

Probing the weak force with neutrinos

The study of high-energy neutrino scattering is providing answers—some of them surprising—to some basic questions concerning the weak interactions.

David B. Cline, Alfred K. Mann and Carlo Rubbia

Interest in neutrino physics has surged up recently, partly because the "little neutral ones" are being groomed for the job (for which they alone are qualified) of probing the interiors of stars. Among elementary particles the neutrino is unique. This is because—as far as we know—it alone interacts with other particles only through the Fermi, or weak, interaction. In this article we will discuss how recent experiments, with new accelerators and detectors, such as the ones at CERN and Fermi Lab, have shed new light on some of the fundamental questions regarding the weak interactions. We will review the recent discoveries of neutral weak currents that conserve strangeness, parity violation and point-like neutrino collisions, as well as some of the implications of these experiments to particle theory.

Many of us know the history of the neutrino, one of the great triumphs of scientific prediction. The charged products of nuclear beta decay were found to carry less energy than the rest energy of the parent nucleus, and Wolfgang Pauli proposed the existence of a new particle with no charge or rest mass. This particle, the neutrino, carried the missing energy and made possible linear and angular momentum conservation in the decay.¹ Shortly after-

ward, Enrico Fermi published his theory of nuclear beta decay,² which has since been generalized to an extensive theory of weak interactions. Until the crucial experimental detection of reactor-generated electron antineutrinos by Fred Reines and Clyde Cowan³ in 1953, all information about neutrinos was obtained indirectly from nuclear decay processes.

The next step was taken about 1960, soon after the alternating-gradient synchrotron at the Brookhaven National Laboratory and the Proton Synchrotron at CERN were constructed. It was recognized by Bruno Pontecorvo in the Soviet Union⁴ and independently by Melvin Schwartz,⁵ that the high yield of pions and kaons that are produced in the collisions of very energetic protons with matter could be used to make neutrino and antineutrino beams as by-products. Although the first neutrino beam at BNL was feeble by present standards, it was adequate to show that the neutrinos (of which there are two types) produced through the decays of pions and kaons were mainly those of the muon variety (ν_μ rather than ν_e , the electron neutrino), a result that had been suspected for some time because of the experimentally observed absence of certain decay modes of the muon.⁶ The suggestion that electrons and muons differ by some quantum number, the conservation of which forbids some rare decays of muons, was independently made by Julian Schwinger and Kazuhiko Nishijima in 1957. This important discovery opened a new chapter in weak-interaction studies in which accel-

erator-produced high-intensity neutrino and antineutrino beams were used in conjunction with massive targets that also served as detectors.

The neutrino is an ideal probe of weak interactions—and, somewhat surprisingly, also of strong interactions. Furthermore, if weak and electromagnetic interactions have a common origin, as the spontaneously broken gauge theories suggest,⁷ the neutrino may also be able to probe the electromagnetic force at very small distances. The study of neutrino scattering by nucleons at the highest energies, where the cross section and the variety of final states are very large, has therefore become of considerable importance at the new proton synchrotron now in operation at Fermi Lab and at a similar accelerator soon to be completed at CERN.

Targets that detect

The first detector of neutrino interactions³ was a relatively modest 10 tons of liquid scintillator and water-loaded CdCl_2 . It was used to observe the collisions of few-MeV antineutrinos from beta decay with matter that resulted in the inverse beta decay reaction,

$$\bar{\nu}_e + p \rightarrow n + e^+$$

The earliest detectors of neutrino scattering at BNL were massive, thick aluminum-plate optical spark chambers.⁶ They were well suited to separating muons from electrons in the final states of the neutrino-nucleon interaction. Later, heavy-liquid (propane and heavy freon) bubble chambers were used extensively at CERN as neutrino detec-

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And another particle?

Evidence accumulated in an experiment at Fermi Lab indicates that the high-energy interactions of neutrinos and antineutrinos with nucleons may be significantly different even after taking into account their opposite helicities. This appears to be a violation of a basic principle of semileptonic weak processes known as charge-symmetry invariance (A. Benvenuti *et al.*, Phys. Rev. Lett. **33**, 984, 1974). It has been conjectured by Alvaro De Rujula and Sheldon Glashow of Harvard University that the production of new particles, in particular those with a new quantum number called "charm," could cause such a violation. Some theories that attempt to unify the weak and electromagnetic interactions have suggested the existence of these particles.

Now, the same experimenters (Carlo Rubbia and Lawrence Sulak from Harvard; William Ford, Ta-Yung Ling, Alfred Mann and Frederick Messing from Pennsylvania; Alberto Benvenuti, David Cline, Richard Imley, Robert Orr, Donald Reeder and

Peter Wanderer from Wisconsin, and Ray Stefanski from Fermi Lab) have recently reported (Phys. Rev. Lett. **34**, 419, 1975) the substantial production, by neutrinos and antineutrinos, of events with two final-state muons (dimuon events). This follows their initial report of two such events at the London Conference on High Energy Physics last summer. It appears that these events require the production of one or more new particles, which could be either leptons or hadrons. Certain characteristics of these dimuon events lead to estimates of mass greater than $2 \text{ GeV}/c^2$ and less than about $5 \text{ GeV}/c^2$ and of lifetime less than 10^{-10} sec.

If the new particle is a hadron, one of the muons in the dimuon events would be a product of the decay of that hadron (along with a neutrino or antineutrino, and possibly other hadrons), while the other muon would be part of the initial neutrino interaction that gave rise to the new particle. These particles may be indirectly re-

These particles may be indirectly relat-

ed to the narrow-width, neutral vector mesons recently discovered at Brookhaven and SLAC (see "Search and Discovery," page 17, this issue). In contrast to the vector mesons, however, the proposed new particle or particles would carry a new quantum number, and decay through the weak interaction. This is because neutrinos and antineutrinos can produce a single particle with any value of a quantum number that is not conserved in weak interactions.

