NEW PARTICLE PRODUCTION BY ANTI NEUTRINOS AND NEW DEGREES OF FREEDOM BEYOND CHARM

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Introduction

The present pace of particle physics is so rapid repeated reviews of the developments in certain areas are necessary to keep abreast of the new results and the most likely interpretations of them. This is particularly true of high energy neutrino scattering because it has given rise to a wide variety of new phenomena, the implications of which are especially far-reaching. Accordingly, it is of value, I believe, to summarize here the significant conclusions to be reached from present neutrino scattering data.

Since this is not a general review talk, I shall confine myself to the data of the Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF) experiments and, to save time, I shall not discuss at length the experimental method which has been described in detail elsewhere.

It is useful, nevertheless, to see a sample event of the single final state muon type, as shown in Fig. 1, superimposed on a schematic outline of the apparatus. The properties of such an event are obtained from the measurements indicated in Fig. 1 and described briefly in the caption to Fig. 1. The single muon data (comprised of 4994 \( \gamma \) - induced events and 2638 \( \bar{\gamma} \) - induced events) will constitute the principal part of this talk. For the moment, however, let us turn to events without a final state muon, i.e., weak neutral current events, because recent neutral current experiments have yielded new data which should be described here.

**Fig. 1.**
Schematic outline of the Harvard-Pennsylvania-Wisconsin-Fermilab neutrino detector showing an event with a single final state muon. The target-detector measures the energy \( E_H \) of the hadron-electromagnetic cascade resulting from the neutrino-nucleon collision. The muon spectrometer measures the momentum \( p_\mu \) of the muon from the neutrino interaction. The energy of the incident neutrino is obtained from \( E_\nu = E_\mu + E_H \).

**Weak Neutral Currents**

Since the discovery of weak neutral currents (WNC) about three years ago, it has been a pressing matter to determine the space-time and isospin structures of the WNC. The quality of the early experiments, although high enough to demonstrate the existence of WNC (see Fig. 2), was not sufficient to specify the detailed nature of the WNC. At Fermilab we have carried out several measurements during
Reproduction of the photographic film showing the spark chamber tracks of a weak neutral current event in two views. The spark chambers here have the same numbering scheme as in Fig. 1. Observe the complete containment of this event.

the past year of
\[
\mathcal{R} = \frac{\sigma_N(\bar{\nu}_\mu N \rightarrow X)}{\sigma_C(\nu_\mu N \rightarrow X)}
\]

where \(N\) is a nucleon and \(X\) is the sum of all hadronic final states, using different incident \(\bar{\nu}\) and \(\nu\) spectra and a smaller, better protected fiducial volume than before [12] .

The experimental arrangement and the spectra are shown in Fig. 3. With this apparatus the corrections for imperfect muon detection efficiency and hadron-through are smaller than in the earlier E2W structure and better understood, as indicated by the data in Fig. 4. The measured values of \(R^{\bar{\nu}}\) and \(R^{\nu}\) are given in Table I, subject to the constraint that the measured energy of the hadron system \(E_H\) recoiling against the outgoing lepton be greater than 4 GeV.

We have extracted from these values of \(R^{\bar{\nu}}\) and \(R^{\nu}\) the corrected values of the ratio of neutrino and antineutrino neutral current cross sections, which are shown in Table II and there compared with the expected values for different combinations of polar vector \(V\) and axial vector \(A\) in the weak neutral current. The combination \((V+A)\) is clearly ruled out by the data in Table II. In addition, the measured value of \(\frac{\sigma_N^{\bar{\nu}}}{\sigma_N^{\nu}}\) is 3 standard deviations away from the value expected for pure \(V\) or pure \(A\). The experimental value of the combination \((V-A)\) is within 1 standard deviation
Fig. 4.

(a) Raw ratio of the number of muonless events to the number with detected muons versus module number, as shown in Fig. 4a. 
(b) The raw ratio corrected for muon detection inefficiency and hadron punch-through versus module number.

of the expected value for that form. We conclude that these results require a significant parity violating component in the weak neutral current, and are consistent with the form (V-A).

Further results of significance are also obtained by combining the data of Table I with similar measurements from other experiments at different average energies \(<E_\nu>\) and \(<E_\nu\) these are shown in Fig. 5 which plots \(R^\nu\) and \(R^\overline{\nu}\) as functions of \(E_\nu\) and \(E_{\overline{\nu}}\). As we have shown before \(\gamma\) and show again below \(\gamma\) the charged current cross section for neutrinos \(\gamma\) rises linearly with \(E_\nu\) up to about 150 GeV within an experimental error of about 15%. Therefore the uniformity of \(R^\nu < E_\nu\) strongly suggests (1) that \(\gamma\) also rises linearly with \(E_\nu\) and (11) that

new particle production in the neutrino neutral current channel is not larger than the experimental errors on \(R^\nu\) in Fig. 5. On the other hand, the uniformity of \(R^\nu\) with \(<E_\nu\) is somewhat surprising since, as we discuss below, experiment indicates that the antineutrino charged current cross section \(\gamma\) increases significantly with \(E_\nu\) above about 30 GeV \(\gamma\). The errors on \(R^\nu\) in Fig. 5 are

Fig. 5.

