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E. Etim[(x)] and P. Picchi: REMARKS ON A POSSIBLE DIRECT PRODUCTION OF MUONS. -

The observation by the Utah neutrino group(1) that cosmic ray muons of energy $>10^{12}$ eV do not obey the sec θ law to be expected if they proceeded from pion and kaon parents has suggested the possibility that a significant fraction of such muons could be produced directly or via an intermediary of very short life time. Recently this possibility has been fully investigated and recommended by Bergeson and his group(2) who assumed the differential muon spectrum M(E) to be a coherent superposition of a direct component on to the conventional spectrum due to π-K decay viz

$$(1) \quad \begin{aligned} M(E) &= C_{\pi} E^{\gamma-1} r^{\gamma} K(E,\theta) B (E \cos\theta^{x} + B)^{-1} + \\ &+ R C_{\pi} E^{-\gamma-1} (\mathrm{cm}^{-2} \sec^{-1} \mathrm{str}^{-1} \mathrm{GeV}^{-1}) \end{aligned}$$

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In eq. (1) the first term is the conventional muon spectrum or the π-K component and the second term is the direct contribution $\gamma = 1,7$, B = = 90 GeV, θ^x is the angle of zenith at the top of the atmosphere of a muon trajectory whose zenith angle at the detector is θ. $C_\pi = 0,225$ and the Osborne factor K(E, θ) is chosen to correct for the ratio of kaons to pions of all charges. The parameter R gives the relative amplitude of the direct process which as seen from eq. (1) is one order of magnitude flatter than the conventional spectrum in the energy variable E.

With the muon spectrum determined in eq. (1) to whitin the parameter R one must obtain the depth-intensity curve and the angular distribution in ref. (1). In ref. (2) this programme was carried out using the method of Hayman, Palmer and Wolfendale(4) to calculate muon intensities and the predicted effective value b_{eff} of the coefficient b in the energy-proportional muon energy-loss term was found to require a photonuclear cross-section $\sigma_{\gamma N}$ which increases with the transferred energy $\mathcal{E}$. With the model set out above Bergeson et al. proposed to explain a large body of cosmic-ray phenomena(1, 5) in particular the INS data on horizontal air showers of very large size(6).

The purpose of this letter is to present a survey of experimental facts which cannot be accomodated in a model of direct muon production with $\sigma_{\gamma N}$ increasing with $\mathcal{E}$.

In Fig. 1 we give the dependence of $\sigma_{\gamma N}$(7, 8) on the energy transfer $\mathcal{E}$; the points 1(⊗ , ⊙); 2(⊗ , ⊙); 3(⊗, ⊙) are given in pairs of which ⊗ is found from the Kessler-Kessler theory(9) and ⊙ from that of Weizsäcker-Williams(10). The figure clearly indicates that for in the range $1 \leq \mathcal{E} \leq 500$ GeV, $\sigma_{\gamma N}$ tends to decrease or at most remains constant. Moreover with b_{eff} given in ref. (2) and spectrum given in eq. (1) at 6 Km. w. c. we find a muon flux of $4,2 \times 10^{-10}$ ($cm^{-2} sec^{-1} str^{-1}$) instead of $7,5 \times 10^{-10}$ ($cm^{-2} sec^{-1} str^{-1}$) as given by Menon and Ramana Murthy(3); at 7 Km. w. c. we find a flux of $6,5 \times 10^{-11}$ instead of $1,8 \times 10^{-10}$. With a b_{eff} constant from 5 Km. w. c. anwards we reproduce quite reasonably the experimental data of ref. (3). Such good agreement is consistent with a photonuclear cross-section $\sigma_{\gamma N}$ which tends toa constant as $\mathcal{E}$ increases.

