FERMILAB-CONF-78-121-E

UM-HE 78-44
(revised)

A Prompt Neutrino Measurement

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October 1978

Presented at the Bartol Research Foundation Workshop
on Charm Production and Lifetimes
October 19, 1978

(To be published by the American Institute of Physics)

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ABSTRACT

A test has been made to explore the possibility of beam dump neutrino experiments with short target-detector separations and modest detectors. Results have given a positive neutrino signal which is interpreted in the context of various charmed-meson production models. A limit to the lifetime and mass of the axion is also a byproduct of this test.

*Supported by the U.S. National Science Foundation and the Department of Energy

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INTRODUCTION

A test experiment has been performed parasitically in the M2 diffracted proton beam of the Meson Lab at Fermilab. A dimuon experiment, E-439,[1] targeted protons on a thick tungsten target which was followed by a 5.5m solid iron magnet assembly magnetized to 2.1 T (B horizontal). The neutrino detector was a 4-ton iron calorimeter[2] located 22 m from the tungsten target behind an additional 5.4m of steel, as indicated in Figure 1.

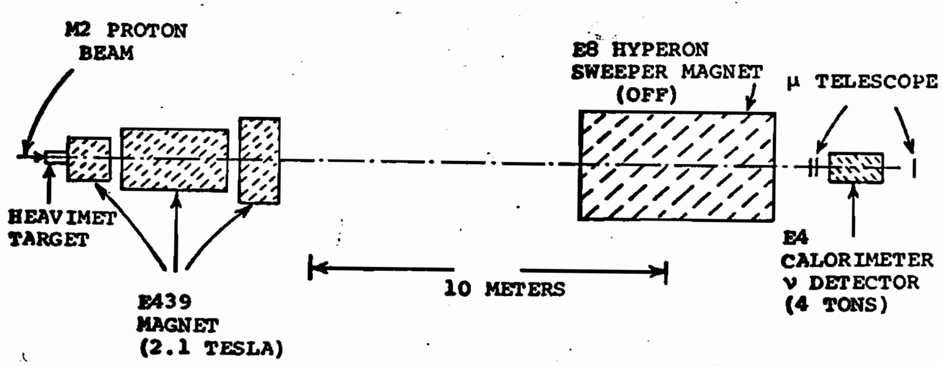
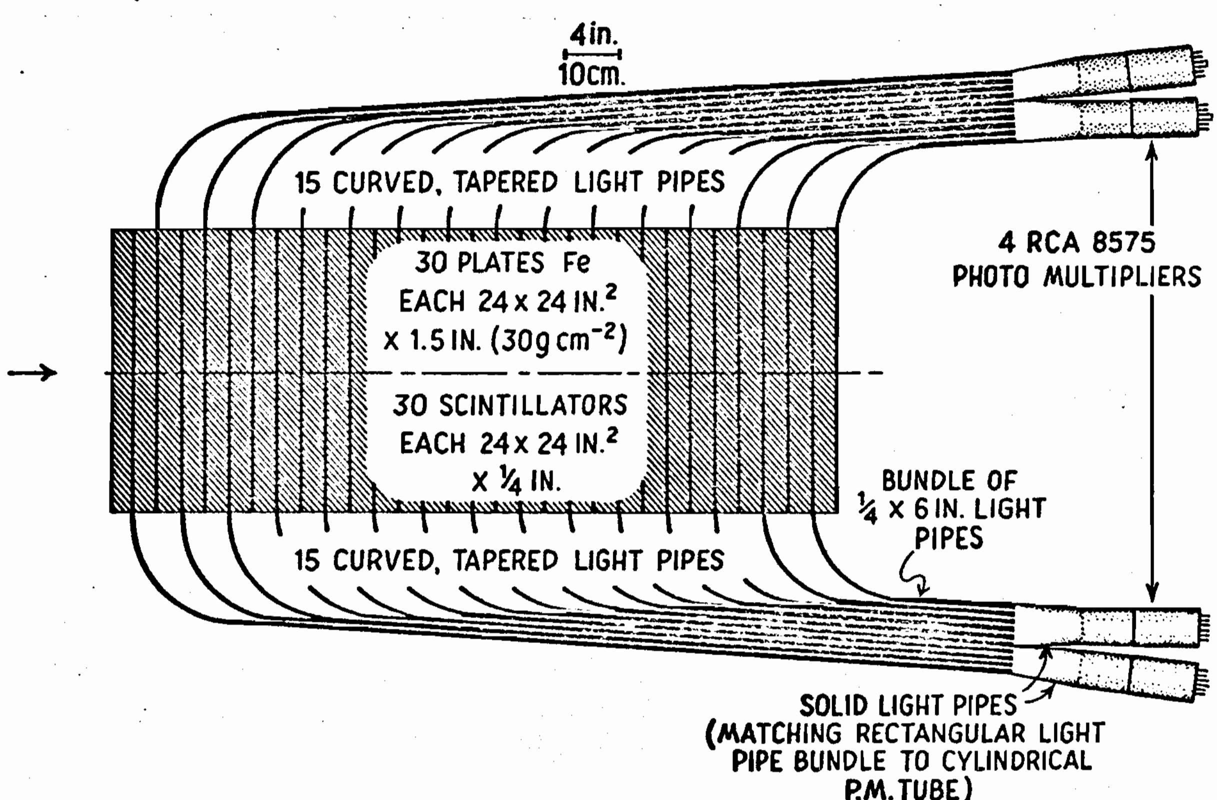