Dependence of \(R^\nu\) and \(R^\overline{\nu}\), the ratios of neutral current to charged current cross sections for \(\nu\) and \(\overline{\nu}\) on \(E_\nu\) and \(E_{\overline{\nu}}\) the average energies of the different beams used in the measurements of \(R\).

still too large and the region of average energy covered is still too small to permit a definitive conclusion to be reached now.

If, however, better measurements indicate that \(\gamma\) follows the energy dependence of \(\gamma\) the implications for particle physics would clearly be important.
Another class of neutrino-nucleon interactions with a particularly striking signature consists of dimuon events. These have been discussed at length in the literature as evidence for the production of single hadrons with a new quantum number though the inverse beta decay process which does not conserve hadronic quantum numbers. The Feynman diagram for the production and subsequent semileptonic decay of a new hadron (Y) is shown in Fig. 6a. From the properties of neutrino-induced dimuons, particularly the transverse momentum distribution of the final state positive muons (Fig. 7) it was concluded that the mass of at least one Y-particle is in the region 2.0-2.3 GeV, and its lifetime is much less than $10^{-10}$ sec [7].

Further evidence has since accumulated from (i) neutrino-induced reactions with $K^0, \pi^+, \pi^-$ and other hadrons) in the final state [8,9], and from (ii) $e^+e^-$ annihilations that give rise to a narrow state decaying to $K^{-} \bar{K}^+$ and $J/\psi \gamma$, and to final states with $K$ and $\pi$ and other hadrons [11], all of which lead to the conclusion that the new quantum number should be identified with the "charm" quantum number proposed earlier on theoretical and semi-empirical grounds [12].

There remain, however, important questions concerning dilepton final states that need to be answered with more data. In particular, the rate of production of dileptons by $\nu_Y$ and those dilepton properties [13] are as yet poorly known. But if the distributions in transverse momentum of the final state odd sign leptons from $\nu_Y$ and $\bar{\nu}_Y$ induced dileptons continue to show a significant difference, as they have done in the early
data \cite{14} it will indicate that the masses of the new hadrons produced by } and } are significantly different. This would, in turn, suggest that the quantum numbers of some of the quarks involved in certain } nucleon interactions are different from those involved in } nucleon interactions and, possibly, that a new combination of } and } is present in the weak hadronic current as well \cite{15}. Other variations on the four-quark model, e.g., color excitation and gluon excitation, would also require serious consideration \cite{16,17}. In brief, we face the question: are there additional degrees of freedom of hadronic matter beyond "charm"?

Single Muon Final States

We are led toward a preliminary positive answer to the question posed at the end of the previous section by studying the single muon data from } and } interactions. The new hadrons with charm and possibly other new quantum numbers will decay nonleptonically as well as semileptonically, as shown schematically in Fig. 6b. If new hadron production is copious and if the nonleptonic decay modes are dominant as expected, there should be visible effects on the distributions in certain dynamical variables of the single muon data due to new hadron production. Such effects have in fact been observed for some time in the } induced single muon data \cite{19}. The primary thrust of those data so far has been to support the conclusion drawn from dimuon production that at least one new quantum number of hadronic matter exists. A second, equally important, thrust is in the strong suggestion that still more degrees of freedom of hadronic matter, in addition to charm, are necessary to account for the differences between the single muon data from } and } . In the remainder of this talk we discuss the evidence from which that suggestion derives.

The useful variables and the differential cross sections for the inelastic scattering of } and } by nucleons are directly obtained from the present phenomenological theory of low energy weak interactions and lepton-nucleon scattering theory \cite{18}. Assuming scale invariance, and defining the scale invariant variables } = ( } ) \rightarrow ( } ) with } = } , } , \sqrt{ } \beta \sqrt{ } the energy of the hadron cascade, } = } + } and } the nucleon mass, we obtain the distributions in the variable } given by

\begin{equation}
\frac{d \sigma}{d x} = \frac{e^2 \mu^2}{\alpha} f_1(x) \left[ 1 - y(1-x)^2 \right] + \frac{2}{x} \left[ 1 + 2 \alpha \frac{x}{y} \right]
\end{equation}

and

\begin{equation}
\frac{d \sigma}{d x} = \frac{e^2 \mu^2}{\alpha} f_2(x) \left[ 1 - y(1-x)^2 \right] + \frac{2}{x} \left[ 1 + 2 \alpha \frac{x}{y} \right]
\end{equation}

with

\begin{equation}
\beta \Delta = \int f_1(x) \frac{d x}{f_2(x)} \\
\Delta \beta = \int f_1(x) \frac{d x}{f_2(x)}
\end{equation}

and

\begin{equation}
\Delta \beta = \int f_1(x) \frac{d x}{f_2(x)}
\end{equation}

where the } are dimensionless, scale-invariant nucleon structure functions.