One can not, however, rule out other possible origins of the dimuon events. For example, the production of a heavy neutral lepton with a partial decay mode into two muons and a neutrino is an alternative, though less probable, explanation of the observed dimuon events. The Harvard-Pennsylvania-Wisconsin-Fermi Lab group plans to repeat the experiment at Fermi Lab during the next few months, and expects to find additional answers to some of the vexing questions relating to these events.

tors. These are useful detectors of neutrino interactions, being relatively massive and allowing the vertex of the scattering event to be observed and reconstructed.

Neutrinos produced by 30-GeV proton accelerators often give rise to several hadrons in the final states of their collisions. The advent of higher-energy neutrino beams and the increased theoretical interest in inclusive lepton scattering, which concentrates on only a few gross properties of the final-state hadrons, such as total hadron energy, have suggested the use of a separated-function neutrino detector. This detector consists of two primary parts: an ionization calorimeter (target-detector) and a magnetic muon spectrometer. The ionization calorimeter serves as the target for the neutrino and also measures the total hadronic energy E_H released in the collision. The muon spectrometer measures the sign of the muon's charge and its momentum p_μ . The laboratory energy of the incident neutrino E_ν is then determined as the sum $E_\nu = E_H + E_\mu$, where to a good approximation, $E_\mu = p_\mu c$.

Target masses of about 100 metric tons have been used; an ionization calorimeter now being constructed at Fermi Lab will have a mass of about 300 metric tons, and will be capable of measuring the direction of the hadronic energy flow and of separating the hadronic component from the electromagnetic component in the final-state shower. Among other things, this should allow the detection of high-energy electron-neutrino interactions as well as muon-

neutrino interactions. At high neutrino energies, the shield employed to protect the target-detector from incident charged particles (particularly the muons from the decays of the initial pions and kaons) is necessarily long, which in turn means neutrino beams of relatively large cross-sectional area. The transverse dimensions of the detectors, especially those of the muon spectrometer, are correspondingly large if the full kinematic range of the outgoing muons is to be studied. For example, one detector at Fermi Lab uses four toroidal iron magnets, each 12 feet in diameter and 4 feet thick; a future detector will add toroids 24 feet in diameter.

The large-solid-angle detectors used in conjunction with the higher neutrino energies and intensities available at Fermi Lab, and the large total neutrino cross section, yield a substantial number of neutrino-induced events per hour of accelerator time. This encourages the performance of relatively brief experiments directed at specific points of enquiry. Occasionally they use neutrino beams of different properties, emphasizing various aspects of the detectors; this in itself is a new trend with significant implications for the future of neutrino physics.

Charged weak currents

A striking property of the weak-coupling constant $G = 1.01 \times 10^{-5}/m_p^2$ observed in low-energy weak interactions is that it has the dimensions of $1/\text{energy}^2$. By dimensional arguments, then, if no fundamental masses enter, the neutrino-nucleon total cross section σ^ν

should depend on the center-of-mass energy E as⁸

$$\sigma^\nu \propto G^2 E^2 \quad (1)$$

For collisions of a massless particle with a nucleon at high energy,

$$E^2 \approx 2M_p E_\nu c^2$$

and thus the cross section should rise linearly with neutrino laboratory energy,

$$\sigma^\nu \propto G^2 E_\nu \quad (2)$$

Recent data from CERN in the few-GeV region, and from Fermi Lab in the region up to 200 GeV, are shown in figure 1, which shows that the cross section indeed depends linearly on neutrino energy within present experimental error.^{9,10,11} It is interesting also to include in figure 1 the cross-section value obtained by Reines and Cowan³ for the process

$$\bar{\nu}_e + p \rightarrow n + e^+$$

and data¹¹ from Argonne at $E_\nu \leq 1$ GeV, where quasielastic scattering and nucleon-resonance production dominate. It might have been expected that above a few GeV some characteristic mass would influence the energy scale, but the observed rise of the total cross section from 0.1 GeV to 10 GeV in figure 1 indicates the absence of any such mass.

The neutrino cross section, in rising linearly with energy, fulfills a prediction of scale invariance that was proposed by James Bjorken¹² and suggested by the MIT-SLAC experiments on electron-nucleon scattering.¹³ For the total

cross section to continue to rise linearly with energy, however, the assumption that the weak interaction is local is required as well as scale invariance.¹⁴ A deviation from linearity would arise, for example, if an intermediate vector boson should serve as the propagator of the weak interaction. Gauge theories that attempt to unify weak and electromagnetic interactions, with coupling constants G and α , respectively, suggest a fundamental mass Λ given by^{7,15}

