ON SOME NEW PRODUCTION PROCESSES FOR $\approx 10^{12}$ eV MUONS *

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Callan and Glashow and Keuffel have proposed the existence of U and W particles respectively, to explain the lack of zenith angular dependence of cosmic ray muons in the experiment by the Utah group. Arguments are presented to show that both these hypotheses are implausible.

In a recent paper Bergeson et al. [1] have presented experimental evidence that cosmic ray muons of energies > 500 GeV have to be produced to a great extent, if not all, in processes other than through the decays of pions and kaons as was widely believed heretofore. The argument briefly stated runs as follows: If the muons are indeed the decay products of pions or kaons one would expect a larger number of muons of a given energy at greater zenith angles because of the progressively decreasing density (with zenith angle) of the air in the region of atmosphere where meson production is copious and the resulting increase in the probability of parent mesons decaying into muons in competition with nuclear interaction. Absence of such an increase as was the case in the experiment of Bergeson et al. [1] is a clear indication that, by and large, the observed particles are either not muons (nor any other particles we know of) or, if they are muons, they are produced through some other process.

Callan and Glashow [2] proposed that what Bergeson et al. [1] had observed were not muons but a new kind of particles (which the authors called U-particles) that were present in the primary cosmic radiation. According to these authors, the U particles, constituting 0.1% of primary flux, are singly charged‡, heavier than 2.5 GeV, and, in general, muon-like in their interaction with matter in order to be able to survive to the depths of observation. Keuffel [3] mooted the idea that the muons observed by their group might be the decay products of intermediate bosons (W-particles) which could be produced only at high energies; he also estimated that muons from such a new process (W-mesons) need be only of the order of 4% as many as charged pions of the same energy at production. Since at these energies only $\lesssim 9\%$ of pions decay, a relatively small production amplitude of W-mesons can very effectively complete ‡‡ with a much larger production amplitude of pions and/or kaons as far as muon intensities are concerned.

There are already three letters published contending that neither the W [4] nor U [5,6] particle hypotheses seems to be likely. In this letter we present additional arguments to show that neither of the two hypotheses seems to be plausible.

The particle intensity is shown as a function of depth in fig. 1a, the data for which are taken from fig. 1 of Bergeson et al. [1]. Since these authors found no angular dependence, their data presented in different zenith angular intervals is all combined and a single curve is drawn. Based on the properties presented for U particles in ref. 2, a range-energy relation [e.g. 7] is derived and the intensity depth curve in fig. 1a is transformed to integral energy spectrum of the U particles at the top of the atmosphere and shown in fig. 1b. Since the particles are prescribed to be massive and not to enjoy strong interactions, the range-energy relation is almost linear. This is very much unlike the case of muons where the pair production and bremsstrahlung losses dominate to make the range-energy relation very non-linear at the energies/ranges we are concerned

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‡ Strictly speaking, there is no evidence that the particles are singly charged, no one ever having measured the charge of particles penetrating to depths $\gtrsim 2000$ hg/cm^2 (1 hg = 10^2 g).

‡‡ This statement is true only if the decay branching ratio of W-mesons into muons is not very small.

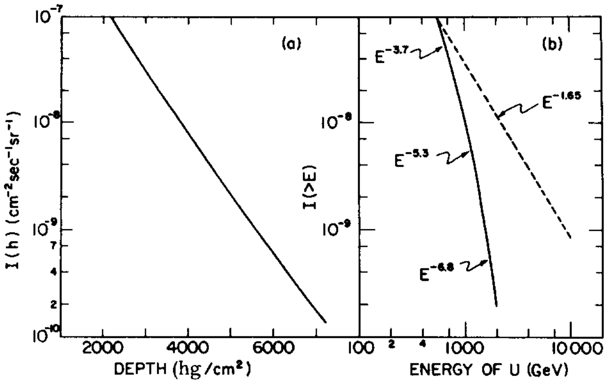

Fig. 1a. The particle intensity as a function of depth. The data are taken from fig. 1 of Bergeson et al. [1]. 1b. The implied integral energy spectrum of U particles at the top of the terrestrial atmosphere derived from the curve in fig. 1a and the properties of U prescribed in ref. 2.

with. The steep depth dependence of the intensity is, therefore, reflected as a steep energy dependence of the U-particle spectrum. To afford a comparison, the shape of the primary proton spectrum is also shown in fig. 1b. Notice that the energy spectrum of U-particles is very steep even to start with and further steepens very rapidly within a short range of energy. There is an overwhelming agreement that the primary cosmic rays are accelerated and contained by the stellar, interstellar and/or intergalactic magnetic fields. Protons and U particles, both being heavy and singly charged, would be treated alike by the magnetic fields that accelerate and contain them and it is hard, almost impossible, to devise means of discrimination between the two species. The U particle hypothesis, therefore, does not appear to be a likely one *.

