B. 1-68-104
August 9, 1968

TM-131
2251

THE NEUTRINO FACILITY AT NAL

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A. INTRODUCTION

The neutrino beams at existing accelerators, BNL, CERN, and Argonne are of the wide-band variety. They use focusing devices to enhance the total neutrino flux, generally they focus mesons of one sign and are most effective for the low-momentum mesons. Keefe and Peterson[1] proposed a narrow-band system where a bending magnet follows the primary target and a system of quadrupoles focuses a meson beam of given momentum. The further the mesons are from the bubble chamber when they decay, the more sharply defined is the neutrino momentum as it enters the bubble chamber. It was believed that this momentum information would aid the analysis of the events. Furthermore, the beam would be primarily ν or $\bar{\nu}$ depending upon the meson charge. Toohig[2] considered a system similar to this, but with the added feature of capturing the decay muons to form a beam for muon physics. Yovanovitch[3] amplified some upon the Toohig system and pointed out some serious background problems that would arise from the regeneration of energetic muons (by neutrinos) in the last muon range length of the muon absorber.

Perkins[4] summarized most of the previous schemes with particular attention given to their use at the proposed 300-GeV European accelerator. He cautioned against trying to replace the large muon shield with sweeping field magnets and small absorber. The energetic neutrons, unaffected by the sweeping field, could generate high-momentum pions and hence some high-momentum muons in the small absorber in front of the chamber. He further pointed out that one should use only the collision loss portion of dE/dx, not the radiation loss portion (that is proportional to Z^2E/A), in calculating the shield length. In this way, one would avoid the trouble of excessive straggling associated with the latter energy loss mechanism.

Perkins pointed out an interesting result, when comparing narrow band with wide-band systems, that the narrow-band system provides little enhancement at a given momentum over the wide-band one and has the disadvantage that it throws away "other neutrinos" that the wide-band system saves.

Boudagov et al., in a CERN internal report entitled "Some Considerations on High Energy Neutrino Experiments with a 76 GeV Accelerator"[5] review the capabilities of present and future neutrino facilities and recommend that their efforts be concentrated on neutrino energies above 10 GeV.

In this report we have collected together our individual contributions. Many of these were easily assimilated into the body of the text without any modification. The work of Camerini and Meyer, which was the most thorough of the beam studies, was an exception. We have borrowed extensively from it, and the reader is referred to its full text (report B.1-68-82) elsewhere in this volume.

Contained in our report are the following studies:

1. The optimum location of the bubble chamber.

2. a. The approximate size and cost of the full muon shield.

2.b. Initiation of focusing device design coupled with muon shielding device design so as to reduce the high cost of the full muon shield.

3. Elimination of the regenerated muons, and the investigation of other forms of background.

4. New schemes for producing pure ν (or $\bar{\nu}$) beams.

5. Examination of the various neutrino reactions to see which of the proposed experiments are actually feasible if done in the proposed 25-foot BNL liquid hydrogen bubble chamber.[6]

6. Ways in which the neutrino flux can be monitored.

7. Nonbubble-chamber type experiments that can be done behind the BNL 25-foot bubble chamber in the neutrino beam.

Some simple ideas about neutrino beams are introduced in section B in order to help in scaling the 200-GeV facility to one at 400 GeV. Some detailed beam design is done in section C where some methods of reducing the expense of the muon shield are discussed. The bubble chamber backgrounds are discussed in section D.

The summary of our work is found in section E.

B. SIMPLE IDEAS ABOUT NEUTRINO BEAMS (M. L. S.)

As Perkins points out in his study of "Neutrino Beams at 300 GeV Laboratory,"[4] some 10 to 15 man years of effort have gone into the design of the present CERN 25-GeV system. A properly designed system for the 200-GeV accelerator will rely heavily upon the use of large digital computers using the meson-production models of Cocconi, Koester, and Perkins;[7] Trilling;[8] and Hagedorn and Ranft.*[9]

Before we lose sight of the problem as it enters the computer, let us propose the following simple model for neutrino production. Perhaps it would be better to call it a mnemonic.

"Cloud Mesons"

The mesons that contribute most to emitting neutrinos into the bubble chamber are those which are "cloud mesons" attached to the incident proton. They are shaken off in the interaction and hence have nearly the same velocity (or $\eta = \beta\gamma$) as the projectile proton.** We shall refer to these as the canonical mesons of the interaction. For a 200-GeV accelerator, the pion and kaon momenta are, respectively,

$$P_\pi = M_\pi(\eta = \frac{P}{M_p} = 200) = 30 \text{ GeV/c},$$

$$P_K = M_K(\eta = 200) = 100 \text{ GeV/c}.$$

If we study the decay of these canonical mesons, we shall learn much that we need to know in order to design the gross features of the neutrino facility. This will be done in the narrow-band discussion of the section on Neutrino Beams and Shielding.

Meson Decay $\pi \to \mu\nu$, $K \to \mu\nu$

Figure 1 is a momentum vector diagram which summarizes the

* Perhaps we shall even benefit from a yet more refined model based upon the forthcoming experimental results from Serpukhov.

** Actually η should be reduced by the factor M_p/M^* where M^* is the mass of the excited "proton." For an excited state that could decay into $K^+\Lambda$ this factor would be < 0.6, and hence $\eta_K \lesssim 0.6\,\eta$.

decay configuration of both π and K.

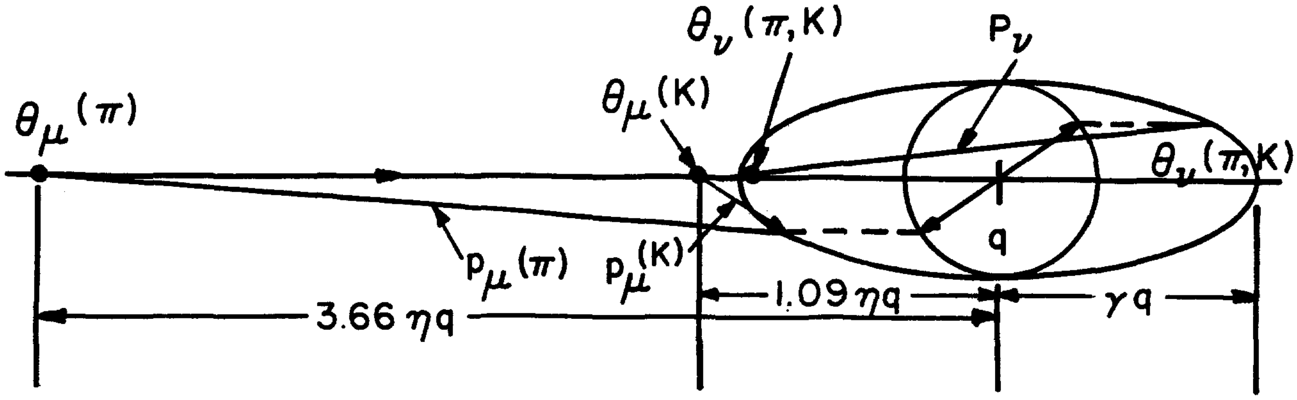

Fig. 1

a) Typical ν decay angle. The most typical decay angle (near 90° in the rest frame) is

$$\theta_\nu \approx \frac{q}{\eta q} = \frac{1}{\eta} = \frac{1}{200},$$

for both canonical π's and K's.

b) Typical ν energy. Correspondingly, the typical ν energies are:

$$E_\nu = \eta\, q = 6 \text{ GeV for } \pi\text{'s}$$

$$= 47 \text{ GeV for K's.}$$

The wide-band system designed by Hyman[10] using only pions shows a maximum in the neutrino spectrum near 5 or 6 GeV. Perkins' report shows the result of a calculation using π's and K's for a wide-band system. The neutrino spectrum show peaks at 9 GeV/c for pion neutrinos and ~ 45 GeV/c for kaon neutrinos. Compare these figures with the canonical values

$$E_\nu = (\eta = 300)(0.03 \text{ GeV}) = 9 \text{ GeV for } \pi,$$

and

$$(\eta = 300)(0.236 \text{ GeV}) = 70 \text{ GeV for } K^{*}.$$

c) Mean decay lengths. Systems will be designed so that a reasonable fraction of the mesons will decay. Therefore, drift distances will be the order of a mean decay length. The mean decay lengths of the canonical mesons are

$$\ell_{\pi} = (\eta = 200)(c\tau_{\pi} = 7.81 \text{ m}) = 1532 \text{ m},$$

$$\ell_{K} = (\eta = 200)(c\tau_{K} = 3.70 \text{ m}) = 740 \text{ m}.$$

Canonical Bubble-Chamber Size

If the neutrino detector is placed a mean decay length away from the target, the neutrinos will be found over a cross-sectional radius,

$$R = (\ell = \eta c\tau) \cdot (\theta_{\nu} \approx \frac{1}{\eta}) = c\tau$$

$$= 7.8 \text{ meters for } \pi\text{'s}$$

$$= 3.7 \text{ meters for K's}.$$

This radius is independent of the machine energy. Technical difficulties restrict us to chambers smaller than these canonical sizes. BNL has proposed[6] the construction of a 25-foot hydrogen chamber shaped like a football, whose sensitive volume (70 m^3) has a radius of 1.8 meters and a length ≈ 6 meters. In units of these canonical radii,

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*This would agree better with the Perkins' value if it were reduced by $M_p/M^* \approx 0.6$ to 42 GeV. (See footnote on page 5 of this report.)

the chamber has the dimension

$$r \equiv \frac{R}{c\tau} = 0.23 \text{ for } \pi\text{'s and}$$

$$= 0.49 \text{ for K's.}$$

Scaling Laws

With the production mnemonic it is clear how one scales the experimental configuration. In going from 200 GeV to 400 GeV, η doubles and so do all the longitudinal components of the beam, i.e., drift space and shield lengths.

It is generally accepted that one will not move the bubble chamber when the energy of the accelerator is increased; one must allow for a maximum target-to-bubble chamber distance of twice that calculated for 200 GeV.

C. NEUTRINO BEAMS AND SHIELDING

The optimum distance of target to detector depends upon the quantity that is optimized. It can be the total neutrino flux in a narrow-band system, the total ν flux in a wide-band system, or the neutrino flux above a threshold energy. In our studies thus far, attempts have been made to maximize the neutrino yields in various energy bands. They fall in the following vague categories.

"Narrow Band" (M. L. S.)

"Wide Band" (L. H., U. C., S. L. M.)

"Ultra-Wide Band" (M. M. B.)

$$1/2 \text{ GeV} < E_\nu < 15 \text{ GeV}$$

"Mid Band" (U. C., S. L. M.)

$3 \text{ GeV} < E_\nu < 15 \text{ GeV}$

"High Band" (M. L. S., U. C., S. L. M.)

$E_\nu > 15 \text{ GeV}$.

Narrow Band

The simplest system to design is the narrow-band one. Keefe[1] studied the characteristics of monoenergetic pencil beams. What follows is an amplification of his work.

a) Neutrino Detection Efficiency. A meson moving parallel to the beam axis has an efficiency for decaying and emitting its neutrino into a bubble chamber of radius R given by the following expression,

$$Y = r^2 e^{-X} \int_{X_o}^{X} \frac{e^y dy}{r^2 + y^2} .$$

Here r is the chamber radius in units of $c\tau$ and X is the bubble chamber-to-detector distance measured in units of $\eta c\tau$ and X_o is the distance from the beginning of the muon shield to the bubble chamber measured in units of $\eta c\tau$.

b) Neutrino Energy Spectrum. The energy spectrum of these neutrinos is the well known narrow-band shape shown in Fig. 2.

c) Optimum Target-to-Bubble-Chamber Distance. In Fig. 3 are plotted values of the optimum target-to-bubble-chamber distance, X_{opt}, for various values of bubble-chamber radii, r, and shielding thickness X_o.

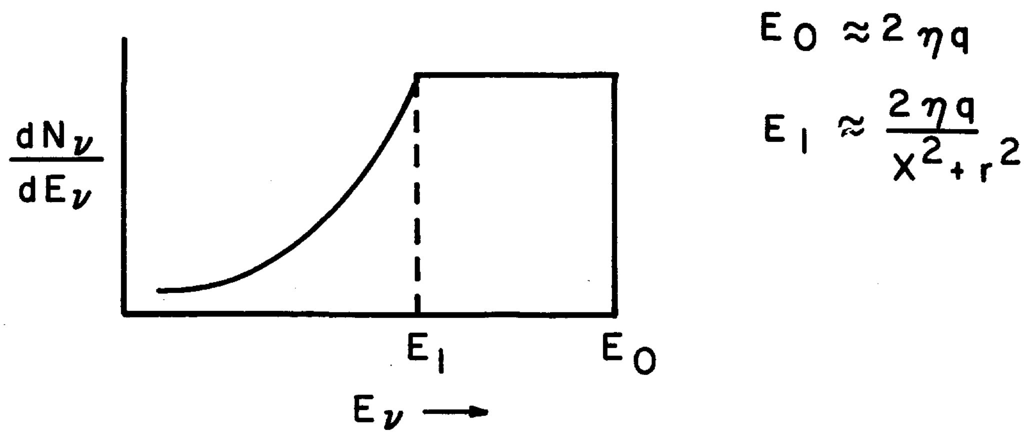

Fig. 2.

The quantity optimized was the total number of neutrinos in the narrow-band energy spectrum (see Fig. 2). It should be emphasized that the yield curves show rather broad maxima so that the choice of the optimum distance is not a crucial one.

Figure 4 summarizes the neutrino detection efficiency at the optimum position. One must multiply these efficiencies by the branching ratios into the $\mu\nu$ mode (1.0 for π's and 0.63 for K's).

These figures are valid for any momentum, any size bubble chamber, and any size muon shield. The only assumption is that some focusing device has made the mesons into a parallel monochromatic beam.

d) Threshold Optimization of Narrow-Band Systems. For threshold-type experiments, one wishes to optimize the number of neutrinos above a threshold energy. The detection efficiency for neutrinos of energy above a fraction ϵ of the maximum neutrino momentum is

$$Y(E > \epsilon E_{\nu max}) = r^2 e^{-X} \left\{ \int_{r\sqrt{\frac{\epsilon}{1-\epsilon}}}^{X} \frac{e^y dy}{r^2 + y^2} + \frac{(1-\epsilon)}{r^2} \left(e^{r\sqrt{\frac{\epsilon}{1-\epsilon}}} - e^{X_o} \right) \right\}.$$

Figures 5 and 6 show how X_{opt} and the neutrino detection efficiency vary when one optimizes the flux of neutrinos with $E > (\epsilon = 1/2) E_{\nu max}$.

Example: Use the canonical kaon (p = 100 GeV/c) which gives

$$E_{\nu max} = 2 \cdot (\eta = 200) \cdot (q = 0.236 \text{ GeV})$$

$$= 94 \text{ GeV}.$$

With a shield length of 160 meters of Fe* and 40 meters between the shield and the chamber, $X_o = 200/(\eta c\tau = 760 \text{ m}) = 0.274$; chamber radius = 0.49. One finds $X_{opt} = 1.06$, $L_{opt} = 805$ meters. Here, $0.18 \times 0.63 = 0.11$ of the kaons yield neutrinos above $(\epsilon = 1/2)(94 \text{ GeV}) = 47$ GeV/c in the 25-foot BNL chamber.**

Wide-Band System (Optimized on neutrinos of all energies)(L. H., U. C., S. L. M.)

Hyman[10] in his report optimized the total neutrino flux from π decay. Using both "CKP"[7] and Trilling[8] production models, he obtained an optimum target-to-bubble chamber distance of 550 meters. This length included a muon shield length of 150 meters of iron. Variations of this beam are presented in the following section and in Camerini and Meyer, Ref. 11.

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* The length is roughly that needed to stop μ's of 200 GeV using only the collision loss part of dE/dX.

** This energy is above threshold for production of an 8 GeV intermediate vector meson.

Mid-Band System (and Wide-Band System) (U. C., S. L. M.)

No serious study has been made of focusing devices. It has simply been assumed that some device could be constructed that would make all the mesons into a parallel pencil beam. For the mid-band system, separate ν and $\overline{\nu}$ beams should be produced. A possible way of achromatically separating positive and negative mesons is shown in Fig. 1 of Ref. 11. As drawn, a pencil beam enters from the target. Some preliminary focusing is called for to minimize the divergence of the beam from the spread of production angles. This system provides a means for getting rid of the bulk of the neutrons which would otherwise plow into the muon shield with full energy and generate muons by pion decay in the shield. By moving the beam stop past the axis, a mechanism is provided for cutting out the high-momentum part of the meson spectrum. This cutting out of the most energetic mesons has the advantage of minimizing the muon shielding problem.

The beam stop could be magnetized and might aid in sweeping out unwanted high-energy muons that were produced by meson decay prior to charge separation and momentum cutoff.

We have calculated various combinations of drift space lengths and shield lengths (here taken to mean the total distance between the end of the drift space and the detector; in general, this space may contain shield, sweeping field and lever arm) to estimate how these affect the neutrino flux at different energies. We have assumed an ideal focusing system for these calculations (pencil beam of parent pions) and used the production spectra obtained from the formulae of Trilling. Results of these calculations are summarized in Figs. 2-6 of Ref. 11.

At this point we should mention certain difficulties with these calculations aside from the question of whether to use the spectrum predictions of Trilling, Cocconi-Koester-Perkins (CKP) or Hagedorn-Ranft. In principle, when a computer becomes more accessible than the one at Aspen, one may repeat the calculations for all of these production spectra and compare the results. However, all of these prescriptions assume production from a nucleon (hydrogen) target. In fact, of course, production will be on a complex nucleus.

We expect that the effects of Fermi momentum and secondary interactions will change all the results, especially those pertaining to the production of the lowest energy neutrinos. Note that the flux of lowest energy neutrinos is small for all the beams considered. This is probably unduly pessimistic. One should, in principle, perform nuclear cascade calculations of the type done by Riddell[12] to optimize the target for the production of low energy neutrinos. An obvious consideration is to make the target several nuclear interaction lengths long, so that the pions produced from the primary interaction themselves interact, to produce lower energy pions. Neutrons produced in the primary collisions would also serve to provide pions through secondary interactions. For the purpose of performing the ν, $\bar{\nu}$ comparison at low neutrino energies, this mechanism would also go some way to improving the ratio of $\overline{\nu}/\nu$ production which is expected to be roughly 1/2 according to Trilling. (Note that our calculations have assumed 100% transport efficiency between target and the start of the drift space, ignoring losses due to finite apertures and decay. The efficiency will be lower for the lower energy pions. The production of lower energy pions, on the other hand, will be enhanced over our estimates by the nuclear cascade effects of complex target production. It may happen that our calculation may not be too far off in a relative sense over the spectrum of pion energies if these neglected effects tend to compensate).

