HIGH-ENERGY NEUTRINO INTERACTION IN MATTER

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(presented by M. Schwartz)

Before beginning, I would like to register an acknowledgment of great appreciation to the people at Brookhaven who contributed enormously to the success of this experiment, in particular to the people at the alternating gradient synchrotron led by Drs. K. Green, J. and H. Blewett and E. Courant. In addition I would like to express the gratitude of our group to Drs. Feinberg, Lee and Yang for much inspiration during the course of the experiment and also to express recognition to B. Pontecorvo who contributed greatly to the conception of the experiment in the early days.

A. THEORETICAL CONSIDERATIONS

Basically the aim of the experiment was to observe the interaction of neutrinos from π decay and there are four points I would like to discuss about these interactions.

I. Cross-section of neutrinos at energies $\sim$500 MeV.
II. Production of intermediate boson.
III. Identity of π decay and β decay neutrinos.
IV. Neutrino flip.

Now I am going to run through these things briefly and tell you what we expect from the point of view of the theory and to what extent this experiment is likely to be sensitive to these four points.

1. Cross-section

As most of you know, the cross-sections for neutrino interactions increase as phase space up to the order of a GeV or so, at which point it begins to damp due to the strong interaction form factor. In particular, in the region of the energies in which we are interested, the cross-sections for the reactions:

$$\nu + N \rightarrow \mu^-(e^-) + P$$

$$\bar{\nu} + P \rightarrow \mu^+(e^+) + N$$

should be of the order of 10^{-38} cm^2. These cross-sections have been calculated by various people including Lee and Yang, Yamaguchi, Gatto and Cabibbo. What they assumed for the form factors is: the vector part is given by the electron scattering data and the axial vector part is taken to be the same. The result which you will hear is that our cross-sections are consistent with these calculations.

2. Production of the boson

It has been pointed out by Lee and Yang and also by Pontecorvo that it is possible to produce intermediate bosons by means of neutrinos through the reaction, for example, $\nu + Z \rightarrow \mu^- + W^+ + Z$, and of course also a comparable thing for the antineutrino. Our experiment has a certain level of sensitivity to it and our result effectively will be, not that we have demonstrated any existence of a boson but that we have not demonstrated the non-existence of a boson. I think this is more meaningful than it may sound, because we were sensitive to a certain region in boson mass and had we seen no candidates for bosons we could have excluded the existence of a boson within a certain mass range.

3. Identity of neutrinos

Until quite recently the general feeling was thas the neutrino from π decay should be the same at the neutrino from β decay. This question was brought into some focus in recent years by independent calculations by Feinberg and by Gell-Mann and Feynman indicating that if an intermediate boson did exist then one would expect the decay $\mu \to e+\gamma$ to occur with a probability of the order of 1 in 10 000, and in fact that the only simple way, provided that boson did exist, of avoiding this, would be to have two independent types of neutrinos. In addition, more recently, Lee and Yang have pointed out that the difficulty with the lack of this decay is in fact deeper than just the involvement with the intermediate boson and that almost any theory which preserves unitarity ought to have some $\mu \to e+\gamma$ decay unless there were two types of neutrinos.

