11. C. Jencks and M. Brown, *Harvard Educ. Rev.* **48**, 126 (1975).
12. J. Crane, thesis, Harvard University, Cambridge, MA (1988).
13. L. Datcher, *Rev. Econ. Stat.* **64**, 32 (1982).
14. M. Corcoran, R. Gordon, D. Laren, G. Solon, unpublished data.
15. C. Jencks and S. E. Mayer, in *Concentrated Urban Poverty in America*, M. McGeary and L. Lynn, Jr., Eds. (National Academy Press, Washington, DC, in press).
16. D. E. Meyers, in *Poverty, Achievement and the Distribution of Compensatory Education Services*, M. Kennedy, R. Jung, M. Orland, Eds. (Office of Educational Research and Improvement, Department of Education, Washington, DC, 1986), pp. D18–D60.
17. A. S. Bryk and M. E. Driscoll, "An empirical investigation of the school as community" (National Center on Effective Schools, Madison, WI, 1988).
18. N. H. St. John, *School Desegregation Outcomes for Children* (Wiley, New York, 1975).
19. R. L. Crain and R. E. Mahard, *Sociol. Educ.* **51**, 81 (1978).
20. R. L. Crain, *ibid.* **44**, 1 (1971).
21. A. Gamoran, *ibid.* **60**, 135 (1987).
22. T. D. Cook, in *School Desegregation and Black Achievement* (National Institute of Education, Washington, DC, 1984), pp. 6–42; D. J. Armor, *ibid.*, pp. 43–67; see also (*19*).
23. A. J. Reiss, Jr., and A. L. Rhodes, *Am. Sociol. Rev.* **26**, 720 (1960).
24. D. P. Hogan and E. M. Kitagawa, *Am. J. Sociol.* **90**, 825 (1985).
25. F. F. Furstenberg, Jr., S. P. Morgan, K. A. Moore, J. Perterson, *Am. Sociol. Rev.* **52**, 511 (1987).
26. R. L. Crain, *Am. J. Sociol.* **75**, 593 (1970).
27. ——— and J. Strauss, "School desegregation and black occupational attainment: Results from a long-term experiment" (Center for the Social Organization of Schools, Report 359, Johns Hopkins University, Baltimore, 1985).
28. D. S. Massey and N. A. Denton, *Am. Sociol. Rev.* **52**, 802 (1987).
29. J. E. Rosenbaum, L. S. Rubinowitz, M. J. Kulieki, "Low income black children in white suburban schools" (Center for Urban Affairs and Policy Research, Northwestern University, Evanston, IL, 1986).
30. R. M. Hauser [*Socioeconomic Background and Educational Performance* (American Sociological Association, Washington, DC, 1971)] and D. F. Alwin [*Sociol. Educ.* **49**, 294 (1976)] discuss the statistical rationale for such methods. See also (*11*).
31. A detailed review of each study and lengthier discussions of the methodological issues raised in this article are in (*15*).

The First High-Energy Neutrino Experiment

MEL SCHWARTZ

This article describes the state of knowledge of weak interactions in 1960, the conception and implementation of the first high-energy neutrino experiment, and the not altogether unexpected result that the muon neutrino is different from the electron neutrino.

In the first part of my article I would like to tell you a bit about the state of knowledge of elementary particle physics as the decade of the 1960s began, with particular emphasis on the weak interactions. In the second part I will cover the planning, implementation, and analysis of the first high-energy neutrino experiment.

Historical Review

By the year 1960 the interactions 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 strong, electromagnetic, and weak interactions.

Strong interactions. This class covers the interactions among so-called hadrons. Among the hadrons are the neutrons and protons that we are all familiar with, together with the pions and other mesons that tie them together into nuclei. Obviously, the interaction that ties two protons into a nucleus must overcome the electrostatic repulsion that 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 two orders of magnitude stronger than electromagnetic interactions. In general, as presently understood, hadrons are combinations of the most elementary, strongly interacting particles, called quarks.

