PART III.1

NEUTRINO EXPERIMENTS

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I. INTRODUCTION

The theoretical background of neutrino experiments with high-energy machines has been given in the lectures of Professor Bernardini. I just want to recall some of the facts that render neutrino experiments possible with high-energy machines, and which determine the experimental problems one can study.

1. The cross-section for a neutrino to produce the elastic reaction[1,2]

$$\nu + n = \mu^- + p \tag{1}$$

increases with neutrino energy[1] until it levels off (Fig. 1) at a level of about 10^{-38} cm^2 because of the limiting effect of the form factors of the weak interaction.

2. These form factors will cause a decrease of the differential cross-section when the momentum transferred to the nucleon is large, that is at large angles.

3. When the momentum transfer to the nucleon is small and the nucleon is bound in a nucleus, as is always the case in the detectors one can consider at present for neutrino experiments the differential cross-section is decreased by the effect of the Pauli principle in the nucleus[3].

4. If the weak interactions are mediated by an intermediate particle, which must be a charged boson of spin 1, this particle should be produced by the reaction

$$\nu \rightarrow W^{+} + \mu^{-} \tag{2}$$

if the neutrino energy E_{ν} is sufficient. The momentum balance of the reaction

$$q \approx M^{2}/2E_{\nu} \tag{3}$$

is provided by the Coulomb field of a nucleus acting on the charge W^{+} and μ^{-} 4). M is the invariant mass of the system $W^{+} + \mu^{-}$, which is mostly made up of the mass of the heavier W^{+}.

If for example the neutrino energy is 5 GeV and the mass M is 1 GeV, the necessary momentum transfer from the nucleus is only 100 MeV/c. Since the momentum transfer decreases with increasing neutrino energy, the cross-section for vector boson production increases very rapidly with increasing neutrino energy, and since only a semi-weak interaction is involved, the cross-section will rapidly become larger than the cross-section for ordinary neutrino reactions like (1).

The mass of the vector boson is known to be larger than the K-meson mass from the very existence of the K meson. The cross-section for producing it with neutrinos in the energy range available from present machines drops very rapidly with the mass.

5. The first high-energy neutrino experiment5) in Brookhaven confirmed the theoretical belief that the neutrino, ν', associated in weak interactions with a muon is a different particle than the ordinary neutrino, ν, associated with an electron.

II. NEUTRINO SOURCES

The most abundantly produced of the secondary particles from high-energy interactions is the pion which by its dominant decay mode

$$\pi^+ \rightarrow \mu^+ + \nu' \qquad (4)$$

is a source of the μ neutrino. The average pion energy from a 25 GeV interaction is about 2 GeV, and since the neutrinos have energies from almost zero to a maximum of 42% of the pion energy, the average neutrino energy from this reaction is low - less than 1 GeV.

The decay distance of pions is about 55 m at a momentum of 1 GeV/c. To produce an intense neutrino flux, a free decay distance must be provided. In the CERN experiment this decay distance is 25 m.

In the decay of the pion the neutrino can receive a transverse momentum of up to 30 MeV/c. Particularly at low neutrino energies the neutrino beam will therefore have a considerably wider distribution than the parent pion beam.

The process (4) produces only μ neutrinos. Electron neutrinos are produced in the rare electronic decay of the pion

$$\pi^+ \rightarrow e^+ + \nu \qquad (5)$$

which, however, is only produced with a branching ratio of 10^{-4}. They are also produced in the muon decay

$$\mu^+ \rightarrow e^+ + \nu + \bar{\nu}' \qquad (6)$$

but the muon lifetime is too long for this reaction to contribute appreciably.

Secondary particles other than pions may also contribute to the neutrino flux, but the only important contribution comes from the K mesons, in the most frequent $K_{\mu 2}$ decay (60% probability)

$$K^{+} \rightarrow \mu^{+} + \nu' . \tag{7}$$

In writing the reaction this way, it has been assumed that the neutrino associated with the muon in K decay is the same ν' as in π decay. This is, however, only an assumption. The identity, or non-identity of the neutrinos produced in different decay reactions can in principle only be proved by performing the inverse reactions with high-energy neutrinos of well defined origin. In the Brookhaven experiment a small fraction of the neutrino flux is caused by K decay. If as proposed by Bludman$^{6)}$ and by Feinberg, Pais and Guersey$^{7)}$ the roles of the two neutrinos are reversed in K meson, 5 electron events should have been expected, whereas no certain cases were observed.

Although the K meson is less abundantly produced in high-energy reactions, by a factor 5 for K^{+}, this is partly compensated by the shorter decay path, 7 m against 55 m. Another important feature is that K neutrinos can carry away up to 80% of the K meson energy as against 42% for the pion decay. Since the production spectra for K mesons and pions are similar and fall off rapidly at high energy, the neutrinos from K decay will dominate in the high-energy tail of the neutrino spectrum. They will be of great importance for the possibility of producing the vector boson with neutrinos from present day machines.

On the other hand the higher possible transverse momentum, 200 MeV/c in $K_{\mu 2}$ decay, will cause the neutrino beam to spread out more in angle than for π decay neutrinos of the same energy.

The smallness of the neutrino cross-sections makes it imperative to maximize the neutrino flux at the detector. The distance between source and detector is determined by the necessity to provide a sufficiently long decay path and to interpose shielding between the end of the decay path and the detector. The thickness of the shielding is set by the maximum energy of the muons which have to be absorbed in it and can only be reduced by the use of heavy shielding materials. If the pion angular distribution is wide over an angular range corresponding to the neutrino angles with respect to the pions, it can be shown that the optimum is to make the decay path equal to the shielding thickness.

The Brookhaven experiment$^{1)}$ had a calculated neutrino flux spectrum as shown by Fig. 2, normalized to 10^{11} protons interacting in the target. This flux spectrum would lead to an interaction rate of only a few events per day in 10 tons of material which was close to the value found in the experiment.

As long as the pion angular distribution is broad compared to the angles involved in the decay to neutrinos, intensity can be gained at the detector by a focusing of the pions beam before it decays. A device which is capable of focusing the pions over a wide range of angles of emission and of momenta to a nearly parallel beam, has been developed by van der Meer$^{8)}$ at CERN. The principle of this device, called the neutrino horn, is shown in Fig. 3. A strong current of several hundred thousand amp generates a circular magnetic field in the volume between two cone-shaped conductors. The current is pulsed on at the same time as an extracted beam from the accelerator hits a narrow target on the axis of the cones. Particles which are emitted at an angle will pass through the inner conductor and will be bent towards the axis trajectory I, by the magnetic field to be re-emitted through the conical conductor with a much smaller angle to the axis than the original emission angle. With the CERN horn, 3 m long and with 300,000 amp, this type of focusing occurs at about 6 GeV/c momentum. Another type of focusing, effective at low momenta, is due to trajectories as the one denoted by II in Fig. 3. The particle makes a first reflection in the cylindrical part of the conductor and a second one in the conical part. If the emission angle is twice the angle of the cone, particles will come out parallel to the axis for a wide range of momenta.

Figure 4 shows the neutrino flux spectrum, calculated at 50 m distance from a target, equipped with a neutrino horn, assuming a decay path of 25 m. These parameters correspond to the experiment which is at present being prepared in CERN. With current in the horn, the spectrum shows two plateaus which correspond to the two momentum bands for which the horn focuses particles on the axis. The total neutrino flux is increased by a factor 7. The number of neutrino elastic interactions per ton per day of ideal running of the CERN proton synchrotron with $4 \cdot 10^{11}$ protons accelerated every 3 sec increases from 0.4 to 5.2. Since the low counting rate is always a problem in neutrino experiments, this increase is of great value.

