Lepton-Hadron Relation and the Problems of Neutrino-Induced Dimuon and Trimuon Events.

P. BANDYOPADHYAY

Indian Statistical Institute - Calcutta-35, India

S. BHATTACHARYYA

Uluberia College - Uluberia, Howrah, West Bengal, India

(ricevuto l'1 Agosto 1977)

The observation of neutrino-induced events in which only two muons are detected in the final state was reported (1,2) roughly two years ago. Lepton-number conservation requires that an unobserved third lepton be present in the final state in the description of the dimuon data. Until the events with three final-state muons were known, the neutrino was supposed to be the most likely candidate as the third lepton and later experimentally confirmed. The plausible description of this set of dimuon events is, therefore,

$$\nu_\mu + (A, Z) \rightarrow \nu_\mu + \mu^- + \mu^+ + \text{hadrons} . \tag{1}$$

Very recently BARISH *et al.* (3) and BENVENUTI *et al.* (4) have reported a few events induced by neutrinos with three muons in the final state. The events contain at least an energetic muon (μ^-) and two additional muons with low kinetic energy in the hadronic rest frame. The salient properties, *inter alia*, are: i) all observed events are of the type $\mu^-\mu^-\mu^+$ and therefore almost certainly arise from a neutrino interaction, ii) several events have small angles between the three muons, iii) the rate of trimuon

(1) A. BENVENUTI, D. CLINE, W. T. FORD, R. IMLAY, T. Y. LING, A. K. MANN, R. ORR, D. D. REEDER, C. RUBBIA, R. STEFANSKI, L. SULAK and P. WANDERER: *Phys. Rev. Lett.*, **35**, 1199 (1975) and **34**, 419 (1975).
(2) A. BENVENUTI, D. CLINE, W. T. FORD, R. IMLAY, T. Y. LING, A. K. MANN, R. ORR, D. D. REEDER, C. RUBBIA, R. STEFANSKI, L. SULAK and P. WANDERER: *Phys. Rev. Lett.*, **35**, 1203 (1975).
(3) B. C. BARISH, J. F. BARLETT, A. BODEK, K. W. BROWN, D. BUCHOLZ, Y. K. CHA, F. SINLLI, E. SISKIND, L. STUTTE, E. FISK, G. KRAFCZYK, D. NEASE and O. FACKLER: *Phys. Rev. Lett.*, **38**, 577 (1977).
(4) A. BENVENUTI, D. CLINE, P. COOPER, M. HEAGY, R. IMLAY, M. E. JOHNSON, T. Y. LING, R. LUNDY, A. K. MANN, P. MCINTYRE, S. MORI, D. D. REEDER, J. RICH, C. RUBBIA, R. STEFANSKI and D. WINN: *Phys. Rev. Lett.*, **38**, 1110 (1977).

to single, muon production is of the order of 10^{-4}, iv) the rate of trimuon production at high energy is estimated to be $\sim 5\%$ of the dimuon rate (5).

The main characteristic feature of this dimuon event is that the observed ratio of the mean laboratory energies $\langle E_{\mu^-}\rangle/\langle E_{\mu^+}\rangle$ is significantly greater than unity and this ratio R is found to be 3.7 ± 0.65. To explain these dimuon events three possible types of reaction (1) have been speculated. i) It proceeds through the production and decay of intermediate vector bosons ($w^\pm$), ii) It proceeds through the production and decay of a heavy lepton L^0 according to the scheme $L^0 \to \mu^- + \mu^+ + \nu_\mu$, iii) It proceeds through the production and decay of a new hadron Y having as yet unidentified quantum number not conserved by the weak interaction and decaying as $Y \to \mu^+ + \nu_\mu + x$. μ^- is produced at the lepton vertex connecting the incident neutrino.