The simplest cheap alternative to ranging out the highest energy muons with an iron shield is to range them out with an earth shield. The ratio between the two absorbers is dependent on the approximate energy loss in Fe of 1.95 GeV/m and in earth of 0.45 GeV/m. Thus, the earth shield will have to be approximately four times as long. We have calculated this for the basic situation and the results are summarized in Figs. 4 and 6 and in Table I of Ref. 11.

As one expects a priori, the larger the shield length, the more one loses flux. However, this loss is dependent on the energy range of neutrinos in which one is interested since that determines the possible drift space length. The table includes data for "compromise" drift space lengths. We have had in mind the enhancement of the neutrino flux in the energy range between 3 and 15 GeV and arbitrarily chose the drift space length corresponding to midway between the

E > 3 GeV and E > 5 GeV maxima. "Optimization" of the drift space varies according as the choice of energy interval. The curves in the figures should be used if an "optimum" drift space is desired for an energy range different from that of the "compromise."

The net loss of flux for the earth shield compared to the iron shield appears to be of the order of a factor of ten below 10 GeV neutrino energy but only 25% above 10 GeV. In fact, above 20 GeV, the flux favors the particular earth shield configuration used. The neutrino fluxes from kaons are shown in Figs. 8 and 10 and do not change the conclusion: a full earth shield produces little if any loss in the flux of high-energy neutrinos compared to yields from a configuration using a full iron shield. [The fluxes of neutrinos from kaons in fact appear to be higher for the earth shield configuration than for the iron shield case. Unfortunately, the kaon flux in Fig. 4 was calculated using 1/10 CKP* and that in Fig. 6 using 1/10 Trilling. Figure 6A shows the flux due to kaons using 1/10 CKP (all figures in Ref. 11).]

The advantages of the earth shield for high-energy neutrino beams (above 10 GeV) are the following: It would certainly appear advisable to target this neutrino beam from the proton beam while it is yet below grade (as we state later, we recommend that this be downstream of the SA station). This saves the magnet system required to deflect the proton beam up. The beam line from the target through the end of the pion

*By "1/10 CKP" we mean that the K momentum spectrum is assumed to have the same shape as the pion one but is down in intensity by 1/10.

drift space requires excavation, of course, but the shield region need not be excavated at all. The tunnel to the shield and the tunnel leading to the detector after the shield would naturally be aligned, but the shield itself could be unexcavated (at least if the high-energy experiment were run first).

While the loss of low-energy flux is undeniable, it is likewise true that the backgrounds also go down with the decreased solid angle. The muon background scales in approximately the same proportion. The increased lever arm will facilitate the use of magnetized iron slabs sunk into the earth shield to remove the (low energy) muons produced in the shield itself. The neutron background in the chamber itself has been investigated. The source of these background neutrons is the interaction of neutrinos in the magnet coils and in the stainless steel shell of the bubble chamber. These neutrons could provide an annoying source of background, especially to the polarization studies suggested in Block's report.[13] The major handle against these background neutrons producing proton recoils is the coplanarity of the two-body interaction in the chamber. Not only will the number of neutrino-induced neutrons go down by a factor proportional to the decrease in the (good) neutrino flux, but the angular definition of the beam neutrinos improves as the lever arm from the drift space region increases.

A mode of operation which reduces the extent of the shield and has merit if it is not too costly in terms of neutrino flux is to remove the highest energy pions from the beam produced by primary protons of the full energy. It would appear from our calculations that one loses mostly the shielding problem and gives up very little in the flux at the lower energies considered important for a major part of the experimental neutrino program. This mode of operation also has the advantage that it scales immediately to machine operation at 400 GeV. Our calculations for this mode of operation are summarized in Figs. 7-10 and Table II of Ref. 11. We have considered the use of both iron and earth shields (except that 100 meters is unduly pessimistic and was chosen only because of the constraints of the computer calculation). We do, of course, lose the very highest energy neutrinos, but the flux of neutrinos above 20 GeV is still substantial. The flux due to kaons has not yet been calculated. Note that the flux above 5 GeV neutrinos <u>for an earth shield</u> and pion cutoff of 100 GeV is quite comparable to that from the 150 m Fe shield case at 200 GeV with no cutoff.

We have also considered the possibility of running the accelerator at less than full energy. This has a twofold advantage: first, the increased repetition rate actually increases the effective number of pions at low energy; second, the fact that the maximum energy of the beam is reduced makes the shielding problem more tractable. We have calculated within our stated approximations the effect of this mode of operation on the neutrino flux in the vicinity of 3 and 5 GeV and above 10 GeV and above 20 GeV. We note that it is possible to obtain low-energy neutrino fluxes which are quite comparable, and in some cases superior, to those obtainable from the basic beam (full muon shield of 150 meters of Fe) although we lose heavily at the high-energy end of the spectrum.

The results of our calculations, including the cases where a pion cutoff momentum is imposed, are summarized in Figs. 11-15 and 15A and in Tables III and V of Ref. 11. Up to an energy of 10 GeV for the neutrinos, the most pessimistic conclusion is that one needs no more than 50 meters of Fe shielding at the outside.

To get a feeling for the space requirements when the machine goes over to 400-GeV operation, we have calculated the basic beams at 400 GeV for both the full iron shield and the full earth shield cases. The results are summarized in Figs. 16 and 17 and in Table IV of Ref. 11. What is most relevant here is the scale of dimensions required for both the drift space and the shield length. This scale must be taken into consideration in deciding the placement of the neutrino facility.

High-Band System (Optimized for $E_\nu > 15$ GeV)

This beam utilizes the most energetic of the mesons. These are likely to be highly collimated in the proton beam direction and will be rare. Because of the expected low beam intensity perhaps the first beam should forego the charge separation. Only the simplest focusing device such as quadrupole lenses need be used. See, for example, Arthur Roberts' report "Simple High Energy Neutrino Beam."[14] Furthermore, an earth shield probably could be used without much loss in neutrino intensity. If the neutrinos come mostly from pion decay, then there is very little loss. Those that come from K-decay will be diminished by a factor of two by using an earth shield rather than an iron one.

The present production models are probably unreliable for the very energetic kaons. Detailed beam design will be difficult. By using the narrow-band calculations of X_{opt} we can obtain some idea of the optimum target-to-chamber distances. We shall assume here that all neutrinos come from pions. In this way, we shall obtain the largest L_{opt}. The following table summarizes the results:

Optimum Target-to-Chamber Distances, L_{opt}.

E_ν (GeV) Threshold Energy	P_π (GeV/c)	$\eta = E_\nu / 0.03$	$\eta c\tau$ (mm)	600 m earth	X_{opt}	L_{opt} (km)
20	93	667	5.20	0.115	0.67	3.5
40	186	1,330	10.37	0.0308	0.59	6.1

Clearly, these optimum lengths are excessive. Some compromises are necessary; any contribution from kaons will reduce these lengths. Perhaps it should be the mid-band beam that determines the location of the bubble chamber.

Simple Ideas About Shielding (M. L. S.)

a) Ideal beam. We have assumed that some focusing device has produced a pencil beam of mesons and that the target location has been optimized for kaon neutrinos. From the ellipse of Fig. 1, one can see that the muons from K-decay have, approximately, the same laboratory decay distribution as the neutrinos. If there were no muon shield, they would be found spread over a circular area of radius $(\theta_\mu^{(K)} = 1/\eta) \times$ $\times$ $(\bar{\ell} = \eta c\tau_K) = c\tau_K = 3.7$ meters at the bubble chamber. The muon shield should have a radius at least this large.

If the drift distance is optimized for K decay, then the μ's from

π's cause little trouble because they are confined to a much narrower angle, $\theta_\mu^{(\pi)} = 1/3.66 \times 1/\eta_\pi$. For a focusing device tailored for 100 GeV/c then $\eta_\pi = 700$ which gives $\theta\mu^{(\pi)} = 3.9 \times 10^{-4}$ radians. The π's are then distributed over a circular area of radius ($\ell_{opt} = 740$ m) ($\theta_\mu^{(\pi)} = 3.9 \times 10^{-4}$) = 0.3 m, a value small compared with 4 meters.

At the outer radius (3.7 meters), the muons have approximately half the kaons' momentum and perhaps the shield needn't be so long at the outer part, provided the meson beam is perfectly "ideal."

b) Nonideal beam. There will likely be a distance from the target to the place where the beam becomes "ideal" in which the beam will have a divergence. Decays that occur in this region will produce muons with a greater transverse distribution. It becomes very clear that the design of the shielding depends crucially on the type of focusing device and on the actual production distribution of the most energetic kaons and pions.

c) Approximate Maximum Shielding Requirements. The transverse distances, calculated at the bubble-chamber position, are smaller when calculated at the beginning and end of the muon shield. They are 2.8 m and 3.0 m, respectively, for a shield length of 160 meters. We choose here the maximum length to stop those muons that are produced in the beam before the meson beam can be made monochromatic.

Allowing for some "nonideal" type decays, the shield must be approximately cylindrical in shape, 4 m in radius and 160 m long. The volume is 7500 m^3 and the cost approximately \$9 million at \$0.07/lb.

In practice it may be better to make the cross section a square rather than a circle. The cost would increase by a factor $4/\pi$ to \$12 million.

d) Possible Ways of Minimizing the Volume of the Shield (A. D. K., M. L. S.). The previous shield estimate assumed that the decay muons encountered no material prior to striking the beginning of the muon shield.

(i) Meson decay tube. If the idealized beam can be made small in cross section, an iron decay tube of the following cross section could force the muons produced near the target to traverse the walls of the tube and some earth prior to striking the beginning of the shield. Not only the radius but the length of the subsequent shield could be reduced as shown by the dashed line of Fig. 7.

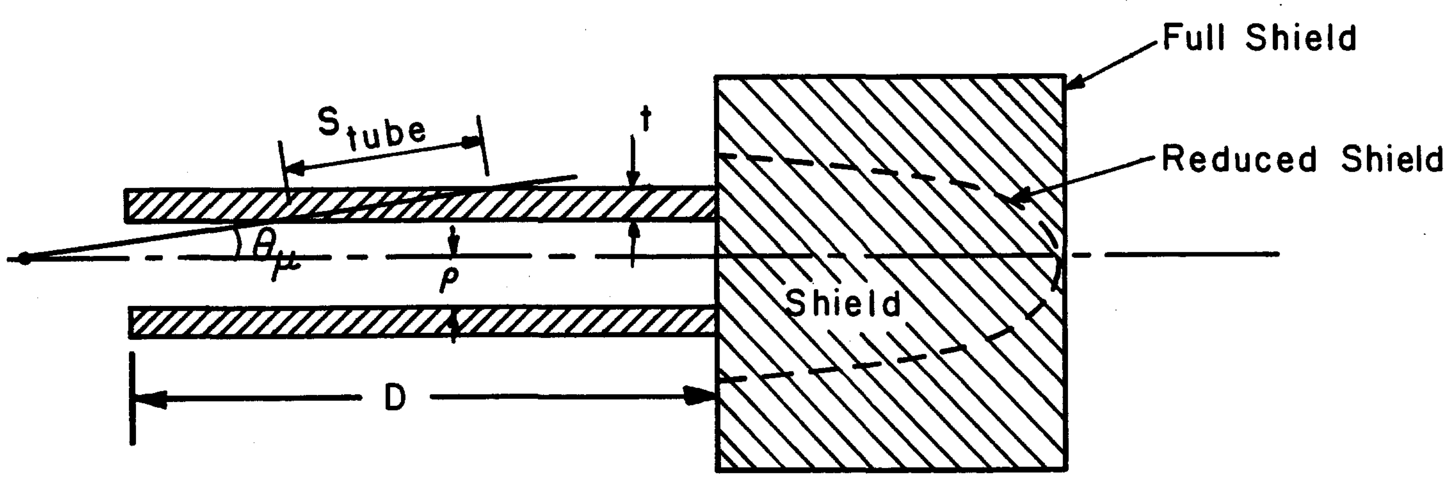


Fig. 7.

This reduction in length occurs at the larger values of ρ, thereby making a greater reduction in the volume of the shield. The path length in the wall of the iron decay tube is:

$$S_{tube} = t/(\theta_\mu \approx 1/\eta).$$

If S_{tube} is chosen to be proportional to the momentum of the meson, i.e., $S_{tube} = K \cdot \eta$, we find that the wall thickness is independent of the meson momentum, i.e.,

$$t = (S_{tube} = K\eta) \cdot (\theta_\mu \approx 1/\eta = K.$$

The earth surrounding the tube would be one-fourth as effective as iron (the density ratio) in stopping μ's. The length D is generally $\approx \eta$ ($c\tau \approx 4$ meters) for kaons. For $\eta = 200$, D = 800 meters, a value sufficiently large to stop most muons before they get to the shield. Therefore, K could be chosen very small, say a centimeter at most. The aperture radius, ρ, would depend upon the nature of the focusing device and the beam optics. The smaller the better, because the volume of the shield following the decay tube would be (150 meters) $\times \pi(f\rho)^2$. Here, f is a safety factor of say 2. If $\rho = 0.5$ m, the cost of the shield could be reduced by a factor of $(4)^2$ to approximately \$1 million.

(ii) Magnetized iron shield. Others[3] have already suggested ways in which magnetized iron could be used to reduce the cost of the shielding. The next round of studies should investigate them in detail.

(iii) Earth shielding vs iron shielding for narrow-band systems.* By what factor does the neutrino flux decrease through the BNL 25-foot chamber if we use a full earth shield rather than a full iron shield? We shall consider two simple cases:

*This has already been discussed for mid-band systems.

a) 100 GeV/c beam, optimized for K decay

(1) Fe Shield. In units of $\eta c\tau_K$(= 740 m) the 160 meters of iron plus the 40-meter shield-to-chamber distance is X_o = 160 + 40 = 200/740 = 0.27. The chamber "radius" is r = 1.8m/(cτ = 3.70) = 0.49. From Fig. 5, we find X_{opt} = 1.06(Fe) and hence the target-to-chamber distance is L_{opt} = (1.06)($\eta c\tau_K$ = 740 m) = 780 m; and from Fig. 6, we obtain a neutrino detection efficiency per 100 GeV/c kaon of Y = (0.18)(0.63) = 0.11.

(2) Earth Shield (ρ = 1.9, ℓ_o = 660 m). X_o = (660 + 40)/760 = 0.92.

Again, from Fig. 5, we obtain X_{opt} = 1.83 which gives L_{opt}(earth) = ($\eta c\tau_K$ = 740)(1.83) = 1390 m, and from Fig. 6 Y = (0.071)(0.63) = 0.045. Thus, the detection efficiency with the earth shield is a factor of 2.5 smaller than that with an iron shield.

b) 30-GeV beam, optimized for π decay of neutrinos of all energies

(1) Fe Shield

$\eta c\tau_\pi$ = 1520 m

X_o = (160 + 40)/1520 = 0.13

r = 1.8 m/7.66 m = 0.23

From Fig. 3, X_{opt} = 0.63, L_{opt} = 960 m, and from Fig. 4, the neutrino detection efficiency is Y = 0.114.

(2) Earth Shield

X_o = (660 + 40)/1520 = 0.46, r = 0.23, and, from Figs.

3 and 4, X_{opt} = 1.13, L_{opt} = 1720 m and Y = 0.04. This detection efficiency is a factor of 3 less than that with iron. The reduction factor is about 2.5 to 3 for the narrow-band beams of 100 GeV/c K's and 30 GeV/c π's.

D. BUBBLE-CHAMBER BACKGROUNDS

A thorough discussion is contained in the report by J. Peoples,[15] to which the reader is now referred.

The "Flux Grabber" (M. L. S.)

As discussed in Ref. 15, the downstream end of the muon shield forms an extended source of regenerated muons. Those muons, regenerated by the semi-elastic process $\nu + N \rightarrow \mu + N'$, will have nearly the same energy spectrum and direction as the neutrino beam itself. If a large air-gap magnet were placed between the shield and the bubble chamber, the muons could easily be swept out. Figure 8 shows a plan view of a scheme that might work.

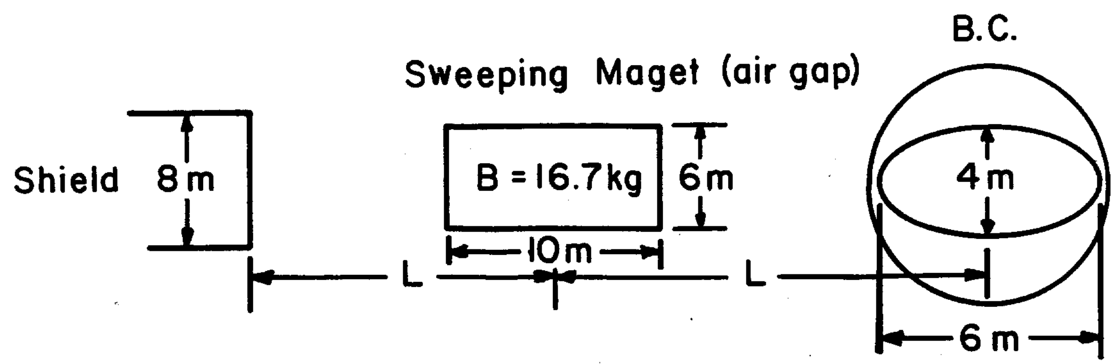


Fig. 8.

The total flux through the sweeping magnet is 10^4 kG · m^2. The total bubble-chamber magnet flux is $\pi(16\ m^2) \times 40$ kG = 2.10^4 kG · m^2

$\int Bdl$ of the sweeping magnet = 167 kG m. Typically, the maximum angle of deflection that is needed is $2 \times 6\,m/L(m)$. Therefore, $P_{max}(GeV) = 5L(m)/12$. For L = 20 m, P_{max} = 8.3 GeV which is well above the canonical 6 GeV neutrino energy.

Figure 9 shows a specific design that uses the stray field of the BNL 25-foot chamber to make the air-gap magnet.

The yoke is made symmetrically to reduce the stress on the coils; in fact, the equilibrium shape of the coils may become elliptical and thereby better match the bubble-chamber shape. The downstream air-gap magnet will serve to sweep the regenerated muons from the heavy muon range spark chambers that will presumably surround the 25-foot chamber. The rear air gap will serve the same function for the neon-filled bubble chamber located downstream from the 25-foot chamber itself.

