The first high-energy neutrino experiment*

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In the first part of my lecture I would like to tell you a bit about the state of knowledge in the field of Elementary Particle Physics as the decade of the 1960s began, with particular emphasis upon the weak interactions. In the second part I will cover the planning, implementation, and analysis of the first high-energy neutrino experiment. My colleagues, Jack Steinberger and Leon Lederman, will discuss the evolution of the field of high-energy neutrino physics beyond this first experiment and the significance of this effort when seen in the context of today's view of elementary particle structure.

I. HISTORICAL REVIEW

By the year 1960 the interaction of elementary particles had been classified into four basic strengths. The weakest of these, the gravitational interaction, does not play a significant role in the laboratory study of elementary particles and will be ignored. The others are as follows.

1. Strong interactions

This class covers the interactions among so-called hadrons. Among these hadrons are the neutrons and protons that we are all familiar with, along with the pions and other mesons that serve to tie them together into nuclei. Obviously the interaction that ties two protons into a nucleus must overcome the electrostatic repulsion which tends to push them apart. The strong interactions are short range, typically acting over a distance of 10^{-13} cm, but at that distance are some 2 orders of magnitude stronger than electromagnetic interactions.

In general, as presently understood, hadrons are combinations of the most elementary strongly interacting particles, called quarks. You will hear more about them later.

2. Electromagnetic interactions

You are all familiar with electromagnetic interactions from your daily experience. Like charges repel one another. Opposite charges attract. The Earth acts like a giant magnet. Indeed matter itself is held together by the electromagnetic interactions among electrons and nuclei. With the exception of the neutrinos, all elementary particles have electromagnetic interactions either through charge, or magnetic property, or the ability to interact directly with charge or magnetic moment. In 1960 the only known elementary particles apart from the hadrons were the three leptons—electron, muon, and neutrino—with some suspicion that there might be two types of neutrinos. Both the electron and the muon are electromagnetically interacting.

3. Weak interactions

Early in the century it was discovered that some nuclei are unstable against decay into residual nuclei and electrons or positrons. There were two important characteristics of these so-called β decays.

(a) They were "slow." That is to say, the lifetimes of the decaying nuclei corresponded to an interaction much weaker than that characteristic of electromagnetism.

(b) Energy and momentum were missing.

If one examined the spectrum of the electrons which were emitted, then it was clear that to preserve energy, momentum, and angular momentum in the decay it was necessary that there be another decay product present. That decay product needed to be of nearly zero mass and have half integral spin. This observation was first made by Pauli. Fermi later gave it the name of neutrino.

The development of the Fermi theory of weak interactions in fact made the neutrino's properties even more specific. The neutrino has a spin of $\frac{1}{2}$ and a very low probability of interacting in matter. The predicted cross section for the interaction of a β-decay neutrino with nucleons is about 10^{-43} cm^2. Thus one of these neutrinos would on the average pass through a light year of lead without doing anything.

The β-decay reactions can be simply written as

$$Z \rightarrow (Z-1)+e^{+}+\nu, \quad Z \rightarrow (Z+1)+e^{-}+\bar{\nu} .$$

By the failure to detect neutrinoless double-β decay, namely, the process $Z \rightarrow (Z-2)+e^{+}+e^{+}$, it was established that the neutrino and antineutrino were indeed different particles. In the 1950s, by means of a series of experiments associated with the discovery of parity viola-

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tion, it was also established that the neutrinos and antineutrinos were produced in a state of complete longitudinal polarization or helicity, with the neutrinos being left-handed and antineutrinos right-handed.

In the 1940s and 1950s, a number of other weak interactions were discovered. The pion, mentioned earlier as the hadron which serves to hold the nucleus together, can be produced in a free state. Its mass is about 273 times the electron mass and it decays in about 2.5×10^{-8} sec into a muon and a particle with neutrinolike properties. The muon in turn exhibits all of the properties of a heavy electron with a mass of about 207 times the electron mass. It decays in about 2.2×10^{-6} sec into an electron and two neutrinos. The presumed reactions, when they were discovered, were written as

$$\pi^+\rightarrow\mu^++\nu,\quad \mu^+\rightarrow e^++\nu+\bar{\nu}\ .$$

It was also known by 1960 that these decays were parity violating and that the neutrinos here had the same helicity as the neutrinos emitted in β decay.

