NEUTRINO BEAMS FROM A HIGH INTENSITY 200 GeV PROTON SYNCHROTRON*)

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In connection with the 200 GeV Accelerator L.R.L. Study Group's investigations of experiments possible with a high intensity 200 GeV proton synchrotron, we have investigated[1,2] means of producing a "monochromatic" beam of high-energy neutrinos (antineutrinos). We hope to use conventional focusing devices and bending magnets. This paper will present some "sample" beams to illustrate how far one can go with straightforward application of charge separation and momentum analysis of high-energy pion and kaon beams, if sufficient intensity of high-energy protons and adequate space are available.

Several well-known features of neutrino production by ultra-high energy protons are worth mentioning. First of all, if we believe the Cocconi-Koester-Perkins description[3] of meson production, the secondary pions and kaons are produced at such small angles at 200 GeV that elaborate focusing devices for high-energy parent mesons seem to be unnecessary. The r.m.s. production angle for both pions and kaons of momentum P (GeV/c) is $\vartheta_{r.m.s.} = 44^{\circ}/P$ in milliradians, or twenty-two milliradians for 20 GeV/c mesons. Secondly, the higher proton energy provides a large increase in the number of neutrinos even below 5 GeV. A 200 GeV proton can generate as many neutrinos above 24 GeV as a 25 GeV proton can generate above 2 GeV; the higher energy proton also produces five times as many 3 GeV neutrinos, sixteen times as many 5 GeV neutrinos and 600 times as many 10 GeV neutrinos. In addition, future proton intensities are predicted to be as high as 3×10^{13} protons/pulse. We have calculated that if a scaled-up version of the present CERN neutrino beam were used at 200 GeV, the elastic neutrino events observed would exceed one event/pulse.

In our event rate estimates we have assumed a 10^5 litre liquid hydrogen-deuterium bubble chamber as the detector. Liquid hydrogen-deuterium offers definite advantages in interpretation of events. The dimensions (6.0 m diameter) are derived primarily from the desired measurement accuracy. The detector cost is probably not out of keeping with the cost of the accelerator.

In future experiments it is assumed that better definition of neutrino energy will be important, as is certain knowledge of the type of neutrino. We have sought to achieve this by applying the following steps in producing a beam:

a) charge separation of pions, kaons, etc., by placing the proton target in a long bending magnet;

b) momentum analysis (about 10% full width) by suitable apertures placed outside of the bending magnet; the mean momentum may be changed by tuning the main magnet, keeping $\Delta p/p$ constant;

c) unwanted higher energy particles are stopped close to the target to minimize the muon background;

d) conventional quadrupole lenses are used to focus and transport the meson beam over distances comporable with the decay length;

e) the meson channel is designed with the view of creating a "pencil" beam aimed at the centre of the detector.

A schematic layout of such a beam is shown in Fig. 1. A beam of 200 GeV protons strikes a target at the entrance of a seven metre long, 25 kG bending magnet. Mesons of 20 GeV/c mean momentum are bent 0.29 radians and drift another seven metres before entering a twelve-inch aperture lens in a heavy shield wall. High-energy protons and mesons are stopped by shielding placed close to the bending magnet. The mean decay lengths for 20 GeV/c kaons and pions are 150 m and 1,100 m, respectively. Within 150 m the mesons are bent again parallel to the original proton beam; this serves to cancel chromatic effects due to the first bending and also provides an enriched "K-neutrino" beam passing through the shielding S_1 into the smaller of two bubble-chamber detectors, D_1. The remaining beam (mainly pions) is then transported over a long distance (of the order of 1,000 m). Pion decays produce a "π-neutrino" beam passing through shielding S_2 into a large bubble-chamber detector D_2. The residual charged particles (mainly protons and muons) in the focused beam are then deflected just before S_2. A relatively pure muon beam can be created by absorbing the pions and protons.

