Neutrino Tridents and W-Z Interference

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We present a measurement of neutrino tridents, muon pairs induced by neutrino scattering in the Coulomb field of a target nucleus, in the Columbia-Chicago-Fermilab-Rochester neutrino experiment at the Fermilab Tevatron. The observed number of tridents after geometric and kinematic corrections, 37.0 ± 12.4, supports the standard-model prediction of 45.3 ± 2.3 events. This is the first demonstration of the W-Z destructive interference from neutrino tridents, and rules out, at 99% C.L., the $V-A$ prediction without the interference.

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A neutrino trident is the scattering of a neutrino in the Coulomb field of a target nucleus (N),

$$\nu_\mu(\bar{\nu}_\mu)+N\rightarrow \nu_\mu(\bar{\nu}_\mu)+\mu^+\mu^-+N\,. \qquad (1)$$

Momentum is balanced by the coherent exchange of a virtual photon between one of the emergent muons and the nucleus. The signature is a dimuon event with zero visible hadron energy. In the standard model this reaction can proceed via two channels (Fig. 1): charged (W) and neutral (Z) boson exchange. A measurement of this process determines the interference between W and Z channels providing a crucial test of the gauge structure of the standard model. We report the first measurement of this destructive interference in ν tridents.

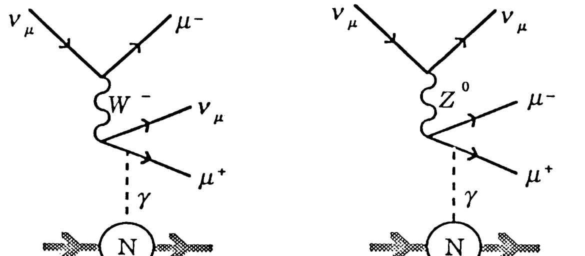

FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

Many theoretical papers discuss ν-trident production.[1-9] As an almost purely leptonic process, its cross section can be precisely calculated using the known electromagnetic form factor of the iron nucleus. Most early theoretical papers deal only with the $V-A$ theory (W exchange alone) ignoring the W-Z interference. However, in the standard model the neutral-current channel (Z^0 mode) interferes *destructively* with the charged-current channel ($W^\pm$). Assuming the standard vector and axial-vector couplings, the interference causes an approximate 40% suppression of the trident production as compared to the prediction using W exchange only.[8,9]

In spite of the elegance of the theoretical prediction, the experimental study of ν tridents has been difficult for two reasons: (a) the extremely small cross section, about 2.3×10^{-5} (4.6×10^{-5}) of the inclusive ν_μ-N ($\bar{\nu}_\mu$-N) charged-current process at $\langle E_\nu\rangle = 160$ GeV; and (b) the relatively low energy of the secondary muon associated with the trident. These difficulties are overcome in a high-statistics high-energy neutrino experiment. Early experimental investigations of ν tridents (for a review, see Ref. 10) failed to conclusively demonstrate their existence.[11-13] More recently, the CCFR experiment[14] and, notably, the CHARM II experiment[15] have reported clear evidence for ν tridents. Although these data are consistent with the standard-model prediction, there has been no demonstration of the destructive interference in this process. In ν_e-e scattering, however, the interference between W and Z exchange has been observed by a LAMPF experiment.[16]

Neutrino data were accumulated using the Fermilab Tevatron quadrupole triplet neutrino beam (QTB) with the Columbia-Chicago-Fermilab-Rochester (CCFR) detector.[17] The QTB beam contained muon neutrinos and antineutrinos in the ratio $\simeq 2/1$, with usable neutrino energy in the range $10 \leq E_\nu \leq 600$ GeV ($\langle E_\nu \rangle = 160$ GeV). The initial sample of 3.7×10^6 muon triggers was required to have, after fiducial cuts, a muon energy $E_{\mu 1} \geq 9$ GeV (where 1 refers to the primary muon). The surviving sample of events with one muon consisted of 1.8×10^6 ν_μ- and 3.6×10^5 $\bar{\nu}_\mu$-induced events. Dimuon events were extracted from this sample by requiring the presence of a second muon track which passed an energy cut $E_{\mu 2} \geq 4.5$ GeV (where 2 refers to the secondary muon). The efficiency of the dimuon selection was checked with a redundant search using counter pulse heights. The resulting dimuon sample consisted of 8532 events.[18]

