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Invariant-Mass Distributions from Inelastic ν and $\bar{\nu}$ Interactions*

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The measured distributions in invariant mass W of the recoiling hadron systems in neutrino- and antineutrino-nucleon inelastic collisions are observed to be significantly different after taking into account the opposite helicities of neutrinos and antineutrinos. These distributions indicate the onset of a new phenomenon in the antineutrino data beginning at an incident energy of about 30 GeV, which appears as an excess of events with $W > 4$ GeV/c^2.

In an earlier paper[1] we presented evidence for a significant difference between the charged-weak-current interactions of neutrinos and antineutrinos with nucleons, distinct from, and in addition to, the difference expected because of the opposite helicities of neutrinos and antineutrinos. Subsequently, we reported other evidence[2] which showed an energy threshold for that effect. Below an energy of about 30 GeV, neutrino and antineutrino interactions were observed to be as expected; above 30 GeV, the difference between neutrino and antineutrino scattering became apparent. In the present paper, with twice the previous data, are given the measured distributions in invariant mass W of the recoiling hadron systems in the neutrino and antineutrino collisions. These distributions also exhibit a distinct difference between neutrino- and antineutrino-induced events, as implied by the scaling-variable distributions from the earlier data,[1] and suggest new particle production by antineutrinos with a mass or masses in the region of 4 GeV/c^2. In addition, they confirm the threshold in antineutrino energy at about 30 GeV.

The experimental method was described in the previous papers[1,2] and also at greater length recently.[3,4] Briefly, an enriched neutrino or antineutrino beam impinged on an ionization calorimeter containing liquid scintillator in which the neutrino-nucleon and antineutrino-nucleon interactions occurred. The total pulse-height output from the calorimeter measured the total energy of the hadron system (E_H) emerging from those interactions. The vector momentum and sign of the electric charge of the outgoing muon were measured in a magnetic spectrometer located directly downstream of the ionization calorimeter. The fractional resolution of the calorimeter,

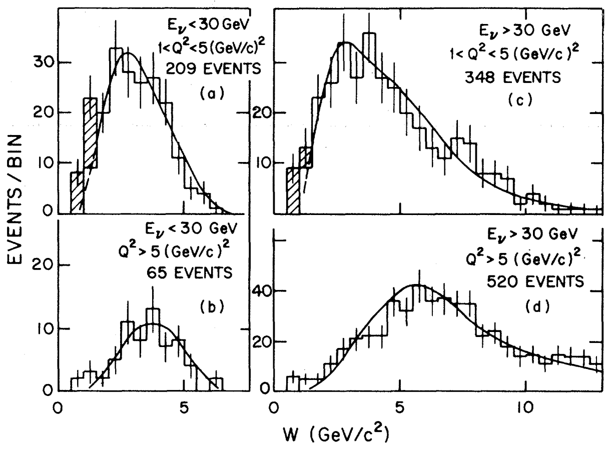

FIG. 1. Invariant-mass distributions of the recoiling hadron systems in inelastic neutrino-nucleon interactions for two regions in Q^2 and two regions in E_ν. The continuous curves are obtained from a model described in the text. The cross-hatched areas signify events due to quasielastic scattering and N^* production.

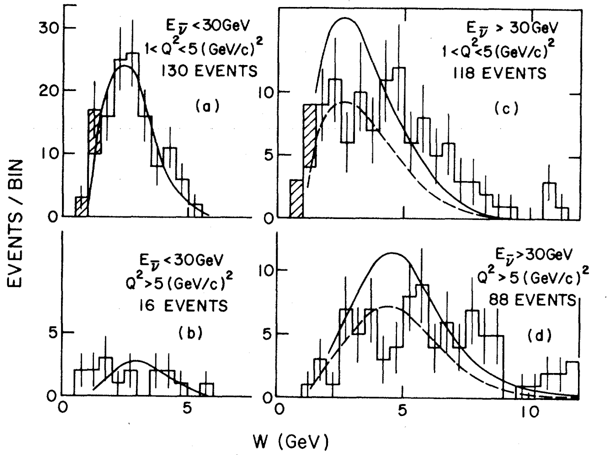

FIG. 2. Invariant-mass distributions for inelastic antineutrino-nucleon collisions in two regions of Q^2 and two regions of $E_{\bar\nu}$. The solid curves correspond to those in Fig. 1. The dashed curves represent a different normalization.