Needless to say, there was a general acceptance in 1959 that the neutrinos associated with β decay were the same particles as those associated with pion and muon decay. The only hint that this might not be so came from a paper by G. Feinberg in 1958 in which he showed that the decay $\mu\rightarrow e+\gamma$ should occur with a branching ratio of about 10^{-4}, if a charged intermediate boson (W) moderated the weak interactions. Inasmuch as the experimental limit was much lower ($\sim10^{-8}$), this paper was thought of as a proof that there was no intermediate boson. Feinberg did point out, however, that a boson might still exist if the muon neutrino and the electron neutrino were different.

One final historical note with respect to neutrinos. In the mid-fifties Cowen and Reines, in an extremely difficult pioneering experiment, were able to make a direct observation of the interaction of neutrinos in matter. They used a reactor in which a large number of $\bar{\nu}$ were produced and observed the reaction $\bar{\nu}+p\rightarrow e^++n$. The cross section observed was consistent with that which was required by the theory.

II. CONCEPTION, PLANNING, AND IMPLEMENTATION OF THE EXPERIMENT

The first conception of the experiment was in late 1959. The Columbia University Physics Department had a tradition of a coffee hour at which the latest problems in the world of physics came under intense discussion. At one of these Professor T. D. Lee was leading such a discussion of the possibilities for investigating weak interactions at high energies. A number of experiments were considered and rejected as not feasible. As the meeting broke up there was some sense of frustration as to what could ever be done to disentangle the high-energy weak interactions from the rest of what takes place when energetic particles are allowed to collide with targets. The only ray of hope was the expectation that the cross sections characteristic of the weak interactions increased as the square of the center-of-mass energy at least until such time as an intermediate boson or other damping mechanism took hold.

That evening the key notion came to me—perhaps the neutrinos from pion decay could be produced in sufficient numbers to allow us to use them in an experiment. A quick "back of the envelope" calculation indicated the feasibility of doing this at one or another of the accelerators under construction or being planned at that time. I called T. D. Lee at home with the news and his enthusiasm was overwhelming. The next day planning for the experiment began in earnest. Meanwhile Lee and Yang began a study of what could be learned from the experiment and what the detailed cross sections were.

Not long after this point we became aware that Bruno Pontecorvo had also come up with many of the same ideas as we had. He had written up a proposed experiment with neutrinos from stopped pions, but he had also discussed the possibilities of using energetic pions at a conference in the Soviet Union. His overall contribution to the field of neutrino physics was certainly major.

Leon Lederman, Jack Steinberger, and I spent a great deal of time trying to decide on an ideal neutrino detector. Our first choice, if it were feasible, would have been a large freon bubble chamber that Jack Steinberger had built. (In the end that would have given about a factor of 10 fewer events at the Brookhaven AGS than the spark chamber which we did use. Hence it was not used in this experiment.)

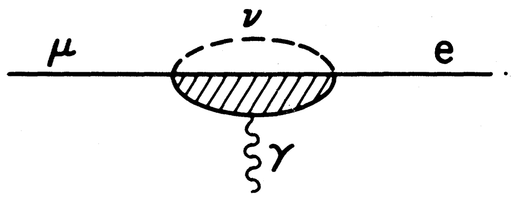
Fortunately for us, the spark chamber was invented at just about that time. Lederman, Gaillard, and I drove down to Princeton to see one at Cronin's laboratory. It was small, but the idea was clearly the right one. The three of us decided to build the experiment around a ten-ton spark chamber design.

In the summer of 1960, Lee and Yang again had a major impact on our thinking. They pointed out that it was essentially impossible to explain the absence of the decay $\mu\rightarrow e+\gamma$ without positing two types of neutrinos. Their argument as presented in the 1960 Rochester Conference was more or less as follows.

1. The simplest four-fermion point model which explains low-energy weak interactions leads to a cross section increasing as the square of the center-of-mass energy.

2. At the same time, a point interaction must of necessity be S wave, and thus the cross section cannot exceed $\pi\lambda^2$ without violating unitarity. This violation would take place at about 300 GeV.

3. Thus there must be a mechanism that damps the total cross section before the energy reaches 300 GeV. This mechanism would imply a "size" to the interaction region, which would in turn imply charges and currents which would couple to photons. This coupling would lead to the reaction $\mu\rightarrow e+\gamma$ through the following diagram:



4. The anticipated branching ratio for $\mu \to e + \gamma$ should not differ appreciably from 10^{-5}. The fact that the branching ratio was known to be less than 10^{-8} was *strong evidence* for the two-neutrino hypothesis.