FIGURE 1: Experiment Configuration

Results from beam dump experiments at CERN[3] have indicated a source of prompt neutrinos, and D-pair production has been suggested as the mechanism. This experiment was implemented toward the end of E-439 running so that the running time corresponded to only about 2×10^{15} protons on target, and this was further significantly reduced by deadtime. Nevertheless a positive signal was obtained. If interpreted as D-pair production, this signal corresponds to a D-production cross-section of 60 to 80 μb.

EXPERIMENTAL DETAIL

Even behind the 10.9m of iron the muon flux was very high; a 30×30cm^2 scintillator telescope straddling the calorimeter on the beam axis recorded 5000 muons per 10^{11} protons on target.[4] As about 10^{-4} of energetic μ's produced an interaction in the calorimeter corresponding to ≳20 GeV energy release, it was necessary to shield the front face of the calorimeter with anticoincidence counters. Another source of false signal could be cosmic ray events (hadrons or air showers) from above. One 60×120cm^2 anticoincidence



MICHIGAN NEUTRON CALORIMETER

FIGURE 2

scintillator was accordingly put on top of the calorimeter. The experiment was located at the end of the Meson Detector Building with no overhead shielding. In order to reduce the calorimeter albedo from desired events from triggering this top counter, 5 cm of borated polyethylene were placed between the calorimeter and this counter.

The calorimeter consisted to 30 steel plates each 61 cm square and 3.9 cm thick with 0.64 cm scintillator between. The scintillator light was piped to four phototubes (Figure 2) which permitted left-right and front-back signal comparisons. Calibration in a test beam gave a calorimeter resolution $\sigma \simeq (73/\sqrt{E})$ % for hadrons of 20-40 GeV. Cherenkov pulses from the phototube light pipes were a possible source of concern; anticoincidence shielding and the requirement of ...

