EXPERIMENTAL STUDY OF PROMPT NEUTRINO PRODUCTION
IN 400 GeV PROTON-NUCLEUS COLLISIONS

CHARM Collaboration

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ABSTRACT

A proton beam-dump experiment using the CHARM neutrino detector has been performed at the CERN SPS. We report the observation of events induced by prompt ν_μ and $\bar{\nu}_\mu$ neutrinos and confirm previous evidence for prompt electron neutrinos. The ratio of prompt $(\bar{\nu}_e + \nu_e)$ and $(\bar{\nu}_\mu + \nu_\mu)$ fluxes is found to be 0.48 ± 0.12 (statistical) ± 0.10 (systematic), whereas a flux ratio of 1 is expected for charmed meson production and subsequent semileptonic decay. The $\bar{\nu}_\mu$ to ν_μ flux ratio obtained is $1.3^{+0.6}_{-0.5}$. We also observe 54 ± 19 (statistical) ± 9 (systematic) prompt muonless events, with shower energy in the range from 2 to 20 GeV, in excess of electron and muon neutrino interactions expected from D and $\bar{D}$ meson decay.

The beam-dump experiment described in the following was performed to study, with improved statistics and better control over background, the magnitude, energy dependence and origin of the flux of prompt neutrinos, from decays of short-lived parents, discovered in earlier experiments.¹⁾ Preliminary results of the experiment have already been reported^{2,3)}.

This letter consists of several sections, first, there are brief descriptions of the detector, the beam layout and of the methods used to extract prompt neutrino fluxes. Secondly, event selection and the energy spectrum of prompt muonless events are discussed. Thirdly the evaluations of prompt ν_μ and of the ratio ν_e/ν_μ are described and finally there is a section on the estimation of the number of ν_e interactions by two methods, one of which is unique to the CHARM detector.

The layout of the experiment is shown in Fig. 1, the fine-grain detector of the CHARM collaboration⁴⁾ being located 910 m from the target. The detector consists of a calorimeter, containing 78 instrumented target planes, surrounded by a magnetized iron frame, and a forward muon spectrometer. It has good energy resolution, and a high power of pattern recognition, so that, for example, muons with momenta as low as 1 GeV/c may be detected reliably. The trigger of the experiment required that at least four scintillator planes were hit and that the shower energy was larger than 0.5 GeV, hence showers with energies as low as 1.5 GeV were detected with essentially full efficiency.

The 400 GeV proton beam of the CERN SPS was extracted in a single turn, 23 μ s, and directed onto a 2 m long copper dump target⁵⁾ in the cave of the West Area Neutrino Facility. The short spill length was used to minimize the cosmic ray background. Monitor counters were installed along the proton beam line⁵⁾ to ensure that occasional beam losses did not contribute significantly to the neutrino flux.⁶⁾

The cylindrical copper dump targets were segmented⁵⁾ to obtain different mean densities by appropriate spacing of the discs. Two target densities 3 g/cm³ and 9 g/cm³ (denoted by $\rho = 1/3$ and 1, respectively) were used during data taking, so that the prompt neutrino flux could be determined directly by extrapolation of the event rates to infinite density.

A second estimate of prompt neutrino flux, by subtraction, was obtained as follows. The muon flux was measured⁵⁾ in the first four gaps of the steel shield, the detector positions corresponding to range requirements of 23, 57, 94, and 136 GeV/c. Copper dump targets⁵⁾ of three mean densities (3, 4.5, and 9 g/cm³) were used in these measurements. Extrapolation to infinite density led to the determination of the flux and the spectrum of prompt and non-prompt decay muons. The muon fluxes, monitored throughout the experiment, were used to calculate the flux of non-prompt neutrinos from the decay of pions and kaons in the dump target, and were then subtracted from the observed overall neutrino flux to obtain the contribution of prompt neutrinos. The two methods, extrapolation and subtraction, are subject to different uncertainties and a comparison of their results is therefore an important check of consistency.