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 directly interact with charge or magnetic moment. In 1960 the only known elementary particles apart from the hadrons were the three leptons—electron, muon, and neutrino—and there was some suspicion that there might be two types of neutrinos. Both the electron and the muon are electromagnetically interacting.

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 decays.

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

2) Energy and momentum were missing.

If one examined the spectrum of the electrons that were emitted, 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 to have half-integral spin. This observation was first made by Pauli. Fermi later gave this product the name neutrino.

With the development of the Fermi theory of weak interactions, more was learned about the properties of the neutrino. The neutrino has a spin of 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 interacting at all.

The author is at Digital Pathways, Inc., Mountain View, CA 94043. This article is adapted from the lecture he delivered in Stockholm on 8 December 1988, when he received the Nobel Prize in Physics, which he shared with Jack Steinberger and Leon Lederman. The article is published here with permission from the Nobel Foundation. The articles by Dr. Steinberger and Dr. Lederman will be published in subsequent issues.

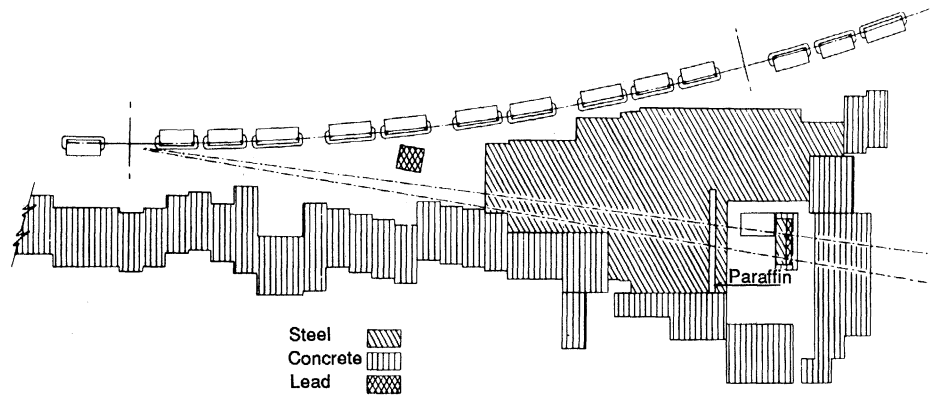


Fig. 1. Plan view of the AGS neutrino experiment. [Adapted from (*6*)]

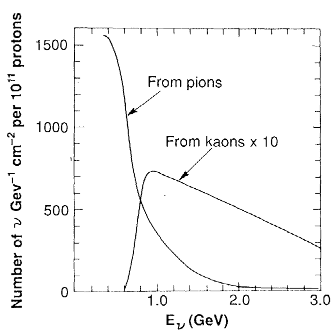


Fig. 2. Energy spectrum of neutrinos as expected for the AGS running at 15 GeV. [Adapted from (*6*)]

The β-decay reactions can be written as

$$Z \rightarrow (Z - 1) + e^+ + \nu$$

$$Z \rightarrow (Z + 1) + e^- + \overline{\nu}$$

By the failure to detect neutrino-less double β decay, namely, the process $Z \rightarrow (Z - 2) + e^+ + e^+$, it was established that the neutrino (ν) and antineutrino ($\overline{\nu}$) were indeed different particles. In the 1950s, in a series of experiments associated with the discovery of parity violation, 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 the antineutrinos right-handed.

In the 1940s and 1950s, a number of other weak interactions had been discovered. The pion, the hadron that holds 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} s into a muon and a particle with neutrino-like properties. The muon exhibits all of the properties of a heavy electron with a mass about 207 times the electron mass. It decays in about 2.2×10^{-6} s into an electron and two neutrinos. The presumed reactions were written as:

$$\pi^+ \rightarrow \mu^+ + \nu$$

$$\mu^+ \rightarrow e^+ + \nu + \overline{\nu}$$

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

Needless to say, there was a general acceptance in 1959 of the idea 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 in a paper by Feinberg in 1958 (*1*) 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 interaction. Inasmuch as the experimental limit was much lower ($\sim 10^{-8}$), 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 development with respect to neutrinos should be noted. In the mid-1950s Reines and Cowen, in an extremely difficult pioneering experiment, were able to directly observe the interaction of neutrinos in matter (*2*). They used a reactor in which a large number of $\overline{\nu}$ are produced and observed the reaction $\overline{\nu} + p \rightarrow e^+ + n$. The cross section observed was consistent with that required by the theory.