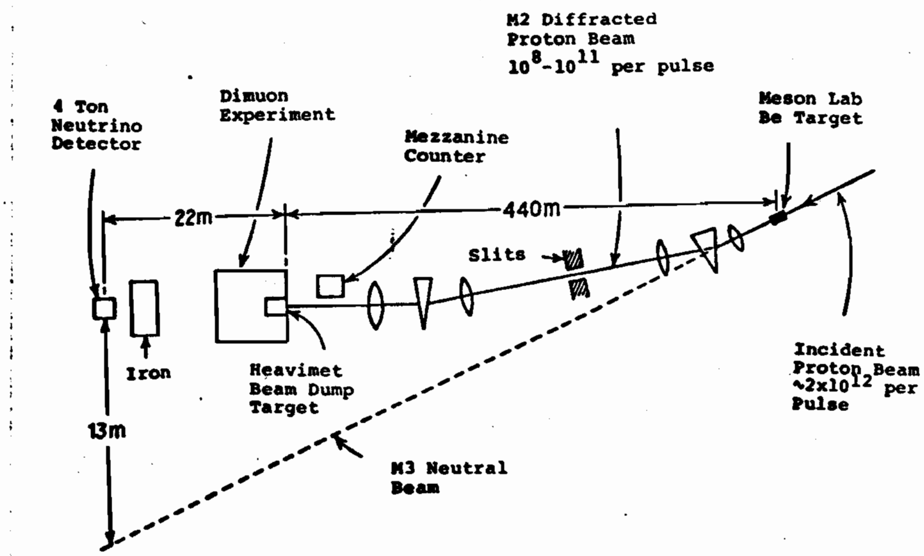


FIGURE 3: Schematic representation of the beam line. The meson target, the beam dump target, and the beam line slits are noted. The mezzanine counter is over the beam line about 3 m.

comparable pulses from phototubes on opposite sides effectively suppresses this problem.

The summed anticoincidence rate was about 5×10^6 per pulse during the data runs, and this limited the system live time to only 22%. The calorimeter threshold was set to about 10 GeV, or about 3.5 times the most probable muon pulse height. The neutrino event candidates were separated from spurious triggers by demanding a ratio of right to left calorimeter phototube pulse heights compatible with the measured resolution and the scatter measured from muon-initiated events. Cosmic ray and other spurious triggers were also reduced by requiring the event time to lie within a 4 ns band relative to the accelerator r.f. signal, again based on the muon calibration. Further, the time difference between the left and right calorimeter signals was required to lie within bounds of 6 ns (low E) and 4 ns (high E). The pulse area from each anticoincidence counter was digitized, in principle providing redundant information as the veto discriminator rejected all events accompanied by pulses in the anticoincidence counters. A cut was made on the veto ADC pulse area corresponding to 1/5 to 1/10 the most probable single particle signal; these result in one set of values in Tables I, II, and III. An upper limit on the true neutrino signal is obtained by ignoring the veto ADC signals and assuming that the anticoincidence electronics functioned ideally. These values are also noted in the tables.

The fiducial volume of the calorimeter is not certain. It is probable that vertices within 5 cm of the side edges of the calorimeter are recorded at significantly lower efficiencies; hence we take the area to be 2500 cm^2 (50×50 cm). The depth will be less that the 900 g/cm^2; again because cascades close to the back of the calorimeter will be detected inefficiently. This effect was studied with muon-induced electromagnetic cascades from which it was deduced that a depth of 700 $g\ cm^{-2}$ was the effective fiducial volume. Together with the edge cut, the effective mass of the detector was 1.75 metric tons.

Because of the anticoincidence counter which lay over the calorimeter to veto cosmic ray air showers, there was some probability that a neutrino event in the calorimeter would produce a scattered particle into this counter and veto itself. This was evaluated by looking both at the fraction of muon initiated events in which this counter fired, and by operating the system in a hadron beam and determining the faction of events in which this counter fired. A value of 30% was obtained from the muon-initiated events. The hadron data for this fraction fit an empirical function

$$f_i = 0.32 + 0.006\,(E_i - 20),$$

so that a corrected number of events can be obtained by scaling with a factor

$$K = \frac{1}{N}\sum_{i=1}^{N} \frac{1}{1 - f_i} .$$

RESULTS

Data were taken under four conditions: (1) high intensity on E-439 (data run) with about 1.5×10^{11} protons per pulse (runs 54 and 58); (2) low intensity on E-439 target at about 10% the data run intensity, or about 1.3×10^{10} protons per pulse (runs 69 and 71); (3) very low intensity, less than 10^9 protons per pulse (runs 74 through 79); and (4) cosmic rays (accelerator off; run 104). During (1), (2), and (3) the beam on the Meson Area target was similar; about 2×10^{12} per pulse.