With these observations in mind, the experiment became highly motivated toward investigating the question of whether $\nu_\mu = \nu_e$. If there were only one type of neutrino then the theory predicted that there should be equal numbers of muons and electrons produced. If there were two types of neutrinos then the production of electrons and muons should be different. Indeed, if one followed the Lee-Yang argument for the absence of $\mu \to e + \gamma$, then the muon neutrino should produce *no* electrons at all.

We now come to the design of the experiment. The people involved in the effort were Gordon Danby, Jean-Marc Gaillard, Konstantin Goulianos, and Nariman Mistry, along with Leon Lederman, Jack Steinberger, and myself. The facility used to produce the pions was the newly completed Alternate Gradient Synchrotron (AGS) at the Brookhaven National Laboratory. Although the maximum energy of the accelerator was 30 GeV, it was necessary to run it at 15 GeV in order to minimize the background from energetic muons.

Pions were produced by means of collisions between the internal proton beam and a beryllium target at the end of a 3-m straight section (see Figure 1). The detector was set at an angle of 7.5° to the proton direction behind a 13.5-m steel wall made of the deck plates of a dismantled cruiser. Additional concrete and lead was placed as shown.

To minimize the amount of cosmic-ray background it was important to minimize the fraction of time during which the beam was actually hitting the target. Any so-called "events" which occurred outside of that window could then be excluded as not being due to machine-induced high-energy radiation.

The AGS at 15 GeV operated at a repetition rate of one pulse every 1.2 sec. The beam RF structure consisted of 20-nsec bursts every 220 nsec. The beam itself was deflected onto the target over the course of 20–30 μsec for each cycle of the machine. Thus the target was actually being bombarded for only 2×10^{-6} sec for each second of real time.

In order to make effective use of this beam structure it was necessary to gate the detector on the bursts of pions which occurred when the target was actually being struck. This was done by means of a 30-nsec time window which was triggered through the use of a Cherenkov counter in front of the shielding wall. Phasing of the Cherenkov counter relative to the detector was accomplished by raising the AGS energy and allowing muons to penetrate the shield.

Incidentally, this tight timing also served to exclude 90% of the background induced by slow neutrons.

The rate of production of pions and kaons was well known at the time and it was quite straightforward to calculate the anticipated neutrino flux. In Figure 2 we present an energy spectrum of the neutrino flux for a 15-GeV proton beam making use of both pion and kaon decay. It is clear that kaon decay is a major contributor for neutrino energies greater than about 1.2 GeV. (These neutrinos come from the reaction $K^+ \to \mu^+ + \nu$.)

Needless to say, the main shielding wall was thick enough to suppress all strongly interacting particles. Indeed, the only hadrons that were expected to emerge from that wall were due to neutrino interactions in the last meter or so. Muons entering the wall with up to 17 GeV would have been stopped by ionization loss. The only serious background was due to neutrons leaking through the concrete floor; these were effectively eliminated in the second half of the experiment.

The spark chamber is shown in Figures 3 and 4. It consisted of ten modules, each of nine aluminum plates, 44 in.×44 in.×1 in. thick separated by $\frac{3}{8}$-in. Lucite

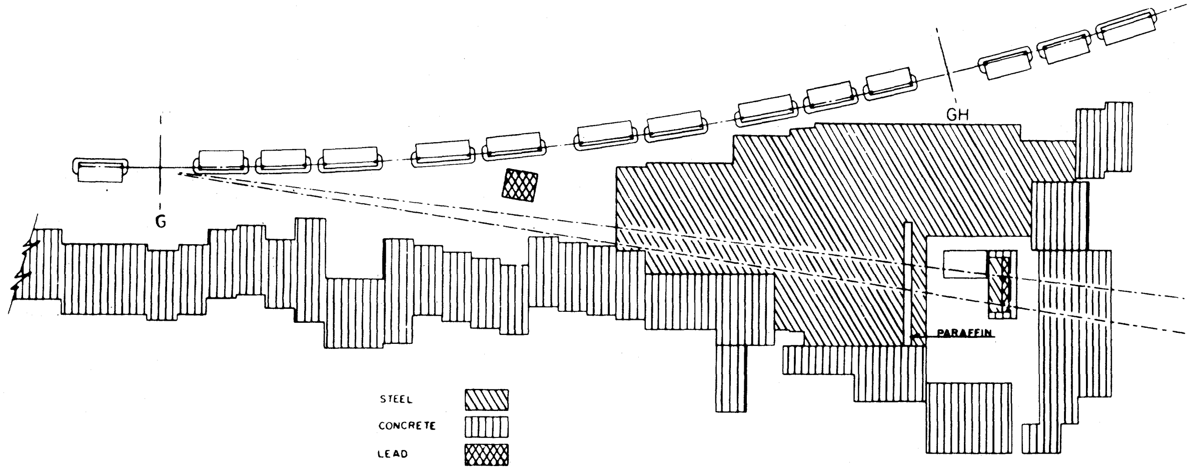


FIG. 1. Plan view of the AGS neutrino experiment.

