First Observation and Cross-Section Measurement of $\nu_e + e^- \rightarrow \nu_e + e^-$

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We report the first observation and cross-section measurement of $\nu_e + e^- \rightarrow \nu_e + e^-$. Using neutrinos of energy less than 53 MeV, we observed 63 ± 17 events consistent with $\nu + e^- \rightarrow \nu + e^-$, of which 51 ± 17 events are assigned to $\nu_e + e^- \rightarrow \nu_e + e^-$. The resulting cross section, $\{[8.9 \pm 3.2(\text{statistical}) \pm 1.5(\text{systematic})] \times 10^{-45}\ \text{cm}^2/\text{MeV}\} E_\nu$, agrees with standard electroweak theory, rules out constructive interference between weak charged-current and neutral-current interactions, and begins to indicate the existence of interference between these two interactions.

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Despite its fundamental importance, the $\nu_e + e^- \rightarrow \nu_e + e^-$ elastic-scattering reaction has not been previously observed although the related reactions, $\bar{\nu}_e e^-$,[1] $\nu_\mu e^-$, and $\bar{\nu}_\mu e^-$ [2–10] have been observed. The $\nu_e e^-$ and $\bar{\nu}_e e^-$ reactions proceed via both the weak charged-current (CC) and the weak neutral-current (NC) interactions. These reactions provide a unique opportunity to test for the existence, sign, and magnitude of the interference between these two interactions.[11] The purely leptonic weak processes provide critical tests of the electroweak theory of Weinberg,[12] Salam,[13] and Glashow[14] (WSG), which predicts a destructive interference for $\nu_e e^-$ scattering. Also, the observation of interference demonstrates that the outgoing neutrino from the NC interaction is identical to the outgoing neutrino from the standard CC interaction.

The Clinton P. Anderson Meson Physics Facility of the Los Alamos National Laboratory (LAMPF) beam stop is an intense source of ν_e's that are produced predominately from stopped π^+ decays leading to ν_μ's, followed by stopped μ^+ decays leading to $\bar{\nu}_\mu$'s and ν_e's. Since the strength of the CC interaction is appreciably larger than that of the CC interaction in the WSG electroweak theory, $\nu_e e^-$ scattering is expected to dominate $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ scattering. In this energy range, νe^- scattering, where ν without the subscript refers to any of these neutrinos, is confined within a forward kinematic cone of 10° for a 20-MeV detection threshold. Backgrounds to elastic scattering from both cosmic rays and the accelerator are expected to be essentially isotropic.

The large duty factor of LAMPF (6%–12%) plus the small anticipated cross section for νe^- scattering results in an extremely high cosmic-ray background relative to the νe^- scattering signal, even with the high current (up to 1 mA) of the LAMPF beam. To reduce this cosmic-ray background to an acceptable level, three active and passive shields were used in conjunction with a fine-grained sandwich detector.[15] The outermost cosmic-ray shield consists of steel and concrete with an effective thickness of more than 900 g/cm^2. This attenuates hadron fluxes by two orders of magnitude. Within this shield is an active anticoincidence system of 594 multiwire proportional chambers (MWPC's) that covers all inner surfaces of the massive outer shield. These counters, typically 520 cm long × 20 cm wide × 5 cm thick, are arranged into four layers in the walls and roof and a single layer on the floor. The MWPC's provide a prompt veto to reduce on-line triggers by a factor of 10^4 and tag cosmic-ray muons for off-line analysis. Lastly, another inert shield averaging more than 100 g/cm^2 of both steel and lead is used inside the MWPC's to attenuate residual cosmic-ray gammas by a factor of 30.

The central detector has a total mass of 15 metric tons arranged in a sandwich structure with forty layers. It is located at a mean distance of 900 cm from the beam stop and shielded by 630 cm of steel to reduce beam-associated neutrons by more than fifteen orders of magnitude. The detector is designed to identify electrons by measurement of dE/dx and to determine electron track direction in spite of large multiple scattering at these low energies.