Another important advantage of the horn is that it only selects one polarity of particles. If set for positive particles it will enhance only the neutrino component, whereas the antineutrinos are instead reduced, because negative particles are deflected away. With the flux from the horn it is thus possible to investigate separately neutrino and antineutrino interactions.

A quadrupole focusing system which also has been considered for increasing the neutrino flux does not have this feature since it focuses indiscriminately particles of both signs.

III. NEUTRINO DETECTORS

Even under the best conditions one can realize at present, the expected event rate per ton of sensitive material is only a few per day. The detector must therefore have a large sensitive mass. Another important requirement is the ability to reject background of cosmic rays or particles from the accelerator which manage to penetrate the shielding around the experiment.

Of present detectors, the bubble chamber, the Wilson cloud chamber and a combination of counters and spark chambers have been considered as detectors for neutrino reactions.

Bubble chambers have been made with volumes up to 500 l. and can be filled with a heavy liquid, such as freon CF_3Br to give a sensitive mass of the order of 1 ton. Since the bubble chamber cannot be triggered, it has to be exposed every burst, and to collect a reasonable number of neutrino events a very large number of photographs must be taken, most of which will be empty. The sensitive time of the bubble chamber is a few ms, short enough so that the background of cosmic rays is not very serious. With a magnetic field on the chamber, the momentum of the particles in the neutrino events can be determined, but with the heavy liquids which have to be used, the multiple scattering is large and the momentum accuracy limited to 10-20%. On the other hand, the short radiation length, 11 cm in freon, allows electrons and γ rays to be easily identified by the shower they generate. A rough measurement of the energy is possible from curvature and track length. With a sensitive mass of only a ton, many particles will leave the chamber without visible interaction, making it difficult to distinguish between muons and pions, except on a statistical basis.

The freon used in the bubble chamber contains no hydrogen but only complex nuclei. The neutrino events, produced in these nuclei, cannot be unambiguously reconstructed kinematically, since the energy of the incoming neutrino and the momentum and energy transfer to the nucleus are unknown. In the case of production of intermediate bosons, which decay into a lepton and a neutrino, energy and momentum are also carried away by the second unseen neutrino. Only in the case of decay in a charged and a neutral pion, which are both seen in the chamber, can the decay of the vector boson be reconstructed and its mass determined.

The big advantage of the bubble chamber lies in the high spatial resolution which for example would allow the study of the production of hyperons or K mesons with high-energy neutrinos. It is also of interest to study the weak coupling to resonance states, such as the excited nucleon states and two or three pion states as ρ, η and ω which are of importance for inelastic neutrino events in which one or several pions are produced.

It would be very interesting to study the more fundamental neutrino reactions in pure hydrogen or deuterium, in which also the kinematics would be better known. Since, however, liquid hydrogen has only $1/20$ the weight of freon, the event rate in even the largest hydrogen bubble chambers existing today is too low with present neutrino fluxes. An enormous bubble chamber of 14 m^3 would be needed to provide 1 ton hydrogen. Although probably technically feasible, such a chamber would be a long term project.

Scintillation counters, either liquid or plastic, can be made in large units and can involve several tons of material. The same is true for water Čerenkov counters, which have the desirable property of being directional so that they can discriminate against cosmic rays and background particles. Addition of a heavy salt, for example lead perchlorate, makes them specific detectors for high-energy γ rays and electrons which produce showers in the solution.

Counters have a time resolution of a few ns. This time resolution allows determination of the time of flight of the neutrinos if the time of production at the accelerator is known. In the accelerator, particles are accelerated by a high frequency voltage, only if they are in the correct phase with this voltage. At the CERN proton synchrotron, for example, the particles are bunched at the end of the acceleration in bunches of 10 ns width occurring at intervals of 95 ns. Because of this bunch structure the time of flight of the particles from target to detector, which is 200 ns for a 60 m distance, can be determined with a precision of ± 5 ns. The timing is a very powerful way of eliminating background of non-relativistic particles and of particles which have been able to penetrate to the detector by roundabout paths.

Good timing by counters will also essentially eliminate cosmic ray background in neutrino experiments. Taking, for example, the case of the CERN proton synchrotron operated with an external beam, 20 bunches of 10 ns width will be ejected every 3 sec, 30,000 times per day. During a twenty day experiment, neutrinos will be produced during a total time of only $20 \times 30{,}000 \cdot 20 \cdot 10^{-8} = 0.12$ sec.

About 100 cosmic ray muons will traverse a 10 m^2 set-up during this time and most of these can easily be rejected by shielding and the use of anti-coincidence counters. The number of neutrino events would be much higher.

Spark chambers. Although counters alone have been considered for neutrino experiments, the information they give on the neutrino events is very rough, since no visual picture is given of the event. They can, however, be used to advantage in a combination with spark chambers. The spark chamber has a sensitive time of 1 μsec and if triggered within this time after the event by a signal from the counters, it will complete the information from the counters with a visual display of the neutrino event. Both the Brookhaven experiment and the experiment now being prepared at CERN use large set-ups of counters and spark chambers. The spark chambers form the bulk of the mass of the set-up and provide most of the material in which the neutrino events occur. In the CERN set-up there are about 20 tons of effective mass in the form of spark chambers, made of aluminium or brass plates and only a few tons of counters, distributed to pick up the neutrino events.

Whereas the bubble chambers have to take a picture every burst of the machine, the spark chambers are only photographed when a possible neutrino event occurs and gives a signal in the counters.

The spark chamber samples the position of the particle trajectories only at discrete intervals where they traverse a spark gap and the picture of a spark chamber event will therefore be much cruder than for a bubble chamber. On the other hand, the larger size of the spark chamber and its high density gives a high stopping power. This allows the energy of particles to be determined from range up to energies above 1 GeV. This method will, of course, only be useful for muons. For other particles the total number of sparks gives a rough determination of the energy of the particle, in particular for electrons and γ rays which produce large showers. Figure 5 shows a beautiful picture of the two γ rays from a neutral pion, produced by charge exchange in a polythene scintillator target.

IV. THE BROOKHAVEN EXPERIMENT

The first experiment with high-energy neutrinos was performed at Brookhaven by a group of physicists from Columbia: Danby, Gaillard, Goulianos, Lederman, Mistry, Schwarz and Steinberger. This experiment used a 10 ton spark chamber, Fig. 6, of 2.5 cm thick aluminium plates, which was installed in a block house at an angle of 7° from a target in the AGS machine. The layout of the experiment is seen in Fig. 7. Thick iron sheets from an old American battle ship were used to shield the detector against muons. With 13.5 m of iron shielding, muons start to leak through when the energy of the AGS is above 15 GeV, and this was the energy at which the experiment was run.

The emphasis of the experiment was to:

i) demonstrate the existence of high-energy neutrino interactions, and measure the cross-section;

ii) check if the neutrinos from π decay are identical with those from β decay;

iii) search for signs of intermediate boson production.

Existence of high-energy neutrino events and measurements of the cross-sections

During the run the detector recorded 119 events which satisfied the selection criteria, and originated inside a fiducial region which excluded the borders of the set-up.

The 119 events could be subdivided into various classes, as follows.

Eighty-three events which showed a single straight track or at most a few extra sparks, probably evaporation prongs from the interaction. Of these, 34 had a visible momentum, if they were interpreted as muons, larger than 300 MeV/c. A few of these are shown in Fig. 8. This visible momentum is, however, only a minimum since all the tracks, except five, left the detector before stopping. The total detector has a stopping power longitudinally of 700 MeV and sideways of only 300 MeV for minimum ionizing particles. Most of the conclusions of the experiment are based on the 34 events with a visible energy of more than 300 MeV/c. The class below 300 MeV/c contains most of the background of neutron interaction. Indeed, during the first half of the run when the shielding was not yet complete, many more short track events were observed than during the latter half.