BENVENUTI *et al.* (2) have analysed these three possible mechanisms and have concluded that the experimentally observed ratio $R = \langle E_{\mu^-}\rangle/\langle E_{\mu^+}\rangle$ and other features have clearly excluded the mechanism involving the production and decay of $w^\pm$ as well as L^0. The main arguments against the production and decay of $w^\pm$ are as follows: 1) The ratio of the average momenta $\langle p_{\mu^-}\rangle/\langle p_{\mu^+}\rangle$ is observed to be significantly greater than unity but is predicted to be significantly less than unity (~ 0.4) for $w^\pm$ production and decay (6), 2) The dependence of $\langle Q^2\rangle = 2mE_\nu$ (ν) on E_ν of the deep inelastic single-muon events would show an appreciable departure from linearity due to the effect of a propagator of mass less than about 10 GeV/c^2 which is not observed (7), 3) The production of $w^\pm$ is expected to occur more frequently as a quasicoherent process than as an inelastic process which is not in agreement with the preponderance of observed dimuon events with large E_{1+}, E_{1+} being the measured total energy of the hadron cascade. It is noted that the dimuon event caused by the production and decay of w^0 is eliminated by the simple fact that the decay $w^0 \to \mu^-\mu^+$ would give rise to sharp structure in the dimuon invariant-mass distribution which is not observed.

On the other hand, PAIS and TREIMAN (8) have shown that the dimuon event caused by the production and decay of the heavy lepton L^0 ($L^0 \to \mu^- + \mu^+ + \nu_\mu$) would lead to the ratio $R = \langle E_{\mu^-}\rangle/\langle E_{\mu^+}\rangle$ lying between 0.48 and 2.1 whereas the experimental value is $R = 3.7 \pm 0.65$. Moreover BENVENUTI *et al.* (2) have pointed out the difficulty of fitting the observed $M_{\mu\mu}$ distribution with the decay products of a single lepton. Besides, it may be remarked that the observation of dimuon events with both muons having the same sing is evidence against both $w^\pm$ and L^0 as possible explanation of dimuons and indeed against any explanation that attributes the origin of dimuons to the lepton vertex.

Failures to account for the observed features of these dimuon events have prompted BENVENUTI *et al.* (2) to speculate the existence of a new hadron Y decaying weakly to a muon, a neutrino and possibly other hadrons and thus Y would necessarily possess a new, as yet unidentified, quantum number not conserved by weak interaction. It is the conservation of this quantum number that prevents the decay of the new hadron by strong and electromagnetic processes. The observed ratio of $\mu^-\mu^-/\mu^-\mu^+$ dimuon events (~ 0.1) indicates the operation of an approximate selection rule in the decay of the Y particle relating to the change in the new quantum number to the change in

(5) A. BENVENUTI, D. CLINE, P. COOPER, M. HEAGY, R. IMLAY, M. E. JOHNSON, T. Y. LING, R. LUNDY, A. K. MANN, P. MCINTYRE, S. MORI, D. D. REEDER, J. RICH, C. RUBBIA, R. STEFANSKI and D. WINN: *Phys. Rev. Lett.*, **38**, 1183 (1977).

(6) R. W. BROWN and J. SMITH: *Phys. Rev. D*, **3**, 207 (1971); R. W. BROWN, R. H. HOOBS and J. SMITH: *Phys. Rev. D*, **4**, 794 (1971).

(7) D. CLINE: *Neutrinos - 1974, AIP Conference Proceedings*, no. 22, edited by C. BALTAY (American Institute of Physics, New York, N. Y., 1974), p. 201.

(8) A. PAIS and S. B. TREIMAN: *Phys. Rev. Lett.*, **35**, 1206 (1975).

charge of the hadrons involved in the decay. However, all these assumptions seem to be quite *ad hoc* and doubtful.

The possible speculated origins of the trimuon events are: i) accidental space-time coincidence of a dimuon with a muon from a single-muon event, ii) decay in flight of a pion or kaon in the hadronic cascade of a dimuon event, iii) direct muon pair production at the hadron vertex, iv) charm-anticharm production by a neutrino with subsequent semi-leptonic decay of both the c and $\bar{c}$ particles, v) sequential semi-leptonic decays of new hadrons, vi) flavour-changing weak neutral-current decay of a charmed hadron, vii) sequential decays of new leptons or leptonlike particles produced at the lepton vertex of the neutrino-nucleon interaction, viii) low-mass muon pairs from virtual photons and/or decay of vector mesons.

