERATION AND INTERACTION OF HIGH ENERGY MUONS

by

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SUMMARY

Intensive studies of cosmic rays have been lately conducted; they consisted in experiments on generation and interaction of high-energy (mostly 10 – several hundred Gev) muons The study of muons of higher energies than several Gev entails the use of devices with substantial increase in transmissivity. This was obtained by the magnetic spectrometer method. The discussion centers on energy release spectra of muons interacting with thick layers of matter (water and soil 1 - 10 km w.e. thickness.

Most of the studies described here were conducted in USSR, namely at SRINP of MSU, MPEI, IPAS GSSR and FIAN*. They are illustrated by a series of diagrams and sketches of the devices used.

The numerous and complex discussions lead to the conclusion that the investigation of photonuclear interactions of muons in the region of particular interest must be made by special devices with geometrical factor > 100 $m^2 \cdot ster^{-1}$ so as to determine a muon pulse $\sim 10^{12}$ ev by the deflection in the magnetic field. These devices obviously can be utilized for obtaining exhaustive experimental data on the energy spectrum and angular distribution of muons with energy E > > $3 \cdot 10^{11}$ ev.

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(*) The explanation of abbreviations is given in the text

Despite rather numerous experiments on the study of (μ,e)- and (μ,p)-scattering, of muon pair and magnetic moment formation, no signs of any kind were up to now revealed in experiments on accelerators of any anomalous interaction of muons that would allow us to distinguish them from electrons.

Particularly intensive studies have been lately conducted in cosmic rays, consisting in experiments on the generation and interaction of high-energy muons. The most detailed, though by no means exhausiting investigations, were lately completed with muons having energies from some ten to several hundred Gev. Studied in this energy region were the energy spectrum of muon flux [2] and their angular distribution relative to the vertical [3]; data were also obtained on electromagnetic and "photonuclear" interactions of muons [4]. The conducted investigations have shown that both the energy spectrum and the angular distribution of such muons are not in contradiction with their generation as a result of $\pi \rightarrow \mu$- (and perhaps also $K \rightarrow \mu$-) decay. As to the interactions of muons of these energies, they also find explanation from the standard representations of quantum electrodynamics and experimental data on the effective photoproduction of pions obtained on accelerators.

The investigation of muons with energy greater than several hundred Gev presupposes a substantial increase of the speed of transmission of the installations utilized. In the conducted experiments this increase was attained at the price of utilizing more indirect methods than those applied at lower energies, namely, that of magnetic spectrometer. The discussion evolves here about investigations of energy liberation spectra of muons, interacting in sufficiently thick layers of matter, and also of the study of muon fluxes under considerable thicknesses of soil or water (1 — 10 km water equivalent).

Obviously, such kind of experimental data are sensitive to the energy spectrum of muons as well as to the character of their interaction with the matter. At the same time, the spectrum of energy release (in the region E > hundreds Gev), owing to the sharply dropping character of the energy release spectrum of muons, is determined with a precision to several percent and, in any case, in heavy matters, still more accurately by the cross-section of radiation deceleration of muons:

$$\int f_{dec}(v)v^{\gamma}dv,$$

where $v = E/E_{\mu}$ (E_{μ} being the energy of the muon); $f_{dec}(v)$ – the bremmstrahlung cross-section and γ the exponent of muons' integral energy spectrum. Contrary to that, the flux of muons under heavy soil thicknesses is determined by all processes leading to muon energy losses (ionization losses, formation of pairs, bremmstrahlung, photonuclear interactions), and is dependent on the quantity $\int f_{tot}(v)v\,dv$, and also on the behavior of the function $f_{tot}(v)$ as a consquence of the fluctuational character of losses.

The investigation of energy liberation spectra, for which muons with energies of several hundred to several thousand Gev, are responsible, were conducted especially intensively in the USSR, namely at the Scientific Research Institute of Nuclear Physics of the Moscow State University (SRINP of MSU) [5], at the Moscow Physics and Engineering Institute (MPEI), at the Institute of Physics of the Academy of Sciences of the Georgian SSR (IPASGSSR) [7] and at the Lebedev Institute of Physics of the USSR Academy of Sciences (FIAN) [8].* One of the works was also performed in Japan [9]. All these works were carried out underground, with soil thickness of the order of several tens of meters water equivalent.

In all the above-enumerated works, the geometrical factor of the installations was computed by tens m^2 stered, while the effective speed of transmission, that is, the speed of transmission computed taking into account the probability of muon interaction was tens of times greater than in experiments with the use of magnetic spectrometer [2, 3].

The greatest statistics of events was obtained in the works of SRINP of MSU and of the Osaka University [9]. The spectrum of great ionization bursts was investigated in these works, that is, <u>not</u> directly the spectrum of energy releases, but that of showers induced by these energy releases in layers of dense matter.

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* (These abbreviations will be used all the way in the following)

The results of measurements, which lasted 6000 hours on the installation of the SRINP of MSU with the use of a lead filter, and nearly 18000 hours at the Osaka University using soil for filter, are shown in Fig.1. The spectrum of bursts in the ground was converted to that of bursts in lead. In the region $n < 10^3$ the data of [9] are, apparently, distorted by the influence of registration threshold. The spectra are constructed for bursts induced by muons with zenithal angles $\theta < 45°$ and $\theta < 50°$.

