PROMPT NEUTRINO PRODUCTION IN A PROTON BEAM-DUMP EXPERIMENT

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ABSTRACT

In the interactions of 400 GeV/c protons with copper nuclei, a flux of prompt neutrinos is observed. The reactions produced by these neutrinos in our apparatus appear consistent with those of electron- and muon-neutrinos. The prompt neutrino fluxes are interpreted as being due to associated production and subsequent semi-leptonic decay of charmed hadrons. The prompt flux ratio $\bar{\nu}_\mu/\nu_\mu = 0.46^{+0.21}_{-0.16}$ suggests a sizeable production of charmed baryons near the forward direction. The ratio of prompt $e^- + e^+$ to $\mu^- + \mu^+$ event rates is $0.64^{+0.22}_{-0.15}$, where unity is expected from e- μ universality.

1. INTRODUCTION

In a first beam-dump experiment carried out at the CERN Super Proton Synchrotron (SPS) in 1977, evidence of an excess of electron-neutrino events over the number expected from conventional sources was reported [1-3]. The purpose of the experiment was the search for neutrinos produced either directly in a proton-nucleus collision or originating from the decay of short-lived particles (lifetime $\leq 10^{-11}$ s). Neutrinos produced in this way are referred to as prompt. The observed prompt flux of electron-neutrinos has been attributed to the production and subsequent semileptonic decay of charmed D mesons.

Here we report results from a second beam-dump experiment performed in 1979 at the CERN SPS, mainly in order to establish a prompt muon-neutrino flux, but also to resolve some discrepancy in the results for the prompt electron-neutrino flux between the CERN-Dortmund-Heidelberg-Saclay (CDHS) counter experiment [2] and the BEBC [3] and GGM [1] bubble chamber experiments.

In Section 2 of this paper, the experimental set-up is described. In Sections 3 to 5, the measurements on muonless, single-muon, and dimuon events are presented. In Section 6, the results are compared with model expectations.

2. EXPERIMENTAL SET-UP

As in the previous experiment [2], a 400 GeV/c extracted proton beam was dumped into a thick copper target at zero degree with respect to our neutrino detector located 890 m downstream from the dump. The secondaries of the primary proton interaction are moderated in one interaction length, so that the neutrino flux from the decay of conventional long-lived particles such as π , K, Λ is reduced by three orders of magnitude relative to the normal neutrino beam obtained from a decay path of 300 m.

An improvement over the previous experiment is the use of two targets with average relative densities of 1 and $1/3$, to permit separation of the prompt from the conventional neutrino flux by extrapolation to infinite target density. Whilst the conventional background is small for electron-neutrinos, it constitutes the

bulk of the observed muon-neutrino flux. Hence the method of extrapolation is of particular relevance to the determination of the prompt muon-neutrino flux.

While the density-1 target consisted of a solid copper block, the density- $1/3$ target was built of 2 cm thick copper disks, spaced 4 cm apart. The detailed design of the targets is shown in Fig. 1.

The proton intensity per burst was measured with a beam current transformer located far upstream in the ejected proton beam line.

The potentially most dangerous source of systematic uncertainties in the determination of the prompt muon-neutrino flux is proton beam-scraping upstream of the dump. Such proton interactions could increase the conventional muon-neutrino flux considerably, as the secondaries have a long decay path. In order to ensure that proton beam-scraping did not significantly increase the conventional flux, eight ionization chambers were installed along the ejected proton beam line. Their readings were recorded continuously during data taking. They were calibrated by flipping a 70 μ m thick Al foil into the proton beam, inducing a proton beam loss of 1.7×10^{-4} . During the whole experiment the signals were kept typically an order of magnitude below this calibration value. The chambers were placed such that all critical bending stations of the proton beam were monitored. Although the monitors did not cover the full azimuthal angle around the beam, it is believed that proton beam-scraping made no significant contribution to the flux of conventional neutrinos originating from the dump.

Additional background was generated by material positioned about 1 m upstream of the dump (target monitor, vacuum windows, etc.). The increase of the conventional background was $(5.8 \pm 0.6)\%$ in the case of the density-1 dump. All prompt and non-prompt rates given below are corrected for this effect.

The neutrino detector used in this experiment has been described elsewhere [4]. It is a magnetized iron/scintillator calorimeter interspersed with drift chambers. Its dominant features are its excellent muon detection and measurement capability, and its large fiducial mass of about 500 t. The detector is well suited to measuring muon-neutrino initiated events with one or more muons in the final state. For

electron-neutrino initiated events the electromagnetic shower of a final-state electron is hidden in the hadronic shower. A flux of electron-neutrinos can thus not be detected on an event-by-event basis, but rather as a global excess of muonless events above the level expected from standard neutral-current events. Higher neutrino flavours (e.g. ν_τ) yield predominantly muonless events, and their detection on top of a substantial electron-neutrino flux seems almost impossible. Muonic events from higher neutrino flavours have anomalous kinematic configurations when reconstructed as muon-neutrino charged-current events [5], but again the separation of such events from the large muon-neutrino background seems impossible.

