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Measurements of Neutrino and Antineutrino Cross Sections at High Energies

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The dependence of the neutrino total cross section σ_ν on neutrino energy has been measured up to 160 GeV. The data are consistent with a linear dependence with slope $(0.58 \pm 0.25)\times 10^{-38}$ cm^2/GeV. The ratio of the antineutrino to the neutrino total cross section $\sigma_{\bar{\nu}}/\sigma_\nu$ has been found to be approximately constant up to 70 GeV at a value which is consistent with the numerical value of $\frac{1}{3}$ expected for the scattering of neutrinos and antineutrinos by relativistic pointlike spin-$\frac{1}{2}$ fermions.

We discuss here the observation of events of the types $\nu_\mu(\bar{\nu}_\mu)+N\to\mu^-(\mu^+)+$ hadrons, from which are obtained (i) a measurement of the dependence of the neutrino total cross section σ_ν on neutrino energy E_ν up to 160 GeV, and (ii) measurements of the ratio of antineutrino to neutrino total cross sections $\sigma_{\bar{\nu}}/\sigma_\nu$ up to 70 GeV.

Details of the experimental arrangement were described previously.[1] Briefly, useful neutrino interactions occurred either in a liquid-scintillator ionization calorimeter, or in the first section of an iron magnetic spectrometer located immediately downstream of the calorimeter. For all events the vector momentum and sign of charge of the secondary muon were measured in the magnetic spectrometer. In the temporary absence of other information we assume that negative and positive muons are produced in neutrino and antineutrino interactions, respectively. For interactions occuring in the ionization calorimeter the energy of the hadron cascade, E_h, was also measured. The detector was activated by either of two coincidence modes: (i) a muon traversing the entire length of the magnetic spectrometer, or (ii) a muon traversing at least the first section of the spectrometer in conjunction with various preset minimum depositions of energy in the calorimeter. Data were taken with primary proton energies E_p of 300 and 400 GeV.

We plot in Fig. 1 the observed distributions in momentum p_μ and angle θ_μ for muons of negative and positive charge, combining data at proton energies of 300 and 400 GeV. Shown also in Fig. 1 are Monte Carlo distributions calculated by assuming scale invariance and form factors obtained from electroproduction[2] and low-energy neutrino data.[3] The calculation includes the geometric and magnetic-focusing properties (detection efficiency) of the detector, and an incident neutrino or antineutrino spectrum.[4] The good agreement between the observed and predicted distributions in p_μ and θ_μ indicates the approximate validity of the combined input to the Monte Carlo calculation.

In Figs. 2(a) and 2(b) are shown the observed and Monte Carlo calculated distributions in hadron energy E_h for interactions that occur in the ionization calorimeter. The agreement on aver-

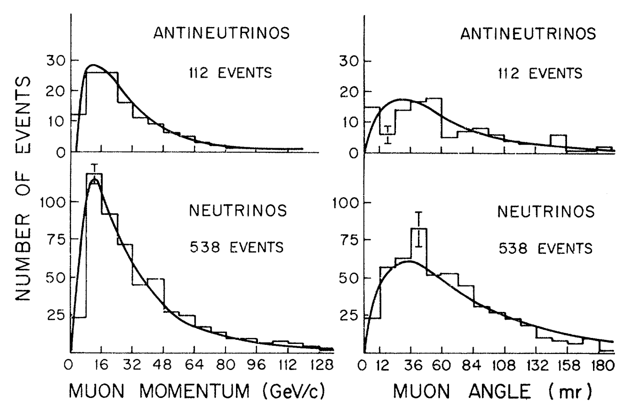

FIG. 1. Observed distributions (histograms) in muon momentum p_μ and angle θ_μ for antineutrinos and neutrinos. Shown as continuous curves are the Monte Carlo calculated distributions normalized in area to the data.

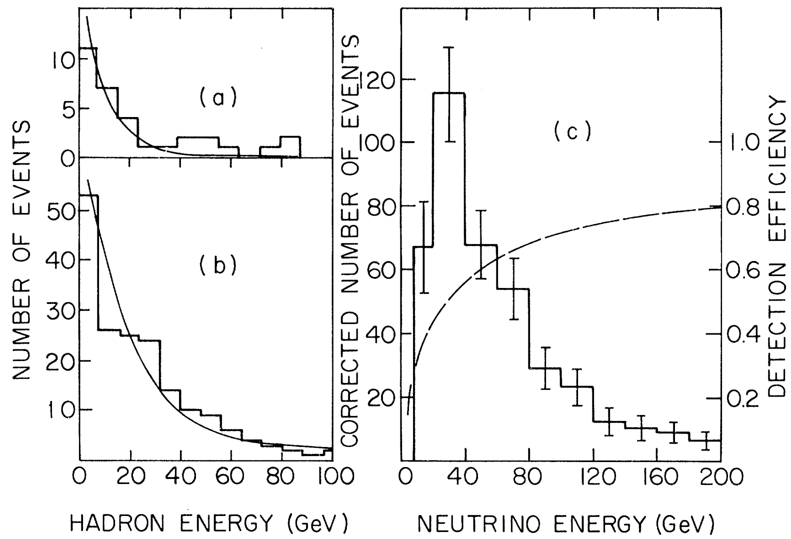

FIG. 2. Observed (histograms) and Monte Carlo calculated distributions in hadron energy E_h for (a) antineutrinos and (b) neutrinos. (c) Event distribution in E_ν after correction for detection efficiency which is shown as the dashed line. Before correction there are 223 neutrino events.