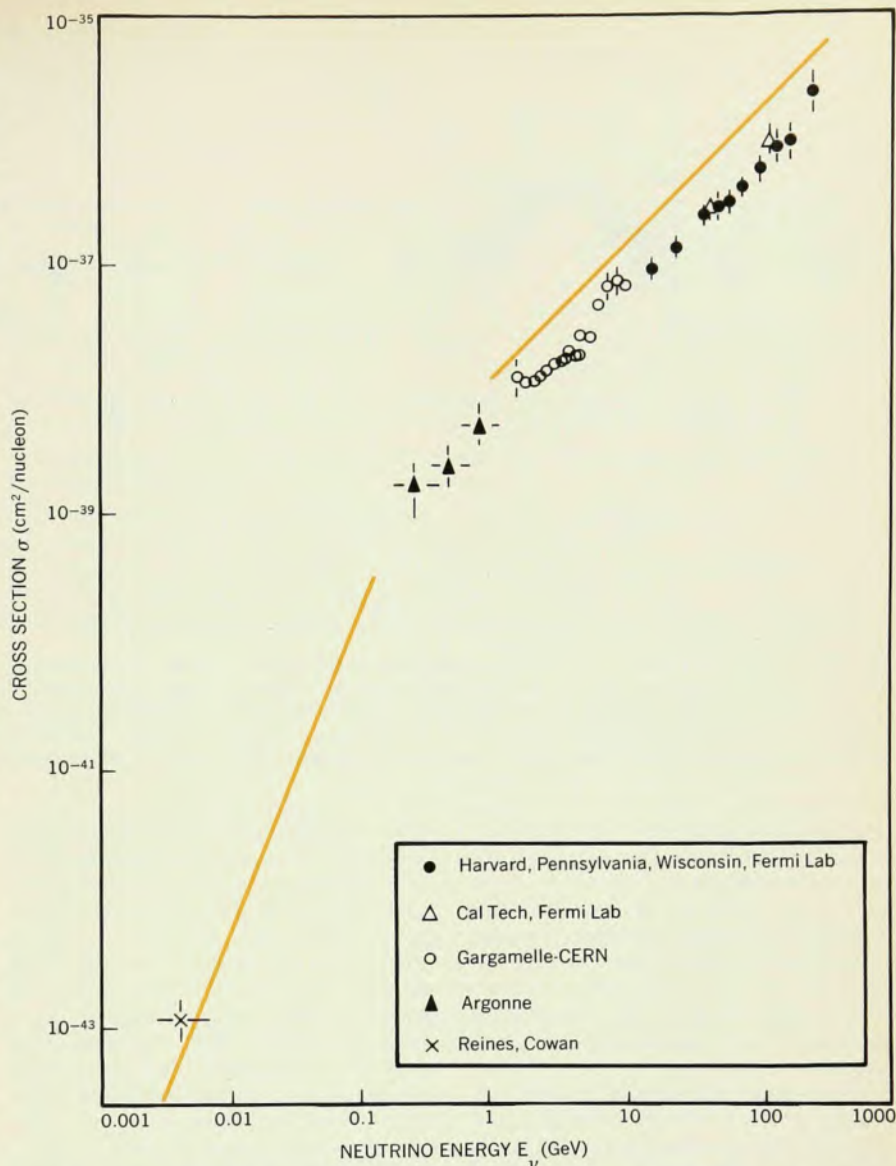
$$G \Lambda^2 \approx \alpha \text{ or } \Lambda \approx 37 \text{ GeV} \quad (3)$$

Other estimates, following from attempts to calculate higher-order corrections to weak interactions, lead to much lower values of Λ , as indicated in the Table on page 26. An upper limit on Λ is presumably obtained directly from the weak-coupling constant itself, since $G^{-1/2} \approx 300 \text{ GeV}$ is the approximate CM energy at which unitarity is violated in the elastic scattering of neutrinos by electrons,⁸ an interaction involving leptons only. The data of figure 1 rule out a propagator of mass less than about 10 GeV. In the next few years, the improved quality of the data should permit the search to be extended to energies as high as 30 GeV.

Maximal parity violation

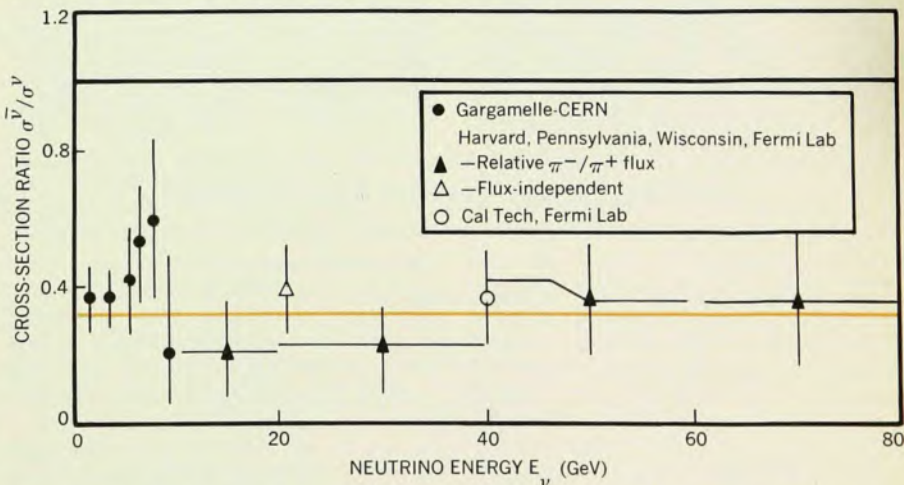
Another striking feature of weak interactions at low energy is the fact that parity violation is almost at its theoretical maximum for the usual model. Before high-energy neutrino interactions were studied, there was no certainty that parity violation would continue to be observed in weak interactions at high energies. Recently, the cross section for muon-antineutrino scattering has been measured in the few-GeV region at CERN and at much higher energies at Fermi Lab.^{9,10,11} This was done with an isoscalar target, which is one that (like He^4 or C^{12}) has equal numbers of neutrons and protons, and hence zero isospin. These results are compared with the measured cross section for neutrino scattering in the energy range of 1 to 80 GeV in figure 2. From the lowest energy to the highest, the cross-section ratio plotted there stays quite close to 1/3, the lowest possible value and one that is expected for the scattering of neutrinos and antineutrinos from a relativistic point-like fermion, as figure 3 illustrates.

This result is surprising in light of the fact that high-energy neutrino and antineutrino collisions are probing the nucleon over very short time intervals (by the uncertainty principle) and virtual fermion-antifermion pairs of very large effective mass are expected to be abundant (as are e^+e^- pairs in quantum electrodynamics). Thus *neutrino-hadron collisions at very high energy continue to show nearly maximal parity violation, which is consistent with the*



