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## A Discussion of Some Recent Results on Cosmic-Ray Muons.

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**Summary.** — We study the unexpected results of recent experiments on cosmic-ray muons of very high energy and the consistency of some of their interpretations. We find that although these interpretations cannot be dismissed outright as untenable, their physical bases will have to await more refined data, hopefully from many experimental groups, before they can be finally established.

The existence of the  $\mu$ -meson, as a heavy electron, is in itself an « anomaly », but perhaps not the only one, since some unexpected results of recent experiments<sup>(1-2)</sup> on cosmic-ray muons of very high energy indicate anomalies in our understanding of this particle.

This circumstance has led to speculations about possible anomalous couplings of the  $\mu$ -meson and on the existence of a new type of particle as, for in-

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<sup>(1)</sup> T. HARA, S. KAWAGUCHI, S. MIKANO, M. NAGANO, K. SUGA, M. TAKANO, G. TANAHASHI and T. MATANO: *XI International Conference on Cosmic Rays* (Budapest, 1969), EAS-22.

<sup>(2)</sup> J. W. KEUFFEL, J. L. OSBORNE, G. L. BOLINGBROKE, G. W. MASON, M. O. LARSON, G. H. LOWE, J. H. PARKER, R. O. STERNESESON and H. E. BERGESON: *XI International Conference on Cosmic Rays* (Budapest, 1969), MU-31.

stance, the  $SU_3$  triplets or some others like the intermediate vector bosons. A less drastic interpretation of these results but one no less important than the hypothesis of exotic particles and interactions takes the view that the results of some of these experiments may be witness to a significant departure of very-high-energy q.e.d. from the predictions of familiar approximation schemes such as the vector-meson dominance model. In the following pages we study the results of the experiments mentioned herein above and the consistency of some of their interpretations. We find that although these interpretations cannot be dismissed outright as untenable, their physical bases will have to await more refined data, hopefully from many experimental groups, before they can be finally established.

### 1. - Muoproduction.

In the analysis of muoproduction data the vector-meson dominance model has been extensively used. According to this model the photon exchanged between the muon and the proton is a vector meson (see Fig. 1) (or better a

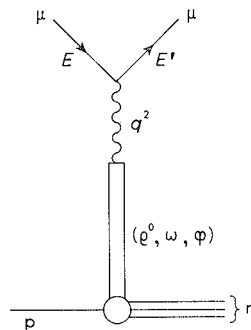


Fig. 1. - Muoproduction in the vector dominance model,  $E' = E - \nu$ ,  $q^2 = 4EE' \sin^2(\theta/2)$ .

number of such mesons) in disguise; from <sup>(3)</sup> it follows that the total photo-absorption cross-section  $\sigma_{\gamma p}(\nu)$  is given by

$$(1) \quad \sigma_{\gamma p} = \alpha \left\{ \frac{16\pi}{\gamma_p^2} \sigma_{\rho\gamma} + \frac{4\pi}{\gamma_y^2} [\sin^2 \theta_y \sigma_{\omega p} + \cos^2 \theta_y \sigma_{\phi p}] \right\},$$

where  $\gamma_p, \gamma_y, \theta_y$  give the couplings of the photon to the neutral vector mesons  $\rho^0, \omega, \phi$  and  $\sigma_{\nu p}$  ( $\nu = \rho^0, \omega, \phi$ ) can be calculated from the diffractive production of these mesons.

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<sup>(3)</sup> W. RILSON: *Comm. Nucl. Part. Phys.*, **2**, 169 (1968).

The application of the vector-meson dominance hypothesis to high-energy e-p and  $\mu$ -p scattering is however not very successful. The general <sup>(4)</sup> expression for the differential inelastic cross-section in terms of the form factors  $W_1(q^2, \nu)$ ,  $W_2(q^2, \nu)$  is

$$(2) \quad \frac{d^2\sigma}{dq^2 d\nu} = \frac{4\pi\alpha^2}{q^4} \frac{1}{E^2} \left[ \frac{1}{2} q^2 W_1(q^2, \nu) + \left( E^2 - E\nu - \frac{1}{4} q^2 \right) W_2(q^2, \nu) \right],$$

where  $W_1$  and  $W_2$  are related to the cross-sections  $\sigma_t$ ,  $\sigma_l$  for the absorption of transversally and longitudinally polarized photons respectively:

$$(3) \quad \begin{cases} W_1 = \frac{1}{4\pi^2\alpha} (q^2 + \nu^2)^{\frac{1}{2}} \sigma_t(q^2, \nu), \\ W_2 = \frac{1}{4\pi^2\alpha} \frac{q^2}{(q^2 + \nu^2)^{\frac{1}{2}}} [\sigma_l(q^2, \nu) + \sigma_t(q^2, \nu)]. \end{cases}$$

The vector-meson dominance parametrization of  $\sigma_t$  and  $\sigma_l$  is usually

$$(4) \quad \sigma_t = \sigma_{\gamma\nu}(v) \left( \frac{m_\rho^2}{m_\rho^2 + q^2} \right)^2, \quad \sigma_l = 0.$$

Substituting from (3) and (4) into (2) gives

$$(5) \quad \frac{d^2\sigma}{dq^2 d\nu} = \frac{\alpha}{\pi} \frac{1}{q^2 E^2} \left[ \frac{1}{2} (q^2 + \nu^2)^{\frac{1}{2}} + \frac{(E^2 - E\nu - \frac{1}{4} q^2)}{(q^2 + \nu^2)^{\frac{1}{2}}} \right] \sigma_{\gamma\nu}(v) \left( \frac{m_\rho^2}{m_\rho^2 + q^2} \right)^2.$$