Data were taken with the full density beam-dump for 6.96×10^{17} protons on target (after correction for dead-time) - abbreviated as POT - and with the 1/3 density beam-dump for 2.60×10^{17} POT. In addition, 33 000 events were recorded using the same trigger, while the accelerator was off, to investigate the cosmic ray background.

Neutrino interaction candidates were selected using the following three criteria:

- i) The interaction vertex occurred in a fiducial volume extending from target plane 3 to target plane 70 and over a cross-sectional area of $2.4 \times 2.4 \text{ m}^2$, corresponding to a fiducial target mass of 100 tons.
- ii) The event contained no charged track entering the front or the sides of the detector. Cosmic-ray tracks entering the muon spectrometer from the back were rejected by a time-of-flight measurement. These requirements strongly reduced the contamination induced by cosmic-ray and accelerator muons.
- iii) The shower energy, after subtraction of the energy loss of muons in charged current interactions, single muon events, was greater than 2 GeV.

Events were classified as "muonless" or as "one-muon" events by computer selection on an event-by-event basis, according to the following criteria:

- i) The "one-muon" events had at least one primary track, defined by its penetration through material from the vertex, corresponding to a range of 1 GeV/c and visible, in at least one projection, outside the hadron shower for a track length corresponding to a range of 0.67 GeV/c. The track had to show no kink or interaction and extrapolate to the vertex.
- ii) All other events were called "muonless".

The reliability of the automatic reconstruction and classification of all neutrino candidates was checked by scanning the sample.

As a result 810 "one-muon" events and 562 "muonless" events were found.

In addition, it was felt necessary to check that the separation of events into the two classes was reliable, especially at low shower energies. To achieve this a sample of 6000 events, composed of ν_μ and $\bar{\nu}_\mu$ induced events in the same proportion as in the beam-dump experiment and recorded during an exposure in the horn-focussed wide-band beam, was analysed using the same criteria. The relative contribution of prompt neutrinos was reduced by a factor of the order of one thousand, because of the focussing of the long-lived parents and the decay path of 300 m length. After corrections for mixing of event classes because of pion and kaon decay, the muon momentum cut-off of 1 GeV/c, and the small contamination by electron neutrinos, the ratio of NC to CC cross-sections for events with shower energy in the range from 2 to 200 GeV was found to be

$$\langle R \rangle = 0.31 \pm 0.02 ,$$

in good agreement with other measurements.⁷⁾ We observe no statistically significant deviation from zero of the difference $N(0\mu) - N(1\mu) \cdot \langle R \rangle$ as a function of energy and therefore conclude that the event classification is reliable.

With regard to the physics interpretation one-muon events arose primarily from the charged-current (CC) interactions of muon neutrinos,

whereas the muonless events included neutral-current (NC) interactions of muon, electron and other neutrinos, and also CC interactions of electron neutrinos and of any other neutrinos ν_X (e.g. ν_τ) with muonless final states.

The energy deposition (E_{sh}) spectrum of prompt muonless events, electron neutrinos (and any ν_X), was obtained from the "muonless" sample by subtraction of both muon neutrino NC interactions and NC and CC interactions of non prompt electron neutrinos. The correction procedure may be listed as follows:

- 1) The correction for muons produced by decay in flight of pions and kaons was determined experimentally⁸⁾ by analysing data taken using an incident pion beam, and di-muon events observed in the CHARM detector.
- 2) The number of soft, undetected muons with momentum ≤ 1.0 GeV/c produced in CC muon neutrino events was computed using the neutrino spectrum derived from the measured CC events and the available description of the y distributions.^{9,10)}
- 3) The number of muons leaving the detector at the side without sufficient visible range was determined by Monte Carlo methods, using the neutrino spectrum derived from the measured CC events.
- 4) The cosmic-ray background was experimentally determined by analysing data taken under identical trigger conditions while the accelerator was off.
- 5) The contribution of NC interactions of muon neutrinos was calculated using the corrected number of single-muon events and the average ratio⁷⁾ of NC to CC cross-sections for neutrinos and antineutrinos, $\langle R \rangle = 0.324$.
- 6) The flux and energy distribution of non-prompt electron neutrinos was calculated by Monte Carlo simulation and normalized to the measured flux of decay muons in the iron shield.⁵⁾