Each 305-cm-high × 305-cm-wide layer consists of a plane of plastic scintillator and a flash-chamber module (FCM). A scintillation plane is constructed from four 2.6-cm-thick pieces, each 76 cm wide and viewed by a 12.7-cm-diam photomultiplier tube, for a total of 160 counters. The scintillation counters average 14 photoelectrons per megaelectronvolt of energy loss. An FCM, 1.4 g/cm^2 thick, contains ten panels of polypropylene flash tubes with alternating coordinate readout, five horizontal and five vertical. Each panel contains 520 flash tubes of dimensions $0.5\times0.6\times305$ cm^3, for a total of 5200 flash tubes per FCM and 208 000 flash tubes in the entire detector. The average overall operating efficiency of the FCM system is 60% per panel[16] and the angular resolution for short electron tracks including multiple scattering is $\pm7°$ per projection. The scintillation system and its associated electronics, and the FCM system, have been described previously.[17] Operational details of the full detector system will be provided elsewhere.[18]

The trigger is defined by a coincidence between at least three adjacent scintillation planes with energy deposition between 1 and 16 MeV per plane, and no veto from the MWPC system. This cosmic-ray veto is defined by MWPC hits in any two of the four planes of a wall or roof resulting in a veto rate of 7 kHz; a veto of 20 μs is required to reduce triggers by electrons from stopped-muon decays. This gives a 15% system dead time, and results in a residual cosmic-ray trigger rate of less than 0.1 per second.

For each trigger, we recorded information from every scintillation counter, FCM, and MWPC. Also, we recorded information from every scintillator and MWPC for 32 μs before the trigger to further suppress backgrounds from stopped-muon decays.

Data were taken during the LAMPF beam spill, and also during a beam-off gate between spills for a cosmic-ray background subtraction. Typically, the beam macrostructure was 0.75 ms beam on, followed by 7.58 ms beam off. The beam-off gate was set four times longer than the beam-on gate so that statistical uncertainties of the cosmic-ray subtraction are small. At the beam stop, the time-averaged proton current, after traversing other targets upstream, was about 600 μA (3.8×10^{15} protons per second), with proton kinetic energy 765 MeV. For the data sample reported here, the beam-associated trigger rate was 14 per mA h. The total exposure was 1.95 A h of protons (4.4×10^{22}) on the beam stop resulting in a sample of 98 558 beam-on and 317 740 beam-off events. The beam-off to beam-on live-time ratio was 4.43. Triggers from cosmic-ray stopped-muon decays and traversing muons were also recorded every 10 min for calibration and efficiency monitoring.

At the first stage of data reduction, the events that showed substantial activity in either the MWPC's or the scintillation counters during the pretrigger period near the trigger were removed. Also, events that had no reconstructable track in either view of the FCM were rejected. Then a fiducial volume cut was applied to remove events within 5 cm of the sides, top, and bottom edges of the detector, or in the first or last scintillation planes. In addition, high-energy events (greater than 60 MeV in the scintillators, corresponding to greater than 100 MeV in the detector), and long events (greater than seven scintillation layers) were removed. These very loose requirements reduced the event sample by about a factor of 10.

At the next stage, additional constraints were used to select candidates for νe^- scattering. A number of cuts were implemented to ensure that energy deposition in individual scintillators was consistent with single electrons and that the final data sample was insensitive to energy thresholds. Requirements were also applied to keep events with only a single contiguous group of scintillators. Using the MWPC information, we also imposed tighter constraints than were applied on line. From the FCM, we added a track-length requirement of at least three modules in either projection. In all, these constraints reduced the data sample by about another factor of 10, leaving 1 127 beam-on and 3 864 beam-off events. The net number of beam-associated events is 255 ± 36.