The bulk of the 8532 events are the hadronic dimuon events arising from decays of D, π, and K mesons.[18] Neutrino-trident events were extracted by utilizing the kinematic properties that distinguish them from these hadronic dimuons. First, the two-muon invariant mass of a trident is considerably smaller than those due to the hadronic dimuons. We present in Fig. 2 the invariant-mass distribution of the 8532 data events (solid symbols) and that expected for tridents from a Monte Carlo calculation described below (histogram). Figure 2 indicates that the trident signal region is contained by $M_{\mu\mu} \leq 2$ GeV. Second, since tridents are associated with no hadron energy at the event vertex region ($E_{\rm had}$) in the detector, the signal would appear at $E_{\rm had}=0$ (commensurate with the detector $E_{\rm had}$ resolution). From a study of background beam muons, which should behave like $E_{\rm had}=0$ single-muon events for these purposes, we determined that the detector should measure $E_{\rm had} \leq 1$ GeV for more than 80% of the true $E_{\rm had}=0$ dimuons.[17] The trident signal is obtained by simultaneously imposing $M_{\mu\mu} \leq 2$-GeV and $E_{\rm had} \leq 1$-GeV cuts. In Fig. 3 we compare the measured $E_{\rm had}$ distribution of dimuon data with $M_{\mu\mu} \leq 2$ GeV (circles) with the $E_{\rm had}$ distribution of dimuon data with $M_{\mu\mu} > 2$ GeV (crosses). The latter data are normalized to the number of events in the first data set in the region $E_{\rm had} > 2$ GeV. We see the clear excess due to tridents in the $E_{\rm had} \leq 1$-GeV bin with $M_{\mu\mu} \leq 2$ GeV.

Several points add to the confirmation of the trident signal. First, the measured $E_{\rm had}$ distribution is demonstrated to be independent of the invariant mass of the dimuons originating from hadronic sources. Figure 4 shows that the $E_{\rm had}$ distribution of the dimuon data with $2 < M_{\mu\mu} \leq 3$ GeV (solid circles) is virtually identical to the $E_{\rm had}$ distribution of the dimuon data with $3 < M_{\mu\mu} \leq 5$ GeV (squares). This observation is confirmed by a Monte Carlo study, shown in the inset of Fig. 4, which simulated the hadronic sources of the dimuons. Second, the background contribution to the trident signal from coherent production of a charged pion[19] and its subsequent decay is estimated to be less than 0.30 event. Third, a possible contribution to $E_{\rm had}=0$ dimuons from the neutral-current diffractive production of J/ψ was eliminated by excluding dimuons with $M_{\mu\mu}=3.1\pm0.4$ GeV.[20] The invariant-mass resolution of our detector is $\approx 8\%$ at the J/ψ peak.

The signal consists of 22 events with measured $E_{\rm had} \leq 1$ GeV and $M_{\mu\mu} \leq 2$ GeV with an observed back-

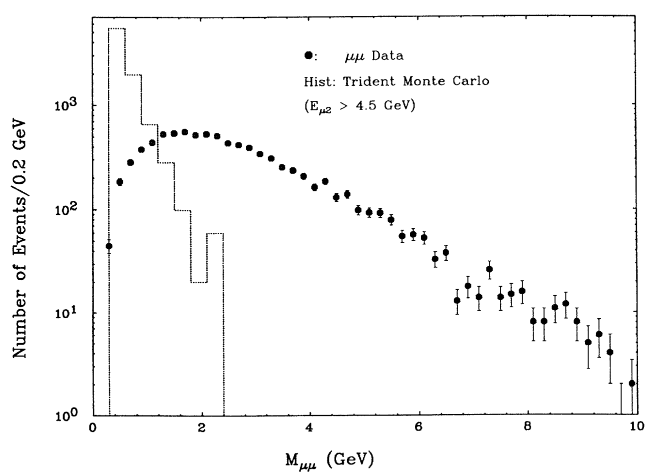

FIG. 2. Invariant-mass distribution of observed muon pairs $M_{\mu\mu}$ (solid symbols), and neutrino-trident Monte Carlo calculation (histogram) normalized to the data (8532 events).