Table 1 summarizes the more important experimental parameters of the beam-dump experiment. About 70% of the data were taken with the density-1 target.

Two other groups, the Aachen-Bonn-CERN-London-Oxford-Saclay (ABCLOS) Collaboration [6], and the Amsterdam-CERN-Hamburg-Moscow-Rome (CHARM) Collaboration [7], were taking data in the same beam-dump exposure, and have reported results.

3. RESULTS ON MUONLESS EVENTS

The separation of muonless events from muonic events is based on the "event length", i.e. the range of the most penetrating particle of the event in iron, projected onto the detector axis. This technique has been used before to measure the neutral- to charged-current ratio (NC/CC) of muon-neutrinos [8].

In our detector, the only measurable kinematic quantity of muonless events is the total shower energy. Since the trigger of the detector is only fully efficient above 4 GeV, a minimum shower energy of 5 GeV is required in the analysis.

When interpreting the muonless event sample as a function of the shower energy, it has to be kept in mind that in the case of charged-current events induced by electron-neutrinos, the shower energy is the total energy, whilst in the case of neutral-current events, the shower energy is the hadronic energy.

The event vertex is required to be within a fiducial region in the first 11 modules of the detector, with radius less than 1.6 m. The fiducial mass is 465 t.

The distribution of the event length for events with $E_{sh} > 10$ GeV is shown in Fig. 2. The peak below event lengths of 150 cm of iron is due to muonless events. A cut in the event length logarithmically dependent upon the shower energy according to $L_{cut} = 75 + 38 \ln E_{sh}$ (GeV) cm has been used to separate muonless from muonic candidates. The candidate event numbers, corrected for cosmic-ray background, are given in Table 2 as function of the shower energy.

The cosmic-ray background contributes mainly to muonless events. This background is subtracted with the help of auxiliary data taken regularly outside the accelerator spill.

The correction for muonic events with a short muon hidden in the hadronic shower is based on the number of events in a "monitor region", with event length between $L_{cut} + 75$ cm and 510 cm. The extrapolation from the monitor region into the region of short event lengths is done by means of a Monte Carlo simulation program. The resulting rates of genuine muonless and muonic events are given in Table 2.

The ratio of muonless to muonic events is 0.82 ± 0.05 , for shower energies above 20 GeV, in the density-1 exposure. This is in agreement with the result of our earlier beam-dump experiment, 0.84 ± 0.08 [2]. The striking difference between this ratio and the one expected from experiments with muon-neutrino beams [8], $R = NC/CC = 0.31 \pm 0.01$, has been interpreted as being due to a prompt flux of electron-neutrinos originating from the semileptonic decay of charmed particles [2].

The determination of the prompt electron-neutrino contribution can be done either by extrapolation to infinite target density, or by subtraction of the muon-neutrino induced neutral-current contribution, and of the calculated conventional background from decays of K_{e3} , Λ_{e3} , etc. Here we prefer the subtraction method, since it yields smaller statistical errors and is at the same time uncritical from the systematic point of view. To have the best signal-to-noise ratio, we limit ourselves to the data of the density-1 exposure. The extrapolation result gives nearly the same results, although with larger errors.

The subtraction of muon-neutrino induced neutral-current events is based on the observed number of muonic events (note that this subtraction removes all ν_μ and $\bar{\nu}_\mu$ induced neutral-current events, the prompt as well as the conventional ones). The subtraction of both neutral- and charged-current events coming from the conventional electron-neutrino background is performed using the fluxes calculated by Wachsmuth [9]. The systematic uncertainty of these fluxes is estimated to be 20%.

The results are given in Table 2, and plotted in Fig. 3 as a function of the shower energy. The remaining excess after all subtractions is interpreted as consisting of charged- and neutral-current electron-neutrino events. It is shown, including the statistical errors, in Fig. 4.

At low shower energies, $2 < E_{sh} < 20$ GeV, a striking enhancement in the excess of muonless events has been reported by the CHARM Collaboration [7]. Our data, in the interval $5 < E_{sh} < 20$ GeV, do not show this anomaly.

4. RESULTS ON SINGLE-MUON EVENTS

The basic selection criterion for single-muon events is that the muon must traverse at least five consecutive drift chambers, or equivalently have a momentum in excess of 5 GeV. The muon momentum is reconstructed by a computer program, except in a few percent of all cases where the reconstruction is done by hand.