If charge symmetry invariance is valid, the simplifying relations hold, viz.

\begin{equation}
\frac{f_1(x)}{f_2(x)} = \frac{f_1(x)}{f_2(x)}
\end{equation}

and

\begin{equation}
\beta \Delta = \beta \Delta
\end{equation}

Furthermore, if parity is maximally violated, i.e., if the space-time structure of the hadronic weak current is pure }-A,

\begin{equation}
\beta \Delta = \beta \Delta
\end{equation}
and we obtain

\[
\frac{d\sigma}{dy} = \frac{e^2 m E \sqrt{\sigma}}{y} \int \mathcal{F}_2(x) \, dx
\]

(5)

\[
\frac{d\sigma}{dy} = \frac{e^2 m E \sqrt{\sigma}}{y} \int \mathcal{F}_2(x) \, dx
\]

and

\[
\sigma \frac{d\sigma}{dy} = \frac{1}{3}
\]

(6)

These simplified distributions in \( y \) are shown in Fig. 8.

![Fig. 8: Distributions in \( \gamma = E\gamma / E\nu \) expected from simplified theory (see text).](image)

The observed distributions \( \gamma^\prime \) in \( \gamma \) for \( \gamma \) and \( \gamma^\prime \) for \( 10 < E_{\gamma^\prime} < 30 \) GeV are shown in Fig. 9. Fitting the data below \( \gamma < 0.6 \) in Fig. 9 yields \( \beta^\gamma = 0.60 \pm 0.30 \) and \( \beta^\gamma = 0.94 \pm 0.99 \), in approximate agreement with the simplified theoretical distributions shown in Fig. 8, if \( \rho^\gamma \) and \( \rho^\gamma \) are taken to zero.

In Fig. 10 are shown the \( \gamma^\nu \) and \( \gamma^\nu \) distributions in the energy region \( E_{\gamma^\nu} > 70 \) GeV, with average energies \( <E_{\gamma^\nu} > = 126 \) GeV and \( <E_{\gamma^\nu} > = 106 \) GeV. Out to the limit of good detection efficiency the \( \gamma^\nu \) distribution is fit with \( \beta^\nu = 0.83 \pm 0.20 \), again consistent with theoretical expectations, and indicating that the almost uniform-\( y \)-distribution for \( \nu \) is insensitive to the precise value of \( \beta^\nu \). In contrast, the \( \gamma^\nu \) distribution in Fig. 10 is best fit with \( \beta^\nu = 0.41 \pm 0.13 \), roughly 4 standard deviations lower than the value of \( \beta^\nu \) determined in the lower energy interval, \( 10 < E_{\gamma^\nu} < 30 \) GeV, in Fig. 9. This is the most direct, though perhaps not the clearest, demonstration that the form of the \( \gamma^\nu \) distribution remains constant with changing \( \nu \) energy while the form of the \( \gamma^\nu \) distribution changes with increasing \( \gamma^\nu \) energy.

The complete energy dependence of the \( \gamma^\nu \)-distributions \( \gamma^\nu \) is shown in Fig. 11 where we plot the first moments \( \gamma^\nu \) and \( \gamma^\nu \) (for all \( x < 0.6 \)) as functions of \( E_{\gamma^\nu} \) and \( E_{\gamma^\nu} \) up to 150 GeV. The \( \gamma^\nu \) data are
not constant at \( <\gamma^v> = 0.5 \) as might be expected, because of the regions of incomplete detection efficiency, i.e., loss of events at large-\( \gamma \), and also to a small extent because of the cut at \( X = 0.6 \). That loss has been taken into account in the Monte Carlo calculation of \( <\gamma^v> \) with which the data in Fig.11 are compared. Again, note that the measurements of \( <\gamma^v> \) do not determine a precise value of \( \beta^v \), but are consistent within experimental error with a large value of \( \beta^v \). On the other hand, the data for \( <\gamma^v> \) which correspond to \( \beta^v = 0.9 \) at \( E_{\gamma} < 30 \text{ GeV} \), rise sharply to a significantly higher value of \( <\gamma^v> \) and therefore to a significantly lower value of \( \beta^v \), at higher \( E_{\gamma} \). There is, however, no single value of \( \beta^v \) which fits the data over the entire energy range 10 to 150 GeV. This is shown by comparison with the Monte Carlo calculated curves for two values of \( \beta^v \), which are based on the same detection efficiency corrections used to obtain the calculated curves for \( <\gamma^v> \). Fig.11 exhibits most clearly the high-\( \gamma \)-anomaly, i.e., the abrupt change with \( \gamma \) of the form of the \( \gamma^v \) distribution.