Twenty-two events were of a more complicated character with more than one track, and all had a high energy release. Seven of these showed a visible energy of more than 1 GeV. Some of these are given in Fig. 9.

Finally, a class of eight events showed in general a single track with irregular structure, so that they are not likely to be due to muons. The first problem was to prove that the 34 single track events are not cosmic ray muons. A cosmic-ray muon from above which stops in the chamber, and stopping instead of a neutrino, will look as a neutrino-induced muon leaving the chamber upwards. A control experiment with the machine turned off showed that neutrino-like events were obtained at a rate of one per second. Since the detector was allowed to trigger only during a 3 μsec period every burst, the total effective time for the whole experiment which lasted $1.5 \cdot 10^6$ pulses was 5 sec. Only five of the 34 single track events could therefore be due to cosmic rays. Another test was the vertical distribution of the 34 events shown in Fig. 10. There is in fact a slight excess of events with a muon which appears to go upwards. However, the majority of the tracks are centred in the horizontal direction, as one should expect from neutrino-induced muons.

As the next problem, one should consider if the events could be caused by strongly interacting particles, mainly neutrons from the machine, which penetrate weak regions of the shielding. Because of the large interaction cross-sections, a very low flux of such particles could contribute to the event rate. The neutrons could not come from the direct line from the target where the shielding was very thick to stop the muons, but would most probably penetrate from the side of the accelerator. The interactions should then show a marked anisotropy in their angular distribution in the horizontal direction. This was not the case. Furthermore the events are quite uniformly distributed in the chamber and there is no evidence for an attenuation, in spite of the fact that the neutron mean free path is small compared to the detector dimensions.

If the 34 - 5 = 29 events were charged pions produced in neutron interactions, one should expect half this number of neutral pions, which should give showers in the detector. These were not seen.

In the 34 single track events no clear cases of scattering or interactions are observed for a total track length of many times the nuclear interactions length. This indicates that the particles are muons.

A further control experiment to check that the events were due to neutrinos was to absorb the pions in an absorber close to the target, before they could decay. This reduced the event rate by a factor which agrees with what could be calculated from the decay length of pions and K mesons.

From these arguments it seems clear that at least the bulk of the 34 single track events and the 22 vertex events observed in the experiment are induced by neutrinos. The 29 single track events are probably examples of the reactions

$$\nu + n \rightarrow \mu^- + p \qquad (8a)$$

or

$$\bar{\nu} + p \rightarrow \mu^+ + n . \qquad (8b)$$

It should be remembered that the beam from the accelerator contains both negative and positive pions which will give rise to both neutrinos and antineutrinos.

At this stage the first important physics question comes in. Twenty-nine events were observed of reactions (8) with a muon produced. A priori one would expect a comparable number of events with an electron produced if the neutrinos from $\pi - \mu$ decay were identical with neutrinos from β decay. The spectrum of the electrons should be very similar to that of the muons. Below 300 MeV/c it may be difficult to distinguish with certainty between an electron and a muon, since the electrons slow down rather than to produce a distinguishable shower. However, above 300 MeV/c, electrons are quite easy to distinguish from muons by the multiplication and scattering they suffer. This the Brookhaven group showed in a control experiment in a pure electron beam from the machine. The distribution of the number of sparks for a 400 MeV/c electron in the spark chamber is shown in Fig. 11. The only events which could possibly be electrons, judging from the appearance of the tracks, are six tracks with the spark distribution given in the lower part of Fig. 11. It is clear that if they are really electrons they must have an energy considerably below 400 MeV/c and there are no clear examples of an electron above 300 MeV as against 29 events with a muon. The conclusion must be that the electron production is strongly suppressed. The most natural conclusion is that the neutrinos from the dominant π-μ decay mode cannot produce electrons and are different from the neutrino in β decay. The six events which were observed and which could possibly be electrons were all observed in the first part of the run when the background conditions were known to be unsatisfactory and they could in fact all be due to neutron interactions.

If we identify the single track events with elastic neutrino reactions by the reaction (8a) and (8b), one can compare the observed rate with the theoretical calculations. The values of the weak interaction coupling constants at very small momentum transfers are quite well known from the study of decay processes. Virtually nothing is known experimentally of how the form factors for the weak interactions behave at high energies. In the neutrino energy range of the Brookhaven experiment, large momentum transfers will be quite common and the form factors will have a considerable influence on the cross-sections (see Fig. 1).

The weak interactions may be represented by four form factors if G-invariance is supposed to hold. Two of these apply to the vector interaction. The conserved vector current hypothesis which recently has received considerable experimental proof in the measurements on B^{12} and N^{12} and in the $\pi^{+}-\pi^{0}$ decay, makes definite predictions for these form factors from the electromagnetic form factors. The form factors of the axial vector term are practically unknown. The main term has a larger value when coupling to the nucleon than to the lepton current by a factor 1.2, probably a renormalization effect. The second term, the induced pseudoscalar term, gives a contribution proportional to the lepton mass squared and can therefore be neglected for electrons, but enhances the muon production.

The theoretical total cross-sections for the elastic interactions, calculated by Lee and Yang, with these assumptions and neglecting the induced pseudoscalar term, are shown in Fig. 1. The difference between the neutrino and antineutrino interactions are due to the interference between the vector and axial terms in the interactions. If these cross-sections are folded together with the neutrino flux spectrum one calculates from the pion spectrum and the geometry of the experiment, one finds an expected number of 25 elastic events which compares very well with the 29 single track events actually found.

The theoretical value will, however, change considerably if other values for the form factors are assumed, or if one invokes the existence of a vector boson which mediates the weak interaction. If one, as previously, accepts the conserved vector current hypothesis, which defines the vector form factors, and neglects the pseudoscalar term, there are still two parameters, the mass of the vector boson and the characteristic length involved in the axial coupling to the nucleon. Variations of the latter between 1.6 and 0 f, and of the former between 500 and 1250 MeV give values for the expected rate ranging between 9 and 40 events. While the order of magnitude agreement of the Brookhaven experiment with theory is extremely satisfying, there are certainly extremely important questions concerning the form factors which must be settled by more detailed experiments.

An additional uncertainty comes from the influence of the induced pseudoscalar term on the result. While it was previously assumed on the basis of the then presumed strength of the coupling that this term will only give a 20% increase of the muon events with respect to the electron events, recent experimental results seem to indicate that the coupling is considerably stronger and the enhancement of the muon interactions therefore larger. Lapidus has pointed out that if the pseudoscalar term is sufficiently large the absence of electrons in the Brookhaven experiment may be due to an enhancement of the muon production by the pseudoscalar term, rather than the forbiddeness of the electron production if the two neutrinos are different. An objection against this argument is that a large pseudoscalar term will not only increase the muon-electron ratio but also the total cross-section. It therefore becomes difficult to reconciliate a sufficiently large pseudoscalar term with the good agreement between the observed and calculated event rate.

So far, we have only been concerned with the interpretation of the simple single track events, which were identified with elastic neutrino events. Events with two or more prongs may tentatively be identified with neutrino reactions where an additional pion is produced. These processes occur on free nucleons if the nucleon is left in an excited state or by formation of a pion-pion isobar in the pion cloud around the nucleon. In the aluminium nuclei, which are the target material of the spark chamber, pions may also be produced by reactions of the energetic recoil nucleon within the same nucleus. The inelastic reactions are therefore very complicated processes where the theoretical predictions are at present very vague. It is, however, not unreasonable that the inelastic cross-section in nuclei could be of the same order as the elastic, as indicated by the comparable number of single track and vertex events, 29 against 22.