The primary data from the high intensity run (1) contained 8 events of over 20 GeV if all cuts are applied, or 14 events if the digitized veto counter levels are ignored. The energies of these events are tallied in Table I.

TABLE I

Energies of prompt neutrino candidates from high intensity beam dump

E(GeV)	20	21	24	26*	29	34*	46
	20*	21*	26	27	33	39*	98*

*Accompanied by small veto signals.

The cosmic ray rate provides a reasonably certain (and statistically sound) background which may be subtracted from each of the data sets. It corresponds to about 10% of the high-intensity event rate. The two lower-intensity runs provide somewhat contradictory data on backgrounds although statistics are sufficiently modest to render an apparent contradiction rather insignificant. The background may be due either to the protons on the meson area target or to the scraping and to the collimators in the M2 beam line. The latter was monitored by a scintillation counter on the mezzanine of the Meson Detector Building and by the muon flux. The muon flux correlated reasonably with the mezzanine counter and these two were adjudged to be a more reliable monitor of background neutrino events than protons per pulse on the meson area target. The measured muon flux per pulse was actually about 1 1/2 times greater during the low intensity runs 69 and 71 than during the data runs 54 and 58. On the other hand, there were over twice as many neutrino events per muon in the data runs as in the low intensity runs. Thus we assume that most of the observed muons and a proportionate fraction (∿40%) of the neutrino events may be from upstream beam scrapping. The proton beam direction at the Meson Area target makes an angle of 27 mr with respect to a line from that target to our detector. However the first bends in the

M2 beam line would effectively channel some π^+ and K^+ along trajectories directed more nearly toward our detector.

TABLE II

Runs	Protons per pulse	Total targetted protons[a]	Pulses[a]	Mezzanine[a] counts	Muon telescope counts[a]	Events[c]
54,58	1.4×10^{11}	4.28×10^{14}	2,929	16×10^{6}	19.3×10^{6}	8(14)
69,71	1.3×10^{10}	2.73×10^{13}	2,091	19.4×10^{6}	29.3×10^{6}	6(9)
74,79	2×10^{8}	2.5×10^{12}	12,052	14.5×10^{6}	---	6(7)
104	0 (cosmic rays)		239,000[b]	---	---	74(103)

a. Corrected for dead time

b. Equivalent pulses

c. Total events without anticoincidence ADC cut in parentheses.

The effective number of beam dump events, with and without the veto ADC data, are corrected for cosmic ray background in Table IIIa, and then for background from neutrinos produced upstream of the beam dump in Table IIIb. In that table it was assumed that (1) the mezzanine counter rate, or (2) the number of pulses (porportional to protons on the meson area target) is proportional to the true background. On grounds of both plausibility and self consistency, it was subjectively decided to weight the corrected number of events 3:1 in favor of the mezzanine-corrected results. When averaged over both sets of lower-intensity runs and corrected for the self-veto effect, a pair of best-estimated net numbers of beam dump neutrino events are obtained: 6.2±4.8 (including veto ADC's) and 13.8±6.2 (ignoring veto ADC's). With the obvious uncertainties reflected by the diverse entries in Table III, we will take 10±5.5 as the best estimate of true neutrino events.

Table IIIa Events in each set of runs corrected for cosmic ray background

RUN	54,58		69,71		74-79		69-79	
a) INCLUDE VETO ADC b) IGNORE VETO ADS	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Net events corrected for cosmic ray rate	7.1	12.8	5.4	8.2	2.3	2.3	7.7	10.5

Table IIIb Beam dump events corrected for upstream neutrino sources based on the indicated low intensity runs (columns) and the background assumptions (rows).