The disadvantages of such an arrangement are the large number of lenses required, the considerable space involved in the experimental area, and the precise alignment of elements required. However, these requirements are comparable with the dimensions and tolerances of the accelerator. A major advantage seems to be that it is possible to obtain either a well-defined neutrino energy, or a high neutrino intensity integrated over the total spectrum, by relatively simple changes in geometry. The layout also lends itself to multiple use for charged particle beams. The same space and lenses may be used for mass separators.

Pencil Beam spectra and intensity

Let us assume that 25 GeV/c pions (10% $\Delta p/p$) are produced within $\vartheta_{r.m.s.}$ and are accepted and transported as a "pencil" beam by magnetic lenses over a distance of one mean decay length. Then we calculate the neutrino spectrum and event rate in a 6.0 m diameter, 10^5 litre liquid hydrogen bubble chamber placed at the end of the channel. Figure 2 shows (at the top) the "total" energy spectra of π-neutrinos and K-neutrinos if all mesons decay; it also gives the energy spectra of neutrinos passing through the bubble chambers D_1 (185 m from the target) and D_2 (1,380 m) from the above pencil beam. The slope at the upper end is influenced by the finite momentum spread of the parent mesons. The spectrum would be flat if the detector were infinitely large. The decrease in intensity at lower energies is due to neutrinos emitted at larger angles missing the detector.

The intensity of neutrinos at any energy from a 10% meson bandwidth and one mean decay length is, of course, less than the intensity derived from the total meson flux. However, the reduction is not great; at 25 GeV, the factor is 8 at 10 GeV. Momentum analysis provides a sharp upper limit in neutrino energy which is very useful for experiments.

In the above example, the total yield of elastic neutrino events for energies greater than 1 GeV, assuming a cross-section of 10^{-38} cm^2, is 0.287 neutrinos/pion initially in the beam, and 0.388 neutrinos/kaon. For 3×10^{13} protons/pulse, 30 pulses/minute, one would expect to see 1,850 π-neutrino and 300 K-neutrino elastic events in 24 hours of running time.

Increased resolution in neutrino energy

The energy spectrum of neutrinos in Fig. 2 is rather broad, even though greatly narrowed by momentum analysis of the meson parents. The sharp upper limit on neutrino energy set by peak meson energy suggests that this meson energy could be varied from run to run, and subtraction methods could be used to derive the contribution of neutrinos in a narrow energy interval. This "neutrino difference method", like the "photon difference method" used with electron synchrotrons, is possible in principle, but it requires very good statistics to apply it in practice.

Longer decay lengths would also serve to improve the resolution since only those high-energy neutrinos aimed nearly forward will strike the detector. However, the additional real estate comes at great expense. Furthermore, when the effects of focusing are folded into the ideal "pencil beam", the result may not be as good as expected.

The simplest and most effective means of narrowing the spectrum appears to be to stop (or deflect) the meson beam at a considerable distance from the detector. Wide-angle neutrinos will then miss the detector, sharply reducing the intensity at lower energies. This "beam stopper" method is illustrated in Fig. 3. The solid curve is the neutrino spectrum from 20 GeV pions (10% bandwidth) decaying over 1,230 m and detected by a 6.0 m diameter bubble chamber. The dotted curve is the spectrum if the pion beam is stopped only 200 m after the meson source. The energy width is narrowed to 1.2 GeV with a peak energy of 9 GeV. The average intensity over this 1.2 GeV interval is reduced by a factor of five. However, it is still possible to obtain over 100 elastic events/day, with resolution of about 15% in neutrino energy.

Focusing effects and beam transmission in the meson channel

The design of the meson channel is of major importance since precise alignment is required to obtain a truly "pencil" beam. Furthermore, the cost of the channel is strongly dependent upon the number and size of the lenses. We have examined only the most elementary aspects of such a channel, using a thin-lens geometrical optics model with chromatic properties of a symmetric triplet quadrupole lens.

