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NEW PARTICLE PRODUCTION BY NEUTRINOS

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1. INTRODUCTION

I shall discuss the recent observations of the Harvard-Wisconsin-Penn-Fermilab Collaboration¹⁾ with a large electronic detector in the high-energy neutrino beam at Fermilab. I would like to review, in particular, the most recent experimental evidence for the production by and for the subsequent weak decay of new hadrons with a new quantum violated by weak interactions. For these objects we shall use the name Y-particles²⁾.

The experimental evidence is based on the following observations which I shall discuss:

- i) multilepton final states (dimuon events);
- ii) anomalies in the deep inelastic single-muon production by neutrinos;
- iii) violation of the symmetry of charge between ν_μ and $\bar{\nu}_\mu$ on an I-spin zero target.

Neutrinos offer a unique way of producing particles with new quantum numbers. After the incoming neutrino has changed the nature of one of the elementary constituents of the target (quarks), final-state hadronic interactions will preserve such a new quantum number. Instead, in the case of hadronic or electromagnetic production, a *pair* production is required and the new particles can easily recombine again before leaving the interaction volume. Indeed, according to the simple thermodynamical models, production of relatively heavy objects is expected to be almost totally suppressed. In the case of neutrinos, on the contrary, the cross-section will remain as determined by the initial lepton-quark coupling.

2. MULTILEPTON FINAL STATES

2.1 Which processes are observed?

The following processes with three leptons in the final state are possible:

$\nu_\mu + N \rightarrow \mu^- \mu^+ \nu_\mu X$	observed
$\mu^- \mu^- \bar{\nu}_\mu X$	observed
$\mu^- \mu^- \mu^+ X$	not observed
$\bar{\nu}_\mu + N \rightarrow \mu^+ \mu^- \bar{\nu}_\mu X$	observed
$\mu^+ \mu^+ \nu_\mu X$	observed, however outside fiducial volume
$\mu^+ \mu^+ \mu^- X$	not observed.

Because of the four-fermion nature of weak interactions and of the inelasticity associated with the process, events have to be interpreted as multiple-step processes.

The experiments recently carried out at Fermilab by our group have collected of the order of 150 events (before fiducial cuts). About two-thirds of them remain within the standard sample. A first, important conclusion is that no three-muon event has been so far observed. This sets an upper limit of $\sim 3 \times 10^{-4}$ to the fractional number of events of three charged muons for neutrino interactions and $\langle E_\nu \rangle \sim 60$ GeV.

2.2 The experimental set-up

The experimental set-up consists of a large liquid calorimeter³⁾ and of a iron core muon spectrometer⁴⁾. Between the liquid calorimeter and the iron spectrometer we have inserted an iron target, in order to be able to subtract experimentally the possible contribution from decays in flight or ordinary particles. Briefly, two targets of very different densities and roughly the same mass have been used:

- i) The liquid scintillator target, 576 g/cm^2 , density $\rho = 0.85 \text{ g/cm}^3$ and $\lambda_{\text{coll}} = 125 \text{ cm}$. A typical event from the liquid is shown in Fig. 1a.
- ii) The iron target, 590 g/cm^2 , density $\rho = 7.87 \text{ g/cm}^3$ and $\lambda_{\text{coll}} = 25 \text{ cm}$. A typical event is shown in Fig. 1b.

Note that for events of type (i) we measure both the total hadronic (and e.m.) energy deposition and the vector momenta of the muons. In the case of events from iron, only the latter information remains available since no calorimetric analysis is possible.

2.3 Beams

Data are available for three different beam configurations:

- a) Horn focusing for ν_μ and short spill time ($\sim 20 \mu\text{sec}$). Those experimental conditions which have been used in the earlier part of the experiment²⁾ are the least favourable because of the large number of relatively low-energy neutrinos and the short duty cycle which introduces an appreciable probability of two neutrino interactions within the resolving time of the detector.
- b) Quadrupole triplet focusing⁵⁾. A triplet of quadrupoles focuses present particles of both signs parallel to the decay channel. The beam contains a large number of high-energy ν_μ and $\bar{\nu}_\mu$ with their "natural" mixture and with good spill-time ($\geq 1 \text{ msec}$) (see Fig. 2). In these conditions most of the events are due to ν_μ , and the probability of multiple interactions is negligible.
- c) Double horn focusing $\bar{\nu}_\mu$ with a central plug and short spill-time ($20 \mu\text{sec}$). An enriched $\bar{\nu}_\mu$ beam with some ν_μ contamination is available (see Fig. 3). Note that flux and consequently the probability of multiple interaction is considerably less than in case of configuration (i).