RUN	69,71		74-79		69-79	
Constant background per pulse	-.5	1.4	6.5	12.2	5.5	10.6
Background correlated with mezzanine flux	2.8	6.1	4.7	10.2	3.4	7.9
Weighted 3/4 mezzanine background, 1/4 pulse background	2.0	5.3	5.2	10.7	3.9	8.6
Overall net beam dump events weighted by self-veto correction factor K=1.6	3.2	8.5	8.3	17	6.2	13.8

ERRORS

The data in Table III indicate the uncertainties in background and true beam-dump neutrino event rate and emphasize both the need for careful beam preparation (to avoid upstream sources of π- and K-decay neutrinos) and of careful measurements to appraise it. The best we can say from Table III is that our true signal appears to be 10±5 events. Various sources of normalization error besides the background subtraction and veto ADC uncertainty remain.

The fiducial mass of the calorimeter is uncertain to ±100 g cm^{-2}, or ±14% in depth, and ±2.5 cm in radius, or ±22% in area (although this is less significant in rates due to the radial fall-off in neutrino flux). Overall, the effective, radially-weighted fiducial mass is uncertain by ±30%. The absolute calibration of the calorimeter is uncertain by ±15%. In view of the observed neutrino event energy spectrum this reflects as a ±30% uncertainty in rate. The various timing cuts and the cut on the ratio of pulse heights from the two halves of the calorimeter cause little uncertainty. Nevertheless, there is perhaps a ±15% uncertainty due to the cumulative uncertainty of these criteria. The self-veto effect from the cosmic ray anticoincidence counter may be uncertain by ±20%.

All of these effects taken together add up to a 50% uncertainty in the results of Table III. They do not, however, modify the 2σ significance of the evidence for a positive beam-dump signal. An estimate of neutrinos from π and K decay within the beam dump based on the CERN BEBC data indicates that ~7% ~~15%~~ of our net beam dump signal may be from this source.

INTERPRETATION

Essentially all of the incident protons interact in the tungsten (Heavimet) target, so that the number of neutrinos produced is

$$N_\nu = N_p \left\{ \frac{\sigma_\nu(pW)}{\sigma_I(pW)} \right\} F(pW) \qquad (1)$$

where σ_ν and σ_I are neutrino production and inelastic cross sections, respectively, for protons on tungsten and F(pW) is an enhancement factor to account for neutrino production by degraded nucleons which continue beyond a first target interaction. The number of detected events is

$$N_{ev} = N_\nu \, \rho \ell \sigma(\nu Fe) \; G(E) \; \Delta\Omega \qquad (2)$$

where $\sigma(\nu Fe)$ is the neutrino interaction cross section on iron, and $G(E)\Delta\Omega$ is the fraction of the produced neutrinos which pass through the fiducial volume of the calorimeter and which, upon interaction, are detected in the calorimeter with a signal corresponding to >20 GeV.

In order to interpret direct neutrino production in terms of a specific model, it was assumed that all neutrinos come from D-decay, and that the branching ratio for semi-leptonic D-decay is 20%,[5] so that

$$\sigma_\nu(pp) = 0.4\sigma_D(pp)$$

where $\sigma_D(pp)$ is the production cross section for D pairs in nucleon-nucleon collisions.

It is necessary to interpret production processes in tungsten in terms of elemental pp processes. As it appears that production of ψ's, direct μ's, and large $p_\perp$ mesons is proportional to $\sim A^{1.0}$, it is reasonable to make the same assumption for direct neutrino production. Then

$$\sigma_\nu(pW) = A_W \sigma_\nu(pp)$$

so that Eq. (1) may be rewritten as

$$N_\nu = N_p \left[\frac{A_W \sigma_I(pp)}{\sigma_I(pW)}\right] \frac{\sigma_\nu(pp)}{\sigma_I(pp)} \; F(pW). \qquad (3)$$

The σ_I's are total interaction or inelastic cross sections and the factor in brackets in Eq. (3) has a value of 3.6 for tungsten. The intra-target cascading factor, F(pW) is estimated to be 1.12 for Drell-Yan processes for $m_{\mu\mu} > 7$ GeV, and does not include effects due to secondary pions. To the extent that the more copious lower energy pions are important in D production, F(pW) = 1.12 is an underestimate, and our deduced cross sections are correspondingly overestimates.