Straightforward probability calculations rule out the possibility of i) being the source. The estimates based on the origins ii) to v) give very low values ($10^{-5}\div10^{-9}$) of the ratio of trimuon production to single muon and render them improbable.

Assuming that some flavour changing weak neutral currents are present in nature BENVENUTI *et al.* have negated by kinematical consideration the possibility of D^0-production source for the trimuon events and sided with the proposition of some new lepton explaining the existence of trimuon events. This new lepton hypothesis (or the variant of it) has currently found favour with a set of theorists and experimentalists [9-11].

It is, at this point, we do have serious reservation as it seems to us that to predict, almost at the drop of a hat, the existence of some new particle has recently become the high-energy physicists' favourite fad. Our attempt, here, is to explain the cardinal features of the trimuon (as well as dimuon) events, in a limited way, within the bounds of known particles and just a new model. Along with the production of a muon in a charge-exchange mechanism from the very structure of the nucleons, the model essentially supports the photonic origin viii) as the main prop of the trimuon events.

In this note, we shall show that the crucial features of neutrino induced dimuon and trimuon events can nicely be interpreted on the basis of a lepton-hadron relation recently proposed by one of the authors [12] (PB) and a new theory of weak interaction based on the photon-neutrino weak coupling and dynamical origin of charge and mass of electron and muon [13].

In a recent paper [12], we have tried to show that leptons may indeed be taken as the basic constituents of hadrons and the internal quantum numbers like isospin, strangeness and baryon number can be related to the internal angular momentum of the constituents. In this model, we have taken that the muonic triplet μ^+, ν_μ, μ^- acts as the basic constituents of all hadrons, where ν_μ is taken to be a Majorana spinor and it is taken that a muonic lepton and mesonic systems composed of muon-antimuon pair move in a harmonic oscillator field with orbital angular momentum $\frac{1}{2}\hbar$ in such a way that the two values of the third component of the orbital momentum represent the two states of matter: particles and antiparticles. In fact in I, we have shown that although for various reasons the half-orbital angular momentum is not allowed in atomic or nuclear configurations, the value $l=\frac{1}{2}$ can be allowed in the special case of elementary particle configurations, where particles and antiparticles are represented by the two

(9) C. H. ALBRIGHT, J. SMITH and J. A. M. VERMUSEREN: *Phys. Rev. Lett.*, **38**, 1187 (1977).
(10) V. BARGER, T. GOTTSCHALK, D. V. NANOPOULOS, J. ABAD and R. J. N. PHILLIPS: *Phys. Rev. Lett.*, **38**, 1190 (1977).
(11) F. BLETZACKER, H. T. NIEH and A. SONI: *Phys. Rev. Lett.*, **38**, 1241 (1977).
(12) P. BANDYOPADHYAY: *Particles and Nuclei* (1974), preprint (1975), submitted for publication, hereafter referred to as I.
(13) P. BANDYOPADHYAY: *Int. Journ. Theor. Phys.*, **8**, 323 (1973).

different l_3 values. Again, if we take the harmonic oscillator potential for the composite system, this scheme helps us to have a geometrical origin of SU_3 symmetry in particle physics ([12]). According to this scheme, strong interactions can be interpreted when we take that any two constituents (muon-antimuon pair) form a π-meson cluster in the structure of the hadron and hadronic processes involving no exchange of hypercharge occur when a π-meson cluster in the structure of the incident hadron interacts with the π-meson in the structure of the target hadron. Since in this scheme, the basic hadronic interaction is the $\pi\pi$ interaction, it also satisfies the requirement of duality in the sense that both the s- and t-channel amplitudes are contributed by the same meson (*viz* ρ-meson). The most interesting aspect of this interpretation of duality is that the inconsistencies which crop up in the $B\bar{B}$ scattering in the naive quark model are removed in this scheme ([14]).