If the contribution of  $\sigma_l$  is included as was shown by SAKURAI <sup>(5)</sup> one has

$$(3') \quad \begin{cases} W_1 = \frac{(v^2 + q^2)^{\frac{1}{2}}}{4\pi^2\alpha} \sigma_{\gamma\nu}(v) \left( \frac{m_\rho^2}{m_\rho^2 + q^2} \right)^2, \\ W_2 = \frac{q^2}{4\pi^2\alpha(v^2 + q^2)^{\frac{1}{2}}} \sigma_{\gamma\nu}(v) \frac{m_\rho^2}{m_\rho^2 + q^2}, \end{cases}$$

and eq. (2) becomes

$$(5') \quad \frac{d^2\sigma}{dq^2 d\nu} = \frac{\alpha}{\pi} \frac{1}{q^2 E^2} \left[ \frac{1}{2} (q^2 + \nu^2)^{\frac{1}{2}} \frac{m_\rho^2}{m_\rho^2 + q^2} + \frac{E^2 - E\nu - \frac{1}{4} q^2}{(q^2 + \nu^2)^{\frac{1}{2}}} \right] \sigma_{\gamma\nu}(v) \frac{m_\rho^2}{m_\rho^2 + q^2}.$$

<sup>(4)</sup> S. DRELL and J. WALECKA: *Ann. of Phys.*, **28**, 18 (1964).

<sup>(5)</sup> J. J. SAKURAI: *Phys. Rev. Lett.*, **22**, 981 (1969).

The cross-section  $\sigma_{\gamma p}(\nu)$  has been measured by various groups <sup>(6)</sup> and some theoretical calculations of it are also available. As seen from Table I,  $\sigma_{\gamma p}(\nu)$  is approximately constant for  $\nu$  above 1 GeV. We shall take for  $\sigma_{\gamma p}(\nu)$  the constant value 125  $\mu\text{b}$ .

TABLE I.

Reference <sup>(6)</sup>	Technique used	Photon energy (GeV)	$\sigma_{\gamma p}(\nu)$ ( $\mu\text{b}$ )
ABBHHM COLLABORATION	Bubble chamber photoproduction	$3.5 < \nu < 5.4$	$116 \pm 17$
BALLAM <i>et al.</i>	Bubble chamber photoproduction	$7 < \nu < 8$	$126 \pm 17$
CALDWELL <i>et al.</i>	Counters	$7.4 < \nu < 9.4$	$118.8 \pm 2.6$
CALDWELL <i>et al.</i>	Counters	$12 < \nu < 15.2$	$114 \pm 2.8$
CALDWELL <i>et al.</i>	Counters	$14.4 < \nu < 18.3$	$113 \pm 2.5$
DAVIER <i>et al.</i>	Vector-dominance model	$\nu = 9$	$130 \pm 30$
KNIES	Quasi-elastic optical theorem	$3 < \nu < 5$	$99 \pm 12$
BUCCELLA and COLOCCI	Regge-pole theory	$\nu > 5$	130

The comparison of eqs. (5) and (5') with experiment is displayed in Table II, where the experimental entries are from KIRK *et al.* <sup>(7)</sup>. What seems noteworthy about the vector-meson dominance model is that recent data by

<sup>(6)</sup> AACHEN-BERLIN-BONN-HAMBURG-HEIDELBERG-MUNCHEN COLLABORATION: *Phys. Lett.*, **27** B, 474 (1968); J. BALLAM, G. B. CHADWICK, Z. G. T. GUIRANGOSSIAN, P. KLEIN, A. LEVY, M. MENKE, E. PICKUP, P. SEYBOTH, T. H. TAN and G. WOLF: *Phys. Rev. Lett.*, **21**, 1544 (1968); M. DAVIER, I. DERADO, D. DRICKEY, D. FRIES, R. MOZLEY, A. ODIAN, F. VILLA and D. YOUNT: SLAC-PUB-503 (1968); G. KNIES: *Phys. Lett.*, **27** B, 288 (1968); F. BUCCELLA and M. COLOCCI: *Phys. Lett.*, **24** B, 61 (1967); D. O. CADWELL, V. B. ELINGS, W. P. HESSE, G. E. JAHN, R. J. MORISON, F. V. MURPHY and D. E. YOUNT: *Phys. Lett.*, **23**, 1256 (1969); C. CASTAGNOLI, M. MUCHNIK, G. GHIGO and R. RINZIVILLO: *Nuovo Cimento*, **19**, 683 (1960).

<sup>(7)</sup> J. A. KIRK, D. M. COTTREL, J. J. LORD and R. J. PISERCHIO: *Nuovo Cimento*, **40** A, 523 (1965); R. L. THOMPSON, J. J. LORD, J. A. KIRK, M. E. NELSON and R. J. PISERCHIO: preprint (unpublished).

TABLE II.

