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COUNTING RATE IN THE PLANNED EXPERIMENT TO DETECT NEUTRINO INDUCED REACTIONS.

by

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SUMMARY

The number of neutrino events to be expected per ton of material at an angle of 6° from an internal target in a short straight section in the PS has been calculated. The same assumptions about the pion spectrum and theoretical cross-sections, were made as in a previous report[1]. However, in addition the limitations in vertical aperture introduced by the coils of the next magnet unit and the angle between the pions and the neutrinos were taken into account. It is found that these effects reduce the expected counting rate by an order of magnitude. For present operating conditions the expected rate is about 0.01 neutrino events of each kind in a 500 kg heavy liquid bubble chamber per day of operation. It is concluded that the experiment is not feasible under these conditions with present machine intensity and with detectors containing only a few tons of matter.

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I. INTRODUCTION

The theoretical interest in the interactions of high energy neutrinos, connected with the possible existence of an intermediate vector boson and the identity of neutrinos emitted in conjunction with electrons and muons, has prompted the preparation of extensive neutrino experiments using the 25 GeV CERN Proton Synchrotron as an intense neutrino source.

In a previous investigation¹⁾ the expected counting rate per ton of material was calculated under certain simplifying assumptions and found to be of the order of 1 event per ton per day, in agreement with an earlier estimate by Bernardini²⁾. Since the available propane bubble chambers could be filled with 0.75 and 0.45 tons of freon respectively, and since for many of the problems a small number of events would be sufficient, the experiment seemed promising. A counter assembly was also made incorporating several tons of lead and using a triggered expansion cloud chamber to observe the neutrino induced interactions.

These three detectors are installed on a line at an angle of 6° from a target in the short straight section 5 and surrounded by about 4000 tons of concrete for shielding. The closest detector, the Ecole Polytechnique bubble chamber, is at a distance of 50 metres from this target.

Pions produced in the target will decay over a 20 m length inside the machine tunnel, before they and their muon decay products are absorbed in 27 metres of concrete shielding in front of the bubble chamber.

At the chosen angle the pions will pass through the fringing field of the next magnet unit in the machine and suffer deflection and focusing or defocusing. Negative pions will be deflected away from the detectors, which will therefore respond to the neutrino decay product of positive pions.

For positive pions the fringing field of the next magnet is focusing in the horizontal direction and defocusing in the vertical direction.

The focusing and defocusing action of the fringing field will cause a net increase in the flux of pions directed towards the detectors, an effect which was taken into account in the previous calculations$^{1)}$.

The extent to which the pion flux will increase will be limited by the existence of apertures near the target, but at that early stage such details could not be considered. As the pion beam decays, producing a neutrino beam, the transverse momentum of the neutrinos will to some extent destroy the original focusing. This effect was also neglected in the original estimates, but will be included in the present calculations.

II. COLLIMATION AND FOCUSING

The present calculations aim at getting an upper limit to the number of events, and the necessary approximations and assumptions will therefore be made optimistically.

Of the three neutrino detectors involved in the experiment, we will only consider the Ecole Polytechnique chamber which has the most favourable position.

The horizontal defocusing of the fringing field causes the beam to diverge horizontally and gives a reduction of the pion flux density at the detectors at the distance L by a factor A_H, which can be determined from the formula, p.11 of ref.1 and the graphs corresponding to straight section 5. It is assumed that there are no obstructions which limit the beam in the horizontal direction.

The vertical aperture of the beam leaving the fringing field is limited by the distance, about 15 cm, between the coils of magnet 5, which are thick enough to absorb most of the pions emitted at larger angles. Since the beam leaves the volume between the coils at a distance of 2.5 m from the target, the vertical half angle Ψ_o is 30 mrad. If the pions did not decay or were absorbed they would "illuminate" a horizontal band of height $\psi^o L$ in the plane of the detector, assuming no vertical focusing indreases the pion flux at the detector.

The focusing effect in the vertical direction reduces the width of this band by a factor $1/A_V$ and by the enhancement factor A_V. This factor can be estimated from the horizontal defocusing factor A_H and the formula :

$$A_V^{-1} = |2 - A_H^{-1}| \qquad (1)$$

which is obtained if the fringing field is approximated by a thin quadrupole lens. The result of this simple formula agrees well with more laborious calculations of the vertical motion of particles in the fringing field.