According to this model of hadrons, the configurations of proton and neutron are found to be given by

$$(2)\qquad \begin{cases} p = (\mu^+\nu_\mu, \pi_2^0\nu_{\mu_3}) = (\pi^+\pi^0\nu_\mu)\,, \\[2ex] n = \dfrac{1}{\sqrt{\alpha^2+\beta^2}}\,[\alpha(\nu_\mu\nu_{\mu_1}\pi_2^0\nu_{\mu_3}) + \beta(\mu^-\mu^+\pi_2^0\nu_{\mu_3})] = \dfrac{1}{\sqrt{\alpha^2+\beta^2}}\,[\alpha(\pi^0\pi^0\nu_\mu) + \beta(\pi^-\pi^+\nu_\mu)]\,, \end{cases}$$

where ν_{μ_i}'s and π_{0_i}'s move with orbital momentum $\frac{1}{2}$ and the isospin is given by the total angular momentum of these constituents. Here π^0 is a combination of the configurations $(\mu^-\mu^+)$ and $(\nu_\mu\nu_{\bar{\mu}})$ so that for π^0 we can write

$$(3)\qquad \pi^0 = \frac{1}{\sqrt{\alpha'^2+\beta'^2}}\,[\alpha'(\mu^-\mu^+) + \beta'(\nu_\mu\bar{\nu}_\mu)]\,.$$

In fact in this model a muonic lepton-antilepton pair can form the pseudoscalar mesons (π^0, η^0), vector mesons (ρ^0, ω^0) and tensor mesons (A_2^0, F^0) ([12]). It may be remarked here that this configuration scheme can well explain the structure function observed in ep deep inelastic scattering data ([15]). Also to have a good fit with the en scattering data, we have to take into account that the weight of the neutral configuration is twice that of the charged configuration so that $\alpha = 2\beta$.

In an earlier paper ([16]) it has been shown that when muons are taken to be fundamental constituents of hadrons, we can explain certain aspects of weak interactions in a nice way. In fact, it has been argued that all $\Delta S = 0$ semi-leptonic–decay processes follow from the decay of the muon in the structure of the hadron and this explains the universality of the weak-decay coupling constant. Furthermore, in a recent paper ([13]) it has been suggested that a charged leptonlike muon and electron can be taken to occupy an elementary domain characterised by a fundamental length l_0 and in view of the photon-neutrino weak coupling, we can consider a unified model of weak and electromagnetic interaction where the mass as well as charge of the electron or muon arises as spontaneous breakdown of γ_5 symmetry. According to this view, we can represent the electron and muon as $(\nu_e s)$ and $(\nu_\mu s)$ respectively, where s represents the system of photons interacting weakly with ν_e and ν_μ over a fundamental space-time

---

([14]) P. BANDYOPADHYAY and S. S. DE: *Lett. Nuovo Cimento*, **4**, 377 (1972).
([15]) P. BANDYOPADHYAY, P. RAY CHAUDHURI and S. S. DE: *Lett. Nuovo Cimento*, **3**, 43 (1972).
([16]) P. BANDYOPADHYAY: preprint (1975), submitted for publication.

domain. The interactions which give charge (as well as mass) to the neutrinos also add two more components transforming a two-component spinor to a four-component one ([17]). It is noted that photons are here taken as fundamental field quanta. Also we have shown that this view of charge helps us to explain the V—A form of the current-current coupling for leptonic-decay processes. However for weak-scattering processes, unlike the current-current coupling theory this model gives cross-sections consistent with unitarity and no unitarity catastrophe occurs at high energy ([18]).