Another fascinating interpretation of the vertex events is as the production and immediate decay of an intermediate vector boson, which has been proposed as mediator for the weak interactions. The vector boson is expected to decay to $(\mu + \nu)$, $(e + \nu)$, to two or more pions. If the mass is sufficiently large, other decay modes with a K meson are possible. If there are two neutrinos, a vector boson is always produced together with a relatively low-energy muon, and the production and subsequent decay of the W would thus appear as a vertex of two or more particles, one of which is a muon, and the other a muon, an electron, or two or more pions. Among the 22 vertex events of the Brookhaven experiment there are several, in particular the three shown in Fig. 9, which would fit in with this interpretation. They can, however, equally well be inelastic events. The event rate depends very critically on the mass of the intermediate boson and drops from 20 expected events for a mass of 550 MeV to 2 events for 950 MeV.

V. THE CERN EXPERIMENT

I have treated rather completely the Brookhaven experiment which yielded a lot of very valuable information and has shown that experiments with high-energy neutrinos are feasible. However, the Brookhaven experiment has left many questions unanswered and it is the purpose of the experiment we prepare in CERN to attempt to answer them.

The CERN experiment has been prepared in parallel with the Brookhaven experiment during the last two years, and is scheduled to start in May of this year.

The proton beam is extracted from the CPS in a two μsec burst by a fast ejection system. Within the burst the beam is further bunched into 20 bunches of 10 ns width. I have previously pointed out the advantage of this bunching for rejection of cosmic ray and neutron background. The ejected beam is transported by a system of quadrupole lenses and bending magnet to the neutrino horn which I have described previously. The beam is focused on a thin tungsten rod target on the axis of the horn. The action of the horn focuses the pions of one side in a narrow beam which is allowed to decay in a 25 m long decay tunnel, Fig. 12. Between the end of this decay tunnel and the detector area is a 25 m long iron shield, which removes the high-energy muons from the neutrino beam by energy loss. This iron shield, which involves about 4000 ton of iron, flares out towards the detector side so that muons cannot escape into the lighter concrete on the sides by multiple scattering during slowing down. The shielding around the decay tunnel also plays an important role in limiting the muon beam to the area which is covered by the iron shield.

Since the neutrino beam is not absorbed by the detector, several neutrino experiments can be set up behind each other in the same beam. In the CERN experiment we will have two main detectors, a heavy liquid bubble chamber and a spark chamber assembly.

The use of a bubble chamber with an effective mass of only about $\frac{1}{2}$ ton is made feasible by the large neutrino flux, given by the extraction of the beam and the use of the neutrino horn. The expected rate in a 20 day run in the bubble chamber is about 50 elastic and a comparable number of inelastic events. While the statistics are too small to allow many quantitative results, these events will give the first detailed qualitative information on the neutrino-induced reactions at high energies.

The spark chamber set-up

The spark chamber and counter set-up which we intend to use is in many respects similar to the Brookhaven set-up. However, the effective mass is considerably larger, 20 tons of spark chamber, and the larger dimensions both in length and width allow particles of higher energy to be stopped and their energy determined by range. We also use thinner plates, on the average 0.75 cm, so as to have better space resolution. One of the 30 units which make up the set-up is seen in Fig. 13. The material in the region where the events are produced is either brass or alternating plates of brass and aluminium. As electrons and γ rays multiply quicker, a distinction between muon and electron for the question of the identity of the two neutrinos can be made more unambiguously in a brass-aluminium mixture than in pure aluminium.

With the increased neutrino flux due to the horn and the higher mass of the detector we expect a 20 day run to accumulate of the order of 500 to 1000 elastic neutrino events.

Two methods of introducing a magnetic field in the set-up are foreseen for the CERN neutrino experiment. The first which is being installed now uses a very large pair of Helmholz coils to produce a 3 kgauss field in the region behind a production region. A fraction of the particles produced in this region will traverse the magnetic field, where their curvature will be determined with a set of spark chambers. In addition a massive range chamber behind the magnetic field section will give range information and will also serve to identify the particle as a muon from the lack of interactions.

The second method mixes the magnetic field more intimately with the production and range region by the use of magnetized iron plates in between the spark chambers. Since this set-up is more compact, it allows the sign determination for a larger fraction of the events. However, the magnetic curvature in magnetized iron outweight the multiple scattering sufficiently only for particles which have traversed more than 300 g/cm^2 of iron and the method is only therefore applicable to high-energy muons. Fortunately in the case of neutrino interactions high-energy muons are the most common reaction products.

Problems to be investigated in the CERN neutrino experiment

It is obvious that the CERN neutrino experiment, like the Brookhaven neutrino experiment, will to a large extent be exploratory only. However, one can already see some of the problems which could be studied in the experiment.

1. One or two neutrinos

Although the Brookhaven experiment seems quite conclusive, there are still a few loopholes in the arguments, some of which I have discussed. The CERN spark chamber experiment should have about 10 times the event rate of the Brookhaven experiment and electrons should be more easily distinguishable because of the thinner plates and the admixture of brass plates in the set-up.

The bubble chamber will have an event rate comparable to that of the BNL spark chamber, but will have no triggering bias which could conceivably make the BNL set-up insensitive to low-energy electrons. It can therefore be hoped that the CERN experiment will patch up the remaining loopholes in the problem.

A related question, where the Brookhaven experiment is much less definite, is the question of the identities of neutrinos from K meson decays. Although these neutrinos could be a new set of neutrinos the simplest assumption would be that they are the same as the neutrinos from decay of ordinary particles. Bludman$^{6)}$, and Feinberg, Gursey and Pais$^{7)}$ have suggested that the K meson neutrinos are associated with muon and electron in the opposite way from the neutrinos in pion decay.

If this theory is true, K neutrinos which constitute about 10% of the neutrino flux, and which are mainly due to $K_{\mu 2}$ decay should give rise to a small number of neutrino events with an electron produced. These electrons should have an energy distribution which reflects the spectrum of the K neutrinos with a much higher mean energy than the pion neutrinos.

2. Intermediate vector boson

One of the most important aims of the experiment is the search for the production and subsequent decay of the intermediate boson, which can be produced by neutrinos in the Coulomb field of nucleons and nuclei, for neutrinos of sufficient energy. Figure 14 shows the cross-section per nucleon in iron for the production of vector bosons, assuming different masses, and in the same figure is plotted the neutrino spectrum we expect in our experiment. It is clear that only the high-energy tail of the neutrino spectrum, which is almost entirely due to K mesons, will contribute to the vector boson production. The rate depends very much on the mass. If the mass is 0.6 proton masses, close to the minimum value one can have, we will expect about 20 bosons produced per day, if the mass is one proton mass we expect 2, and at 1.4 proton masses we would be at the limit of observation where only a few events will be observed in the whole experiment. It should be added that these figures are very uncertain since they depend on the details of K meson spectrum at high energies, which is only very sporadically known. Another team in CERN will, however, in the next few weeks carry out a comprehensive survey of the production spectra of K mesons in the momentum range of interest to the neutrino experiment.

The possibility of distinguishing vector boson production from other events will to a large extent depend on the details of the vector boson decay. In general the vector boson will carry off the major part of the neutrino energy leaving behind a low-energy negative muon. If the vector boson decays in a positive muon and a neutrino, and the positive muon gets a large part of the energy, its sign can be determined by the magnetic field of the spark chamber set-up and provide a good signature for vector boson decay. There are, however, some indications, from calculations made by Veltmann, that the vector boson gets polarized in the production process in such a way that it decays with the muon predominantly backwards, and thus with low energy in the lab system. If this is true the identification of the vector boson gets more difficult in the spark chamber, but easier in the bubble chamber.

