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SEZIONE II

(Fisica, chimica, geologia, paleontologia e mineralogia)

Fisica. — *Some implications of muon intensity measurements at 4500 m.w.e.* Nota di BRUNO BASCHIERA, LAURA BERGAMASCO e MARIA CRISTINA TABASSO, presentata (*) dal Socio G. WATAGHIN.

RIASSUNTO. — Si presenta un risultato sperimentale sull'esponente dello spettro di energia integrale dei muoni di energia $> 10^3$ GeV, per mezzo di misure di intensità di muoni. Le misure sono state svolte nella Stazione del M. Bianco alla profondità di (4400 ± 80) m.a.e. Il valore di γ così ottenuto viene discusso e confrontato con i risultati di altri autori e con presenti teorie sui processi di produzione multipla.

1. In this Note we report an experimental result on the exponent of the high energy muon spectrum in the TeV energy range, obtained from muon intensity measurements deep underground. The muon spectrum for $E > 10^3$ GeV is not yet investigable directly by magnetic spectrographs because of the smallness of their solid angle of acceptance, and the available estimates in this region are usually derived either by the burst size distribution or by ionization calorimeters measurements.

These great depth measurements are useful also for the information they may give on the multiple production process at very high energies.

2. The experimental apparatus has been working for several months in the Mount Blanc Station, at a depth of (4400 ± 80) m.w.e. There we have an omnidirectional liquid scintillator detector watched by fast photomultipliers put in fourfold coincidences to select the physical event of the muon passage out of the phototube noise and local radioactivity events. The events so selected are photographed on an oscilloscope for the subsequent analysis of the pulses. The geometrical factor $\Gamma = (8.1 \pm 0.6)\, 10^3\ \mathrm{cm}^2\ \mathrm{sr}$ has been calculated with the angular distribution law for great depths and large zenithal angles [1]

$$I(\theta) = I(0) \sec\theta \left\{ \exp - \left(\frac{x}{(810 \pm 50)} (\sec\theta - 1) \right) \right\}.$$

The experimental vertical intensity in the station under the Mount Blanc rock ($Z^2/A = 0.511$, $Z/A = 0.494$, $\rho = 2.6\ \mathrm{gr \cdot cm^{-3}}$) is

$$I_v\,(4400 \pm 80\ \mathrm{m.w.e.}) = (3.31 \pm 0.28)\ 10^{-9}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$$

which after conversion to standard rock ($Z^2/A = 0.55$) results in excellent agreement with the intensity-depth curve for $x > 4000$ m.w.e. [1] based on the experimental results of many authors [2–5].

(*) Nella seduta del 14 febbraio 1970.

3. The integral energy spectrum at sea level of high energy muons is usually represented by the power law $J(E) = J(0)\,E^{-\gamma}$, with the value of the exponent γ increasing with the muon energy range.

Let us define the ratio

$$y(x) = \frac{I_{\text{fluct}}(x)}{I_0(x)} \tag{1}$$

where

$$I_0(x) = \int_{E_0}^{\infty} J(E)'\,dE = \frac{J(0)}{\gamma}\,[E_0(x)]^{-\gamma}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

is the intensity at depth x (threshold energy E_0) assuming all energy losses as continuous, and $I_{\text{fluct}}(x)$ is the intensity taking the fluctuations into account, that is considering also the catastrophic processes where muons lose a great fraction of their energy in any single interaction. That is

$$I_{\text{fluc}}(x) = \int_{E_{\min}}^{\infty} J(E)'\,P(E\,,x)\,dE \qquad \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} \tag{2}$$

where $P(E\,,x)$ is the survival probability of a muon of initial energy E at depth x, and $E_{\min}$ is the energy loss due only to continuous processes of a muon which survives just to depth x. The survival probability has been calculated by many authors under different assumptions and with different calculation methods [6–12]. We estimated $P(E\,,x)$ by means of a Montecarlo calculation, using for the energy loss the expression

$$-\frac{dE}{dx} = k(E) + bE \tag{3}$$

where $k(E)$ is the collision energy loss term, and b is a term which accounts for the energy loss processes of bremsstrahlung, nuclear interactions and pair production, calculated with the expression derived in previous works of our group [14, 15]

$$b = b_{\text{brem}} + b_{\text{nucl}} + b_{pp} = (1.8 + 1.1 + 1.0)\,10^{-6}\,\text{gr}^{-1}\,\text{cm}^2 = 3.9\,10^{-6}\text{gr}^{-1}\,\text{cm}^2. \tag{4}$$

The greatest uncertainty comes from the nuclear process term: our accepted value of b_{nucl}, obtained from the theoretical approach outlined in a recent work by Castagnoli *et al.* [16], has been however satisfactorily checked in a recent experiment for depths down to 300 m.w.e. [17].