Having considered these points, we depict here the dimuon event $\nu_\mu+(\mathrm{A}, \mathrm{z})\to \to \mu^-+\mu^++\nu_\mu+$hadrons according to the following scheme:

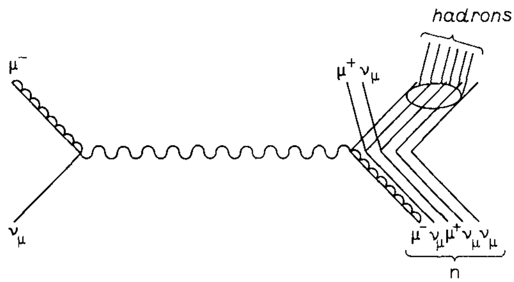

Fig. 1. – Diagram for the dimuon event $\nu_\mu+(\mathrm{A}, \mathrm{z})\to\mu^-+\mu^++\nu_\mu+$hadrons.

Here the system of photons giving rise to the negative charge of the muon (μ^-) is exchanged and is captured by the incident neutrino giving rise to μ^- in the final state. Again one μ^+ and ν_μ in the structure of the nucleon came out while the meson formed by the $\nu_\mu\bar{\nu}_\mu$ pair give rise to hadron cascade with the preservation of baryon number.

In view of this model of hadrons, the value of E_{H}, the measured total energy of the hadron cascade can be represented in terms of the energy shared by the leptons in the structure of hadrons. So the differential energy spectrum of the outcoming μ^+ will be related to the differential energy spectrum of the μ^- in the neutrino-muon scattering.

$$\nu_\mu+\mu^-\to\mu^-+\nu_\mu\,. \tag{4}$$

Now considering that in the high-energy region, the nucleon will be Lorentz contracted and the whole scattering phenomena can be depicted as incoherent scattering with the constituents, the energy and momentum transfer to the nucleon will be approximately equally shared by the interacting constituents and this suggests that $\mathrm{d}\sigma/\mathrm{d}E_{\mu^+}\simeq(1/n)\cdot \cdot(\mathrm{d}\sigma/\mathrm{d}E_{\mu^-})$, where n is the number of the interacting constituents. As from the diagram (fig. 1) we note that only four constituents actively take part in the dimuon event as one ν_μ remains as a spectator all through, we will have

$$R=\langle E_{\mu^-}\rangle/\langle E_{\mu^+}\rangle\simeq 4\,. \tag{5}$$

This is in excellent agreement with the experimentally observed value $R=3.7\pm0.65$.

So far as the ratio $(\mu^-\mu^-)/(\mu^-\mu^+)$ of the dimuon events is concerned we note that $\mu^-\mu^-$ events may occur due to the presence of an extra muon μ^- apart from the one which gives away the charge to the incident ν_μ is the structure of the nucleon. Now

([17]) P. BANDYOPADHYAY: *Prog. Theor. Phys.*, **30**, 563 (1963).
([18]) P. BANDYOPADHYAY: *Lett. Nuovo Cimento*, **3**, 437 (1970).

from the configurations of proton and neutron as given by (2) with the configuration of π^0 given by (3) and taking into account $\alpha = 2\beta$ with the normalisation condition $\alpha^2 + \beta^2 = 1$ so that $\alpha = 0.90$ and $\beta = 0.45$, we find that the number of μ^+ in the structure of a proton can utmost be 2 and the maximum number of μ^+ in the structure of a neutron is 2 with the weight factor 0.90 and 1 with the weight factor 0.45. This is to be compared with the maximum number of an extra μ^- in the structure of a neutron which is 1 with weight factor 0.90. Summing and multiplying by the square of the respective weights and taking the average, we have

$$R_1 = \frac{\mu^-\mu^-}{\mu^-\mu^+} = \frac{1}{2}\,\frac{0.8}{3.8} \simeq 0.1 \,. \tag{6}$$

This is also in close agreement with the experimental value [2]. It may be added that this ratio may change if the number of neutrons is much in excess of the number of protons in the target.

