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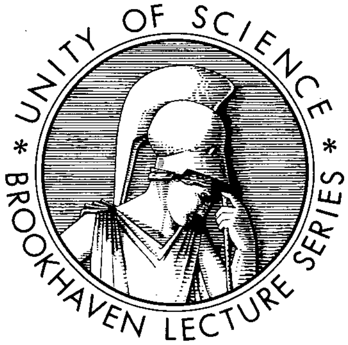
BROOKHAVEN LECTURE SERIES

Neutrino Physics

LEON M. LEDERMAN



Number 23

January 9, 1963

BROOKHAVEN NATIONAL LABORATORY

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FOREWORD

The Brookhaven Lectures, held by and for the Brookhaven staff, are meant to provide an intellectual meeting ground for all scientists of the Laboratory. In this role they serve a double purpose: they are to acquaint the listeners with new developments and ideas not only in their own field, but also in other important fields of science, and to give them a heightened awareness of the aims and potentialities of Brookhaven National Laboratory.

Before describing some recent research or the novel design and possible uses of a machine or apparatus, the lecturers attempt to familiarize the audience with the background of the topic to be treated and to define unfamiliar terms as far as possible.

Of course we are fully conscious of the numerous hurdles and pitfalls which necessarily beset such a venture. In particular, the difference in outlook and method between physical and biological sciences presents formidable difficulties. However, if we wish to be aware of progress in other fields of science, we have to consider each obstacle as a challenge which can be met.

The lectures are found to yield some incidental rewards which heighten their spell: In order to organize his talk the lecturer has to look at his work with a new, wider perspective, which provides a satisfying contrast to the often very specialized point of view from which he usually approaches his theoretical or experimental research. Conversely, during the discussion period after his talk, he may derive valuable stimulation from searching questions or technical advice received from listeners with different scientific backgrounds. The audience, on the other hand, has an opportunity to see a colleague who may have long been a friend or acquaintance in a new and interesting light.

The lectures are being organized by a committee which consists of representatives of all departments of the Laboratory. A list of the lectures that have been given and of those which are now scheduled appears on the back of this report.

Gertrude Scharff-Goldhaber

The drawing on the cover is taken from a 5th Century B.C. relief on the Acropolis in Athens, the "Dreaming Athena," by an unknown sculptor.

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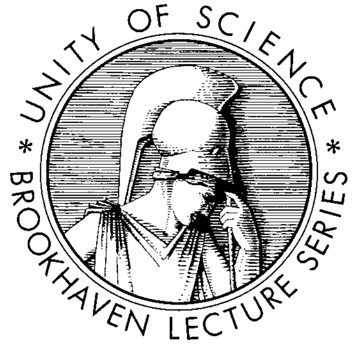
Neutrino Physics

LEON M. LEDERMAN
Physics Departments,
Columbia University and Brookhaven National Laboratory



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INTRODUCTION

The speaker for this evening is Professor Lederman of Columbia University, also Guest Physicist at Brookhaven National Laboratory, and he is going to talk about neutrino physics. Dr. Lederman was born and brought up in New York City and educated in the public school system, at a time that I like to think isn't so long ago because we went to grade school together, but this was before those extra properties of the educational system, the switch-blade knife and the enriched curriculum, had been invented, and physics hadn't yet reached its present magnificent status in popular opinion. Nevertheless, by the time Lederman reached City College he had found that he was interested in the natural sciences, and by the time he graduated he had fixed on physics as a natural habitat.

He was graduated from City College in 1943, which, as you remember, was a year when it was very easy for a bright young fellow to find himself a position, and in no time at all he was suitably outfitted in what was our very distinguished company, which consisted, as I remember, of some of the Who's Who of Modern Physics. But in 1946, with suitable expressions of mutual regret and esteem, Captain Lederman and the Signal Corps parted company, and he came to Columbia and began his graduate work.

Many students came back after the war, but Lederman was one of those people who have a certain quality of spontaneity, of originality, a certain ability to see what's there – the unobvious – that made it perfectly obvious to his contemporaries that this was a young man who was going to be a very fine physicist with a whole list of ideas, contributions, and real accomplishments. We were quite right, and I am going to mention only the highlights of the list as it is rather long. Lederman got his Ph.D. from Columbia in 1951, and in the index of *The Physical Review* for 1950 and 1951 there is a substantial list of his papers. He stayed on at Columbia, in one guise or another, as Assistant Professor, Associate Professor, and finally full Professor.

His early work, and as a matter of fact his continuing work for some time, was with what was then the newest of particles that physicists were concentrating on – the π mesons, and his papers described experimental studies done at the Columbia Nevis machine and concerned with the intrinsic properties of π mesons. The titles of the papers indicate the kind of physics that was going on. Papers appeared on the nuclear interactions of the π mesons, nuclear scattering of the π, nuclear absorption of the π, the lifetime of the π, the mass of the π, work that was very obviously in the forefront of physics as it was then. Strange particles were discovered and Professor Lederman, in collaboration with William Chinowsky, discovered a long-lived neutral meson, the so-called K_2^0, here at the Brookhaven Cosmotron.

In the great development concerned with the discovery of parity violations in the weak interactions, some important contributions had Lederman's name among the authors. Experimental studies on the parity violating properties of the μ meson contributed in a very real and important way to the understanding not only of the μ meson but also of the nature of the weak interactions themselves; from this he has gone on to study various other interactions of the μ meson and the fundamental nature of the μ meson, its magnetic moments, mass, and charge. These studies reflect the very real interest in trying to understand how this weakly interacting particle fits into the hierarchy of particles in physics. He has gone on to study other characteristics of the μ meson and is continuing to work with it, but let me mention now the newest field in experimental physics, work on the very weakest of interacting particles, the neutrino.

It was beginning to be understood that, if only experiments with high energy neutrinos could be carried out, a whole rich new vista would open up for physics. But such experiments seemed very difficult to do. Let me anticipate the climax and say that in the July 1, 1962, issue of *Physical Review Letters* there is a letter by Danby, Gaillard, Goulianos, Lederman, Mistry, Schwartz, and Steinberger announcing that by using the Brookhaven AGS they had in fact been able to carry out just this series of very beautiful experiments with the neutrino, opening up that vista that Professor Lederman is going to speak about tonight.

Joseph Weneser

Neutrino Physics

I would like to talk about the neutrino experiment we did and, if possible, about some of the experiments we hope to do, but first I have to introduce the subject. Elementary particle physics reduces all natural phenomena to a set of three classes of forces or interactions: the strong, the electromagnetic, and the weak. What I am going to talk about is an incident in the development of our understanding of weak interactions. The forces differ chiefly in the strength of the interaction, which varies by vast amounts such that if it is taken as 1 for strong interactions, it might by 1/100 for electromagnetic interactions and of the order of 10^{-12}, a very small number, for weak interactions.

In introducing the elementary particles to a wide audience like this one, I always remember the statement of the great Enrico Fermi who said, "If I could remember the names of these particles, I would have been a botanist." I will therefore restrict myself to a small fraction of the particles in order to keep the discussion simple. Probably the proton, the neutron, and the electron are familiar to all of you – you may even own some. In addition I must talk about the π meson, the μ meson, and the neutrino. These are listed in Table 1 along with their masses. The mass of the electron is always taken as 1, and the others are measured in relation to it. The mass of the neutrino is presumably zero.

Table 1

Particle	Mass (in units of mass of the electron)	Interactions
Proton (p)	2000	All
Neutron (n)	2000	Strong + weak*
Electron (e)	1	Electromagnetic + weak
Pi meson (π)	270	All
Mu meson (μ)	200	Electromagnetic + weak
Neutrino (ν)	~0	Weak

*Actually, the neutron, although uncharged, has some subtle electromagnetic properties.

In addition to the particles, let me once and for all say that we believe and know to be true that for every particle there is an antiparticle, i.e., the antiproton, the antineutron, etc. If I call an electron e^-, then there would be an e^+; for the π^- there is a π^+ (there is also a neutral pion, but that is not relevant here). For a μ^- there is a μ^+, and for the neutrino (ν) there is an antineutrino ($\bar{\nu}$). This is a fundamental symmetry law in physics. The particle and the antiparticle are related; their properties are often identical, and in fact one characteristic of these two particles is the capability of annihilating (for example, $e^- + e^+$ can annihilate) with the energy being disposed of in some suitable way that seems to be appropriate for the particular reaction. This is one of the qualities of the relation between particle and antiparticle.

With respect to the interactions, the first few figures were prepared to show the way I sometimes think about these things. I will first discuss Figure 1. The strong interaction is denoted by the heavy hook-like symbol. The strong interaction is a short-range force extending a distance no longer than the size of nuclei; it is shown with the proton, the neutron, and the π meson out of our cast of characters. The electromagnetic interaction is distinguished by the electric charge of particles, and I have indicated it by fading-out sets of lines. It is shown with the proton but not the neutron; the

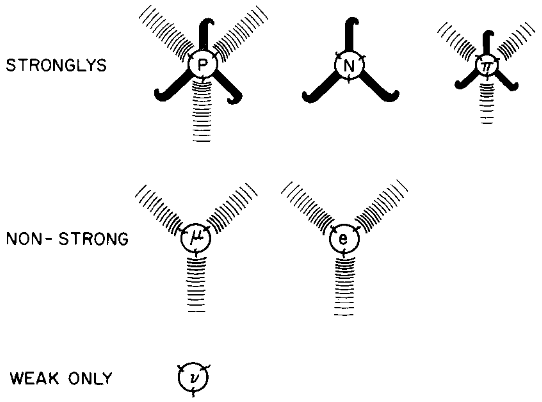


Figure 1. Schematic indication of which particles undergo which interactions.

charged π mesons have this electromagnetic interaction, and the μ meson and the electron. The latter two do not have the strong interaction. In addition there are little wiggles, shown with all the particles, that represent the weak interaction.

These embellishments to the idea of particles represent the couplings and in fact represent the only way we have of studying these particles, i.e., by means of their interactions. The neutrino is unique in that it has no strong interactions and no electromagnetic interaction but is susceptible only to weak interactions. There may be particles which have none of these interactions, but I can't list them because we don't know about them.

The strong interaction is the thing that holds the nucleus together. The difference between interaction as we talk about it and the normal kind of force that everyone knows about is that these interactions are not only capable of attraction and repulsion in the usual way but are also capable of generating transformations. For example, a π^+ meson can disassociate itself into a proton and an antineutron:

$$\pi^+ \rightarrow p^+ + \bar{n}^0 \, . \tag{1}$$

This is evidence of the strong interaction at work.

The electromagnetic interaction, from our point of view, is relevant only in that charged particles leave tracks in bubble chambers and spark chambers and uncharged particles do not. There is also a transformation which involves the electromagnetic interactions, for example, an electron can radiate, can give rise to another electron and a photon (which I did not list as a particle, but you can "see" that it is one):

$$e \rightarrow e + \gamma \, . \tag{2}$$

I might also state, for future use, that the probability of this reaction varies as $\sim 1/m^2$, where m is the mass of the particle involved; an electron, being a light particle, just loves to radiate.

Finally, there are the weak interactions, and so far the only types of weak interactions are transformations; we have not yet observed the other kind of effect. The transformations of the weak interactions are very well known in this Laboratory; they are manifest in the radioactivity of nuclei. The most important example is the decay of a proton or a neutron in the nucleus, i.e., neutron gives rise to proton plus electron plus, in this case, antineutrino:

$$n^0 \rightarrow p^+ + e^- + \bar{\nu}^0 \, . \tag{3}$$

This, then, occurring in the nucleus gives rise to the vast phenomena of beta radioactivity.

The story of this reaction tells the basic history of the neutrino, which I can review only very briefly.

In the early days only the charged particle was observed in the disintegration of the nucleus when, say, an electron was emitted. The energies of the electron in successive disintegrations were distributed over a wide region. Although the change in energy of the disintegrating nucleus was always the same, only *part* of this energy was carried away by the emitted electron. One school of physics was ready to give up the law of conservation of energy, but Pauli, with great insight and with an appreciation of other things involved, like angular momentum, held on to it and postulated an unseen particle in order to preserve conservation of angular momentum and energy. This was in 1930, and in the next 20 years or so a vast amount of data succeeded in confirming this hypothesis. Fermi was the first one to write down the detailed theory of this reaction.