Conception, Planning, and Implementation of the Experiment

The idea of a high-energy neutrino experiment was first considered 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 discussions. At one of these meetings Professor T. D. Lee was leading 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 about what could 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 (*3*). I called 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 such an experiment and what the detailed cross sections were.

Not long after, 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 (*4*), 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 had been feasible, would have been a large Freon bubble chamber that Jack Steinberger had built. [In the end that would have given fewer events by about a factor of 10 than the spark chamber at the Brookhaven alternating gradient synchrotron (AGS) that we did use. Hence the bubble chamber was not used in this experiment.]

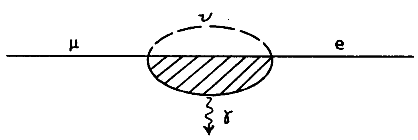
Fortunately for us, the spark chamber was invented at just about that time. Lederman, Jean-Marc Gaillard, and I drove down to Princeton to see one at J. Cronin's laboratory. It was small, but the idea was clearly the right one. The three of us decided to build the experiment around a 10-ton spark chamber design.

In the summer of 1960, Lee and Yang pointed out that it was essentially impossible to explain the absence of the decay $\mu \rightarrow e + \gamma$ without positing two types of neutrinos (*5*). Their argument, as presented at the 1960 Rochester Conference, was more or less as follows:

1) The simple four-fermion point model, which explains low-energy weak interactions, leads to a cross section that increases 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 $\pi ƛ^2$ (where $ƛ = \lambda/2\pi$) 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 that would couple to photons. This coupling would lead to the reaction $\mu \rightarrow e + \gamma$ through the diagram:



4) The anticipated branching ratio for $\mu \rightarrow e + \gamma$ 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, we 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 number of electrons and muons produced should be different. Indeed, if one followed the Lee-Yang argument for the absence of $\mu \rightarrow e + \gamma$, then the muon neutrino should produce no electrons at all.

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

Pions were produced as a result of collisions between the internal proton beam and a beryllium target at the end of a 3-m straight section (Fig. 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 shielding 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" that occurred outside of that window could then be excluded as not due to machine-induced, high-energy radiation.

The AGS at 15 GeV operated at a repetition rate of one pulse every 1.2 s. The radio-frequency structure of the beam consisted of

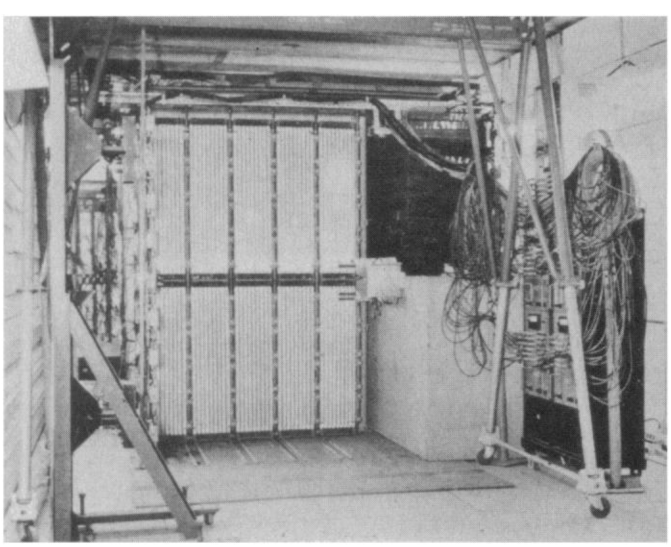


Fig. 3. Photograph of the spark chamber and counters.