The event vertex is required to be within a fiducial region in the first 12 modules of the detector, with radius less than 1.6 m. The fiducial mass is 492 t. In the density-1 exposure, 1506 single-muon events with $E_{tot} \geq 20$ GeV are observed; 1352 events are observed with density $1/3$. The data are given in Table 3 as a function of the total energy.

The ratio of observed μ^+ to μ^- events, uncorrected for cuts, is 0.198 ± 0.014 in the density-1 run. This is in agreement with the ratio 0.22 ± 0.02 measured in our earlier beam-dump experiment [2].

In Fig. 5 the measured distributions in $y = E_H/E_\nu$ are compared with a Monte Carlo simulation of the distributions expected for ν_μ and $\bar{\nu}_\mu$ induced charged-current events. The agreement is good. Hence we will assume that all these events -- prompt as well as conventional -- originate from ν_μ and $\bar{\nu}_\mu$ interactions.

The magnetic field of the magnet toroids was oriented such that negative muons were focused towards the axis of the spectrometer. The over-all acceptance is shown in Fig. 6 as a function of the neutrino energy. For large energies the acceptance is better for antineutrino events because of the dominant $(1 - y)^2$ term in the y -distribution. At low energies the focusing property of the magnetic field favours neutrino events.

The normalized rates of μ^- and μ^+ events for the runs with density-1 and density- $1/3$ are given in Table 3, and plotted in Figs. 7a and 7b, as function of the total energy.

The determination of the conventional background due to neutrinos from π and K decay is performed in two ways: by density extrapolation, and by calculation on the basis of the muon fluxes measured in the shield.

The extrapolation method is straightforward and safe, but requires large statistics and a precise relative normalization of the runs at different dump density. The extrapolation is made according to the expression

$$R_{\text{prompt}} = [(3 + \beta)R_1 - (1 + \alpha)R_{1/3}]/(2 + \beta - \alpha) ,$$

where

R_{prompt} is the prompt rate,

R_1 is the rate obtained with the density-1 target,

$R_{1/3}$ is the rate obtained with the density- $1/3$ target,

$\alpha = (5.8 \pm 0.6) \times 10^{-2}$ is the calculated conventional neutrino background from proton interactions upstream of the dump relative to that from the density-1 target, and

$\beta = (3.8 \pm 0.4) \times 10^{-2}$ is the same quantity for the geometry of the density- $1/3$ target.

The subtraction method is superior from the point of view of statistical accuracy, but is more affected by systematic uncertainties. The calculation of the flux of conventional neutrinos originating from the interactions of 400 GeV/c protons in a solid copper dump has been performed by Wachsmuth [9]. It is based on measurements of the muon flux in the iron shield. The measurements were made at four shielding depths, corresponding to minimum muon momenta of 23, 57, 94, and 136 GeV/c, within an angle of 1 mrad with respect to the forward direction. Measurements at three dump densities 1, $\frac{1}{2}$, and $\frac{1}{3}$, permitted the extrapolation to infinite density to obtain the muon flux from conventional π , K decays. This flux is then compared with the muon flux predicted by a simple model where all protons interact in the beginning of the dump. In this model, the nuclear cascade developing in the copper dump is replaced by a decay path of one absorption length (18 cm for π , 21 cm for K). The distributions of positive and negative π 's and K's as a function of angle and momentum are adjusted such as to reproduce the results from 400 GeV p-Be collisions, where the secondaries have been measured at transverse momenta of 0 and 500 MeV/c, and at longitudinal momenta of 60, 120, 200, and 300 GeV/c [10]. The difference in production in Be and Cu at 400 GeV is accounted for by scaling (in the ratio of the longitudinal momentum to the incident proton momentum) particle production ratios of Be and Cu measured at 24 GeV/c incident proton momentum to a proton momentum of 400 GeV/c. Finally, thick target effects are taken into account by fitting the theoretical muon flux to the measured flux of conventional muons by varying the absolute number and the momentum distribution of the π 's. The procedure results in a depletion at large π momenta, and in an increase at small momenta.

The systematic uncertainty of the conventional neutrino flux is estimated by Wachsmuth at the level of 10% [9]. An additional error arises from the neutrino total cross-section which is needed to calculate event rates. We assume a cross-section slope $\sigma/E = (0.65 \pm 0.06) \times 10^{-38} \text{ cm}^2/\text{GeV}$ for neutrinos, and $\sigma/E = (0.30 \pm 0.03) \times 10^{-38} \text{ cm}^2/\text{GeV}$ for antineutrinos, where the 10% error accounts for systematic uncertainties of the absolute normalization and of deviations from the linear energy dependence.

The results for prompt μ^- and μ^+ rates from both extrapolation and subtraction are listed in Table 4 and plotted in Fig. 8. The systematic errors quoted for the rates above 20 GeV total energy reflect an over-all uncertainty of 5% in the relative normalization of the density-1 and density- $1/3$ runs, and a 15% over-all uncertainty in the calculation of the conventional muon-neutrino background.