2.4 Event selection and backgrounds

Events were selected on the basis of standard cuts. The trigger requires an ABC condition and therefore events from the liquid and iron are collected simultaneously. The picture information is used to introduce a fiducial volume cut and that of the dimuon vertex, which is observed by three different stereo angles, be compatible with the calorimeter information. Finally, all electronic information, i.e. timing pulse heights and so on, are required to be consistent with the expected patterns.

Under these selection criteria, backgrounds are expected to be negligible. Two types of background are of potential danger and have to be considered in detail:

- a) An accidental space and time coincidence of two standard muon events. From the number of events in which this coincidence is actually observed we can estimate the number of events in which confusion may arise. This number is completely negligible, except for some early runs when the beam horn focusing ν_μ has been used.
- b) Decays of relatively long-lived particles, such as $\pi^\pm$, $K^\pm$, Λ^0 and so on. There are several tests which ensure that also this background contribution is negligible. The rate both from dense and diluted targets is independent of density and proportional to the mass (see Fig. 4). It is apparent from the figure that $\lambda_{\text{coll}} \gg \lambda_{\text{dec}}$ for the decay process responsible of the dimuon signal. Other independent evidence against this background comes from the fact that the sign distribution and the kinematics are sharply different from the expectations of decays. Finally, also the calculated rates from $K^\pm$, $\pi^\pm$ decays are much smaller than experimental observations.

We conclude that we are in the presence of a genuine new phenomenon of non-trivial origin.

2.5 Main features of the dimuon events

We shall review briefly the main characteristics of the events:

- a) Branching ratios. We have selected a restricted sample from the q-pole triplet beam, in order to ensure a reasonable fiducial volume and a good detection efficiency. In order to estimate the event losses in the absence of any known production mechanism, we have used a crude calculation which consists in moving the origin and the azimuthal angles of the dimuon system over the fiducial volume in order to evaluate a detection probability for the events.

Results for the q-pole triplet beam (ν_μ):

$$\frac{R(\mu^-\mu^+\nu_\mu X)}{R(\mu^-X)} = (0.8 \pm 0.2) \times 10^{-2}$$

$$\frac{R(\mu^-\mu^-\bar{\nu}_\mu X)}{R(\mu^+\mu^-\nu_\mu X)} = (0.1 \pm 0.05)$$

and for the antineutrino beam:

$$\frac{R(\mu^+\mu^-\bar{\nu}_\mu X)}{R(\mu^+X)} \approx 2 \times 10^{-2} \text{ (based on four events) .}$$

- b) The production cross-section appears to be smooth for $E_\nu > 50$ GeV. There is no evidence for sharp threshold, although the qualitative statement that the cross-section for $E_\nu < 30$ GeV is substantially smaller (up to a factor of 10) can be made.
- c) The hadronic inelasticity is large. On the average, approximately 1/2 of the total viable energy appears in the calorimeter (see Fig. 5). *Note the absence of quasi-elastic or of elastic events.* In other words, the lack of events at $E_h \approx 0$ is not due to experimental biases, since the trigger does not require hadronic energy deposition.
- d) The μ - μ invariant mass $M_{\mu\mu}$ is shown in Fig. 6. It is smooth, with no specific structure, and it extends to about 8 GeV/c². At larger M masses the detection efficiency is sharply cut off.
- e) An important observation is the existence of leading particle effects. For q-pole triplet data (mostly ν_μ), we observe generally that $p_{\mu-} > p_{\mu+}$ (Fig. 7a). For the $\bar{\nu}_\mu$ -horn data (mostly $\bar{\nu}_\mu$) the opposite is observed, i.e. $p_{\mu+} > p_{\mu-}$ (Fig. 7b). The small fraction of events in the q-pole run, where $p_{\mu+} > p_{\mu-}$, are consistent with the expected $\bar{\nu}_\mu$ constant of the beam.
- f) We can define p_T , the projection of the transverse momentum of the muon with respect to the plane defined by the incident neutrino and the leading muon (μ^- for ν_μ and μ^+ for $\bar{\nu}_\mu$). The advantage of choosing such a variable is that it can be constructed from the muon variables only (see Fig. 8). The distribution is flattish and it has an end-point at $p_T \approx 1.6$ GeV/c (Fig. 9). Note that for $\pi^\pm \rightarrow \mu^\pm$, $K \rightarrow \mu^\pm$, and so on, one expects a distribution of the general form e^{-9p_T} , which is in complete disagreement with our data.