In table I is given, as a function of the momentum (column 1) the horizontal and vertical enhancement factor and their product (columns 2, 3 and 4).

III. PRODUCTION SPECTRUM

For the production spectrum, I have used the predictions of Hagedorn for proton-proton collisions, corrected for the fact that different momenta correspond to different production angles, due to the fringing field. These values were kindly supplied to me by Dr. Salmeron. They are given in column 5 of table I.

Some brief remark about the validity of this theoretical spectrum will be made in the conclusion.

IV. EFFECT OF THE TRANSVERSE MOMENTUM OF THE NEUTRINOS

Consider the flux of neutrinos in the median plane at the detector from pions decaying at an angle Θ^* in the rest system of the pion with the pion direction as polar axis. The laboratory neutrino momentum is given by

$$p_\nu = p \cdot 0.215 \, (1 + \cos \Theta^*) , \qquad (2)$$

where p is the pion momentum. The laboratory angle, Θ, between the pion and neutrino directions is given by

$$\Theta \simeq \frac{\mu c}{p} \, \frac{\sin \Theta^*}{1 + \cos \Theta^*} \qquad (3)$$

where $\mu c = 0.14$ GeV/c.

All laboratory angles are assumed to be small.

Assume that the pion decay occurs at a distance L_1 in front of the detector. The centre of the detector plane will receive neutrinos from the decay of pions, which, if they had not decayed, would have traversed the detector plane on a circle of radius ΘL_1 around the centre (see fig. 1). Since each pion gives one neutrino, the flux density of neutrinos is equal to the average flux density of pions along the circumference of the circle, which is the flux density in the illuminated band multiplied by the fraction α of the circle which lies inside the band:

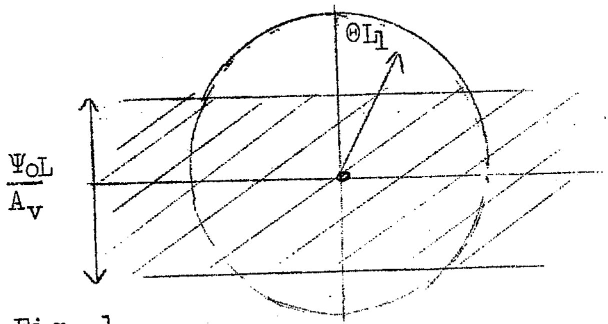

Fig. 1

$$\left.\begin{array}{ll} \alpha = \frac{2}{\pi} \arcsin \left(\Psi_o L / A_v \Theta L_1 \right) & \text{if } \frac{\Psi_o L}{A_v} < \Theta L_1 \\ \alpha = 1 & \text{if } \frac{\Psi_o L}{A_v} > \Theta L_1 \end{array}\right\} (4)$$

In the following calculations we have used for the ratio L_1/L its average value 0.8.

To get the rate of neutrino events, we should multiply by the cross-section $\sigma^i(p\,\nu)$ for an event of type i. Integration over all decay angles Θ^* yields the "effective cross-section":

$$\sigma^i_{eff}(p) = \frac{1}{2} \int_{-1}^{+1} d(\cos\Theta^*) . \alpha . \sigma^i(p\,\nu) \quad . \qquad (5)$$

which differs from the definition in ref. 1 by the factor α, which varies with Θ^* as given by Eqs. (3) and (4), and depends on the geometry of the system as well as on the elementary cross-sections.

The integrand of Eq.(6) is shown in fig. 2 as a function of $\cos\Theta^*$.

The effective cross-sections have been calculated by numerical integration of Eq. (5), using Simpson's formula with 10 intervals in $\cos\Theta^*$. The result is given in column 6 of table I. The effective cross-sections calculated in this way are considerably smaller than the cross-sections assumed in the previous report. The reduction is particularly large for momenta where the vertical enhancement factor is large and the beam thus well collimated, but is small at high momenta where the focusing is unimportant and the decay angles small.