If the cross section of the iron pole tip is maintained throughout the yokes, then the volume of the iron yoke is $2 \times 60\,m^2 \times 50\,m = 6 \times 10^3\,m^3$. Its cost would be about \$6 million.

A more detailed calculation of the energy spectrum of the muons emerging from the muon shield might allow the cantilever length of 20 m to be reduced to 15 m and perhaps even 10 m, reducing the cost accordingly. Leaving aside the utility of the flux-grabber for reducing the muon background, one could justify building such a device for other reasons. The stray field is likely to produce safety problems and make it difficult for other equipment to work nearby. The rear air-gap magnet would be a very useful physics facility in its own right.

E. SUMMARY

The neutrino physics program can be grouped into the categories:

Narrow Band	
Ultra-Wide Band	($E_\nu > 1/2$ GeV)
Mid Band	3 GeV $< E_\nu <$ 15 GeV
Wide Band	$E_\nu > 3$ GeV
High Band	$E_\nu > 15$ GeV

Bubble Chamber Location

The latter two categories are those that determine the bubble chamber location. If the bubble chamber is located approximately 3 kilometers from a potential target station (when the machine energy is increased to 400 GeV) it will not seriously diminish the maximum yield of neutrino for the high-band system. For the other systems the proton beam can be transported to the appropriate optimum location. The unit cost of this transport system is approximately $1 million/kilometer.

We recommend that the basic neutrino beam facility be placed in proximity to beam switching station SA.* To be specific, we believe that it should be taken off the primary proton beam somewhat downstream of SA. The reasons for this recommendation are as follows:

*See Fig. 1 of Report D.1-68-55, Plans for Experimental Areas at the NAL 200-400 BeV Accelerator, by J. Sanford and T. Elioff.

a. Beam station SA will undoubtedly be the first construction item. The importance of the neutrino facility is such that delay in its implementation should be avoided.

b. Placement close to SA permits the longest possible neutrino beam. This provides a degree of flexibility which is highly desirable whatever the initial choice of neutrino beam. It is particularly important to have this flexibility in view of the eventual upgrading of the machine energy. It is clear that the beam can always be shortened by transporting the proton beam further (assuming, naturally, the fixed positioning of the 25-foot bubble chamber) but the maximum length is always delimited by the space available. This available space is maximal for station SA.

c. Placement at this position permits geographic isolation of the bubble chamber from the rest of the detector area. Assuming the decoupling of strong interaction physics from the chamber, this appears to be desirable. Should a decision be made at a later time to use the bubble chamber for this purpose, a beam originating from station SB could be brought to the chamber. It would be highly desirable because of the neutron and muon backgrounds to have the facility below ground. However, we leave this decision for later after further engineering and operational studies have been made.

Muon Shielding

By keeping the meson decay tube as small in diameter as possible, we feel confident that the shielding cost will be less than $2 million for the 200-GeV phase of the accelerator operation. For the high-band system using an earth shield these costs can be negligible.

A Possible Experimental Schedule

The fact that the high-band system requires the simplest focusing and shielding system and the nature of the physics (e.g., initial W searches) does not require high statistics nor long running time suggests that it might be the first program to be carried out. Concurrently, meson production spectra could be measured. This would aid in the focusing device design for the wide band and mid-band systems.

Another concurrent activity that could be carried out in a parasitic mode of operation would be the measurement of the muon flux at various longitudinal and transverse distances along the neutrino beam. Only a small fraction of the beam, used in a long spill mode, would be needed for this. The agreement of these measurements with the predicted ones (via Monte-Carlo calculation) would give confidence that one can handle the neutrino shielding problem when the earth shield is removed to install the iron shield.

Focusing Device Design

Work should begin immediately on the design of the focusing device for the mid-band and wide-band systems using the present production models. The electrode shape should be made modular so that an updated module, designed from the measured meson spectra, could replace it as soon as possible.

Further Engineering Study of the BNL 25-Foot Chamber

Engineering studies should be initiated immediately to understand the effect on the superconducting coils of adding large amounts of iron above and below the bubble chamber. Although it is not certain at the moment whether a "flux grabber" is really needed it would be prudent to know what the "neutral shape" of the coils would be for various types of flux grabbers.

Neutrino-Monitoring System

The system which would measure the muon distribution in the parasite experiment could evolve into a system that would monitor the neutrino flux during the actual bubble chamber runs.

F. ACKNOWLEDGMENTS

We wish to express our appreciation to the Aspen Center for Physics for the opportunity of working under such pleasant conditions. Our thanks go also to Robert Rathbun Wilson and the staff of the National Accelerator Laboratory for inviting us to participate in this Summer Study.

TM-131
2251

NPA/Int. 68-18
25.7.1968

SOME CONSIDERATIONS ON HIGH ENERGY NEUTRINO EXPERIMENTS WITH A 76 GeV ACCELERATOR

This report is the result of a series of discussions among colleagues concerned with various aspects of high energy neutrino experiments.

Those participating in the discussions, which took place during the first half of 1968, were :

I. Boudagov, D.C. Cundy, W. Knight, B. Langeseth,
G. Myatt, D. Perkins, B. Pattison, C.A. Ramm, S. Tovey,
K.-M. Vahlbruch, W. Venus, H. Wachsmuth.

CONTENTS

1. The Rôle of Serpukhov in Future Neutrino Experiments

One of the consequences of the operation of the new proton accelerator at Serpukhov is that neutrino experiments at higher energies and with more intense fluxes are now feasible. In response to an invitation from our colleagues at Serpukhov, we have assembled some scientific and technical data which are relevant to the planning of a neutrino facility and its experimental programme. We have concluded, from the considerations in the pages which follow, that neutrino experiments at the 76 GeV accelerator will make unique and decisive contributions in the field of the weak interactions.

Interactions of high energy neutrinos have been studied at Brookhaven,[1] CERN[2,3] and Argonne[4] with installations having the spectra shown in Fig. 1. A few tens of events per day have been obtained in bubble chambers and a few hundreds per day in spark chambers. Preliminary estimates of event rates at Serpukhov[5,6] and, for comparison, from a 300 GeV[7] accelerator, are also shown in Fig. 1, together with improvements which will come, over the next few years, from new power supplies and injectors for the present accelerators.[8]

It is clear from Fig. 1 and also from Fig. 2, which depicts event rates for various detectors, that a neutrino programme starting in 1972 could not be markedly superior to the programmes at CERN and Brookhaven in the energy region below 5 GeV. These laboratories either have already, or in an advanced stage of construction, neutrino beam installations, machine intensity improvement programmes and giant bubble chamber detectors. During the next four years they will have accumulated a substantial body of data on the more common reactions of neutrinos and antineutrinos on nucleons for which the cross-sections reach their asymptotic limits below 5 GeV.

The essential justification for a neutrino installation at the 76 GeV accelerator must therefore rest on the assessment of the physics programme possible with neutrino energies above 10 GeV.

It is our opinion that this programme is of fundamental importance. Possible experiments which will be described in outline in this report, and which are oriented specifically to high neutrino energies, may be summarized briefly as follows :

(1) Experiments having as their aim the extension of the studies of neutrino processes which have been made at existing accelerators. An important example is the investigation of total and differential cross-sections on nucleons in the high-energy region. The behaviour of these cross-sections is crucial for the detection of the expected breakdown of the local current-current hypothesis. Neutrino experiments at Serpukhov would extend the range of such measurements from the region of up to 10 GeV, accessible today, to 40 or 50 GeV.

(2) A neutrino installation at Serpukhov would allow the study of interactions whose thresholds were not previously attainable. As examples of this type of experiment, we mention the elastic scattering of muon neutrinos by electrons which has a threshold energy of 10 GeV, and the certainty of producing and detecting the intermediate boson W, if its mass is less than 5 GeV. This latter possibility is still perhaps the most urgent of all neutrino experiments,(*) especially in view of several recent theoretical speculations[9] suggesting a W mass in the region of a few GeV.

(3) In discussing the justification of a higher-energy facility, the possibility of the discovery of new and unexpected phenomena must be borne in mind. Some of the many possibilities which have been discussed in theoretical studies in this field are mentioned later.

(*) " In any event, experimental studies of weak interactions at high energies and especially the search for W quanta, constitute some of the most important future problems (of particle physics)" A. Pais - Physics Today 21, 25, 1968.

(4) Finally, experiments at Serpukhov, even if oriented to high energy, will yield of course many lower energy events which will result in invaluable and independent contributions to the study of amplitudes and form-factors for the common transitions. They will provide an assured programme of research because of the great wealth of data which will be obtainable, but as we have stated already, we do not maintain that they are a primary justification for the neutrino programme.

Both wide and narrow band neutrino beams have been considered.[6] The wide-band system optimized for the neutrino flux above 10 GeV seems to be superior for the type of programme envisaged, since practically all experiments require a wide range of neutrino energy with the maximum possible flux. Detailed calculations based on a scaled-up version of focusing element parameters, shielding requirements and fluxes of the present CERN system have been carried out.

It has been assumed that the neutrino interactions would be detected in large bubble chambers like SKAT or MIRABELLE and also, for selected processes, in massive spark chamber arrays. The expected numbers of events have been computed for an experiment using 3×10^{18} protons on the target of the magnetic horn, probably about 1 million pulses with the accelerator intensity then available. They are listed in the following pages, but it is useful to summarize some of them here :

(a) A search for the intermediate boson could usefully be carried out with both bubble chambers and spark chambers. For $M_W = 4$ GeV, about 600 events would be expected in SKAT filled with CF_3Br. The corresponding number for $M_W = 6$ GeV is 10 events. For such masses, the pionic decay mode of the W would probably dominate, and certainly for $M_W \leqslant 5$ GeV, such boson events would be readily detectable against the general inelastic background.

(b) With a massive spark chamber, the leptonic decay mode of W would be detectable in much more certain conditions than were possible in the CERN and Brookhaven experiments. For $M_w = 4$ GeV, there would be 70 identifiable events per 100 tons of spark chamber, assuming a leptonic branching ratio of only 1%. For $M_w > 5$ GeV, background effects from direct lepton pair production, itself of great intrinsic interest, become important.

(c) Bubble chambers, both hydrogen and heavy-liquid, are especially suitable for studies of high-energy neutrino-nucleon cross-sections. In general such interactions are of high multiplicity and might be best studied using SKAT filled with freon and possibly also equipped with plates. This would ensure good identification of the outgoing lepton, which is essential. Some 500 events for a neutrino energy above 30 GeV would be obtained in such an exposure. Hydrogen or deuterium chambers would be more suitable for investigating the detailed energy dependence of cross-sections in the simpler channels of elastic reactions and single pion production.

(d) It is feasible to attempt to detect at Serpukhov, for the first time, examples of neutrino-electron elastic scattering with a massive spark chamber array. Such experiments would give more information on the four lepton interaction than can be obtained from muon decay, the only process of this type experimentally accessible at present. For the inverse reaction $\nu_\mu + e^- \to \mu^- + \nu_e$, about 100 events could be obtained per 100 tons of detector. These events would have a very characteristic appearance; just a single muon of energy above 20 GeV which would be within an angle of less than 7 mrad to the neutrino direction. The problems of background are considerable, but not insurmountable.

During our studies, we have become increasingly aware that by their very nature, higher energy neutrino experiments will be more difficult than all previous neutrino experiments. For example, many of the experiments described below, depend much more critically on a reliable determination of the neutrino flux than any previous ones. They will demand extremely careful preparations, from the choice of the scientific aim to the construction of the apparatus and the operation and analysis of the experiment. The host of problems which will arise will provide many stimulating challenges to experimentalists; their solution is also an essential stage in the evolution of neutrino experiments which are again considered as a fundamental justification for the 300 GeV and other future accelerators.

We are of the opinion that it is completely justified to devote the intellectual and material scientific effort which is essential to this field of research. High energy neutrino experiments are the only means by which the phenomena of weak interactions can be studied over an extensive range in energy and momentum transfer. Neutrino experiments with a 76 GeV accelerator give the only possibility, during the next decade, of investigating many of the most fundamental problems of the weak interactions.

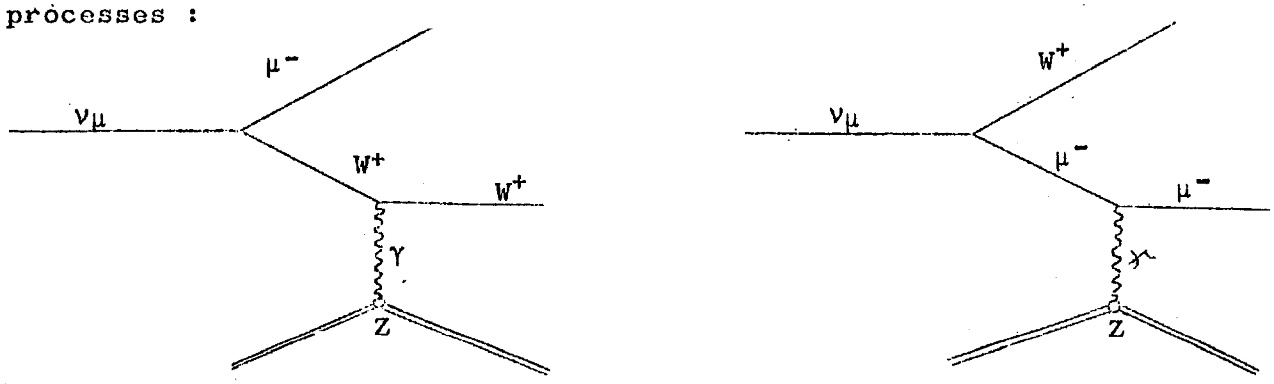
2. OUTLINE OF A POSSIBLE PHYSICS PROGRAMME

2.1. Search for the Intermediate Vector Boson W.

The neutrino experiments performed at CERN(10) and Brookhaven(11) have put a lower limit of about 2 GeV/c^2 on the mass of the intermediate vector boson. It has been clear for some time that a large increase in the lower limit for the mass cannot be obtained merely by increases in flux or detector size at existing accelerators. This is not simply because the boson yield falls off sharply with increasing mass, but rather that once a low value of the boson production cross-sections is reached, background contributions from other processes become overwhelming. Thus, any substantial increase in the limit on M_W can only come from the use of higher energy neutrino beams.

(A). Production and Decay of W - Boson

Wu et al.[12] have considered elastic W production by the processes :



where Z represents either a nucleus or a single nucleon. Cross-sections were calculated up to $M_w = 2.5$ GeV/c^2 and neutrino energy of 20 GeV. These cross-sections have been extrapolated to $M_w \sim 4$ GeV and $E_\nu \sim 40$ GeV; the errors from the extrapolation should not exceed a factor of 2. Fig. 3 shows the integral rate as a function of M_w for various spectra.

For W-bosons of mass greater than 2 GeV/c^2, many decay modes are possible. e.g.:

$$W^+ \longrightarrow \mu^+ + \nu_\mu \qquad (a)$$
$$e^+ + \nu_e \qquad (b)$$
$$\pi^+ + \pi^o \qquad (c)$$
$$K^+ + \pi^o \qquad (d)$$
$$p + \bar{n} \qquad (e) \qquad \text{etc...}$$

The decay rates for (a) and (b) can be estimated reliably and for $M_w > 2$ GeV/c^2 they put an upper limit on the mean life of the W-boson of 10^{-19}sec. The decay rates for processes (c), (d), (e) etc., are difficult to estimate, however Yamaguchi[13] has argued that the branching ratio into modes (a) and (b) should tend to $\sim 1/10$ as $M_w \longrightarrow \infty$.

(B). Detection of Pionic Decays of the W-Boson

An exposure of the heavy liquid chamber SKAT in a neutrino beam would be an excellent means of studying the pionic decay modes. It would be necessary to identify the negative muon among the many mesons in an event. For this purpose a plate system in the chamber would increase the number of interaction lengths available.

A major problem would be to distinguish boson events from the background of inelastic interactions not involving real bosons. Fig. 4 shows the differential boson rate as a function of E_ν for various M_w. For comparison, the inelastic rate is shown for a cross-section of the form $\sigma = 0.6 \times 10^{-38} E_\nu$ cm^2/nucleon, suggested by the early CERN experiments.(14) The boson rate for $M_w \sim 4$ GeV would be more than 12% of the total rate for neutrino energies well above the threshold.

To identify the boson events, the following criteria could be applied :

a) A cut in E_ν to select candidates well above the W-threshold. For $M_w \sim 4$ GeV, the cut could be $E_\nu > 20$ GeV, so that the inelastic background would be reduced.

b) A cut in E_{μ^-}. For $M_w > 2$ GeV, the accompanying μ^- will have momentum less than 20% of the neutrino momentum, since the W and the μ^- will have low relative momentum in their centre of mass system. A cut $E_{\mu^-} < 0.2E_\nu$ might eliminate 75% of the inelastic events, without removing many boson events.

With these criteria, and for $M_w \sim 4$ GeV/c^2, boson candidates should show a signal to noise ratio of $\sim$ 1:1 in the pion invariant mass distribution.

From Fig. 4 it can be seen that a 1 million pulse exposure could extend the boson search to a mass $\gtrsim 4$ GeV/c^2 if the pionic branching ratio were ~ 0.5.

(C). Detection of the Leptonic Decays of the W-Boson

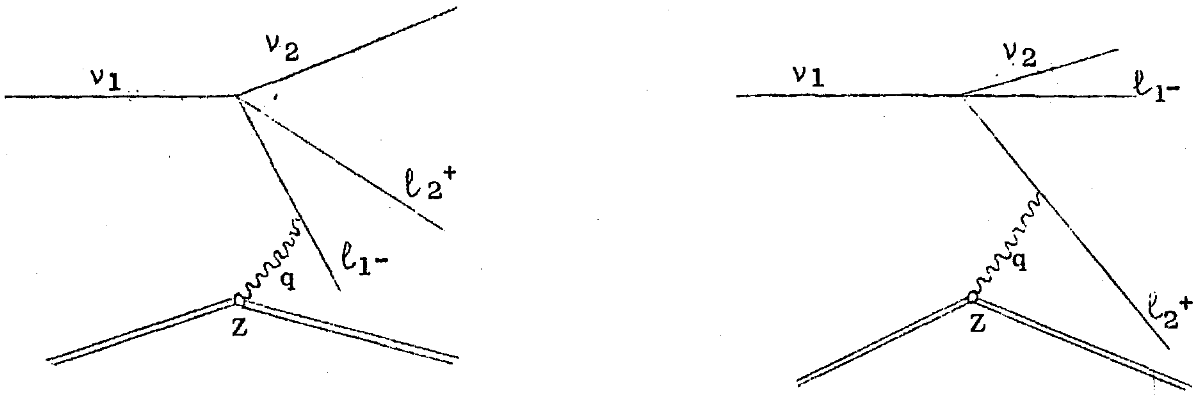
The exposure of SKAT considered above would also yield excellent data on the decay mode $W^+ \rightarrow e^+ + \nu_e$. There is very little background in this mode ($\leq$ 1 event in 450 in the CERN experiment[14]). If the branching ratio for leptonic modes were > 0.1, then a lower limit of 4 GeV/c^2 could be placed on the mass of the W.