2.6 Possible origins of the dimuon events

Several mechanisms can *a priori* generate events with two muons in the final state. We shall list a number of possible alternatives. All but one can be excluded.

a) Higher-order weak and electromagnetic process (weak tridents). The graph is shown in Fig. 10a. The process can easily be excluded since:
i) the calculated rate is 10^3 times smaller; ii) $M_{\mu\mu}$ mass should peak at very low values (few tens of MeV); and, iii) the process should be mostly elastic, i.e. $E_H \ll E_{vis}$.

b) Production and decay of a neutral W or of other vector mesons:

$$\begin{aligned} \nu_\mu + N &\rightarrow V^0 + \nu_\mu + X \\ &\quad \searrow \\ &\quad \mu^+ + \mu^- \end{aligned}$$

where V^0 is a narrow state ($W^0, J, \psi \dots$). This is excluded by the absence of a peak in the $M_{\mu\mu}$ distribution.

c) Production and decay of a charged W, according to the diagram of Fig. 10b. This is again excluded since: i) this process is expected to be mostly elastic; ii) the p_T should be larger; iii) additional evidence should be expected in normal scattering due to propagator effects; and, iv) $\langle p_{\mu-} \rangle \approx 0.4 \langle p_{\mu+} \rangle$ instead of $p_{\mu-} \gg p_{\mu+}$.

d) Production and decay of a new heavy lepton (L^0) according to diagram of Fig. 10c. Model-dependent calculations exclude the simple production and decay⁶⁾. However, more complicated references in which the L^0 might not be produced directly, i.e.,

$$\begin{aligned} \nu + N &\rightarrow L^+ + \text{hadrons} \\ &\quad \searrow \\ &\quad L^0 + \text{hadrons} \\ &\quad \searrow \\ &\quad \mu^+ + \mu^- + \nu \end{aligned}$$

or

$$\nu + N \rightarrow \text{many kinds of leptons}$$

could be eventually be postulated. A more general argument has been developed by Pais and Treiman⁷⁾, who have shown that in complete generality on production and decay mechanisms, bounds exist for the quantity

$$R(\nu) = \frac{\langle p_{\mu-} \rangle}{\langle p_{\mu+} \rangle}$$

(for $\bar{\nu}_\mu, \mu^+$ and μ^- are exchanged).

They are

$$1/2 < R^{(\nu, \bar{\nu})} < 2 \quad (V, A)$$

$$\frac{9 - 4\sqrt{2}}{7} < R^{(\nu, \bar{\nu})} < \frac{9 + 4\sqrt{2}}{7} \quad (S, T, P, A, V) .$$

Experimentally $R^{(\nu)} = 8.5 \pm 1.7$, excluding in a more general way the heavy-lepton hypothesis.

We are then left with the inescapable conclusion that any conceivable mechanism which attributes the source of the effect to the lepton vertex of the interaction is unable to explain the experimental observations. The only possible alternative is then that the origin of the dileptons is related somehow to the hadronic vertex of the interaction (Fig. 10d).

Further evidence discussed below confirms this assignment.

3. ANOMALIES IN THE DEEP INELASTIC SCATTERING

3.1 Definitions

We shall use the standard scaling variables

$$x = \frac{Q^2}{2M\nu} , \quad y = \nu/E_\nu ,$$

where $\nu = E_h$ is the energy of the hadronic system and M the mass of the initial target. The scattering process is in general a function of the three structure functions, which are only functions of the variable x :

$$\frac{d^2\sigma^{\nu, \bar{\nu}}}{dx dy} = \frac{G^2 M E_\nu}{\pi} \left[\left(1 - y + \frac{y^2}{2}\right) F_2^{\nu, \bar{\nu}}(x) - \frac{y^2}{2} F_L^{\nu, \bar{\nu}}(x) + y \left(1 - \frac{y}{2}\right) x F_3^{\nu, \nu}(x) \right] ,$$

where G is the Fermi constant.