Muon energy (GeV/c)	Cross-section per nucleon in $\mu$ b meson production events		
	Experimental	eq. (5)	eq. (5')
2.5	$3.6 \pm 0.7$	5.22	5.6
5	$5.1 \pm 0.5$	7.83	8.37
10.5	$11.4 \pm 1.4$	10.8	11.5

WILSON *et al.* <sup>(8)</sup> and by PERL *et al.* <sup>(9)</sup> are better fitted with eq. (5') than with eq. (5). It must be remembered though that eq. (5') was motivated by the failure of eq. (5) to fit high-energy <sup>(10)</sup> e-p data and that one consistency test of eq. (5'), namely the ratio between the longitudinal and transverse cross-sections  $\sigma_l, \sigma_t$  predicted to be proportional to  $q^2/m_p^2$  by SAKURAI, has been contradicted in e-p <sup>(11)</sup> scattering.

Information on  $\mu$ -p scattering in cosmic rays comes mainly from measurements underground. Such measurements are plagued by large uncertainties due to experimental difficulties, especially that of distinguishing between nuclear and electromagnetic showers.

In Fig. 2 we have plotted the shower cross-section defined by

$$(6) \quad \sigma_{sh}(x) = \int_{E(\min)}^{\infty} F(E, x) dE \int_{\nu_{\min}}^{E-m_{\mu}} \frac{d\sigma}{d\nu}(E, \nu) \bigg/ \int_{E(\min)}^{\infty} F(E, x) dE,$$

where  $F(E, x)$  is the muon spectrum at a depth  $x$  underground against  $x$ , using eqs. (5) and (5') to get  $d\sigma/d\nu$ . For  $\nu_{\min}$  we have used 2 and 5 GeV.

<sup>(8)</sup> C. M. HOFFMAN, A. D. LIEBERMANN, E. ENGELS jr., D. C. IMRIE, P. G. INNOCENTI, R. WILSON, C. ZAJDE, W. A. BLAMPED, D. C. STAIRS and D. DRICKEY: *Phys. Rev. Lett.*, **22**, 659 (1969).

<sup>(9)</sup> B. D. DIETERLE, T. BRAUNSTEIN, J. COX, F. MARTIN, W. T. TONER, M. L. PERL, T. F. ZIFF, W. L. LAKIN and H. C. BRYANT: *Phys. Rev. Lett.*, **23**, 1187 (1969); M. L. PERL, T. BRAUNSTEIN, J. COX, F. MARTIN, W. T. TONER, B. D. DIETERLE, T. F. ZIFF, W. L. LAKIN and H. C. BRYANT: *Phys. Rev. Lett.*, **23**, 1191 (1969).

<sup>(10)</sup> E. D. BLOOM, D. H. COWARD, H. DESTAEBLER, J. DREES, G. MILLER, L. W. MO, R. E. TAYLOR, M. BRIEDENBACH, J. I. FRIEDMAN, B. C. HARTMANN and H. W. KENDALL: *Phys. Rev. Lett.*, **23**, 935 (1969); M. BRIEDENBACH, J. I. FRIEDMAN, H. W. KENDALL, E. D. BLOOM, D. H. COWARD, H. DESTAEBLER, J. DREES, L. W. MO and R. E. TAYLOR: *Phys. Rev. Lett.*, **23**, 939 (1969).

<sup>(11)</sup> W. ALBRECHT, F. W. BRASSE, H. DORNER, W. FLAUGER, K. H. FRANK, J. GAYLER, H. HULTSCHIG, V. KORBEL, J. MAY and E. GANSSAUGE: preprint DESY-69/46 (1969).

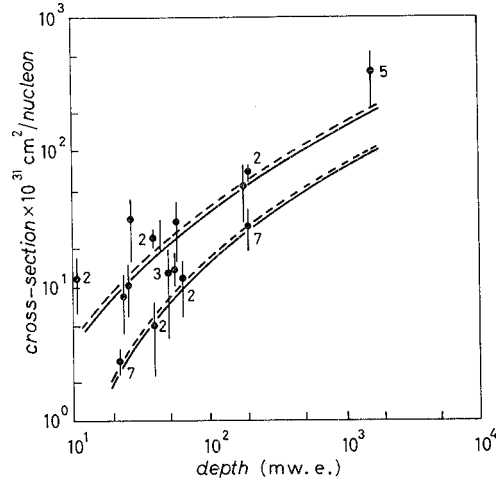


Fig. 2. - Cross-section for shower production under rock. The solid and dashed lines are obtained using eq. (5) and eq. (5') respectively with  $\nu_{\min} = 2$  and 5 GeV. The value of  $\nu_{\min}$  in each experiment, which differs from 1 GeV, is given near the experimental point.

Equations (5) and (5') are in agreement with these data<sup>(12)</sup>. In Table III the predictions of vector dominance after normalization at  $q^2 = 2(\text{GeV}/c)^2$  have been compared with the measurements of HIGASHI *et al.*<sup>(13)</sup> of the integral muon spectrum with respect to  $q^2$  for  $\nu \geq 5$  GeV. There is a marked preference for eq. (5') instead of eq. (5).

TABLE III.

$q^2 ((\text{GeV})^2)$	eq. (5)	eq. (5')	Experimental (HIGASHI)
2	10	10	$10 \pm 2$
5	0.97	3.95	$5 \pm 1.4$
10	0.0098	1.13	$2.3 \pm 1.1$

The above-discussed agreement of the vector-meson dominance model with cosmic-ray data is to be contrasted with the fact that recent measurements underground<sup>(14)</sup> show an anomalous behaviour with respect to it. The same

<sup>(12)</sup> D. KESSLER and R. MAZE: *Physica*, **22**, 69 (1956); E. AMALDI, C. CASTAGNOLI, A. GIGLI and S. SCIUTI: *Nuovo Cimento*, **9**, 969 (1952); S. HIGASHI, T. OSHIO, H. SHIBATA, K. WATANABE and Y. WATASE: *Nuovo Cimento*, **5**, 592 (1957); N. CHAUDHURI and M. S. SINHA: *Nuovo Cimento*, **57 A**, 753 (1968).