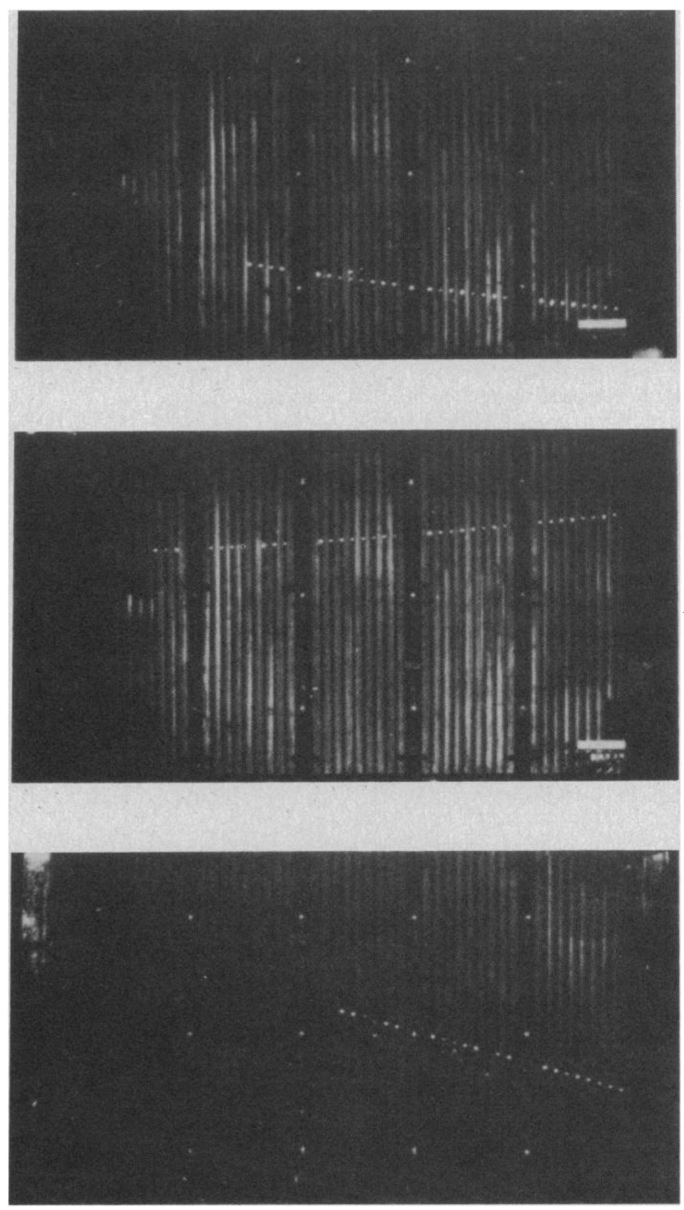


Fig. 4. Some typical "single muon" events. [Adapted from (*6*)]

20-ns bursts every 220 ns. The beam itself was deflected onto the target over the course of 20 to 30 μs for each cycle of the machine. Thus the target was actually being bombarded for only 2×10^{-6} s for each second of real time.

In order to make effective use of this beam structure, we found it necessary to gate the detector on the bursts of pions that occurred when the target was actually being struck. This was done by means of a 30-ns time window that was triggered through the use of a Cerenkov counter in front of the shielding wall. We accomplished the phasing of the Cerenkov counter relative to the detector by raising the AGS energy and allowing muons to penetrate the shield. This tight timing also excluded 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. Figure 2 shows 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 reactino $K^+ \rightarrow \mu^+ + \nu$.)