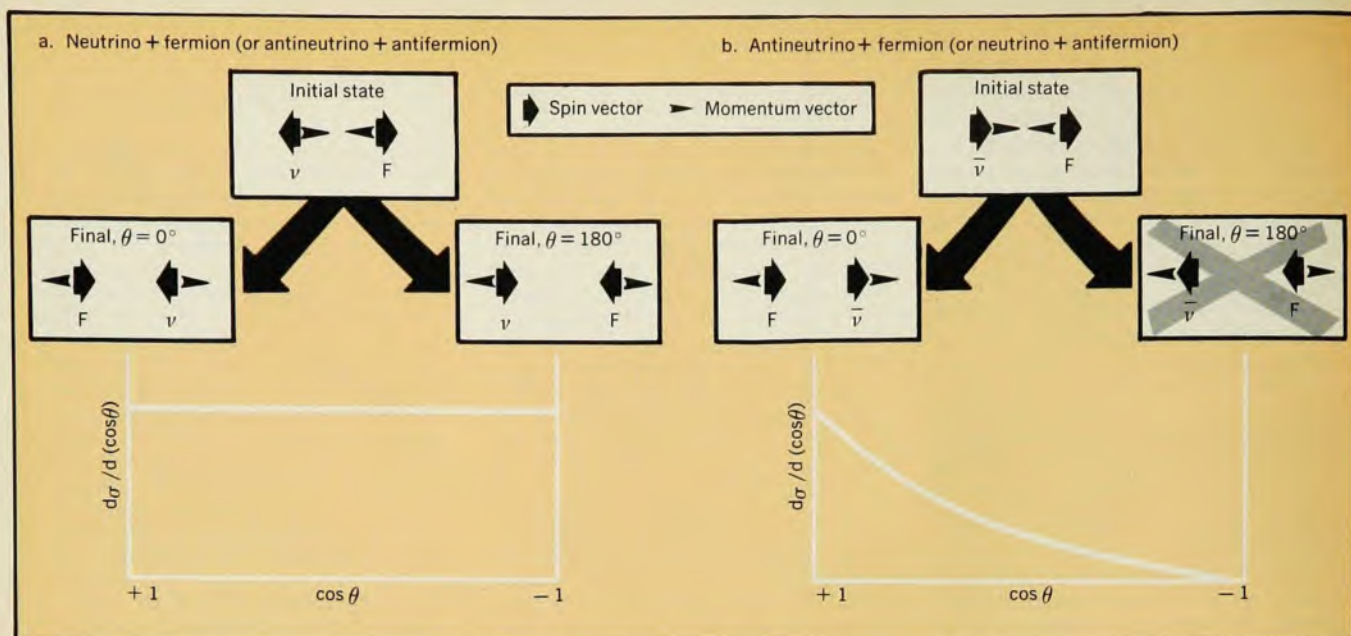
The neutrino cross sections that have been measured, at energies ranging from 8 MeV to 200 GeV, are compiled here. The point with lowest energy is for interactions of electron antineutrinos; all the others are for those of muon neutrinos. The lower line is the low-energy theoretical prediction and the upper line is that for point protons.

Figure 1



The measured ratio of total cross section for antineutrinos to that for neutrinos. The black line at 1.0 represents the value expected when parity is conserved, such as when scattering from an equal mixture of fermions and antifermions. The colored line at 1/3 is that for maximal parity violation, expected with scattering from relativistic point-like fermions, as indicated in figure 3. It represents the ratio of $\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$ to $\nu_e + e \rightarrow \nu_e + e$ interactions.

Figure 2



How the ratio of 1/3 arises. The three upper diagrams in (a) represent two extreme cases of neutrino-fermion collisions in the center-of-mass frame. As total angular momentum is zero, scattering angles of 0 or 180 deg are possible, as shown in the diagrams. The curve below generalizes this to all angles: The angular distribution is

flat. For antineutrino-fermion collisions (b), a final state with $\theta = 180$ deg is impossible, because angular momentum would then not be conserved; the angular-distribution curve generalizes this. The ratio of the area under the right-hand-curve to that under the left is 1/3: This is the total cross-section ratio of figure 2.

Figure 3

conjecture that nucleons are composed of low-effective-mass fermions and almost no antifermions. A model of the nucleon as made up of "partons" was invented by Richard Feynman. In such constituent models of the nucleon, the value of the effective mass is determined approximately by the slope of the linear rise of the neutrino total cross section.

These examples constitute two surprising results that have been obtained with high-energy neutrinos in the study of the weak interaction. They are, of course, surprises only in the sense that essentially the same behavior of the weak interaction is observed at high as at low energy. There is no evidence of space-time structure in the weak interaction up to a laboratory energy of about 200 GeV. These examples also raise the question: Why are these high-energy, high-momentum-transfer inter-

actions of nucleons, which are thought to be soft, complicated objects, so similar to the predicted weak interactions of primitive, point-like fermions, as suggested by figure 3?

It is amusing to note that, in 1964, the data from the CERN neutrino experiments, then being carried out in a small propane bubble chamber, frequently showed very wide-angle muons arising from neutrino-nucleon collisions, which suggested that the collisions were more point-like than predicted by any theory at that time. Now, ten years later and with laboratory energy about 100 times higher, we begin to recognize the deeper simplicity implied by these early results.

High-energy neutrino studies bear on a number of other questions in weak interactions, some of which are treated in question-and-answer form on page 27. The remainder of this article will be

concerned with three of those questions and the answers to them as far as they are available at present. These are the conserved-vector-current hypothesis, charge-symmetry invariance in deep-inelastic neutrino scattering and the existence of neutral weak currents. Although we will not discuss further the other subjects in the box on page 27, it is a tribute to the power of the neutrino as a probe that many of them will be addressed by neutrino experiments in the next few years.

A conservation, an invariance

Two theoretical predictions, conservation of vector current and charge-symmetry invariance, have been verified. Low-energy weak interactions involving one lepton are described in lowest order by the product of a leptonic current J^L and a hadronic current J^H . The latter is in turn composed of a vector part V^H and an axial-vector part A^H . For weak-interaction processes in which the strangeness of the initial and final states is the same, V^H and A^H currents in low-energy processes have some remarkably simple properties. One is the conservation of the vector current V^H , which was first postulated to explain the near equality of the vector-coupling constants observed in nuclear β decay and μ decay.¹⁶ This situation is similar to that in electromagnetic processes, where the matrix elements of

$$e^+ + e^- \rightarrow e^+ + e^-$$

$$\text{and } e^- + p \rightarrow e^- + p$$

are identical at low momentum transfer. In spite of the presence of strong interactions, the matrix element is de-

Some mass scales that have been suggested

Mass	Theoretical conjecture
~2600 GeV	Unitarity violation for $\nu + \bar{\nu} \rightarrow W + W$
~300 GeV	Unitarity violation for $\nu_\mu + e \rightarrow \nu_e + \mu$
~30 — 70 GeV	Gauge theory unification of weak ^b and electromagnetic interactions for leptons
~4 — 15 GeV	Perturbation calculation of the $K_L - K_S$ mass difference ^c and suppression of higher order weak interactions in $K_L \rightarrow \mu + \mu$
$\lesssim 10$ GeV	New particles needed to incorporate ^d hadrons into gauge theories and remove $\Delta S = 1$ neutral currents.