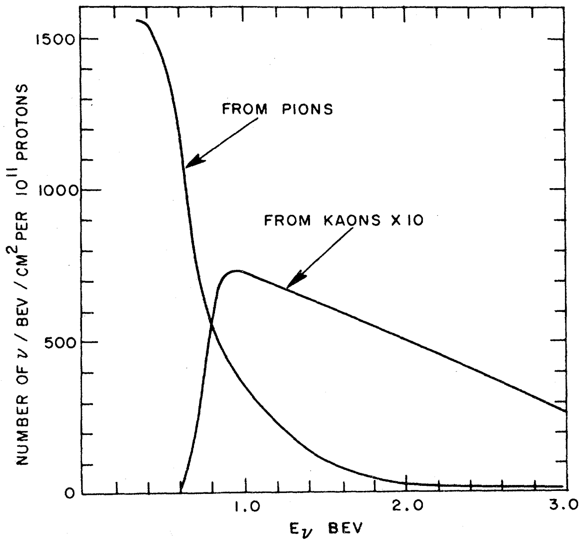


FIG. 2. Energy spectrum of neutrinos as expected for AGS running at 15 GeV.

spacers. Anticoincidence counters covered the front, top, and rear of the assembly, as shown, to reduce the effect of cosmic rays and muons which penetrated the shielding wall. Forty triggering counters were inserted between modules and at the end of the assembly. Each triggering counter consisted of two sheets of scintillator separated by $\frac{3}{4}$ in. of aluminum. The scintillators were put in electronic coincidence.

Events were selected for further study if they originated within a fiducial volume that excluded the first two plates, two inches at top and bottom, and four inches at front and rear of the assembly. Single-track events also needed to stay within the fiducial volume if extrapolated back for two gaps. Single tracks were not accepted unless their production angle relative to the neutrino direction was less than 60°.

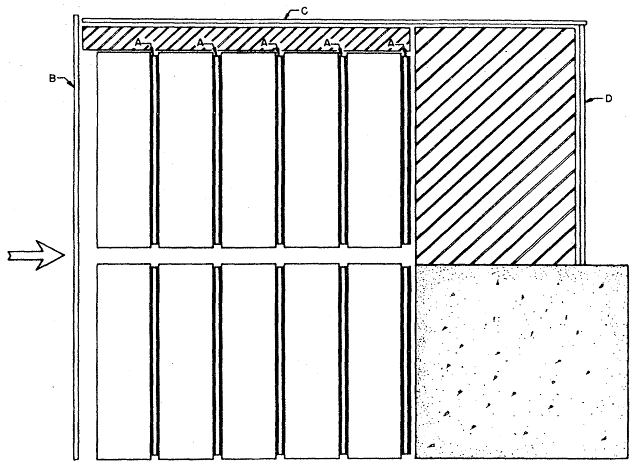


FIG. 3. Spark chamber and counter arrangement. This is the front view with neutrinos entering on the left. *A* are the trigger counters. *B*, *C*, and *D* are used in anticoincidence.

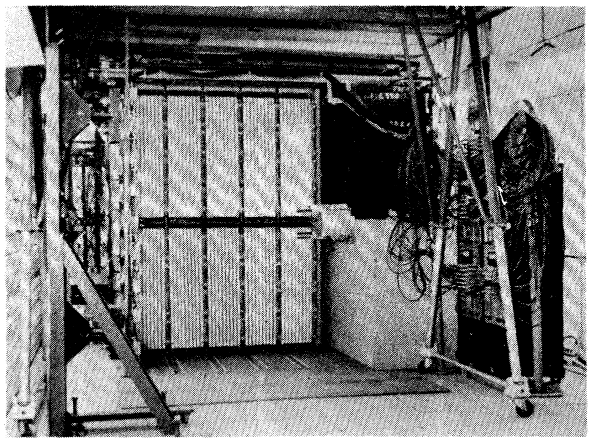


FIG. 4. A photograph of the chambers and counters.

A total of 113 events were found which satisfied these criteria. Of these, 49 were very short single tracks. All but three of these appeared in the first half of the experiment before the shielding was improved, and they were considered to be background. In retrospect, some of these were presumably neutral-current events, but at the time it was impossible to distinguish them from neutron-induced interactions due to leakage over and under the shield.