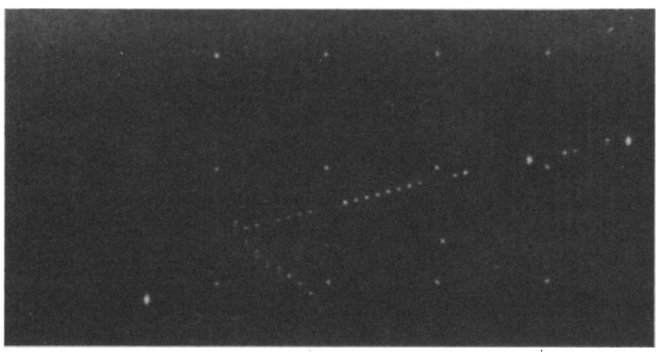


Fig. 5. A typical "vertex" event. [Adapted from (*6*)]

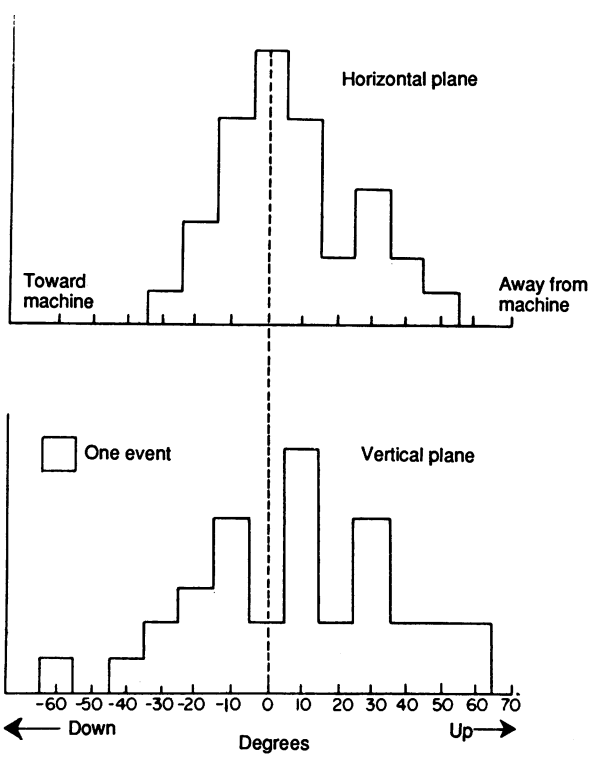


Fig. 6. Projected angular distribution of the single-track events. The neutrino direction is taken as 0°. [Adapted from (*6*)]

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 energies 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, shown in Fig. 3, consisted of ten modules, each composed of nine aluminum plates, 44 inches by 44 inches by 1 inch separated by 3/8-inch Lucite spacers. Anticoincidence counters covered the front, top, and rear of the assembly to reduce the effect of cosmic rays and muons that might penetrate the shielding wall. A total of 40 triggering counters were inserted between modules and at the end of the assembly, each consisting of two sheets of scintillator separated by 3/4 inch of aluminum. The scintillators were put into electronic coincidence.

Events were selected for further study if they originated within a fiducial volume that excluded the first two plates, 2 inches at the top and bottom, and 4 inches at the 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 for

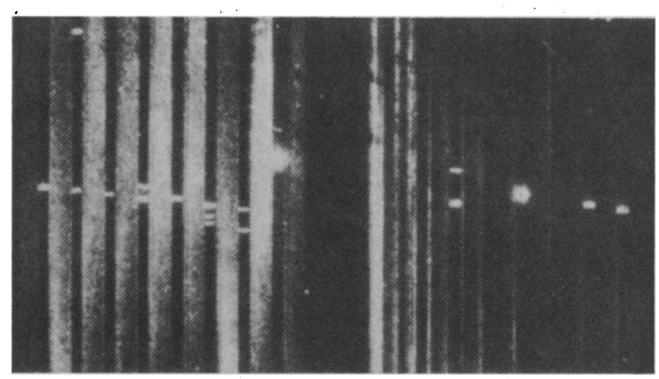


Fig. 7. Typical 400 MeV/*c* electrons from the Cosmotron calibration run. [Adapted from (*6*)]