^a See reference 32.

^b See references 3, 9, 10, 11 and 12.

^c See reference 33.

^d See reference 31.

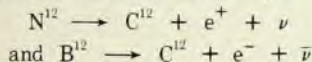
terminated by the charge of the targets, and electric charge is conserved.

A second important property of semileptonic interactions at low energy is charge-symmetry invariance, which is established by experiments on the beta decay of mirror nuclei (pairs of nuclei for which proton and neutron number are interchanged) and on the strangeness-conserving beta decay of the sigma particle^{16,17}

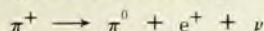


Simply stated, this principle says that the weak hadronic current, when rotated through 180 deg in isotopic-spin space, becomes its hermitian adjoint. In a model in which the exchange of (possibly fictitious) charged intermediate vector bosons accounts for the weak interaction, charge-symmetry invariance requires the weak amplitude to be independent of the charge of the exchanged boson. However, the amplitude may still depend on the helicity of the exchanged boson.

The combination of the conserved vector current and charge-symmetry invariance results in the isotriplet current hypothesis, which directly links the isovector weak amplitude with the isovector electromagnetic amplitude. The classic low-energy tests of this hypothesis are measurements of the "weak-magnetism" terms in the decays



and of the extremely small value of the branching ratio for the decay²⁰



The conservation of the vector current and charge-symmetry invariance reflect the conservation of isospin (the quantum number that distinguishes the proton from the neutron) by the strong interaction, and the isotriplet hypothesis follows from the conservation of hypercharge (related to baryon number and strangeness) by the electromagnetic interaction.^{16,18}

Extension to high energies

The isotriplet hypothesis and charge-symmetry invariance are concepts derived from the study of semileptonic processes involving a limited number of hadrons at very low energy and momentum transfer. In contrast, at high energy and high momentum transfer, neutrino interactions proceed largely through processes that involve many hadrons in the final state; it is therefore by no means clear that these simple properties should continue to describe the semileptonic weak interaction.

The failure of these hypotheses for neutrino energies above some threshold energy would be a signal of an important change in either the weak interaction or the nature of the hadronic final states. For example, new hadronic de-

Some fundamental questions in high-energy weak interactions, circa 1960-1974.

• Question

Is ν_μ identical with ν_e ?

Do first-order neutral currents exist? Are they V-A interactions also?

What is the lepton conservation rule for ν_e and ν_μ ?

Does charge-symmetry invariance hold?

Is the vector current conserved at high energies?

Is the weak interaction pointlike at high energies?

Is there a *universal* weak interaction that includes neutral and charged currents?

What is the origin of CP violation?

Is there a universality between ν_μ and ν_e neutral currents?

Do the weak interactions (charged currents and neutral currents) proceed by the exchange of massive vector bosons?

Why are higher-order weak interactions so "weak"?

Are there heavier leptons in nature?

• Answer

No, they are different, as observed in the first accelerator neutrino experiment at Brookhaven National Laboratory.

No, for low-energy reactions that change strangeness. **Yes**, for neutrino collisions (strangeness non-changing). The V-A property is *not tested yet*.

Additive quantum numbers experimentally preferred in electron-neutrino interactions.

Probably yes, but it may appear to fail if new particles are made at high energy.

Probably yes, but it has only been weakly tested.

Yes, as far as now tested, up to a mass of about 10 GeV.

Not known, but it is conjectured that a new quantum number ("charm") can restore universality between strangeness-changing and strangeness-preserving neutral current processes.

Not known, but it is conjectured that a new superweak interaction may exist.

Not tested yet—can be tested when enriched electron-neutrino beams become available.

Not tested so far. The mass of the charged boson is greater than 10 GeV. No meaningful limit has been set on the neutral boson.

Not known, but partially explained if gauge theories are correct and if low-mass "charmed" particles exist.

Not well tested, but for some varieties mass limits of 2-7 GeV have been set.

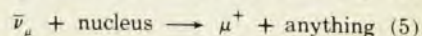
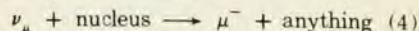
grees of freedom excited at high energy could cause a failure of both charge-symmetry invariance and the isotriplet hypothesis. The production of single strange particles also provides an example of how these two hypotheses can be broken. Because neither isospin nor hypercharge is conserved in such processes, there is no simple reason why the vector current should be conserved, or that charge-symmetry invariance should hold. However, the expected level of symmetry breaking in this case is only about 5%, due to the known small cross section for strange-particle production. Thus the test of the isotriplet hypothesis and of charge-symmetry invariance with high-energy neutrinos can be thought of as a *search for new particles* that have different isospin or hypercharge properties from nucleons.

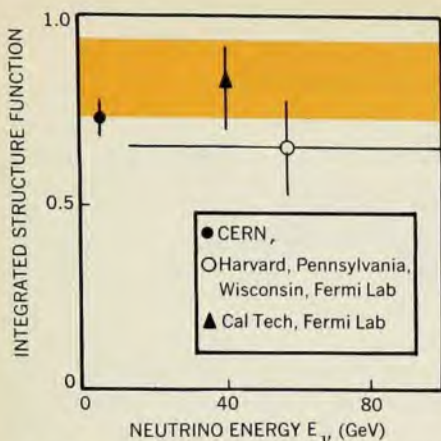
A preliminary test of the isotriplet hypothesis can be made by comparing the integral of the structure function $F_2(x)$ of the nucleon that is obtained in electron-nucleon scattering with that in neutrino-nucleon scattering on isoscalar targets.⁹ The electron-nucleon integral is taken directly from the MIT-

SLAC experiment.¹³ To estimate the isovector part of the electromagnetic structure function, the electromagnetic current has been assumed to obey the SU(3) predictions for the relative coupling of the $I = 1$ and $I = 0$ components. This decomposition fits the experimental data on photoproduction.