V. CALCULATION OF THE RATE OF NEUTRINO EVENTS

With the redefinition of the effective neutrino cross-section given in the previous section we can calculate the rate by the same formula as the previous authors :

$$R = \eta_1 \eta_2 \eta_3 I_p \, Q \, N \frac{W}{2} \frac{1}{L^2} \sum_i \int \sigma^i_{eff}(p) \left(1 - e^{-s/\lambda p} \right) A^i(p) \frac{\delta^2 N}{\partial p \partial \omega} \, dp \qquad (6)$$

where :

η_1 is the efficiency of the detector, e.g., fraction of chamber volume useful for analysis

η_2 is the target efficiency

η_3 is proportion of the useful machine time

I_p is number of circulating protons per pulse of the machine

Q is theoretical number of machine pulses per day

N is Avogadro's number

w is total mass of the detector sensitive volume

L is distance target-detector.

Column 7 in Table I gives the decay probability $(1 - \exp(- s/p\,\lambda)$ where s is the length of the decay volume, 20 m λ the mean decay length, 55 m, for 1 GeV/c pions.

The value of the integrand is given in column 8. Integration over pion momentum by Simpson's formula gives a neutrino event rate of 0.032 per day, which is more than an order of magnitude less than the previous estimate. I have used the same parameters:

$\eta_1 \eta_2 \eta_3 = 1/3$

$I_p = 3 \cdot 10^{11}$ protons per burst

$Q = 29000$ bursts per day

$w = 0.75$ ton .

VI. DISCUSSION

When applied to the case of the Ecole Polytechnique chamber (useful weight of 0.4 ton) and the present beam intensity of $2 \cdot 10^{11}$ protons per burst, one is led to an event rate of about 0.01 per day of machine operation, or one event every 8 months at the present schedule of 75 hours per week.

Since some of the other effects, such as finite target size and aberrations of the fringing field have been neglected even this figure may be somewhat optimistic.

The calculations are based on the Hagedorn predictions and on a target efficiency of about 1/2. Recent measurements on the pion flux[3)] under conditions similar to those of the neutrino experiment indicate a production which is lower by a factor 1.5. This is easily explained as due to the reduction in going from a free proton interaction to the bound proton interaction, and to the angular distribution which seems to be more peaked than predicted. A detailed comparison is made difficult by the focusing effect of the fringing field.

The measurements do not show a pronounced peak at a momentum when the target is focused on the detector, and this may be taken as an indication that the aberrations of the fringing field smear out the focusing effects.

It would seem from the present estimate that the experiment will only be feasible with a drastic increase in machine intensity or complete rethinking of the detector and beam problem. The present calculations show that the enhancement due to focusing of the pions in the fringing field is almost useless since it is compensated by the divergence in the neutrino decay angles. A stronger beam with larger aperture can only be made in a long straight section at an angle large enough not to be limited in aperture by the coil of the next magnet. It would need a focusing device, such as the magnetic horn proposed by van der Meer[4)], able to accept a large solid angle. An improvement by perhaps a factor of 10 could be achieved. The external beam seems however better indicated for this magnetic horn.

TABLE I

Momentum P GeV/c	Enhancement			Spectrum $\frac{d^2N_\pi}{d\omega dp}$ GeV/c^{-1} ster^{-1}	Neutrino σ_{eff} $\times 10^{-38}$ cm^2	Decay prob.	Integrand in (6) $\times 10^{38}$ GeV/c^{-1} cm^2 ster^{-1}
	Hor. A_H	Vert. A_V	Total A				
1	0.36	1.32	0.48	0.9	0.070	0.306	0.0092
1.5	0.42	2.5	1.04	1.0	0.086	0.216	0.0194
2	0.46	6[1] (6.6)	2.76	1.1	0.068	0.166	0.0343
2.5	0.50	6[1] (∞)	3.00	1.0	0.088	0.136	0.0334
3	0.52	6[1] (10)	3.12	0.9	0.104	0.114	0.0334
4	0.56	3.3	1.85	0.60	0.276	0.087	0.0257
5	0.62	2.5	1.57	0.39	0.372	0.070	0.0160
6	0.67	2.00	1.33	0.24	0.494	0.059	0.0094
7	0.70	1.75	1.20	0.17	0.580	0.051	0.0058

[1] Maximized to 6. Real value within bracket.

REFERENCES

1) F. Krienen, R.A. Salmeron and J. Steinberger, CERN PS/Int. EA 60 - 10.