<sup>(13)</sup> Y. WATASE, S. HIGASHI, T. KITAMURA, Y. MITANI, S. M. YAMOTO, T. OSHIO, H. SHIBATA and K. WATANABE: *Journ. Phys. Soc. Japan*, **17**, Suppl. A-III, 362 (1962).

<sup>(14)</sup> *XI International Conference on Cosmic Rays* (Budapest, 1969), EAS-22.

is true of a muoproduction event of energy transfer  $\nu \simeq 300$  GeV observed by HIGASHI *et al.* <sup>(15)</sup> during a year and a half of observation. The frequency of this anomalous event taking account of the experimental geometry is about ten times what one would expect from either eqs. (4), (5) or (5'). The comparison <sup>(16)</sup> of the sea-level muon energy spectrum with the depth-intensity curve through  $dE/dx$  can give scarce information on  $\mu$ -p scattering because of the errors in the relevant experimental parameters (exponent of the spectrum, bremsstrahlung, pair production) and also because a large part of the energy loss is due to interactions with small  $q^2$  and  $\nu$ . In conclusion it is clear from the above that eq. (5') fits the high-energy cosmic-ray muon data better than eq. (5), suggesting that for high-energy transfer  $\nu$ , there is a possible anomalous increase in the muon-nucleon cross-section with respect to the conventional picture.

## 2. - Horizontal air showers.

The frequent extensive horizontal air showers observed by the Tokio <sup>(1)</sup> group and later confirmed by WOLFENDALE *et al.* <sup>(17)</sup> are of considerable interest to muon physics. The characteristic properties of these horizontal air showers (HAS) are:

- i) The primaries of HAS for zenith angle  $\theta > 70^\circ$  are clearly different from those for  $\theta < 55^\circ$ .
- ii) The zenith angle distributions for  $60^\circ \leq \theta \leq 75^\circ$  follows the  $\sec\theta$  law exactly as for muons.
- iii) There is a significant departure from the  $\sec\theta$  law for  $\theta > 75^\circ$ ; the corresponding attenuation length is between  $(2000 \div 1000)$  g/cm<sup>2</sup>.
- iv) The exponent of the spectrum of the HAS as a function of the energy transfer (size) is  $-2.8 \pm 0.3$  for  $\theta > 70^\circ$ .
- v) A large percentage of HAS nuclear cascade showers is observed in HAS.

These properties, especially v), point to two possible facts:

- a) The  $\mu$ -p cross-section increases at high energy ( $E > 10^3$  GeV).

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<sup>(15)</sup> S. HIGASHI, T. KITAMURA, Y. MISHIMA, S. MIYAMOTO, T. OSHIO, H. SHIBATA and Y. WATASE: *Nuovo Cimento*, **22**, 304 (1961); S. HIGASHI, T. KITAMURA, Y. MISHIMA, S. MIYAMOTO, Y. WATASE and H. SHIBATA: *Nuovo Cimento*, **33**, 107 (1965); S. CHIN, Y. HANAYAMA, T. HARA, S. HIGASHI, T. KITAMURA, S. HIONO, S. MIYAMOTO, M. NAKAGAWA, S. OSAKI, T. TAKAHASHI, K. TSUJI, Y. WATASE, K. KOBAYAKAWA and H. SHIBATA: *Can. Journ. Phys.*, **46**, S 1112 (1968).

<sup>(16)</sup> C. CASTAGNOLI, P. PICCHI and R. SCRIMAGLIO: *Nucl. Phys.*, **87**, 641 (1967).

<sup>(17)</sup> D. ALEXANDER *et al.*: *XI International Conference on Cosmic Rays* (Budapest, 1969), MU-35.



b) The primaries of the HAS are not muons but another type of particle with a strong coupling.

These two possibilities and their consequences are discussed below.

2'1. *Inapplicability of the vector-meson dominance model.* – In Sect. I we have seen that although cosmic-ray data on  $\mu$ -p scattering are in accord with the vector-meson dominance model for relatively low energy; they suggest that at high energy there could be an anomalous increase in the  $\mu$ -p cross-section.

If the HAS are due to muons<sup>(18)</sup>, then from their properties listed above they are the first experimental information on muoproduction with  $\nu > 10^3$  GeV and a large cross-section which disagrees with the vector-meson dominance model eqs. (5) and (5'). In fact the use of eqs. (5) and (5') to compute the integral flux of HAS

$$(7) \quad J(\nu_{\min}) = \int_{\nu_{\min}}^{\infty} dE M(E) \int_{\nu_{\min}}^{\infty} d\nu \frac{d\sigma}{d\nu} N \Delta X$$

gives a very poor result as seen by the dashed curve in Fig. 3.

In eq. (7)  $M(E)$  is the conventional differential muon spectrum,  $N$  Avogadro's number and  $\Delta X = 400 \text{ g} \cdot \text{cm}^{-2}$  is the mean distance between the point of origin of the event and that of observation.