We obtain the integrated vector part of the structure function for neutrino scattering from the slope of the energy dependence of the total cross section (figure 1), and a comparison of neutrino and antineutrino scattering (figures 2 and 3). The latter comparison permits the contribution of the structure function associated with Λ^H to be taken into account. Figure 4 shows a comparison of the two structure functions and a test of the isotriplet hypothesis.^{9,10} Within experimental error there is good agreement between the two integrated structure functions.

The test of charge-symmetry invariance relies on the comparison of the details of the reactions





A test of the hypothesis of conserved vector current. The experimental points are integrated vector structure functions and the colored band is the estimated isovector electro-production structure function. Figure 4

and on the use of a hadronic target of zero isotopic spin, $I = 0$.

For these systems the prediction of charge-symmetry invariance is particularly simple: The three individual nucleon structure functions for neutrino and antineutrino processes with $I = 0$ are equal,

$$F_2^{\nu} = F_2^{\bar{\nu}}, \quad i=1,2,3 \quad (6)$$

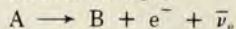
Equation 6 is a consequence of the fact that the amplitudes for these processes are hermitian adjoints of each other and therefore charge-symmetry invariant. Under the assumption of charge-symmetry invariance these reactions can only differ if the helicities of the outgoing and incoming leptons are different (as, for example, in the model of collisions with relativistic fermions, figure 3).

The first test of the invariance of charge symmetry, in which the validity of scale invariance is assumed, has been carried out by comparing the ratio r of two structure functions for processes 4 and 5. If charge-symmetry invariance holds, the ratios r^{ν} and $r^{\bar{\nu}}$ should be the same for neutrino- and antineutrino-initiated reactions. Comparison of these ratios has been made at various values of the dimensionless scaling variable $x = Q^2/2mE_H$, where Q^2 is the square of the four-momentum transfer and E_H is the hadronic energy measured in the neutrino collision. Figure 5 shows the results of the test.¹⁹ We see that for the larger values of x (>0.1), the data are compatible with charge-symmetry invariance, while in the lower x region a discrepancy exists. This discrepancy at small x , if it survives future experimental tests, suggests that a surprise may be in store for us: The violation of charge-symmetry invariance may be due to the production of particles with new quantum numbers in high-energy neutrino and antineutrino collisions. Recent devel-

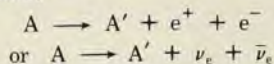
opments in the search for these new particles are discussed in the box on page 24.

Observation of weak neutral currents

Historically, weak interactions were detected²⁴ through charge-current semileptonic nuclear decays,

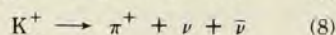
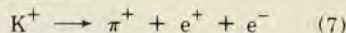


The observation of weak decays with two charge-conjugate leptons in the final state,

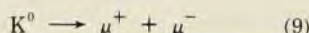


would have provided evidence for neutral weak currents. The experimental search for neutral currents with two charged leptons in the final state is effectively impossible in nuclear decays because the probability for a neutral-current transition is many orders of magnitude smaller than that for a corresponding electromagnetic transition. The search for weak nuclear decays with two neutrinos is equally difficult. Thus the question of weak neutral currents was never put to an experimental test in the study of nuclear decays.

The earliest definitive search for weak neutral currents focussed on the decays of strange particles. The semileptonic weak decays of K mesons by neutral currents,²⁰



and



are forbidden for electromagnetic interactions and, therefore, provide excellent tests for weak neutral currents that change strangeness. Over the past twelve years, intensive experimental searches for these and similar decays have been carried out. No example of a weak neutral-current decay of first order has been found—and the experimental limits are by now extremely low.

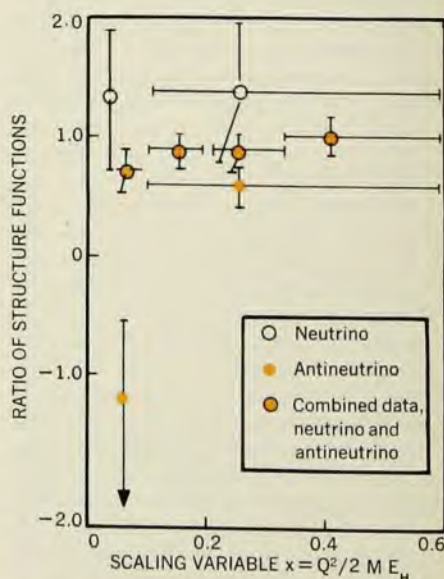
Neutrino interactions provide another way to search for weak neutral currents without competition from electromagnetic interactions. In neutrino interactions it is possible to search for both strangeness-changing and strangeness-conserving weak neutral currents by searching for neutrino-induced events without charged leptons in the final state. In the neutrino experiments carried out in the 1960's, several experimental searches for weak neutral current interactions were reported, and limits were placed²² on various neutral-current processes that conserve strangeness. Along with the null results obtained from strange-particle decays, these results from neutrino scattering were taken as further indication that first-order semileptonic neutral weak currents are absent in nature. There were even instances of rejections by

journals of theoretical papers that predicted large neutral-current rates because it was "well known that first-order neutral currents did not exist."

Is it a neutrino or a neutron?