With the above requirements imposed, we show in Fig. 1(a) the histogram of the number of events versus $\cos\theta_e$ for the beam-on and the beam-off events, normalized by live time. Here θ_e is the reconstructed angle of the upstream part of the recoil electron track relative to the direction of the neutrino. Figure 1(b) shows the histogram of the number of events versus $\cos\theta_e$ for the difference between these beam-on and beam-off samples. In the forward cone, defined as $\cos\theta_e \geqslant 0.96$, there is a well-defined peak containing 74.1 ± 13.5 beam-associated events. The $\cos\theta_e \geqslant 0.96$ ($\theta_e \leqslant 16°$) cut is selected with consideration of νe^- kinematics, multiple scattering, and detector angular resolution. Beam-associated background in the forward cone is 11.4 ± 7.0 events.[19] This is determined from the number of beam-associated events in the $\cos\theta_e$ interval between 0.84 and 0.96, assuming a flat distribution and accounting for the fraction of νe^- events outside the forward cone as determined by a Monte Carlo simulation. The extent of the chosen $\cos\theta_e$ interval for this background subtraction comes from doubling the forward cone angle, but varying the extent of the $\cos\theta_e$ interval in this subtraction does not significantly change this background.[19] This background is due to ν_e charged-current interactions with nuclei, and possibly from capture of energetic neutrons scattered around the 630-cm-thick beam-stop iron shield. We attribute the remaining 62.7 ± 16.7 beam-associated events[19] in the forward cone to νe^-

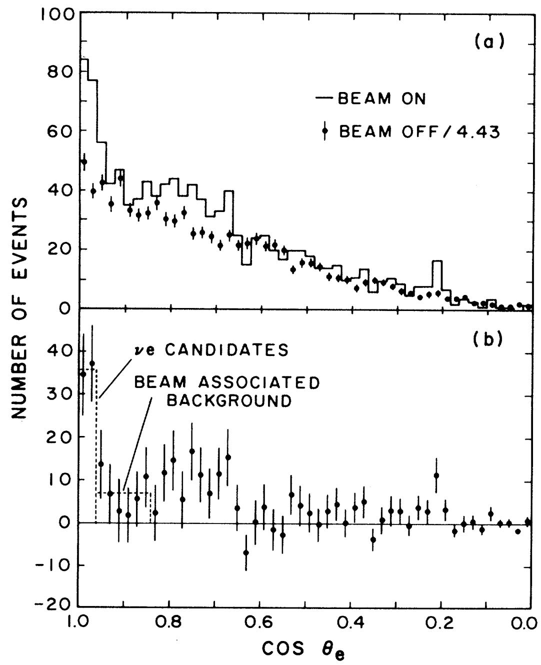

FIG. 1. Histograms of the number of events vs $\cos\theta_2$ in bins of 0.02. (a) For beam-on and normalized beam-off events after the analysis described in the text. Here θ_e is the recoil-electron angle relative to the direction of the incident neutrino. (b) For the beam-associated events above. Events in the forward peak are candidates for νe^- scattering. Beam-associated backgrounds in the forward peak are estimated from outside the forward peak. The uncertainty in this estimate includes effects of the beam-associated events in the $\cos\theta_e$ region near 0.75 (see Ref. 19); the source of these events, which might be from energetic neutron capture, is not yet understood. Only statistical errors are shown.

scattering. The uncertainty in this estimate includes effects of the beam-associated events in the $\cos\theta_e$ region near 0.75. The source of these events, which might be from energetic neutron capture, is not yet understood.

To determine the cross section, the efficiency for detecting νe^- scattering was evaluated by use of a Monte Carlo simulation and the monitoring events. The simulation, based on the electron-gamma-shower (EGS3) code,[20] took into acount light attenuation in scintillators and photoelectron statistics. The simulated events were then passed through the data-reduction and -analysis programs. Cosmic-ray stopped-muon decay events were also simulated and compared with observation to provide confidence in the Monte Carlo analysis. Several aspects of the detector performance that were not simulated were considered separately by use of the monitoring events. These included the performance of the MWPC system and details of the flash-chamber performance. Altogether we assigned a 9% systematic error to the absolute detection efficiency.

An experiment to determine the number of stopped π^+ decays followed by stopped μ^+ decays per incident 720-MeV proton in an instrumented copper beam stop was carried out at the Lawrence Berkeley Laboratory 184-in. cyclotron in order to determine the neutrino source intensity.[21] For the present neutrino experiment, a 20-cm water degrader was inserted in front of the beam stop to increase, by 35%, the number of such decays per proton. A computer simulation of the effect of different proton energy and beam-stop composition was also carried out. The result is 0.089 ± 0.011 stopped π^+ decays per incident 765-MeV proton. Combining in quadrature the 9% uncertainty in absolute detection efficiency and the 12% uncertainty in neutrino source intensity results in an overall systematic error of 15%.