The remaining events included the following categories.

(a) 34 "single muons" of more than 300 MeV/*c* of visible momentum. Some of these are illustrated in Figure 5. Among them are some with one or two extraneous sparks at the vertex, presumably from nuclear recoils.

(b) 22 "vertex" events. Some of these show substantial energy release. These events are presumably muons accompanied by pions produced in the collision (see Figure 6).

(c) 8 "shower" candidates. Of these, six were selected so that their potential range, had they been muons, would correspond to more than 300 MeV/*c*. These were the only candidates for single electrons in the experiment. We shall consider them in detail shortly.

It was quite simple to demonstrate that the 56 events in categories (a) and (b) were almost all of neutrino origin.

By running the experiment with the accelerator off and triggering on cosmic rays it was possible to place a limit of 5±1 on the total number of the single-muon events which could be due to such background. Indeed, the slight asymmetry in Figure 7 is consistent with this hypothesis.

It was simple to demonstrate that these events were not neutron induced. Referring to Figure 7 we see how they tend to point toward the target through the main body of steel shielding. No more than 10^{-4} events should have arisen from neutrons penetrating the shield (other than from neutrino-induced events in the last foot of the shield itself). Indeed, removing four feet of steel from the front would have increased the event rate by a factor of 100; no such increase was seen. Furthermore, if the events were neutron induced they would have clustered toward the first chambers. In fact they were uniformly spread throughout the detector subject only to the 300-MeV/c requirement.

The evidence that the single-particle tracks were primarily due to muons was based on the absence of interactions. If these tracks were pions we would have expected eight interactions. Indeed, even if all of the stopping tracks were considered to be interacting, it would still lead to the conclusion that the mean free path of these tracks was four times that expected for hadrons.

As a final check on the origin of these events we effectively replaced four feet of the shield by an equivalent amount as close as possible to the beryllium

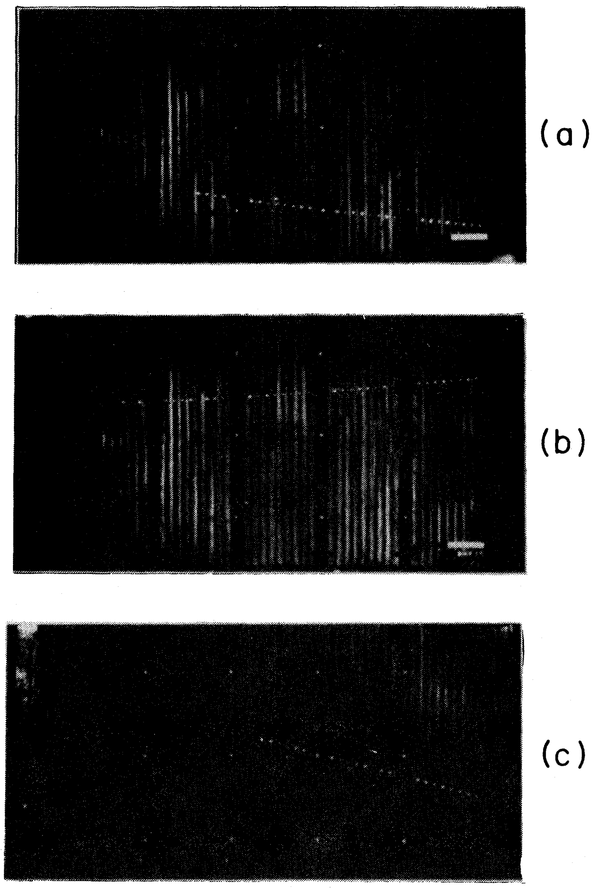


FIG. 5. Some typical single-muon events.