age between the data and the Monte Carlo calculations validates this method[5] of measuring E_h. Moreover, Figs. 1 and 2(b) taken together indicate the average accuracy with which the energy of an incident neutrino, E_ν, may be determined from the sum E_h+E_μ for a given event. We estimate the mean accuracy in E_ν to be better than $\pm 20\%$.

Shown in Fig. 2(c) is the observed event distribution in E_ν, after correction for detection efficiency only. This directly yields values of the integrals

$$H_\nu \equiv \int_{E_i}^{E_j} \sigma_\nu(E_\nu) N(E_\nu)\, dE_\nu$$

in the intervals $E_j - E_i$, where $N(E_\nu)$ is the neutrino flux. Note that no assumption about the energy dependence of the cross section or of scale invariance or of any constituent model is involved in extracting the values of H_ν from the event distribution. Taking $N(E_\nu)$ from particle production data and a semiempirical model,[4] we obtain the dependence of σ_ν on E_ν which is shown in Fig. 3(a). The data are consistent with a linear dependence on E_ν up to 160 GeV.

The absolute values on the cross-section axis in Fig. 3(a) were obtained by using events of the types $\nu_\mu + n \to \mu^- + p$ (quasielastic) and $\nu_\mu + N \to \mu^- + N^*$ (resonance production). The shapes of the observed distributions in q^2 and W^2, at low q^2 and W^2, which are shown in Figs. 3(b) and 3(c), indicate that events of these types are directly recognized in the detector. (W^2 is the square of the invariant hadron mass.) Among the events that comprise Fig. 3(a) there is a corrected total of 13 events with $12 \leq E_\nu \leq 45$ GeV, $q^2 \leq 1$ GeV^2,

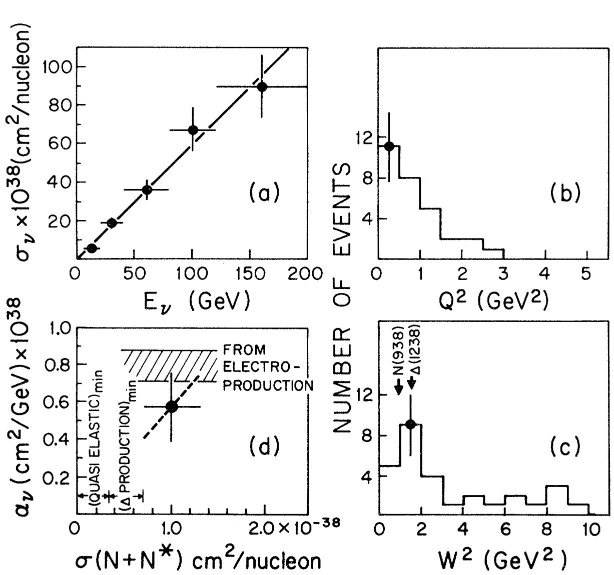

FIG. 3. (a) Neutrino total cross section σ_ν versus E_ν. (b) Distribution in q^2 for events with $W^2 \leq 4$ GeV^2. (c) Observed distribution in the square of the invariant hadron mass, W^2, for events with $q^2 \leq 1$ GeV^2. (d) Plot showing the dependence of the measured slope $\alpha_\nu = \sigma_\nu / E_\nu$ on the sum of the partial cross sections σ(quasielastic) + σ(resonance production). The dashed line indicates the uncertainty in α_ν due to $\sigma(N+N^*)$.

and $W^2 \leq 3.5/\mathrm{GeV}^2$. The corrected total number of events in the same interval in E_ν is 204, and the measured mean energy of these events is 27.2 GeV. The sum of the cross sections for quasielastic scattering and resonance production can be estimated from low-energy neutrino data and phenomenological calculation[6,7] as $(1.0 \pm 0.3) \times 10^{-38}$ cm^2/nucleon, assumed to be independent[8] of E_ν above a few GeV. The absolute value of the slope α_ν of the straight line in Fig. 3(a) is then determined to be $(0.58 \pm 0.25) \times 10^{-38}$ cm^2/GeV. To emphasize the dependence of this result on the low-energy cross-section data, we show in Fig. 3(d) the relation of α_ν to the sum of the partial cross sections. For comparison, the value of α_ν calculated by assuming conservation of vector current and chiral symmetry, and using electroproduction data,[2] is also shown in Fig. 3(d). A value of $\alpha_\nu = (0.74 \pm 0.02) \times 10^{-38}$ cm^2/GeV has previously been measured[3] for neutrino energies between 1 and 10 GeV.