All sorts of measurements, on the spectrum of electrons, on the angular correlation, on conservation of momentum, led to a confirmation of the hypothesis that a neutral particle of very small mass was needed. Finally, in 1956, Reines and Cowan succeeded in doing an experiment in which they actually took neutrinos from an intense source of radioactivity (a nuclear reactor) and produced a reaction of this kind,

$$\bar{\nu} + p^+ \rightarrow n^0 + e^+ \, , \tag{4}$$

which is essentially a rearrangement of the particles involved in beta radioactivity. It was the first time the reaction was generated on purpose rather than spontaneously, as in the decay

$$p^+ \rightarrow n^0 + e^+ + \nu^0 \, . \tag{5}$$

Therefore, this was the final confirmation that this particle had a real existence, although the reality of the neutrino had pretty much been accepted by about that time or even before. In the 1950's, and through the incident of the violation of parity conservation, a large number of people contributed to the subject of beta decay and the subsequent observation of other decays. After the war the mesons had taken the stage, and a large variety of these particles were observed. For example, the μ meson was observed to decay into an electron plus a neutrino plus an antineutrino, and the π meson was discovered to decay into a μ meson plus a neutrino:

$$\pi^+ \to \mu^+ + \nu \quad \text{pion decay,} \tag{6}$$

$$\mu^+ \to e^+ + \nu + \bar{\nu} \quad \text{muon decay.} \tag{7}$$

The μ meson was also observed to be capable of being swallowed up by a proton to give a neutron plus a neutrino:

$$\mu^- + p \to n + \nu \quad \text{muon capture.} \tag{8}$$

These reactions are being studied intensively at various cyclotron laboratories like Nevis. The last, Eq. (8), is analogous to a reaction observed in beta decay which is called K capture: an electron in being swallowed up by a proton also gives rise to a neutron plus a neutrino:

$$e^- + p \to n + \nu \quad K\ \text{capture.} \tag{9}$$

Finally, the pion, in addition to its decay into muon and neutrino as in Eq. (6), was, after long search, discovered also occasionally to decay into an electron and neutrino:

$$\pi^+ \to e^+ + \nu \quad \text{alternate pion decay.} \tag{10}$$

All these reactions were studied experimentally, and a set of theories were developed. The theory of Feynman and Gell-Mann, in particular, was rather successful; aside from electromagnetic theory, probably the most successful theory we have in this field. This particular theory of weak interactions tries to account for a very large set of observations, hence it is often called "universal." It also describes the properties of the forces involved; in this theory there are two types: a "vector" force and an "axial vector" force – the names represent certain mathematical behavior. Thus, the over-all nickname of the Feynman–Gell-Mann theory is universal $V-A$ theory, implying that the axial vector interaction (A) enters with equal magnitude but opposite sign to the vector force (V). The $V-A$ theory seemed to be in extremely good shape as far as all the above listed reactions were concerned.

This was the situation in the late 1950's, but some of the difficulties with this theory grew in 1959 to the status of a crisis. A crisis is a good thing because, if you resolve the crisis, you learn a lot. This particular crisis had two forms. One was the crisis of unobserved reactions, reactions which did not take place. A series of reactions can be written which seem to conserve or follow all the rules we know, but somehow they are absent. A famous one, for example, is the μ meson giving rise to an electron plus a γ ray:

$$\mu \to e + \gamma\,. \tag{11}$$

This conserves charge, it conserves spin, it conserves angular momentum, it conserves energy, it conserves linear momentum, it conserves everything you can think of, and yet it is not observed. Gell-Mann's theorem, which is the totalitarian theorem, says that in physics anything that is not forbidden is compulsory. This is one reason why people were disturbed at not seeing this reaction. The lack of observation was very, very sensitive. All the theories predicted that this reaction should compete with the normal decay of the μ meson, Eq. (7), to about 1 part in 10,000 and possibly could be made to compete to a somewhat greater extent. On the other hand, the observations in a most precise experiment done at the Columbia Nevis Laboratories by Devons and Sachs were sensitive to nearly one part in 10^8, and yet this reaction was not observed. It is not only the totalitarian theorem but also the fact that this reaction can be predicted from a chain of events, all of which do happen, that is very disturbing. To indicate the trouble, I can outline the steps. First, μ decay gives rise to an electron plus a neutrino plus an antineutrino, Eq. (7). In the second step, this electron can give rise to another electron and a γ ray, Eq. (2), which is certainly a possible step. And finally, a particle plus antiparticle must be able to annihilate in the third step, leaving a μ which in turn gives an electron plus a γ ray. Since all the intermediate steps are known to take place and with known probability, it is very disturbing that one does not see this reaction.

Somehow the logical chain must be broken, and many theorists proposed that it could be broken at the third step. The only way to prevent the neutrino plus antineutrino annihilation and yet preserve a large body of physics that we would like to preserve is to assume that these are not particle and antiparticle but are different and should be written with subscripts; a and b, for example. But then, in order to still have a theory that is universal and accounts for all the other reactions, it is clear that the subscript a refers to a specific thing, the electron, and b to the μ meson. This would mean that in the decay of the π meson, Eq. (6), the neutrino would have a subscript μ, because it is born with a μ meson, and in the decay of the π meson to an electron and neutrino, the latter would have a subscript e:

$$\pi \to e + \nu_e\,. \tag{12}$$

One has to go over all the reactions given above to see whether the neutrino is involved with an electron or a μ and add the appropriate subscripts:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu\,, \tag{6'}$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu\,, \tag{7'}$$

$$\mu^- + p \rightarrow n + \nu_\mu\,, \tag{8'}$$

$$e^- + p \rightarrow n + \nu_e\,. \tag{9'}$$

If these are the actual reactions, then the two particles cannot annihilate and μ cannot decay into an electron plus a γ ray, and a variety of other reactions would also be forbidden which are in fact not observed. This is one way out. This solution postulates that there are two neutrinos which are different, and it provided one of the chief motives for trying to extend experimental physics into the neutrino domain. Before going on to the experimental part of this, I would like to describe the second crisis.

The second crisis was the high energy crisis. In the vast majority of the reactions given above, something happens more or less spontaneously in the decay of an unstable particle. Thus, most of the data on which the theory is based are limited to spontaneous decay of an unstable particle. This is a bad way to explore the structure of a force or an interaction. Classically, to probe the structure of an interaction, one tries to do a collision experiment: as a particle comes in and goes out, a target particle recoils with some momentum q, and if q is varied then the spatial structure of the particle can be studied. This is the classical way in which Hofstadter, for example, measured the shape of a proton, that is, by doing experiments at higher and higher values of the recoil momentum q. One of course requires higher and higher energy of the bombarding particle. This is the way one would like to explore the structure of the weak force. Concerning the structure of the weak force, the theory says that the cross sections, i.e., the probability of something happening, varies about as the square of the momentum of the particle in the center-of-mass system, and this is good for the experimentalists because it means the cross section increases as the momentum is made higher. On the other hand, for the theorists it is very disturbing because there is no limit to the increase of probability as the momentum goes higher and higher, and soon the result for high enough momentum is obviously absurd. Therefore, T.D. Lee, and others, but principally Lee, pointed out to us that this theory must be modified at some energies – something must somehow change it as the energy is made higher. The crucial question would be, how does the theory get modified? I hope, a little later, to show what hopes we have in this field.

This problem was another strong motivating force for doing collision experiments. Let me discuss for a moment the difficulty with collision experiments and why it took rather a long time before they were attempted. For this some numbers are needed. The typical lifetimes of weak interactions are 10^{-6} and 10^{-8} sec, so that 10^{-7} may be taken as a rough value for the probability that something happens in a weak interaction. If a particle which has a weak interaction is sent through a nucleus, how long a time will it spend in the nucleus? The nucleus is 10^{-13} cm in diameter, which, divided by the velocity of the particle, taken as roughly the velocity of light, 10^{10} cm/sec, gives 10^{-23} sec for the time spent in the nucleus. Since 10^{-7} sec are required for something to happen, 10^{+16} passes through the nucleus are needed. This is easy to compute. In the case of a strongly interacting particle, such as a π meson or a proton, only one pass is needed to make something happen. To make a π meson interact in something like lead requires 10 cm of lead, that is, in 10 cm of lead there is a good chance of a pass through the nucleus. For a weak interaction 10^{16} passes are needed, which requires 10^{17} cm of lead, and this is a thickness of one light year! And that's a little too much lead even for the AEC. At a million volts, this reaction rate is typical of very low energy particles. At a billion volts, since the cross section goes up with momentum, the situation is much better: the requirement is more like 10^{12} cm (10^7 km) – say an astronomical unit – of lead. That is for one neutrino, but for a lot of neutrinos not so much lead is needed. Calculations were done in early 1960 and, in fact, both Schwartz at Columbia and Pontecorvo at Dubna independently evaluated the feasibility of using high energy accelerators. One calculation showed that something like 10 tons of aluminum would give a reasonable chance of observing some collisions with a large accelerator; thus, the experiment looked feasible.

To do collision experiments, one is obviously led to use neutrinos, since, with other particles, even in a light year of lead, it would be very difficult to see the weak interactions because they would be obscured by the other vastly more powerful forces. Only the neutrino, as far as we know, has the weak interaction alone (see Figure 1) so that anything it does will be due to the weak interaction. It is therefore the only particle available. It has another advantage in that it is easy to screen out all other particles by shielding the detector with thick steel walls; these will not impede the neutrinos. To summarize: for purposes of studying the weak interactions we are led to neutrinos by general considerations, and also specifically in order to answer the question whether, in nature, one or two neutrinos occur.

Consider the following reactions:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \, . \qquad (6')$$

This is a high energy source of neutrinos. Now recall

$$\mu^- + p \rightarrow n + \nu_\mu \, , \qquad (8')$$

$$e^- + p \rightarrow n + \nu_e \, . \qquad (9')$$

The plan is fairly straightforward. Remember that in the above reaction the arrows can be pointed the other way, and consider the reactions going in the other direction. If we shine neutrinos on neutrons (and aluminum has neutrons), then, *if there is no subscript*, i.e., if the neutrinos are the same, the reaction, if the neutrino energy is high enough, should go equally well via both Eq. (8′) and Eq. (9′) and we should find μ mesons and electrons emerging in equal numbers. On the other hand, if there are subscripts and we use special neutrinos, neutrinos of the μ variety, then we should see only μ mesons. In the Brookhaven experiment we planned, the source of neutrinos was π decay, Eq. (6′) and therefore they all have the subscript μ.

In reviewing the experiment, the particle symbols may be helpful. The AGS provides 30-Bev protons, indicated on the left in Figure 2, and a block of beryllium is put inside the machine as a target. (As shown in Figure 2, this contains protons and neutrons in the beryllium nucleus locked in the strong interaction.) Figure 3 shows the results of the ensuing devastating collision: out come the protons and neutrons and also lots of π mesons, which are products of the reaction of high energy protons and neutrons; these strongly interacting particles all emerge from the Be target in the AGS in large numbers.

Figure 4 shows what happens to an emerging pion. In its flight path, while traveling with an energy of several billion volts, it can decay into a μ meson and a neutrino. Neutrinos can be produced in this way, and the neutrino obtains its high energy from the initial high energy of the π meson.

Figure 5 shows a big steel wall into which many particles are entering. It is hoped that only the neutrinos can get through. All the others are stopped by a strong interaction with the steel nuclei or by their electromagnetic interaction (in the case of the μ meson, which, although it penetrates much further, also is eventually stopped). Thus, beyond the wall we have a pure beam of neutrinos, and the only problem is to detect them. We provide here a detector in which the neutrino can make an occasional collision.

Figure 6 shows the collision. The two boxes schematically represent many aluminum plates, and occasionally a neutrino will collide possibly giving rise, for example, to a recoil proton and a μ meson. The setup is indicated more scientifically in Figure 7, which shows what happens on the AGS floor The drawing shows part of the AGS with a target, and a flight path about 40 ft long, through steel shielding, from the target to the detector. About 10% of the flux of π mesons will decay along the flight path. Neutrons and protons also occur in this region in enormous numbers, of the order of perhaps 10^{12} particles/pulse coming out. The steel wall is 40 ft by about 12 ft and has some sort of detector behind it. This was the original shielding arrangement.