Figure 2 shows the energy spectrum for both target densities, the data being summed because the dominant correction for NC interactions of muon neutrinos does not depend on whether these neutrinos are of prompt

or of conventional origin. The spectrum shows a rise below $E_{sh} = 20$ GeV and a broad distribution above $E_{sh} = 20$ GeV with a mean visible energy of $\bar{E}_{sh} = (71 \pm 7)$ GeV. The raw event numbers and the corrections applied for the energy bin $2 \text{ GeV} \leq E_{sh} \leq 20 \text{ GeV}$ are given in Table 1 and for $E_{sh} > 20 \text{ GeV}$ in Table 2.

Tables 1 and 2 also give the systematic uncertainties of the corrections which have been added quadratically. It may be concluded that there is clear evidence for prompt electron neutrino production.

The full points in Fig. 2 represent an estimate of the spectrum of prompt electron neutrino interactions by NC and CC, calculated under the assumption that they arise from pair production and subsequent semileptonic decay of charmed D mesons.¹¹⁾ The distribution is normalized to the number of observed events with $E_{sh} > 20 \text{ GeV}$. Integrating the cross-section for D pair production over the full phase space it is found that the product of total cross-section and branching ratio of semileptonic D decay, assuming that the cross-section is proportional to the number of nucleons, is given by

$$\sigma_T(pp \rightarrow D\bar{D} + X) \cdot BR(D \rightarrow \nu_e e X) = 1.5 \pm 0.5 \mu\text{b}.$$

The error includes the uncertainties of the production model.

Below $E_{sh} = 20 \text{ GeV}$, Fig. 2 shows a deviation of the observed spectrum from the expectation of this conventional model of $D\bar{D}$ production and decay. Assuming that the model describes prompt electron neutrino production also in this energy region, an excess of 54 ± 19 (statistical) ± 9 (systematic) events is observed. However, there may exist other sources of prompt electron neutrinos contributing to the low energy region. In a later part of this letter we describe the direct detection of CC electron-neutrino events and discuss their contribution to the apparent excess.

In the search for prompt muon neutrinos we used the sample of one-muon events obtained with the dump target of full density and subtracted the contribution of non-prompt muon neutrinos as determined experimentally.⁵⁾ We find positive evidence for prompt muon neutrino production for $E_\nu > 20 \text{ GeV}$, as summarized in Table 3. The mean neutrino energy of these events¹²⁾ is $E_\nu = (93 \pm 8) \text{ GeV}$. The analysis procedure is outlined as follows.

For one-muon events with $p_\mu > 4$ GeV/c, the charge of the muons can be determined by the muon spectrometer.¹³⁾ Selecting events with a negative muon we find for $E_\nu > 20$ GeV, by extrapolation to infinite density, a rate of non-prompt ν_μ charged-current interactions for $\rho = 1$ of (0.29 ± 0.08) events/(ton $\cdot 10^{17}$ POT), in agreement with the predicted rate⁵⁾ of (0.289 ± 0.035) events/(ton $\cdot 10^{17}$ POT). Using this predicted non-prompt ν_μ rate and the ratio⁵⁾ of events from non-prompt $\bar{\nu}_\mu$ and ν_μ ,

$$\frac{N(\bar{\nu}_\mu)}{N(\nu_\mu)} = 0.17 \pm 0.01 ,$$

derived from precise measurement of π^-/K^- and π^+/K^+ production by 400 GeV protons¹⁴⁾ we obtain a predicted rate of non-prompt $\bar{\nu}_\mu$ charged-current interactions of (0.050 ± 0.006) events/(ton $\cdot 10^{17}$ POT) at full density. We use this value for subtracting the non-prompt background from $\bar{\nu}_\mu$ induced charged-current events, observed with a dump target of full density and obtain a prompt rate of 0.069 ± 0.015 (statistical) ± 0.006 (systematic) events/(ton $\cdot 10^{17}$ POT).