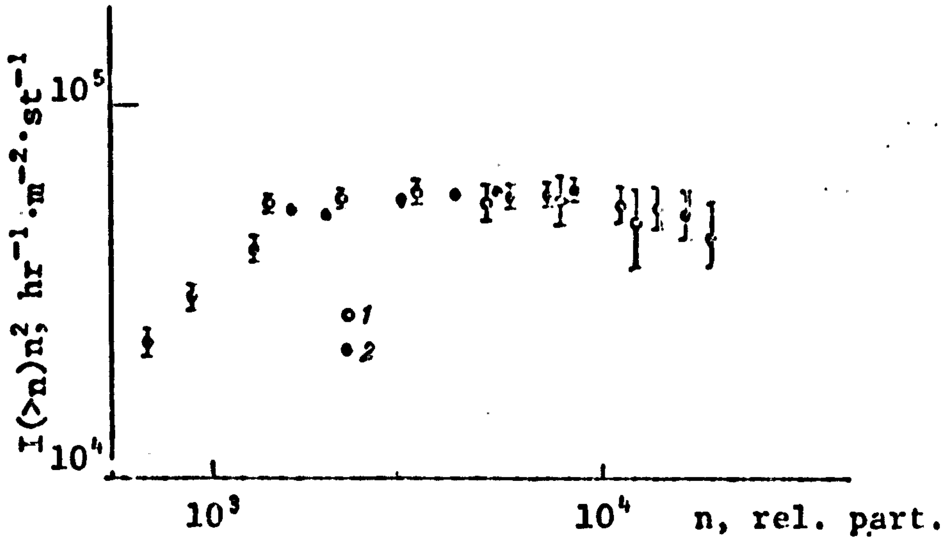

Fig.1
Integral spectrum of bursts induced by muons at depth of 40 m water equivalent. Numeral 1 corresponds to data of [5] with $\theta = 45°$ and in the lead, while 2 refers to the data of [9] in the ground at the depth of 20 m w.e. $\theta < 50°$; n is the ionization (*)

Presented in Figures 2 and 3 is a schematic image of the installations uilized. The MSU device consists of three rows of ionization chambers (IC) with area of 5 m^2 each and of five rows of hodoscopic counters (HC). The ionization chambers registered the magnitude of the burst. The direction of the muon was determined with a precision to 7° with the aid of hodoscopic counters. The installation of the Osaka University consists of two scintillator layers of ~20 m^2 area each and of a system of photomultipliers between them. The coordinates of shower axis, of muon direction, having induced the shower and of latter's magnitude are determined by the ratio of the light fluxes registered by the different photomultipliers. (The shower magnitude is here in reality that of the burst). When converting the spectrum of [9] to that of [5], it was assumed that the magnitudes of bursts in Pb n_{Pb} and in the ground n_{gr} are linked by the relation $n_{Pb} = n_{gr} \cdot \beta_{Pb}/\beta_{gr}$, where β_{Pb} and β_{gr} are respectively the critical energies for electron-photon

(*) expressed in the number of relativistic particles avalanches in lead and ground. The spectra, plotted in Fig.1 are very close at $n = 1.5\cdot10^3 - 1.5\cdot10^4$, in their shape and correspond to exponents $\gamma = 2.15 \pm 0.1$ [5] and $\gamma = 1.95 \pm 0.1$ [9]. At the same time, to first points of spectra corresponds a statistics of nearly 2000 events, and to the last ones – one of several tens of events.

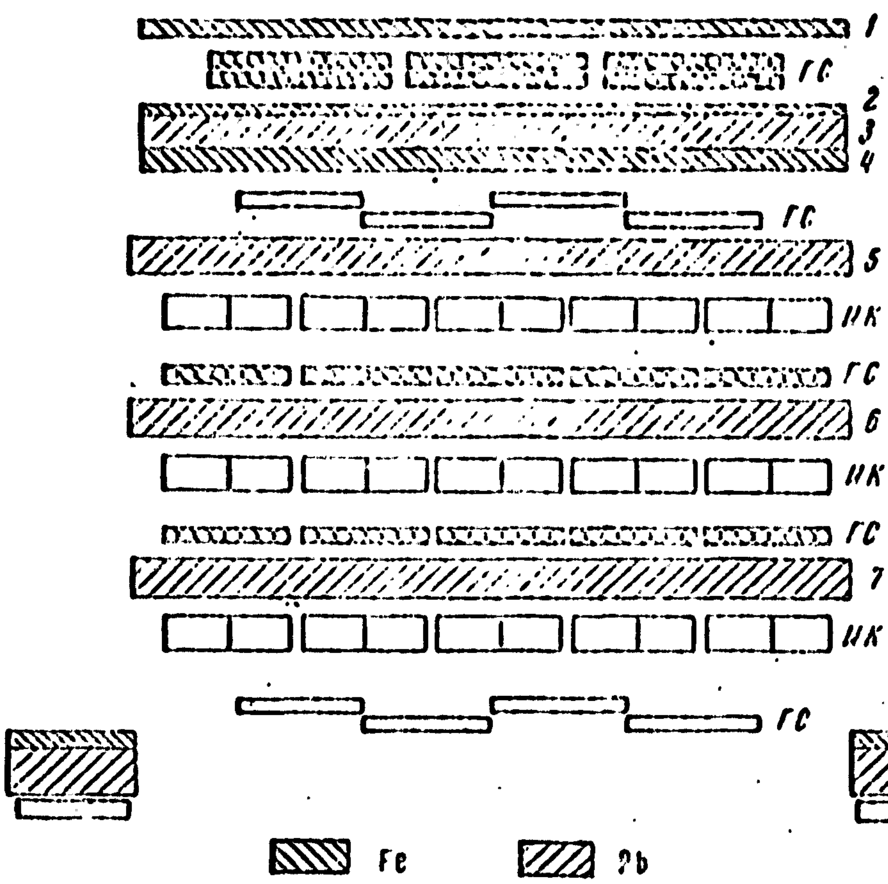

Fig.2

Installation of MSU for the investigation of bursts induced by muons in lead

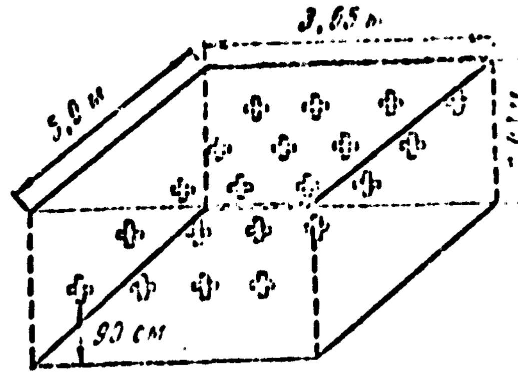

Fig.3

Installation at Osaka [10]

Comparison of experimental data of [5] with the spectra of bursts theoretically computed at various assumptions on the generation of muons through π- and K-measons, taking into account only the electromagnetic interactions of muons. The exponent values $\gamma_{\pi,K} = 1.6$ and various ratios of the absolute values of K/π were assumed for the integral energy spectra of π- and K-mesons.