Within the context of the quark-parton model with three quarks ( \( u, d \) and \( s \) ) it is possible to evaluate the fraction of antiquarks indicated by the \( \gamma^v \) distributions below 30 GeV and well above that energy. The parameter \( \beta^v \) in eq. (2) is related to the fraction of antiquarks by the equation

\[
\beta^v = 1 - 2 \int \bar{f}(x) \frac{dx}{\bar{f}(x) + f(x)} \, dx,
\]

where \( f(x) \) and \( \bar{f}(x) \) are the momenta in the non-strange quarks and antiquarks.

Thus, the curves marked \( \beta^v = 0.90 \) and \( \beta^v = 0.40 \) in Fig.11 correspond to \( \int \bar{f}(x) \frac{dx}{\bar{f}(x) + f(x)} \, dx = 0.90 \) and \( \int \bar{f}(x) \frac{dx}{\bar{f}(x) + f(x)} \, dx = 0.40 \) respectively, but recall also that the data
for $<\nu^2>$ are not fit over the entire energy region by a single value of $B^{1/2}$.

From Fig. 9 measured $\nu/\overline{\nu}$ distribution in the energy interval $10 < E_\nu < 30 \text{ GeV}$ yields $\int \frac{dX}{E_{\nu}(x)} = \frac{E_{\nu}(x)}{E_{\nu}(x) + g(x) \frac{d\nu}{dx}(x)_{E_{\nu} = 0.05}}$. This is consistent with the value of 0.09 to 0.10 obtained from data [20] at $E_{\nu}/\overline{\nu} < 10 \text{ GeV}$, and with the limit of 0.10 from recent muon-nucleon scattering data [21]. Consequently, $\nu$ scattering from the anti-quarks of the conventional three-quarks model is too small to account for the magnitude of the high-$\nu$ anomaly. Furthermore, the model is unable to explain the energy threshold for the high-$\nu$ anomaly. For these reasons, as we stated earlier, the single muon data have been advanced as evidence for the existence of new hadronic quantum numbers.

An alternative, but closely related dynamical variable in which to display the single muon data is $W$, the invariant mass of the recoiling hadronic system in the $\nu/\overline{\nu}$ nucleon collision [14]. The variables $X$, $Y$ and $W$ are related by the expression $W = S \nu(y(x) + \mu)$ where $S = \frac{1}{2} \mu E_{\nu}/\overline{\nu}$. It is advantageous to look at the $W$-distributions because, in a given interval of $S$, they allow a search to be made for both narrow and broad anomalous structure. Such structure at high-$W$ would be built of events at high-$\nu$ and low-$x$, while structure at low-$W$ would correspond to events with low-$\nu$ and high-$x$. But no explicit cut in $X$ or $Y$ is necessary.

To interpret the experimental $W$-distributions, we again utilize the differential cross sections of eqs. (1) and (2), assuming scale invariance and charge symmetry invariance. Further, we make use of $\nu$ and $\overline{\nu}$ data in the interval $3 < E_{\nu}/\overline{\nu} < 30 \text{ GeV}$ [22,23,24] and also $e$-nucleon [25] and $\mu$-nucleon [26] inelastic scattering result to determine empirically the functions $B(x)$, $r_{el}(x)$ and $F_{\overline{\nu}}(x)$ that appear in eqs. (1) and (2).

The observed and calculated $\nu$ distributions in the interval $10 < E_\nu < 30 \text{ GeV}$, shown in Fig. 12a, are then normalized to have the same area above 2 GeV; below that $\nu$ value, quasielastic scattering and $N^p$ production dominate the scattering at energies less than 30 GeV. Once the low energy $\nu$ distributions are normalised in this way, the relative normalisation of the calculated and observed distributions in any energy interval, as in Figs. 12b through 12f, is completely specified by the equations

$$
\frac{A^\nu(E)}{A^\overline{\nu}(E)} = \frac{\sigma^{\nu}(E)}{\sigma^{\overline{\nu}(E)}} \frac{f^{\nu}(E)}{f^{\overline{\nu}(E)}} \frac{\nu(E)}{\overline{\nu}(E)}
$$

where the $A(E)$ are the numbers of events in any calculated distribution at mean energy $E$, the $f(E)$ measure the $\nu$ and $\overline{\nu}$ fluxes that give rise to the observed events at energy $E$, and the $\nu(E)$ are corrections that take into account the change of acceptance of the apparatus with $E$. We obtain the $f(E)$ from the numbers of events with $W < 1.6 \text{ GeV}$ in any energy interval, following a technique justified by Sakurai [27]. In Table III are given the values of $f(E)$ and $\nu(E)$ for $\nu$ and $\overline{\nu}$ in each energy interval in Fig. 12.

