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An Interpretation of Cosmic-Ray Data by SU_3 Triplet Particles.

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The observation by the INS group (1) of horizontal air showers of large size ($10^3 < N < 10^5$) has given rise to great difficulty in understanding high-energy muon-nucleon interaction. The theoretical analysis of the INS experiment has up to date consisted in a judicious exclusion of alternatives; for instance it is unlikely that the observed events could be (1):

i) air showers produced by primary (nucleons) cosmic-ray particles;

ii) bremsstrahlung of high-energy muons;

iii) showers produced by the nuclear interaction of neutrinos.

It was consequently thought that the observed showers could be the result of high-energy muon-nucleon interactions (1-3) and that the extrapolation of the Kessler-Kessler method, already in good agreement with experiment for small energy transfer (4), to the high-energy transfer region would be able to reproduce the observed data.

The agreement of this extrapolated theory with experiment was so disappointing that many were forced to invoke a new type of interaction between muons and nucleons while others dismissed the observed events as simply anomalous (2,3).

In a first step we have investigated a possible electromagnetic muon-nucleon interaction as an explanation of the INS events and have arrived at a negative conclusion. Our reasoning is as follows: independently of what happens at the nucleon vertex the energy transfer (in the laboratory system) $\varepsilon = E - E'$ given as the difference between

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(1) T. MATANO, M. NAGANO, S. SHIBATA, K. SUGA, T. KAMEDA, Y. TOYODA, T. MAEDA and H. HASEGAWA: *Proc. Int. Conf. Cosmic Rays* (London, 1965), p. 1045; *Proc. Int. Conf. Cosmic Rays*, M 4 IV-22 (Calgary, 1967).

(2) K. FUJIMURA: *Progr. Theor. Phys.*, **34**, 1 (1965).

(3) T. KITAMURA and R. SUGANO: *Progr. Theor. Phys.*, **36**, 1014 (1966).

(4) C. CASTAGNOLI, P. PICCHI and R. SCRIMAGLIO: *Nucl. Phys.*, **87**, 641 (1967).

the initial and final muon energies is unambiguously defined; therefore from unitary

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}\varepsilon}+\frac{\mathrm{d}\sigma_{\mathrm{in}}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}\sigma_T}{\mathrm{d}\varepsilon} \tag{1}$$

where σ_{el}, σ_{in}, σ_T are the elastic, inelastic and total cross-sections respectively. The ratio

$$P(\varepsilon)=\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}\varepsilon}\bigg/\frac{\mathrm{d}\sigma_T}{\mathrm{d}\varepsilon} \tag{2}$$

defined as the probability for elastic scattering is nothing else but the square of the form factor of the nucleon normalized to unity for $\varepsilon=0$. In the limit as the energy E and the energy transfer $\varepsilon=t/2M$ (t is the square of the 4-momentum transfer and M the nucleon mass) tend to infinity it can be shown (5,6) that the elastic cross-section is given by

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}\sigma_{\mathrm{B}}}{\mathrm{d}\varepsilon}G_M^2(\varepsilon)\,, \tag{3}$$

where $G_M(\varepsilon)$ is the nucleon magnetic form factor, and σ_{B} the Born approximation. From (1), (2) and (3) and making use of the fact that $G_M(\varepsilon)\to 0$ as $\varepsilon\to\infty$ we have, resolving (1), for σ_{in}

$$\frac{\mathrm{d}\sigma_{\mathrm{in}}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}\sigma_{\mathrm{B}}}{\mathrm{d}\varepsilon}\,\frac{G_M^2(\varepsilon)}{P(\varepsilon)}\,. \qquad \varepsilon\to\infty\,. \tag{4}$$

From the meaning attached to $G_M(\varepsilon)$ and $P(\varepsilon)$ and the fact that the electric form factor $G_E(\varepsilon)<G_M(\varepsilon)$ one expects the ratio $G_M^2(\varepsilon)/P(\varepsilon)$ to tend to a constant of the order of unity as $\varepsilon\to\infty$. However this expectation is not borne out; in fact, if the INS data are due to electromagnetic interaction of muons with nucleons, then our comparison of (4) with experiment yields $G_M^2(\varepsilon)/P(\varepsilon)\sim 10^8$!

Such a large value of $G^2(\varepsilon)/P(\varepsilon)$ would imply that the photonuclear cross-section $\sigma_\gamma(\varepsilon)$ increases with ε.

From accelerators $\sigma_\gamma(\varepsilon)$, for ε sufficiently large (between 1 and 10 GeV), decreases with ε (7). BOROG *et al.* (8) indicate, on the basis of their experiment, that there is no significant increase of $\sigma_\gamma(\varepsilon)$ in the range of energy between 1 and 500 GeV.

To further ascertain that $\sigma_\gamma(\varepsilon)$ cannot increase with energy it is instructive to examine the muon energy spectrum at high energies. This spectrum, as is well known, can be derived from the depth-intensity relation and from the size frequency of muon bursts. In these two methods QED takes part in different forms and if it is assumed that QED is applicable to high-energy muons and if there is no anomalous muon-nucleon interac-

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(5) G. KALLEN: *Elementary Particle Physics* (Reading, Mass., 1964).

(6) H. A. KASTRUP: *Phys. Rev.*, **147**, 1130 (1966).

(7) CAMBRIDGE BUBBLE CHAMBER GROUP: *Phys. Rev.*, **146**, 994 (1966); **155**, 1477 (1967); **163**, 1510 (1967); L. J. FRETWELL jr. and J. H. MULLINS: *Phys. Rev.*, **155**, 1497 (1967); G. BUSCHHORN, P. HEIDE, U. KÖTZ, R. A. LEWIS, P. SCHMÜSER and H. J. SKRONN: *Phys. Rev. Lett.*, **20**, 230 (1968); B. M. CHASAN, G. COCCONI, V. T. COCCONI, R. M. SCHECTMANN and D. H. WHITE: *Phys. Rev.*, **119**, 811 (1960).