Theoretical calculations may yield a satisfactory agreement with the experimental spectrum of bursts, if one only diminishes the value of $\gamma_{\pi,K}$ to 1.2 – 1.3. This cannot be done for spectra of π-mesons without entering into contradiction with experimental data on γ-quantum spectra in startosphere [11 - 13]. However, it is possible to assume that the ratio K/π is a rising function of energy E of π- and K-mesons, $K/\pi \sim E^{\alpha}$ and to select α in a manner allowing us to obtain a spectrum of muons equivalent to $\gamma_\pi = 1.2$ for values $\gamma_\pi = 1.7$ and $\gamma_K = 1.7 - \alpha$. Such a spectrum is obtained at $K/\pi = 0.3(E/3\ 10^{11}\ ev)^{0.45}$. However, the introduction of such a mechanism of K-meson generation results also in a contradiction with the experimental data of [11] and [12] (see Fig.5).

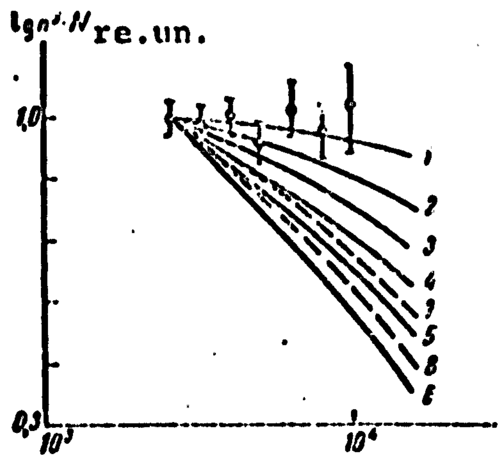

Fig.4

Co.parison of differential spectrum of bursts in lead (MSU) with theoretical calculations performed in various assumptions on the energy spectrum of π- and K-mesons. The curves 1, 2, 3, 4, 5, 6 correspond to $\gamma_\pi = 1.2$; 1.3; 1.'; 1.5; 1.6; 1.7; the ratio $K/\pi = 0$; 7, and 8) $\gamma_\pi = \gamma_K = 1.7$ and $K/\pi \neq 0.2$ respectively. All curves are normalized with respect to the first point

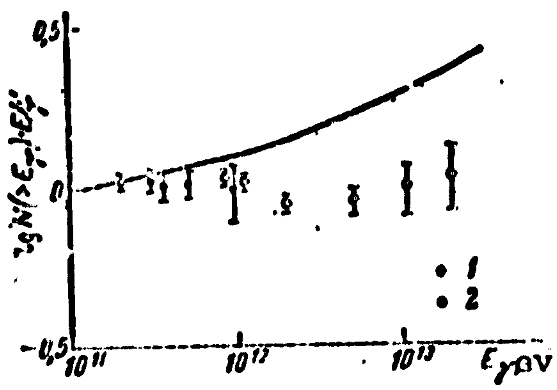

Fig.5

Comparison of the energy spectrum of γ-quanta in the stratosphere (re. [11-13]) with the theoretical spectrum in the assumption of increasing role of K-mesons relative to ions with their energy rise. At $E = 3\cdot10^{11}$ ev, the value $K/\pi = 0.3$ corresponds to the upper lijit of experimental data (1 corresponding to data of work [11] and 2 – to those of works [12 – 13]

Therefore, in order to explain the observed spectrum of bursts, it remains to assume that: 1) either the interaction cross-section of muons begins to rise noticeably with energy, or 2) the spectrum of muons is more slanting that that obtained from the pattern $\pi \to \mu$- and $K \to \mu$-decays, i. e. there exists of a more rapid generation of muons than the π- and K-decays.

The first possibility drops off if one conducts comparison of burst spectrum with the curve for the depth course of muons for depths $>10^3$ m.w.e. If we assume that the burst spectrum exponent is exactly equal to that of the energy spectrum of muons (in reality it can only be smaller than the former), then it is possible to estimate the maximum admissible increase of the cross-section of photonuclear interaction of muons from the requirement of agreement between the spectrum of muons and the depth course. (As regards the cross-sections of other processes, it is assumed that they are known eith a precision to ~5%). For example, for the integral muon spectrum exponent $\gamma \approx 2$, this increase in the ground may take place five times at transition from energy range $10^{10} - 10^{11}$ ev to the range $10^{12} - 10^{13}$ ev (see [14]).

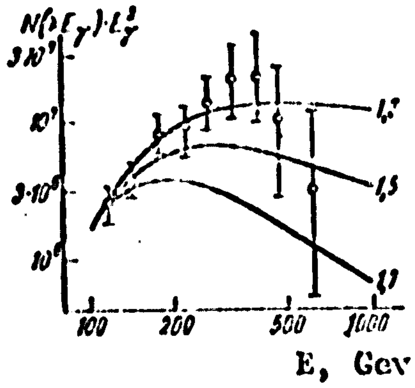

Fig.6

Comparison of the spectrum of energy liberations E, registered by the installation of [7] with spectra of E expected at various assumptions on spectra of generated pions. Numerals at curves refer to values of γ_π. The diagram has been borrowed from [7]