The decay mode $W^+ \rightarrow \mu^+ + \nu_\mu$ would also be observed in the bubble chamber, but since the detection depends on the identification of muon pairs by their penetration, a better method would be to use a large spark chamber assembly, where more interaction lengths are available. Boson production by the high average neutrino energy at Serpukhov would yield higher energy muon pairs than in all preceding experiments. Their greater range would permit a much better discrimination of muons from pions, which is a difficulty in certain aspects of earlier work. The use of spark chambers with iron plates up to 50 cm thick would be feasible and would yield some 7000 events per 100 tons for $M_W \sim 4$ GeV and 3.10^{18} protons on the horn target. Even for a branching ratio $W^+ \rightarrow \mu^+ + \nu$ of only 1%, a boson could be detected up to the limit $M_W \sim 5$ GeV, at which stage the alternative mechanisms of muon pair production become important.

Recently, several theoretical papers have appeared giving estimates of the boson mass. A value of order 8 GeV is obtained from current algebra predictions in $K \rightarrow 2\pi$[15] and of order 4 GeV from perturbation theory and the observed $K_L - K_S$ mass difference.[9]

2.2. Direct Lepton Pair Production

Cross-sections for processes of the type :
$\nu_\mu + Z \rightarrow \nu_\mu + \mu^+ + \mu^- + Z$, have been calculated by Czyz, Sheppey and Walecka,[16] who considered the following diagrams :



Their results are shown in Fig. 5.

If the search for muonic decays of the W-boson showed that its mass > 5 GeV/c^2 and that backgrounds were sufficiently low, one could envisage the construction of a larger detector in order to study the process. For example, an exposure of an iron plate spark chamber to 3×10^{18} protons on the horn target would yield ~ 10 events of this type pèr 100 tons of detector.

2.3. Cross-Sèctions in the Very High Energy Region

The concept of the four-fermion point weak interaction gives an excellent account of muon decay and other low-energy weak interactions but extrapolates to impossible results at very high energies. For example, s-wave e-ν scattering would lead to a cross-section violating the wave-theory limit $(\frac{\pi\bar{\lambda}^2}{2})$ at a centre of mass energy of 300 GeV. In a correct theory, such difficulties would presumably be removed by introducing non-localities in the form of a mediating boson and contributions from higher order graphs. However, attempts to take into account higher order processes in general lead to divergences. It is well to remember that the only known second-order weak interaction is the $K - \bar{K}$ transition with $\Delta S = 2$, the resulting $K_L - K_S$ mass difference yielding a finite experimental result. This has been interpreted in terms of cut-offs, or a finite boson mass of under 4 GeV.

Lee and Yang[17] assuming only the local current-current interaction hypothesis, have expressed the differential cross-section for the process $\nu + N \longrightarrow \mu + N^*$ in the form :

$$\frac{d^2\sigma}{dq^2 dM^{*2}} = \frac{A(q^2, M^{*2})}{E_\nu^2} + \frac{B(q^2, M^{*2})}{E_\nu} + C(q^2, M^{*2})$$

where M* is the mass of the hadronic final state and A, B and C are structure factors. This simple quadratic form follows directly from the local current assumption. If this assumption were invalid, one would in general expect a much more complicated dependence of the cross-section with, for example, terms depending on the differences of lepton energies. If non-local effects occur at high q^2 and at high E_ν, then they may be detectable at Serpukhov, where it will be possible to have access to a completely unexplored region of momentum transfer and centre of mass energy several orders of magnitude above the values where the conventional theory is known to hold rigorously.

If an anti-neutrino run were also performed, then it would be possible to test the "sum rules" by the method proposed by Adler,[18] which is to investigate whether $\frac{d\sigma_\nu}{dq^2} - \frac{d\sigma_{\bar{\nu}}}{dq^2}$ tends to a constant value.

The Pomeranchuk theorem leads to equality of the asymptotic total cross-section for particle and anti-particle interactions. Further detailed considerations of dispersion relations[19] have led to asymptotic relations for cross-sections for strangeness non-changing processes which could be tested in neutrino and anti-neutrino experiments. The relations are :

$$\frac{d^2\sigma(\nu p)}{dq^2 dM^{*2}} = \frac{d^2\sigma(\bar{\nu} n)}{dq^2 dM^{*2}} \quad : \quad \frac{d^2\sigma(\bar{\nu} p)}{dq^2 dM^{*2}} = \frac{d^2\sigma(\nu n)}{dq^2 dM^{*2}}$$

where the cross-sections are integrated over all combinations of hadrons. As with all studies involving the energy dependence of cross-sections, the higher neutrino energy at Serpukhov is advantageous. The rates of elastic and inelastic neutrino interactions to be expected in various detectors at Serpukhov are given in Table 1.

2.4. Neutrino-Electron Scattering

Neutrino-electron elastic scattering is in principle the best way to investigate the behaviour of weak interactions at high energy and high momentum transfer without complications from strong interaction structure. Unfortunately the range of momentum transfer available with a 76 GeV machine is only of the same order as that in muon decay, so that deviations from the classical four-fermion point interaction are likely to be negligible. Nevertheless, it is most important to demonstrate this interaction with free neutrinos, with all the flexibility and choice of variables which collision processes permit, in contrast to decay processes.

The reactions which can occur are :

Reaction	Threshold Energy	Cms. angular distribution of charged lepton	Approximate Cross-Section Dependence
1) $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$	10.8 GeV	isotropic	$\frac{G^2}{\pi} \quad \frac{(2mE_\nu - M_\mu^2)^2}{2mE_\nu}$
2) $\nu_e + e^- \rightarrow e^- + \nu_e$	0	isotropic	$\frac{G^2}{\pi} \cdot 2mE_\nu$
3) $\bar{\nu}_e + e^- \rightarrow e^- + \bar{\nu}_e$	0	$(1-\cos\theta^*)^2$	$\frac{1}{3} \quad \frac{G^2}{\pi} \cdot 2mE_\nu$
4) $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$	10.8 GeV	$(1-\cos\theta^*)^2$	$\frac{1}{3} \quad \frac{G^2}{\pi} \frac{(2mE_\nu - M_\mu^2)^2}{2mE_\nu}$

The reactions (1) and (2) show strong forward peaking of the charged lepton in the laboratory system, $\theta \sim \sqrt{\frac{2m_e}{E}} \sim \frac{1}{\sqrt{1000\ E_\nu\ (\text{GeV})}}$

The forward cross-section $\left(\frac{d\sigma}{d\Omega}\right)_{0^o} \sim \frac{G^2E^2}{\pi^2}$ has the same value as for the reaction $\nu_\mu + n \rightarrow \mu^- + p$ on a free neutron target. For the antineutrino reactions, the forward amplitude is zero, the overall distribution is consequently broader, and the cross-sections reduced by a factor 3. The neutrino cross sections (1) and (2) are more favourable for measurement, especially as the anti-neutrino beam is intrinsically less intense than the neutrino beam.

The cross-sections for these processes are indicated in Fig. 6 and are of order 10^{-2} of the asymptotic elastic cross-section $\nu_\mu + n \rightarrow \mu^- + p$; in the region above the threshold of reaction (1), they are about 10^{-3} of the total cross-section. Since the ν_e flux is only about 1% of the ν_μ flux, the rate of (2) will be of order 10^{-5} of the total neutrino event rate. Thus, it seems that reaction (2) could only be studied, if at all, with massive spark-chamber detectors.

In the (ν, e) scattering reactions, the charged lepton is emitted very near to the incident neutrino direction and with about the full neutrino energy (e.g. at 20 GeV, $\theta < 7$ mrad). This aspect could be used in principle to identify the reaction. However, the deflection of the secondary electron through radiation losses, would inhibit the identification of reaction (2) in a spark chamber and therefore the inverse muon decay reaction (1) seems the only feasible study at present. The ν_μ flux above the threshold for this interaction is only a few per cent of the total flux.

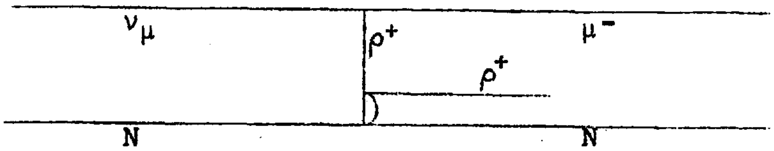
Fig. 7 shows the relative event rates for reaction (1) at Serpukhov and CERN per incident proton; the 76 GeV machine yields an integrated rate almost exactly 100 times that of a 25 GeV machine. Evidently, even with this situation, which corresponds to 10^{-4} of the total ν-event rate, rather than 10^{-6}, such an experiment would still be extremely difficult, although it is likely that neutrino-electron scattering processes will account for 1% of all muons more energetic than 20 GeV.

The numbers of events in a 100 ton detector of radius 0.7 m, with 3.10^{18} protons on the target, are as follows :-

E_ν GeV	CERN (25 GeV)	Serpukhov (76 GeV)
10 - 15	0.39	6
15 - 20	0.44	23
20 - 25	-	26
25 - 30	-	22
30 - 35	-	16
35 - 40	-	8
Total < 40 GeV	0.8	101

2.5. Direct Meson Production, Tests, etc.,

The investigation of the direct production of mesons by neutrinos is the only way of investigating the weak interaction properties of these particles. The cross-section for diffraction production of ρ^+ mesons by the process :



has been estimated[20] to be $\sim 10^{-39} cm^2$ at 4 - 6 GeV neutrino energy. For heavier mesons such as the A_1, higher energies are needed to obtain the same cross-sections. This type of study lends itself well to the Serpukhov accelerator.

The tests of CVC and PCAC can also be studied with advantage at Serpukhov. It is predicted that the studies of the variation of cross-sections with $A^{2/3}$ would be improved by the availability of higher energy neutrinos.[21]

2.6. New Particles

There are many postulates of possible new particles which might be detected in neutrino experiments. In addition to the W already discussed, we select the following three types of particles as subjects of typically feasible experiments.

a) The scalar boson proposed by Kinoshita[22] would have a cross-section of $\sim 10^{-34} cm^2$ for neutrino interactions on complex nuclei. In the 1963-65 CERN experiments, a lower limit to its mass was set at 4 GeV. An experiment at Serpukhov could set a lower limit of ~ 8 GeV.

b) Ericson and Glashow[23] and more recently Callan[24] have proposed that vector bosons have strong quadratic coupling. Such particles could be produced in pairs in strong interactions, or singly, via intermediate coupling, by neutrino beams. Existing experiments set a lower limit of 3 - 4 GeV for the mass. Experiments at Serpukhov would raise this limit to 7 or 8 GeV.

An interesting feature of such a boson theory is that neutral and charge-changing currents have equal coupling, except that crossing symmetry forbids neutral couplings at low q^2 (as observed). For a massive boson, the ratio $d\sigma(\nu + p \rightarrow \nu + p) / d\sigma(\nu + n \rightarrow \mu + p)$ is of order $R = \frac{E_\nu}{M_p} \frac{q^2}{M_W{}^2}$, instead of the value $\alpha^2 \sim 10^{-4}$ expected for electromagnetic neutrino scattering in the usual theory. A search at Serpukhov for $\nu + p \rightarrow \nu + p$ events of high E_ν and q^2 in a hydrogen chamber could certainly set a limit for $R < 10^{-2}$ (depending on neutron background) and thus, $M_W > 20$ GeV.

c) Lifetimes and decay modes of a group of heavy leptons which could participate together with ν_μ and ν_e in the leptonic current have been calculated by S. Gerstein and V. Folomeshkin.[25] These particles could have the same or different quantum numbers as the known leptons and might be produced by the reaction:

$\nu_\mu + n \rightarrow \mu^{\pm} + p$

$\mu^{\pm} \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\mu, \; e^- + \bar{\nu}_e + \nu_\mu, \; \pi^- + \nu_\mu, \; K^{\mp} \nu_\mu, \; n\pi + \nu_\mu$ etc.

Lifetimes have been estimated to be 10^{-11} to 10^{-13} secs., for masses between 1 and 2 GeV. The CERN results set lower limits to the masses at about 1 GeV, the Serpukhov facility could extend this to about 2 GeV.

d) S. Gerstein and Folomeshkin [25] have also considered a heavy lepton λ with its own lepton number and which could be produced in the decay $W^+ \longrightarrow \lambda^+ + \nu_\lambda$ for $m_\lambda = \frac{m_W}{2}$:

$$\frac{W^+ \longrightarrow \lambda^+ + \nu_\lambda}{W^+ \longrightarrow \mu^+ + \nu_\mu} \sim 0.6.$$

3. A POSSIBLE EXPERIMENTAL LAYOUT

The actual design of an optimized installation for a neutrino experiment at Serpukhov would take considerable time. We have not made this detailed study, instead we have considered an extrapolation of the CERN installation, a procedure which will give realistic results but which certainly could be improved in an actual design study.

The neutrino installation considered here has the following features : (see Fig. 8)

1) The focusing system would be a scaled-up version of the present CERN system.

2) The muon shield has been designed so that the amount of iron is minimum, ($\sim$3000 t in the neutrino filter, $\sim$1000 t in the decay tunnel wall, $\sim$500 t around the target and R_1).

3) The detectors would be one or more of those available at Serpukhov: SKAT, MIRABELLE, spark chambers and later perhaps the 60 m^3 hydrogen bubble chamber.

4) A built-in muon flux measuring system to determine the neutrino spectrum.

3.1. Neutrino Beam :

(A). Extrapolation of the CERN Focusing System

The present CERN system is designed to maximize the neutrino yield from pions and kaons in the energy range of 3 to 10 GeV. It has been assumed that the momentum spectrum of the secondary particles at Serpukhov will be broadly similar to that at CERN, but scaled up in energy by about a factor of three, corresponding to the increased proton energy. The neutrino yield for the extrapolated system at Serpukhov has been maximized for parents in the energy band of 10 to 40 GeV, giving neutrinos from pions (ν_π) of between 4 and 16 GeV and neutrinos from kaons (ν_K) up to 40 GeV.

For approximately the same radial dimensions as previously for the proton beam, the target, the focusing elements and the detector, all linear dimensions parallel to the beam axis have been trebled except those of the focusing elements themselves and the first focusing element, whose entry surface requires modification to cope with the longer target.

(B). Computational Results

A beam design with these principles has been tested by computer calculations. The pion spectrum used was that deduced according to a modification by Perkins,[26] of the Cocconi-Koester-Perkins formula and is shown in Fig. 9. The K^+/π^+ ratio was assumed to be 0.15. The basic parameters used are as follows :

Decay path	D	=	210 m
Shield length	S	=	55 m
Target : Length	l	=	2.5 m
Radius	r	=	2 mm
Proton interaction Length	λ_p	=	0.9 m
Detector radius	R	=	0.70 m

The entry surface of the horn was adjusted to maximize the neutrino flux. The absorption length in the target of the secondary particles (λ_s) was assumed equal to the interaction length for the primary protons (λ_p). The ν spectrum calculated for these conditions is shown in Fig. 10. The calculated neutrino spectrum for a single focusing element is in agreement with that of Alekseev et al.[5] using the same input conditions.

The "perfect focusing" curves correspond to the parameters of Table 2 and a limiting assumption that any particle entering the field of a focusing element emerges along the beam axis. Target inefficiency and reabsorption in the target and the entry surface of the horn are therefore included in the "perfect focusing" curve.

The flux appears to be substantially higher than that from the previously proposed single element system and is within a factor 2 of that obtained from "perfect focusing" throughout the energy range chosen. The potential gain achievable by adopting some radically different focusing system would at first sight appear to be fairly small, but it must not be overlooked that the "perfect focusing" curve itself will change if any of the parameters in Table 2 are changed. It must be appreciated therefore that this data cannot exclude that further substantial improvements might be made by changing these parameters. Significant improvements may come also from a refined study of the target design.

The dimensions of the focusing devices R_1, R_2, R_3, and their power supplies are shown in table 2. The requirement to focus the fast ejected protons onto a 4 mm diameter target is feasible for a beam transport system.

3.2. Shielding

Shielding accounts for an important part of the cost of neutrino experiments. The size of the shielding should be kept as small as possible, not only because of the expense of shielding material, but also because of the loss of neutrino flux density due to the reduction in solid angle or decay path length. A thickness of about 50 m of iron would reduce the muon flux at the detector to less than 1 per m^2 and 10^{12} protons, as can be seen from the muon attenuation curve in Fig. 11. This filter thickness could be adjusted as soon as the results of the particle production experiments are available.

Table 3 illustrates the gain in neutrino flux, in a given layout, for a filter of half the thickness required if it were iron. Such a thin shielding would be sufficient if the central core consisted of uranium ($\sim$ 840 t) or if it were magnetized. The feasibility of magnetizing the neutrino filter and the corresponding muon flux distribution will be studied further in detail.

In the layout sketched in Fig. 8, the deçay tunnel and the 50 m iron filter are designed so that a detector area of 6 m width and 6 m height is kept free from muons. Due to the narrow decay tunnel, the actual iron filter need not be wider than 2.5 m, the rest of the detector surface is shielded by the side walls consisting of $\sim$ 25000 t of concrete and $\sim$700 t of iron. The reduction in neutrino flux above 5 GeV is only a few percent, as long as the decay tunnel width is not smaller than the detector diameter. The muon flux distribution calculated for a homogeneous iron filter is shown in Fig. 12. Further studies are needed on the modification due to the concrete walls.

To measure the muon flux distribution (§ 3.4) transverse gaps or channels must be foreseen. As in the present CERN layout, a mercury-filled pipe on the axis of the shielding could give a muon test beam for the neutrino detectors.

3.3. Detectors

Due to the low cross-section of neutrino interactions, a detector containing a large mass of target material is needed. The detector finally chosen should be determined by the type of reaction of interest and the methods of their identification.