This evaluation of prompt muonless and one-muon signals relies on subtraction of a background of non-prompt neutrinos. Although the rate and the spectrum of this background were determined by measurement, it is useful to check these results by extrapolating the event rates observed at two different dump-target densities to infinite density. The prompt rates are compared with those obtained by subtraction in Tables 1 and 2 for muonless events and in Table 3 for one-muon events. The results obtained by both methods are in good agreement, although the statistical errors are larger in the extrapolation procedure.

We next compare the fluxes of prompt $\bar{\nu}_\mu$ and ν_μ using a ratio of $\sigma_{\bar{\nu}_\mu}^- (\text{CC}) / \sigma_{\nu_\mu} (\text{CC}) = 0.48^{10)}$, and find

$$\frac{\phi(\bar{\nu}_\mu)}{\phi(\nu_\mu)} = 1.3 \pm 0.5 \text{ (statistical)} \begin{matrix} +0.4 \\ -0.2 \end{matrix} \text{ (systematic)} . \quad (1)$$

From the prompt rates obtained by extrapolation to infinite density (see Table 3) we find a ratio of 1.8 ± 1.1 . If the observed prompt neutrinos are due to semileptonic decays of D mesons we expect a flux ratio of 1.

Next the flux ratio of prompt electron and muon neutrinos can be evaluated by the number of their CC interactions. In this comparison the different response⁴⁾ of the calorimeter to electromagnetic and to hadronic energy deposition was taken into account. This analysis is restricted to data obtained with full dump density in order to minimize the systematic error due to the subtraction of non-prompt background.

We find 138 ± 20 (statistical) ± 29 (systematic) prompt events of the reaction $(\bar{\nu}_{\mu})_N \rightarrow \mu^{\pm} X$, with total observed energy $E_{vis} > 20$ GeV. The systematic error is due to an estimated 12% uncertainty⁵⁾ of the rate of non-prompt muon neutrino events. It should be stressed that this result is quoted for $E_{vis} > 20$ GeV. The result for prompt single muon events given in table 3 differs slightly from the above number as the energy cut there corresponds to $E_{\nu} > 20$ GeV.

The number of electron neutrino interactions by NC and by CC has been determined by two distinct and independent methods. In the first the calculated spectrum of prompt neutrinos from $D\bar{D}$ production and semi-leptonic decay was used to describe the observed energy spectrum of prompt muonless events for $E_{sh} > 20$ GeV (see Fig. 2) and it was found that $(83 \pm 1)\%$ of all events with $E_{sh} > 20$ GeV result from CC interactions of electron neutrinos, giving 67 ± 12 (statistical) ± 3 (systematic) events. Hence, the ratio of the two fluxes above a total observed energy of 20 GeV is

$$R_{\phi} = \frac{\phi(\bar{\nu}_e + \nu_e)}{\phi(\bar{\nu}_{\mu} + \nu_{\mu})} = \frac{N(\bar{\nu}_e)_N \rightarrow e^{\pm} X}{N(\bar{\nu}_{\mu})_N \rightarrow \mu^{\pm} X} = 0.48 \pm 0.12(\text{statistical}) \pm 0.10(\text{systematic}) \quad (2)$$

By extrapolation to infinite density the first method gives

$$R_{\phi} = 0.49 \pm 0.21. \quad (3)$$

The systematic error in Eq. (2) includes the uncertainties in the corrections applied to the raw data, the uncertainties in the rates⁵⁾ of non-prompt muon neutrinos ($\pm 12\%$) and electron neutrinos ($\pm 21\%$), and the uncertainty in the production mechanism of D mesons¹¹⁾ by varying the exponent describing the dependence on $x = p_L/p_L^{\max}$ from $n = 3$ to 5.