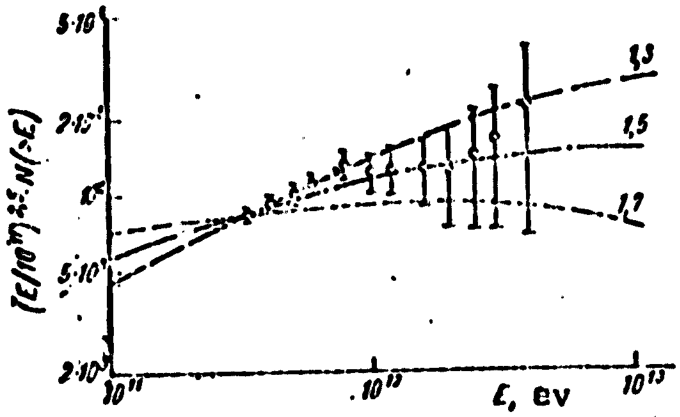

Fig.7

Same as in Figure 6 but after the work [7]. $\theta < 50$, $\pi \to \mu$. This diagram has been borrowed from the work [8]

such a value of b_{nuc} (losses to photonuclear interactions) and b_{brem} (losses to bremmstrahlung) in the ground become identical. Taking into account that ohe photonuclear interaction cross-section ~ A, while that of bremmstrahlung (at the expense of which burst mainly occur) is ~ Z^2, one may obtain that at transition from ground (Z = 10, A = 20) to lead (Z = 80, A = 200), in the case of the SRINP of MSU experiment, the relative role of photonuclear interactions in the creation of bursts drops 6 to 7 times and does not exceed 20%. Therefore, the maximum possible decrease of burst spectrum's exponent on that account is no more than 0.07. (In reality this decrease is still less, since in the above estimate the difference in heights of avalanche maximum from γ-quantum and $\pi^{\pm}$-mesons produced in the photonuclear interaction has not been taken into account. In the latter case, the maximum height will be 2 to 3 times less and this is why the role of bursts from photonuclear interactions may be still further reduced).

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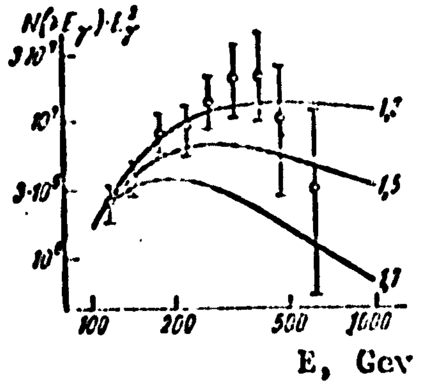

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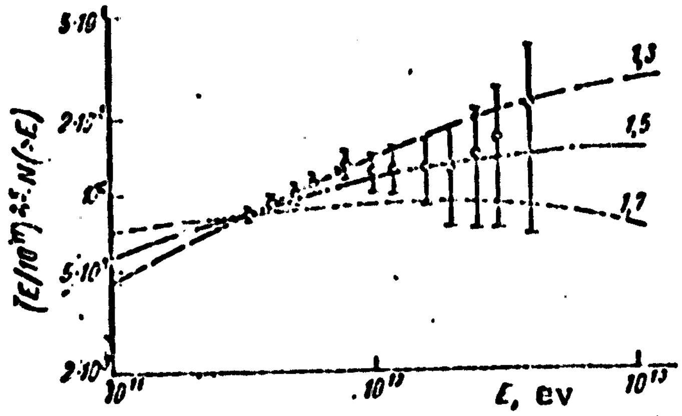

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Note that, as b_{nuc} increases to the value of b_{brem} in the ground, we must obtain for the experiments of the Osaka group a lesser value of the exponent γ of burst spectrum than for the SRINP of MSU experiments. Such tendency exists in the experimental data: as already noted, according to data of MSU, $\gamma \approx 2.15 \pm 0.1$, and, according to Osaka team $\gamma \approx 1.95 \pm 0.1$.

Thus, for the explanation of experimental data on burst spectrum one must assume that, in the region of considered energies, a more rapid generation mechanism of muons begins to act than the π- and K-decay. As to the possible nature of such a mechanism, it will be discussed below.

As mentioned earlier, the spectra of energy relases of muons in the interval $3 \cdot 10^{11} < E < 3 \cdot 10^{12}$ ev were previosuly investigated in the MPEI and IPASGSSR and also at FIAN. These works were conducted with the aid of ionization calorimeters which, in principle, permit the determination of energy release in each individual case according to the total development pattern of the avalanche. However, in practice, the number of rows of ionization chambers, utilized for the determination of energy release, unfortunately and, as a rule, were never more than three. This is why the calculations of electron-magnetic cascade theory were essentially utilized for obtaining final results.

Figures 6 and 7 (preceding page) show the experimental data on spectra of energy E releases after the data of MPEI and IPAGSGSSR [7] (Fig.6) and FIAN (Fig.7) [8]. As may be seen from the diagrams, the statistics obtained in these measurements is insufficient to derive a conclusion on muon spectra with presently required precision. The theoretical curves in Fig.6 and 7 are given for various values of γ_{π}, and the value $\gamma_{\pi} = 1.2 - 1.3$, following from experiments at MSU and OSAKA team are not in contradication with the above experimental data either.

Among other works carried out by this method one should note an earlier wotk at PPEI on the investigation of energy releases induced by muons moving at great angles to the vertical ($\theta > 60°$, $\bar{\theta} = 75°$ [6]) In this work the statistics of events was broader than in the previously mentioned ones. The value of the exponent γ in the energy interval of muons $2 \cdot 10^{11} - 2 \cdot 10^{12}$ ev was found to be 2.1 ± 0.1. In combination with the results of MSU this result can not be explained strating from the generation pattern of muons at the expense of $\pi \to \mu$-decay. It is evident that in the case of pattern's $\pi \to \mu$-decay validity, we must obtain a notable decrease of the exponent γ (by 0.3 – 0.4) at transition from the vertical direction to $\bar{\theta} \approx 75°$. The list of works devoted to the investigation of the energy spectrum of muons in the energy region $>3\cdot10^{11}$ ev ($3\cdot10^{11} - 3\cdot10^{12}$ ev) is, therefore, indeed limited to the above-mentioned ones. It follows from works [5] and [9], completed with highest statistical precision, that the energy spectrum of muons is in contradiction with the standard pattern of their generation.