Of the nine showers observed by the Tokyo group(6) two (one of size 9×10^4N and another of size $\sim 10^4$N) are of nuclear origin of the remaining seven (the zenith average angle is $\sim 75^o$) it is difficult to say which are due to nuclear interaction of muons and which to purely electromagnetic processes such as bremsstrahlung (the differential cross-section for pair production is proportional to v^{-3}, where v is the ratio $\mathcal{E}$/E of the transferred energy to the total E, while the bremsstrahlung differential cross-section falls off as v^{-1}). Using the spectrum given in eq. (1) and with $\sigma_{\gamma N} = 500$ μb we have calculated separately the contri-

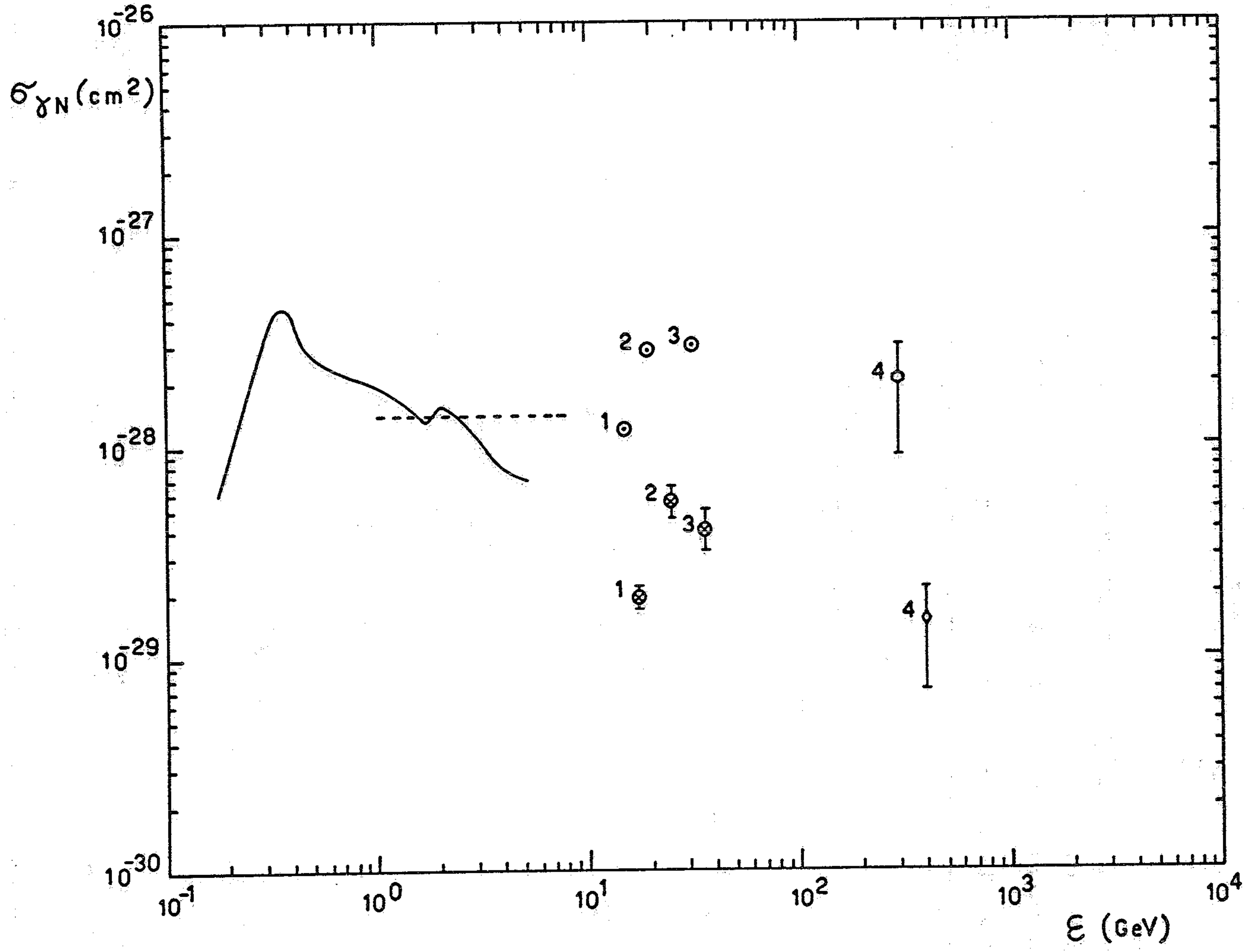

FIG. 1 - The dependence of the cross section of the photonuclear process on the energy ε. —— The accelerator data (Cambridge group, Fretwell, Chasan, White). ----N. Chaudhuri, M.S. Sinha (W.W. spectrum). 1) S. Higashi (1964); 2) H. Shibata (1961); 3) P. Kessler, M. Maze (1957); 4) W.W. Borog (1968).

bution to the observed INS showers due to muon-nuclear interaction and to bremsstrahlung. In Fig. 2a (continuous line) we display the muon-nuclear contribution. The formula used is

$$J = \int_{\varepsilon_{min}}^{\infty} M(E)\, \sigma_{\gamma N} \frac{\alpha}{\pi} \ln \left(\frac{E}{\varepsilon}\right)^2 dE\, N_a \Delta x \tag{2}$$

where $(\alpha/\pi) \ln (E/\varepsilon)^2 \sigma_{\gamma N}$ is the integrated muon-proton cross-section evaluated with the virtual photon spectrum of Weizsäcker-Williams(10). N_a is Avogadros number and $\Delta x^{(11)} = 300$ gm cm^{-2}.