Since π and K decays produce muon neutrinos rather than electron neutrinos, proton beam losses upstream from the dump target might produce a muon excess as large as the one observed (eq. (2)). However, from the rates of monitor counters installed along the proton beam line there is no evidence⁶⁾ for beam losses sufficient to explain the observed asymmetry. The estimated number of one-muon events for $\rho = 1$ caused by beam scraping is less than 16, thus subtracting this number from the observed 138 prompt one-muon events increases the flux ratio to 0.55.

Evaluating R_ϕ as a function of the total observed energy above 20 GeV we find that R_ϕ is energy independent within the errors quoted in eq. (2).

In the second method electron neutrino CC events are identified directly.¹⁵⁾ The procedure is based on three characteristic features of electromagnetic showers: their small width, their regular longitudinal profile and the strong correlation between the total shower energy and the energy detected at the shower maximum. The energy detected in a road of scintillators, each counter 15 cm wide, starting at the vertex and crossing the shower maximum, has been calibrated using isolated electron showers obtained in a test beam. Ninety per cent of the total electron energy is detected in such a road with a resolution of $\sigma(E)/E \approx 0.25/\sqrt{E(\text{GeV})}$. For $\nu_e N \rightarrow eX$ events we apply a correction for hadron shower energy overlapping the road. Neutral current events with π^0 's of large energy may simulate ν_e CC events. We determine this contribution using muonless events obtained in the wide band beam and subtract it from the beam-dump data for each energy bin.

For total observed energy larger than 20 GeV and $\rho = 1$ we find, after subtraction of non-prompt contributions, 60.7 ± 13 (statistical) ± 5.3 (systematic) CC events induced by electron neutrinos. The second method thus gives

$$R_\phi = \frac{\phi(\nu_e + \bar{\nu}_e)}{\phi(\nu_\mu + \bar{\nu}_\mu)} = 0.44 \pm 0.11 \text{ (statistical)} \pm 0.10 \text{ (systematic)} \quad (4)$$

in agreement with the charm model-dependent result of eq. (2). The result given in eq. (4) only depends on the assumption that the fluxes of ν_e and $\bar{\nu}_e$ are equal. Varying their ratio by $\pm 50\%$ produces only small changes in the value and they have been taken into account in the estimate of the systematic error.

The visible energy (E_{vis}) spectrum of all (prompt and non-prompt) CC ($\nu_e + \bar{\nu}_e$) events for data obtained with $\rho = 1$ and $1/3$ is shown in fig. 3. The points give the sum of the CC ($\nu_e + \bar{\nu}_e$) spectrum expected from $D\bar{D}$ decay¹¹⁾ and from non-prompt sources.⁵⁾ We note reasonable agreement of the measured and calculated CC spectra and hence supporting evidence for using the standard $D\bar{D}$ model in evaluating the excess of prompt muonless events with observed energy release lower than 20 GeV.

In conclusion, we have observed prompt electron neutrinos and muon neutrinos originating from the decay of short-lived parents produced in 400 GeV proton-nucleus interactions. The flux of prompt electron neutrinos with visible energy above 20 GeV is found to be about one-half of the flux of prompt muon neutrinos, the excess of the latter being established with three standard deviations. The number of prompt muonless events with $E_{\text{sh}} < 20$ GeV is in excess of those expected from standard $D\bar{D}$ production and subsequent semileptonic decay, this excess occurs at a level of 2.4 standard deviations.