The minimum and maximum values of  $q^2$  used are

$$q_{\min}^2 = \nu^2 m_{\mu}^2 / E(E - \nu), \quad q_{\max}^2 = 2 M_N \nu.$$

*Faute de mieux* we have adopted the parametrization

$$(8) \quad W_2(\nu, q^2) = \frac{C}{\nu} = \frac{0.3}{\nu}$$

of  $\nu W_2$  found to fit the SLAC-MIT<sup>(19)</sup> data for  $\nu/q^2 \geq 5 \text{ (GeV)}^{-1}$  and for both  $\nu$  and  $q^2$  separately large (minimum value of  $q^2 \simeq 0.5 \text{ (GeV)}^2$ ) in eq. (7), and the resultant form of  $J(\nu_{\min})$  is the full curve in Fig. 3, which as seen is quite close to the experimental points. This agreement of eq. (8) with the HAS data is rather surprising since  $q^2$  for these events is small and we know both theoretically and experimentally<sup>(20)</sup> for  $\nu$  up to 20 GeV that  $\nu W_2 \propto q^2 \sigma_t$  tends

<sup>(18)</sup> C. CASTAGNOLI, E. ETIM and P. PICCHI: *Lett. Nuovo Cimento*, **2**, 595 (1969).

<sup>(19)</sup> R. TAYLOR: *Proceedings of the Conference on Expectations for Particle Reactions at the New Accelerators*, Univ. of Wisconsin (1970).

<sup>(20)</sup> E. D. BLOOM, R. L. COTTRELL, D. H. COWARD, H. DE STAEBLER jr., J. DREES, G. MILLER, L. W. MO, R. E. TAYLOR, J. I. FRIEDMAN, G. C. HARTMANN and H. W. KENDALL: SLAL-PUB-653 (1969).

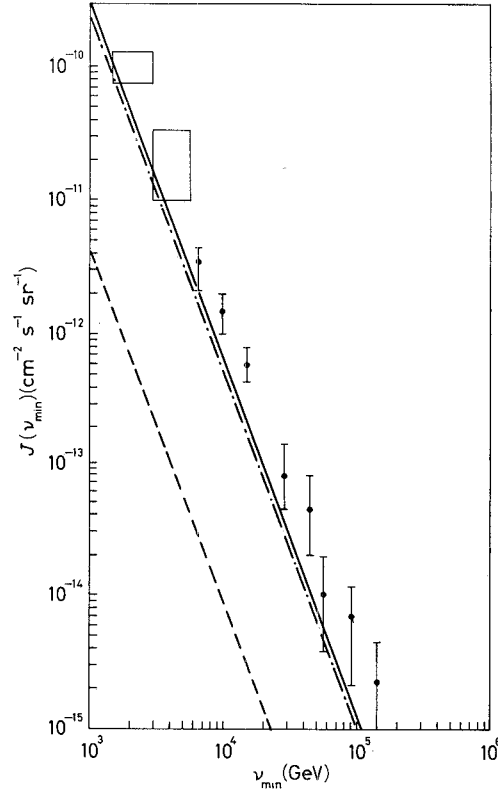


Fig. 3. - Plot of the integral flux  $J(\nu_{\min})$  against the minimum energy transfer  $\nu_{\min}$ . The dashed curve is the result of eqs. (5) and (5'); the full and dash-dotted curves are drawn using the parametrization eq. (8) in the two extreme cases  $\sigma_i/(\sigma_i + \sigma_t)$  equal to one and zero.

to zero for  $q^2 \rightarrow 0$ . If the HAS are due to muons then the agreement of eq. (8) with experiment implies *ipso facto* a breakdown of the Weizsacker-William approximation following which  $\sigma_i(\nu, q^2)$  for  $q^2 \ll m_\rho^2$  can be expanded in a convergent series about  $q^2 = 0$ :

$$(9) \quad \sigma_i(\nu, q^2) = \sigma_{\nu\nu}(\nu)(1 + aq^2 + bq^4 + \dots).$$

Equation (8), on the other hand, gives

$$(10) \quad \sigma_i(\nu, q^2) = \frac{4\pi^2\alpha}{q^2} C$$

even for small  $q^2$  provided  $\nu$  is large,  $\nu \rightarrow \infty$ .

A conclusion that can be drawn from the above comparison of eqs. (9) and (10) with experiment for large  $\nu$  and small  $q^2$  is that high-energy q.e.d.

may differ from what, out of habit, is expected of it on the basis of familiar approximation methods.

2'2.  $SU_3$  triplet particles. — If the HAS are not from muon parents one is forced to conclude that they are produced by strongly interacting parents <sup>(21)</sup>. Since such strongly interacting parents cannot be nucleons (the inelasticity  $K_N$  of nucleons is 0.5 and they are therefore absorbed at large zenith angle), it must be supposed that they are particles heavier than the nucleon and therefore with a small inelasticity  $K_p$ . This hypothesis would fit in well with the properties iii) and v) of the HAS. The likely candidates could be the massive particles whose possible existence is a consequence of the  $SU_3$  symmetry. We