In Fig. 2b (continuous line) on the other hand we display the bremsstrahlung contribution. The calculation was performed using the formula

$$J = \int_{\varepsilon_{min}}^{\infty} M(E)\, \sigma_B(\varepsilon, E)\, dE\, N_a \Delta x \tag{3}$$

where $\sigma_B(\varepsilon, E)$ is given(12) by

$$\sigma_B(\varepsilon, E) = \int_{\varepsilon/E}^{v_{max}} \frac{dv}{v} \cdot \alpha \left(2 Z r_o \frac{m}{\mu}\right)^2 \left(\frac{4}{3} - \frac{4}{3} v + v^2\right) \cdot$$

$$\cdot \ln \frac{\frac{2}{3} A \frac{\mu}{m} Z^{-2/3}}{1 + \frac{A\sqrt{e}}{2} \frac{\mu^2}{mE} \frac{v}{1-v} Z^{-1/3}}$$

$$v_{max} = 1 - \frac{3}{4} \sqrt{e} \frac{\mu^2}{mE} \frac{v}{1-v} Z^{1/3}, \qquad A = 189.$$

$\Delta x = 400$ g/cm^2 is the thickness(13) the most favourable for the frequency of the air showers at max of the curve of the shower produced in air by a γ.

The curves in Fig. 2 indicate quite clearly that neither muon-nuclear interaction, nor bremsstrahlung nor the sum of the two can account, for the data of the INS group with the spectrum in eq. (1) especially at energy transfer ($\varepsilon \sim 10^3$ GeV) where eq. (1) is nearly equal to the conventional π-K component.