Positivity requires that $F_2^{\nu, \bar{\nu}}(x) \geq 0$, $F_L^{\nu, \bar{\nu}} \geq 0$, and $F_2^{\nu, \bar{\nu}}(x) - F_L^{\nu, \bar{\nu}}(x) \geq x |F_3^{\nu, \bar{\nu}}(x)|$. We can define

$$B^{\nu, \bar{\nu}}(x) = - \frac{x F_3^{\nu, \bar{\nu}}(x)}{F_2^{\nu, \bar{\nu}}(x)} .$$

The above conditions limit $|B^{\nu, \bar{\nu}}(x)| \leq 1$. Note also that B can be positive or negative since it represents a V, A interference term which changes sign under the exchange $\nu_\mu \leftrightarrow \bar{\nu}_\mu$. Also we can set

$$|R_L^{\nu, \bar{\nu}}(x)| = \frac{|2xF_L^{\nu, \bar{\nu}}(x) - F_2^{\nu, \bar{\nu}}(x)|}{F_2^{\nu, \bar{\nu}}(x)}$$

and the cross-section can be re-written as:

$$\begin{aligned} \frac{d^2\sigma^{\nu, \bar{\nu}}}{dx dy} &= \frac{G^2 M E_\nu}{\pi} F_2^{\nu, \bar{\nu}}(x) \times \\ &\times \left\{ 1 - y \left[1 \mp B^{\nu, \bar{\nu}}(x) \right] + \frac{y^2}{2} \left[1 \mp B^{\nu, \bar{\nu}}(x) \right] - \frac{y^2}{2} |R_L^{\nu, \bar{\nu}}(x)| \right\}. \end{aligned}$$

3.2 Simple quark-parton model

Assume first a simple quark-parton model with no new particle being produced. We expect

- i) charge symmetry invariance, i.e. $F_i^{(\nu)} = F_i^{(\bar{\nu})}$ for an isoscalar target;
- ii) $R_L^{(\nu, \bar{\nu})} \rightarrow 0$; note that in general this term produces a *decreasing* term in the y -distribution and it cannot explain an excess of events at large y ;
- iii) $B^{(\nu)} = B^{(\bar{\nu})} = +1.$, i.e. $xF_3(x) = -F_2(x)$.

This leads to the simple distributions

$$\frac{d^2\sigma^{\nu}}{dx dy} = \frac{G^2 M E_\nu}{\pi} F_2(x),$$

$$\frac{d^2\sigma^{\bar{\nu}}}{dx dy} = \frac{G^2 M E_\nu}{\pi} (1-y)^2 F_2(x).$$

Results of the experiment are shown in Fig. 11. While the neutrino distributions and the antineutrino distributions below 30 GeV are in agreement with the simple model, the data for $\bar{\nu}$ and $E > 30$ GeV are, for $x \leq 0.1$, inconsistent with the expectations of the above-mentioned model.

3.3 Main features of the y anomaly

The anomaly, which has persisted through several improvements of the experimental technique, has the following qualitative features:

- i) It occurs mainly for $E_{\bar{\nu}} > 30$ GeV. To show this, we have plotted the $\langle y \rangle$ for antineutrinos as a function of the energy of the (anti)-neutrinos (Fig. 12). One can see that there is clear evidence of a threshold effect.
- ii) The effect is concentrated at low values of x , i.e. $x \leq 0.0$. Small x and high y means large hadron recoiling masses W , since $W^2 = E_{\text{cm}}^2 y(1-x)$.
- iii) It is impossible to understand simultaneously the $B(x)$ distributions for neutrinos and antineutrinos at small x (see Fig. 13). For $x < 0.1$ $B^{\nu} \simeq 1$, while $B^{\bar{\nu}} \simeq -1$. Hence charge symmetry is apparently violated. Antiquark mixtures at low x cannot explain the effect since it should still be charge symmetric (see also Fig. 14).

3.4 Can Y particles explain the effects?

Y particles were abundantly produced at high energies and would have a sizeable non-leptonic decay branching ratio, effects would be expected in the deep inelastic channels:

$$\nu + N \rightarrow \mu^- + X + Y$$

$\downarrow$
hadrons .

Qualitatively we could speculate that it would be easy to explain the anomalies if this were to be the case. In fact, small x should be favoured if it takes a "quark" from the sea to produce the Y , and the charge symmetry violation would be the natural consequence of the presence of a new quantum number.

It is, however, far too early to establish unambiguously a connection between the y anomaly and the Y particles.

4. PROPERTIES OF Y PARTICLES

4.1 Kinematics

If the emission of the second muon is associated with the weak decay of the Y particle, i.e.

$$\begin{aligned} \nu + N &\rightarrow \mu^- + X + Y \\ &\quad \searrow \mu^+ + \bar{\nu}_\mu + X \end{aligned}$$

we can define a number of kinematic variables of the hadronic complex, including the Y particle, recoiling with respect to the μ^- . Because of the unknown energy carried away by the neutrino, only limits can be stated for some of the variables.