We consider three large bubble chambers : SKAT, MIRABELLE and the 60m^3 hydrogen bubble chamber project of Dubna, and for a comparison, a spark chamber with 100 tons of iron plates, which is an approximate scaling for the Serpukhov energies of earlier spark chamber neutrino experiments of BNL and CERN.

In table 1, the expected numbers of elastic and inelastic events are presented for these detectors.

3.4. Experimental Spectrum Determination

During the last CERN neutrino experiments, the muon flux in the neutrino filter has been used to determine the neutrino spectrum. This is possible since the muon flux within about 70 cm of the axis of the shielding comes mainly from pion decay; there is only a small contribution of kaon decay muons. This separation is due to the fact that the pions and kaons are well collimated, and to the larger energy released in the kaon decay. Hence the muon flux as a function of the filter depth is a measure of the momentum spectrum of pion neutrinos. The high energy part of the neutrino spectrum, due to the kaons, must be deduced from the experimental $K/_{\pi}$ production ratio.

From detailed calculations of both the neutrino spectrum in the detector plane and the muon flux at several depths in the filter, one finds that the correlation between muon and neutrino fluxes is strongest for $p_\nu \lesssim p_{\mu\ min} \lesssim 1.5\ p_\nu$ where $p_{\mu\ min}$ is the lowest momentum of muons which can reach the point of observation in the filter. In order to obtain the neutrino spectrum between 4 and 14 GeV/c for the layout of Fig. 8, it is necessary to measure the muon flux for at least 6 filter depths; as an example, the following table shows for a certain choice of measurement planes, how the pion neutrino spectrum can be derived from the number of muons traversing these measurement planes :

measurement plane at iron depth	3.3	4.5	6.9	9.3	10.5	12.9	m
corresponding $p_{\mu\ min}$	4.25	5.9	9.3	12.8	14.5	18	GeV/c
Effective neutrino momentum	4	6	8	10	12	14	GeV/c
Neutrinos per m^2 per GeV, averaged over 70 cm radius detector, per muon observed	.0268	.0254	.0184	.0155	.0108	.0123	

The detailed relationships depend on the focusing currents and on the detector size. Proton intensity and focusing current monitors must be operated continuously during a neutrino experiment. If the pion spectrum is not known, a differential fit to the muon flux distribution must be made varying the parameters in one of the empirical pion production formulae. By measuring the muon flux during the whole neutrino experiment, the corresponding absolute neutrino spectrum can be determined to about 10% up to 14 GeV/c. The accuracy above 14 GeV/c depends on the knowledge of the $K/_\pi$ production ratio. The errors are unlikely to exceed 15%, the overall precision of course depends strongly on the homogeneity of the iron filter.

4. CONCLUSIONS

This report is not intended as a presentation of specific proposals for neutrino experiments, but rather to illustrate the type of programme which we consider feasible for the next phase of higher energy neutrino experiments.

The general conclusions are :

1) Neutrino beams offer the only possibility of studying many of the most fundamental problems of weak interactions, especially those concerned with high momentum and energy transfer. A neutrino installation at Serpukhov, aimed specifically at neutrino energies above 10 GeV, would make a decisive and unique contribution in this field, and study a wide range of problems not otherwise accessible.

2) Higher energy neutrino experiments will be technically complex and difficult, requiring not only large detectors and long running time, but very careful planning, especially in regard to monitoring of neutrino fluxes over a wide energy range. We believe these technical problems are soluble, and that the effort required is justified in relation to the scientific interest of the subject.

3) The neutrino processes we have considered could not possibly all be studied by one type of detector alone. A giant hydrogen chamber would be the only satisfactory instrument for detailed investigation of the energy dependence of elastic and single-pion cross-sections and neutral currents. The same chamber, using neon, or a heavy liquid chamber, would be necessary for

evaluation of complex inelastic processes up to very high energies ($\sim$50 GeV). A massive spark chamber array is the only conceivable instrument for study of neutrino-electron scattering. It is clear that the question of suitable detectors is related very closely to the priorities in the physics programme envisaged.

4) A simple sacling-up of the existing CERN neutrino beam system could provide fluxes which would be comparable to existing installations at neutrino energies below 5 GeV and much more intense above. A more refined study should still further improve this situation.

ACKNOWLEDGEMENTS

We record our appreciation of the invitation by our colleagues from Serpukhov to prepare this report. Our thanks are due to many of our other colleagues also for individual and enlightening exchanges of view; especially J.S. Bell, C. Franzinetti, T.B. Novey, R. Palmer, T. Rijken, B. Roe and H. Yoshiki.

We thank Mme Cabel and Miss Sleap for their help in the preparation of the text and diagrams.

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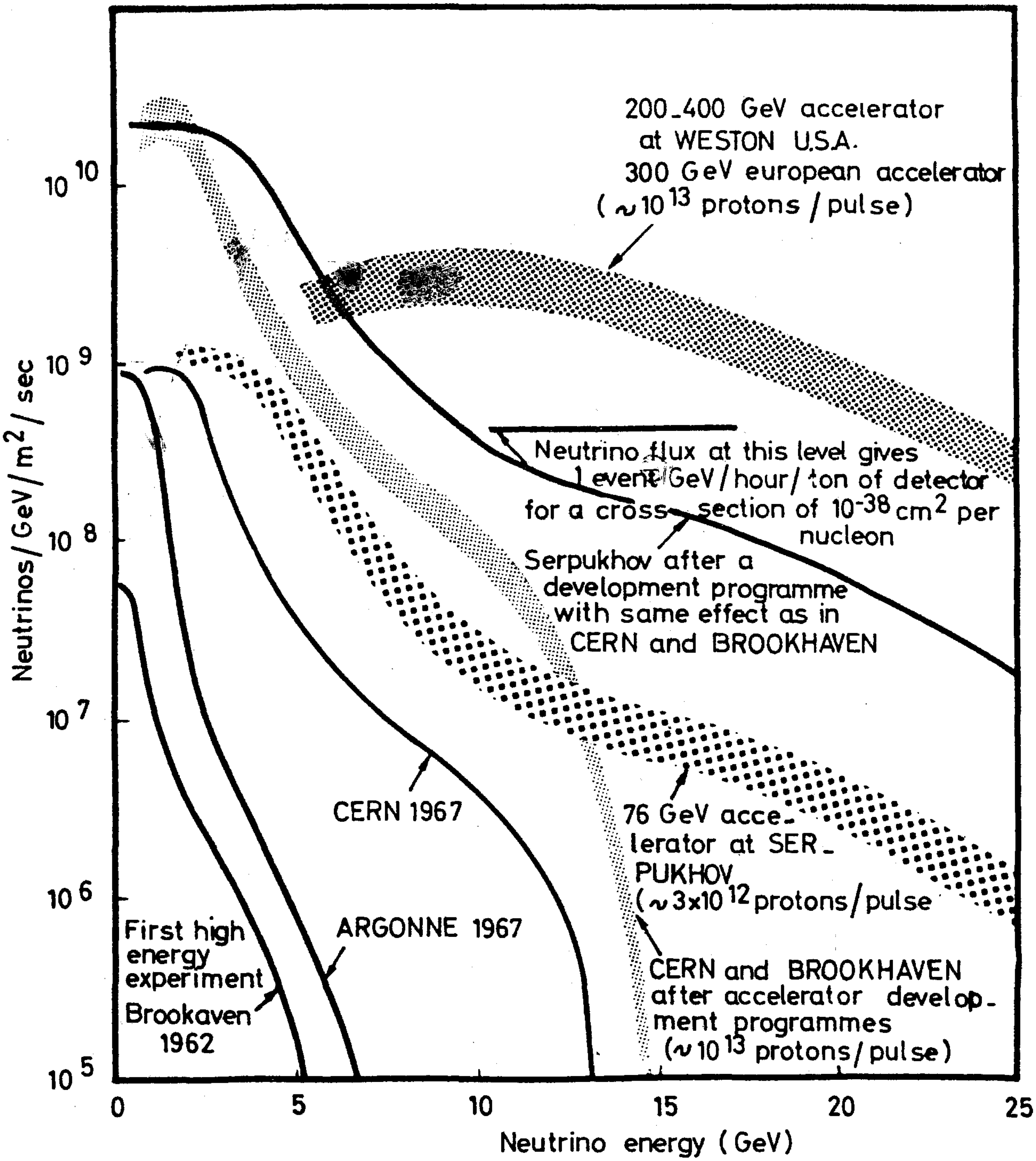

FIG.1. Estimated development of neutrino fluxes at the large accelerators

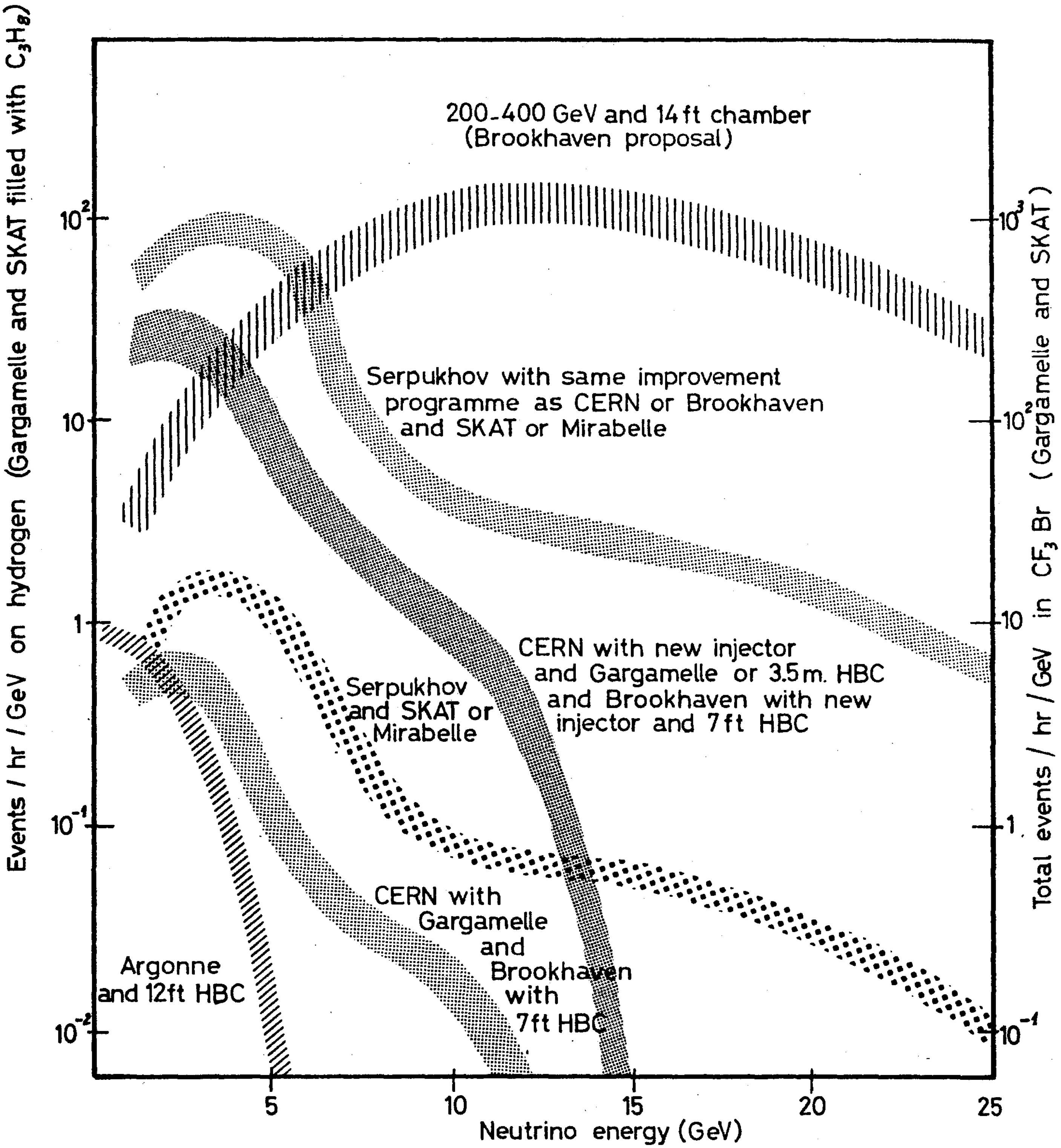

Fig. 2 Estimated neutrino event rates
($\sigma = 0.6 \times 10^{-38}\, cm^2 \times E_\nu$)

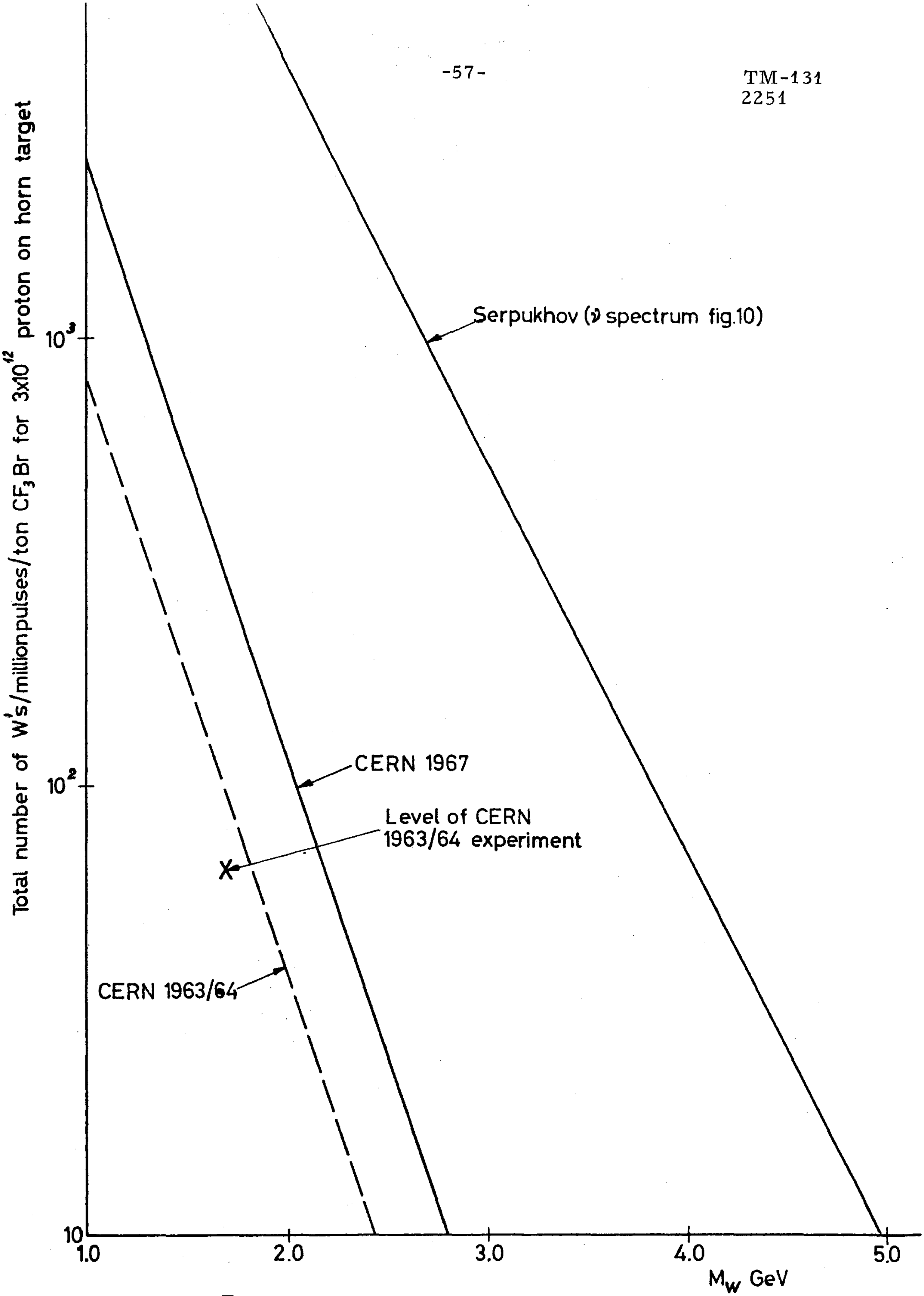

Fig. 3 **Boson Production Rates at Serpukhov and CERN extrapolation of W_u et al. from M_W=2.5 to 4.0 GeV**

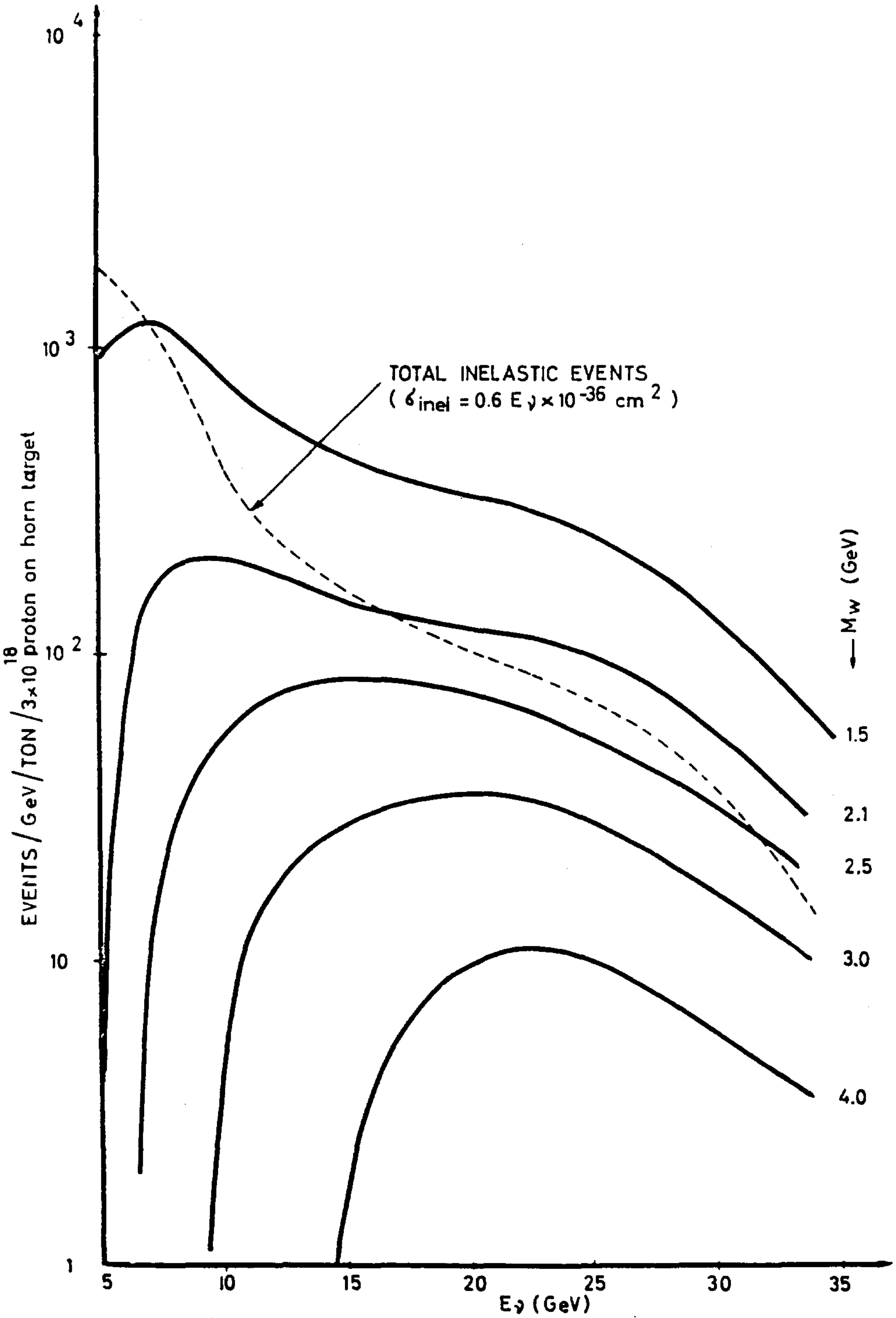

FIG.4 - W-BOSON PRODUCTION AT SERPUKHOV.
($\nu_\mu + Z \to \mu^- + W^+ + Z$)