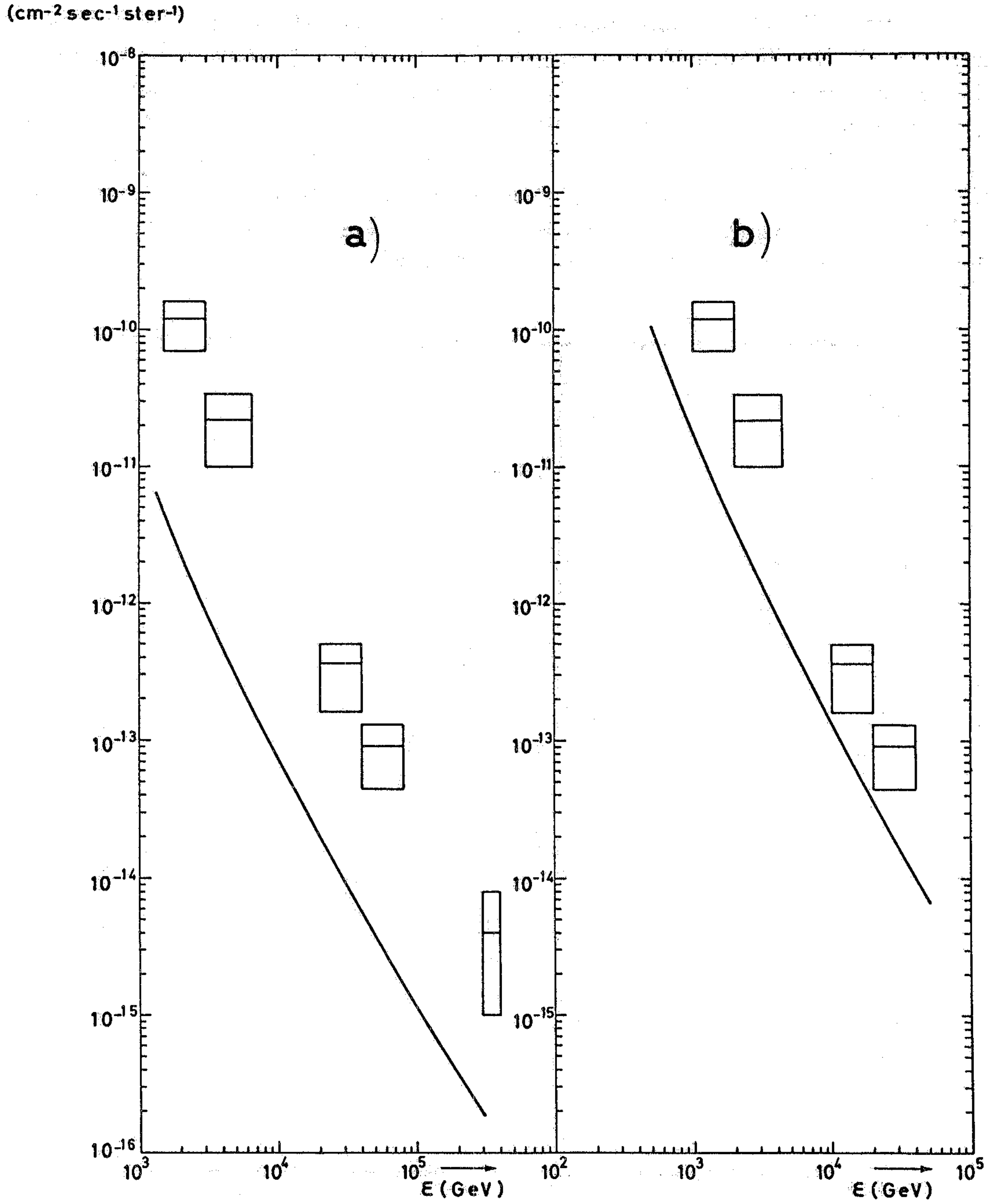

FIG. 2 - a) The contribution (continuous line) to the observed INS showers due to muon-nuclear interaction using the spectrum given in eq. (1) and with $\sigma_{\gamma N} = 500\ \mu b$. b) The contribution (continuous line) to the observed INS showers due to bremsstrahlung using the spectrum given in eq. (1).

In ref. (2) eq. (1) was used at $\theta = 0^o$ to fit the underground burst spectrum of the Osaka City group$^{(5,14)}$ and the spectrum of eq. (1) was shown to be favoured over the conventional component. Since the data of the Osaka City group reported in ref. (5) are consistent with those in ref. (15) (of Fig. 3a) we plot in Fig. 3b the integral vertical muon spectrum from the latter paper together with the spectrum of Krasilinokov$^{(16)}$ (shaded bands) obtained from underground burst measurements. Integral vertical muon spectra were also calculated for the two cases R = 0 and R = 0,02.