Turning to the W-particle hypothesis, we mentioned earlier that, in order to explain the data Bergeson et al. [1] the number of muons produced through this process is required to be $\approx 4\%$ of the number of pions of the same energy. This would imply that the cross-section σ^{W}_{NN} for the process

$$N + N \rightarrow N + N + W + n\pi \qquad (1)$$

where $n \geqslant 0$ would have to be in the range 10^{-26} to 10^{-28} cm^2 depending upon the details of the interaction. The smaller value of 10^{-28} cm^2 corresponds to the most efficient mechanisms of energy transfer first to the W and then to muon. We proceed with the discussion with this smaller value first. Consider the following interactions:

$$\nu + p \rightarrow \mu + W + N\,, \qquad (2)$$

$$\mu + p \rightarrow \nu + W + N\,. \qquad (3)$$

The cross sections $\sigma^{W}_{\nu N}$ and $\sigma^{W}_{\mu N}$ are closely related to σ^{W}_{NN}. To our knowledge, there are no published theoretical predictions for σ^{W}_{NN} at these energies $\gtrsim 1000$ GeV. Details of precise theoretical calculations apart, the *important point here is to recognize that* σ^{W}_{NN} which depends on a semi-weak and an electromagnetic or strong vertex *bears a close relationship to* $\sigma^{W}_{\nu N}$ *and* $\sigma^{W}_{\mu N}$ which depend on a semi-weak and an electromagnetic vertex. At $M_W \approx 1$ GeV, published [9,10] theoretical calculations indicate $\sigma^{W}_{NN} \approx 10^{-32}$ to 10^{-34} cm^2 and $\sigma^{W}_{\nu N} \approx 10^{-36}$ cm^2. If we adopt this same ratio of cross-sections at energies ≈ 1000 GeV, the implication is that one should be producing W-mesons in very high energy νN collisisions with cross sections $\approx 10^{-30}$ to 10^{-32} cm^2. The secondary muon flux from reaction (2) is therefore given by ‡

$$I^{\nu}(\mu) = \int_{E_{\nu \mathrm{th}}}^{\infty} I(E_{\nu}) \frac{f E_{\nu} N Z}{\beta A} \sigma^{W}_{\nu N} \, dE_{\nu} \qquad (4)$$

where $I(E_{\nu})$ is the differential muonic neutrino energy spectrum, f the fraction of the neutrino energy the muon receives, N the Avagadro number, β the energy loss of the muon per g/cm^2, Z the atomic number and A the atomic weight of the medium. Taking the published [12] values of $I(E_{\nu})$ and the implied cross-sections for $\sigma^{W}_{\nu N}$, one expects for the neutrino-produced muon flux deep underground $\approx 10^{-8}$ to 10^{-10} /cm^2·sec·st for $M_W \approx 23$ GeV ($E_{\nu} = 1000$ GeV). This expected flux goes even higher for lower values of M_W. In the two deep underground neutrino experiments in India [13] and in South Africa [14], the measured neutrino induced muon flux is only $\approx 10^{-12}$ /cm^2·sec·st. This is clearly two, possibly four, orders of magnitude lower than the expectations in the W-meson hypothesis with the indicated cross-sections ‡‡ of σ^{W}_{NN} and $\sigma^{W}_{\nu N}$.

If on the other hand, $\sigma^{W}_{NN} \approx 10^{-26}$ cm^2, then $\sigma^{W}_{\nu N}$ would be correspondingly higher. The neu-

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* This objection has been independently raised by the Utah group [8].

‡ See ref. 11 for details. Notice that many of the uncertainties in the deduction of W-produced muon flux like the decay branching ratio of W into a muon, the fractional energy the muon receives in a W decay etc. are common and hence do not affect the ratio of σ^{W}_{NN} and $\sigma^{W}_{\nu N}$.

‡‡ See next page.

trinos, getting absorbed in the overlying rock seldom reach the depths of the experiments in refs. 13 and 14 and the argument advanced in the preceding paragraph does not apply. The higher cross-section σ^{W}_{NN}, however, implies that $\sigma^{W}_{\mu N}$ is correspondingly higher. This results in a strong attenuation of the vertical cosmic ray muon beam underground. The measured [15] vertical muon intensity values deep underground contradict this alternative.

We conclude that, while the experimental results of Bergeson et al. [1] continue to be of great interest and to provoke thought, the U and W particle hypotheses advanced to explain them seem to be unlikely.

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‡‡ One can invert the argument to say that the observations in deep underground neutrino experiments [13,14] either indicate that $\sigma^{W}_{\nu N} \gtrsim 10^{-29}$ cm^2 or place an upper limit to $\sigma^{W}_{\nu N} \sim 2.8 \times 10^{-36}$, 2.3×10^{-35}, and 3.1×10^{-34} cm^2 corresponding to $M_W = 2.4$, 7.3 and 23 GeV respectively.

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