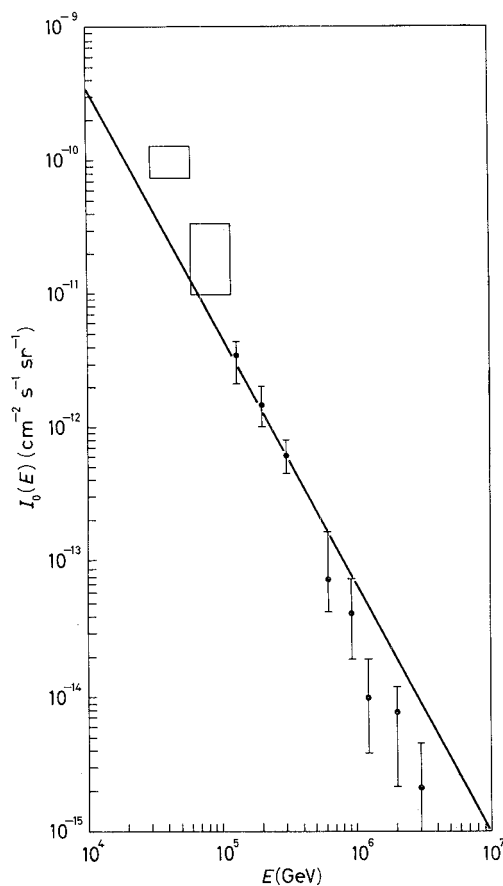


Fig. 4. — Integral vertical sea-level flux  $I_0(E)$  of heavy primaries against energy  $E$ . The experimental data have been obtained using the HAS data. The straight line is from eq. (12).

<sup>(21)</sup> C. CASTAGNOLI, E. ETIM and P. PICCHI: *Lett. Nuovo Cimento*, **1**, 197 (1969).

have examined the data of DARDO *et al.* <sup>(23)</sup> on triplets whose mass  $m_x$  should be between 10 and 15 GeV and whose mean free path  $\lambda_x$  is between 2 and 3 times that of the nucleon  $\lambda_N$ . The value of  $\lambda_x$  given by DARDO *et al.* is just about what one would expect theoretically.

The inelasticity  $K_x$  can be calculated from the relation  $K_x M_x \simeq K_N M_N$ .

Using the formula

$$(11) \quad J(\nu) = I_0(E_{\min}) \Delta x / \lambda_x$$

to calculate the integral flux  $I_0(E_{\min})$  of the assumed heavy primaries with energy  $E > E_{\min}$  ( $E_{\min} = \nu_{\min} / K_x$ ) from the integral flux  $J(\nu_{\min})$  of the HAS with energy  $\nu > \nu_{\min}$ , we find the result displayed in Fig. 4 (the horizontal flux has been converted to the vertical by means of the experimental ratio from DARDO *et al.*). Starting from the experimental flux ( $\sim 10^{-7}$  cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>) of DARDO *et al.* referring to a triplet energy near threshold,  $3(M_x^2/M_N)$ , one can obtain the flux in the energy interval concerned:

$$(12) \quad I_0(E) = 10^{-7} \left( \frac{E}{3M_x^2/M_N} \right)^{-\gamma},$$

with  $\gamma = 1.6$  the exponent of the primary spectrum. Equation (12) is a straight line which passes very close to the  $I_0$  values obtained from the HAS data with corresponding errors.

### 3. - Zenith angle distribution of high-energy muons.

In a series of underground experiments the Utah group <sup>(2)</sup> has provided evidence that the intensity of ultra-high-energy muons ( $E > 10^{12}$  eV) does not show the  $\sec\theta$  enhancement that is expected of it if the main source of muons is the decay of pion and kaon parents. The almost isotropic zenithal-angle distribution reported points to the existence of muons that are produced directly, either in the nucleon-nucleon collision in the atmosphere or through an intermediary of very short lifetime itself produced in the  $\mathcal{N}$ - $\mathcal{N}$  collision; the overall muon spectrum is best fitted by the formula

$$(13) \quad M(E) = C_\pi E^{-\gamma-1} \gamma^\gamma K(E, \theta) B(E \cos \theta^* + B)^{-1} + \\ + RC_\pi E^{-\gamma-1} (\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} (\text{GeV})^{-1})$$

in which the first term represents the conventional muon spectrum of  $\pi$ -K derived muons and the second term is the contribution from the direct process; the parameter  $R \simeq 0.02$  which fixes the direct spectrum is simply the ratio

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<sup>(23)</sup> M. DARDO, P. PENENGO and K. SITTE: *Nuovo Cimento*, **58** A, 59 (1968).

of muons derived from the direct process to the total number of pions of the same energy;  $C_\pi = 0.225$ ,  $\gamma = 1.7$ ,  $r = 0.76$ ,  $B = 90$  GeV and the factor  $K(E, \theta)$  which varies between 1.16 and 1.38 corrects for the ratio of kaons to pions of all charges.

Suggestions as to the origin of the direct process are many and varied: CALLAN<sup>(23)</sup> and GLASHOW have argued that not all the particles observed underground are muons but that there is a new type of stable particle, the u-particle, which arrives at the detector from the top of the atmosphere without interacting. The u-particle hypothesis is in conflict with the experimentally<sup>(24)</sup> confirmed fact that the penetrating component of cosmic rays consists only of muons.