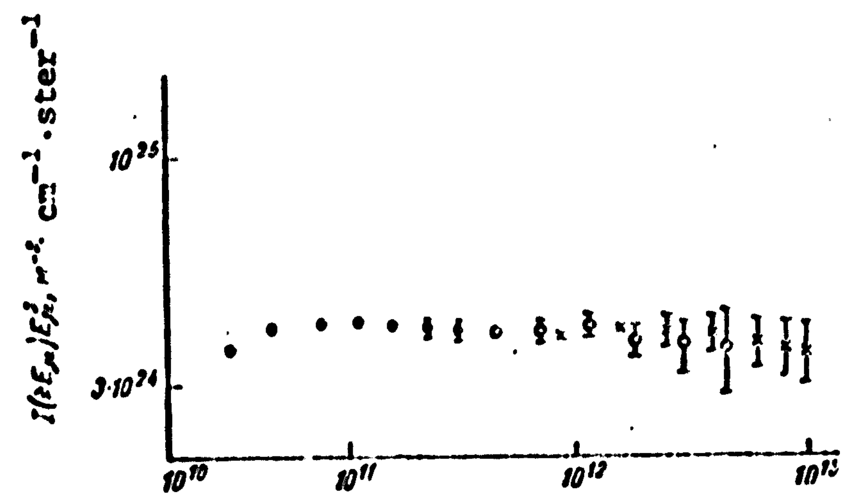

Fig.8

Energy spectrum of muons in the energy region $E_\mu \approx 2\cdot10^{10} - 10^{13}$ ev obtained with the utilization of magnetic spectrograph data [2] and of works [5] and [9]. The nonnormalized spectra of works [2] and [5] coincide near the point $3\ 10^{11}$ ev with a precision to 20 percent Normalization at the point $3\cdot10^{11}$ ev is brought out in this diagram.
1) refers to data of [2]; 2) – to [5]; 3) – to [9]

Shown in the above Figure 8 is the energy spectrum of muons in the energy range $10^{10} - 10^{13}$ ev after the data of magnetic measurements of [2] and of great ionization bursts of [5] and [9]. At the same time, when passing from the spectrum of bursts to the energy spectrum of muons, it was assumed that the latter has an exponential form. The γ-exponent of the muon spectrum was determined form the γ-exponent of burst spectrum taking into account the corrections for the precise form of bremmstrahlung cross-section [15]. The value $\overline{E}_\mu = (3\cdot10^{8}\ n)$ ev was compared with the magnitude <u>n</u> of the burst.

Note that the spectrum of muons, shown in Figure 8, could allow us to determine also the frequency of air showers with particle number $N > 10^4$, created by muons, provided only this spectrum is extrapolated into the region of energies $E > 10^{13}$ ev [16]. Then the frequency of these showers was determined by us starting from horizontal air showers according to [16] in the assumption that the angular distribution of muons follows the law sec θ. If the spectrum of muons in the energy region $>3 \cdot 10^{11}$ ev is represented by the exponential law $\gamma = 2.5$, the anticipated frequency of air showers from muons will be three times less than the observed one at angular distribution of muons sec θ and 25 times smaller than the observed one at isotropic angular distribution of muons (total number of events (26)). From the above considerations it is clear that the measurement of the energy spectrum of mions should necessarily be conducted in the indicated energy region ($3 \cdot 10^{11} - 10^{13}$ ev) by any kind of direct methods.

As already noted, the investigation of muon fluxes at great depths (1 – 10 km w.e.) underground allows us to obtain information, which in the general case, depends simultaneously on the spectrum, angular distribution in the atmosphere and the general character of interaction of muons. The installations of such a type have a transmissivity 1000 times greater than those based upon the principle of registration of great energy releases. Despite the complex character of information obtained with installations of similar type, one may, at sufficient mehodical and statistical accuracies, attempt to extract from this information data on angular distribution of muons in the atmosphere. Such attempts were recently made in the works [17 – 19].

The installation of the American team [17, 18] allowed them to determine the direction of muon trajectory with a precision to 1° and to study the angular distribution of muon fluxes passing at different angles θ and ϕ for an about identical rock thickness, i. e. having approximately identical energies. In this way, the problem of separating out the angular dependence of high-energy muon fluxes was resolved by way of specific choice of rocky ground's thickness. Plotted in Fig.9 are the data on muon fluxes observed at various angles ϑ in accord with [18]. The given depth is determined with a precision to ± 100 m.w.e.

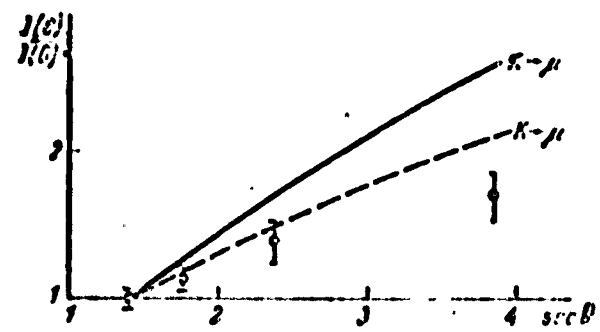

Fig.9

Angular distribution of muons of high energy (>10^{12} ev) obtained on the basis of experimental data of work [18] (see text). For the sake of comparison theoretical angular distributions of muons are brought out, which were obtained by way of averaging the theoretically expected curves for various depths, isolated in the experiment, and for the cases of $\pi \to \mu$- and $K \to \mu$- decays

The result brought out in Fig.9 is obtained from data of [18] by way of construction of the angular distribution for separate depths and subsequent averaging of data in the 2500 — 5500 m.w.e. depth range. Note that, by comparison with earlier published data of [12], the data [18] differ from the former, despite the fact of their obtaining on the basis of the same empirical material, but with the utilization of refined data on soil density. The minimum energy of muons in experiments of [17, 18] constituted 10^{12} ev. It may be seen in Figure 9 that the angular distribution of muons with energy 10 ev, obatined for $\pi \to \mu$- and $K \to \mu$-decays differs from the experimental one.

The Japanese-Indian team conducted measurements of the angular distribution of muons at the depth of 1500 m.w.e. with the aid of a telescope made of scintillators and "Konversi"* tubes under a plane layer of soil. The precision in the determination of the angle constituted ~ 1.5%. The conversion of the results of measurements [19] to angular distribution in the atmosphere and its comparison with the anticipated theoretical angular distributions is brough out in Figure 3,c of [19]. The conversion of direct empirical data presupposes the assignment of the curve of the depth flux of muons in the 1.5 — 5 km w.e. range. At the same time, there exist in this interval measurements at separate discrete points, and the form of the curve for the course in depth can not be considered as established with sufficient accuracy. Therefore, although in work [19] the angular distribution obtained was in contradiction with the results of [17, 18], additional experiments are required for a correct solution of the problem.