(8) V. V. BOROG, V. G. KIRILLOV-UGRYUMOV, A. A. PETRUKHIN and V. V. SHESTAKOV: *Can. Journ. Phys.*, **46**, S381 (1968).

tion then the same muon energy spectrum should be obtained from both methods. This is in fact so, for up to incident muon energy of 6 TeV the muon energy spectra derived from these two methods agree with each other, with $\sigma_\gamma(\varepsilon)$ equal to a constant ([9]). With $\sigma_\gamma(\varepsilon)$ a constant up to a value of ε about 3 TeV corresponding to a mean muon energy of 6 TeV it is not possible to reproduce the first two data of the INS group.

This large discrepancy has forced us to conclude that the interaction in question cannot be electromagnetic and that it must be of the strong species. Since as noted earlier ([1]) the showers could not be produced by nucleons we are led to suppose that they are produced by a particle of mass greater than that of the nucleon.

The possible strongly interacting candidates with a mass many times that of the nucleon must be looked for amongst the as yet new massive cosmic-ray particles whose possible existence has been suggested as a consequence of SU_3 theory ([10-12]). We have therefore examined the data on the triplet particle reported by DARDO *et al.* ([13]), who pointed out that it is not inconsistent to identify the particles which caused the positive delays in their underground experiments with the SU_3 triplet particle. They found the following reasonable data for the triplet characteristics: mass $M_{\mathrm{T}} \sim 10 M_{\mathcal{N}}$; the interaction mean free path λ_{T} about 2 or 3 times that of the nucleon $\lambda_{\mathcal{N}}$. The inelasticity K_{T} can be related to that of the nucleon assuming $K_{\mathrm{T}} M_{\mathrm{T}} \simeq K_{\mathcal{N}} M_{\mathcal{N}}$. We note that the value of λ_{T} found by DARDO *et al.* is in good agreement with what one would expect theoretically.

To find out if the triplet particle could be responsible for the shower events observed by the INS group we have used the formula

$$I_0(\varepsilon_m) = J_0(E_m)\frac{\Delta X}{\lambda_{\mathrm{T}}} \tag{5}$$

to derive the integral flux $J_0(E_m)$ of the incident primaries with energy greater than E_m. We have compared $J_0(E_m)$ so derived with that given by DARDO *et al.* $I_0(\varepsilon_m)$ is the integrated flux of secondaries with energy greater than ε_m which can be obtained from ref. ([1]) (the horizontal flux has been converted to vertical using the experimental ratio given by DARDO). $\Delta X \simeq 400$ g cm^{-2} is the mean distance between the starting point of the event and the point of observation ([1]). On the average E_m is given by $E_m = \varepsilon_m / K_{\mathrm{T}}$.

In Fig. 1 we have plotted $J_0(E_m)$ so obtained from the INS data with corresponding errors (rectangles) against the energy E_m. Starting from the experimental flux ($\sim 10^{-7}$ cm^{-2} s^{-1} sr^{-1}) of DARDO *et al.* referring to a triplet energy near threshold, $3M_{\mathrm{T}}^2$, one can obtain the fluxes in the energy interval concerned:

$$J_0(E) = 10^{-7}(E/3M_{\mathrm{T}}^2)^{-\gamma} \tag{6}$$

with γ the exponent of the primary spectrum $= 1.6$.

([9]) K. KOBAYAKAWA: *Can. Journ. Phys.*, **46**, S395 (1968).
([10]) M. GELL-MANN: *Phys. Lett.*, **8**, 214 (1964).
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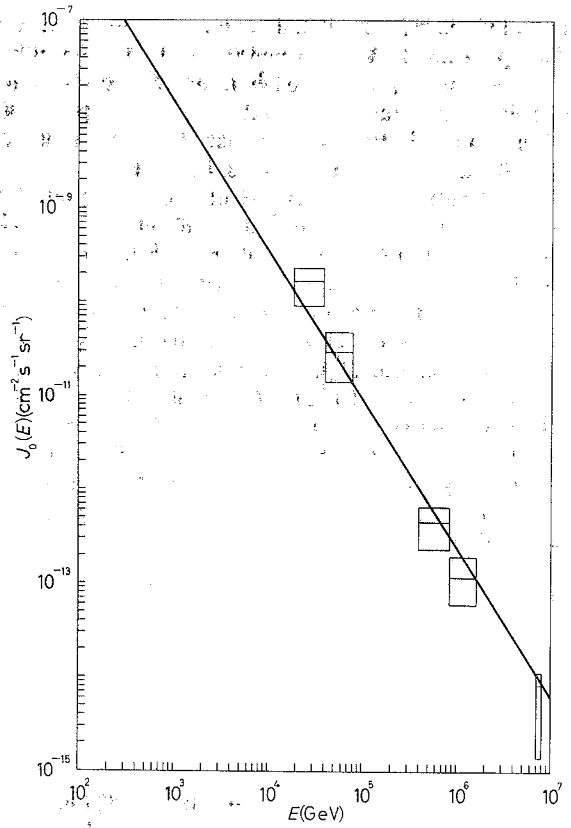

Fig. 1. – Integral vertical sea-level flux $J_0(E)$ against energy E. The rectangles have been obtained using the INS data. The straight line is from eq. (6).

Equation (6) is a straight line in Fig. 1 which passes through the INS data. A fire-ball model of triplet production in ref. ([13]) normalized with respect to Dardo's experimental values also gives a straight line in agreement with the one shown in Fig. 1.

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