The advent of a new generation of heavy-liquid bubblechambers, neutrino beams of higher energy and higher intensity and massive target-calorimeter detectors reopened the search for weak neutral currents.^{23,24} Caution must be exercised in distinguishing neutrino events from the background, as there are two mechanisms that can stimulate neutrino-induced events without final-state charged leptons. The most important of these comes from neutral hadrons that are incident on the experimental detector. Proton accelerators produce copious quantities of neutrons and neutral kaons. The interactions of these particles in neutrino detectors are easy to distinguish from high-energy charged-current neutrino events because of the presence of a charged lepton in the final state. However, neutral-current events, those without the charged lepton in the final state, are very difficult to separate from neutron and K^0 interactions. Furthermore, neutrons and K^0 mesons are also produced in quantity by the neutrino beam itself in the shielding used to protect the neutrino detector from muons. A second source of background tracks for neutral-current events is provided by charged-current events in which the outgoing charged lepton either escapes from the detector before identification or is misidentified as a hadron.

Since muon neutrinos are the principal source of high-energy neutrino interactions, events with undetected



The ratio of structure functions for reactions initiated by neutrinos and antineutrinos versus scaling variable as a test of charge-symmetry invariance. Figure 5

muons are the largest source of background from charged-current interactions. Thus, to search for neutral currents, good muon identification is required, and interactions due to incident neutral hadrons must be either suppressed or subtracted out.

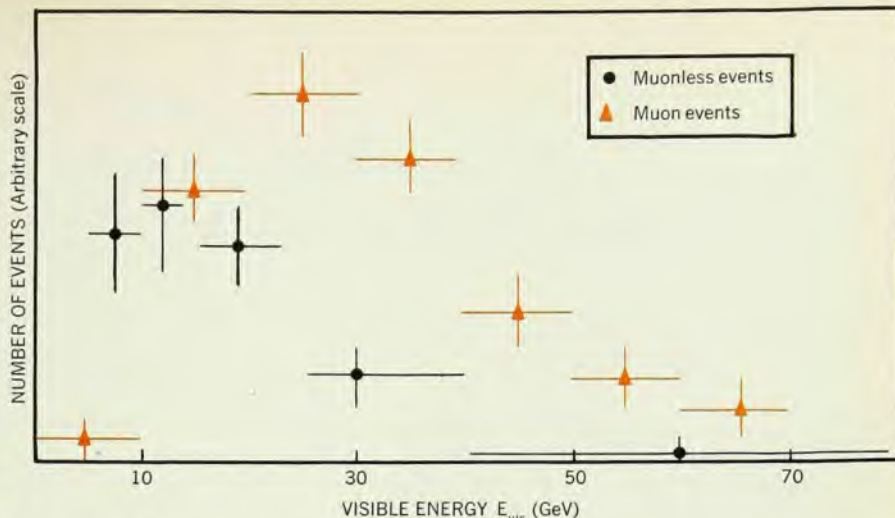
One of the observations of events without muons in the final state has been carried out at CERN with the large bubble chamber, Gargamelle. In this experiment a semiempirical estimate of the neutron flux and subtraction of the background eliminated neutron and K^0 interactions.²³ The charged-current background is eliminated by selecting events in which all particles are identified as hadrons through scattering or decay.²³

The electronic experiments with large-mass target-detectors cope with the background in another way. It is experimentally observed that the neutral hadron interactions are eliminated by choosing a target volume that requires the hadrons to traverse many protective interaction lengths of material, in which the neutrons and K^0 mesons are attenuated.²⁴ Identification and rejection of charged-current events is carried out by placing a hadron filter near the detector through which the muons pass.^{24,25}

The primary uncertainty is related to the semiempirical estimate of the efficiency for muon detection. In the experiments at Fermi Lab that were carried out by physicists from Harvard, Pennsylvania and Wisconsin as well as from Fermi Lab, the detection efficiency was obtained directly from the muon angular distribution that was measured out to 500 mrad, and a muonless event signal was observed after correcting for detection efficiency.^{24,25} The existence of this signal does not depend on the muon's angular distribution outside of the measured angular region, as can be shown by the following simple argument:

The kinematics of high-energy neutrino collisions require that, in events in which muons were produced at angles greater than 500 mrad, the hadronic energy carried away in the collision be nearly equal to the incident neutrino energy; this is a direct consequence of the conservation of transverse momentum in the collision. Thus, if the observed muonless signal were actually due to misidentified charged-current events at wide angles, the spectrum of visible energy for the muonless events should approximate the incident neutrino spectrum.

The comparison shown in figure 6 of the spectra for the muonless events with that for the charged-current events indicates a substantial difference. The muonless events also have the uniform spatial distribution in the detector that is expected from neutrino interactions.



Comparison of the visible energy spectra for events with and without muons led to the conclusion that muonless events induced by neutrinos have been observed. If the muonless events were actually misidentified muon events, the two distributions should be the same, but the average visible energy is 15 GeV for muonless and 35 GeV for muon events. Figure 6

This evidence led to the conclusion that neutrino-induced muonless events had been observed.^{24,25}

Visible energy

The primary conclusion from the CERN-Gargamelle and the Harvard-Pennsylvania-Wisconsin-Fermi Lab experiments is that, unlike earlier neutrino-scattering experiments, they show a significant number of neutrino- and antineutrino-induced events without muons in the final state. It is important to note that this positive signal is obtained in both experiments even though the experimental methods are so different. It is also of interest that the average energy of the events observed in the two experiments is quite different; in the CERN experiment it was about 3 GeV, as compared to about 40 GeV in the HPWF experiment. Other evidence is now available to support these observations.^{26,27}

The energy spectra in figure 6 also indicate that, on the average, approximately one-half of the incident neutrino energy does not appear as "visible" energy in the final state; energy, that is, that was carried by particles detected in the bubble or spark chambers. Since the events are born in the middle of a massive detector, the escaping energy must be carried by a long lived, weakly interacting particle. The simplest hypothesis concerning the nature of these events is that they are examples of the neutral-current processes

$$\nu_\mu + \text{nucleon} \rightarrow \nu_\mu + \text{anything} \quad (10)$$

$$\bar{\nu}_\mu + \text{nucleon} \rightarrow \bar{\nu}_\mu + \text{anything} \quad (11)$$

which have been long sought after. However, we cannot rule out the possibility that they are manifestations of other, as yet unrecognized, processes. For now we shall call them weak neu-

tral-current events, although keeping in mind that this interesting possibility is not conclusively proven.