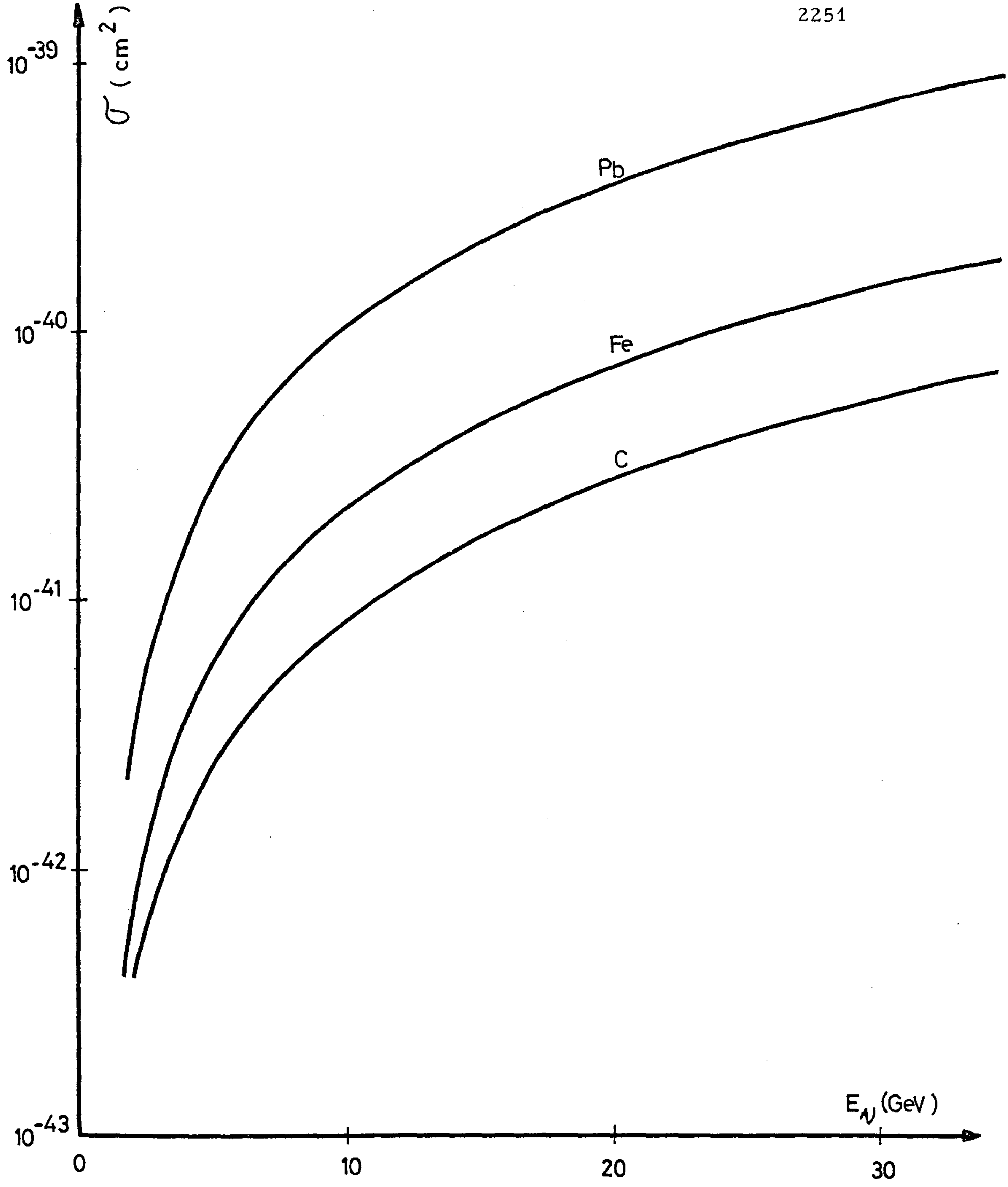

Fig.5 Cross-sections for lepton pair production

$(\nu_\mu + Z \to \nu_\mu + \mu^- + \mu^+ + Z)$

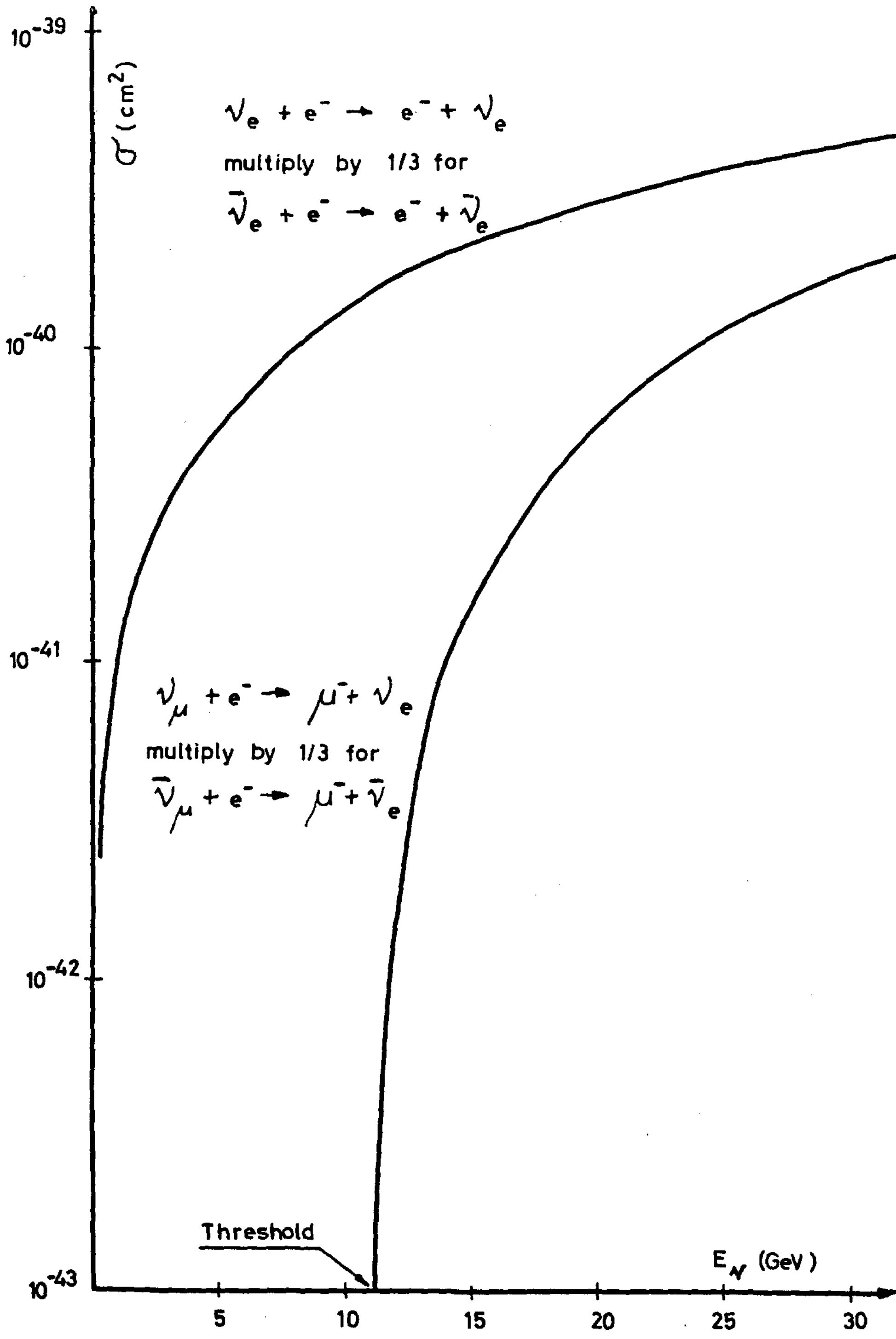

Fig. 6 Neutrino-electron scatering cross sections

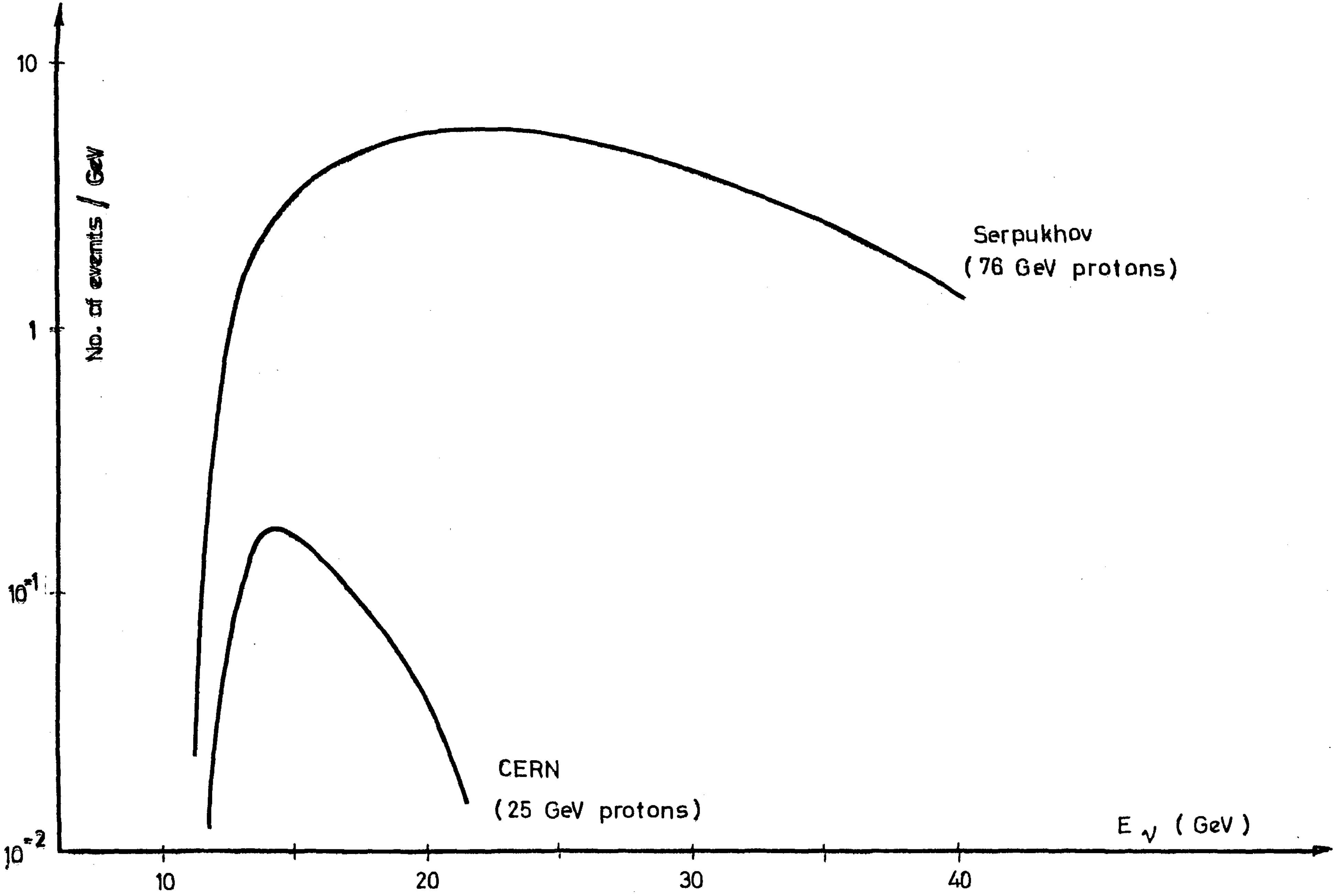

Fig. 7 Neutrino - electron scattering event rates

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

(Per 100 tons of detector per 3.10^{18} protons on the horn target)