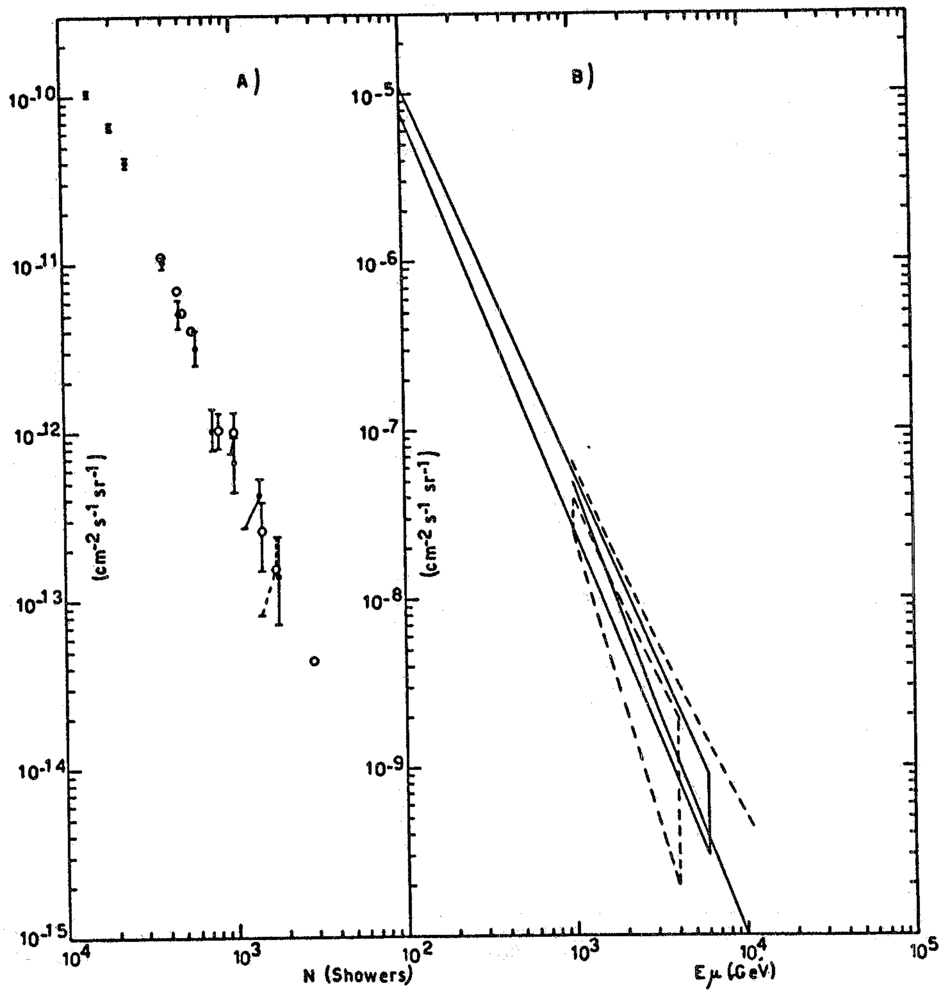

FIG. 3 - a) Ɨ Underrok burst Higashi (1964); ɸ underrok burst Higashi (1968). b) Band with broken lines shows the spectrum of muons at sea level in the vertical direction obtained by Higashi (1964) from burst spectra and the band with continuous line shows the spectrum obtained by Krasilinokov (1964).—— Spectrum (1) with R = 0. ---Spectrum (1) with R = 0.02.

As seen from Fig. 3b the conventional muon spectrum (R=0) is favoured over the proposed eq. (1).

Apart from the experimental facts outlined above it is important to state that also on theoretical grounds it is difficult to accept a theory of direct muon production. To account for the anomalies in cosmic ray muon measurements Callan and Glashow(17) had previously advocated a theory according to which the particles observed in the muon measurements were not all muons but consisted also of a new type of stable particles. U-particles which arrive at the detector from the top of the atmosphere without interacting. The experiment of Kropp(18) which confirms the usual conclusion that the penetrating component (of cosmic rays) consists only of muons, together with the arguments of Sitte(19) and Ramana Murthy(20) which reinforce such idea, makes it easy to disbelieve in the U-particle hypothesis.

To find a parent for the directly produced muons Bergeson et al.(2) suggest either the W-particle or an integral-charge SU(3) triplet.

For a W-particle to directly produce muons with R = 0,02 (of equation (1)) one would need a cross-section $\sigma_{NN}^{(W)}$ for the process

(4) $$N + N \rightarrow N + N + W + n\pi, \qquad n \geq 0$$

of the order of 10^{-27} to 10^{-28} cm^2. Following Ramana Murthy(20) and taking note of the relationship between the reaction in (4) and the processes

(5) $$\nu + p \rightarrow \mu + W + N$$

(6) $$\mu + p \rightarrow \nu + W + N$$

$\sigma_{\gamma N}^{(W)}$ in (5) would then have to be of the order of 10^{-31} to 10^{-32} cm^2. Such a value for $\sigma_{\nu N}^{(W)}$ would give a flux of muons from neutrinos underground of the order of 10^{-8} to 10^{-10} cm^2 sec^{-1} str^{-1} for a massa of W too big (the flux goes even higher for smaller masses of W). Neutrino experiments underground give a value of 10^{-12} cm^{-2} sec^{-1} str^{-1} for the flux(21, 22).

Likewise the SU(3) triplet hypothesis is unattainable. In a recent underground experiment Sitte et al.(23) observed strongly interacting particles with significant positive delays and found for them a mass between 10 to 15 nucleon masses. Their cross-section for these strongly interacting particles is exactly that attributed theoretically to the SU(3) triplets. These facts made it easy to interprete the events of Sitte et al. as due to SU(3) triplet particles. The experimental integral flux of these particles $\phi(E) \sim 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{str}^{-1}$ for $E = 300$ GeV; the flux of the direct muon component according to eq. (1) is $10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{str}^{-1}$ at $E = 300$ GeV. The equality of these fluxes fixes the mean life-time of the SU(3) triplet much longer than that of π or K $\cdot$ ($\sim 10^{-6}$ to 10^{-7} sec). A particle with such a long life-time cannot directly produce muons the which process requires the direct parent to be very short-lived.

