Prompt Muon-Neutrino Production in a 400-GeV Proton Beam-Dump Experiment

R. C. Ball, C. T. Coffin, H. R. Gustafson, L. W. Jones, M. J. Longo,
T. J. Roberts, B. P. Roe, and E. Wang

University of Michigan, Ann Arbor, Michigan 48109

and

C. Castoldi and G. Conforto

Istituto Nazionale di Fisica Nucleare, Firenze, Italy

and

M. B. Crisler, J. S. Hoftun, T. Y. Ling, T. A. Romanowski, and J. T. Volk

Ohio State University, Columbus, Ohio 43210

and

S. Childress[a]

University of Washington, Seattle, Washington 98195

and

M. E. Duffy, G. K. Fanourakis, R. J. Loveless, D. D. Reeder,
D. L. Schumann, and E. S. Smith

University of Wisconsin, Madison, Wisconsin 53706

The prompt ν_μ and $\bar{\nu}_\mu$ flux produced by 400-GeV protons has been measured with a detector located 56 m from a tungsten target. The cross section for the hadronic production of charm is determined to be $27 \pm 4 \pm 5$ μb/nucleon subject to the following assumptions: $D\bar{D}$ production only; A^1 variation of cross section; and a parametrization of the D-production cross section which is $(1 - x)^4 \exp(-2m_\perp)$. The ratio of prompt $\bar{\nu}_\mu$ flux to prompt ν_μ is measured to be $1.12 \pm 0.24 \pm 0.17$, consistent with predominantly $D\bar{D}$ production.

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Previous beam-dump experiments have reported observations of a flux of prompt ν_μ and $\bar{\nu}_\mu$ which have been interpreted as arising from the associated production and subsequent decay of charmed hadrons.[1-3] These experiments were made with small geometric acceptance ($\sim 10^{-5}$ sr in the laboratory frame), with uncertainties in upstream sources of background, and with a large background of nonprompt neutrinos. In the present experiment we address these problems by (1) simultaneously measuring neutrino production at angles from 0 to 37 mrad (80×10^{-5} sr), (2) constructing and continuously monitoring a clean proton beam, and (3) maximizing the prompt flux relative to the nonprompt flux from pion and kaon decay through the use of a high-density (tungsten) target. Data were collected during two running periods. The data presented here are from the earlier run only.

The Fermilab 400-GeV proton beam was directed into different density targets; the hadron cascade which resulted was largely absorbed in the target. The considerable flux of muons produced was deflected vertically by a series of solid iron magnets as shown in Fig. 1. Because of this active shielding the detector was located about 56 m from the target, rather than the 850 m characteristic of the CERN experiments. The residual muon flux at the face of the detector was 2.3×10^5 for a typical pulse of 2×10^{12} protons on target.

The neutrino detector was a calorimeter composed of thirty modules, each of which had twelve lead plates interspersed with liquid scintillator, so that the shower was sampled every 1.2 radiation lengths. Each module totaled 14.4 radiation lengths and 0.5 absorption lengths (105 g/cm^2), and was divided vertically into five cells which were viewed at either end by a photomultiplier tube. The calorimeter had a linear energy response with a measured resolution $0.53\sqrt{E}$ for hadrons and $0.27\sqrt{E}$ for electrons. The gains of
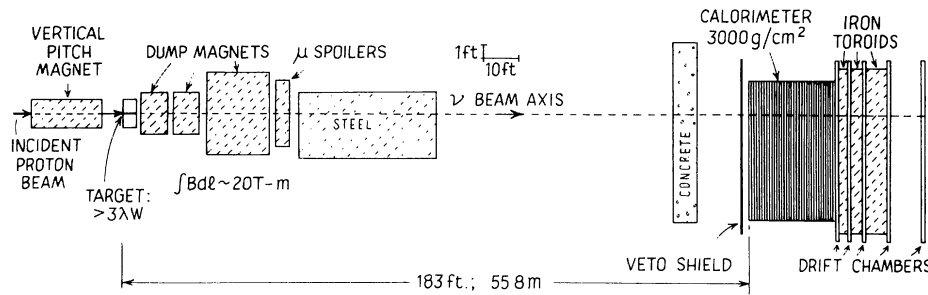
FIG. 1. Schematic layout of the experiment.

the 300 phototubes were set and frequently moni-
tored by recording the response to muons.