The first step in the experiment was to see whether the shielding was adequate. In studies which I can't go into here, we determined after a reasonable amout of time that there was in fact a leak of strongly interacting particles coming through. With the interaction rate we expected, of the order of 1 event/day, enormously rare processes can somehow succeed in getting strongly interacting particles into the detector, and such a particle will almost surely give rise to an interaction that might be confused with a neutrino interaction. Therefore fantastic care has to be taken, and we sought very, very hard for leaks in the shield, cracks in the iron, conduits underneath the floor, and so forth. Finally, we traced it down to part of the beam escaping the target and hitting the wall of the vacuum chamber so that neutrons would come down into the concrete and underneath and scatter from the concrete up into the detector. This was the chief source. At the time there was a line beyond which Mr. G.K. Green,

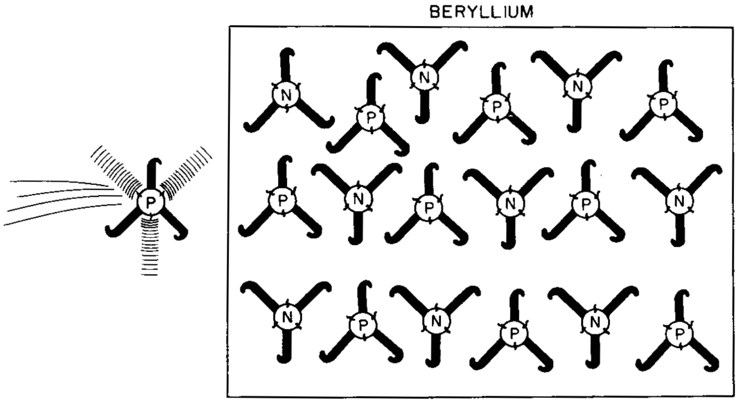


Figure 2. Proton entering Be block.

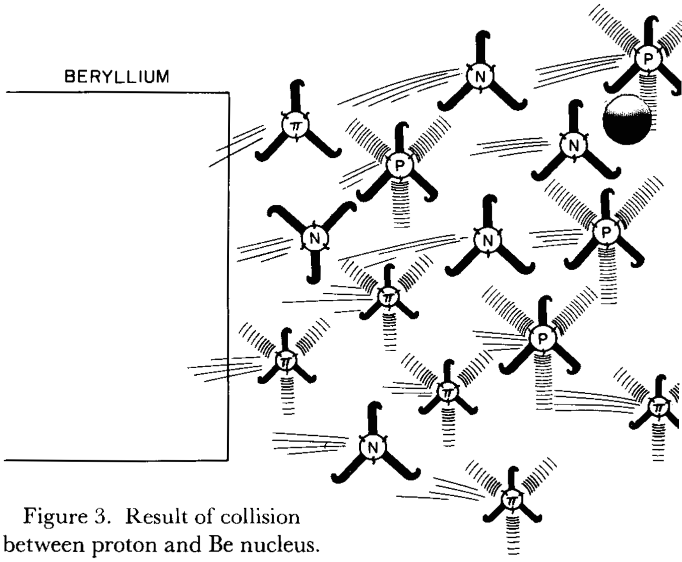


Figure 3. Result of collision between proton and Be nucleus.

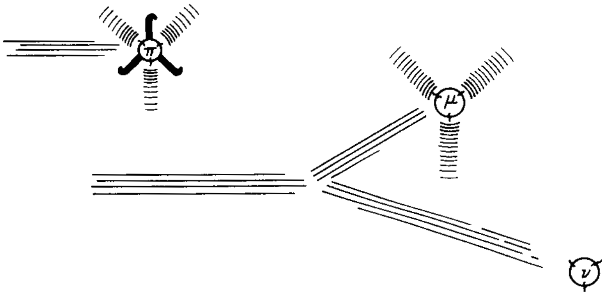


Figure 4. Decay of pion into μ meson and neutrino.

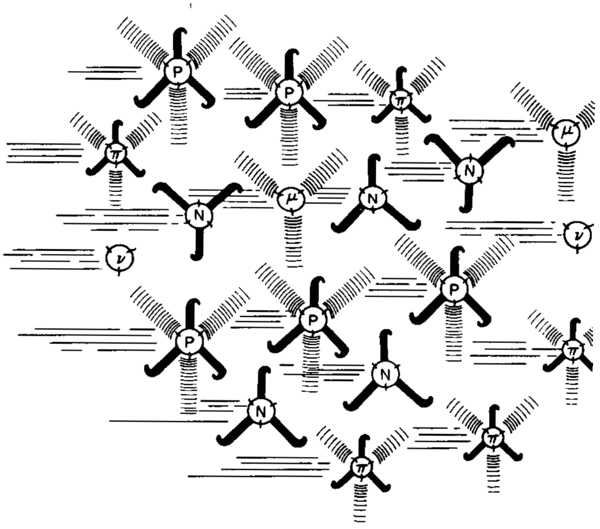


Figure 5. Steel wall acting as shield against all particles except the neutr

who is in charge here, said we could put shielding only over his dead body; this would have made a small but unsightly lump in the shielding. We compromised.

I might take this opportunity to say that the cooperation between the experimenters and the AGS people, Green, the Blewetts, Ernest Courant, Julius Spiro, and Bill Walker, was incredible. Time after time we would have been stuck had the machine people not come to our rescue. That this delicate and expensive machine, the world's largest atom smasher and America's claim to high energy supremacy, etc., could be tampered with by laying tons of rusty iron and lead up against the vacuum chamber is a tremendous thing and yet it was done.

And it was necessary. Without the ability to keep the machine running in spite of all this stuff, our experiment couldn't have been successful. When we put this iron in, we cured the background problem, and we were able to proceed. This process looks very simple when drawn on a piece of paper. When it comes to putting the iron down, it is a difficult job. The iron is in small pieces and it is rusty and bent. If you look closely, you can see that some of the steel is marked *U.S.S. Missouri.* This steel is available only because these battleships are obsolete, and in fact during the Cuban crisis we were afraid the Navy would take it back. The application of obsolete Naval equipment to high energy physics is interesting. In another experiment we are planning now at the AGS, we use some of the cannons from perhaps the same ship – large cannons make very good collimators. They have tremendous wall thickness and are 50 ft long. The only trouble is they have rifling, and we had to have a graduate student crawl in to smooth it out. He quit, and I don't know where we'll find another student of his caliber.

Figure 8 shows the result of pions decaying. In doing an experiment with neutrinos, a large energy range of pions is used, and the spectrum of neutrinos from this is rather broad with a peak at a surprisingly low energy. This is one of the characteristic things we have learned about high energy machines: they don't produce high energy pions; they produce lots of relatively low energy pions. Figure 8 is interesting from the point of view of what one hopes to do in the future. Most of the neutrinos are at about 300, 400, or 500 Mev, with a tail which is much reduced at energies as high as 2 Bev, and by that point *K* mesons start making contributions. The big problem for the future is to try to get much higher energy neutrinos.

Having discussed the formation of the neutrino beam and the shield which is supposed to give a *pure* neutrino beam so that anything seen inside the enclosure presumably will be due to neutrinos, I can go on to the detector. Figure 9 shows the spark chamber. Fortunately, about the time we were designing this experiment, developments in the spark chamber business were very rapid. The chamber is simply a series of parallel plates. Alter-

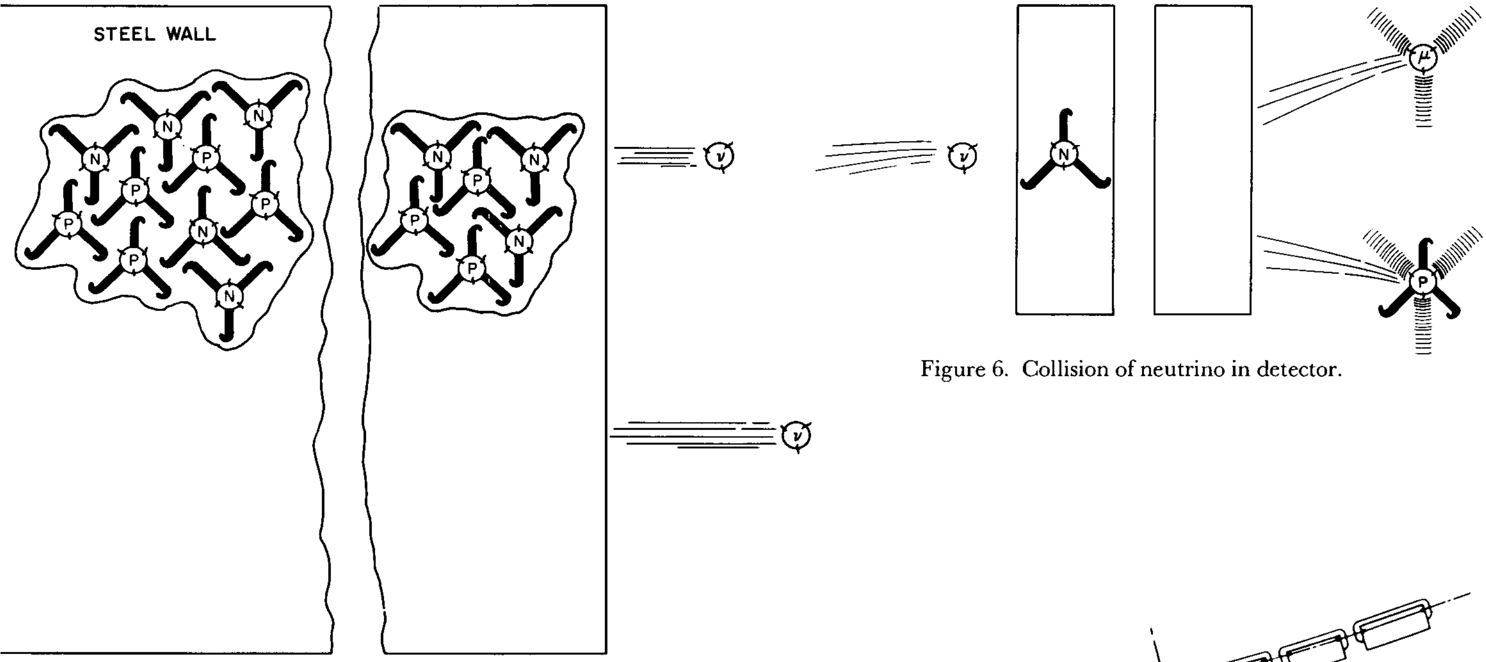


Figure 6. Collision of neutrino in detector.

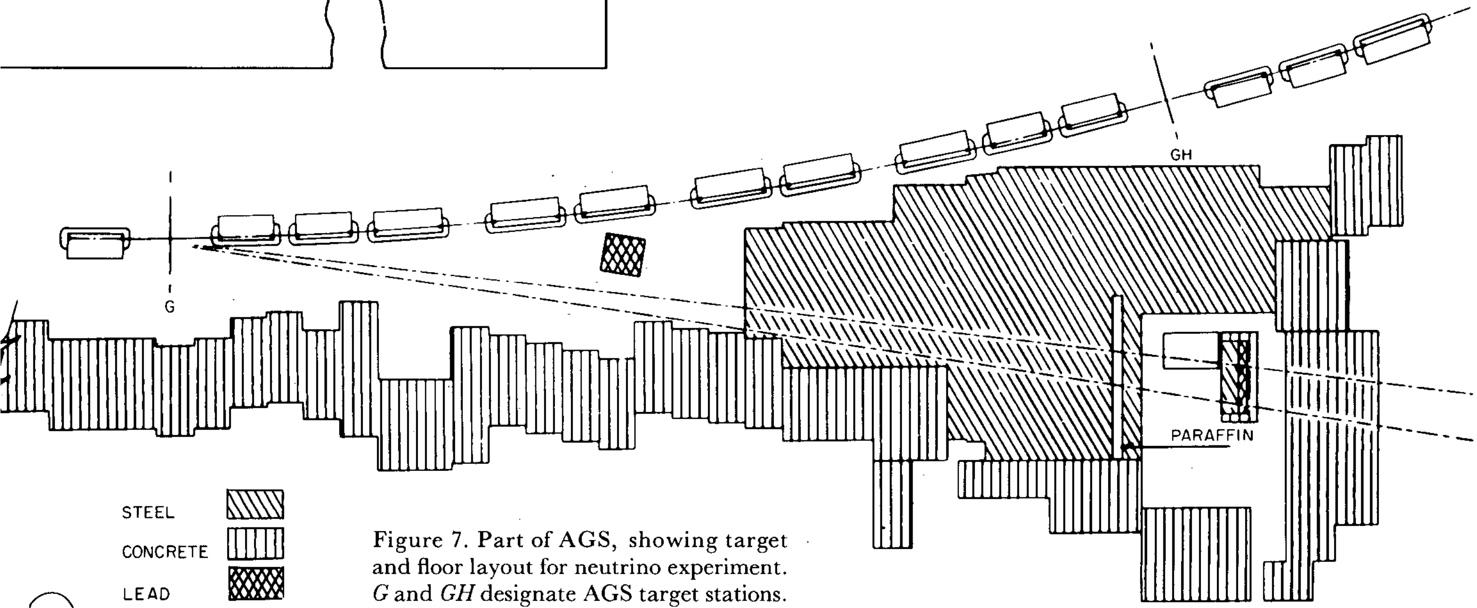


Figure 7. Part of AGS, showing target and floor layout for neutrino experiment. *G* and *GH* designate AGS target stations.

nate plates are connected to a source of very fast high voltage pulse. The particle goes through. If it is electrically charged, it will leave a trail of free electrons in the gap. These free electrons will remain for up to 10 μsec if desired, or they can be swept away in of the order of 1 μsec. If, within that time interval, a high voltage pulse is applied, the electrons will be accelerated and will avalanche and cause a spark. If the gap contains neon gas, the spark will be red, and the track will light up like a neon light. The main feature of this device is that it is triggered. Only when the counters indicate that something has happened, is the high voltage pulse applied. It is active for a very short time and it shows what happened in the previous microsecond and that is all. The great advantage of this device is that if, for example, a million particles/sec are going through, if one of them does something interesting, the pulse can be turned on and only that one track will be seen. It can be picked out of a million other particles because of the very good time resolution.