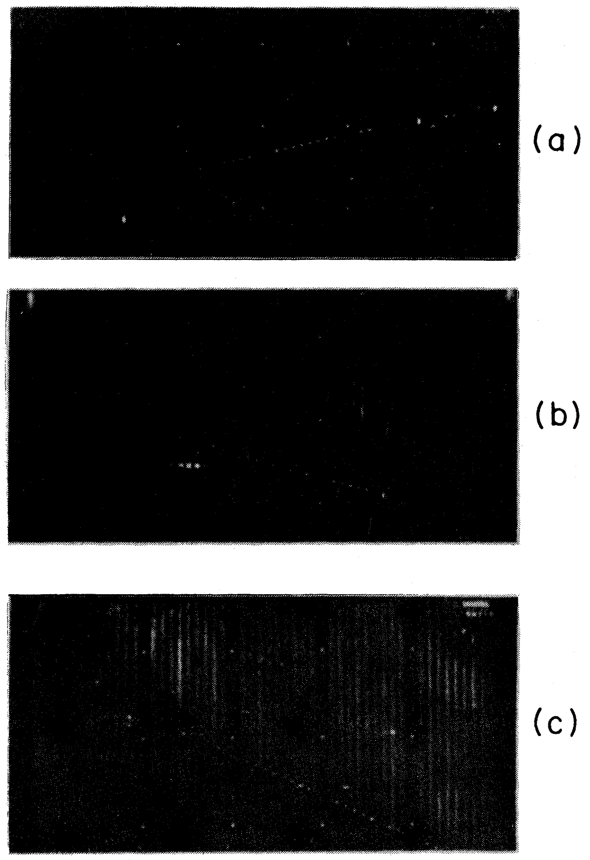


FIG. 6. Some typical "vertex" events.

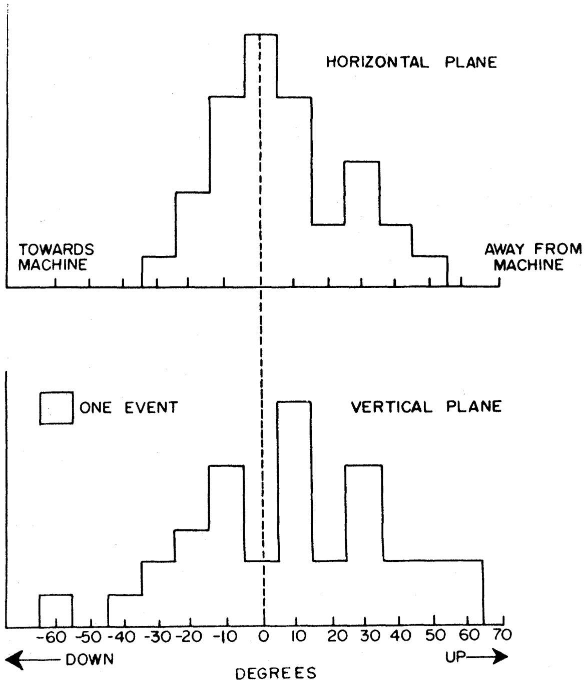


FIG. 7. Projected angular distribution of the single-track events. The neutrino direction is taken as zero degrees.

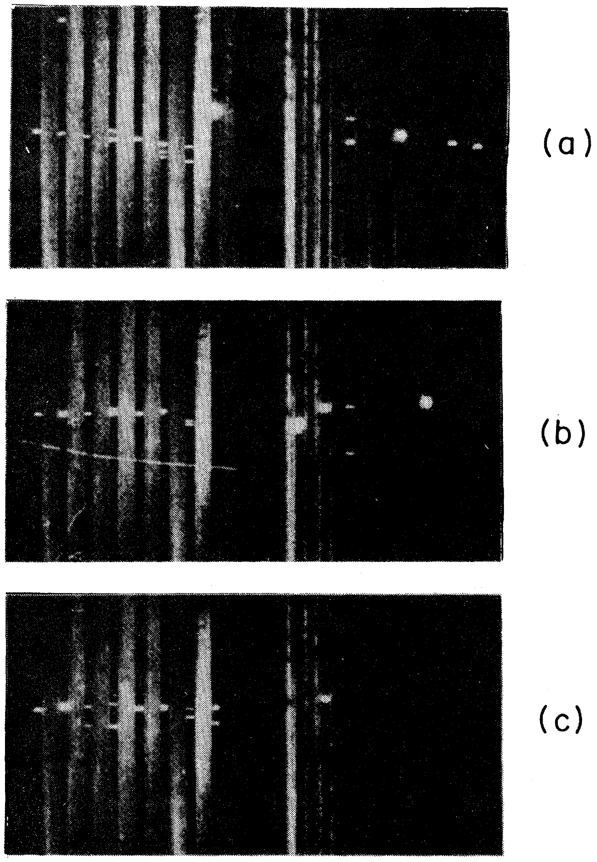


FIG. 8. Typical 400-MeV/c electrons from the Cosmotron calibration run.