On the other hand, the accurate knowledge of soil density and thickness and also of the efficiency and aperture of the devices for various angles θ and ϕ (in particular at great angles in Indo Japanese team's experiments) has a great significance in both experiments of [17 – 19]. However, the work of [17, 18] still bears a more direct character, for it does not assume the preassignment of the curve of depth course and utilized an installation more advantageously oriented for the registration of the sec θ interval of interest to us.

The angular distribution of high energy muons was also investigated in the already mentioned works [7, 8]. The utilization of ionization chambers for obtaining the angular distribution is, in our opinion, beset with the difficulty in the determination of the number n or relativistic particles, induced in filter's layer above the chambers by the ionization n_0 observed in chambers. In this case the relation $n = n_0 \cos\theta$ is usually applied, which, however, and strictly speaking, is incorrect and is dependent upon the details of angular distribution of particles in the shower, the geometry of the chambers, on the transitional effect and on particles' return current.

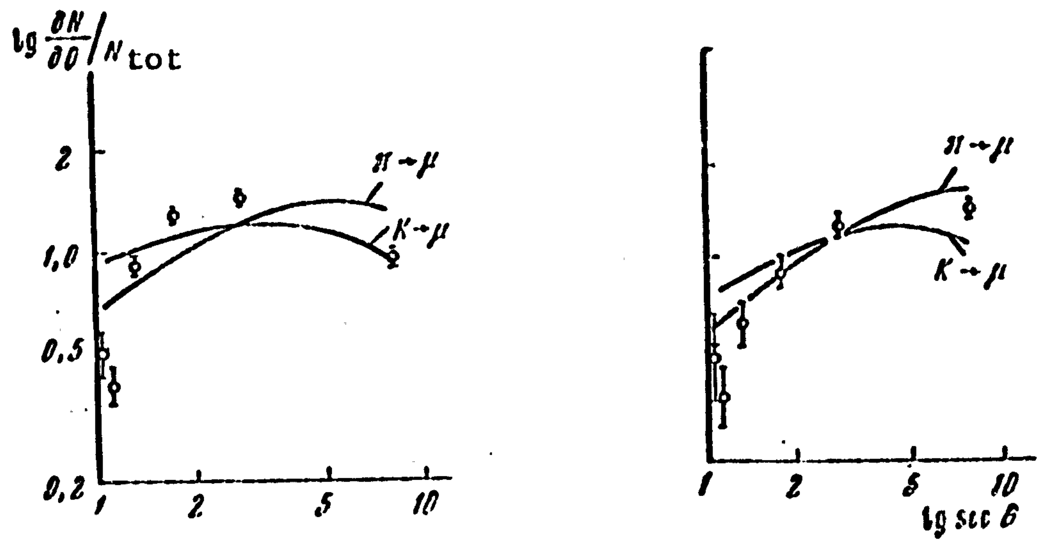

Fig.10

Angular distribution of muons, yielding energy release: a)refers to $E > 10^{11}$ ev, b) – to $E \geq 3\cdot10^{11}$.ev. The experimental points are plotted in accord with the data of work [8]. Solid curves refer to the theoretical computation for $\pi \to \mu$- and $K \to \mu$- decays

In the work [7] the angular distribution was investigated only at small sec θ, where various generation mechanisms of muons are little differ

The data on angular distribution of muons with $E > 10^{11}$ ev and $E > 3\cdot10^{11}$ ev, where E is the energy release in the calorimeter, are plotted in Figure 10.(*) The data for $E > 3\cdot10^{11}$ ev agree well with the pattern of $\pi \to \mu$-decay. The data for $E > 10^{11}$ ev are in essential contradiction with it. This provides the basis to assume that the density increase of angular distribution with θ may be of methodical nature.

Therefore, summing up the above results, we should underscore the existence of a serious indication [17, 18] on the anomalous character of the angular distribution of high-energy muons ($E > 10^{12}$ ev).

As already noted above, the energy spectrum of muons obtained by us and characterized by the index $\gamma = 2.2$, results in the requirement of either a substantial increase in the photonuclear interaction cross-section of muons beginning with $E_\mu < 3.10^{11}$ ev, or the introduction for them of some new anomalous interaction, when compared with data [14] on underground measurements. If we consider that the indicated anomaly is necessarily linked with the production of particles of nuclear nature, the simplest setting of the experiment on the study of this anomaly presupposes the search for such interactions of muons that are attended with the onset of nucleo-active particles.

The first attempts to investigate this question in the energy region $E_\mu > 3\cdot10^{11}$ ev belong to the MPEI team [20]. This team conducted analysis of avalanches observed in an horizontal ionization calorimeter. The main part of avalanches registered in the work [20] constituted cases of emergence of measurable ionization in no more than three rows of ionization chambers. The ascertaining among such events of nonelectromagnetic avalanches is hardly possible on account of the existence of fluctuations in the electron-photon avalanche, even if one estimates that the averaged theoretical electromagnetic cascade curves are quite accurately known. However, cases were observed of avalanche penetration through four and more rows of ionization chambers. Among such events several tens of avalanches were detected, which knowingly could not be described by the electromagnetic cascade theory. Despite the small statistics of such events, one still may derive the conclusion that if the observed avalanches are linked with photonuclear interactions, of muons, the cross-section of this interaction in the energy region of the

(*) The mean energy of muons reponsible for energy E release >E is, according to [8] $\bar{E}_\mu = 3E$.

order of hundreds Gev has a significance, at least no smaller than at energies ~10 Gev.