The value for $\rho\ell$ for the 700 g cm^{-2} (fiducial length) calorimeter is 4.2×10^{26} cm^{-2}. The neutrino interaction cross section is taken as $\sigma(\nu Fe) = A_{Fe}\, \sigma(\nu N)$. The values of cross sections are taken as

$$\sigma(\nu N) = 0.6 \; E(GeV) \times 10^{-38} \; cm^2,$$
$$\sigma(\bar{\nu} N) = 0.25 \; E(GeV) \times 10^{-38} \; cm^2. \qquad (5)$$

Equal numbers of neutrinos and antineutrinos are assumed. The interaction cross section was further scaled by 1.32 to include neutral current events, so that the effective $\sigma(\nu N)$, averaged over ν and $\bar{\nu}$, is $0.55E \times 10^{-38}$ cm^2 (E in GeV). The function G(E) is derived by folding the calorimeter resolution function with the calculated hadronic plus electro-magnetic products of the neutrino interactions (assuming equal numbers of ν and $\bar{\nu}$). This distribution is sketched in Figure 4 for 40 GeV neutrinos.

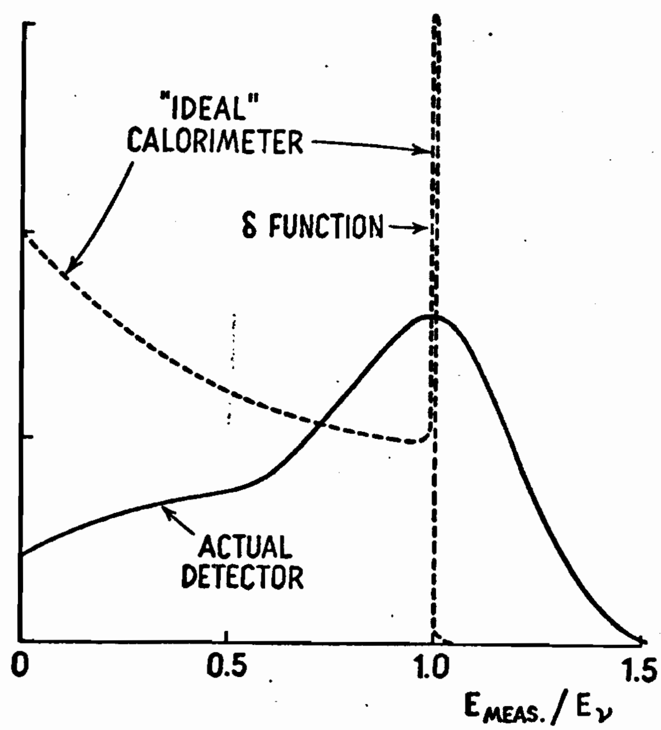


FIGURE 4: The expected response of an ideal detector (dashed line) and of a calorimeter with the experimental resolution to the assumed equal mix of ν_e and ν_μ. For neutral current events and ν_μ charged current events only the hadron cascade is detected with $0 \le E_h \le E_\nu$; for ν_e charged current events ($\sim$ 1/3 of the total) the entire neutrino energy appears in the cascade.

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The fraction of neutrinos within the calorimeter solid angle fraction $\Delta\Omega$ was calculated assuming that all ν came from D decays, $D \to K + \ell + \nu$ or $K^* + \ell + \nu$ using the computed ν spectrum. A sample of 30,000 events was run through a Monte Carlo program for each of several assumed D production models. The results of these calculations are tabulated in Table IV. From the observed neutrino events, the resulting calculated D-production cross sections are also tabulated for the different production models. We have also compared our results with the CERN BEBC 0 mr observations, considering only the electron neutrino events. The CERN beam dump target was copper, for which the factor $A\sigma_{pp}/\sigma_{pA} = 2.54$. A factor F(pCu) of 1.12 is applied to the CERN data to determine the cross section values of Table IV. The assumptions of the various D-production models are spelled out below.