The value of the $y(x)$ ratio has been calculated for various depths of the M. Blanc rock and for various values of the spectrum exponent γ. The results, shown in fig. 1(a) may be set in a simple relation

$$\log y(x) = a(x)\,\gamma - b(x) \tag{5}$$

where $a(x)$ and $b(x)$ are plotted versus depth x in fig. 1(b) and 1(c). It is therefore possible to estimate γ from the M. Blanc experimental results

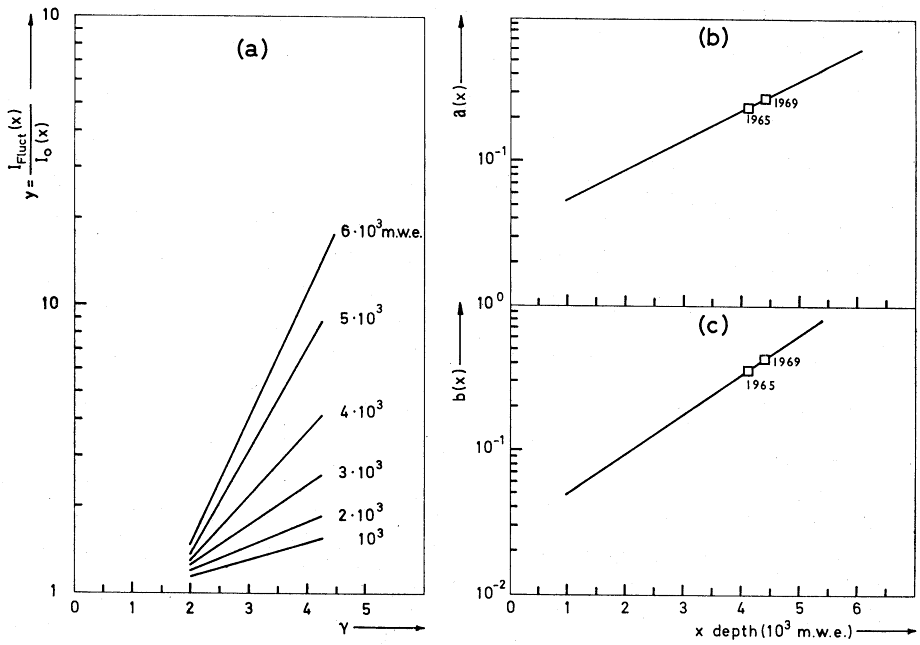

Fig. 1.

obtained by our group some years ago at $x = (4100 \pm 110)$ m.w.e. [18] and now at $x = (4400 \pm 80)$ m.w.e.

In fact $y(x)$ may be interpreted experimentally as the ratio between the observed intensity at the depth x and $I_0(x)$, from which, by means of the set of values relative to the two depths shown in Table I, we obtain $\gamma = 2.47$ with a 10 % probable error.

TABLE I.

Depth	(4100 ± 110 m.w.e.)	(4400 ± 80) m.w.e.
$E_0(x)$	(2.5 ± 0.2) TeV	(2.8 ± 0.1) TeV
I_{obs}	(1.00 ± 0.23) 10^{-8} cm^{-2} s^{-1} sr^{-1}	(3.15 ± 0.41) 10^{-9} cm^{-2} s^{-1} sr^{-1}
$a(x)$	0.24 ± 0.01	0.27 ± 0.01
$b(x)$	0.36 ± 0.01	0.44 ± 0.01

This determination of γ is not too sensible to the value of the energy loss parameter b; namely $\frac{\Delta\gamma}{\gamma} \leq \frac{1}{2}\frac{\Delta b}{b}$, and the percentage uncertainty on the many terms of b, shown in [4], is not greater than 10 %.

Table II reports a survey of the most recent experimental results on γ:

TABLE II.

Author	Method	γ	Energy Range
HIGASHI [19]	Burst size	$2.5^{+1.0}_{-0.2}$	$0.1 < E < 4$ TeV
KRESILNIKOV [20]	Burst size	2.4 ± 0.1	$0.1 < E < 6$ TeV
CHIN [21]	Burst size	2.5 ± 0.1	$1 < E < 8$ TeV
ERLYKIN [22]	Ionization calorimeter	2.59 ± 0.05	$0.2 < E < 10$ TeV
PRESENT WORK	muon intensity at M. Blanc	2.47 ± 0.20	$E > 2$ TeV

three of them are obtained from the size frequencies of muon bursts [19, 20, 21], perhaps the most extensively used method for the estimate, one of them from ionization calorimeter measurements [22].

Our value, also reported, turns out to be in good agreement with the other results, and shows that the figure $\gamma = 2.1$, suggested recently by some authors [23] for the energy range $0.3 \leq E \leq 3$ TeV is too low, at least for the higher energy values.

As the agreement among the various determinations of γ is good we can assume for the TeV region the mean weighted value $\overline{\gamma} = 2.49 \pm 0.09$.

4. As we said previously, the knowledge of the esponent γ may give an insight into the multiple production process at very high energies.

At our energies, in fact, the source function P_μ for $\pi - \mu$ decay is given by

$$P_\mu(x, E) = \frac{1}{1 - (m_\pi/m_\mu)^2} \int_E^{E(m_\pi/m_\mu)^2} \frac{dE_0}{E_0} \frac{B_\pi}{E_0 x} F(x, E_0) \tag{6}$$

where $B_\pi = 139$ GeV/c is the decay constant. The mechanism of multiple pion production enters into the equation through the production spectrum of π mesons in the nuclear collisions of primary energy E_0, and is related to $F(x, E_0)$ by the usual diffusion equations. The three multiple production models which appear more favoured nowadays [24, 25] and namely 1) two fireball (FB) model, 2) aleph model of Koshiba and others [26], 3) H quantum (HQ) theory of Hasegawa [27] predict different values for the exponent γ of the muon integral spectrum at sea level [25]. They are respectively

$$\gamma_{FB} = 2.8 \quad ; \quad \gamma_X = 2.7 \quad ; \quad \gamma_{HQ} = 2.6 .$$

The results here discussed seem to favour the H quantum model rather than the aleph model, and to exclude the fireball model. This suggestion is confirmed by the recent results of Fujimoto [25], and by a Montecarlo calculation of Castagnoli *et al.* [28] which shows how the fireball model does not explain the intensity-depth relation for the associated penetrating particles process.

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