We are interested in the transmission of a system of N lenses, where N is between 20 and 80, as a function of momentum. The hope is to pass at least 10% bandwidth. In addition, we want to have small aperture lenses spaced far apart to reduce the number and cost, and to define a pencil beam as nearly as possible. The focused mesons should be confined within a cone whose half-angle equals the maximum desired neutrino decay angle. Kinematics of neutrino decay at angle ϑ and energy E from a moving meson, whose total-energy/mass ratio is γ, yields:

$$E/E_{max} = (1 + \gamma^2 \vartheta^2)^{-1}. \qquad (1)$$

Thus, if we wish to have a lower limit on neutrino energy of 0.90 of the maximum energy, then $\vartheta = 1/3\gamma$. For pions of 20 GeV, ϑ = 2.4 milliradians, which is much smaller than the production angle, $\vartheta_{r.m.s.}$ = 22 milliradians.

Two arrangements of focusing lenses which seem capable of broadband transmission of pions over long distances are shown in Fig. 4. Figure 4a (beam "B-4") consists of 80 equally spaced 6 in. diameter lenses extending over 1,100 m; at each image point a field lens is placed to contain off-axis rays from a finite source. The lenses are thus spaced a distance 2f apart, where f is the focal length of each lens.

It is clear that with this arrangement mesons accepted by the first lens will be completely transmitted for the mean momentum; i.e., the transmission $T(\bar{p}) = 1.0$. For particles differing by Δp in momentum, the change in focal length for one lens is Δz, which for a symmetric triplet is $\Delta z = \ell(\Delta p/p)^2$, where ℓ is the image distance. ($\ell = 2f$ in our case.) The maximum number of lenses which can be used before the beam diverges and is lost due to shift in image point is $N(\text{mad}) = 2f/\Delta z = (p/\Delta p)^2$. For magnetic lenses the symmetric quadrupole triplet minimizes Δz, and we find that 100 lenses are possible for 10% momentum bandwidth.

The transmission of the N lens channel for momenta different from the mean has been calculated by Matsubara[4] using matrix methods. The first case considered was that of Fig. 4a: N equally strong and equally spaced lenses. We assumed a small source (3 mm diameter) and a focal length of 6.8 m, and the lens aperture was 15 cm diameter. The transmission as a function of momentum for this system of 80 lenses is shown in Fig. 5 (solid curve). This beam channel (called "B-4") is not very wide-band, and is just capable of transmitting 10% bandwidth without a large loss. A defect is that the initial lens angular aperture is less than the meson production cone, and only 25% of available mesons are accepted.

In order to remedy this defect we have considered placing the first lens closer to the source, matching the acceptance angle to the production angle (Fig. 4b, Beam "B-5"). Thus, essentially all mesons produced are focused into the meson channel. Since the source is small compared with the channel lens aperture, we can afford to use a long image distance, reducing the exit angular spread at the expense of increasing the image size. By magnifying nine times, we can couple the 22 milliradian production angle to the mucn smaller lens acceptance angle of 2.4 milliradians.

The transmission of a 41-lens system with 30 cm initial aperture lens of focal length 6.8 m, followed by 40 lenses of 10 cm diameter aperture spaced 21 m apart, is shown in Fig. 5 (dotted line). The channel now readily transmits 10% bandwidth, mainly due to the smaller number of lenses. Both the number and size of the lenses is substantially reduced from the previous case.

The effect of the focusing alone on the neutrino spectrum from monochromatic 20 GeV pion beam has been calculated[5] and is shown in Fig. 6. The solid line is the spectrum from mesons decaying in Beam "B-5". The pion beam is produced in a small target and is stopped 840 m downstream; the bubble chamber is an additional 340 m further away, making total target-to-detector distance of 1,170 m. We consider the spectrum of neutrinos striking the centre of the bubble chamber only, due to pions decaying anywhere within the upstream channel. The resulting spectrum has a sharp lower limit of 90% of the maximum neutrino energy in accordance with equation (1). Over 50% of the pions decay within the channel, and the total number of elastic events in a 10^5 litre bubble chamber is 20% of those contained within the same energy interval in the ideal "pencil" beam of Fig. 3 if 10% meson bandwidth is selected.