Model I

$$\frac{d^2\sigma}{dy\,dp_\perp^2} \propto e^{-6m_\perp}\Bigg]_{-y_{lim}}^{+y_{lim}} \; ; \; m_\perp^2 = p_\perp^2 + m_D^2 ; \qquad (5)$$

where the y distribution was assumed flat between the cm y limits of ±0.5, ±1.5, or ±2.5.

Model IIa

$$\frac{d^2\sigma}{dx\,dp_\perp} \propto e^{-(1.75p_\perp + 10|x|)} \; ; \; x = (p_\parallel / p_\parallel(\max)_{cm}) . \qquad (6)$$

This model has been used by Lauterbach[6] as a fit to ψ production. Using this form and examining μ polarization data,[7] he sets a limit of 1 μb to D production by 400 GeV protons.

Model IIb

$$\frac{d^2\sigma}{dxdp_\perp^2} \propto e^{-(1.75p_\perp + 10|x|)}, \qquad (7)$$

in accord with a more commonly accepted $p_\perp$ distribution.

Model IIIa

$$E\,\frac{d^3\sigma}{dp^3} \propto (1-|x|)^4\, e^{-1.6p_\perp}, \qquad (8)$$

as fit to J/ψ production[7,8].

Model IIIb

$$E\,\frac{d^3\sigma}{dp^3} \quad (1-|x|)^4 e^{-2.2p_\perp}. \qquad (9)$$

Model IV

$$\frac{d^2\sigma}{dxdp_\perp^2} \; e^{-(2.2p_\perp + 9.7x')}, \qquad (10)$$

where $x' = p_{lab}/p_{beam}$. This model is used to fit data from another J/ψ production experiment.[9] The results are shown in Table IV.

Table IV

Cross Sections for Production of D-Pairs[1]

		This Experiment			CERN BEBC
Model[2]	y_{limit}	Probability $G(E)\Delta\Omega$(M.C.) for E>20 GeV released in cal.	$\bar{E}_\nu$	$\sigma(\mu b)$[4]	$\sigma(\mu b)$[5] 0 mr
Ia	0.5	0.008	26	700	500
Ib	1.5	0.052	51	60	50
Ic	2.5	0.131	87	17	5
IIa		.020	52	202	128
IIb		.05	54	76	46
IIIa		.102	55	72	50
IIIb		.115	54	64	44
IV		0.042	49	75	45

1. Semileptonic decays of D's of 20% assumed source of ν; equal numbers of $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$
2. See text for details of models
3. Based on Monte Carlo calculation of 30,000 events, $G(E)\Delta\Omega$(M.C.) defined in text.
4. Based on a signal of 10 events. See text for systematic errors.
5. Based on 15 e^+e^- events. (see Ref. 3)

The most sensitive published counter search for D's from hadronic interactions by Ditzler et al.[10] determined 95% c.l. upper limit cross sections for $K^-\pi^+$ $(K^+\pi^-)$ production at the D° mass. With $d\sigma/dp_\perp^2 \propto e^{-1.6p_\perp}$, they determined B $d\sigma/dy$ < 360 nb (290 nb) at y = -0.4 for $D° \to K^-\pi^+$ $(\bar{D}° \to K^+\pi^-)$. If D production is flat in $d\sigma/dy$ over $-1.5 < y < +1.5$ (equivalent to a hybrid of our models Ib and IIIa), these results are equivalent to an upper limit for $B\sigma$ for approximately 1 μb. If branching ratio for $D° \to K^-\pi^+$ of 1.8±0.5% is included, we have $\sigma(D°)$ < 48-60 μb per nucleon. If

$\sigma(D^{\circ}) = \sigma(\bar{D}^{\circ}) \doteq \sigma(D^{+}) = \sigma(D^{-})$, and all contribute equally to the neutrinos observed in this and the BEBC experiment, the limits correspond to an upper limit for D-pair production of about 100 μb, comfortably compatible with most of the values of Table IV.