Now, taking $\sigma_\nu = \alpha_\nu E_\nu$ and $\sigma_{\bar{\nu}} = \alpha_{\bar{\nu}} E_{\bar{\nu}}$, and using the corrected event distributions as functions of incident energy, we find values of the ratio $\alpha_{\bar{\nu}} I_{\bar{\nu}} / \alpha_\nu I_\nu$ in specified energy intervals, where, e.g.,

$$I_{\bar{\nu}} = \int_{E_i}^{E_j} N_{\bar{\nu}}(E_{\bar{\nu}}) E_{\bar{\nu}}\, dE_{\bar{\nu}}.$$

To determine the ratio $I_\nu / I_{\bar{\nu}}$ we again use particle production data and a semiempirical model.[4] Fig. 4(a) shows the ratio $\alpha_{\bar{\nu}}/\alpha_\nu$ as a function of E_ν up to 70 GeV. Above that energy neutrinos and antineutrinos from charged-kaon decay contribute importantly to the interaction rates and, since the uncertainties in secondary kaon production are large, we do not yet attempt to specify $\alpha_{\bar{\nu}}/\alpha_\nu$ beyond 70 GeV.

If we combine all of the observed neutrino and antineutrino data by taking the same distribution in E_ν for events in the iron as for events in the liquid scintillator, we obtain $\alpha_{\bar{\nu}}/\alpha_\nu = 0.34 \pm 0.03$ at a mean neutrino energy of 27 GeV, where the error is purely statistical. To emphasize the dependence of $\alpha_{\bar{\nu}}/\alpha_\nu$ on $I_\nu/I_{\bar{\nu}}$, we show the relationship betwwen these ratios and their uncertainties in Fig. 4(b). Clearly, improved measurements of $I_\nu/I_{\bar{\nu}}$ are necessary for high precision determinations of $\alpha_{\bar{\nu}}/\alpha_\nu$.

In summary, within experimental error, we reach the following conclusions from the data presented here.

(i) The neutrino total cross section is rising approximately linearly with neutrino energy up to 160 GeV. A linear rise was initially predicted by Bjorken[9] as a consequence of scale invariance.

(ii) In view of conclusion (iii) below, the value $(0.58 \pm 0.25) \times 10^{-38}$ cm^2/GeV of the slope α_ν of the linear rise is consistent with the conserved vector current hypothesis relating weak and electromagnetic transition amplitudes.

(iii) The ratio of the antineutrino to the neutrino total cross section $\alpha_{\bar{\nu}}/\alpha_\nu$ is approximately $\frac{1}{3}$ and constant up to an energy of 70 GeV. A similar value has been reported for the energy region below 10 GeV by workers at CERN.[3] This is of particular interest at the higher energies because of the deep inelasticity of most of the interactions. These properties are consistent with a parton model[10] of nucleon constituents in which the partons are relativistic and predominantly spin-$\frac{1}{2}$ fermions, not antifermions.

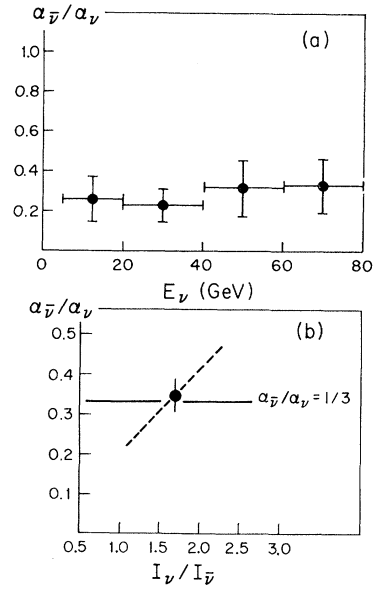

FIG. 4. (a) Plot of $\alpha_{\bar{\nu}}/\alpha_\nu$ versus E_ν. The data points are obtained from a total of 34 antineutrino events and 131 neutrino events. Values of $I_\nu/I_{\bar{\nu}}$ of 1.1, 1.5, 1.9, and 2.2 were used at $E_\nu = 10$, 30, 50, and 70 GeV, respectively. (b) Dependence of $\alpha_{\bar{\nu}}/\alpha_\nu$ on $I_\nu/I_{\bar{\nu}}$. The errors shown on $\alpha_{\bar{\nu}}/\alpha_\nu$ in (a) and (b) are statistical only. The estimated uncertainty due to $I_\nu/I_{\bar{\nu}}$ is indicated by the dashed line in (b).

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