Figure 10 shows how we made such spark chambers for the neutrino experiment. We used 4-ft-square aluminum plates. They are spaced to provide the gap by Lucite spacers with rubber O-rings and are stacked. The new spark chamber we are building for the second stage of the neutrino experiment will be very similar, except that part of the chamber will be made of 8-ft-square plates. There seems to be no limit to how large these can be made.

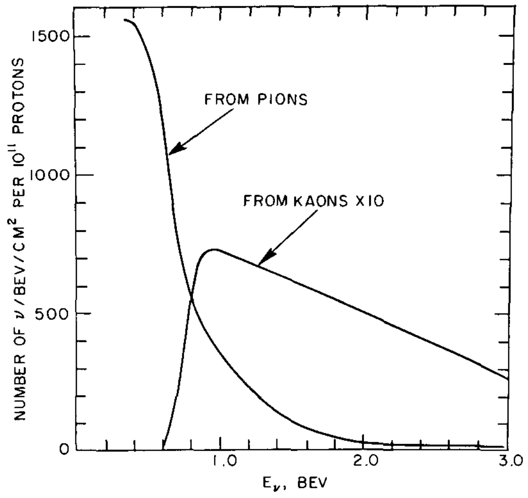


Figure 8. Number of neutrinos produced vs. neutrino energy.

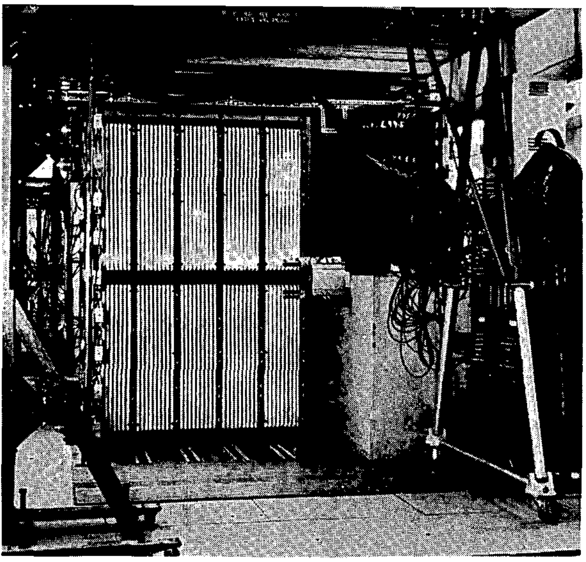


Figure 9. Spark chamber.

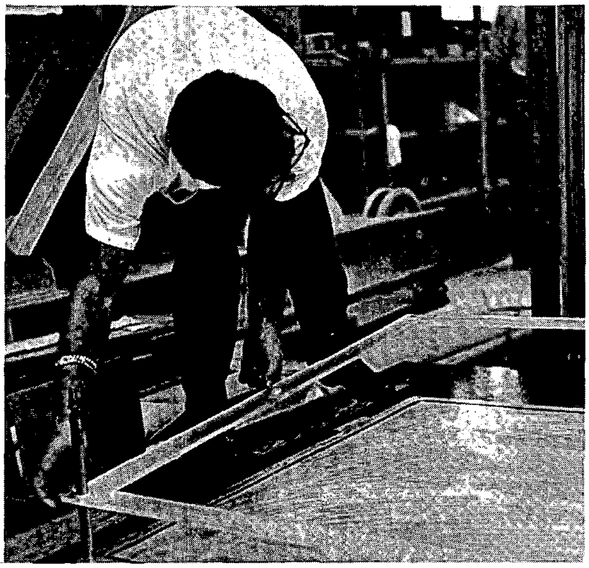


Figure 10. Process of assembling spark chamber.

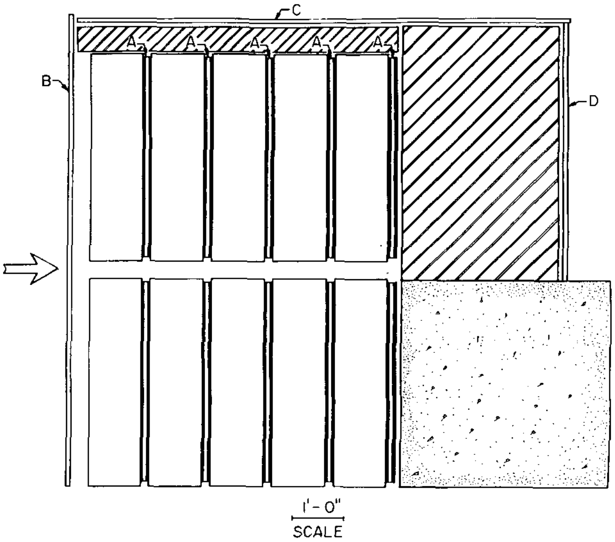


Figure 11. Schematic drawing of spark chamber. *A* represents the triggering counters. *B*, *C*, and *D* are counters in anticoincidence.

Figure 11 is a schematic of the arrangement. There are 10 units, each with 9 plates, a total of 10 tons of aluminum. The black lines indicate scintillation counters. These have to be triggered in some way. (Incidentally, when you mention trigger, and ask for a response from somebody, if he says "gun" he is a normal person, if he says "bias" he is probably a physicist with some bitter experience.) When a counter is turned on, the problem is whether it is being turned on for a fair sampling of the events. Remember that the purpose of the experiment is to see whether neutrinos can produce μ mesons and electrons in equal numbers or not. If we had just put counters behind the chamber and looked for something coming out, we would have seen only μ mesons. The observation would have been correct, but we would have been subject to critism from colleagues, who would say, "The electrons that you made only went a certain distance and they didn't get out because they radiate, because their mass is small, whereas the μ meson can go all the way through." For this reason the counters and the detector must be so finely meshed that there will be a minimum of bias against electrons, and that is why there are so many counters. We used a total of about 150 very large counters. Another problem is the entrance of cosmic rays, and anticoincidences are provided as a partial shield against them.

The experiment was run as follows: if a count occurs in the scintillators and if at the same time there is no count in any of the anticoincidence shields, then we fire the spark chamber; one additional condition is that the AGS be on. The last turned out to be in fact the crucial condition because of cosmic-ray background. In this assembly, even with the anticoincidences, the cosmic-ray counting rate was of the order of 80 per second.

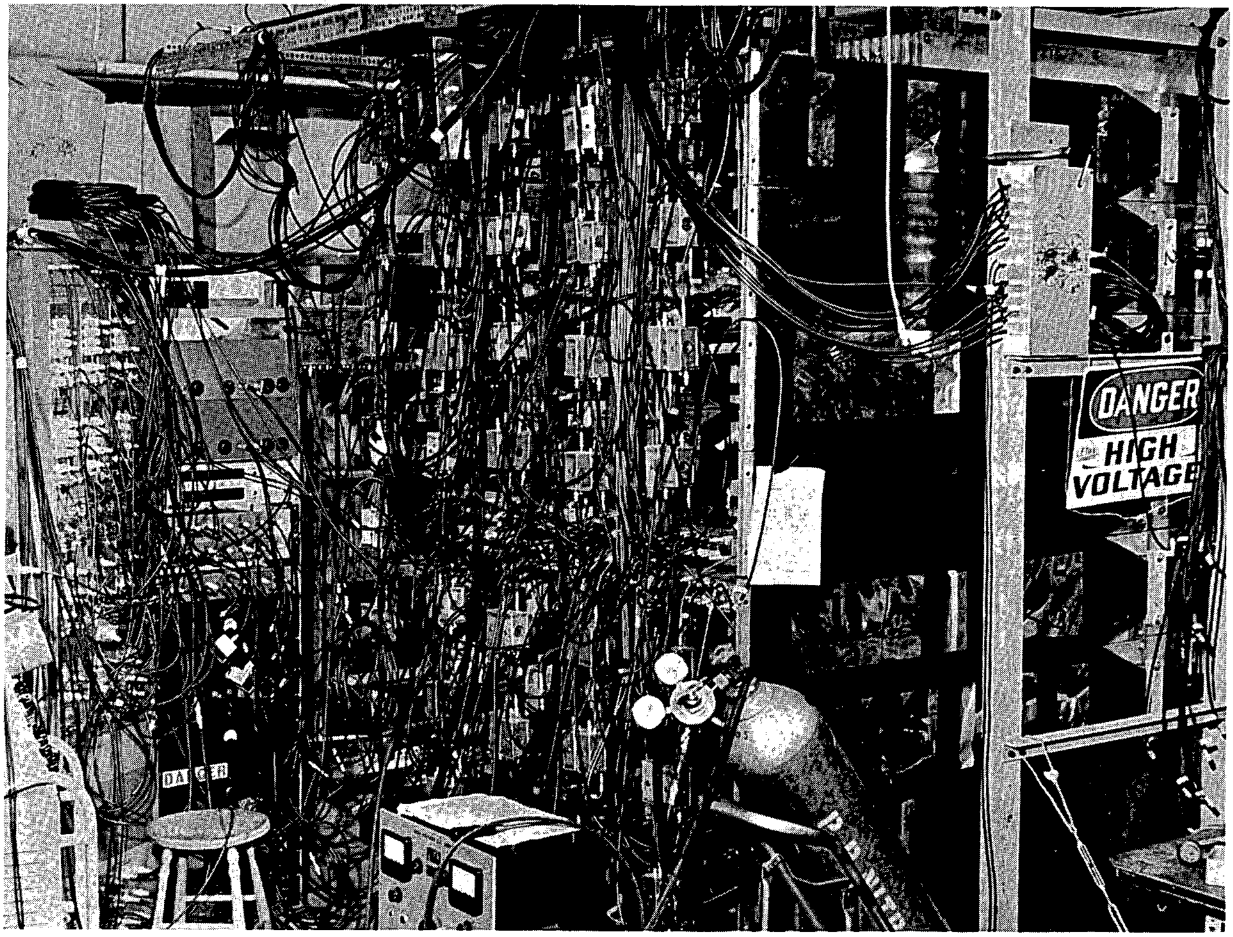


Figure 12. Rear view of spark chamber showing wiring.

Actually the AGS is on so rarely that the cosmic rays do little harm. Let me explain that briefly – so that I can get more running time.

The nature of the radiation from the AGS, as it was run for us, is to produce very short bursts of radiation intermittently. Each short burst lasts of the order of 25 μsec, and then the machine has to receive and accelerate more particles, which takes about 1 sec. However, the burst of radiation is not smooth but is divided up into pulses – it is really on only 10% of the time. Thus the AGS is actually on only 2.5×10^{-6} sec for every pulse. Our experiment used of the order of 2 million pulses, which took 8 months, but during that time the AGS was on for us only for $2.5\times10^{-6}\times2\times10^{6}$, which is 5 sec! And not many cosmic rays get in in 5 sec. Thus the duty cycle of the machine was a very important consideration. Otherwise the setup would have been flooded by cosmic rays. Even as it was, about 10% of our events were due to cosmic rays.

Figure 9 looks very neat and simple, with the spark chamber assembled, the *Missouri* in place, and everything closed up into a nice claustrophobic enclosure, in which we more or less lived from September 1961 to June 1962. Figure 12 shows a little more honestly what is involved. It shows the other side of the arrangement, with some of the 100 or so counters and the transistor coincidence circuits side by side with high voltage spark gaps which deliver something like a total of 100,000 amp rising in 20 nanosec. The triggering and high voltage engineering involved in the operation of the spark chamber was highly complicated.