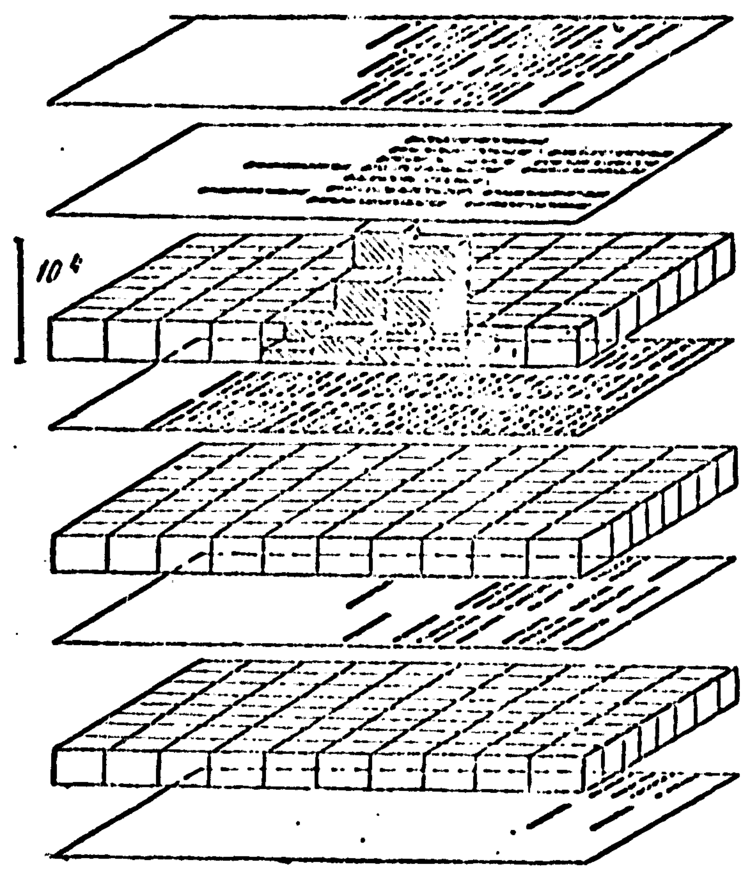

Fig.11

Case of nonelectromagnetic interaction of muons in the installation of ref. [5]. Five rows of hodoscopic counters and three rows of ionization chambers are schematically re-represented. The black bands indicate the used up counters. A burst ~10^4 relativistic particles is observed in the first row of chambers (it is shown how ionization is distributed between separate chambers)

Another attempt to investigate photonuclear interactions of muons in the energy regions greater than several hundred Gev belongs to Moscow State University (MSU). The case is presented in Figure 11, identified as a nonelectromagnetic interaction of muons. It is characteristic of similar kind of cases that, besides registration of a major ionization burst, showers are observed in other rows, registered by hodoscopic counters. Let us recall that in the MSU detector the rows are separated from one another by lead filters of 28 t-units thickness; this is why the observed events can not be explained at the expense of a single electron-photon avalanche. Nor can they be explained at the expense of several consecutive interactions of one muon.

This is directly attested by experimental data on the frequency of shower formation n_1, n_2 of solitary muons inducing bursts of the given magnitude n (see Table 1). According to these data, the probability of observing events of type shown in Figure 11 is at least tens of times smaller than the experimental probability of these events.

TABLE 1

PROBABILITIES OF NUCLEAR INTERACTIONS AND EXPECTED PROBABILITIES OF THEIR IMITATION CONSTRUCTED ON THE BASIS OF EXPERIMENTALLY DETERMINED PROBABILITIES OF ELECTROMAGNETIC PROCESSES

n, rel.par.	Process	Type of Events*					
		$n_1 \geq 1$, $n_2 \geq 1$	$n_1 \geq 2$, $n_2 \geq 2$	$n_1 \geq 3$, $n_2 \geq 3$	$n_1 \geq 4$, $n_2 \geq 4$	$n_1 \geq 5$, $n_2 \geq 5$	$n_1 \geq 10$, $n_2 \geq 10$
10^3	Nuclear	$(5\pm1)\cdot10^{-2}$	$(4\pm1)\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$	$(3\pm1)\cdot10^{-2}$	$(1,2\pm0,5)\cdot10^{-2}$
	EM	$(9\pm8)\cdot10^{-3}$	$3\cdot10^{-3}$	$8,3\cdot10^{-5}$	$2,3\cdot10^{-5}$	$6,3\cdot10^{-6}$	$7,6\cdot10^{-7}$
10^4	Nuclear	$(1,3\pm0,6)\times10^{-1}$	$(1,3\pm0,6)\times10^{-1}$	$(8\pm5)\cdot10^{-2}$	$(5\pm4)\cdot10^{-2}$	$(5\pm4)\cdot10^{-2}$	—
	EM	$1,6\cdot10^{-2}$	$1,6\cdot10^{-2}$	$4,5\cdot10^{-4}$	$1,9\cdot10^{-4}$	$1,9\cdot10^{-4}$	—

* n_1,n_2 is the number of particles arising simultaneously in two rows at the expense of muon interaction. The probability of the event ($n_1 n_2$) is determined as the product of experimentally obtained events.

The dependence of the share of such events as a function of magnitude n of the burst (this fraction is considered relative to the total number of events with burst magnitude, n). The observed increase is not related to the requirements that were imposed on the number of used up hodoscopic counters; thus, in the indicated events the number of used up counters exceeded the minimum required one even at $n = 10^3$. The increase in the share of such events with the rise of n (thats is, of the mean energy of muons could not take place in accord with the existing theories of photonuclear production of muons if one considers that the photonuclear interaction cross-section of γ-quanta σ_γ is independent of energy.

These theories do indeed provide expressions for cross-sections that are homogenous functions of $E/E_\mu = v$. In this case the ratio of the frequency of energy releases >E at the expense of photonuclear interaction of muons to that of energy releases >E at the expense of EM-interactions constitutes

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a quantity

$$\sim \sigma_\gamma \cdot \frac{\int_0^1 f_{nuc}(\nu)\,\nu^\gamma\,d\nu}{\int_0^1 f_{dec.}(\nu)\,\nu^\gamma\,d\nu}.$$

On the other hand it should be noted that, from the viewpoint of the method, the indicated experiment is not faultless, for the direction of particles inducing the analyzed showers can not always be determined with the required precision.