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- 1) P. Alibrand et al., Gargamelle Collaboration, Phys. Lett. 74B (1978) 134; T. Hansl et al., CDHS Collaboration, Phys. Lett. 74B (1978) 139; P.C. Bosetti et al., BEBC-ABCLOS Collaboration, Phys. Lett. 74B (1978) 143.
- 2) M. Jonker et al., CHARM Collaboration, Neutrino '79, Proc. Int. Conf. on Neutrinos, Weak Interactions and Cosmology, Bergen, Norway, 1979 (University of Bergen, 1980), Vol. 1, p. 27; M. Jonker et al., Contribution to the XVth Rencontre de Moriond; Les Arcs, 1978.
- 3) H. Wachsmuth, Recent data on prompt single-lepton production in hadron-nucleus collisions, preprint CERN-EP/79-115 (1979) and Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies, Batavia, 1979 (Fermilab, Batavia, 1980), p. 541.
- 4) A.N. Diddens et al., CHARM Collaboration, A detector for neutral-current interactions of high-energy neutrinos, preprint CERN-EP/80-63 (1980), to be published in Nucl. Instrum. Methods.
- 5) H. Wachsmuth, Neutrino and muon fluxes in CERN 400 GeV proton beam-dump experiment, preprint CERN/EP 79-125 (1979).
- 6) Comparing the neutrino rates, normalized to these monitor counter rates, in runs with and without thin foils of aluminium in the proton beam, we obtain an experimental value of $(2 \pm 1.7)\%$ for neutrino background by scraping. Material in front of the dump produces a non-prompt background of 6.1% of the total rate for $\rho = 1$ and of 1.3% for $\rho = 1/3$. The prompt event rates have been corrected for this effect.
- 7) $\langle R \rangle = [R \cdot N(\mu^-) + \bar{R} \cdot N(\mu^+)] / [N(\mu^-) + N(\mu^+)]$ using $R = 0.314 \pm 0.006$, $\bar{R} = 0.378 \pm 0.015$, the average of measurements performed in the CERN narrow-band beam (to be published) and $r = N(\mu^+)/N(\mu^-) = 0.185 \pm 0.035$ for $\rho = 1$ and $1/3$ data together below 20 GeV gives $\langle R \rangle = 0.324 \pm 0.006$.
- 8) The probability of π/K decay giving a muon according to the definitions given in the text has been found to rise linearly with the hadron energy, E_h , as $1.4 \times 10^{-2} + 2 \times 10^{-4} (E_h/\text{GeV})$.

- 9) y distributions, including quasi-elastic contributions and total cross-sections have been parametrized using all presently available data.
- 10) See, for example, R. Turlay, Proc. EPS Int. Conf. on High-Energy Physics, Geneva, 1979 (CERN, Geneva, 1980), Vol. 1, p.50.
- 11) We have used a parametrization for the pair production of $D\bar{D}$

$$\frac{d^2\sigma}{dx dp_T} = a(1 - |x|)^4 \frac{p_T}{E_D^*} e^{-2p_T} \text{ with } x = p_L/p_L^{\max},$$

which gives reasonable agreement with the observed visible energy spectrum above 20 GeV. Contributions due to the shower cascade in the beam dump have been included; they amount to 10% of the event rate. For the semileptonic decay of D mesons we have used the model of N. Cabibbo and L. Maiani, preprint No. 145, Ist. Fisica Univ. Roma (1979) and Phys. Lett. 79B (1978) 109. $\Lambda_c^+ \bar{D}$ associated production has been neglected.

- 12) In approximately 10% of these events the muon leaves the detector without traversing enough detector planes to perform a momentum measurement by magnetic deflection. A lower limit of muon momentum determined by the visible range is used for these events to calculate the visible total energy.
- 13) The charge of muons leaving the detector, only 10%, without momentum analysis has been assigned using the observed spectrum and the currently known shape of the y distributions; see also ref. 9.
- 14) H.W. Atherton et al., Precise measurements of particle production by 400 GeV/c protons on Be targets, Report CERN 80-07 (1980).
- 15) M. Jonker et al., CHARM Collaboration, Direct detection of charged current electron neutrino events in a fine-grain calorimeter, to be published in Nucl. Instrum. Methods.