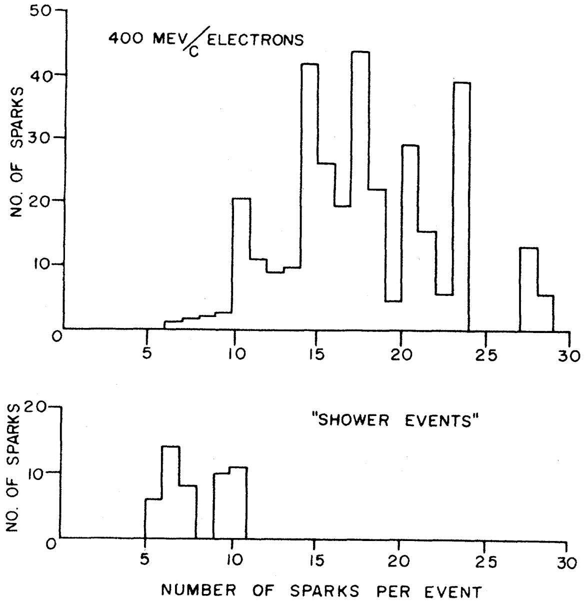


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers should $\nu_\mu = \nu_e$. Also shown are the observed "shower" events.

target. This reduced the decay distance by a factor of 8. The rate of events decreased from 1.46 ± 0.2 to 0.3 ± 0.2 per 10^{16} incident protons.

All of the above arguments convinced us that we were in fact looking at neutrino-induced events and that 29 of the 34 single-track events were muons produced by neutrinos (the other five being background due to cosmic rays). It is these events that were to form the basis of our arguments as to the identity of ν_μ and ν_e. But first we must see what electrons would look like in passing through our spark chambers. An electron will on the average radiate half of its energy in about four of the aluminum plates. This will lead to gammas, which will in turn convert to other electron-positron pairs. The net result is called a "shower." Typically an electron shower shows a number of sparks in each gap between plates. The total number of sparks in the shower increases roughly linearly with electron energy in the 400-MeV region.

In order to calibrate the chambers we exposed them to a beam of 400-MeV electrons at the Brookhaven Cosmotron (see Figure 8). We noted that the triggering system was 67% efficient with respect to these electrons. We then plotted the spark distribution as shown in Figure 9 for a sample of $\frac{2}{3} \times 29$ expected showers. The six "shower" events were also plotted. Clearly the difference between the expected distribution, had there been only one neutrino, and the observed distribution was substantial. We concluded that $\nu_\mu \neq \nu_e$.

As a further point, we compared the expected rate of neutrino events with that predicted by the Fermi theory and found agreement within 30%.

The results of the experiment were described in an article in *Physical Review Letters,* Vol. 9, pp. 36–44 (1962).

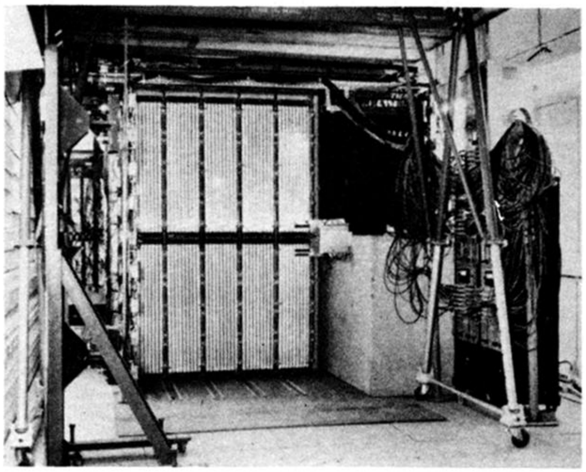


FIG. 4. A photograph of the chambers and counters.