In the case of μ^- events, the results from the extrapolation and subtraction techniques agree within errors (see Table 4). Moreover, the number of prompt events above 20 GeV total energy is significantly different from zero, establishing the existence of a prompt ν_μ flux in the beam-dump experiment. In the case of μ^+ events, the results from the two methods do not agree as well as they should on the basis of the stated errors. Whilst the subtraction method yields a non-zero flux of prompt $\bar{\nu}_\mu$, the result from the extrapolation method indicates a very small prompt flux of $\bar{\nu}_\mu$, if any.

5. RESULTS ON DIMUON EVENTS

In the 1977 and 1979 beam-dump experiments, several dimuon events have been observed. In order to improve the small statistics, the events observed in the 1977 density-1 exposure have been included in the analysis.

For dimuon candidates it is required that both muons traverse at least five consecutive drift chambers, and that the total visible energy $E_{\text{vis}} = E_H + E_{\mu_1} + E_{\mu_2}$ exceeds 20 GeV. The assignment of the "leading" muon is made such that the transverse momentum of the non-leading muon with respect to the shower direction assumes the smaller value. This definition stems from the interpretation of the dominant source of dimuon events as being due to single charm production and subsequent semileptonic decay.

In Table 5 the observed number of opposite-sign and like-sign dimuon events is compared with the number expected from the measurement of ν_μ and $\bar{\nu}_\mu$ interactions in wide-band beam exposures [11,12]. The observed and expected numbers of events are comparable. Although the observed number of events is somewhat higher, the numbers are very small and we do not consider the difference to be significant.

6. DISCUSSION OF RESULTS

6.1 Prompt neutrino rates

The observed prompt signals of muonless and single-muon events confirm the main results of the earlier beam-dump experiments [1-3]. They are interpreted as being due to charged- and neutral-current interactions of electron- and muon-neutrinos. There is no experimental evidence for interactions of as yet unobserved particles such as the ν_T . Moreover, the expected fluxes of ν_T are well below the observed levels. Hence we assume that we are dealing with prompt fluxes of electron- and muon-neutrinos only.

The most precise result is the prompt rate of electron-neutrino interactions with shower energy above 20 GeV: 1.16 ± 0.11 (stat.) ± 0.11 (syst.) events per t of detector and 10^{18} protons (see Table 2). This rate is the sum of charged- and neutral-current interactions of ν_e and $\bar{\nu}_e$, but we have no experimental way to disentangle this complexity.

For the prompt rate of single-muon events, we shall use below the weighted average of the results obtained by extrapolation and subtraction. The systematic error on the average values is reduced since the two methods employed have quite different systematic uncertainties. The averaging procedure is questionable for the prompt μ^+ rates since the results from the two methods do not agree very well. Still, the average may be the most reliable value in the absence of additional information.

The average prompt rates are 1.23 ± 0.13 (stat.) ± 0.27 (syst.) μ^- events per t of detector and 10^{18} protons, and 0.27 ± 0.06 (stat.) ± 0.05 (syst.) μ^+ events (see Table 4). It should be kept in mind, however, that the quoted systematic error of the average prompt μ^+ rate is probably underestimated.

The flux, per incident proton, of prompt ν_μ with energy greater than 20 GeV is $(4.3 \pm 1.2) \times 10^{-8}$ $\nu_\mu/\mu\text{sr}$, and has an average energy of 60 GeV. This prompt flux refers to the small forward cone subtended by the detector.

The flux of prompt ν_μ in this forward cone may be compared with the number of π^+ mesons with energy greater than 20 GeV emitted into the same cone. The result is a ratio of prompt ν_μ to π^+ of $(9.2 \pm 2.8) \times 10^{-6}$, using the π^+ production calculated by Wachmuth [9].

6.2 Comparison of prompt $\bar{\nu}_\mu$ and ν_μ fluxes

The experimental result for the prompt $\bar{\nu}_\mu$ to ν_μ flux ratio is $0.46^{+0.21}_{-0.16}$ for neutrino energies greater than 20 GeV. Statistical and systematic errors are added in quadrature. The ratio is obtained from the observed prompt event rates after correcting for the difference in the $\bar{\nu}_\mu$ and ν_μ total cross-sections.

It is most immediate to interpret the prompt neutrino fluxes in terms of associated production and semileptonic decay of charmed hadrons. The prompt $\bar{\nu}_\mu$ to ν_μ flux ratio is then relevant for understanding the production mechanism of charmed hadrons in proton-nucleus collisions (see Section 6.3).