On the basis of the disagreement between the measurement of FARLEY *et al.* of the muon  $g$ -factor

$$(14a) \quad a_\mu^{(\text{expt})} = \frac{1}{2}(g-2)_\mu = (11\,664.5 \pm 33) \cdot 10^{-7}$$

and the theoretical value

$$(14b) \quad a_\mu^{(\text{th})} = \frac{1}{2}(g-2)_\mu = (116\,564 \pm (10 \div 20)) \cdot 10^{-8}.$$

NEITO<sup>(25)</sup> pointed out that the deviation of (14a) from (14b), which could be explained by postulating the existence of a neutral vector boson whose coupling constant  $f$  to the muon is related to its mass  $M$  by

$$(15) \quad \frac{1}{M^2} \left( \frac{f^2}{4\pi} \right) \simeq (33 \text{ GeV})^{-2},$$

is consistent with the direct production mechanism, since if such a boson is exchanged between an incoming and an outgoing muon it can also decay into a muon pair. However with the recent measurements of FARLEY *et al.*<sup>(26)</sup>

$$(16a) \quad a_\mu^{(\text{expt})} = \frac{1}{2}(g-2)_\mu = (116\,616 \pm 31) \cdot 10^{-8}$$

and the detailed calculations of  $a_\mu^{(\text{th})}$  by ALDINS *et al.*<sup>(27)</sup>

$$(16b) \quad a_\mu^{(\text{th})} = \frac{1}{2}(g-2)_\mu = (116\,587 \pm 3.4) \cdot 10^{-8},$$

<sup>(23)</sup> C. G. CALLAN jr. and S. L. GLASHOW: *Phys. Rev. Lett.*, **20**, 779 (1968).

<sup>(24)</sup> W. R. KROPP jr., F. REINES and R. W. WOODS jr.: *Phys. Rev. Lett.*, **20**, 1256 (1968).

<sup>(25)</sup> M. M. NEITO: *Phys. Rev. Lett.*, **21**, 488 (1968).

<sup>(26)</sup> J. BAILEY, W. BARTL, G. VON BUCHMANN, R. C. A. BROWN, F. J. M. FARLEY, H. JÖSTLEIN, E. PICASSO and R. W. WILLIAMS: *Phys. Lett.*, **28 B**, 288 (1968).

<sup>(27)</sup> J. ALDINS, T. KINOSHITA, S. J. BRODSKY and A. J. DUFNER: *Phys. Rev. Lett.*, **23**, 441 (1969).

the discrepancy between theory and experiment is essentially eliminated and the small difference between (16a) and (16b) could most probably be due to experimental and theoretical uncertainties. In this case the near agreement between (16a) and (16b) places a stringent limit on the electromagnetic coupling to the higher-mass hadrons which can contribute to the muon  $g$ -factor through vacuum polarization. The general formula<sup>(28)</sup> for the hadronic contribution to  $a_\mu$  is

$$(17) \quad a_\mu(\text{hadrons}) = 4\alpha^2 \int_0^\infty \frac{\varrho(x) K(x)}{x^2} dx,$$

where the spectral function  $\varrho(q^2)$  is related to the total cross-section  $\sigma_h(e^+e^-)$  for  $e^+e^-$  annihilation into hadrons by

$$(18) \quad \sigma_h(e^+e^-) = \frac{16\pi^3\alpha^2}{q^4} \varrho(q^2)$$

and  $K(q^2)$  is a slowly varying function defined by the integral

$$(19) \quad K(q) = \int_0^1 dz \frac{z^2(1-z)}{z^2 + (1-z)(q^2/m_\mu^2)} \simeq \frac{m_\mu^2}{3q^2}$$

with  $m_\mu$  the muon mass. Substituting from (18) and (19) into (17) and simplifying gives

$$(20) \quad a_\mu(\text{hadrons}) \simeq \frac{m_\mu^2}{12\pi^3} \int_0^\infty \frac{dx \sigma_h(e^+e^-)}{x}.$$

It follows from (20) that if the small difference  $\delta a_\mu$  between (16a) and (16b) is regarded as the upper limit of the theoretical error of having neglected the contribution of higher-lying hadrons with mass greater than  $\sqrt{x_0} > m_\varphi$  then eq. (20) implies

$$(21) \quad \int_{x_0}^\infty \frac{dx}{x} \sigma_h(e^+e^-) < \frac{12\pi^3}{m_\mu^2} \delta a = 8.2 \mu\text{b}.$$

Thus a reduction of the experimental errors apart from confirming the q.e.d. calculation would seriously limit the cross-section for  $e^+e^-$  annihilation into hadrons. An upper bound similar to (21) is placed on whatever hypothetical

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<sup>(28)</sup> E. ETIM and P. PICCHI: Frascati report LNF-69/33 (1969).

coupling is held responsible for the small difference  $\delta a_\mu$ . In the case of the vector boson considered above one would have <sup>(29)</sup>

$$(22) \quad 0 < \frac{f^2}{4\pi} \frac{1}{M^2} < (45 \text{ GeV})^{-2}.$$

Other particles such as the  $SU_3$  triplets or a new class of hadrons capable of decaying into hadrons states containing muons have come under examination for their possible responsibility for the direct mechanism of muon production. Whatever hypothesis advanced in support of the direct production mechanism comes under two serious tests:

i) To find a physical explanation for the large cross-section  $\sigma(\text{pp} \rightarrow \text{x})$ , which would be between  $10^{-26}$  and  $10^{-28} \text{ cm}^2$ , where x is the intermediary in the chain  $\text{p} + \text{atmospheric nucleus} \rightarrow \text{x} \rightarrow \mu + ?$

ii) With the new muon spectrum in eq. (13) determined to within the parameter  $R$  one must obtain the depth-intensity curve of muon under rock which is known to be in agreement with the conventional pion- and kaon-derived muon spectrum at sea level.