$\Delta E_H/E_H$, and of the magnetic spectrometer, $\Delta p_\mu/p_\mu$, were Gaussian with $\sigma(E_H) \approx 15\%$ and $\sigma(p_\mu) \approx 15\%$ over the entire range in E_H and p_μ of the data presented here. In terms of the directly measured quantities, E_H and p_μ, the invariant mass of the recoiling hadron system W is given by

$$W = (m^2 + 2mE_H - Q^2)^{1/2},$$

where $Q^2 = 4E_\nu E_\mu \sin^2(\theta_\mu/2)$ is the square of the four-momentum transfer to the outgoing muon, $E_\nu = E_\mu + E_H$, and m is the nucleon mass.

Figure 1 presents the measured distributions in W for incident neutrinos. The data have been divided into two regions of Q^2 and two regions of E_ν to show the dependence on those variables. The continuous curves also shown in Fig. 1 are obtained from the scale-invariant differential cross section for inelastic neutrino-nucleon scattering,[5] $d^2\sigma^\nu/dx\,dy$, with two assumptions. (i) The distribution in the scaling variable $y = E_H/E_\nu$ is uniform in y for all values of the scaling variable $x = Q^2/2mE_H$. (ii) The distribution in x measured in neutrino-nucleon scattering then yields directly the form of the only nucleon structure function $F_2(x)$ necessary to specify $d^2\sigma^\nu/dx\,dy$ completely. These assumptions are consistent with available high-energy neutrino scattering data,[1,6] but we emphasize that $d^2\sigma^\nu/dx\,dy$ determined in this way is used as a particularly simple trial function against which to make semiquantitative comparisons of the data in one region of Q^2 or E_ν with the data in another region. Later, with a modification of the y distribution nominally appropriate to antineutrinos, we employ the same phenomenological expression to facilitate comparison of the W distributions of neutrinos with those of antineutrinos. The experimental detection efficiency and resolution have been folded into the calculated W distributions which are then compared with the uncorrected data, both normalized to have the same area.

Apart from the region in W at 1.0 GeV/c^2 which, as expected, is dominated by quasielastic scattering and N^* production[7] at low Q^2, the shapes of the measured W distributions in Fig. 1 agree well with those of the calculated distributions in both regions of Q^2 and both regions of E_ν. In addition, the ratios of observed events, i.e., ratios of areas, in the four regions of Fig. 1 are in agreement with the predicted ratios within the statistical errors, indicating agreement between the Q^2 and E_ν dependences of the data and the theoretical model.

The W distributions for antineutrino-induced events in the same regions of Q^2 and $E_{\bar\nu}$ are shown in Fig. 2. The calculated curves are obtained from $d^2\sigma^{\bar\nu}/dx\,dy$ assuming a y distribution for antineutrinos of the form $(1-y)^2$. Each solid, calculated curve is normalized to the same number of events as the data in that region. Below 30 GeV, there is agreement, within the limited statistics, between the calculated and observed distributions. Above 30 GeV, in both intervals of Q^2, the shapes of the observed distributions are significantly different from the predicted shapes. If the calculated W distributions for $E_{\bar{\nu}} > 30$ GeV are normalized to have the same average values as the data in the interval $1.5 < W < 3$ GeV/c^2, the dashed curves in Fig. 2(c) and 2(d) result. This normalization is motivated by the observation that the events which lie above the dashed curves in Figs. 2(c) and 2(d) have low values of x ($\lesssim 0.1$) and a flat distribution in y, suggestive of a violation of charge-symmetry invariance.[1]

Although scale invariance is not necessarily expected to hold in the region $Q^2 < 1$, it is interesting to attempt a comparison of the observed with the model W distributions in that region. This is shown in Fig. 3 for both neutrinos and antineutrinos in two different energy intervals as before. Again the normalization is to the total number of events in each plot (solid curves). The numbers of events in the neutrino W distribution [Figs. 3(a) and 3(c)] are consistent with the assumed Q^2 dependence and the neutrino data in Fig. 1. There is significant disagreement in shape only in the antineutrino data at $E_{\bar{\nu}} > 30$ GeV [Fig. 3(d)], independent of the normalization procedure.

Figures 1, 3(a), and 3(c) indicate that the invariant-mass distributions for neutrino-induced events are satisfactorily described by the phenomenological model of inelastic neutrino-nucleon scattering discussed earlier at all neutrino energies and all Q^2 values reached in this experiment.[8] A similar conclusion is obtained from Figs. 2(a), 2(b), and 3(b) for inelastic antineutrino-nucleon scattering at energies less than 30 GeV. There is, however, substantial disagreement between the model and the antineutrino data in the energy region above 30 GeV, particularly at low and intermediate values of Q^2. We have verified by direct measurement[1] and by calculation that this disagreement is not appreciably diminished by allowing the y distributions assumed in the theoretical model to vary in the low-x region in a way compatible with charge-symmetry invariance and no V-A interference in that region. Hence, the discrepancy exhibited in the antineutrino data above 30 GeV [Figs. 2(c), 2(d), and 3(d)] suggests the onset of a new phenomenon at or below that energy, which is manifested by an excess of events with $W \gtrsim 4$ GeV/c^2.