The decay mode of the vector boson to an electron and a neutrino has the advantage that the background of ordinary neutrino events with electrons is small, since our beam contains mainly muon neutrinos. In the spark chamber the possibility to determine the sign drops out since the electron will quickly produce a shower. The most dangerous background is expected to be inelastic neutrino events in which a neutral pion is produced whose decay γ rays materialise in the same plate. Since the plate thickness is a fair fraction of the radiation length, the probability for this is not negligible. Many of these cases can be eliminated if the two γ rays give separate showers, but some will remain where the two showers superimpose, or one is very small.

In the bubble chamber the electron decay mode offers perhaps the most prominent possibility to detect the vector boson production since the high resolution and longer radiation length allows the sign to be determined and a discrimination made against the case of neutral pion production. However the rate of production will be sufficient for the bubble chamber only if the mass of the W is low.

The decay modes of the W in two pions will be particularly prominent if the mass of the W happens to coincide with the mass of the ρ meson 740 MeV. In this case the production and decay of a W will look just as the production of a ρ meson in an inelastic neutrino interaction.

In principle a distinction could be made by the fact that the ρ resonance has a substantial width, 50-100 MeV, whereas the W meson is extremely narrow. Unfortunately, neither the bubble chamber nor the spark chamber will be able to determine the mass of the object to better than 20%, which is not good enough for this purpose. Instead one will have to argue the case of the W from the shape of the spectrum and perhaps also the charge distribution. The W made in a neutrino beam should always be positive. When ρ mesons are made in inelastic neutrino events, there should also be a positive excess, because they are always produced together with a negative muon, but this excess should not be so marked.

If evidence for the vector boson is found, it will be interesting to determine its mass. This can be done from the rate of vector boson production which is a very sensitive function of the mass. For the decay mode into a charged and neutral pion, the kinematics of the decay can be reconstructed to give a rough value of the mass. For the decay to a muon or lepton and a neutrino, this is not possible since the neutrino is not observed. Since, however, the theory of the production processes indicates that the vector boson is produced with low transverse momentum relative to the neutrino direction, the transverse momentum distribution of the decay lepton will be dominated by the kinematics of the decay process and may yield a value for the mass.

3. Elastic events

For the elastic events the Brookhaven experiment was limited to the determination of a rough total cross-section for a mixture of neutrinos and antineutrinos which agreed with theory.

In the CERN experiment, it would be of great interest to investigate the behaviour of the form factors of the weak interactions at large momentum transfers. The behaviour at small momentum transfers is not so interesting since it is known from other processes. In addition, neutrino reactions with complex nuclei, as opposed to hydrogen, are not very suitable for this problem, since at small transfer momenta the cross-sections are highly influenced by the Pauli exclusion principle and the Fermi momentum of the nucleus.

For momentum transfers beyond the Fermi momentum, say 300 MeV/c, however, the bound nucleons behave as if they were free and there is hope that neutrino experiments on complex nuclei can give information on the fundamental nucleon interaction. The Brookhaven experiment was not very well adapted to the study of interactions with large momentum transfers. The relatively small size of the experimental set-up allowed most of the muons produced in these events to escape before stopping, so that only their angular distribution, but not the energy distribution, could be determined. As this angular distribution is an average over the neutrino spectrum, large-angle events will be dominated by the events with low momentum transfer, produced by the more abundant low-energy neutrinos.

The main part of the CERN set-up is also of too low density to contain efficiently the muons produced in reactions with momentum transfers above 300 MeV/c. The low density is a consequence of the desire to have a high spatial resolution which has led us to use 5 mm thin plates in the production region. It is, however, intended to use a magnetized iron plate chamber behind the present production region which is compact enough to contain particles with transverse momenta up to 500 MeV/c. This chamber will consist of 5 cm iron plates magnetized to 18 kgauss, and separated by spark chambers and counters. The higher containment power of this more compact chamber would be at the expense of the spatial resolution and the information on the details of each event. However, for simple elastic neutrino events with muon production, this restriction can be accepted.

A very interesting problem which could be studied in this compact chamber would be the difference of the event rate for the two polarities of the neutrino horn, that is between neutrino and antineutrino interactions. As the materials we use in the set-up contain approximately an equal number of neutrons and protons, this difference should be dominated by the interference term between axial and vector coupling which is responsible for the difference between the elementary neutrino and antineutrino interactions on nucleons. The complications of the Pauli principle and Fermi momentum should be the same in both cases. As we believe we know the behaviour of the vector form factors from the conserved vector current hypothesis, we could then deduce the behaviour of the axial form factors.

4. Inelastic processes

The study of the inelastic processes will certainly be a very important part of the experiment but the variety of processes which can occur will make this study more phenomenological than systematic. Even if the primary process on the individual nucleon is simple, leading for example to a $(3/2, 3/2)$ isobar resonance, the subsequent interaction of this isobar with the rest of the nucleus before the pion escapes makes a detailed treatment very difficult. The Fermi momentum of the target nucleon and the fact that the energy of the incoming neutrino is unknown will also make a kinematic reconstruction impossible.

A somewhat different class of inelastic events are those producing hyperons in the two body reactions with neutrinos

$$\nu + n \rightarrow \Sigma^+ + \mu^- \qquad (9)$$

or antineutrinos

$$\bar{\nu} + n \rightarrow \Sigma^- + \mu^+ \qquad (10a)$$

$$\bar{\nu} + p \rightarrow \Lambda^0 + \mu^+ \qquad (10b)$$

$$\bar{\nu} + p \rightarrow \Sigma^0 + \mu^+ . \qquad (10c)$$

K mesons can be produced in three body reactions

$$\nu + N \rightarrow N + \mu^- + K. \qquad (11)$$

To identify the strange particles a good spatial resolution is required and the bubble chamber is certainly the most suitable detector in this respect. Unfortunately, however, it must be expected that the strange particle production in neutrino interactions will be reduced with respect to non-strange neutrino events by the same factor, about ten, that is found for the leptonic decays of the hyperons, and the rate will then be too small for the bubble chamber. The spark chamber set-up will not be able to identify Σ hyperons but could in favourable cases identify Λ^0 decays from reaction (10b) and (10c), and K^0 and K^+ decays from reaction (11).

* * *

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DISCUSSION

Evans : Why does one not observe the recoil proton as well as the μ meson in $\nu + n \rightarrow \mu^- + p$?

Von Dardel : We define vertex events as those with the second track having more than four sparks. Hence, on this criterion we do not generally observe proton recoils.

Bott-Bodenhausen : Do you use spark chambers in a strong magnetic field at CERN?

Von Dardel : No. We place a magnetic field between the chambers.

Spitzer : How many bubble chamber pictures do you expect to take?

Von Dardel : 300,000; we can afford to take double exposures as most pictures will be blank.

Harmsen : Is there any interest in doing a similar experiment with ordinary machines? If yes, do you see any possible source for these high-energy neutrinos?

Von Dardel : Yes. One can use high-energy electrons, for example, from the projected accelerator at Stanford, when one would use the intermediate vector boson

$$e \rightarrow \gamma \rightarrow W^+ + W^-$$

$$W^+ \rightarrow e^+ + \nu$$

$$\rightarrow \mu^+ + \nu .$$

This seems to be the most efficient way but it also produces an equal number of neutrettos. One also gets a contamination of an ordinary neutretto beam with neutrinos from $\pi \rightarrow e + \nu$ and $K \rightarrow \pi + e + \nu$ but the reaction rate is very small, $\sim 10^{-4}$.