2) G. Bernardini, Rochester Conference on High-Energy Nuclear Physics (1960).

3) G. von Dardel and G. Weber (to be published as an NP Internal Report).

4) S. van der Meer, "A directive device for charged particles and its use in an enhanced neutrino beam" - CERN 61 - 7.

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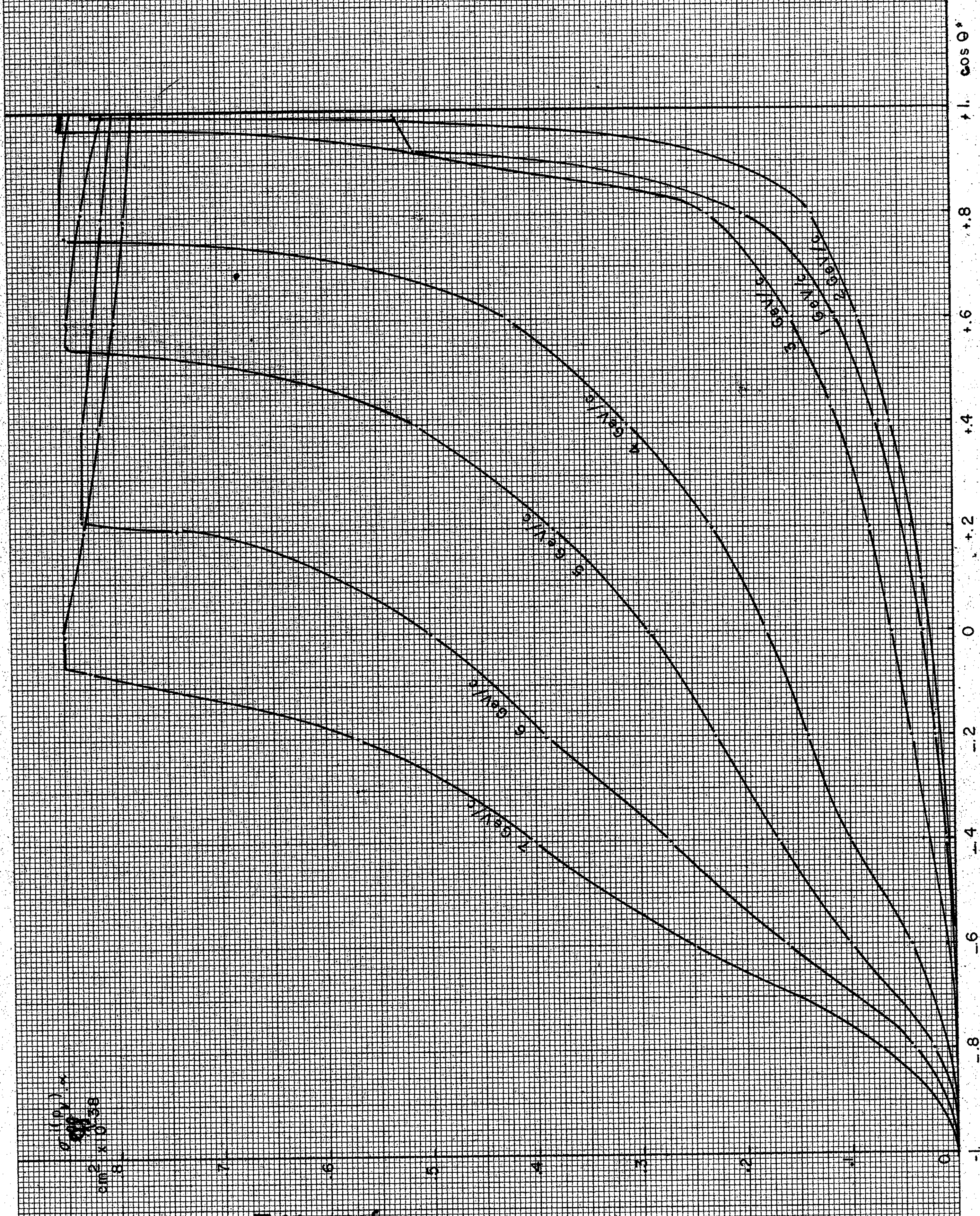
Figure 2



Effectif Neutrino cross section multiplied with accepted angular fraction

Vertical aperture : 30 mrad.