After each module were two planes of horizon-
tal and vertical proportional-wire-chamber wires
with 2.5-cm spacing operated in a proportional
mode with pulse-height readout. The transverse
dimensions of the vertex fiducial volume were
2.6×1.0 m^2; only neutrino interactions in modules
3 through 25 were used, and the fiducial volume
contained 65 metric tons. The beam was cen-
tered vertically but offset 0.75 m to the left of
center, which allowed the calorimeter to accept
neutrinos to production angles of 37 mrad.

Downstream from the calorimeter was a muon
spectrometer consisting of five superplanes of
five drift chambers each and three magnetized
iron toroids of transverse dimension 3.6×2.4
m^2. Upstream of the calorimeter was a triple
wall of counters used to prevent triggering by
incident charged particles.

The readout of the apparatus was triggered
when sufficient energy was deposited within any
of 24 overlapping groups of 16 contiguous cells.
The trigger efficiency was greater than 95% at
10 GeV and, averaged over the fiducial volume,
exceeded 50% for hadron energies greater than
6.5 GeV. The trigger threshold and efficiency
were calibrated with use of the electromagnetic
interactions of muons.

Data were collected with 1.6×10^{17} protons
dumped into a full-density tungsten (Hevimet)
target (4 absorption lengths) and into a segment-
ed tungsten target (3 absorption lengths) whose
average density was one-third normal. The total
exposure after correction for live time (~70%)
and elimination of bad spills (described below)
was 6.7×10^{16} protons on the full-density target
and 1.6×10^{16} on the partial-density target. The
triggering rate was about 30 per pulse of which
10 were caused by cosmic rays, 0.1 were neu-

trino induced, and the remainder were due most-
ly to particles produced by muon interactions in
the floor or the concrete roof shielding blocks.
The rate and characteristics of events caused by
cosmic rays were monitored with a second gate
identical in length to the 1-sec beam-spill gate.

Great care was taken to minimize background
events produced by beam scraping upstream of
the target. 26 halo monitors were placed along
the beam and were calibrated by introducing foils
of known thickness into the beam and by varying
the beam-line vacuum. Spills were eliminated
in which more than two halo monitors indicated
twice the nominal background or target monitors
indicated the beam was not centered on the target.
For the remaining spills, the background due to
sources upstream of the beam intensity monitors
was determined to be less than 2.0% of the prompt
neutrino flux. The beam intensity devices (seg-
mented-wire ionization chambers, secondary-
emission monitors, etc.), vacuum windows, and
air just upstream of the target introduced a larg-
er but calculable background (5% for full density,
3% for partial).

Charged-current ν_μ and $\bar{\nu}_\mu$ interactions have
an outgoing μ which provides an umambiguous
signal in the detector. We require that the muon
pass through at least three drift-chamber super-
planes and that the event have a total energy
greater than 20 GeV. The overall efficiency
(scan and muon reconstruction) is estimated to
be 96% by comparison of two independent analyses.
The average acceptance of the detector for neu-
trino interactions with $E_\nu > 20$ GeV within the
fiducial volume is calculated by several methods
to be 0.6 with use of the measured neutrino struc-
ture functions.[4,5] The numbers of raw events ob-
tained in the full- (partial-) density target are
423 (196) ν_μ events and 135 (55) $\bar{\nu}_\mu$ events. The
corrected event rates per 10^{16} protons (not in-

cluding azimuthal acceptance) for full (partial) density are 94.4 ± 4.8 (177.0 ± 13.1) for ν_μ and 28.9 ± 2.8 (45.9 ± 6.6) for $\bar{\nu}_\mu$.