There are three significant features of the $W$-distributions in Fig. 12.

(i) Below 30 GeV, there is good agreement between the observed and calculated distributions for both $\nu$ and $\overline{\nu}$ for $W > 2 \text{ GeV}$.

(ii) Apart from a small, but statistically significant, excess of events centered about the invariant mass of $2.2 \pm 0.3$, the $\nu$ distributions scale linearly with $E$, between
10 and 100 GeV, as the agreement within the experimental error of ±15% of the observed and calculated distributions of Fig.12 indicates.

(iii) In all the $\bar{\nu}$ data above 30 GeV there is a substantial excess of events above $W=4$ GeV, which constitutes the high-$y$ anomaly. In the energy interval $50 < E_\gamma < 100$ GeV the total excess with $W > 4$ GeV approximately equal to the calculated inelastic scattering continuum.

We see from these results that new hadron production by $\nu$ is less than 15% of the calculated inelastic $\nu$ cross section in the interval $50 < E_\gamma < 100$ GeV, while new hadron production by $\bar{\nu}$ may be as large as the calculated $\bar{\nu}$ inelastic cross section in that energy interval. The relative magnitudes of these effects in $\nu$ and $\bar{\nu}$ are, as we shall see, very difficult to account for in any quark model (with only left handed weak hadronic currents) containing two ordinary quarks and a strange and a charm quark, but no other degrees of freedom.

To sharpen this point, it is useful to make explicit the $x$ and $\nu$ dependence of the several parts of the $W$-distributions in Fig.12. We show in Figs. 13 and 14 $W$-distributions for $\nu$ and $\bar{\nu}$ in the two higher energy intervals in two different regions of $x$. It is clear that the excess in the $\bar{\nu}$ distributions occurs principally at low $x$, although Fig.14d indicates that some of the $\bar{\nu}$ excess is present at $x > 0.15$.

In Fig.15 and 16 are shown the observed $y$-distributions for $\nu$ and $\bar{\nu}$ in the same energy intervals and in the same two regions of $x$. The solid curves in Fig.15 and 16 are the calculated $y$-distributions from eqs. (1) and (2) with the same normalization as described above for the $W$-distributions in Figs. 13 and 14.

In Fig.12, invariant mass ($W$) distributions for $\nu$ and $\bar{\nu}$ in the energy intervals 10 to 30, 30 to 50 to 100 GeV. The numbers shown are corrected events. The shaded regions are calculated assuming charge symmetry and scale invariance and exhibit the total error in the calculation. The broken vertical lines mark the interval $1.8 < W < 3.4$ GeV.

In Fig.13, $W$-distributions for $\nu$ and $\bar{\nu}$ in the energy interval 30 to 50 GeV and in the $x$-regions $0 < x < 0.15$ and $0.15 < x < 0.6$. Shaded regions as in Fig.12. Cross hatched regions here and in Fig.12 are discussed in the text.
Same as Fig. 13 but the energy interval is 50 to 100 GeV. Shaded regions as in Fig. 12.

**Fig. 14.**

**E_{\nu,\bar{\nu}} 50 - 100 GeV**

Same as Fig. 15 but for the energy interval 50 to 100 GeV. These distributions in y correspond to the W-distributions in Fig. 14.

One sees the prominent excess at low-y in the W distribution of Fig. 15b which is made up of the same events centered at W = 2.2 ± 0.3 GeV shown in Fig. 13b. A similar structure may also be present in the \( \bar{\nu} \) data as indicated in Figs. 13d and 15d, but for \( \bar{\nu} \) this structure may perhaps be an extension of the high-y anomaly to lower values of y. In other respects the y-distributions of Figs. 15 and 16 corroborate the conclusions obtained from the W-distributions of Figs. 13 and 14, as would be expected if the data are internally consistent.

We turn now to the dependence on energy of the \( \nu \) and \( \bar{\nu} \) charged current total cross sections \( \sigma_{c,\nu} \) \( \nu \) \( \bar{\nu} \). These results have been anticipated in the differential distributions \( d\sigma/dy \) and \( d\sigma/dW \) described above, but the regions of \( X \) covered and the corrections...
applied in comparing data with theory are different for the differential cross sections and the total cross sections. Thus we test in still another, very direct, way the internal consistency of the data and the method of analysis.