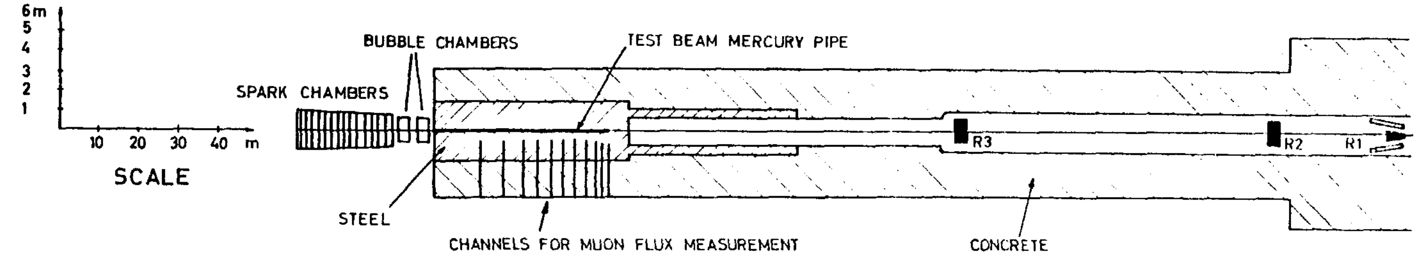

FIG. 8a. Schematic layout of a neutrino experiment at 76 GeV

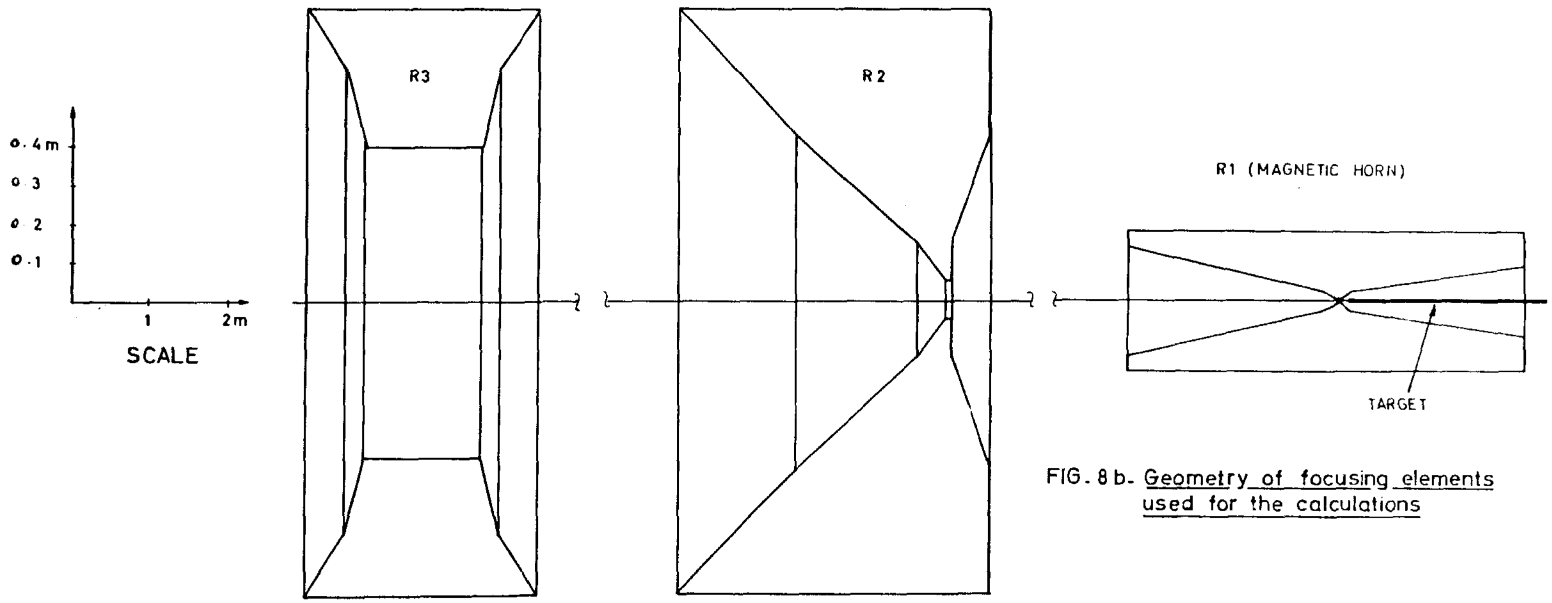

FIG. 8b. Geometry of focusing elements used for the calculations

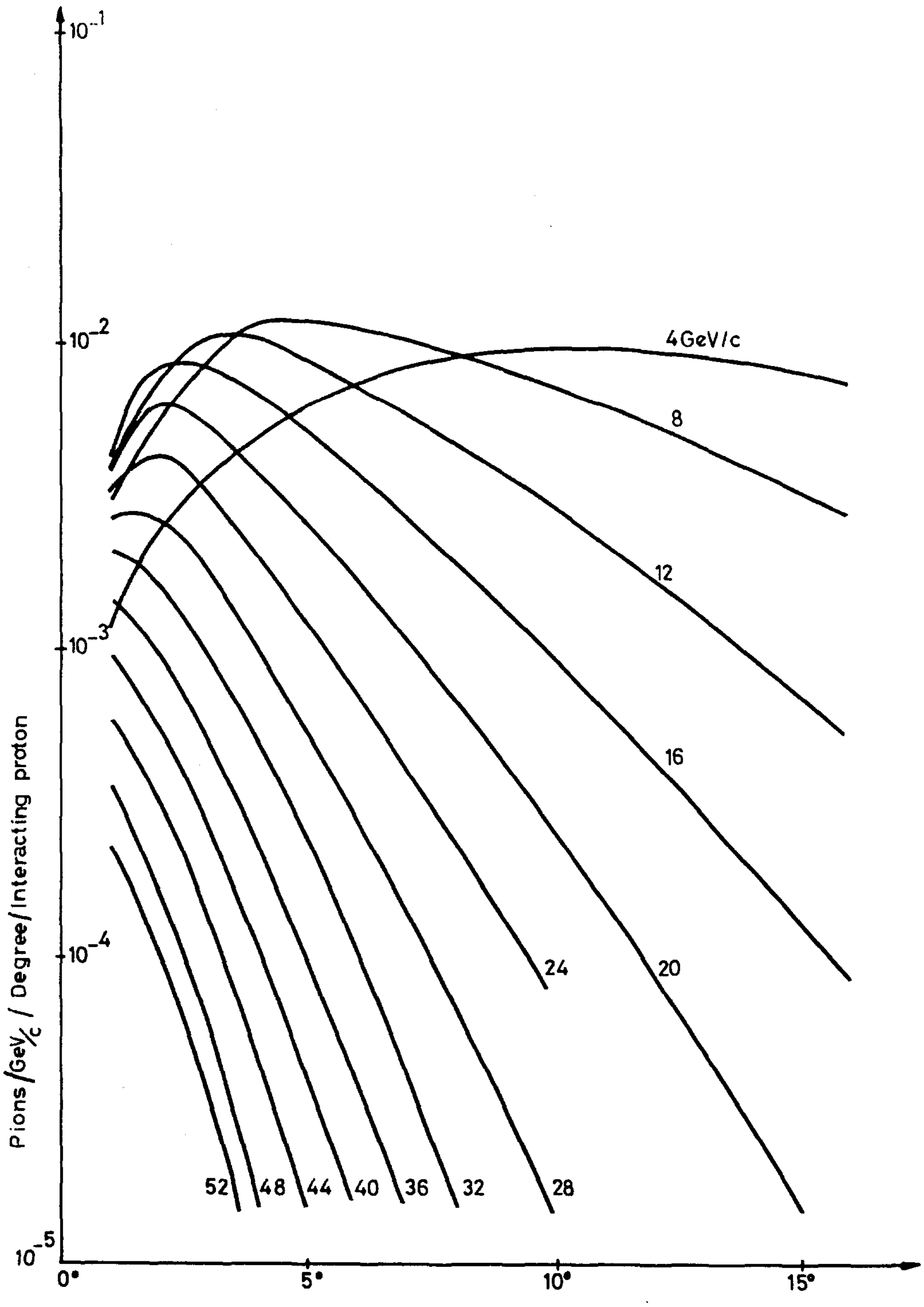

Fig.9 Pion spectrum estimated for 76 GeV (p,Be) collisions

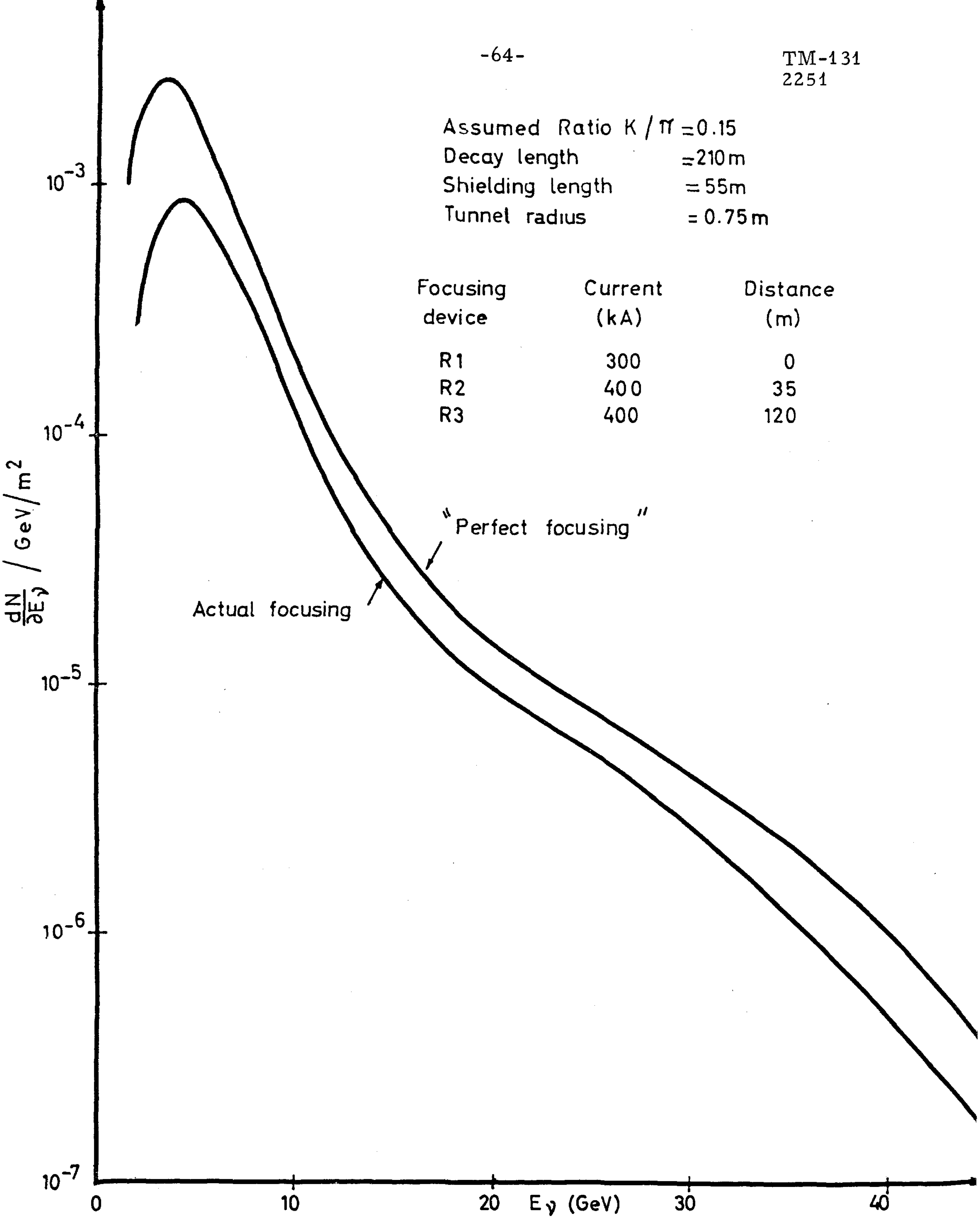

FIG.10. Neutrino spectrum for 76 GeV protons using the pion production spectrum shown in fig 9.

(Neutrinos averaged over a detector of 70 cm radius per proton on the Horn Target)

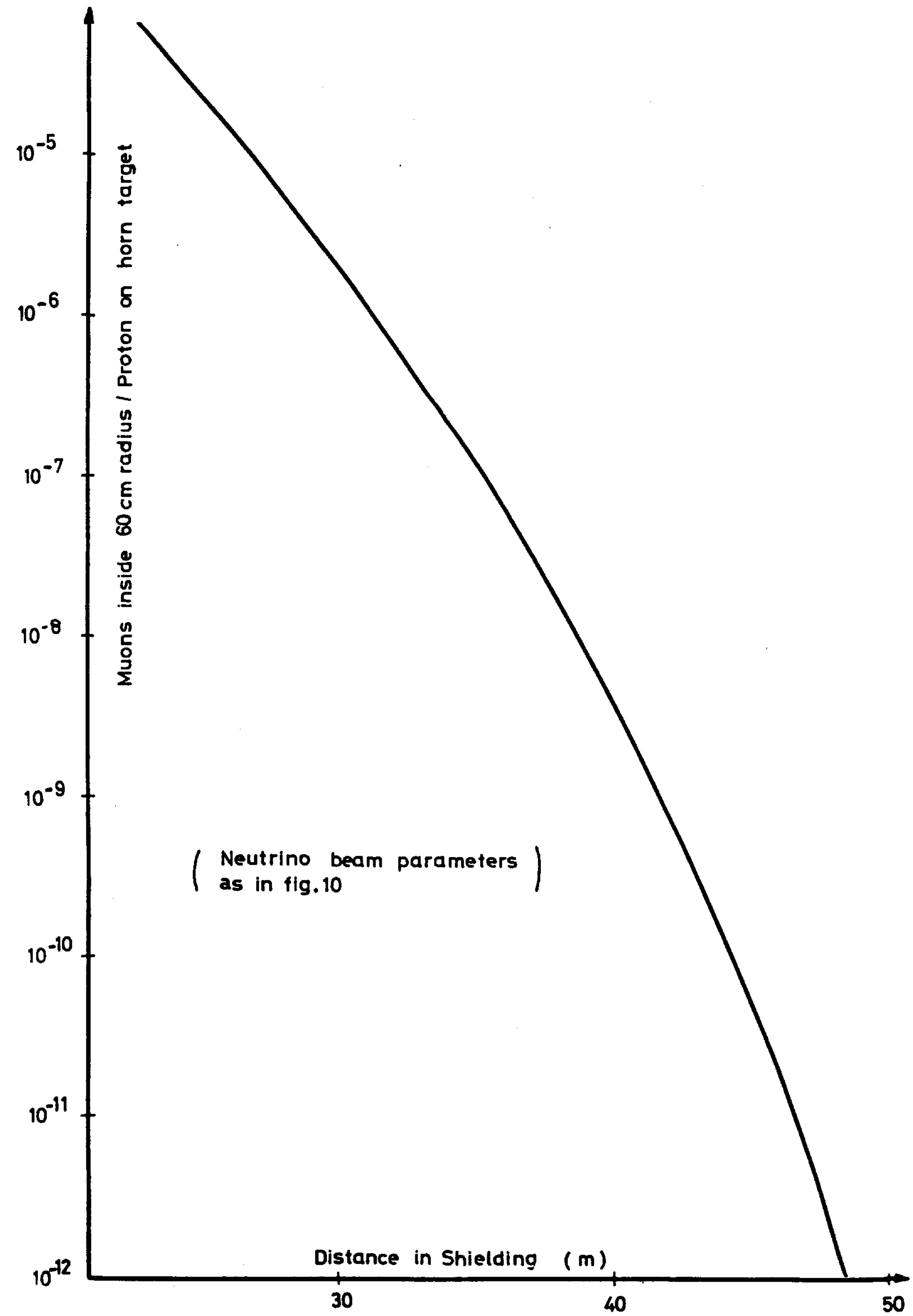

Fig.11 Muon flux attenuation estimated for 76 GeV protons

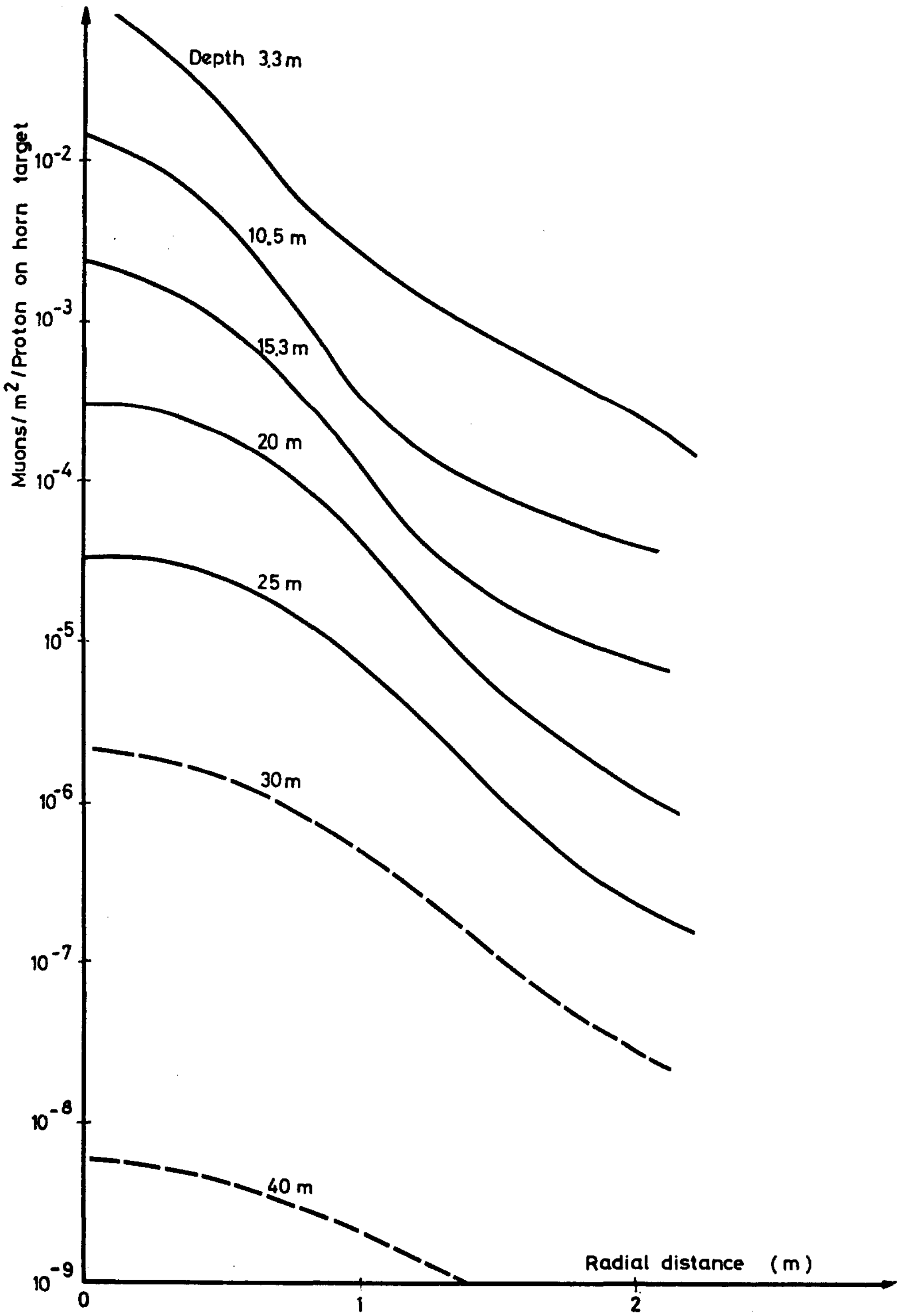

Fig.12 Muon flux distribution in neutrino shielding (ρ=7.5gm cm^{-3})

TABLE 1

A) INELASTIC NEUTRINO EVENTS ($\sigma = 0.6\ E_\nu \times 10^{-38} cm^2$ per nucleon)

E_ν	SKAT + CF_3Br ($1m^2 \times 4m$)	$60m^3$ HBC ($6m^2 \times 4.5m$)
10 - 20 GeV	2.8×10^4	4.7×10^3
20 - 30 "	1.0×10^4	1.6×10^3
30 - 40 "	2.8×10^3	470
40 - 50 "	510	80

B) ELASTIC EVENTS $\nu + n \rightarrow \mu^- + p$ ($\sigma = 0.75 \times 10^{-38} cm^2$ per neutron)

	MIRABELLE D_2 ($1m^2 \times 3m$)	$60m^3$ HBC ($6m^2 \times 4.5m$)
5 - 10	660	4000
10 - 20	107	640
20 - 30	20	120
> 30	5	30

The estimates assume the spectrum of Fig.10 and 3×10^{18} protons on the target of the magnetic horn.

For elastic antineutrino events $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ in H_2 or D_2, divide above numbers by ~ 3.

For elastic hyperon events $\bar{\nu}_\mu + p, n \rightarrow \mu^+ + \Lambda, \Sigma$, in H_2 or D_2, divide above numbers by ~ 30.

A heavy liquid chamber is probably not suitable for precise measurements of elastic cross-sections at high energy, because of the lack of kinematic constraints and the ensuing energy - dependent background problems.