Our result favours a smaller flux of prompt $\bar{\nu}_\mu$ than of ν_μ , in partial disagreement with the results of other experiments. The ABCLOS Collaboration [6] reports a ratio of 0.79 ± 0.62 , and the CHARM Collaboration [7] a ratio of $1.3^{+0.6}_{-0.5}$. Another result which is of relevance here is reported by the CalTech-Stanford Collaboration [13]: in a search for prompt single muons in proton-iron collisions the ratio of prompt μ^- to μ^+ was measured to be 1.3 ± 0.3 in the forward hemisphere (note that the prompt μ^- to μ^+ ratio and the prompt $\bar{\nu}_\mu$ to ν_μ ratio should be identical in the same kinematical domain).

6.3 Cross-section for charm production

We parametrize the invariant inclusive cross-section for charm production in the form

$$E \frac{d^3\sigma}{dp_L dp_T^2} \propto (1 - |x_F|)^n e^{-2p_T},$$

where $x_F = p_L/p_{L\max}$, and where E , p_L , and p_T denote the energy and the longitudinal and transverse momentum of the charmed hadron. Our discussion is restricted to the simplest processes: $D\bar{D}$ and $\Lambda_c^+\bar{D}$ production, where D is a mixture of D^0 and D^+ .

Since our measurements refer to the very forward direction, it seems appropriate to apply quark counting rules [14] which find qualitative experimental support in the analogous case of forward production of strange hadrons by high-energy protons [15]. Inclusive Λ_c^+ , $\bar{D}$, and D production is then predicted to have exponents of the $(1 - |x_F|)$ term of $n = 1, 3$, and 7 , respectively.

In Fig. 9 we show the acceptance of neutrinos with energy greater than 20 GeV, originating from the semileptonic decay of the Λ_c^+ and the D , as a function of x_F . Large values of x_F are strongly favoured, so that the detection of a charmed particle is more efficient for flat x_F -dependence of the cross-section, or, equivalently, for small exponent n .

For the production of $D\bar{D}$ pairs, one would then expect a prompt $\bar{\nu}_\mu$ (from $\bar{D}$) to ν_μ (from D) flux ratio larger than unity. Since we observe the reverse, we conclude that $\Lambda_c^+\bar{D}$ production, which gives a ratio smaller than unity, is the dominant production mechanism in our small forward cone.

The shower energy distribution expected from Λ_c^+ with $n = 1$ and from $\bar{D}$ with $n = 3$ is shown in Fig. 4 as a dashed line. The data points are clearly shifted towards lower energy, and favour therefore higher values of n . The full line in Fig. 4 corresponds to $n = 3$ for Λ_c^+ and $n = 5$ for $\bar{D}$ production. All model calculations assume that the semileptonic branching ratios of the Λ_c^+ and the D are equal.

With an invariant inclusive cross-section for Λ_c^+ production of the form $(1 - |x_F|)^3 e^{-2p_T}$, and a linear A -dependence ($A = 63.5$ for copper), we obtain from the rate of prompt μ^- events a product of the cross-section and the semileptonic branching ratio of

$$\sigma(p + N \rightarrow \Lambda_c^+ + X) \times BR = (3.9 \pm 1.0) \mu\text{b/nucleon} ,$$

where the quoted error reflects measurement uncertainties only. The contribution from the hadronic cascade, after the primary proton interaction, is neglected in view of the large inherent uncertainties in the evaluation of the cross-section, arising mainly from the unknown A -dependence and the limited validity of the parametrization used in the entire phase space.

6.4 Comparison of prompt $e^- + e^+$ and $\mu^- + \mu^+$ event rates

The rate of prompt single-muon events, given in Table 4, can be compared with the rate of prompt single-electron events, or equivalently charged-current events induced by electron-neutrinos. The latter is obtained from the excess of muonless events (Table 2) by multiplying by a factor of 0.83 ± 0.02 in order to correct for the contribution of neutral-current events. In Table 6 the resulting rate is compared with the rates of prompt single-muon events. For these, the results are given separately for the extrapolation and subtraction methods and for the average.

Irrespective of charmed baryon or charmed meson production, e - μ universality predicts equal prompt $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$ fluxes, and equal rates of single-electron and single-muon events. Whilst the result with the prompt $\mu^- + \mu^+$ events obtained from extrapolation is consistent with unity, the result obtained from subtraction shows a more pronounced asymmetry. Adding statistical and systematic errors in quadrature, the result obtained from the average prompt $\mu^- + \mu^+$ rate is

$$\frac{\text{prompt } e^- + e^+}{\text{prompt } \mu^- + \mu^+} = 0.64 \begin{array}{c} + 0.22 \\ - 0.15 \end{array}.$$

We see no compelling reason to believe in a difference between the prompt e^- and e^+ and $\mu^- + \mu^+$ event rates, but a relatively large asymmetry is also not excluded by the data.