Figure 13 is a Land photograph showing what is seen in the spark chamber. These were taken periodically to monitor the operation, with the camera held open for a while to show cosmic-ray μ-meson tracks. These are characteristic tracks, but it is seldom that we find a picture, such as this, in which there isn't a single missing gap. There is a bar which occasionally hides some gaps, but these are always seen in the other view. Also, there are scintillation counters imbedded in the black strips, so there shouldn't be any sparks there.

We ran this experiment for 8 months, clocking up something like 800 hr of running time. After we debugged, eliminated as much of the background as possible, and made sure the electronics was working, we started the automatic cameras. They operated about 5 to 10 times per hour, indicating that something went through the counters and triggered them. Most of these pictures were

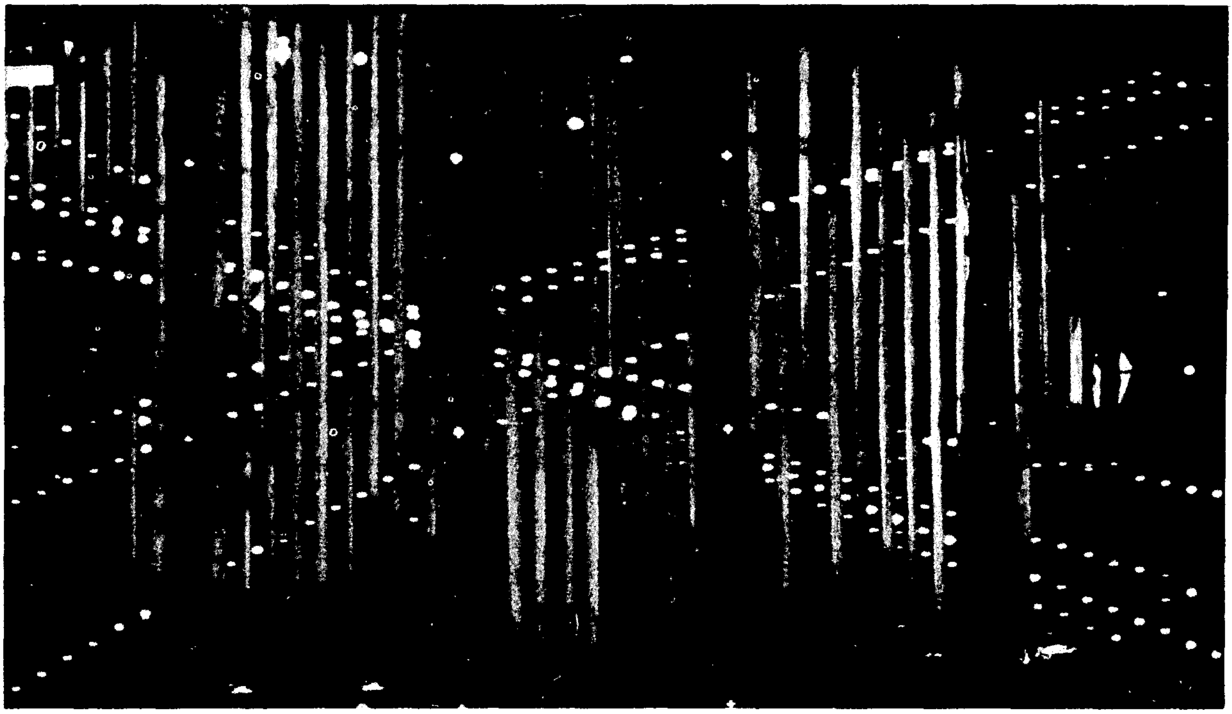


Figure 13. Spark chamber photograph, showing cosmic-ray μ-meson tracks.

blank, we never did understand why. A fair number of tracks were due to μ mesons which somehow got in under or over the shield and triggered off the counter. These were easily identified because they came in from the outside, and therefore could not have been neutrino events. Most of the other tracks were due to cosmic rays that went straight through, somehow missing the anticoincidences; these were usually obvious because they had come in from the outside, mainly from the top. About once every two calendar days something would occur that we could call an event. Since running time on the AGS is very expensive, we had to maintain a constant vigil to make sure that we weren't wasting machine time. Figure 14, from our data book, indicates constant vigil, at this time by Drs. Schwartz and Mistry among others (the Land camera is a two-edged sword).

Since the spark chamber is a new instrument, one has to make sure, in order to answer the crucial question of the nature of these events, that one understands the difference between a μ-meson track and an electron track. Figure 13 shows cosmic-ray μ-meson tracks. Note that these are rather straight and continuous and that very occasionally double sparks occur due to knock-on electrons or δ rays. To gain information on electron tracks, we took some of the chambers over to

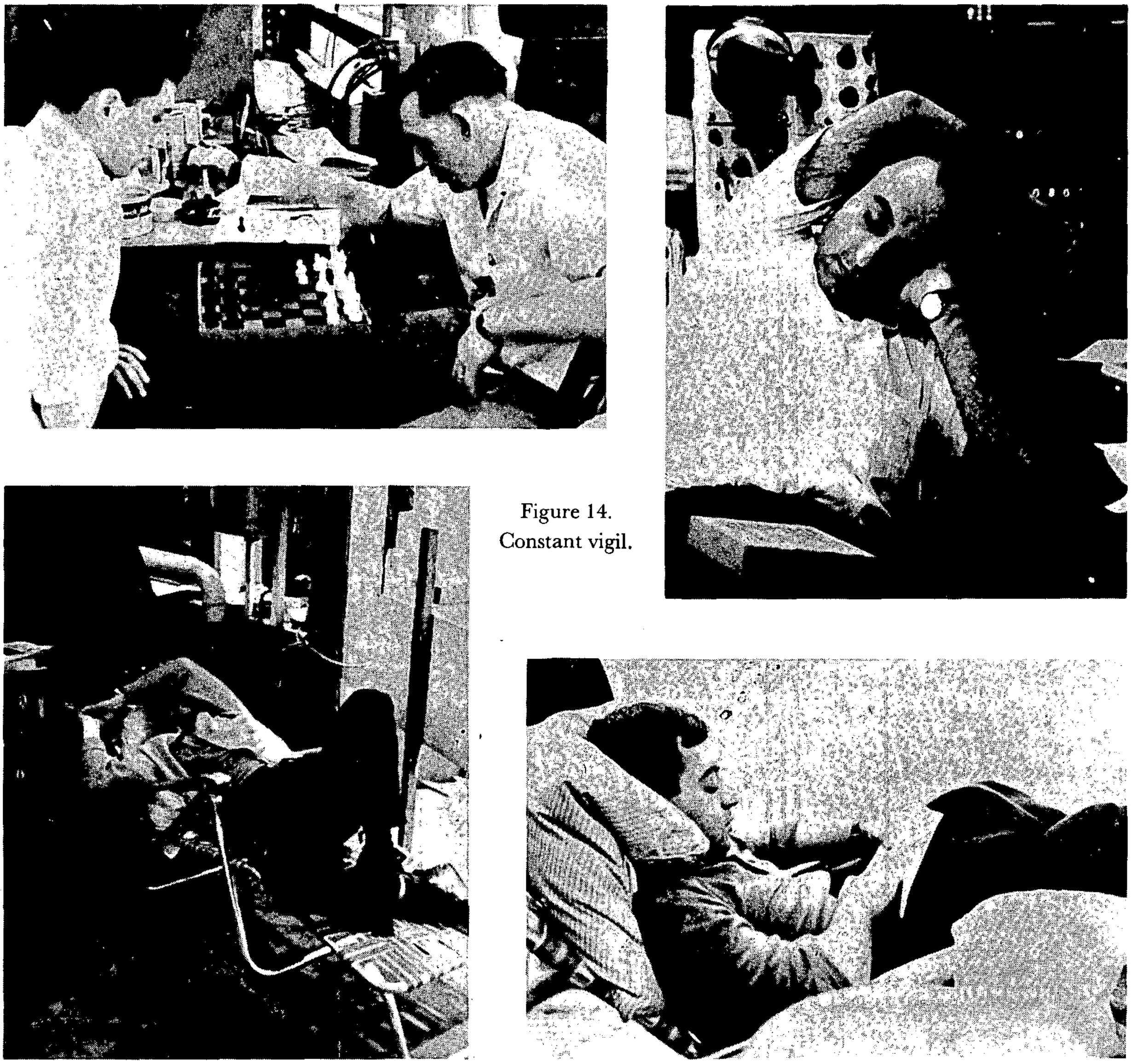


Figure 14.
Constant vigil.

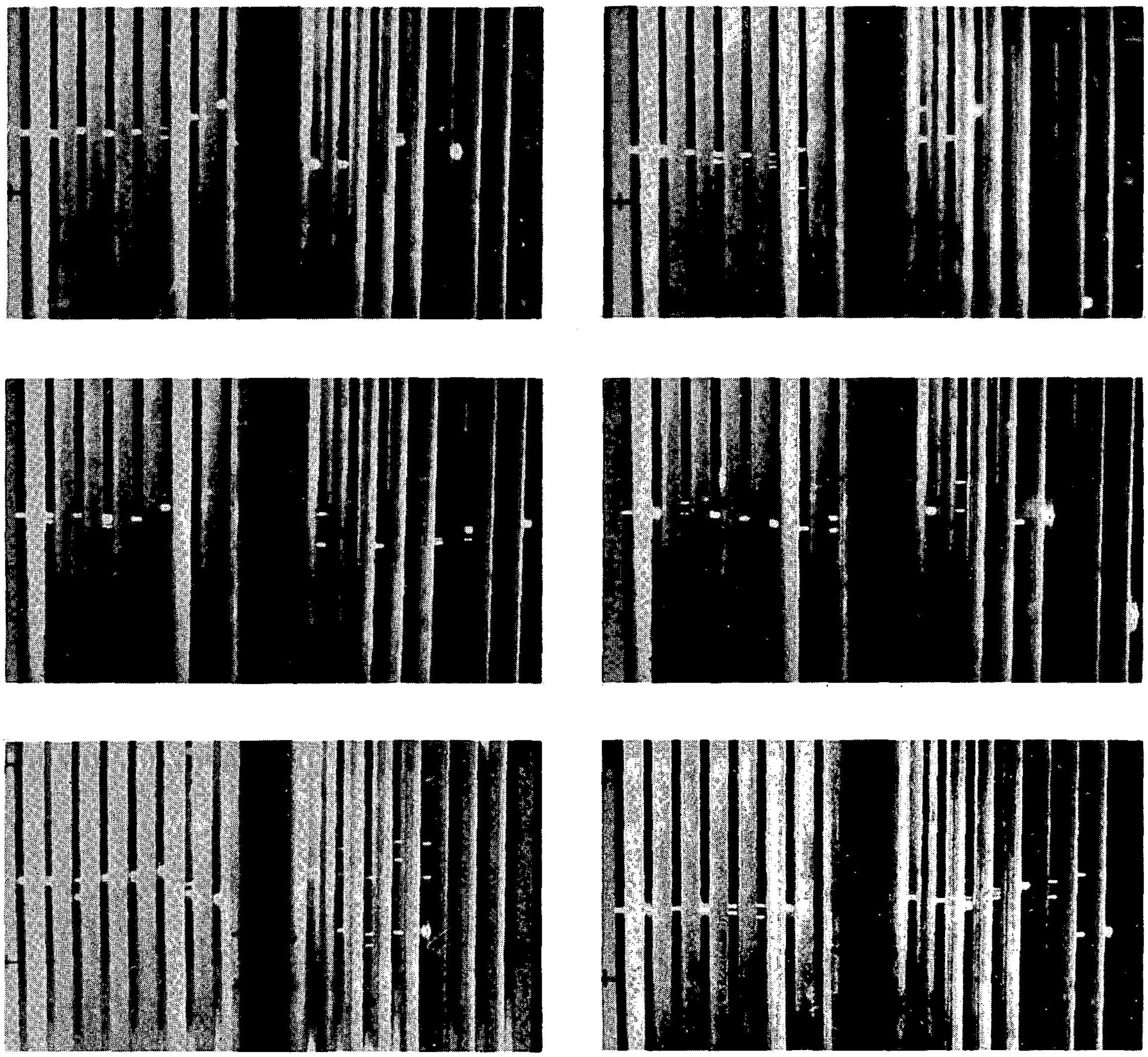


Figure 15. Electron tracks.

the Cosmotron and triggered them only on electrons. Figure 15 shows a typical 400- or 300-Mev electron track, and it looks quite different. There are very often double or triple tracks, very often missing gaps, and straggling of energy; sometimes all the energy of the electron is in γ rays and the γ rays convert back into electrons. These are rather typical electron tracks. Thus the track characteristics for μ mesons and electrons are quite different, and we felt that it would be fairly easy to distinguish them in most cases. We collected about 56 events that we think are really due to neutrinos. The next group of figures shows some of them.