We may remark here that the existence of the propagator (equivalent to the exchange of a system of photons) in the diagram (fig. 1) may remarkably change the energy dependence of the cross-section. In general it would predict $\sigma \sim 1/s$ as in QED. However, we must observe that in the region $q^2 \simeq 0$ the system of photons will behave as real photons and in that case, nonlocality would suggest a charge nonconserving process like $\mu^- \to \nu_\mu + \gamma$. So in low-$q^2$ region implying small-angle scattering nonlocality is destroyed and the interaction can occur only in the local limit. That means in the low-q^2 region ($\theta \simeq 0^0$) the process can occur only as a current-current coupling and in that case there will be linear rise in the dimuon cross-section as observed in experiments [1].

Extrapolating our above ideas regarding the origin of dimuon events, we may note that trimuon events of the type $\nu_\mu + (\mathrm{A}, \mathrm{z}) \to \mu^- + \mu^- + \mu^+ +$hadrons may occur according to the diagram (fig. 2) where one energetic μ^- comes out at the lepton vertex and the other dimuon pair $\mu^-\mu^+$ is produced by a virtual proton emitted by a charged constituent like μ^+ (or μ^-) in the structure of the nucleon. Obviously the electromagnetic vertex responsible for the production of $\mu^-\mu^+$ pair gives rise to a cross-section for such an event satisfying the relation

$$\frac{N(\mu^-\mu^-\mu^+)}{N(\mu^-)} \sim \alpha^2 \sim 10^{-4}$$

as observed in experiments. The crucial prediction of such a model is that in neutrino (antineutrino) induced event only one $\mu^-(\mu^+)$ emerging from the neutrino (antineutrino)

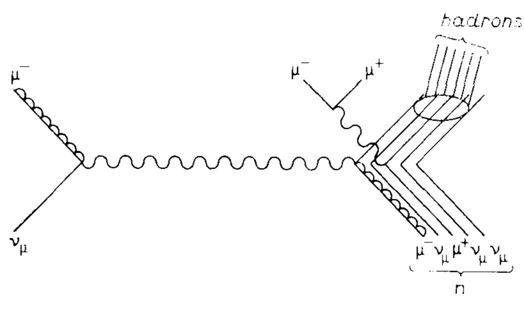

Fig. 2. – Trimuon production in neutrino-induced event $\nu_\mu + (\mathrm{A}, \mathrm{z}) \to \mu^- + \mu^+ + \mu^+ +$hadrons.

vertex will be more energetic than the other $\mu^-\mu^+$ pair produced by the virtual photon. This is supported by the experimental observation by BARISH *et al.* [3]. Finally, we point out that a crucial test of the present model lies in the dielectron (electron-positron) events from a reaction of the type

$$\nu_e + (A, z) \to e^- + e^+ + \nu_e + \text{hadrons}\,, \tag{7}$$

where our model predicts significantly larger value for $R' = \langle E_{e^-}\rangle/\langle E_{e^+}\rangle$ than R in the dimuon event as the positron can arise only from the decay of the outcoming μ^+ from the structure of nucleons whereas electron appears in the lepton vertex. This also indicates that $e^-\mu^+$ events will be more frequent than e^-e^+ events in ν_e induced reaction in our scheme. However, the Y model of BENVENUTI *et al.* [2] predicts that $R' = R$ as the positron will arise from the weak decay of the Y particle $Y \to e^+ + \nu_e + x$ similar to the μ^+ production in reaction (1). Again for $\bar{\nu}_\mu$ induced dimuon events, our model predicts $\mu^+\mu^-$ events similar to reaction (1) but in Y model, due to the suppression of μ^- production from the Y-decay, as is evident from the very small ratio $(\mu^-\mu^-)/(\mu^-\mu^+)$ (~ 0.1) dimuon events $(\mu^+\mu^-)$ will be highly suppressed compared to that observed in ν_μ-induced interaction.

Direttore responsabile: CARLO CASTAGNOLI

Stampato in Bologna dalla Tipografia Compositori coi tipi della Tipografia Monograf
Questo fascicolo è stato licenziato dai torchi il 14-XII-1977