Experimentally, it is more direct and more accurate to study the ratio of cross sections $\sigma_C^\gamma / \sigma_C^\nu$, because most systematic effects cancel out of the ratio. Furthermore, it is possible to make a relatively precise measurement of the ratio that is independent of the $\nu$ and $\bar{\nu}$ fluxes. We show in Fig. 17 the measured ratio $\sigma_C^\gamma / \sigma_C^\nu$ in the energy region from 10 to 60 GeV. Here the relative normalization of $\sigma_C^\gamma$ to $\sigma_C^\nu$ is provided by $\gamma$ and $\bar{\gamma}$ events involving quasielastic scattering and $N^-$ production, which appear clearly in the invariant mass plots of the data, Figs. 12, 13 and 14. The signature of these events is taken to be the joint requirement $W < 1.6$ GeV and $Q^2 < 1.5$ GeV$^2$. Above 60 GeV the fraction of all events satisfying this requirement diminishes which accounts for the absence of points above 60 GeV in Fig. 17.

\[ \int_0^{W_{\text{MAX}}} \frac{d\sigma_C^\gamma}{dW} dW = \int_0^{W_{\text{MAX}}} \frac{d\sigma_C^\nu}{dW} dW \]

in a given energy region with a given precision. The range of energy over which $\sigma_C^\gamma / \sigma_C^\nu$ may be obtained from the data is extended by this normalization procedure, as is shown in Fig. 18 in which we have utilized the Sakurai prescription and variations thereof.

Finally, we show in Fig. 19 the ratio $\sigma_C^\gamma / \sigma_C^\nu$ obtained by using semiempirical determinations of the actual $\nu$ and $\bar{\nu}$ fluxes. This subsample of data was acquired with a primary proton beam of energy 380 GeV impinging on a target, and a triplet of quadrupole magnets set of focus the 200 GeV positive and negative secondaries from that target. The resulting $\nu$ and $\bar{\nu}$ fluxes were determined using the

The justification for using quasielastic scattering and resonance production for normalization lies in the fact that, for $E_{\nu, \bar{\nu}} \geq 3$ GeV
\[ \frac{\Gamma_{\mu+N^+\rightarrow D^+}}{\Gamma_{\mu+N}} = \frac{\sigma_{\mu+N^+\rightarrow \mu^+D^+}}{\sigma_{\mu+N}} \] (9)

which is known empirically and also expected on very general theoretical grounds. An alternative normalization procedure of greater generality arises from the relation
\[ E_{\nu, \bar{\nu}} \sigma_{\mu+N^+\rightarrow \mu^+D^+} \rightleftharpoons \sigma_{\mu+N} \] (10)

initially obtained by Lee and Yang /28/ and others /29/, who recognized that
\[ E_{\nu, \bar{\nu}} \sigma_{\mu+N^+\rightarrow \mu^+D^+} \rightleftharpoons \sigma_{\mu+N} \] (11)

which, in conjunction with charge symmetry invariance, leads to eq. (10). The validity of eq. (10) at finite values of $E_{\nu, \bar{\nu}}$ has been discussed by Sakurai /27/ who specifies the upper limits of the integrals for which
\[ \int_0^{W_{\text{MAX}}} \frac{d\sigma_C^\gamma}{dW} dW = \int_0^{W_{\text{MAX}}} \frac{d\sigma_C^\nu}{dW} dW \]
Energy dependence of the ratio $\sigma(\gamma)/\sigma(\gamma')$ obtained by the Sakurai flux-independent normalization procedure (black dots). $M_{m_{\gamma\gamma}}$ refers to the maximum invariant mass ($m_{\gamma\gamma}$) that is used in the normalization procedure. The open triangle, circle and square denote the value of $\sigma(\gamma)/\sigma(\gamma')$ obtained if $M_{m_{\gamma\gamma}}$ is varied as shown.

Conclusions

There seems little doubt that a new quantum number of hadronic matter—presumably charm—has been discovered in neutrino interactions through the observation of dimuons. This has since been confirmed and made more explicit by the observation of other dilepton final states in neutrino interactions and of narrow resonances resulting from $\gamma \gamma$ annihilation.

There is a salient question that now arises: is this the full extent of the new physics or is there evidence of other degrees of freedom which must be incorporated in a complete description of the new physics?

The single muon data of the last section appear to provide evidence, albeit in preliminary and as yet unconfirmed form. We summarize the reasoning here. We know from the $\gamma \gamma$-induced dimuons that new particle production by $\gamma \gamma$ takes place. We expect that in addition to the semileptonic decay modes of the new particles there will be abundant nonleptonic measured yield of hadrons /30/ and the focusing properties of the quadrupole triplet. The estimated systematic uncertainty in the $\gamma'$ and $\gamma$ flux ratio is approximately 10%.