Figure 16 has the neutrino beam coming in from the left. In stereo view the track shown in Figure 16 starts from the middle of the chamber, which is an important characteristic. This track is very similar to the μ-meson tracks in Figure 13. On the basis of one picture, no conclusion can be drawn, but on the basis of many (we had about 34 tracks very much like this), we were convinced we had tracks showing the properties of μ mesons. The track in Figure 16, born in the middle of the chamber, goes down and out; the direction in which it is moving is shown by the δ ray. Another track is shown in Figure 17, going uphill, again a simple straight track, with occasionally some double sparks, but very clearly characteristic of a μ meson. Thus it seemed that as a result of neutrino bombardment, μ-meson type tracks were being produced in our spark chamber.

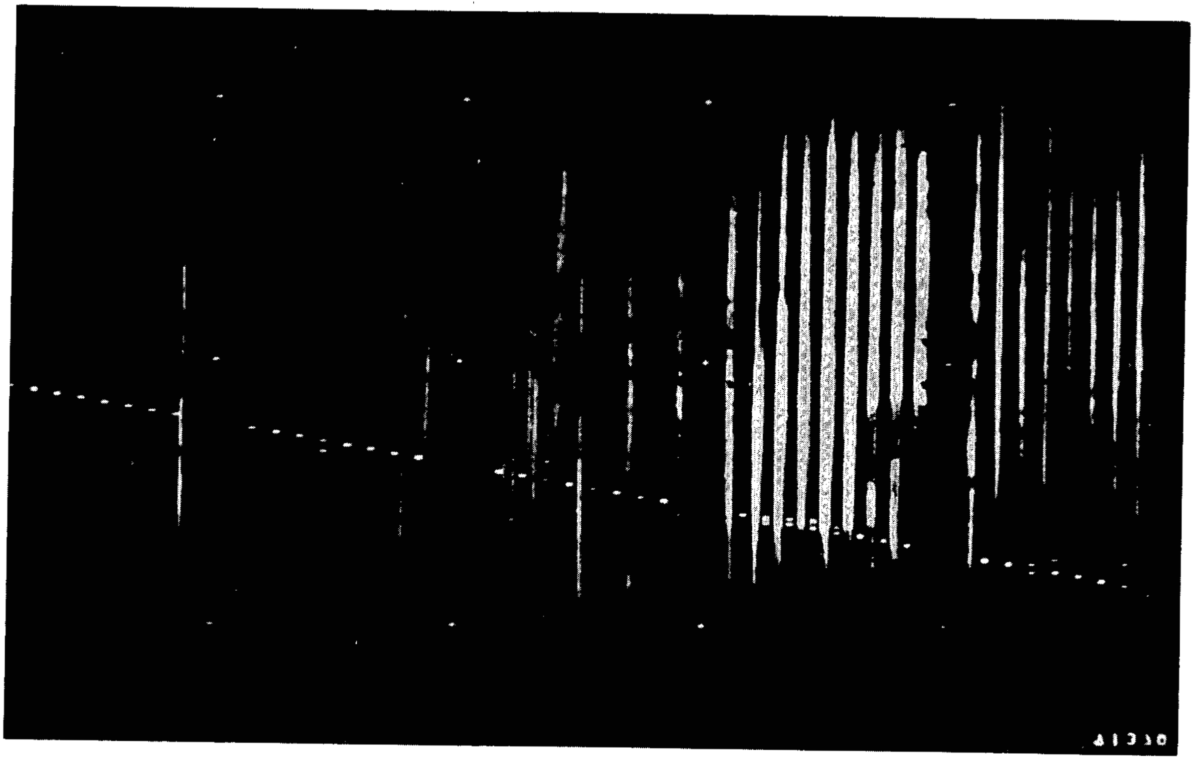


Figure 16. μ-Meson track assumed to be due to a neutrino event.

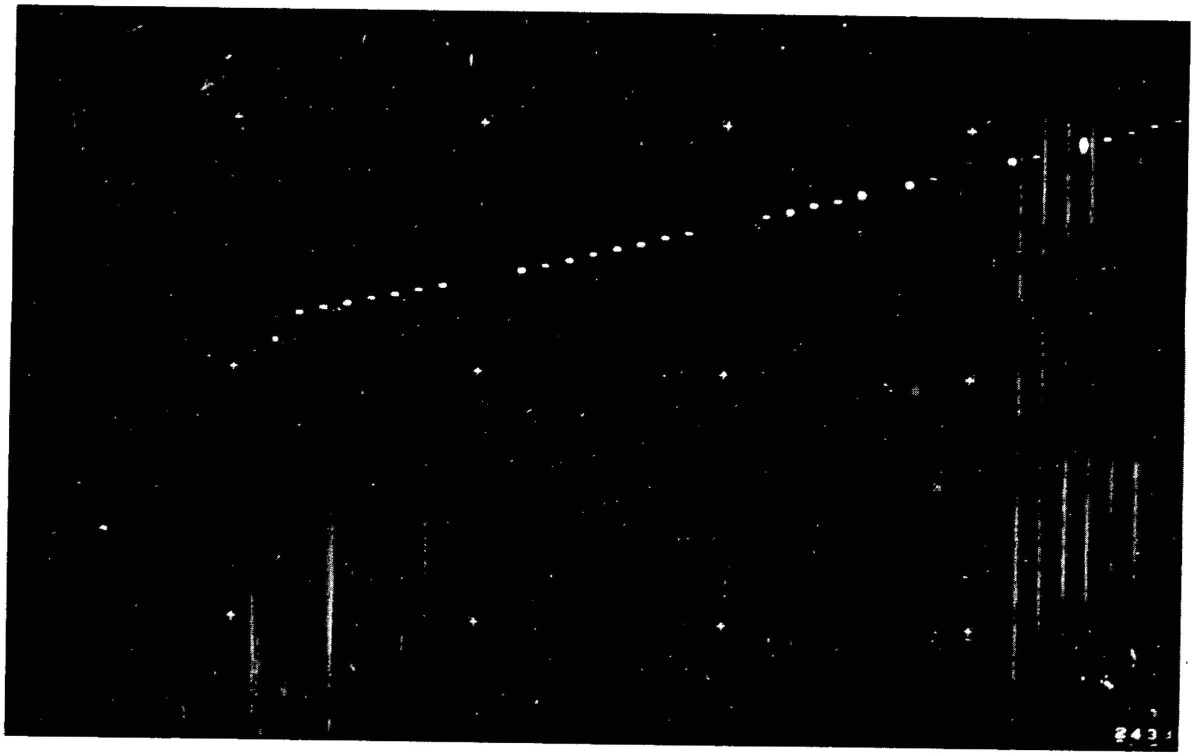


Figure 17. μ-Meson track assumed to be due to a neutrino event.

In analyzing the data on these 34 tracks, we had to make sure they satisfied all the criteria for neutrino events and were not due to neutrons entering somehow. Figure 18 shows the statistical analysis, which indicates, from the angular distribution in both the vertical and horizontal planes, that these tracks are pointing through the 40 ft of steel at the target, which is one of the necessary conditions that these be neutrino events. By a variety of arguments of this kind (we also came fairly close to being able to turn off the neutrino flux but leaving other things more or less the same, and found happily that the events went away), we were convinced that these were in fact neutrino events; and, judging from the events we had seen before, in this group of 34 events (of which we think 5 are due to cosmic rays) we are *not* seeing electrons – we are seeing only μ mesons.

The fact that in shining a neutrino beam on neutrons we see only μ mesons means that the reaction forming electrons is forbidden. The only explanation for its being forbidden is that the neutrino in Eq. (8′) is not the same as that in Eq. (9′) and they need subscripts. We therefore felt that we had satisfactorily supported the conclusion that there are two neutrinos and that in fact the neutrino which is always involved with μ mesons in these reactions is different from the neutrino involved with electrons.

Furthermore, we also determined that the low energy $V-A$ theory was in rough agreement with our data (perhaps to 30%) – that the cross section did go up as predicted by the theory. Nothing anomalous was yet observed.

Further information can be gleaned from this experiment, from other categories of events which we observed and which we call inelastic events or complicated events. These complicated events were almost always characterized by a long μ-meson track (Figure 19). Sometimes it would go out of the chamber at an earlier time so that we were not convinced it was a μ meson, but very often we identified one of the tracks in the complicated events as being due to a μ meson. We saw many other unusual tracks which unfortunately did not give us much information, for one reason because the plates are 1 in. thick and therefore hide a great deal. In other words, the spatial resolution of the spark chamber is not nearly as good as that of a bubble chamber. Had we 10 or 15 bubble chamber pictures like this, I think the experiment would have been much richer in its yield, and this is something we are keeping in mind for the next experiment. We plan to make the plates ¼ in. thick and to have 200 of them, so that we can gain more detailed information about complex events.

Figure 20 is another photograph which is intriguing. It again shows a definite μ-meson track, the long one going up. Another track looks very much like an electron track and strongly suggests that perhaps a γ ray or photon was born and then converted to an electron-positron pair. This is one of our most provocative pictures. The connection of a μ meson and an electron possibly is evidence for a mechanism that can halt the relentless increase of cross section with energy alluded to earlier. This is because it could be the signature for a new particle, the W, about which I shall say a bit more later.

Now I would like to go on to what lies ahead in this field. First, there are many groups planning neutrino experiments. Probably the next one will be done in Geneva, at CERN, where they are preparing an experiment very similar to the one we hope to prepare here. The major changes will be that both experiments will use beams extracted from the AGS, which will make it possible to get at the higher fluxes in the forward direction. They will

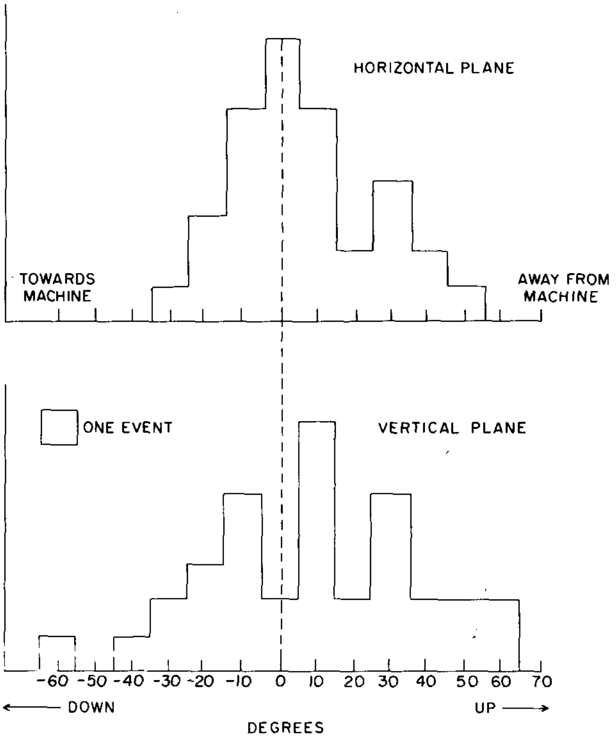


Figure 18. Projected angular distributions of μ-meson tracks assumed to be due to neutrino events.