A plot of the difference between the antineutrino data and the calculated distribution for $E_{\bar{\nu}} > 30$ GeV and all Q^2 is shown in Fig. 4. The falloff at higher values of W is presumably due to the rapid decrease with increasing energy of the incident antineutrino flux. The difference signal in Fig. 4 comprises approximately 14% of the total number of observed antineutrino-induced events. Almost all of those events have $a \lesssim 0.1$. If the cross section for this effect were the same for neutrinos as for antineutrinos, the excess of neutrino-induced events with $W \gtrsim 4$ GeV/c^2 would be about 5% of the total neutrino sample. Or if production of this effect by neutrinos were to give

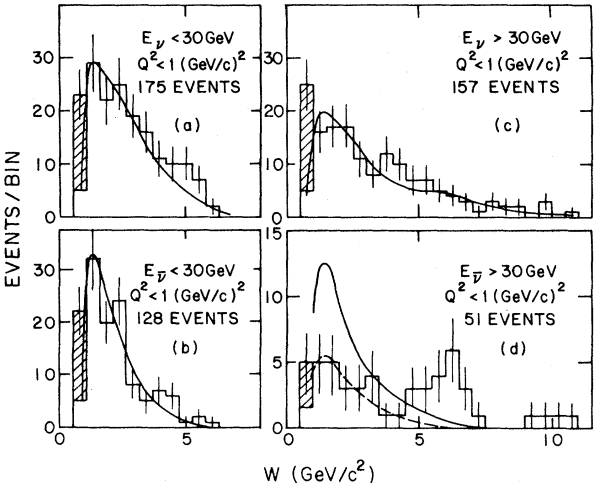

FIG. 3. Invariant-mass distributions for inelastic neutrino- and antineutrino-induced events with $Q^2 < 1$ in two regions of E_ν and $E_{\bar{\nu}}$. The solid and dashed curves have the same significance as in Fig. 2.

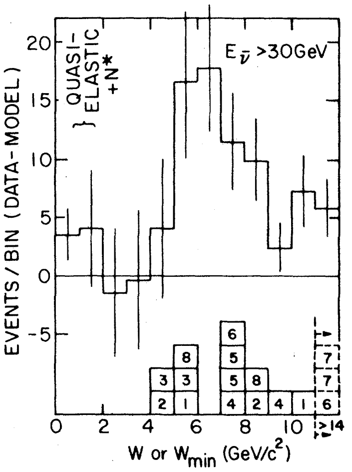

FIG. 4. Excess of antineutrino-induced events with $E_{\bar{\nu}} > 30$ GeV as a function of invariant hadron mass, and values of W_{min} for eight events with two final-state muons. Two values of W_{min} are entered for each dimuon event.

rise to an approximately flat y distribution, there would be little change in the W distributions for neutrinos. In these instances, among others, the effect would be difficult to observe directly in the W distributions for neutrinos, and may account for a fortuitous agreement, within experimental error, of the observed and modeled distributions. Accordingly, that agreement should not be taken as conclusive evidence for the absence of low-mass new phenomena in neutrino-nucleon scattering.

There are also shown in Fig. 4 values of $W_{\min}$ for the subset of eight events with two final-state muons described in more detail in an earlier publication.[9] $W_{\min}$ is the minimum invariant mass of the system recoiling against either of the outgoing muons. Since we do not know which is primary muon and which is secondary, we have plotted two values for each dimuon event in Fig. 4. The fact that all values of $W_{\min}$ are greater than 4 GeV/c^2 is significant because only 0.6 of all single-muon events with $E_{\bar{\nu}}$ or $E_\nu > 30$ GeV have invariant mass greater than 4 GeV/c^2.

A possible common explanation of both the muon-pair events and the invariant-mass distributions for single-muon events involves the production of one or more new hadrons with mean life much less than 10^{-10} sec and mass in the region 2–4 GeV/c^2. (The lower limit on the mass region is inferred from the transverse-momentum distribution of muons in dimuon events.[9]) These decay weakly into hadrons and also, through either a leptonic or a semileptonic mode or both, into a muon and a neutrino or antineutrino. From the data in Fig. 4 the ratio of the decay into muon and neutrino to the decay into hadrons is roughly a few percent. Such particles would necessarily carry a new quantum number,[10] not conserved in weak interactions, to permit them to decay weakly and thus make possible their detection in this experiment.

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