These data contain a mixture of prompt and nonprompt neutrinos. The target densities corrected for finite target length are $0.93\rho_W$ and $0.38\rho_W$ for the full and partial densities, respectively.[6] The prompt-neutrino spectrum is determined by a bin-by-bin extrapolation and also by a constrained fit which fixes the nonprompt $\bar{\nu}/\nu$ flux ratio, $R = 0.17$, and the shape of the energy spectra. The nonprompt spectra in tungsten are calculated from the measured $\pi^\pm$ and $K^\pm$ spectra in different targets.[7-9] From the constrained fit the prompt $\bar{\nu}_\mu$ (ν_μ) rate for $E_\nu > 20$ GeV, $\theta_\nu < 37$ mrad, is $81 \pm 21 \pm 15$ ($38 \pm 6 \pm 7$) per 10^{16} protons.[10] The prompt errors for pure extrapolation are 31% (36%) for ν_μ ($\bar{\nu}_\mu$) whereas the constrained statistical errors are reduced to 26% (16%). The substantial decrease in the $\bar{\nu}_\mu$ error arises from combining the statistical accuracy of the nonprompt ν_μ determination with the small value of R. A 20% systematic change in R results in a 4% (10%) change in the prompt $\bar{\nu}_\mu$ (ν_μ) event rate. The ratio of prompt to nonprompt for the full-density target (1.0) is larger than for previous experiments[1-3] (~0.4) primarily because the tungsten target has a greater density than the CERN copper target. The expected distributions in scaling variables x and y, after inclusion of the distortions due to acceptance, are in good agreement with the data.

The prompt flux is unfolded from the measured events with use of the $\bar{\nu}_\mu$ and ν_μ cross sections on lead.[11] In order to calculate the cross section for charmed-hadron production from the measured prompt ν_μ and $\bar{\nu}_\mu$ flux the following assumptions are made: (1) The production of $D\bar{D}$ pairs predominates; (2) the cross section is proportional to the atomic number of the target (A^1); (3) the muon semileptonic branching ratio is (8.2 ± 1.2)% [12,13]; (4) the proton elasticity is $\epsilon = 0.3$; and (5) the cross section varies[14,15] as $s^{1.3}$ [needed to calculate charm production by secondaries (~6%)]. Previous analyses have used different values; e.g., the CERN BEBC group used $\epsilon = 0.67$ and $s^{0.5}$. The customary parametrization of the invariant $D\bar{D}$ cross section is

$$d^3\sigma/dp^3 \propto (1-x)^n \exp(-am_\perp),\qquad (1)$$

where x is the absolute value of Feynman x and $m_\perp = (p_\perp^2 + m_D^2)^{1/2}$. The best fit to the data occurs for $n = 4 \pm 1$, $a = 2 \pm 0.5$,