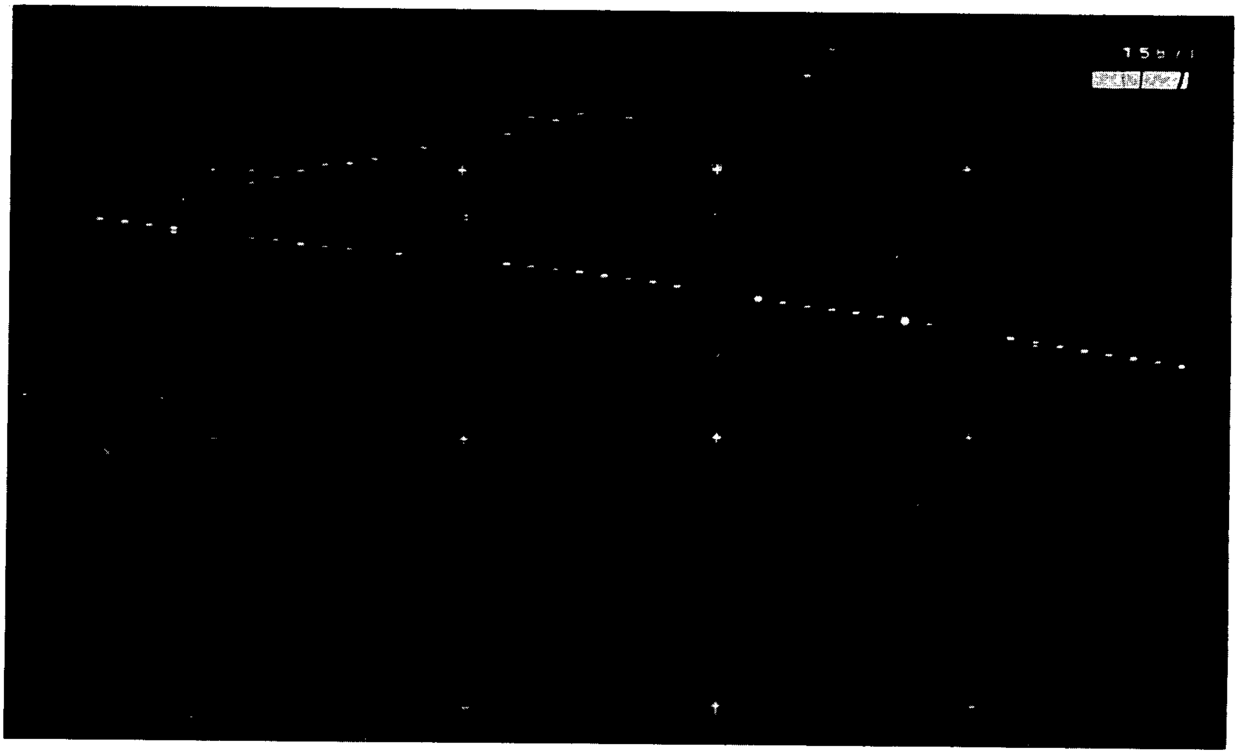


Figure 19. Long μ-meson track.

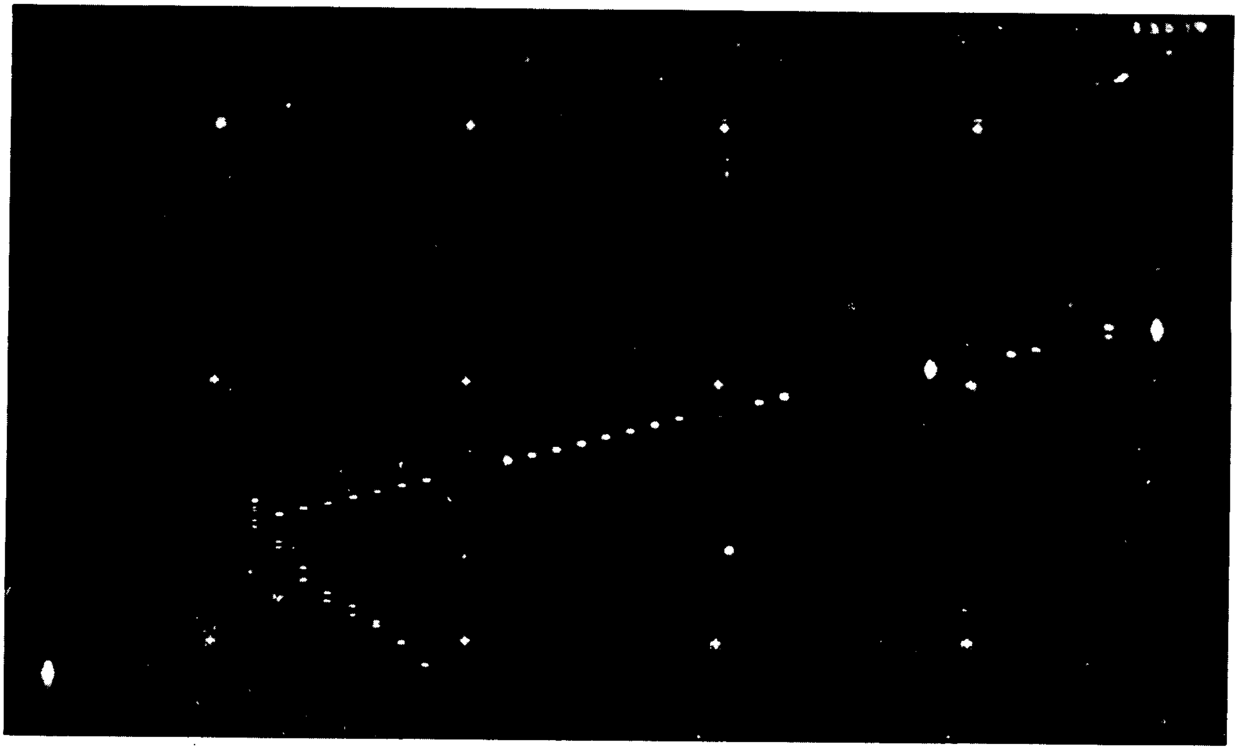


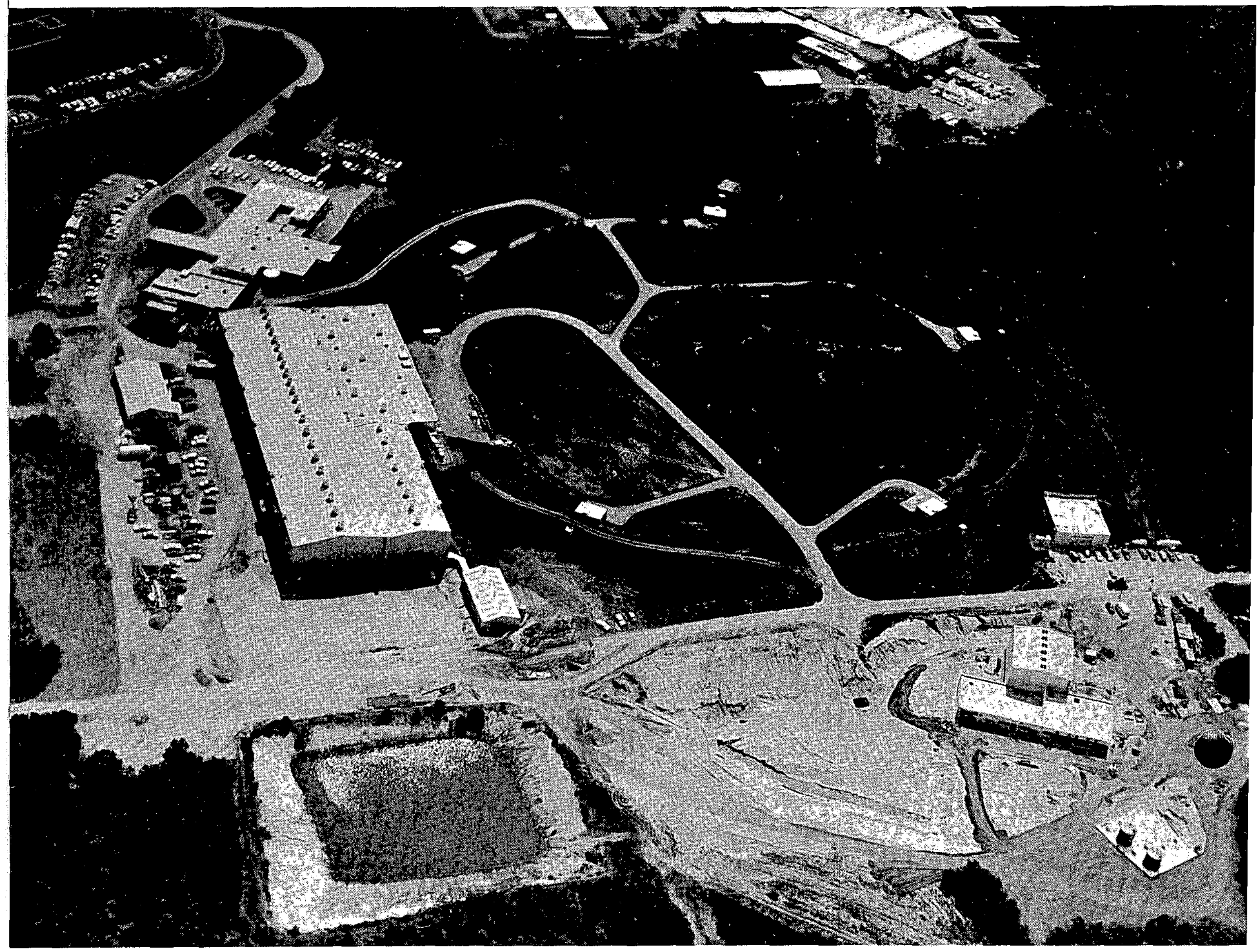
Figure 20. Long μ-meson track with electron track .

probably both use magnetic systems for increasing the neutrino flux so that conservatively the event rates will be higher by a factor of from 10 to perhaps 50. That is, instead of 50 events, the experiment would provide 500 or perhaps several thousand events. The spatial resolution will be considerably improved so that many of the events will give more information.

The next group of figures shows some of the plans for the Brookhaven enterprise. Figure 21 is an aerial view of Brookhaven showing the old target building and the ring. The neutrino facility, being fairly obnoxious to other experimentalists, will be put further out in the new experimental area, and will look something like the plan in Figure 22, which shows an external beam tunnel with a 75-ft flight path to a big detector in a room lightly enclosed with concrete. We will be relieved of the boundary conditions imposed by a machine nearby and will be able to have a very neat solid steel shield 75 ft long. This drawing shows the plans; the present status of the area is shown in Figure 23.

Figure 24 shows the status of the new spark chamber assembly. The front chambers (left) are 6 ft long and made with 6×6-ft square plates, ¼ in. thick, 200 of which will form about a 12-ton detector. We hope that all the particles born in these smaller, thin-plate chambers, or at least a large fraction of them, will eventually stop in the 8×8-ft detectors, which measure their energy. The 8×8-ft spark chamber weighs about 40 tons, has 100 plates, and also contains steel graded in thickness so that it can stop particles with energies probably up to about 2 Bev. In addition, the front half of this detector will provide us with events of the same quality as we had before, since its plates

Figure 21. Aerial view showing AGS ring and old target building. The new neutrino area is located at the top center, here shown covered with trees.



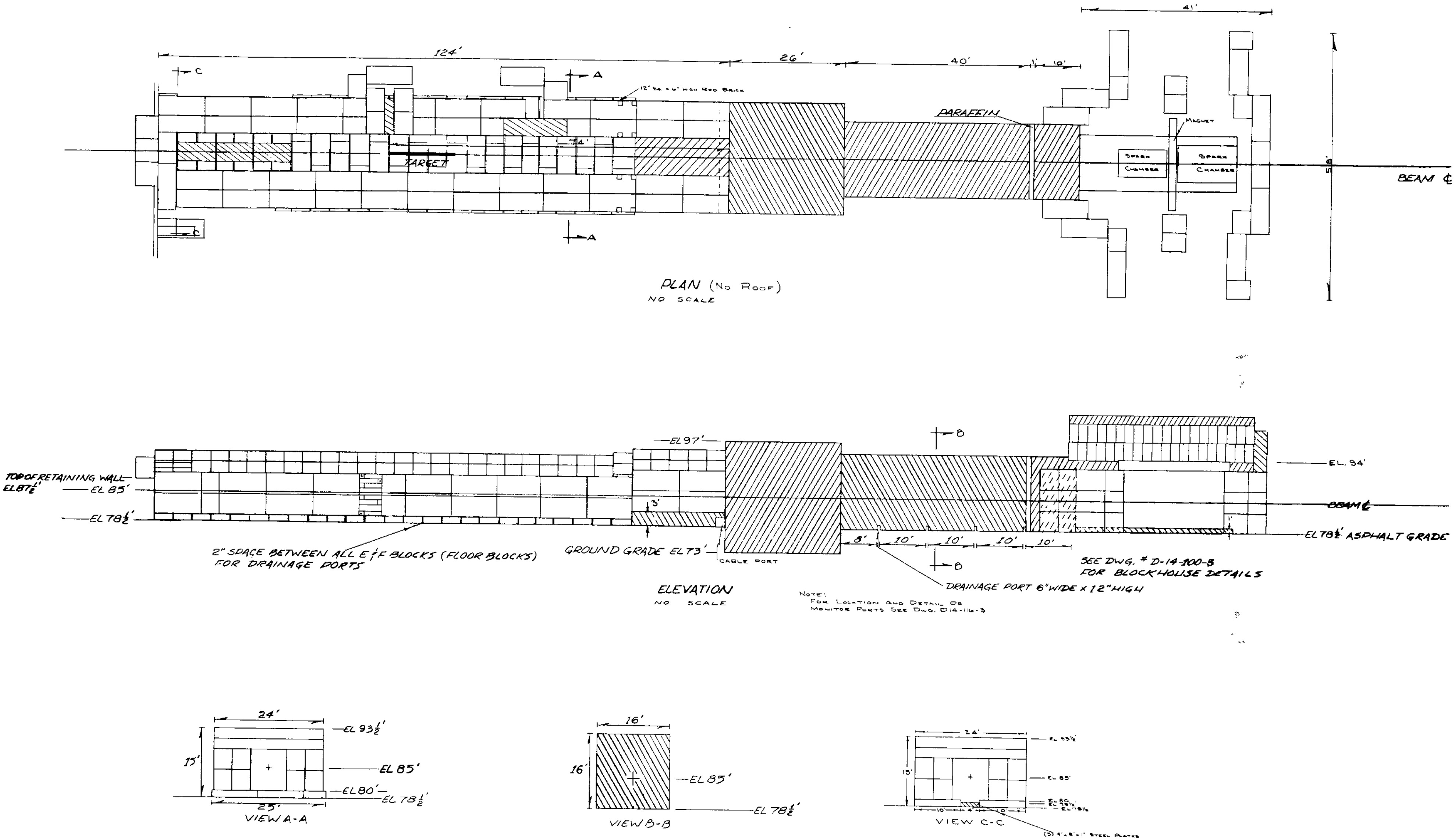


Figure 22. Plan of new neutrino facility.