As to the first difficulty, one can, at least for the moment, overlook it since anomalously large cross-sections are nothing new to cosmic-ray events. It is sufficient to remember that the large cross-section for nucleon pair production in extensive air showers with energy greater than 100 GeV is very much greater than the geometrical cross-section  $\sigma_{\bar{\nu}} = \pi \lambda_{\bar{\nu}}^2$  ( $\lambda_{\bar{\nu}} = \hbar/M_N c$  is the Compton wavelength of the proton), while that for the production of  $\bar{\text{p}}$  at 30 GeV ( $\sigma_{\bar{\nu}} \sim 10^{-30} \text{ cm}^2$ ) is approximately equal to the geometrical cross-section; the corresponding cross-sections for the productions of  $\pi$ , K and p in p-p collisions follow the geometrical law as originally suggested by ADAIR and PRICE <sup>(30)</sup>. The second difficulty is more demanding since one must find an additional mechanism of energy loss by muons in order to take account consistently of those directly produced. One way of circumventing this difficulty was suggested by BERGESON *et al.* <sup>(31)</sup> and consists in assuming that the photonuclear cross-section  $\sigma_{\gamma\text{p}}(\nu)$  increases with the energy transfer  $\nu$  in such a way that eq. (13) matches the depth-intensity curve. Using the formula

$$- \left( \frac{dE}{dx} \right)_{\text{nucl}} = b_{\text{nucl}} E,$$

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<sup>(29)</sup> I. YU. KOBZAREV and L. B. OKUN': *Sov. Phys. JETP*, **14**, 859 (1962); S. J. BRODSKY and E. DE RAFAEL: *Phys. Rev.*, **168**, 1620 (1968).

<sup>(30)</sup> R. K. ADAIR and N. J. PRICE: *Phys. Rev.*, **142**, 844 (1966).

<sup>(31)</sup> H. E. BERGESON, J. W. KEUFFEL, M. O. LARSON, G. W. MASON and J. L. OSBORNE: *Phys. Rev. Lett.*, **21**, 1089 (1968).

one finds under this assumption that  $b_{\text{nucl}}$  increases up to a factor six above the normal value. This large increase is however not observed in underground experiments because the events characterized by high muon energy and very large energy transfer ( $\nu > 10^8$  GeV) which should give rise to it are rare deep underground.

However, if the HAS are muon-produced, then from the work of the last Section we have an example of individual interactions with large energy transfer  $\nu$  characterized by an anomalous increase in the cross-section which can account for the needed energy loss necessary to match eq. (13) with the depth-intensity curve.

New leptonic interactions such as those illustrated in Fig. 5 a), b) and c) have come under consideration through the possible existence of the intermediate vector bosons  $W^\pm$  as likely mechanisms of the muon energy loss. The diagrams in Fig. 5 a) and b) can be evaluated and shown to give cross-sections of order of  $10^{-37}$  cm<sup>2</sup> at most. Diagrams of the type in Fig 5 c), although possible, are mainly speculations.

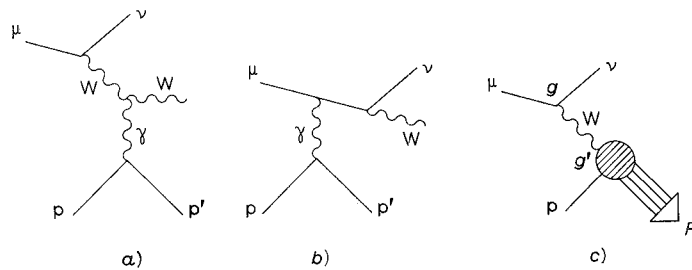


Fig. 5. - a), b) Muoproduction of W. c) Muoproduction of strong W.

A possible experiment to detect a possible anomalous interaction giving rise to two muon secondaries in the final state following the chain

$$(23) \quad \mu + p \rightarrow \mu + X \begin{matrix} \downarrow \\ \mu + ? \end{matrix}$$

is an underground measurement at different depths of the ratio  $S$  of the number of decaying muons to the total number of incident ones. If interactions such as (23) do not exist then  $S$  should fall off precipitously with the depth as the mean muon energy increases. But if (23) exists with significant probability then  $S$  would have a slower fall-off with increased depth by reason of the added secondaries.

**4. - Conclusion.**

High-energy physics, because of its very nature and the speculations which go into making it, does not permit an easy interpretation of our conclusions



on its results, even those obtained experimentally. For instance the work of ALDIN *et al.* has almost completely destroyed any basis for hope in explaining many experimental facts such as direct muon production by arguments based on the possible existence of the W. Nonetheless the HAS, the experiments of the Utah group and that of the Torino group on triplets combine to feed the suspicion that there is something new happening in the ultra-high-energy region. To have definitive answers to the problems which have been touched upon above more and new data, especially those from visual techniques, are greatly needed.

● RIASSUNTO

Si studiano i risultati inaspettati di recenti esperimenti con muoni cosmici di altissima energia e le loro possibili interpretazioni. Si conclude che occorrono nuovi e più precisi dati sperimentali per avere sicure risposte ai problemi che sono sorti.

**Последние результаты по мюонам космических лучей.**

**Резюме (\*).** — Мы исследуем неожиданные результаты последних экспериментов по мюонам космических лучей с очень высокой энергией и непротиворечивость некоторых интерпретаций этих результатов. Мы находим, что хотя эти интерпретации не могут сразу быть отклонены, как несостоятельные, их физические обоснования должны ждать уточненных данных, желательно от многих экспериментальных групп, прежде чем они могут быть окончательно приняты.

(\* ) *Переведено редакцией.*

C. CASTAGNOLI, <i>et al.</i> 1 Gennaio 1971 <i>Il Nuovo Cimento</i> Serie 11, Vol. 1 A, pag. 133-148
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