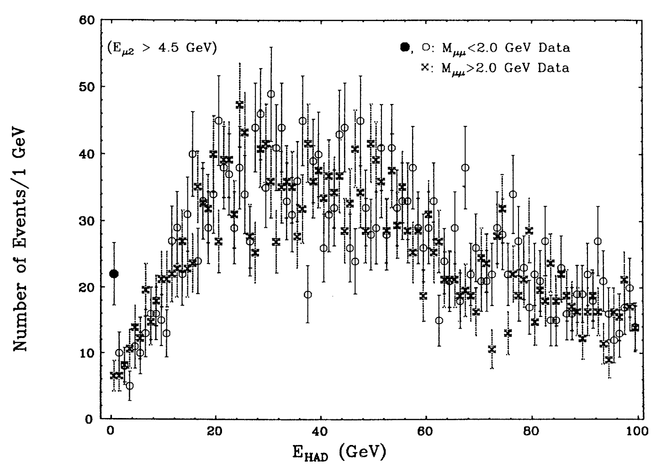

FIG. 3. Measured $E_{\rm had}$ distribution of the dimuon data with $M_{\mu\mu} \leq 2$ GeV (circles), compared with the measured $E_{\rm had}$ distribution of the dimuon data with $M_{\mu\mu} > 2$ GeV (crosses). The trident signal appears in the lowest hadron-energy bin.

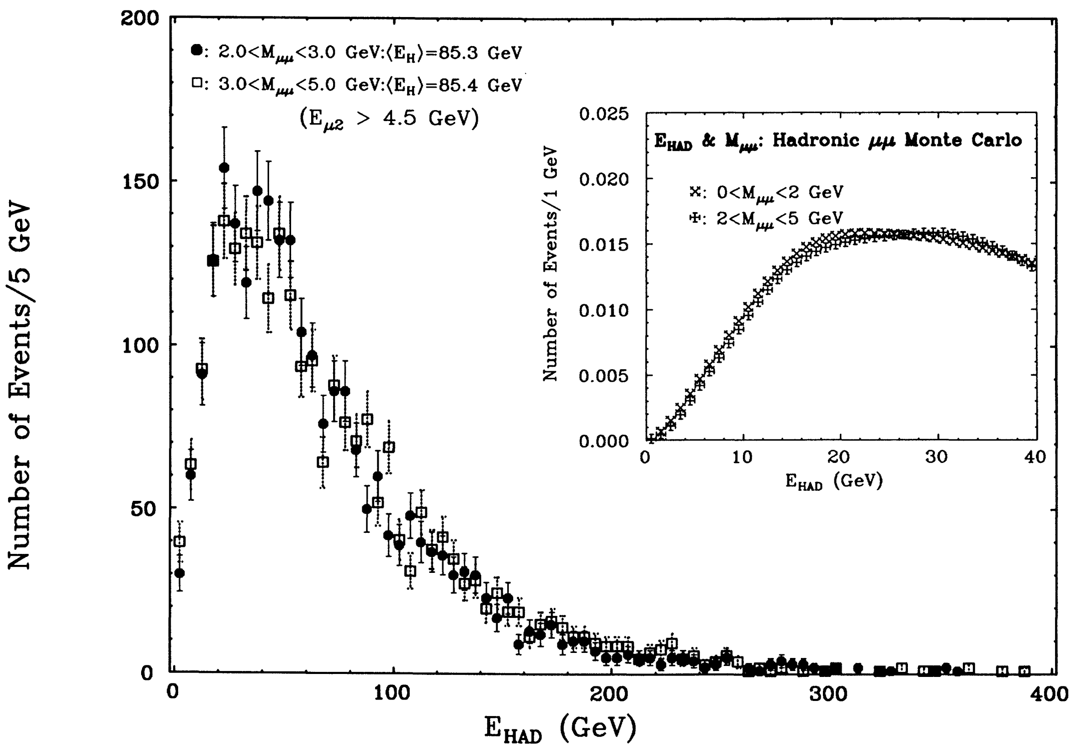

FIG. 4. $E_{\rm had}$ distribution of the dimuon data with $2 < M_{\mu\mu} \leq 3$ GeV (solid circles), and with $3 < M_{\mu\mu} \leq 5$ GeV (squares). Inset: A hadronic dimuon Monte Carlo simulation of $E_{\rm had}$ distribution with $0 < M_{\mu\mu} \leq 2$ GeV, compared to that with $2 < M_{\mu\mu} \leq 5$ GeV.