To obtain the experimental points in Figs. 17, 18, and 19, it is necessary to compensate for the incomplete detection efficiency correction described above in a model dependent way. The magnitude of this compensation is moderate; for example, above 50 GeV, it is less than 20% for $\gamma$ and less than 2% for $\gamma'$. Note that the results for $\sigma(\gamma)/\sigma(\gamma')$ obtained by the three normalization methods are in agreement. Below 30 GeV, one obtains $\sigma(\gamma)/\sigma(\gamma') = 0.30 \pm 0.06$, consistent with the value expected from the simplified theory (eq. (6)), but above 50 GeV the ratio is observed to rise to about twice its value at lower energy.
decay modes which will contribute to the single muon data. We obtain an experimental upper limit to the cross section for new particle production by \( \sqrt{s} \), which we call \( \sigma_{\sqrt{s}}(A,T) \) namely

\[
\frac{\sigma_{\sqrt{s}}(A,T)}{\sigma_{\sqrt{s}}(K^+)} \sim 50 < \frac{1}{100 \text{ GeV}} \tag{13}
\]

where \( \sigma_{\sqrt{s}}(A,T) \) is the observed total charged current section for inelastic neutrino interactions. Note that a branching ratio for the semi-leptonic decay into \( (A,T) \) and hadrons of order 0.1 leads to consistency between the observed \( \sqrt{s} \) induced dimuon rate (0.9 \( \pm \) 0.3)% of single muon production above 30 GeV and the limit in eq. (13).

Now in the quark model with \( t, s, c \) and \( d \) quarks the experimental limit in eq. (13) is completely compatible with the production of charmed particles through the quark reactions

\[
v_{\mu} r d \rightarrow \mu^- + c \quad \text{goes as } \sin^2 \theta_{\text{c}} \text{ off valence quarks}
\]

and

\[
v_{\mu} s \rightarrow \mu^- + c \quad \text{goes as } \cos^2 \theta_{\text{c}} \text{ off "sea" quarks}
\]

The total yield of charm production from these reactions is expected to be roughly 0.1 \( \sigma_{\sqrt{s}}(K^+) \), i.e., consistent with the limiting value in eq. (13).

On the other hand, we know from \( \sqrt{s} \) induced new particle production by \( \sqrt{s} \) also takes place, and again we expect abundant nonleptonic decay modes. However, the single muon \( \sqrt{s} \) data yield

\[
\frac{\sigma_{\sqrt{s}}(A,T)}{\sigma_{c}(K^+)} \sim \frac{\sigma_{c}(A,T)}{\sigma_{c}(K^+)} \sim 30 < E_{\mu} < 100 \text{ GeV} \tag{14}
\]

where again \( \sigma_{\sqrt{s}}(A,T) \) is the observed total charged current cross section. This value is significantly larger than the yield of charmed particles expected from the dominant permissible quark reaction

\[
\sqrt{s} + \sqrt{s} \rightarrow \mu^+ + \mu^- + c \quad \text{goes as } \cos^2 \theta_{\text{c}} \text{ off "sea" quarks}
\]

which should certainly be less than 0.15 \( \sigma_{\sqrt{s}}(A,T) \). This last value comes from assuming the magnitude of the strange quark "sea" to be 5% of the quark total and noting the uniform-y-distribution of \( \sqrt{s} \) interactions with "sea" quarks. Again, observe that a semileptonic branching ratio (to \( \mu, \mu^- \) and hadrons) of order 0.05 leads to consistency between the observed \( \sqrt{s} \) dimuon rate (2.5 \( \pm \) 1)% of the single muon yield above 30 GeV and the relative rate of new particle production given in eq. (14).

Thus it seems that charmed particle production alone can explain the observed rate of new particle production by \( \sqrt{s} \). In contrast, charmed particle production by itself seems not be sufficient to account for the large magnitude of new particle production indicated by the \( \sqrt{s} \) data. It remains now for future experiments to make this result more firm and to delineate the nature of the unidentified, additional new degree of freedom involved in the new particle production by \( \sqrt{s} \).
Table I. The values of $R^\gamma$ and $R^{\bar{\nu}}$ for $E_H > 4$ GeV