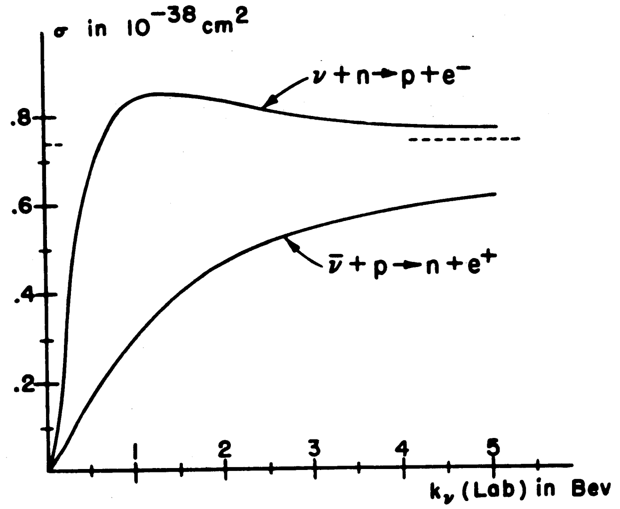

Fig. 1 Total cross section for neutrino interactions on free nucleons [1].

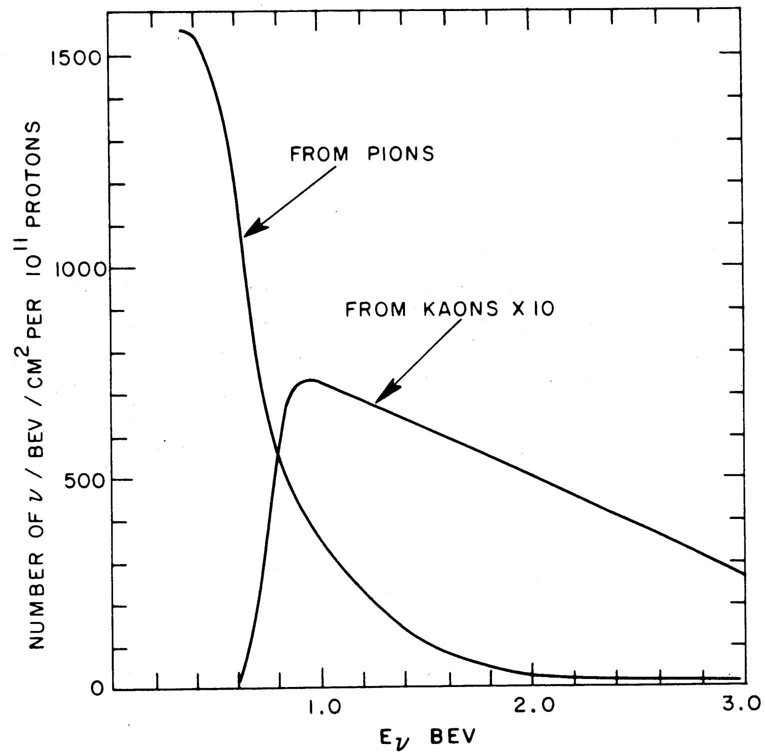

Fig. 2 Flux spectrum under the conditions of the Brookhaven neutrino experiment [5], Curve I : neutrinos from pion decay.

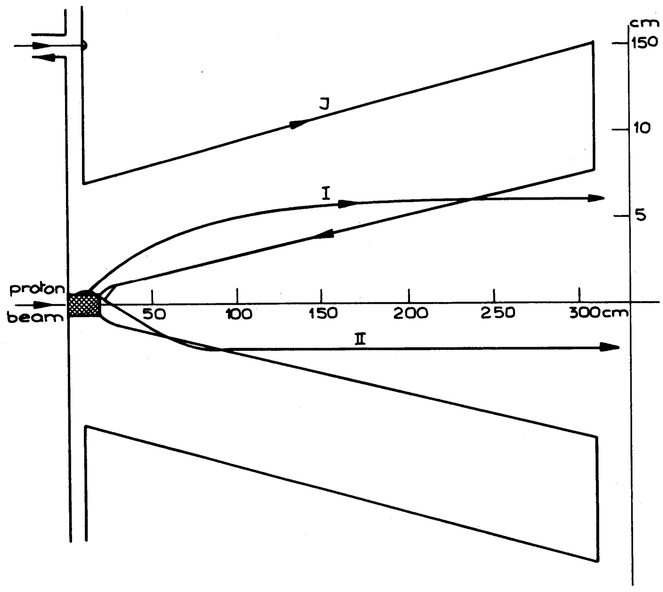

Fig. 3 Principle of the "neutrino horn" [8], and its focusing action on particles of high (I) and low momentum (II) .

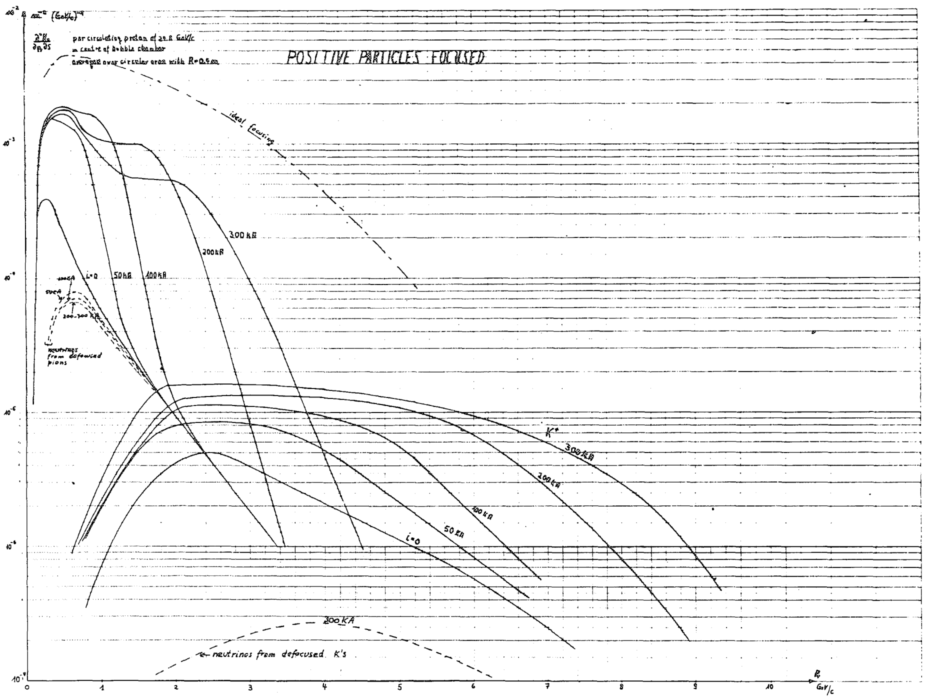

Fig. 4 Neutrino flux spectrum at 50 m distance for 25 m decay path, for 0, 10^5, 2×10^5 and 3×10^5 A current in the horn. If compared with fig. 2, the flux value should be multiplied by 10^7.