$$\sigma(D\bar{D}) = 27 \pm 4 \text{ (statistical)}$$

$$\pm 5 \text{ (systematic)}\ \mu\text{b/nucleon},\qquad (2)$$

for which $\chi^2 = 14.0$ for 19 degrees of freedom. The systematic errors include target density (14%), ν_μ ($\bar{\nu}_\mu$) charged-current acceptance (10%), σ_ν on lead (6%), charm excitation (3%), fiducial-volume cut (3%), analysis efficiency (2%), and upstream background (1%). Model-dependent errors [assumptions (1)-(3)] have not been in-
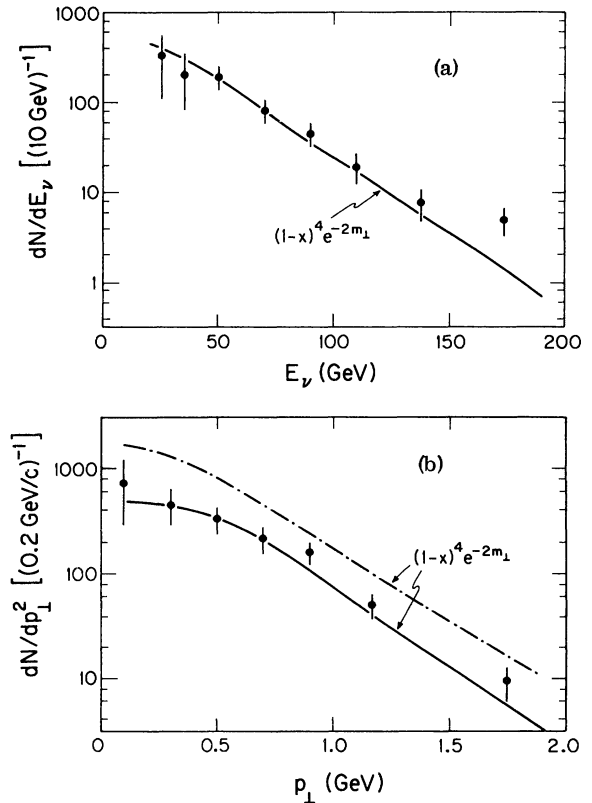

FIG. 2. (a) Energy distribution of prompt ν_μ and $\bar{\nu}_\mu$ charged-current events corrected for azimuthal, hadronic, and muonic acceptance of the spectrometer ($E_\nu > 20$ GeV, $\theta_\nu < 37$ mrad). The solid lines in (a) and (b) are the predictions of the model with $n = 4$ and $a = 2$. The errors shown include both statistical and systematic effects. (b) Transverse-momentum distribution of the prompt ν_μ and $\bar{\nu}_\mu$ charged-current events. The dot-dashed line indicates the $p_\perp$ distribution for the $n = 4$, $a = 2$ model without the restriction of $E_\nu > 20$ GeV, $\theta_\nu < 37$ mrad showing that the experimental acceptance does not bias the $p_\perp$ distribution.

cluded. In a model where $\sigma(D\overline{D}) \sim (1-x)^3 \exp(-2p_\perp)$ the result is $\sigma(D\overline{D}) = 20 \pm 3$ μb/nucleon. If the charm production cross section varies as $A^{0.67}$ the best-fit value becomes $154 \pm 23 \pm 28$ μb/nucleon.

When the results of all experiments are translated to a common parametrization [Eq. (1)] with $n = 4$, $a = 2$, $\epsilon = 0.3$, and $s^{1.3}$, the $D\overline{D}$ production cross sections are 84 ± 28 μb (BEBC ν_μ),[1] 48 ± 28 μb (BEBC ν_e),[1] and 28 ± 9 μb (CHARM),[2] compared with the value 27 ± 6 μb for this experiment. A similar beam-dump experiment[16] (CCFRS) with 350-GeV incident protons in which muons are detected rather than neutrinos finds $\sigma(D\overline{D}) = 25 \pm 4$ μb for a similar model, $n = 6$ and an $\exp(-2.5p_\perp)$ dependence. The LEBC result for $\sigma(D\overline{D})$ in pp interactions is 24^{+9}_{-5} μb.[17]

This is the first measurement of both the x and $p_\perp$ dependence of prompt neutrinos. Figures 2(a) and 2(b) show a comparison of the prompt-neutrino data to the model with $n = 4$ and $a = 2$.

The ratio of prompt $\overline{\nu}_\mu$ flux to prompt ν_μ is measured to be $1.12 \pm 0.24 \pm 0.17$. For pure extrapolation this result is 1.10 ± 0.52. This result is larger than the CDHS result[3] $0.46^{+0.21}_{-0.16}$ but in good agreement with other data: 0.79 ± 0.62 (BEBC)[1]; 1.3 ± 0.6 (CHARM)[2]; and 1.1 ± 0.2 (CCFRS).[16]

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(a)Present address: Fermilab, Batavia, Ill. 60510.

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