<table>
<thead>
<tr>
<th>Beam type</th>
<th>$R^\gamma$</th>
<th>$R^{\bar{\nu}}$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single horn</td>
<td>0.31±0.06</td>
<td>Pure $\gamma$</td>
<td>beam, $&lt;E_H&gt;$ = 53 GeV</td>
</tr>
<tr>
<td>1974 Quadru-pole</td>
<td>0.24±0.06</td>
<td>Mixed beam</td>
<td>$&lt;E_H&gt;$ = 78 GeV</td>
</tr>
<tr>
<td>triplet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975 Quadru-pole</td>
<td>0.29±0.04</td>
<td>Mixed beam</td>
<td>$&lt;E_H&gt;$ = 85 GeV</td>
</tr>
<tr>
<td>Double horn,</td>
<td>0.39±0.10</td>
<td>Pure $\bar{\nu}$</td>
<td>beam, $&lt;E_H&gt;$ = 41 GeV</td>
</tr>
<tr>
<td>with plug</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table II. The measured values of $\frac{\sigma^\gamma}{\sigma^{\bar{\nu}}}$ after correction for the loss of events with $E_H < 4$ GeV according to the form of the weak neutral current in the first column. The corresponding values of $\frac{\sigma^\gamma}{\sigma^{\bar{\nu}}}$ expected from theory, are given in column three. An antiquark contribution of 5% has been assumed.

<table>
<thead>
<tr>
<th>From of the weak neutral current</th>
<th>Corrected experimental value</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu - A$</td>
<td>0.61 ±0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>$\nu$ or A</td>
<td>0.40 ±0.17</td>
<td>1.00</td>
</tr>
<tr>
<td>$\nu + A$</td>
<td>0.37 ±0.16</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Table III. Values of the average detection efficiency $\epsilon$ and the flux factor $\beta$ (in number of events) for $\gamma$ and $\bar{\nu}$ in each energy interval $\Delta E$.

<table>
<thead>
<tr>
<th>$\Delta E$(GeV)</th>
<th>$\epsilon^\gamma$</th>
<th>$\epsilon^{\bar{\nu}}$</th>
<th>$\beta^\gamma$</th>
<th>$\beta^{\bar{\nu}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–30</td>
<td>0.56</td>
<td>0.88</td>
<td>233</td>
<td>435</td>
</tr>
<tr>
<td>30–50</td>
<td>0.75</td>
<td>0.96</td>
<td>145</td>
<td>95</td>
</tr>
<tr>
<td>50–100</td>
<td>0.84</td>
<td>0.98</td>
<td>92</td>
<td>29</td>
</tr>
</tbody>
</table>

References and Footnotes

6. See, for example, D. Cline and A. K. Mann, Comments in Nuclear and Particle Physics, 2, 75 (1976).
A Measurement of Neutral Current Coupling in High Energy Neutrino Interactions

California Institute of Technology

H. E. Fisk, and G. Krafczyk

Fermilab

This paper reports on inclusive neutral current (NC) neutrino interactions of the type \( \nu + N \rightarrow \nu + \text{hadrons} \). A separate paper on the charged current (CC) data \( \nu + N \rightarrow \nu + \text{hadrons} \) is reported in the deep inelastic scattering section of these proceedings. The general idea of the neutral current experiment is to determine, from hadron energy distributions due to NC interactions in the narrow band beam (1), the form of the neutral current coupling: \( V = A, V - A, A, S, P, \text{etc.} \)

Data were obtained using the Caltech-Fermilab detector (2). In addition to the normal muon trigger used to collect CC events, a special hadron energy deposition trigger was devised to obtain NC data. The mean threshold of this hadron energy trigger was 8 GeV. A subsequent cut of \( E_h > 12 \text{ GeV} \) was applied at the time of analysis to guarantee a trigger efficiency of greater than 90%. The trigger threshold was determined by the trigger rate due to cosmic rays (\( \approx 60 - 100 \text{ Hz} \)) and necessitated running the experiment with a 1 ms beam spill from the accelerator. The secondary beam was tuned to 170 GeV and for the CC interactions this produced mean \( v_\nu \) and \( v_\bar{\nu} \) energies of 52 and 116 GeV, respectively.

For each event the penetration, \( p \), was defined to be the length (in collision lengths of Fe/100g) of the longest track. Using this definition three categories of events were determined as shown in Table 1. For Class 1 events the muon penetrated the toroidal magnet downstream of the target calorimeter and had as measured variables \( E_\nu, E_\mu, \text{and } E_h \). Class 2 events had a muon identified by penetration of at least 1.6 meters of Fe but missed the magnet \( E_\nu, E_\mu \) measured. Class 3 events consisted of CC events with a low energy or wide angle muon and NC events. A histogram of the penetration parameter, \( p \), is given in Figure 1. The obvious excess of events in the \( p \leq 16 \text{ region} \) is due primarily to NC events.

<table>
<thead>
<tr>
<th>Class by Events</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )</td>
<td>875</td>
<td>988</td>
<td>1033</td>
</tr>
<tr>
<td>( \bar{\nu} )</td>
<td>185</td>
<td>122</td>
<td>239</td>
</tr>
<tr>
<td>Measured Variables ( E_\nu, E_\mu, E_h )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Types by Events</td>
<td>CC</td>
<td>CC</td>
<td>CC</td>
</tr>
</tbody>
</table>