The ratio of prompt $e^- + e^+$ to $\mu^- + \mu^+$ events is sensitive to proton beam-scraping upstream of the dump. Ignoring a subset of the data with the largest response of the scraping monitors had no influence on the result.

Similar results for the ratio of prompt $e^- + e^+$ to $\mu^- + \mu^+$ events have been reported by the ABCLOS [6] and CHARM [7] Collaborations: $0.59^{+0.35}_{-0.21}$ and 0.48 ± 0.16 , respectively.

There have been speculations about a possible interpretation of a smaller electron-neutrino flux in terms of oscillations of ν_e 's into some other type of neutrino, possibly ν_τ 's [16]. The experimental result presented in this paper is not sufficient to help resolve this important question.

6.5 Limit on axion production

Bardeen et al. [17] have proposed a search for high-energy axions (a^0) via the Bethe-Heitler process,

$$a^0 + Fe \rightarrow \mu^+ \mu^- + X.$$

Since the coherent production process gives the dominant contribution, the experimental signature is an opposite-sign dimuon event with small $\mu^+ \mu^-$ invariant mass and no hadronic energy.

We observe no opposite-sign dimuon event with such characteristics. Thus from the 1977 and 1979 data together, we obtain the upper limit (90% c.l.) for the product of the axion production and interaction cross-sections:

$$\sigma(p + N \rightarrow a^0 + X_1) \times \sigma(a^0 + Fe \rightarrow \mu^+ \mu^- + X_2) < 1.9 \times 10^{-70} \text{ cm}^4/\text{nucleon}^2,$$

where a linear A-dependence for the production cross-section, and an axion spectrum identical to the π^0 spectrum from the primary proton interaction are assumed.

Bardeen et al. [17] have given the interaction cross-section: above 20 GeV the average cross-section is 6.5 pb/nucleon. Hence we obtain the following upper limit (90% c.l.) for the production cross-section of axions:

$$\sigma(p + N \rightarrow a^0 + X) < 29 \text{ pb/nucleon}.$$

7. SUMMARY

This beam-dump experiment has confirmed the earlier observation of a prompt flux of electron-neutrinos originating from the interactions of 400 GeV/c protons with copper nuclei. It has established the existence of a prompt flux of ν_μ , but indicates that the flux of prompt $\bar{\nu}_\mu$ is smaller than the flux of prompt ν_μ . This observation would require a dominant contribution of charmed baryon production in the forward direction.

The measured ratio of prompt electron-neutrino and muon-neutrino fluxes is smaller than unity, but not significantly so in view of the systematic errors. An inequality of the prompt electron-neutrino and muon-neutrino fluxes, if true, would require important new phenomena for its explanation.

The search for an anomalous rate of trimuon events was the initial aim of the first beam-dump experiment. No trimuon event has been found so far, only a few dimuon events with a rate roughly as expected.

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therein.

Table 1

Summary of the experimental parameters
of the beam-dump experiment

	Density-1	Density- $\frac{1}{3}$
Eff. number of protons	6.62×10^{17}	2.48×10^{17}
Spill length	23 μ s	
Distance dump-detector	890 m	
Fid. mass in 1μ analysis	492 t	
Fid. mass in 0μ analysis	465 t	
Angle subtended by the detector	1.02×10^{-5} sr	

Table 2

Candidate event numbers, rates of muonless and muonic events, conventional $(\bar{\nu}_e)$ background, and excess rate of muonless events as a function of the shower energy. The candidate event numbers are corrected for cosmic-ray background only. All rates are normalized to 10^{18} protons on target and 1 t of detector. The data refer to the density-1 exposure.