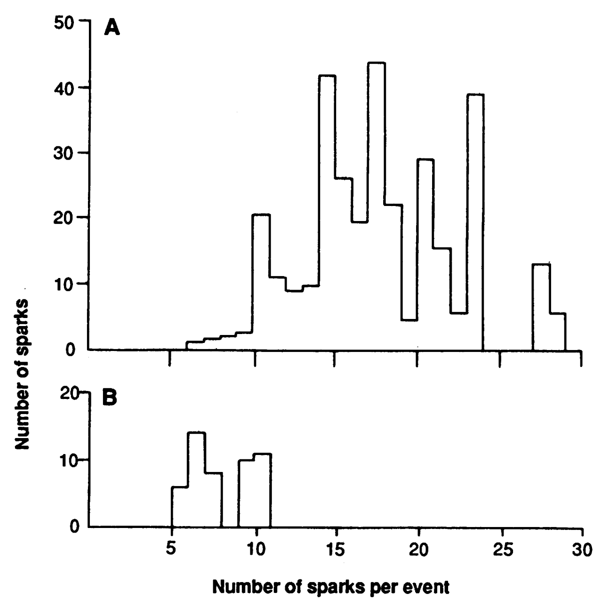


Fig. 8. (**A**) Spark distribution for 400 MeV/*c* electrons normalized to the expected number of showers, should $\nu_\mu = \nu_e$. (**B**) Observed "shower" events. [Adapted from (*6*)]

study unless their production angle relative to the neutrino direction was less than 60°.

A total of 113 events were observed that 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, it is now clear that 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:

1) There were 34 "single muons" of more than 300 MeV/c in visible momentum (c is the speed of light). By "visible momentum" is meant the minimum momentum that the particle must have in order to pass through the number of plates that it has passed through. Some of these are illustrated in Fig. 4, among which are some with one or two extraneous sparks at the vertex, presumably from nuclear recoils.

2) There were 22 "vertex" events, some of which showed substantial energy release. These events were presumably muons accompanied by pions produced in the collision (see Fig. 5).

3) There were eight "shower" candidates, of which 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. I will consider them in detail below.

It was quite simple to demonstrate that the 56 events in the first two categories 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 that could be due to such background. Indeed, the slight asymmetry in Fig. 6 is consistent with this hypothesis.

It was simple to demonstrate that these single-track events were not neutron-induced. Referring to Fig. 6, we see how they tend to point toward the target through the main body of steel shielding. No more than 10^{-4} event should have arisen from neutrons penetrating the shield (other than from neutrino-induced events in the last part of the shield itself). Indeed, removing 4 feet of steel shielding 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 aluminum plates. 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, this result 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 4 feet of the shielding by an equivalent amount situated as close as possible to the beryllium target. This reduced the decay distance by a factor of 8. The rate of events decreased from 1.46 ± 0.02 to 0.3 ± 0.2 per 10^{16} incident protons.

All of the above arguments convinced us that we were looking at neutrino-induced events and that 29 of the 34 single-track events were muons produced by neutrinos (the other 5 being background due to cosmic rays). It is these events that will 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 as they pass through our spark chamber. An electron will, on the average, radiate half of its energy in about four of the aluminum plates. This will lead to gamma rays, 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 spark chamber, we exposed it to a beam of 400-GeV electrons at the Brookhaven Cosmotron (see Fig. 7). The triggering system was 67% efficient with respect to these electrons. We then plotted the spark distribution as shown in Fig. 8 for a sample of 2/3 × 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 $\nu_\mu \neq \nu_e$. When we compared the expected rate of neutrino events with that predicted by the Fermi theory, we found agreement within 30% (*6*).

REFERENCES

1. G. Feinberg, *Phys. Rev.* **110**, 1482 (1958).
2. F. Reines and C. Cowan, *ibid.* **113**, 273 (1959).
3. M. Schwartz, *Phys. Rev. Lett.* **4**, 306 (1960).
4. B. Pontecorvo, *J. Exp. Theor. Phys. (USSR)* **37**, 1751 (1959) [translation: *Sov. Phys. JETP* **10**, 1236 (1960)].
5. T. D. Lee and C. N. Yang, *Phys. Rev. Lett.* **4**, 307 (1960).
6. For more details of this experiment, see G. Danby *et al.*, *ibid.* **9**, 36 (1962).