Finally, a third attempt of investigating the photonuclear interaction of muons of still higher energy (>tens of thousand Gev) belongs to the Tokyo University team, having registered the presence of muons of low energies (>1 Gev) and nucleo-active particles in the composition of horizontal air showers [16]. Although in the 26 showers registered in the course of 14,000 hours of operation only three of them were observed with particles of nonelectromagnetic nature, taking into account the small area of the detectors by comparison with that, into which the penetrating particles diverge, their ratio being < 1/10), it should be recognized that the role of photonuclear interactions of muons in the creation of horizontal showers is extremely great. It is not even excluded that the main part of horizontal showers ocuurs at the expense of photonuclear interactions of muons.

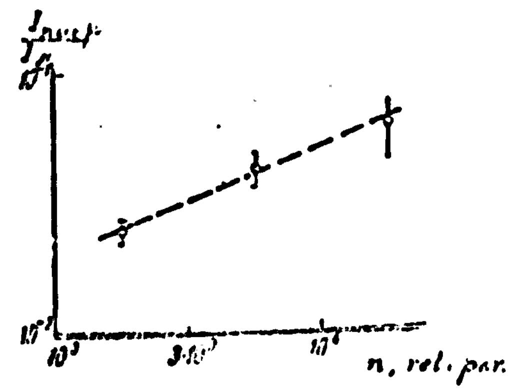

Fig.12

Dependence of the share of bursts with magnitude >n, induced by nonelectromagnetic interaction of a muon, on the quantity <u>n</u> for events of the type $n_1 \geq 5$, $n_2 \geq 5$ (see Table 1)

Therefore, the experimental data brought out raise the question of the further detailed quantitative investigations of photonuclear interactions of muons quite sharply. What possibilities of such investigations are, in principle, available? It would seem that the simplest experiment consists in the measurement of the course in depth of the frequency of photonuclear showers with small energy release. At the same time, one could, for example, sort events corresponding to the photonuclear shower with the help of a neutron monitor. However, in reality the mean energy of muons under the ground layer increases with its thickness x only for small $x < 1$ km w.e. At greater depths > 1 km w.e. (when bremmstrahlung processes and pair formations enter the picture), the mean energy of muons remains independent of the depth and equal to ~ 300 Gev.(*)

Thus, the investigation of photonuclear interactions at effective energies $E > 3\cdot 10^{11}$ ev by such a method does not appear to be possible. It is obvious that, for such investigations with $E > 3\cdot 10^{11}$ ev, it is necessary to create installations, foreseeing the determination of the energy of the interacting muon by, for example, the magnetic deflection method.

Let us estimate the frequency of anticipated photonuclear interactions for $E \gtrsim 10^{12}$ ev. If we admit that the products of photonuclear interactions emerge from the part of the filter, which has a thickness ~ 100 $g\cdot cm^{-2}$ and consider that $\sigma_{phnuc} \sim 10^{-30}$ $cm^2\cdot nucleon^{-1}$, $I \sim 1$ $hour^{-1}\cdot m^{-2}\cdot sterad^{-1}$, then the frequency of photonuclear interactions induced by muons with energy $E > 10^{12}$ ev has a magnitude

$$\cdot A \frac{N}{A} \cdot 100\ g\cdot cm^{-2},\ I\ (> 10^{12}\ ev) = 10^{-30}\ cm^2\cdot nucleon^{-1}\cdot 6\cdot 10^{23}\cdot 100\cdot 1 \approx \approx 10^{-4}\ hour^{-1}.m^{-2}.sterad^{-1}.$$

Therefore, in order to investigate the photonuclear interactions of muons in the region of interest to us, it is necessary to construct devices with geometrical factor of no less than 100 m^2 sterad $^{-1}$, which would then allow us to determine a muon pulse of ~10^{12} ev by the deflection in the magnetic field. It is natural that such installations may simultaneously by utilized for the obtaining of exhaustive experimental data on the energy spectrum and angular distribution of muons with energy > $3\cdot 10^{11}$ ev.

In conclusion we should make a few remarks on sources of rapid generation of high energy muons, possible from the standpoint of theory. According to [21], intermediate bosons, produced in strong interactions by pair, and rapidly decaying according to the scheme $W \to \mu + \nu$, can constitute such a source.

(*) We shall demonstrate that at sufficiently great energies E of the muon at soil boundary, the energy spectrum of muons under the soil layer is independent of the depth x. Ef the integral spectrum by E_0 is $AE_0^{-\gamma}$,

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According to [21], the hypothesis on production of boson pairs does not lead to the appearance of any kind of new effects in weak interactions at low energies, and, in this context, it is not in contradiction with the experimental data available for small energies. On the other hand, the process of direct generation of muons as a result of charge fluctuation in the Fermi volume within the framework of multiple production Fermi-Landau, was considered as early as in work [22], and lately in [23]. If the experimental indications on the rapid generation of high-energy muons, to which it was referred in the present work, are confirmed, then the choice between the various theoretical variants for the explanation of rapid generation [21, 23] may be made by way of setting up already more complex experiments with muons of high energy in the composition of extensive air showers. Indeed, the theoretical variants of [21, 23] will yield an essentially different spatial distribution of high-energy muons in an extensive air shower because of the essentially different distribution of transverse pulses of produced muons (in the case [21] $p_{\perp}$ will be substantially greater than in the case [23]).

This is why the investigation of spatial distribution of muons with energy $E_\mu > 3 \cdot 10^{11}$ ev, and the obtaining of a detailed information on muon beams are of particular interest.

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the spectrum at depth x should be $A[f(E_\mu(x))]^{-\gamma}$, where $E_\mu(x)$ is the muon energy at depth x on the condition that at ground boundary this muon have an energy E_0, Integrating the fluctuations, one may obtain the form of functions $f(E_\mu(x))$. For $bE_0 > a$ (a being the losses to ionization, b — to pair formation, e^+, e^- — the bremmstrahlung), $E_0 = (e^{bx}/b)[a + bE(x)]$. Thus, the spectrum by $E_\mu(x)$ is described by $[a + bE_\mu(x)]^{-\gamma}$ and $E_\mu(x) \sim a/b$ and is independent of x.

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