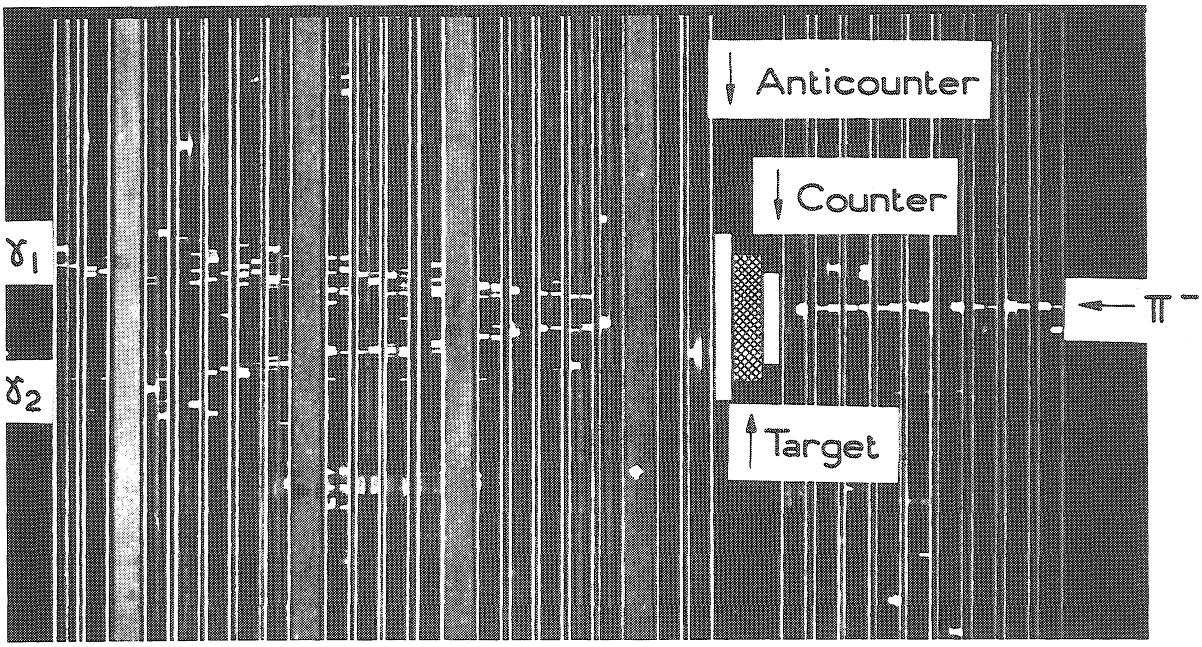

Fig. 5 Charge exchange reaction of π^- as seen in the spark chambers for the CERN neutrino experiment.

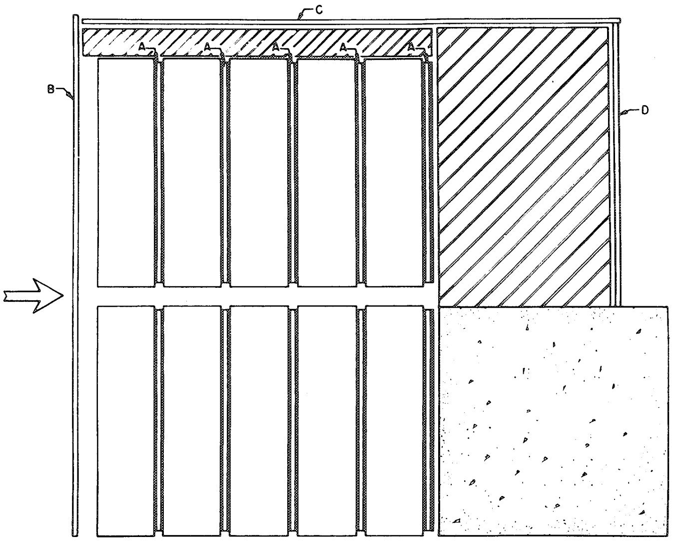

Fig. 6 Spark chamber set-up of the Brookhaven neutrino experiment.

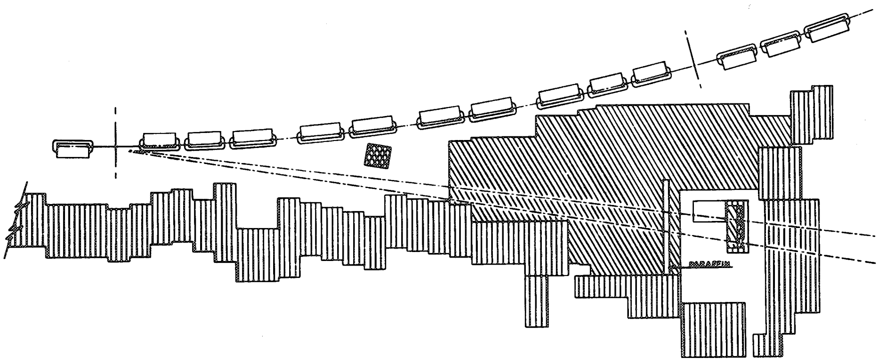

Fig. 7 Layout of the Brookhaven neutrino experiment.

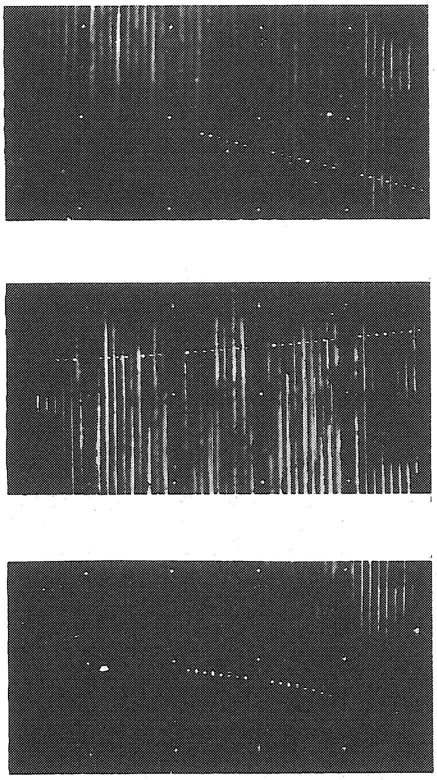

Fig. 8 "Single track" neutrino events in the Brookhaven experiment.

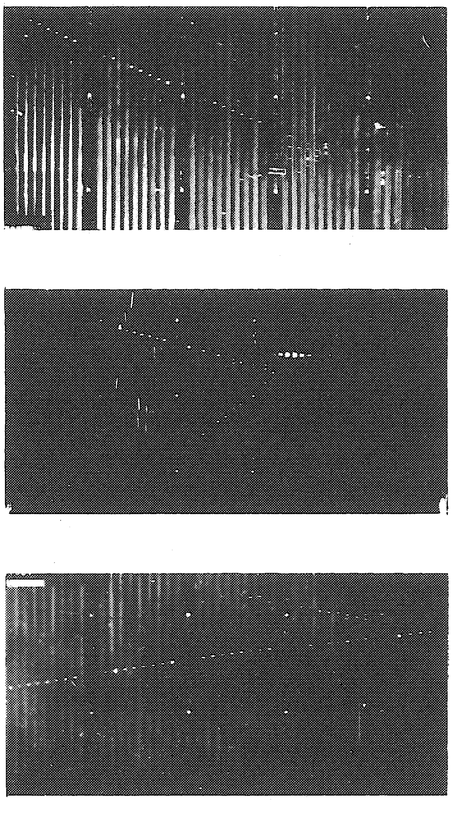

Fig. 9 "Vertex" events in the Brookhaven experiment. A possible interpretation is vector boson production with subsequent decay, according to the reactions