are 1 in. thick. This experiment will be much richer both because the particle flux is higher and because the detector mass is higher. One additional problem is that, if the same amount of scintillator is used as before, mixed in intimately so as not to have any bias, it will be difficult to obtain sufficient scintillation material. In addition, we would still miss events that might be interesting but have very low energy release. For example, a simple neutrino-proton scattering, in which the neutrino plus a proton yields a neutrino plus a proton is an interesting process which may or may not exist in nature. This would be hard to see with counters because the recoiling proton would have low energy. It would have a hard time getting from where it was born out to where the counter is.

An alternative scheme that probably will be used to avoid bias is to leave out the scintillation counters and even the anticoincidence shield, but to make use of the fact that the external beam coming in will have a very short time structure, even shorter than the one used last time (so that cosmic rays may not be a problem), and trigger the spark chamber after every pulse. The beam pulse lasts about 3 μsec or less. The memory time of the spark chamber can easily be as long as 3 μsec. It stores up everything that happened in 3 μsec in the form of free electrons deposited along the track. Applying the high voltage pulse will then show what there is without any bias at all. The only problem with this scheme is that to photograph this monstrous object requires at least four 70-mm cameras, which, for a million pictures or so, would use a fabulous amount of film. We are working on various means of lowering the film consumption by the addition of some sort of logical device so that the film would move only when there is a reasonable chance that something interesting has happened. This scheme should considerably improve the yield of neutrino events.

In conclusion, the question is, what will be learned in future neutrino experiments? At all the laboratories such as Argonne, Brookhaven, CERN, and Dubna, people are planning neutrino facilities; we are in a period of what Jack Steinberger calls neutrino hysteria. There must be some reason for this. I think the number of things that can be studied by using intense neutrino beams constitutes a long and imposing list, headed by two problems: that of the intermediate boson, and that of the relationship between μ mesons and electrons.

Figure 23. Present status of site of new neutrino facility.

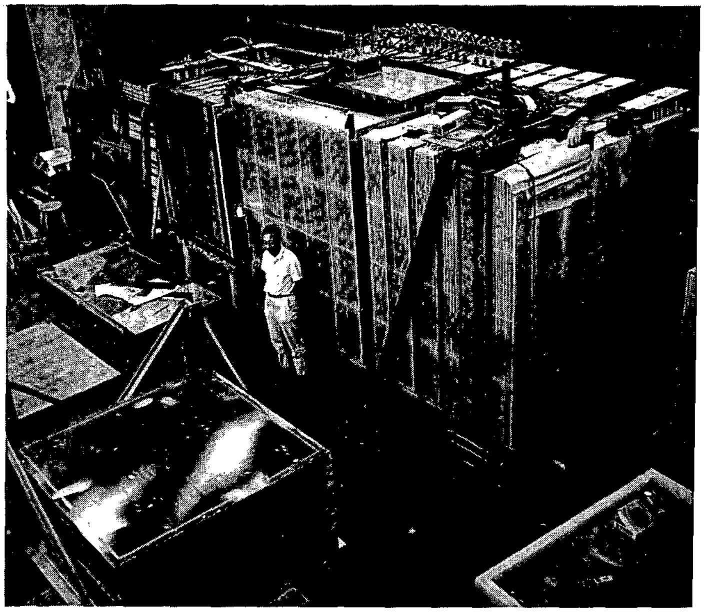


Figure 24. New spark chamber assembly.

The neutrino is a tool for the extension of our understanding of weak interactions. The crucial problem that may be clarified in the next year if the two or three planned experiments are done is the question of the intermediate boson (W). This particle has long been postulated as the intermediate particle in all weak interactions – the key to weak interactions. For example, in this W theory, if the π meson decays, it is somehow first converted into a W, and the W gives rise to the μ meson plus the neutrino. The W is analogous to the photon which is exchanged between charged particles in the electromagnetic theory, or to the π meson which is the glue that holds the nucleus together in the case of strong interactions. The W would be the antiglue which breaks up the nucleus (the case of beta decay). It is the last intermediate particle. In the three types of interactions, two of the intermediate particles are known: the pion for strong, the photon for electromagnetic. The W, if it exists, is yet to be found. Whether it is found or not depends largely on its mass. Since it is not known to exist, its mass is unknown. We like to think that its mass is of the order of a Bev, mainly because if it is much higher, we will not be able to see it: our neutrino energies are too low. It is difficult to get energies much above 1 Bev. The spectrum of neutrinos from the planned external beams will be considerably better than the one shown in Figure 8. Generally, with magnetic focusing, the peak will be at about 1.5 Bev, and there will be a reasonable flux out to 2 or perhaps even 3 Bev, if one includes neutrinos from K mesons. This is certainly one of the short-range immediate goals of the next experiment.

The second problem is related to the two-neutrino problem. It is curious that for any reaction in which a μ meson is produced, there is always a corresponding reaction involving an electron. This symmetry between μ mesons and electrons has been an intriguing puzzle for many years. The μ meson seems to be exactly like an electron. In the K decays, in the detailed static properties, even in the electromagnetic properties to high precision, the μ meson is identical to the electron except that it weighs 200 times as much. This has been speculated about. Why are there these two particles which seem to be the same in every way except for the mass? As Feyman has put it, "Why does the μ meson weigh?" What is the nature of its mass? Now, after the neutrino experiment, we have, in addition to the μ and the electron, a μ neutrino and an electron neutrino which are separate. For lack of anything better, we say that there is some sort of property, similar perhaps to the quantum number, that can be called the "mu-ness." Mu-ness is a property which the μ meson and its neutrino have but which the electron and other particles do not have; the electron has an *e*-ness property. If it is assumed that this property is conserved, then it provides another formal explanation for the occurrence or nonoccurrence of reactions. The nature of this mu-ness is intriguing because there is no other known property which is coupled to it.

There may be two ways of looking for a possible resolution of this problem. First, it is possible that we have not yet probed deeply enough into the structure of the particle but have studied it only in a superficial way. By analogy, certain chemical experiments on helium and argon show no difference between them, and one could ask why these two atoms are the same except that their weights differ. The answer of course is that these experiments did not go beyond the outer electron shells, which of course are the same. Another analogy, which T.D. Lee favors and which is therefore probably right, compares mu-ness and *e*-ness to, say, electric and magnetic fields. The thing that reveals the relation of electric and magnetic fields is the Lorentz transformation; when we find the transformation that converts μ mesons to electrons, it may have almost as much significance for theoretical physics.

NOTE ADDED IN PROOF: The CERN neutrino experiment ran successfully and was reported at a BNL Conference on Weak Interactions in September 1963. The event rate is indeed higher by a factor of about 30. It is too soon to draw conclusions from the new data; the question of the W in particular is still open.

LIST OF BROOKHAVEN LECTURES (Continued)

(Those with BNL numbers given have been published or are in press)

19.	The Renewal of Cells and Molecules – The Fountain of Youth Walter L. Hughes, Medical Department	September 19, 1962
20.	A Neutron's Eye View of Magnetic Materials Julius M. Hastings, Chemistry Department	October 17, 1962
21.	Landscaping the Groves of Academe R.C. Anderson, Director's Office	November 14, 1962
22.	Chemical Communication Systems in the Cell Henry Quastler, Biology Department	December 12, 1962
23.	Neutrino Physics, BNL 787 Leon M. Lederman, Physics Department	January 9, 1963
24.	The Use and Misuse of the Atmosphere, BNL 784 Maynard E. Smith, Instrumentation and Health Physics Department	February 13, 1963
25.	The Nucleus Today Denys Wilkinson, Physics Department	March 6, 1963
26.	Trace Metals: Essential or Detrimental to Life, BNL 828 George C. Cotzias, Medical Department	April 10, 1963
27.	The Early Days of the Quantized Atom Samuel A. Goudsmit, Physics Department	May 15, 1963
28.	Catalysis in Life and in the Test Tube Daniel E. Koshland, Jr., Biology Department	June 19, 1963
29.	Collisions of "Elementary" Particles With Protons at High Energies Samuel J. Lindenbaum, Physics Department	September 25, 1963
30.	Chemistry of Isotopes Jacob Bigeleisen, Chemistry Department	October 16, 1963
31.	The Nuclear Reactor Comes of Age, BNL 838 Jack Chernick, Nuclear Engineering Department	November 13, 1963
32.	Radio Galaxies David Heeschen, National Radio Astronomy Observatory	January 15, 1964

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(Those with BNL numbers given have been published or are in press)

1. Radioastronomy and Communication Through Space, BNL 658
   Edward M. Purcell, Physics Department — November 16, 1960
2. Current Ideas on the Endocrine Regulation of Cellular Processes, BNL 685
   Irving Schwartz, Medical Department — December 14, 1960
3. Inside the Protein Molecule, BNL 649
   Werner Hirs, Biology Department — January 11, 1961
4. Nuclear Chemistry Research With the Cosmotron
   Gerhart Friedlander, Chemistry Department — February 15, 1961
5. Neutron Physics Of and With the High Flux Beam Research Reactor, BNL 664
   Herbert Kouts, Nuclear Engineering Department — March 15, 1961
6. High Energy Accelerators, BNL 747
   Ernest Courant, Physics Department — April 12, 1961
7. Dislocations in Crystal Lattices
   George H. Vineyard, Physics Department — May 17, 1961
8. The History of Cosmic Rays and Meteorites, BNL 779
   Oliver A. Schaeffer, Chemistry Department — June 14, 1961
9. The Physics of Semiconductor Radiation Detectors, BNL 699
   G.L. Miller, Instrumentation and Health Physics Department — September 27, 1961
10. Theory of the Gene, BNL 739
    Milislav Demerec, Biology Department — October 18, 1961
11. Fundamental Particles of Physics
    Maurice Goldhaber, Director, Brookhaven National Laboratory — November 15, 1961
12. Excessive Salt Intake and Hypertension: A Dietary and Genetic Interplay, BNL 733
    Lewis K. Dahl, Medical Department — December 13, 1961
13. Galaxies, BNL 710
    Otto Struve, National Radio Astronomy Observatory — January 17, 1962
14. A Computer Learns To See, BNL 725
    Paul Hough, Physics Department — February 14, 1962
15. Wet Electrons – The Radiation Chemistry of Water
    A.O. Allen, Chemistry Department — March 14, 1962
16. Fundamental Studies of Radiation Damage in Graphite, BNL 745
    Donald G. Schweitzer, Nuclear Engineering Department — April 17, 1962
17. The Role of the Cell Nucleus in Determining Radiosensitivity, BNL 766
    Arnold H. Sparrow, Biology Department — May 16, 1962
18. Accelerators of the Future, BNL 741
    John P. Blewett, Accelerator Department — June 13, 1962

(Continued inside back cover)