The total neutrino energy spread due to focusing alone (0.9 GeV) in Beam "B-5" is substantially less than the width due to finite bubble chamber size, and is comparable with the spread due to 10% meson energy bandwidth. The dotted curve in Fig. 6 shows the broad neutrino energy spectrum (averaged over the detector) resulting from poorly focused mesons in Beam "B-4". It is clear from this comparison that good energy resolution can be achieved within a fiducial sub-volume of a large bubble chamber if a carefully designed focusing channel is constructed.

Thus, we have shown that it is practicable to define neutrino energy within 10% by practical means and with good intensity.

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4) C. Matsubara, Investigation of beam transmission in a momentum analysed meson beam for neutrino production, University of Hawaii internal report, December (1964).

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FIGURE CAPTIONS

Figure 1 : Schematic layout (not to scale) of proposed "pencil" beam of momentum-analysed pions and kaons to produce neutrinos. See text for description.

Figure 2 : Neutrino spectra from 10% momentum analysed and separated 25 GeV pion and kaon beams. The decay space in each case is one mean decay length for the parent. The detector is 6.0 m in diameter. Shown for comparison are "ideal" spectra resulting from the total decay of all pions and kaons produced by one 200 GeV proton if all neutrinos are counted. The dashed lines show how the spectra would change if the mean momentum is increased to 30 GeV keeping all dimensions fixed.

Figure 3 : Neutrino spectrum resulting from decay of 20 GeV pions in a channel 1,230 m long. A "pencil" beam and a 6.0 m diameter detector are assumed. The effect if stopping the beam only 200 m after the source is shown by the dashed line; the energy resolution becomes 1.2 GeV.

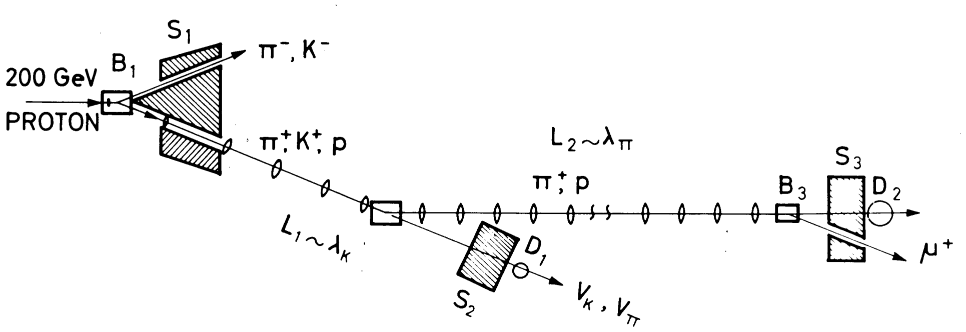
Figure 4 : Two possible channel-lens arrangements utilizing field lenses to contain off-axis rays from a finite source.

4a : N identical lenses placed 2 f apart. The action of the field lenses is shown.

4b : The first lens has a wide aperture matched to the production cone, and the exit cone is matched to the (smaller) angle of maximum neutrino decay. The resulting magnification of the source must be kept much less than semi-aperture of channel lenses.