We conclude therefore that while the data of Bergeson et al.$^{(1)}$ and the INS group$^{(6)}$ continue to be of puzzling$^{(24)}$ interest their interpretation by means of a model of direct muon production with $\sigma_{\gamma N}$ increasing with ε, qualifies as an hypothesis which is difficult to accept on the basis of recent experimental results.

REFERENCES. -

(1) - H.E. Bergeson, J.W. Keufell, M.O. Larson, G.W. Mason and J.L. Osborne, Phys. Rev. Letters 19, 1487 (1967).

(2) - H.E. Bergeson, J.W. Keufell, M.O. Larson, G.W. Mason and J.L. Osborne, Phys. Rev. Letters 21, 1089 (1968).

(3) - M.G.K. Menon and P.V. Ramana Murthy, Progress in Cosmic Ray and Elementary Particle Phys. (Noth-Holland Publishing Company, Amsterdam, 1967), Vol. IX.

(4) - P.J. Hayman, N.S. Palmer and A.W. Wolfendale, Proc. Roy. Soc. (London), A 275, 391 (1963).

(5) - S. Chin et al., Can. J. Phys. 46, S 297 (1968).

(6) - T. Matano et al., Can. J. Phys. 46, S 369 (1968).

(7) - Cambridge bubble chamber group, Phys. Rev. 146, 994 (1966); Cambridge bubble chamber group, Phys. Rev. 155, 1477 (1967); Cambridge bubble chamber group, Phys. Rev. 163, 1510 (1967); L.J. Fretwell Jr. and J.H. Mullins, Phys. Rev. Letters 20, 230 (1968); B.H. Chasan, G. Cocconi, V.T. Cocconi, R.M. Schectman and D.H. White, Phys. Rev. 119, 811 (1960); N. Chaudhuri and M.S. Sinha, Nuovo Cimento 57, 753 (1968); S. Higashi, S.T. Kitamura, Y. Mishima, S. Miyamoto, Y. Watase and H. Shibata, Nuovo Cimento 38, 107 (1964); H. Shibata, J. Phys. Soc. Japan 16, 372 (1961); P. Kessler and M. Maze, Nuovo Cimento 5, 1540 (1957).

(8) - V.V. Borog, V.G. Kirillov-Ugryumov, A.A. Petrukhin and V.V. Shestakov, Can. J. Phys. 46, S 381 (1968).
(9) - P. Kessler and D. Kessler, Compt. Rend. 244, 1896 (1957).
(10) - W. Heitler, The quantum theory of radiation (Oxford, 1954).
(11) - T. Matano et al., Proc. Int. Conf. Cosmic Ray, London (1965).
(12) - A.A. Petrukhin and V.V. Shestakov, Can. J. Phys. 46, S 377 (1968).
(13) - G. Cocconi, Handbuch Der Physik XLVI/1, 220 (1961).
(14) - Bergeson et al. (S. Ozaki, private communication).
(15) - S. Higashi, T. Kitamura and Y. Watase, Nuovo Cimento 32, 1 (1964).
(16) - D. Krasilinokov, Proc. Int. Conf. Cosmic Rays Jaipur, (1964) Vol. V293.
(17) - C.G. Callan Jr. and S.L. Glashow, Phys. Rev. Letters 20, 779 (1968).
(18) - W.R. Kropp Jr., F. Reines and R.M. Woods Jr., Phys. Rev. Letters 20, 1256 (1968).
(19) - J. Sitte, M. Dardo and P. Penengo, Nuovo Cimento LVIB, 349 (1968).
(20) - P.V. Ramana Murthy, Phys. Letters 28 B, 38 (1968).
(21) - F. Reines et al., Can. J. Phys. 46, S 350 (1968).
(22) - M.C.K. Menon et al., Can. J. Phys. 46, S 344 (1968).
(23) - M. Dardo, P. Penengo and K. Sitte, Nuovo Cimento LVIIIA, 59 (1968).
(24) - C. Castagnoli, E. Etim and P. Picchi (to be published Nuovo Cimento).