TABLE 2

TABLE OF PARAMETERS OF EXCITATION OF NEUTRINO FOCUSING DEVICES :

	R_1	R_2	R_3
Location from target (m) :	0	40	120
Peak current (kA) :	400	500	500
Energy of storage capacitor (kJ) :	200	200	150
Capacitor voltage (kV) :	12	12	12
Pulse duration (μs) :	200	200	150

TABLE 3

CALCULATED GAIN IN NEUTRINO FLUXES FOR A MODIFICATION
OF THE DECAY LENGTH FROM 200 m to 225 m AND
OF THE SHIELD LENGTH FROM 50 m to 25 m
(TUNNEL WIDTH 3m, DETECTOR RADIUS 1 m)

E_ν (GeV)	2	3	5	7	10	15	20	25	30
ν_π	1.38	1.25	1.15	1.12	1.12	1.12	1.11		
ν_K			1.26	1.38	1.39	1.36	1.17	1.15	1.13

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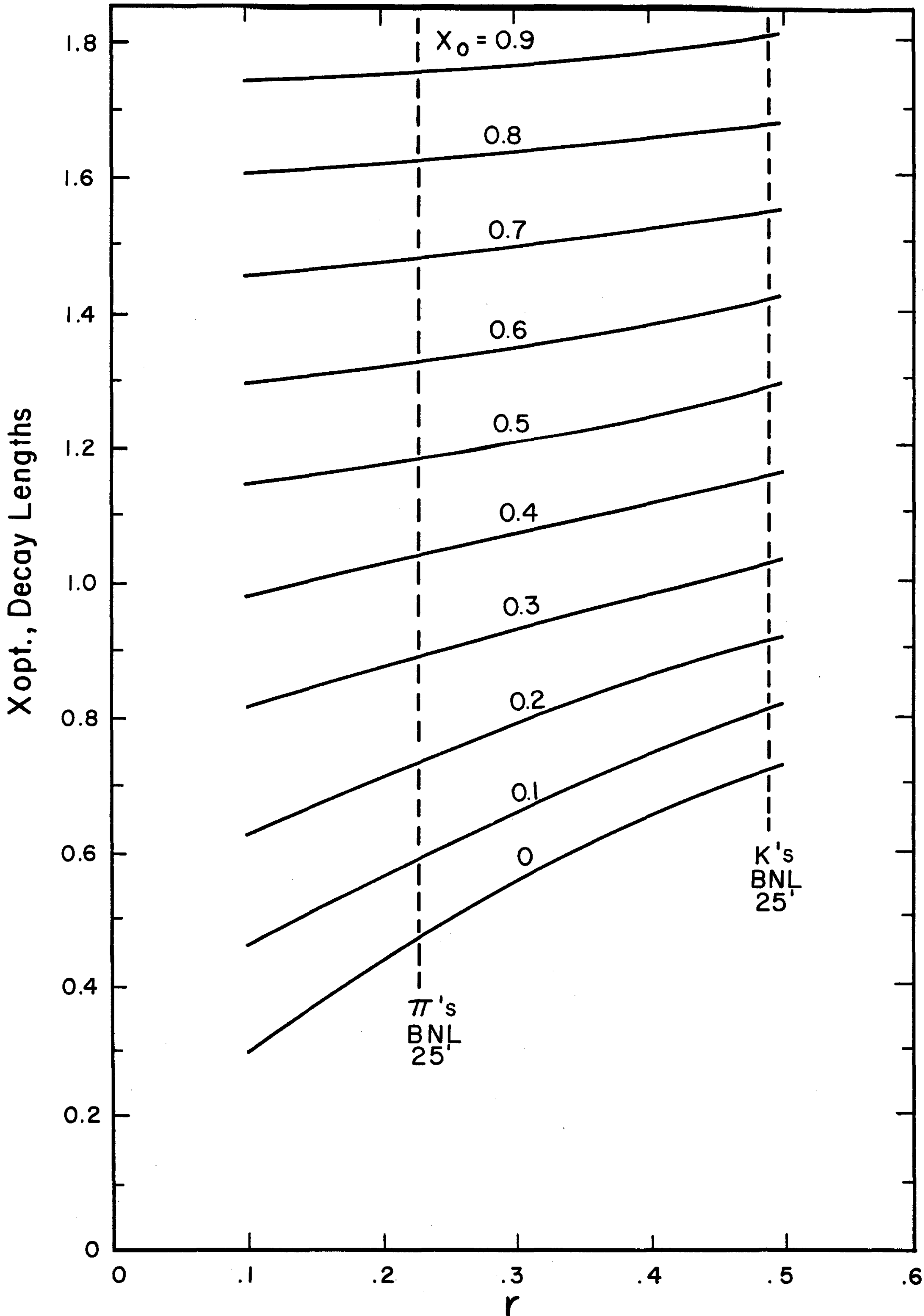

Fig. 3. Optimum target-to-bubble chamber distance X_{opt}, in decay lengths, vs bubble-chamber radius r in units of cτ. Parameter X_o is shield thickness.

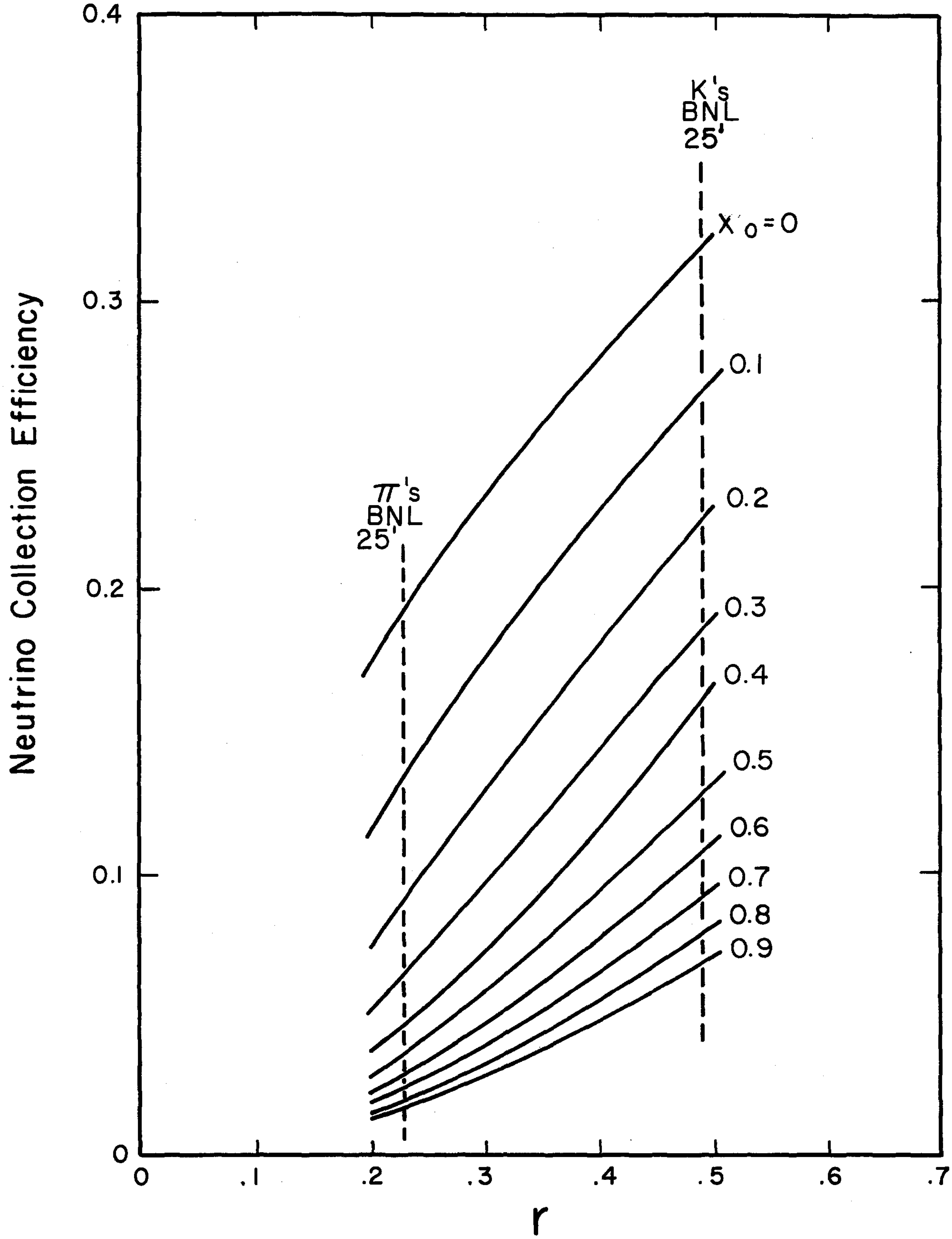

Fig. 4. Neutrino collection efficiency at optimum distance. $K^{\pm}$ branching ratios are not included.

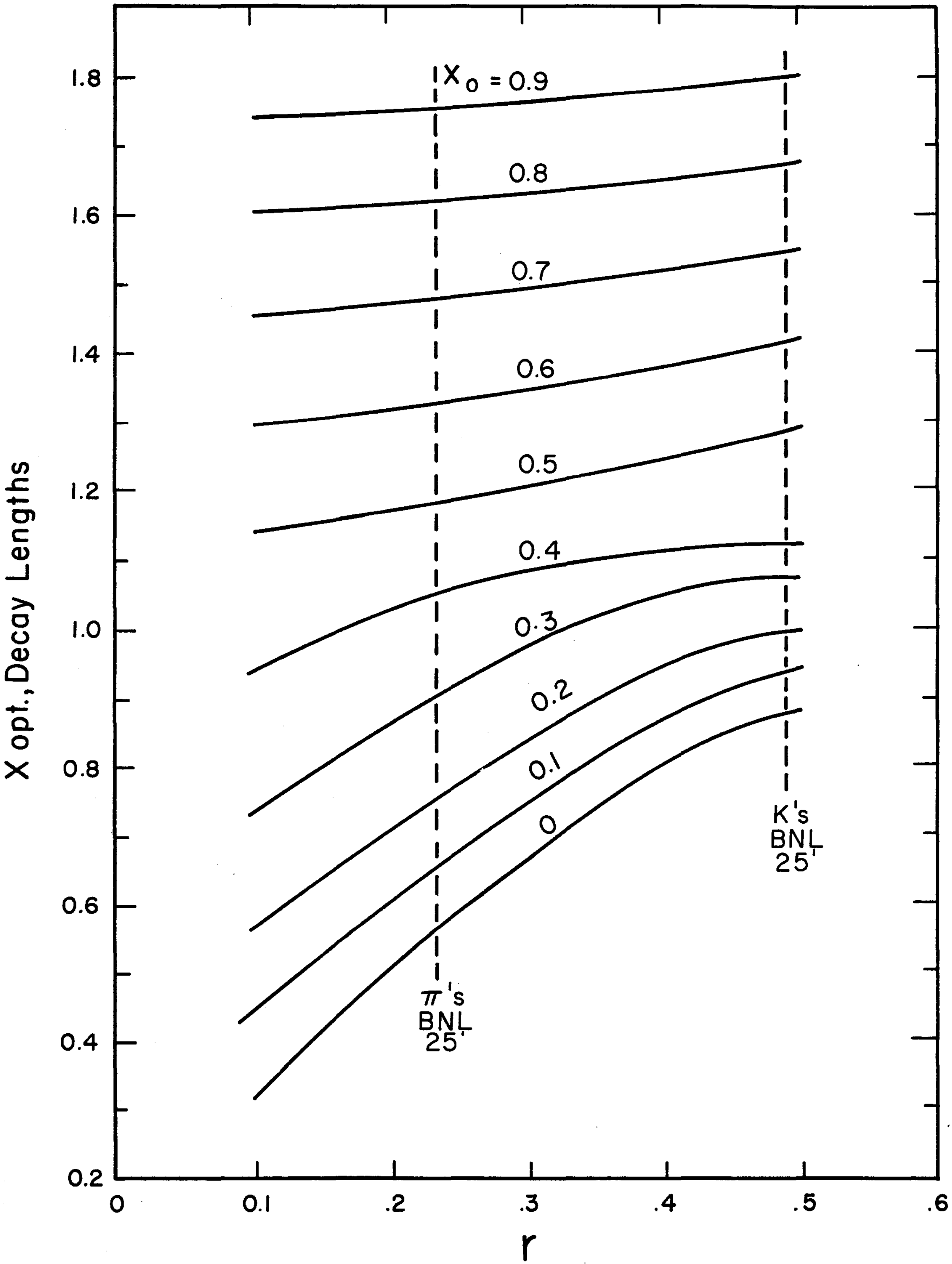

Fig. 5. Variation of X_{opt} when neutrino flux is optimized for energies $E_\nu > 1/2\ E_{max}$.

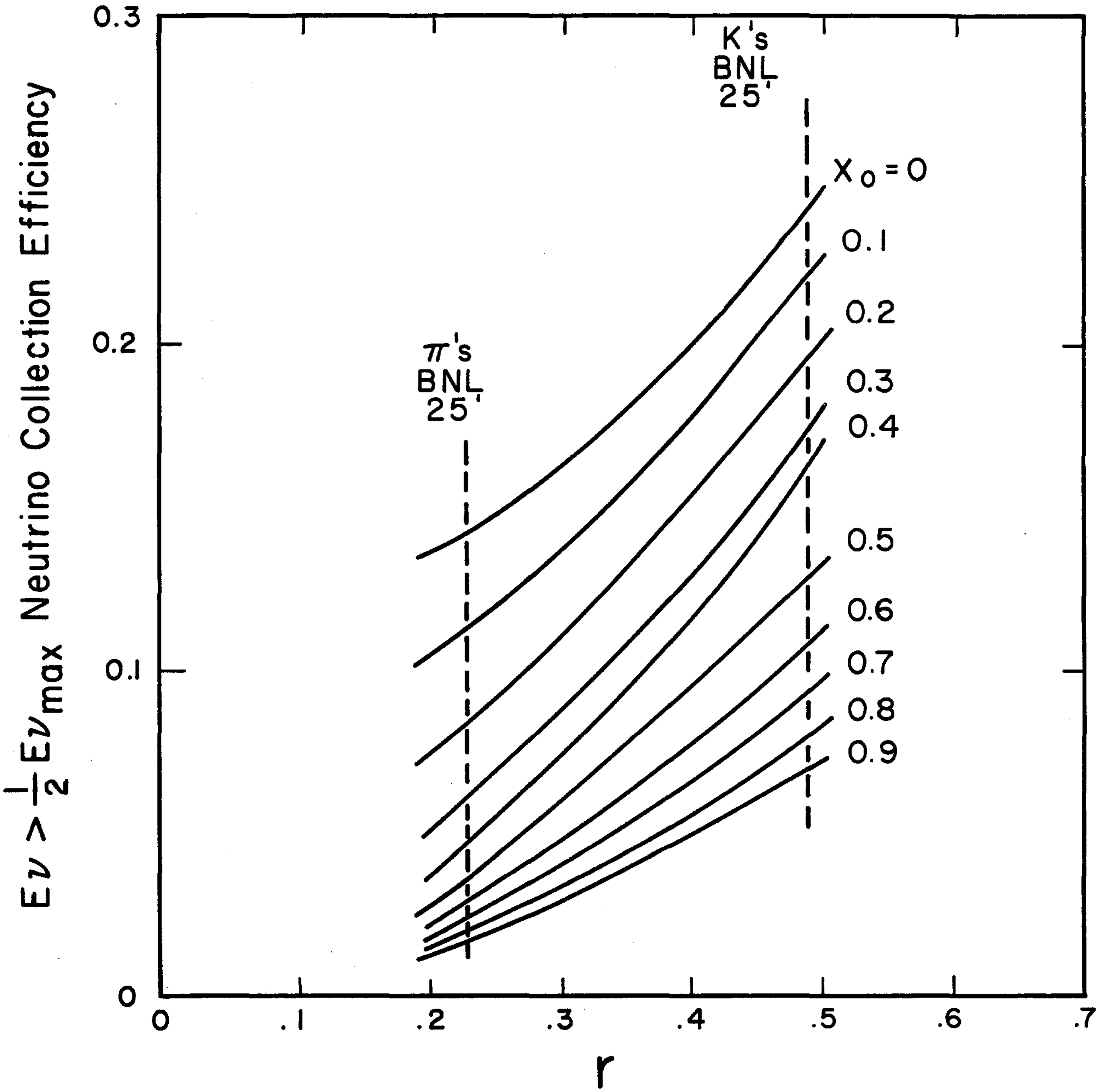

Fig. 6. Neutrino collection efficiency when neutrino flux is optimized for energies $E_\nu > 1/2\, E_{max}$.

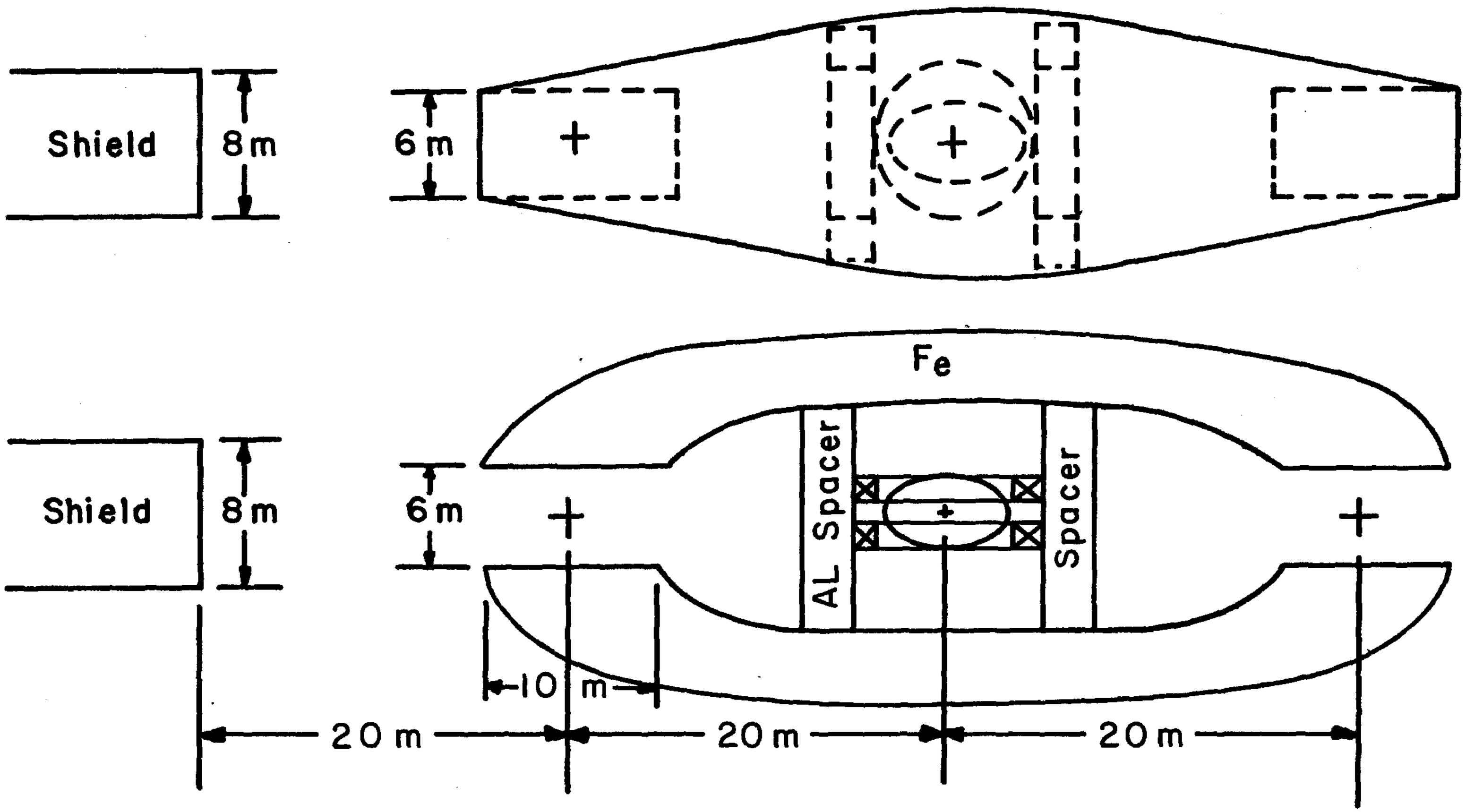

Fig. 9. Design of an iron yoke to use bubble chamber magnetic flux to make a sweeping magnet.