ground of 6.4 events calculated from 8 events with $E_{\rm had} \leq 1$ GeV and $M_{\mu\mu} > 2$ GeV. The excess of 15.6 events should be corrected for the acceptance of the $E_{\rm had} < 1$-GeV cut, the geometric reconstruction, the $E_{\mu 1} > 9$-GeV cut, and the $E_{\mu 2} > 4.5$-GeV cut. The efficiency for the last three cuts (which was calculated to be 0.50 for the $E_{\mu 2} > 4.5$-GeV cut) was determined from a ν-trident Monte Carlo calculation discussed below. The Monte Carlo calculation indicates, and the data confirm, that the most sensitive cut is that on $E_{\mu 2}$. We therefore repeated the analysis with an $E_{\mu 2}$ cut at 5 and at 9 GeV. The results are enumerated in Table I which shows that our extraction of this signal is independent of the choice of the $E_{\mu 2}$ cut. We report a trident signal, after all corrections, of

$$N(\text{data}) = 37.0 \pm 12.4 . \quad (2)$$

To confront the theoretical prediction and calculate efficiencies, trident production was simulated using the exact calculation by Fujikawa.[4] The trident matrix-element calculation of the Feynman diagram in Fig. 1 was explicitly checked against the exact calculations due

TABLE I. Trident analysis: Extraction of trident signal for three different $E_{\mu 2}$ cuts: 4.5, 5, and 9 GeV. Whereas the 4.5- and 5-GeV cuts employ muon range in the target, the "9-GeV" cut requires the spectrometer reconstruction of the nonleading muon.

$E_{\mu 2}$ cut	≥ 4.5 GeV	≥ 5.0 GeV	≥ 9.0 GeV
$(E_{\rm had} \leq 1$ GeV$) + (M_{\mu\mu} \leq 2$ GeV$)$	22	20	12
$(2 \leq E_{\rm had} \leq 52$ GeV$) + (M_{\mu\mu} \leq 2$ GeV$)$	1527	1330	578
$(E_{\rm had} \leq 1$ GeV$) + (M_{\mu\mu} > 2$ GeV$)$	8	6	3
$(2 \leq E_{\rm had} \leq 52$ GeV$) + (M_{\mu\mu} > 2$ GeV$)$	1908	1691	959
Signal	15.5	15.3	10.2
Geometric and kinematic corrections	2.39	2.52	3.69
Fully corrected tridents	37.0	38.5	37.6
(Error)	(12.4)	(12.3)	(13.3)

to Czyz *et al.*[2] and Brown *et al.*[7] These agreed within 3%, and were also in agreement with the approximate calculation (using a virtual-photon approximation) in Refs. 1 and 9. The iron-nucleus electromagnetic form factor was taken from the electron scattering data.[21] The contribution to the trident signal from incoherent scattering from target *nucleons* (as opposed to scattering off target *nuclei*) was also included, where the nucleon form factor was taken from Olsson *et al.*[22] Target nucleons contribute approximately $\frac{1}{5}$ of the tridents produced by target nuclei.[23] It should be noted that the trident calculation is rather precise; the form-factor measurements do not constitute the largest source of error. The largest source of theoretical uncertainty is the estimation of the Pauli suppression which affects only the neutrino-nucleon trident production (16% of the total trident production cross section). The combined systematic error on the theoretical prediction of ν tridents is estimated to be 5%. For W exchange alone, or for the $V-A$ theory, the predicted number of trident events is

$$N(\text{trident}, V-A) = 78.1 \pm 3.9\,. \tag{3}$$

The prediction of the standard model including both W and Z exchange is

$$N(\text{trident, standard model}) = 45.3 \pm 2.3\,. \tag{4}$$

Our data, with 37.0 ± 12.4 events, clearly support the destructive-interference hypothesis, and rule out the lack of interference at > 99% C.L.

The trident cross section can be calculated from the measured absolute ν-N charged-current cross section of[17]

$$\sigma_{\nu N}(\text{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \text{cm}^2/\text{GeV}\,,$$

and the observed rate of tridents with respect to all charged-current interactions [rate $= (1.33 \pm 0.43) \times 10^{-5}$]. The cross section is

$$\sigma(\nu\ \text{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\text{cm}^2}{\text{Fe nucleus}} \quad \text{at } \langle E_\nu \rangle = 160\ \text{GeV}\,. \tag{5}$$

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[1]M. A. Kozhushner and E. P. Shabalin, Zh. Eksp. Teor. Fiz. **41**, 949 (1961) [Sov. Phys. JETP **14**, 676 (1962)].