$$\nu' \rightarrow W^+ + \mu^-$$

$$\mu^+ + \nu' \qquad \text{(a)}$$

$$e^- + \nu \qquad \text{(b)}$$

$$\pi^+ + \pi^0 \qquad \text{(c)}$$

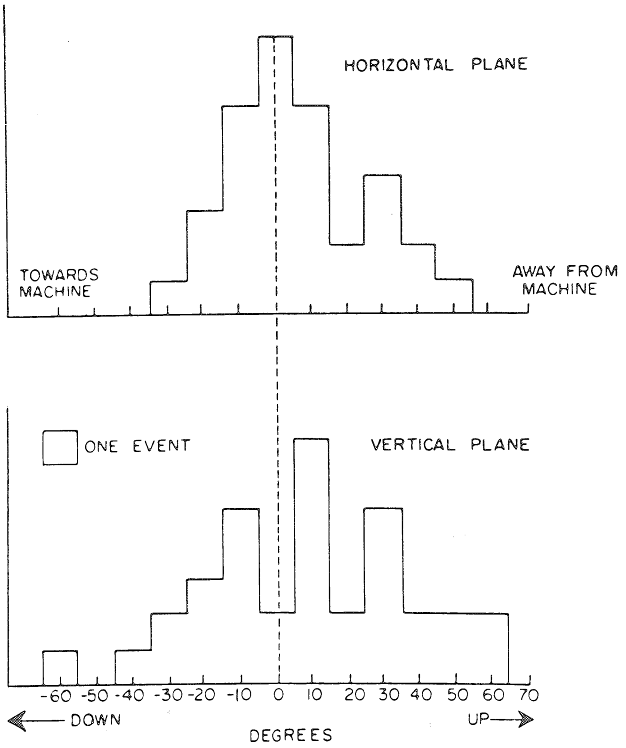

Fig. 10 Angular distribution of single track events in a horizontal and vertical plane around the neutrino direction.

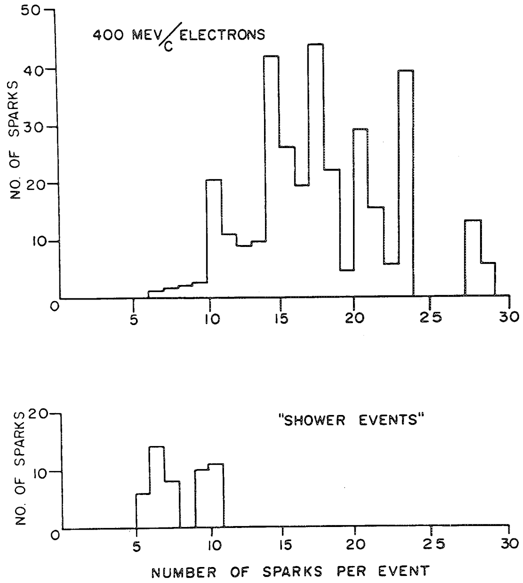

Fig. 11 Distribution of the number of sparks for 6 possible electron tracks of the neutrino experiment (bottom) compared with 400 MeV/c electrons in an external beam (top).

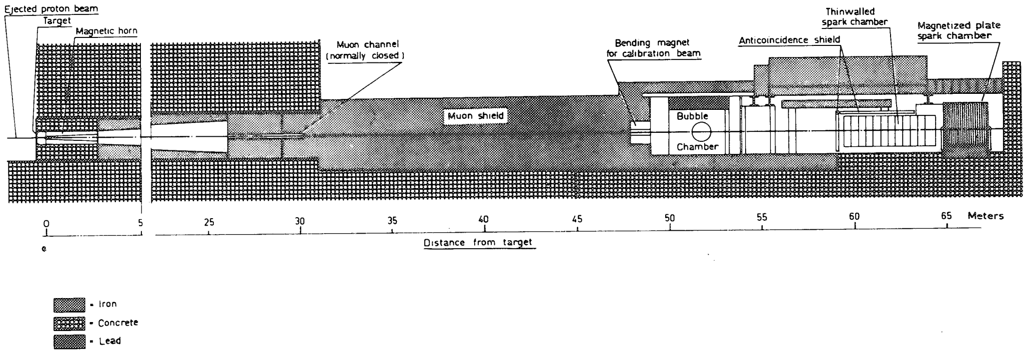

Fig. 12 Vertical cut through the planned CERN experiment showing decay tunnel, muon absorber, the detectors and the shielding around them.

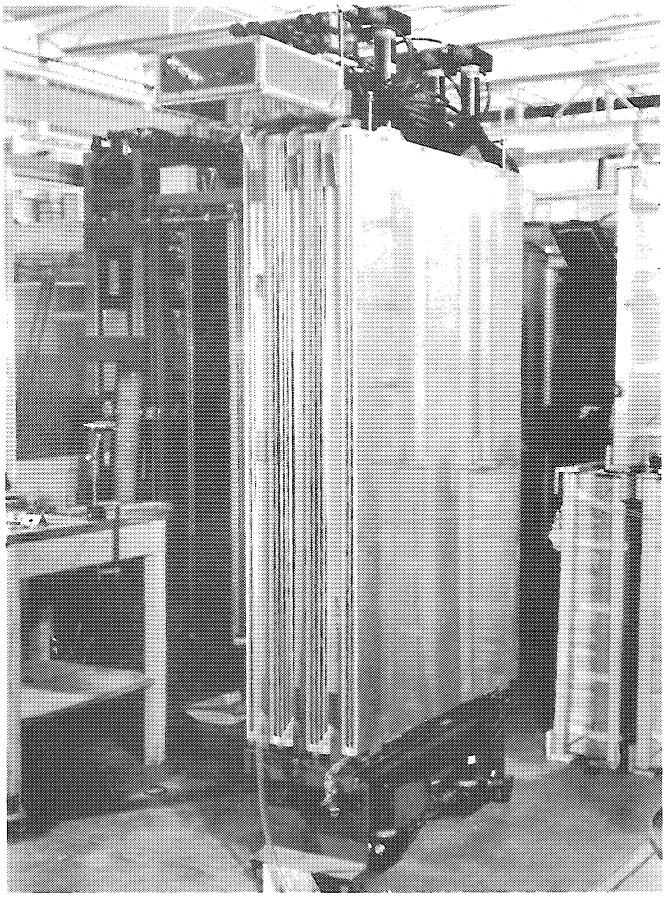

Fig. 13 Chariot carrying 9 two-gap spark chambers and two layers of scintillation counters for the CERN neutrino experiment. 30 of these units will be used in the experiment.

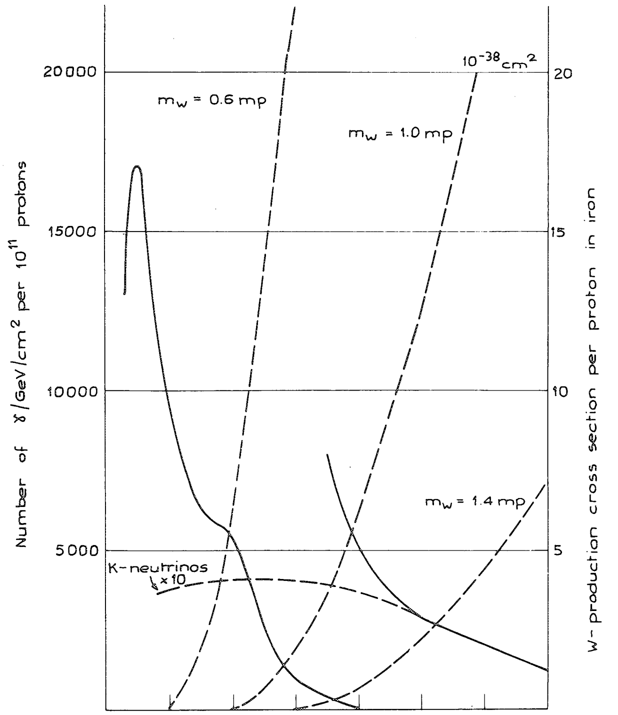

Fig. 14 Total cross section per nucleon for the production of intermediate bosons [4) by neutrinos in iron, as a function of neutrino energy for three values of the boson mass. (dotted curves). The full curves give the neutrino spectrum expected in the CERN neutrino experiment.