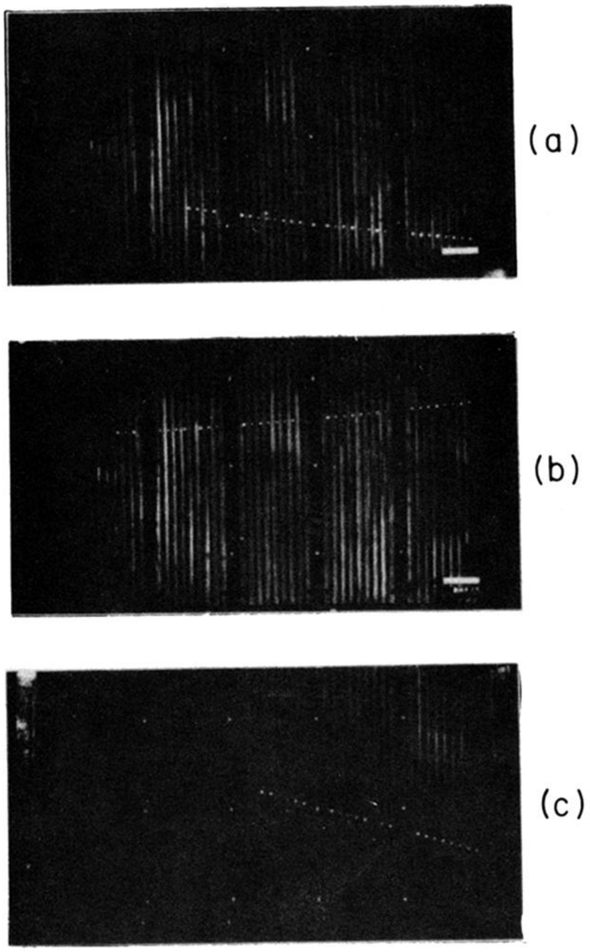


FIG. 5. Some typical single-muon events.

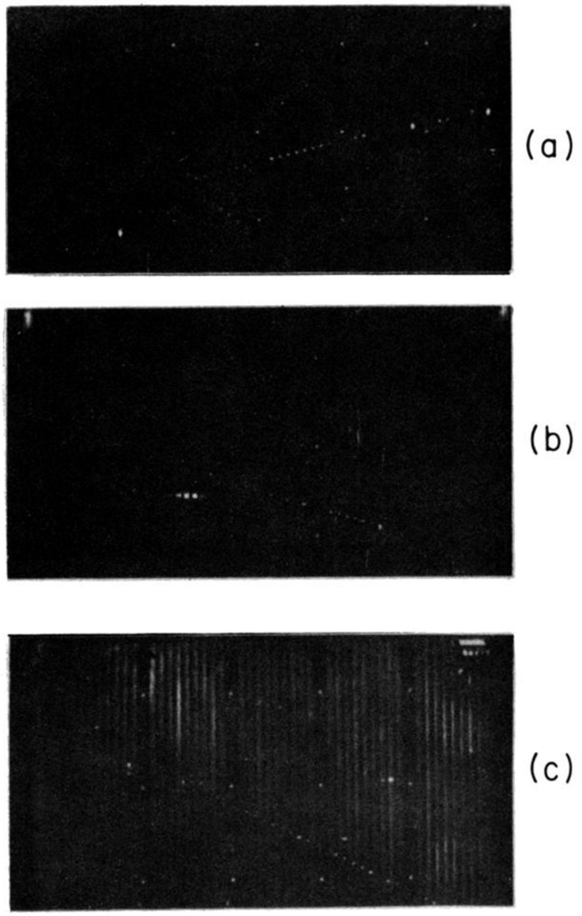


FIG. 6. Some typical "vertex" events.

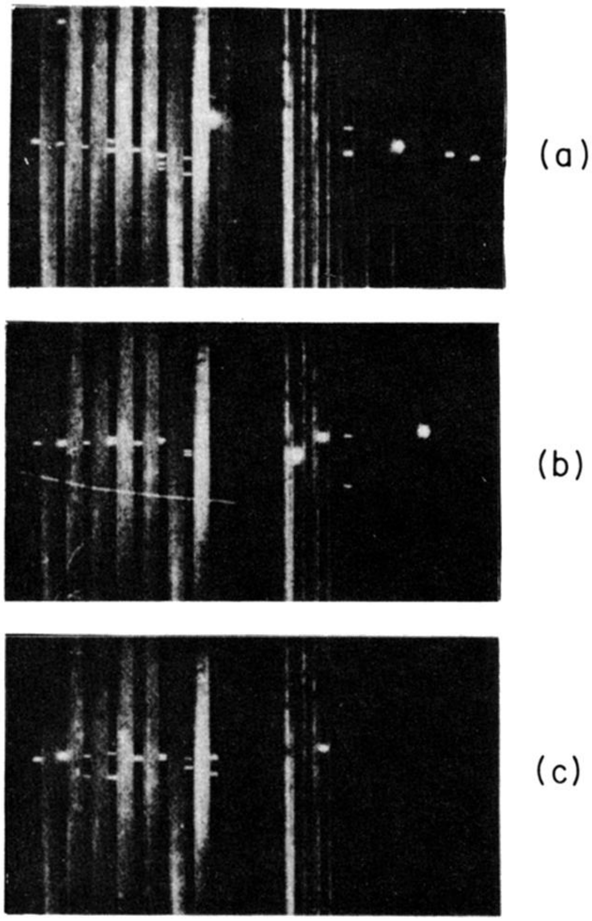


FIG. 8. Typical 400-MeV/c electrons from the Cosmotron calibration run.