As can be seen in Table IV, our limits vary enormously depending on the model. For all but Model Ic, our results are consistant with the CERN 0 mr BEBC data. Both our result and the BEBC result are consistant with reasonable models which assume that prompt neutrinos are from D-decays.

AXIONS

The results of this experiment may also be interpreted to set limits on axion lifetimes and hence mass. The observed number of axions would be given by relations analogous to Eqs. (1) and (2). Again, since axion production is a semi-weak process, we may expect the production of axions in tungsten, $\sigma_a(pW)$ to be given by

$$\sigma_a(pW) = A_W \, \sigma_a(pp)$$

so that

$$N_a = N_p \left(A_W \frac{\sigma_I(pp)}{\sigma_I(pW)} \right) \frac{\sigma_a(pp)}{\sigma_I(pp)} \quad F'(pW), \qquad (11)$$

analogous to Eq. (3). The intra-target cascading factor $F'(pW)$ may be considerably larger than for neutrino production via D-pairs as the axion threshold is presumably quite low. We will take $F'(pW) = 3.0$ assuming that first-generation pions and nucleons are effective in producing axions of over 20 GeV. There is also a factor for the decay of the axion, $\exp(-7.3\times10^{-8}/\gamma\tau)$ over our 22 m target-detector separation. For $E_{axion} = 24$ GeV, the exponent is unity for $\tau/m = 1.8\times10^{-12}$ sec MeV^{-1}. The observed number of axion interactions would then be (neglecting decay)

$$N'_{ev} = N_p \frac{\sigma_a(pp)}{\sigma_I(pp)} F'(pW) \left[\frac{A_W \sigma_I(pp)}{\sigma_I(pW)}\right] \left\{\rho \ell \sigma_I(ap) \Delta\Omega\right\}, \quad (12)$$

where $\sigma_I(ap)$ is the axion interaction cross section per nucleon in the calorimeter. The solid angle fraction, $\Delta\Omega$ was determined from $d^2\sigma/dydp_\perp^2 \propto \exp(-6m_\perp)$, with $m = 0.1\ m_\pi$ and a uniform y distribution over $-2.5 < y < +2.5$. This gave $\Delta\Omega = 0.09$. The resulting number of detected axions is then (neglecting decay)

$$N_{ev} = 5 \times 10^{66} \sigma_a(pp)\ \sigma_I(ap).$$

If our 10 events are all axions, our results would yield

$$\sigma_a(pp)\sigma_I(ap) = 2 \times 10^{-66}\ \text{cm}^4$$

This may be compared with the prediction by Ellis and Gaillard[11] of

$$\sigma_a(pp)\ \sigma_I(ap) \geq 9 \times 10^{-66}\ \text{cm}^4.$$

Even considering our large uncertainties our results appear to be incompatible with axions of very low mass.

As the axion lifetime is given[12] as

$$\tau > 10^{-10} \text{ (sec)},$$

our data may be interpreted as setting a lower limit to the axion mass of $\sim$ 25 MeV.

CONCLUSION

A two σ positive signal for direct neutrino production is observed, although the background is $\sim$1/3 of the signal, and normalization uncertainties are considerable. If the data are interpreted in terms of D production and semi-leptonic decay, they agree with the CERN BEBC beam dump results when reasonable D production kinematics are assumed. If on the other hand the neutrinos had an angular distribution characteristic of π and K decays, they would be produced in too small a solid angle to account for the signal we observe and the BEBC results. Our results are also in agreement with a preliminary report on a Fermilab measurement of direct muon production[13] and with upper limits to D production set by Fermilab counter experiments. We are in disagreement with the negative results on charm production from some hadron emulsion experiments.

Our results may be interpreted in terms of axion production only if the axion mass is greater than $\sim$ 25 MeV.

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