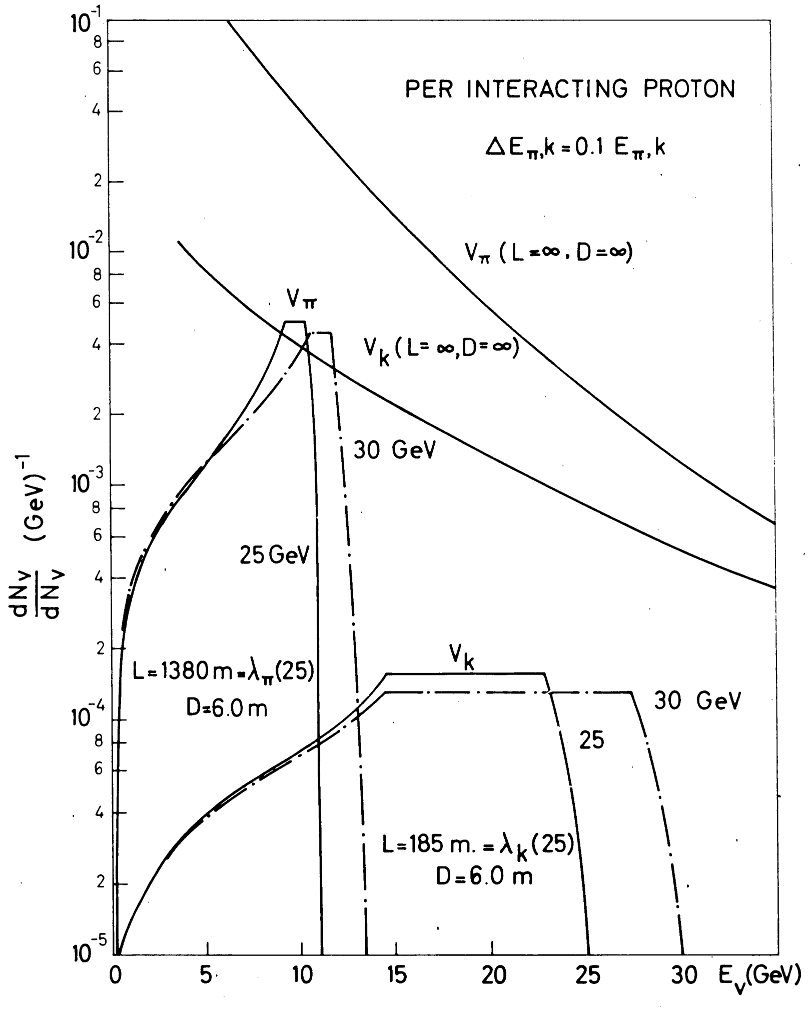
Figure 5 : The transmission of Beam "B-4" (Fig. 4a) and Beam "B-5" (Fig. 4b) as a function of momentum. The former involves 80 lenses of 6 in. aperture space 13.7 m apart; the latter involves 41 lenses of 4 in. aperture spaced 21 m apart, following a 12 in. matching lens. In both cases 10% meson momentum bandwidth is transmitted.

Figure 6 : Neutrino spectra resulting from beams "B-4" and "B-5". The solid line shows the effect of focusing only, over 840 m; the spectrum is as observed in the centre of the detector and monochromatic pions are assumed. The dotted line gives the average spectrum over a 6.0 m bubble chamber for monochromatic pions, and includes the focusing of Beam "B-4".



200 GeV
PROTON
B_1
S_1
π^-, K^-
π^+, K^+, p
$L_2 \sim \lambda_\pi$
π^+, p
S_3
B_3
D_2
$L_1 \sim \lambda_K$
D_1
S_2
ν_K, ν_π
μ^+

Fig. 1



PER INTERACTING PROTON
$\Delta E_{\pi,k} = 0.1\ E_{\pi,k}$
ν_π (L = ∞, D = ∞)
ν_k (L = ∞, D = ∞)
ν_π
30 GeV
25 GeV
L = 1380 m = λ_π(25)
D = 6.0 m
ν_k
30 GeV
25
L = 185 m. = λ_k(25)
D = 6.0 m
$\frac{dN_\nu}{dN_\nu}$ (GeV)$^{-1}$
E_ν(GeV)