[2]W. Czyz *et al.*, Nuovo Cimento **34**, 404 (1964).

[3]M. S. Marinov *et al.*, Yad. Fiz. **3**, 598 (1966) [Sov. J. Nucl. Phys. **3**, 437 (1966)].

[4]K. Fujikawa, Ann. Phys. (N.Y.) **68**, 102 (1971).

[5]R. W. Brown and J. Smith, Phys. Rev. D **3**, 207 (1971).

[6]J. Lovseth and M. Radomski, Phys. Rev. D **3**, 2686 (1971).

[7]R. W. Brown *et al.*, Phys. Rev. D **6**, 3273 (1972).

[8]K. Fujikawa, Phys. Rev. D **8**, 1623 (1973).

[9]R. Belusevic and J. Smith, Phys. Rev. D **37**, 2419 (1988).

[10]S. R. Mishra, in *Proceedings of the Thirteenth International Conference on Neutrino Physics and Astrophysics, Boston, Massachusetts,* edited by J. Schneps *et al.* (World Scientific, Singapore, 1988), p. 259.

[11]A. E. Asratyan *et al.*, Yad. Fiz. **25**, 1051 (1977) [Sov. J. Nucl. Phys. **25**, 558 (1977)].

[12]F. W. Busser *et al.*, in *Proceedings of the Conference Neutrino '81, Hawaii, 1981,* edited by V. Peterson (HEP Group, Dept. of Physics, University of Hawaii, 1981), p. 328.

[13]F. Bergsma *et al.*, Phys. Lett. **122B**, 185 (1983).

[14]B. A. Schumm *et al.*, in *Proceedings of the Twenty-Third Recontre de Moriond on Electroweak Interaction and Unified Theories, Les Arc, Savoi, France, March 1988* (Editions Frontiers, Gif-sur-Yvette, France, 1988), pp. 413–420.

[15]G. Geiregat *et al.*, Phys. Lett B **245**, 271 (1990).

[16]R. C. Allen *et al.*, Phys. Rev. Lett. **64**, 1330 (1990).

[17]The relevant energy is the nonmuonic energy associated with the event at the vertex region. For details of the calibration see W. K. Sakumoto *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **294**, 179 (1990); B. A. Schumm, Ph. D. thesis, University of Chicago, 1989 (unpublished); P. Z. Quintas, Ph. D. thesis, Nevis Laboratories, Columbia University, 1991 (unpublished); also S. R. Mishra *et al.*, Phys. Rev. Lett. **63**, 132 (1989); S. R. Mishra *et al.*, Phys. Lett. B **252**, 170 (1990).

[18]We have published results on the charm-induced opposite sign dimuons with $E_{\mu 2} \gtrsim 9$-GeV cut [C. Foudas *et al.*, Phys. Rev. Lett. **64**, 1207 (1990)], and with $E_{\mu 2} \gtrsim 5$-GeV cut [M. Shaevitz, in Proceedings of Neutrino '90, CERN, Geneva, June 1990 (to be published)].

[19]P. Marage *et al.*, Z. Phys. C **43**, 523 (1989).

[20]The contribution to our entire dimuon sample from diffractively produced vector mesons, other than J/ψ, and their subsequent decay into muon pairs is negligible (< 0.2 event); for the neutrino production of J/ψ we used a calculation by V. Barger *et al.*, Phys. Lett. **92B**, 179 (1982). The estimated J/ψ contribution to dimuons with $E_{\text{had}} \lesssim 1$ GeV was less than 3 events, centered about the mass 3.1 GeV.

[21]R. Hofstadter and H. R. Collard, in *Landolt-Bornstein: Numerical Data and Functional Relationship in Science and Technology* (Springer-Verlag, Berlin, 1967), Vol. I, Pt. 2, p. 26.

[22]M. G. Olsson *et al.*, Phys. Rev. D **17**, 2938 (1978).

[23]In the neutrino-nucleon trident production calculation, we included the Pauli suppression operative at small momentum transfers.