E_{sh} (GeV)	Muonless event candidates	Muonless (0μ) event rate	Muonic event candidates	Muonic (1μ) event rate	Convent. $(\bar{\nu}_e)$ backgr.	Excess rate a)
5-20 ^{b)}	631 $\pm$ 36	1.60 $\pm$ 0.13	880 $\pm$ 34	3.48 $\pm$ 0.12	0.190	0.33 $\pm$ 0.13 $\pm$ 0.13 (syst.)
20-40	302 $\pm$ 18	0.81 $\pm$ 0.07	371 $\pm$ 19	1.46 $\pm$ 0.07	0.136	0.22 $\pm$ 0.07
40-60	164 $\pm$ 13	0.49 $\pm$ 0.05	157 $\pm$ 13	0.58 $\pm$ 0.05	0.078	0.23 $\pm$ 0.05
60-80	118 $\pm$ 11	0.34 $\pm$ 0.04	103 $\pm$ 10	0.40 $\pm$ 0.04	0.041	0.18 $\pm$ 0.04
80-100	81.0 $\pm$ 9.1	0.27 $\pm$ 0.03	44.0 $\pm$ 6.7	0.15 $\pm$ 0.02	0.019	0.21 $\pm$ 0.03
100-120	50.7 $\pm$ 7.2	0.14 $\pm$ 0.03	27.0 $\pm$ 5.3	0.12 $\pm$ 0.02	0.009	0.09 $\pm$ 0.03
120-140	36.0 $\pm$ 6.1	0.11 $\pm$ 0.02	16.0 $\pm$ 4.1	0.07 $\pm$ 0.02	0.004	0.08 $\pm$ 0.02
140-160	21.0 $\pm$ 4.7	0.07 $\pm$ 0.02	9.0 $\pm$ 3.2	0.04 $\pm$ 0.01	0.002	0.05 $\pm$ 0.02
160-180	11.8 $\pm$ 3.6	0.04 $\pm$ 0.01	4.0 $\pm$ 2.2	0.01 $\pm$ 0.01	0.001	0.04 $\pm$ 0.01
> 180	18.0 $\pm$ 4.4	0.06 $\pm$ 0.02	4.0 $\pm$ 2.2	0.01 $\pm$ 0.01	0.000	0.06 $\pm$ 0.02
> 10	1088.9 $\pm$ 33.7	3.04 $\pm$ 0.12	1108.9 $\pm$ 33.3	4.29 $\pm$ 0.12	0.384	1.33 $\pm$ 0.13
> 20	801.8 $\pm$ 28.5	2.33 $\pm$ 0.10	734.7 $\pm$ 27.1	2.85 $\pm$ 0.10	0.290	1.16 $\pm$ 0.11 $\pm$ 0.11 (syst.)

a) Excess = $0\mu - 0.31 \times 1\mu - \text{convent. } (\bar{\nu}_e) \text{ background.}$

b) All entries scaled to a 20 GeV bin width.

Table 3

Raw observed numbers of μ^- and μ^+ events, and corrected rates per 10^{18} protons on target and 1 t of detector

E_{tot} (GeV)	Density-1				Density- $1/3$			
	μ^-		μ^+		μ^-		μ^+	
	No. of events	Rate	No. of events	Rate	No. of events	Rate	No. of events	Rate
5- 10	90	2.86 ± 0.31 a)	13	0.73 ± 0.26 a)	93	8.05 ± 0.86 a)	23	3.45 ± 0.82 a)
10- 20	198	1.86 ± 0.13	65	0.67 ± 0.08	222	5.68 ± 0.38	56	1.56 ± 0.21
20- 40	411	1.63 ± 0.08	102	0.41 ± 0.04	364	3.94 ± 0.21	109	1.18 ± 0.11
40- 60	263	0.95 ± 0.06	61	0.22 ± 0.03	274	2.69 ± 0.16	65	0.63 ± 0.08
60- 80	181	0.63 ± 0.05	29	0.10 ± 0.02	153	1.45 ± 0.12	32	0.30 ± 0.05
80-100	114	0.39 ± 0.04	26	0.088 ± 0.018	99	0.93 ± 0.09	16	0.15 ± 0.04
100-120	106	0.36 ± 0.04	11	0.037 ± 0.012	58	0.54 ± 0.07	15	0.14 ± 0.04
120-140	53	0.18 ± 0.03	8	0.026 ± 0.010	53	0.48 ± 0.07	2	0.018 ± 0.015
140-160	42	0.14 ± 0.02	5	0.016 ± 0.008	35	0.32 ± 0.05	8	0.070 ± 0.026
160-180	31	0.10 ± 0.02	3	0.010 ± 0.006	22	0.20 ± 0.04	0	
> 20	1257	4.57 ± 0.13	249	0.91 ± 0.06	1101	10.92 ± 0.33	251	2.51 ± 0.16

a) Scaled to a 20 GeV bin width.

Table 4

Rates of prompt μ^- and μ^+ events per 10^{18} protons
on target and 1 t of detector

E_{tot} (GeV)	Extrapolation		Subtraction (density-1 only)	
	μ^-	μ^+	μ^-	μ^+
20- 40	0.40 ± 0.16	-0.01 ± 0.08	0.30 ± 0.08	0.12 ± 0.04
40- 60	0.02 ± 0.12	-0.00 ± 0.06	0.15 ± 0.06	0.08 ± 0.03
60- 80	0.19 ± 0.09	-0.01 ± 0.04	0.17 ± 0.05	0.03 ± 0.02
80-100	0.11 ± 0.07	0.06 ± 0.03	0.12 ± 0.04	0.06 ± 0.02
100-120	0.27 ± 0.06	-0.02 ± 0.03	0.19 ± 0.04	0.02 ± 0.01
120-140	0.01 ± 0.05	0.03 ± 0.02	0.07 ± 0.03	0.03 ± 0.01
140-160	0.05 ± 0.04	-0.01 ± 0.02	0.08 ± 0.02	0.02 ± 0.01
160-180	0.05 ± 0.04	0.02 ± 0.01	0.07 ± 0.02	0.01 ± 0.01
> 20	1.17 ± 0.26 ± 0.32 (syst.)	0.05 ± 0.12 ± 0.07 (syst.)	1.33 ± 0.13 ± 0.49 (syst.)	0.38 ± 0.06 ± 0.08 (syst.)
> 20	Average rate of prompt μ^- Average rate of prompt μ^+		$1.23 \pm 0.13 \pm 0.27$ (syst.) $0.27 \pm 0.06 \pm 0.05$ (syst.)	