Fig. 2

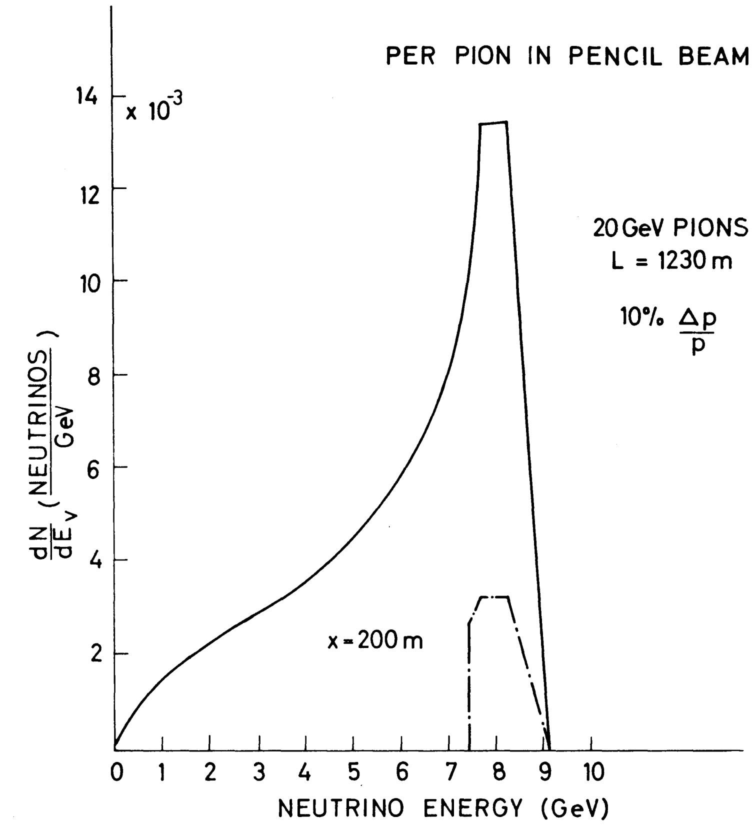

PER PION IN PENCIL BEAM
14
x 10-3
12
10
8
6
4
2
20 GeV PIONS
L = 1230 m
10% Δp/p
dN/dEν (NEUTRINOS/GeV)
x = 200 m
0 1 2 3 4 5 6 7 8 9 10
NEUTRINO ENERGY (GeV)