Table 1

Event summary ($2 < E_{sh} < 20$ GeV) .
Combined data from density 1 and density 1/3 runs

	Muonless events	One-muon events	Systematic error
Raw event numbers	291	469	
Corrections from:			
πK decay muons	$+ 3.7 \pm 0.2$	$- 3.7 \pm 0.2$	± 1.6
soft muon loss	-23.3 ± 1.7	$+23.3 \pm 1.7$	± 4.0
side muon loss	-11.5 ± 0.5	$+11.5 \pm 0.5$	± 2.0
cosmic background	$- 9.5 \pm 1.5$	0	0
Corrected event numbers	250.4 ± 17.2	500.1 ± 21.7	± 4.7
Expected contributions:			
muon neutrino NC	162 ± 7		± 3.0
electron neutrino (non-prompt)	19.7 ± 0		± 4.0
Prompt events:			
by subtraction	69 ± 19		± 8
by extrapolation	43 ± 38		
Prompt excess:			
over $D\bar{D}$	54 ± 19		± 9

Table 2

Event summary ($E_{sh} > 20$ GeV)
Combined data from density 1 and density 1/3 runs

	Muonless events	One-muon events
Raw event numbers	271	341
Corrections from:		
π/K decay muons	+ 7 $\pm$ 0.6	- 7 $\pm$ 0.6
soft muon loss	-10.6 $\pm$ 0.4	+10.6 $\pm$ 0.4
side muon loss	- 5.9 $\pm$ 0.3	+ 5.9 $\pm$ 0.3
cosmic background	0	0
Corrected event numbers	261.5 $\pm$ 17 (stat.) $\pm$ 2 (syst.)	350.5 $\pm$ 18.7 (stat.) $\pm$ 2 (syst.)
Expected contributions:		
muon neutrino NC	113.5 $\pm$ 6.1	
non-prompt neutrinos	39.6 $\pm$ 8.2 ($\nu_e + \bar{\nu}_e$)	226.5 $\pm$ 26.0 ($\nu_\mu + \bar{\nu}_\mu$)
Prompt events:		
by subtraction	108 $\pm$ 18 (stat.) $\pm$ 8.5 (syst.)	124 $\pm$ 19 (stat.) $\pm$ 26 (syst.)
by extrapolation	116 $\pm$ 37	90 $\pm$ 38

Table 3

Prompt one-muon event rates ($E_\nu > 20$ GeV)
corrected for a muon momentum cut of 4 GeV/c

Reaction	Rate/(ton ($\times 10^{17}$ POT) a) Subtraction of conventional background (from density-1 runs)	Rate/(ton ($\times 10^{17}$ POT) a) Extrapolation to infinite density
$\nu_\mu N \rightarrow \mu^- X$	0.107 ± 0.027 (stat.) ± 0.033 (syst.)	0.106 ± 0.054
$\bar{\nu}_\mu N \rightarrow \mu^+ X$	0.069 ± 0.015 (stat.) ± 0.006 (syst.)	0.091 ± 0.029

a) POT is an abbreviation of protons on target corrected for dead-time.

Figure captions

- Fig. 1 Layout of the beam-dump experiment
- Fig. 2 Shower energy distribution of prompt muonless events in excess of muon neutrino NC interactions for $\rho = 1$ and $1/3$. The points show the distribution of electron neutrino interactions expected from standard $D\bar{D}$ production and decay. The content of the bin from 2 to 10 GeV is increased by a factor of 1.25. ν_X denotes other possible neutrinos leading to muonless final states.
- Fig. 3 Observed visible energy spectrum of CC ($\nu_e + \bar{\nu}_e$) events of prompt and non-prompt origin for $\rho = 1$ and $1/3$. The content of the bin from 2 to 10 GeV is increased by a factor of 1.25. The sum of prompt CC ($\nu_e + \bar{\nu}_e$) events from standard $D\bar{D}$ decay and of non-prompt CC ($\nu_e + \bar{\nu}_e$) events is also shown.

Fig. 1

Fig. 2

Fig. 3