The rate for the observed weak neutral currents in neutrino and antineutrino collisions is not greatly different from the corresponding charged-current processes, quite in contrast to the very low limits on strangeness-changing neutral currents obtained for K decays. A convenient comparison is provided by the ratio of the neutral-current rate to the charged-current rates, R^ν for neutrino and $R^{\bar{\nu}}$ for antineutrino processes. Figure 7 shows the published values of these ratios.^{23,25} While the actual experimental values need to be further refined by better data, this figure shows the latitude of physical possibilities for this new phenomenon. For example, if neutral currents conserved parity, a ratio of 3 would be expected between R^ν and $R^{\bar{\nu}}$, which would in turn reflect the maximal parity violation in the charged-current interaction discussed previously.

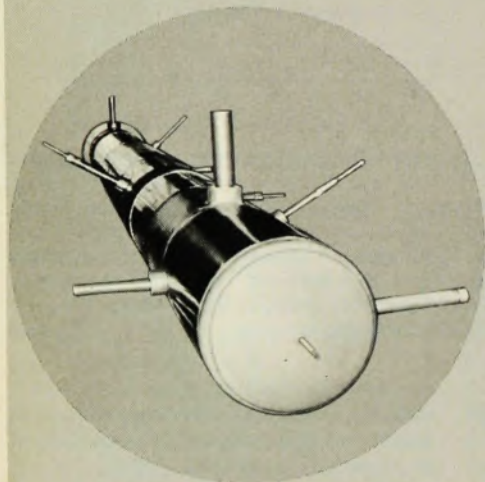
Alternatively, the Weinberg-Salam gauge model⁷ of the weak and electromagnetic interactions, in which weak neutral currents as well as weak charged currents make a natural appearance, suggests a different relation between R^ν and $R^{\bar{\nu}}$. It may be that weak neutral currents are a part of the weak interaction that has been missing for 77 years, which forms a direct connection between the weak and electromagnetic interactions. Whatever their origin, the neutral weak currents promise to be a rich field of study in high-energy neutrino collisions.

Future directions

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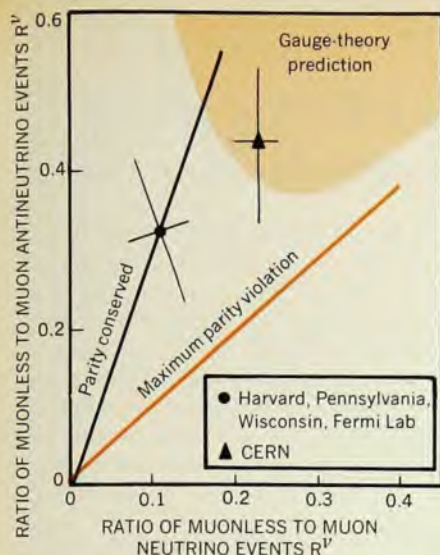
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Measured values of the ratio of neutral-current to charged-current rates for neutrino and antineutrino processes are here compared with the predictions of three different theoretical models. Figure 7

with the neutrino hypothesis and the Fermi theory in the 1930's, continued with the universality of the weak interaction for hadrons and leptons in the 1940's, parity violation and V-A coupling in the 1950's, CP violation and SU(3) universality in the 1960's, and so far include strangeness-conserving neutral weak currents and point-like high-energy neutrino collisions in the 1970's.

The preliminary results of the study of high-energy charged-current reactions with neutrino and antineutrino beams have already provided some interesting surprises. These results indicate that the deep inelastic scattering cross sections from protons and neutrons are similar to the scattering expected from elementary or primitive fermions with approximately one-half of the nucleon mass. Tests of charge-symmetry invariance and the isotriplet hypothesis at high energies show qualitative agreement with low-energy data, with the possible exception of a deviation at higher energies and at low x values.

Models that have been invented to explain these and other results on deep inelastic scattering of charged leptons, such as the quark-parton model, suffer from the difficulty that the constituent quarks have never been dislodged from the nucleon and experimentally observed. Also the results of recent experiments on high-energy e^+e^- annihilation to hadrons appear to disagree with these models.²⁸

Thus we are left with experimental results that suggest a profound simplicity in the interaction of leptons with hadrons at high energy, but without a complete picture of the origin of that simplicity. Perhaps there is a deeper reason that underlies these results, hav-

ing to do with a common origin of the weak, electromagnetic and strong forces, as suggested in attempts to formulate unified field theories. Steven Weinberg has written an excellent introduction to this subject.²⁹

New low-mass hadrons?

The charged-current experiments have also set a new lower limit of about 10 GeV on the effective mass of any charged particle that might serve as the propagator of the weak interaction. This can be interpreted as a lower limit on the mass of the charged intermediate vector boson. Thus, charged-current weak interactions appear to be point-like at least down to distances of the order of 10^{-15} cm.

The existence of muonless events—presumably neutral-current weak interactions—is now established in high-energy neutrino collisions. The next step is to delineate the matrix element of this interaction. Let us hope that the study will take less than the twenty years needed to go from the first Fermi theory to the V-A theory!

Finally, we may note that the ratio of the strangeness-changing to the strangeness-conserving neutral current amplitude is less than about 10^{-4} , if we compare results from K decay and neutrino interactions. For charged currents this ratio is approximately $1/6$, as observed from low-energy decay processes. Thus universality of the weak interaction, insofar as it incorporates all known weak processes, is no longer apparent. The origin of this non-universality is unknown, but it is conjectured that universality would be restored if a new class of massive hadrons exist and carry a new quantum number called "charm."^{30,31} The possible violation of charge-symmetry invariance discussed earlier might be related to the production of these new hadrons. Direct searches for such particles through their leptonic or semileptonic decays are in progress. The recently discovered narrow vector bosons (called ψ on the West coast and J in the East) have also been conjectured to be bound states of charm-anticharm. The remarkable possibility exists that a new family of hadrons lies roughly 1 GeV from the well established hadron states that were discovered more than twenty years ago.

* * *

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