Fig. 3

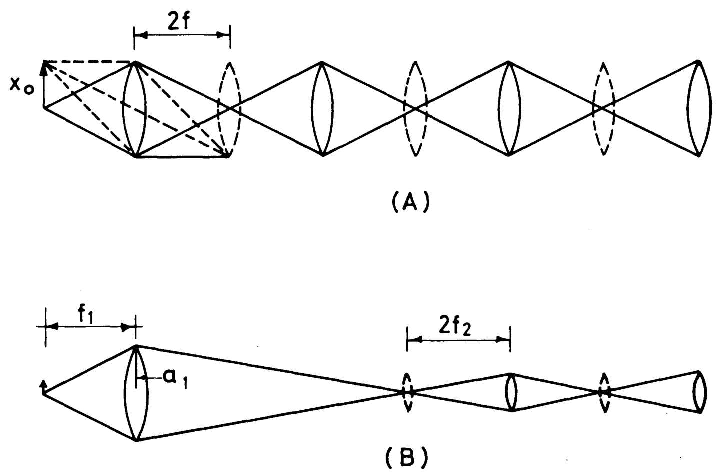
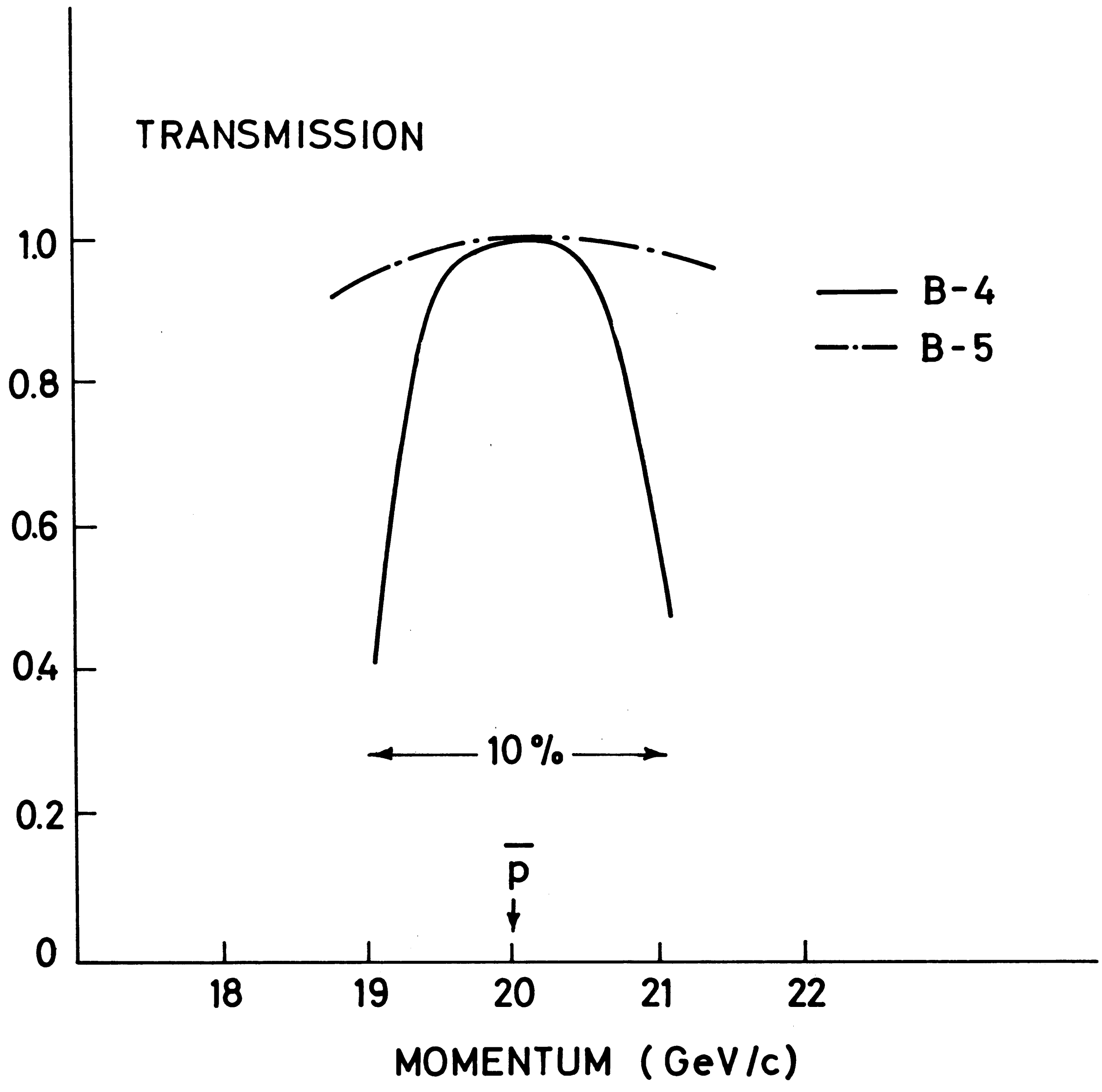
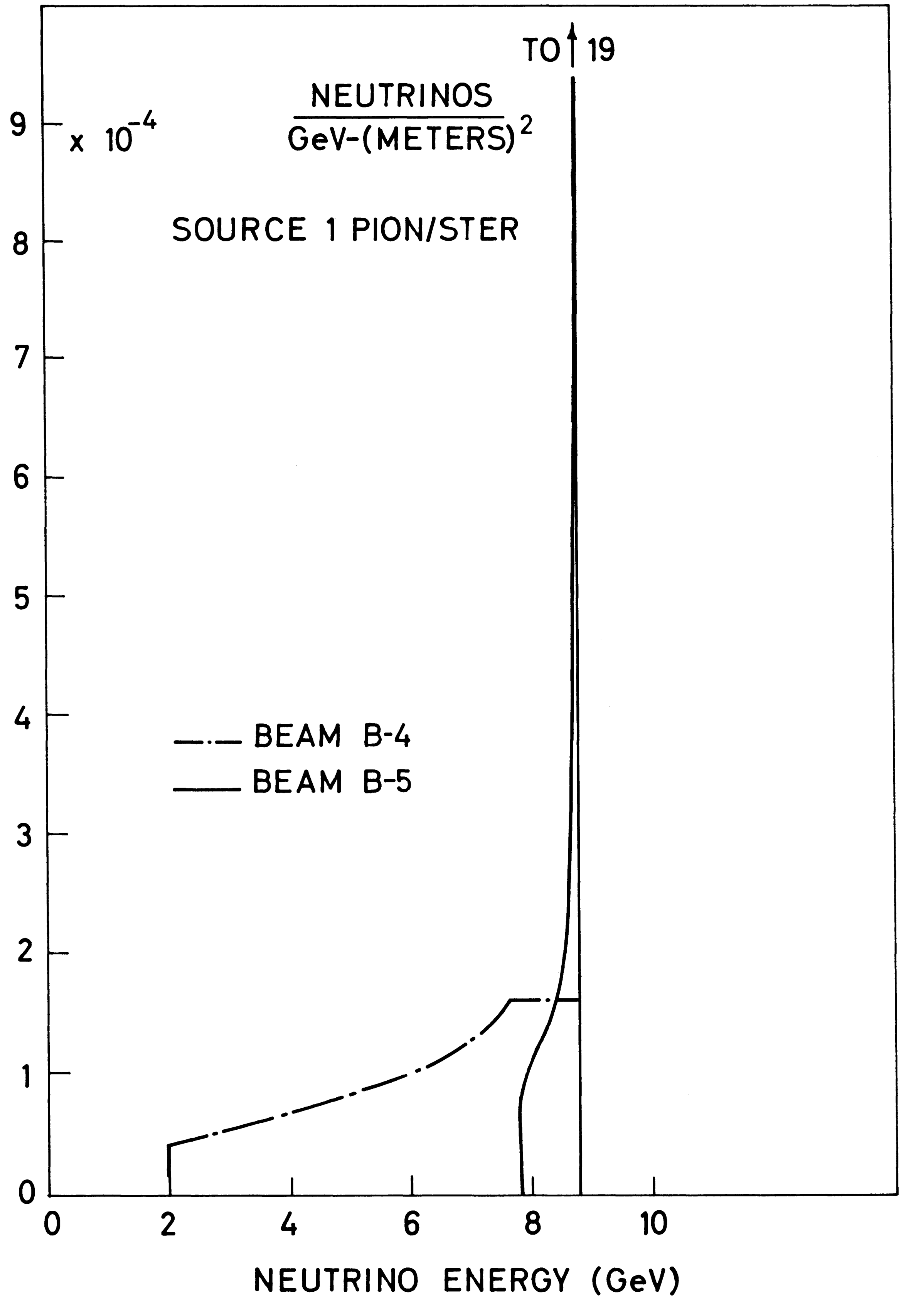

2f
x0
(A)
f1
2f2
a1
(B)

Fig. 4



TRANSMISSION
1.0
0.8
0.6
0.4
0.2
0
B-4
B-5
10 %
$\bar{p}$
18
19
20
21
22
MOMENTUM (GeV/c)

Fig. 5



TO 19
NEUTRINOS / GeV-(METERS)^2
x 10^{-4}
SOURCE 1 PION/STER
BEAM B-4
BEAM B-5
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8
10
NEUTRINO ENERGY (GeV)

Fig. 6