Table 5

Summary of dimuon events

Exposure	Single- μ events	Dimuon events observed ^{a)}	Dimuon events expected ^{a)}
Density-1	$1980 \mu^- + 410 \mu^+$	$5\mu^- \mu^+ + 1\mu^+ \mu^-$ $1\mu^- \mu^-$	$2.2\mu^- \mu^+ + 1.3\mu^+ \mu^-$ $0.5\mu^- \mu^-$
Density- $1/3$	$1100 \mu^- + 250 \mu^+$	$4\mu^- \mu^+ + 2\mu^+ \mu^-$ $2\mu^- \mu^-$	$1.2\mu^- \mu^+ + 0.7\mu^+ \mu^-$ $0.3\mu^- \mu^-$

a) The first muon denotes the leading muon, the second the non-leading muon.

Table 6

Comparison of prompt $e^- + e^+$ and $\mu^- + \mu^+$ rates for $E_{\text{tot}} > 20$ GeV.
The rates are normalized to 10^{18} protons on target and 1 t of detector.

	Rate	e/ μ ratio
Prompt $e^- + e^+$ rate (subtr. meth.)	$0.96 \pm 0.09 \pm 0.09$ (syst.)	
Prompt $\mu^- + \mu^+$ rate (extrap. meth.)	$1.23 \pm 0.29 \pm 0.39$ (syst.)	$0.78^{+0.26+0.35}_{-0.16-0.20}$ (syst.)
Prompt $\mu^- + \mu^+$ rate (subtr. meth.)	$1.70 \pm 0.14 \pm 0.57$ (syst.)	$0.56^{+0.08+0.29}_{-0.07-0.15}$ (syst.)
Prompt $\mu^- + \mu^+$ rate (average)	$1.50 \pm 0.14 \pm 0.32$ (syst.)	$0.64^{+0.09+0.19}_{-0.08-0.13}$ (syst.)

Figure captions

- Fig. 1 : Design of the dumps with average density-1 and density- $\frac{1}{3}$. All dimensions are given in millimetres.
- Fig. 2 : Event length distribution of events with $E_{sh} > 10$ GeV. The shaded background from cosmic-ray events is obtained from auxiliary measurements outside the accelerator spill.
- Fig. 3 : Data reduction in the analysis of muonless events, as a function of E_{sh} .
- Fig. 4 : Excess of electron-neutrino initiated, charged- and neutral-current events obtained by the subtraction method (black points). The errors shown are statistical only. The full and the dashed lines show the expectation from $\Lambda_c^+ \bar{D}$ production, with an invariant cross-section $\propto (1 - |x_F|)^n e^{-2p_T}$. The full line represents $n = 3$ for Λ_c^+ and $n = 5$ for $\bar{D}$, whereas the dashed line represents $n = 1$ and $n = 3$, respectively. Both expectations are normalized to the observed number of events above $E_{sh} = 20$ GeV.
- Fig. 5 : y -distribution of μ^- (a) and μ^+ (b) events with $E_{tot} > 20$ GeV. The full line represents a Monte Carlo simulation of the y -distribution of ν_μ and $\bar{\nu}_\mu$ CC events, including quasi-elastics, with the same cuts as applied to the data.
- Fig. 6 : Acceptance of ν_μ and $\bar{\nu}_\mu$ CC events as a function of E_{tot} . Both the geometrical acceptance and the acceptance in y are taken into account.
- Fig. 7 : Rates of all μ^- (a) and μ^+ (b) events for 10^{18} protons and 1 t of detector, from the density-1 exposure, as a function of E_{tot} . The errors shown are statistical only.
- Fig. 8 : Rates of prompt μ^- and μ^+ events for 10^{18} protons and 1 t of detector, as a function of E_{tot} . The points are obtained from the

extrapolation method, the full and dashed lines represent the results from the subtraction method. The errors shown are statistical only.

Fig. 9 : Acceptance of neutrinos from the semileptonic decays $\Lambda_c^+ \rightarrow \Lambda e \nu$ and $D \rightarrow K(K^*) e \nu$ ($K:K^* = 1:1$), as a function of x_F . The neutrinos are requested to hit the detector with energy greater than 20 GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7a

Fig. 7b

Fig. 8

Fig. 9