The 62.7 ± 16.7 events attributed to $\nu + e^- \to \nu + e^-$ contain $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$, as well as $\nu_e e^-$ candidates. Using the Monte Carlo simulation, we determined the number of expected $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ events from the measured cross sections[9,10] and assigned 4.3 ± 1.1 and 7.3 ± 1.7 events, respectively, to these two reactions. The remaining 51.1 ± 16.7 events are thus assigned to $\nu_e + e^- \to \nu_e + e^-$. This number is consistent with the WSG electroweak theory with

$$\sin^2\theta_W = 0.21 \pm 0.12(\text{statistical}) \pm 0.05(\text{systematic}),$$

and a $\nu_e e^-$ cross section of

$$\sigma(\nu_e e^-) = \{[8.9 \pm 3.2(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-45}\ \text{cm}^2/\text{MeV}\} E_\nu.$$

The WSG electroweak theory predicts destructive interference between the NC and the CC interactions for values of $\sin^2\theta_W$ less than 0.5. Using the measured value for the NC interaction from $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ scattering[9,10] and the standard CC interaction, we show in Table I the observed number of $\nu_e e^-$ events and the calculated numbers assuming "destructive interference" (WSG), "no interference," and "constructive interference." Our result rules out "constructive interference" by almost four standard deviations and begins to rule out the "no interference" case.

The 62.7 ± 16.7 events have also been compared directly with expectations of the WSG electroweak theory for $\nu + e^- \to \nu^+ e^-$ with $\sin^2\theta_W$ as the single adjustable parameter. The result, consistent with the above conclusions, gives

$$\sin^2\theta_W = 0.21^{+0.09}_{+0.13}(\text{stat})^{+0.05}_{-0.07}(\text{syst}).$$

Efforts to decrease both the statistical and the systematic errors of this experiment are continuing. Shielding improvements have been made that will further decrease neutron-induced backgrounds from the beam stop and from cosmic rays. With this anticipated

TABLE I. The number of observed $\nu_e + e^- \rightarrow \nu_e + e^-$ events is compared with several possibilities involving interference between NC and CC interactions. The indicated uncertainties for this measurement are statistical only, and for the expected number of events, systematic only.

This measurement:	51.1 ± 16.7
Expected number of events:	
(i) Destructive interference (WSG)	53.1 ± 8.0
(ii) No interference	108.0 ± 16.0
(iii) Constructive interference	163.0 ± 25.0

lower background, we are taking additional data to increase the event sample by more than a factor of 2. The neutrino source intensity from the LAMPF beam stop will be better determined in a separate calibration experiment and the Monte Carlo simulation will be carried out in more detail. With this additional effort, we expect to improve the cross-section measurement significantly and to determine the existence and magnitude of the interference between NC and CC interactions.

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[16]With five horizontal and five vertical panels per FCM and a track length requirement of three FCM's in analysis, the 60% efficiency per panel leads to an overall tracking efficiency, including effects from noise, of $(85 \pm 3)\%$ for νe^- candidates.

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[19]The beam-associated background of 11.4 ± 7.0 events would result in a νe^- signal of 62.7 ± 15.2 events. We have also estimated the beam-associated background in the forward cone by using different $\cos\theta_e$ intervals and alternative efficiency distributions, e.g., uniform $\cos\theta_e$ efficiency distribution or the observed cosmic-ray distribution [Fig. 1(a)]. These estimates give between 7.0 ± 9.8 and 16.4 ± 4.4 background events in the forward cone. This leads to a range of 57.7 ± 14.2 to 67.1 ± 16.7 events to be compared with 62.7 ± 15.2 events attributed to νe^- scattering. To be conservative, we use 11.4 ± 9.8 events for the beam-associated background in the forward cone and assign 62.7 ± 16.7 beam-associated events in the forward cone to νe^- scattering.

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