With the usual notations, we can write:

$$v = x \cdot y = \frac{E_{\mu^-}}{M} \sin^2 (\theta_{\mu^-}/2) ,$$

$$E_{vis} = E_{true} - E_{\nu} = E_{\mu^-} + E_{\mu^+} + E_h ,$$

$$y_{min} = \frac{E_{vis}}{E_{vis} - E_{\mu^-}} \leq y ,$$

$$x_{max} = v/y_{min} \geq x ,$$

$$w_{min} = \text{minimum recoil mass against } \mu^- \leq W .$$

4.2 What can we say about Y particles?

The distribution of W_{min} shows a clear threshold at $W_{min} \sim 5 \text{ GeV}/c^2$. This threshold coincides with the threshold for charge symmetry violation²⁾ observed by our group in the single muon production (Fig. 15). As is well known, charge symmetry violations are expected for production of particles with additional quantum numbers which are not conserved by weak interactions. The distribution in the scaling variable x_{max} shows that dimuons from $\bar{\nu}_\mu$ come mostly from the low-x region. This is exactly the region in which charge symmetry violations have been observed. Also the distribution in the scaling variable y_{min} shows that the events,

especially for $\bar{\nu}_\mu$, come mostly from the region at high y . This matches the behaviour of the high- y anomaly in $\bar{\nu}_\mu$ scattering (Fig. 16).

If the *whole* y -anomaly is associated with the dimuons we conclude that:

$$\frac{R(Y \rightarrow \text{semi-leptonic})}{R(Y \rightarrow \text{non leptonic})} = \frac{0.02}{0.2} = \frac{1}{10} .$$

From the $W_{\min}$ and p_T distribution, we can say that the mass or the masses are between 2 and 4 GeV.

The preference of equal-sign muons, $(+-)/(--)\approx 10/1$, indicates the presence of an approximate selection rule in the Y -production and decay, relating to the change of the new quantum number to changes of the charge of the leptons (similar to $\Delta Q = \Delta S$ selection rule for strange decays).

Likewise, the absence of trimuons forbids the decay of Y by neutral currents:

$$Y \not\rightarrow \mu^+ + \mu^- + X .$$

4.3 The question of equal-sign dimuons

The experimental observation of equal-sign dimuons with smaller rates is a very important element in the phenomenology of the Y particles. If further experimental investigation will definitely confirm the presence of this effect, a number of possible explanations are possible:

- i) The charge selection rule of Y particles may be simply approximate.
- ii) Associated production of pairs of Y particles occurs at the level of $\approx 1/100$ of all ν_μ -induced interactions. This would look very promising for the possible production of these states by hadron or electron beams.
- iii) There are as yet more quantum numbers in addition to charm (i.e. friendship, sex, and so on).

It is evident that further investigations are of great interest and they are being pursued at Fermilab and elsewhere.

5. CONCLUDING REMARKS AND OUTLOOK TO THE FUTURE

It is now well established that Y particles exist. They are most likely *hadronic* states with a new quantum number. They are copiously produced by neutrinos *and* antineutrinos at high energies.

The connection to charm and to the beautiful ψ -complex has yet to be established, although it appears to be likely.

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Fig. 1 A typical event in the liquid (1a) or in the iron absorber (1b).

Fig. 1b

Fig. 2 Neutrino from quadrupole triplet focus.

Fig. 3 Spectrum of antineutrinos from horn focusing.

Fig. 4 Infinite density extrapolation for dimuon events.

Fig. 5 Visible inelasticity of dimuon events.

Fig. 6 Dimuon invariant mass.

Fig. 7 p_+ versus p_- for neutrinos (7a) and p_- versus p_+ for anti-neutrinos (7b). Note the leading particle effects.

Fig. 8 Transverse momentum variable (definition).

Fig. 9 Distribution of events in the transverse momentum variable.

Fig. 10 Feynman diagram of possible processes leading to dimuon production.

Fig. 11 Scaling distributions for different energies.

Fig. 12 Average value of y ; $\langle y \rangle$ for $\bar{\nu}$ as function of the incident $\bar{\nu}$ energy.

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Fig. 13 Charge symmetry violation.

Fig. 14 Average value of y ; $\langle y \rangle$ for $\bar{\gamma}$ as function of the incident energy.

Fig. 15 Comparison between the charge symmetry violation and dimuon events. Note the apparent identical threshold effect.

Fig. 16 Scaling variable distribution of dimuon events for neutrinos (16a) and antineutrinos (16b).

Fig. 16b