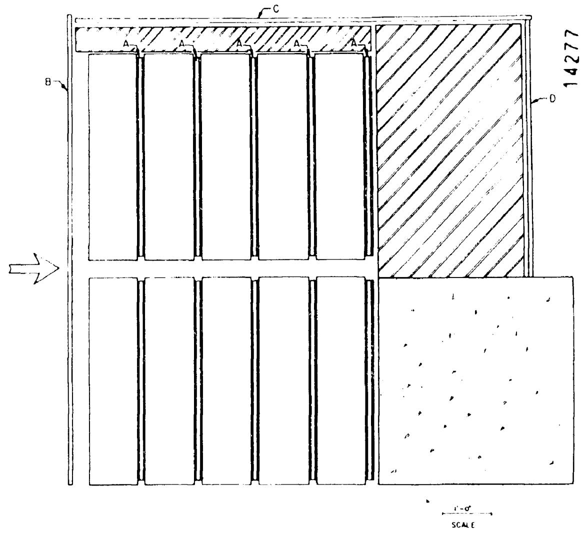

Fig. 2

4. Neutrino flip

Bludman and independently Feinberg, Gursey and Pais have pointed out that, were there two types of neutrinos, one could in fact reverse the assignment for strangeness violating weak interactions. For example if $\pi \to \mu + \nu_\mu$, then it is possible that the K would decay into a $\mu + \nu_e$. Our sensitivity to a check of this hypothesis in the experiment depends of course on the number of neutrinos we have from K decay.

B. EXPERIMENTAL DETAILS

1. Experimental set up

Fig. 1 shows the AGS neutrino facility at least as it existed until a very short time ago. Normally circulating in the AGS are 2×10^{11} protons/second accelerated up to 15 GeV. These protons are allowed to impinge on a beryllium target in a 10 ft straight

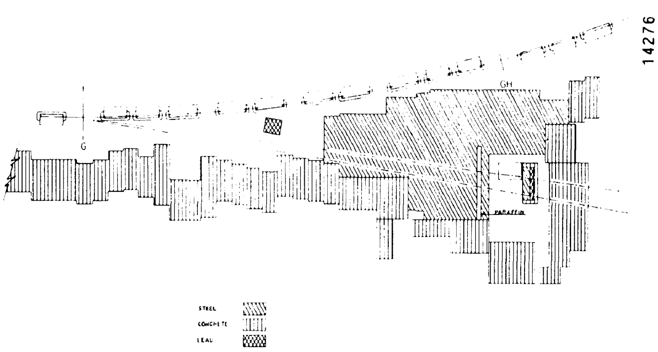

Fig. 1 Neutrino experiment floor layout.

section and then of course the pions come out predominantly in the forward direction. Roughly 10% of the pions decay in the 70 ft flight path. After this there is a 42 ft shielding wall essentially made of solid iron whose purpose is to filter out everything but the neutrinos. These neutrinos will then pass through and enter the room where a 10 ton spark chamber is set up. The aim of the experiment of course is to observe the interactions of these neutrinos in the spark chamber.

Let me point out now one relevant thing to which I will come back later. At one point in the talk I will make some differentiation between data taken in the second half of the run and data taken in the first half of the run. The essential difference between these two pieces of data was a little section of shielding on the machine side consisting of the order of several hundred tons out of 5 000 tons of shielding which apparently made a rather substantial difference in our background. It will make no substantial difference in the results.

Fig. 2 is a sketch of the spark chamber showing the relative parameters. These chambers are 4 ft$\times$4 ft and roughly 1 ft wide, consisting each of 9 plates, $44'' \times 44'' \times 1''$ of aluminium. Each of these chambers weighs of the order of 1 ton and there are 10 such chambers together in this array. Between each pair of chambers, in the positions marked A, are black slabs and light slabs. The black slabs are counting material, scintillator, and the white slabs in between are sheets of aluminium. Basically these are our triggering counters and we trigger the chamber only when we have a track which traverses any pair of these black slabs. The first requirement for firing the chamber is to get a coincidence between a pair of black slabs. In addition to that there are sheets, marked *B*, *C* and *D*, which are anti-coincidence slabs and which eliminate to a very large extent the cosmic ray background which enters the chamber during the time that we are on and also eliminate any energetic μ's which may be penetrating the shield and entering the chamber.

2. Operation of the chamber

The beam was deflected into the target by means of a magnetic rapid beam deflector and the pulse lasted 25 microseconds. Furthermore the protons circulate around the machine in 12 bunches; namely there is an RF structure which is in the machine and which was extremely useful for us and made possible very accurate timing in the course of the experiment. This RF structure is as follows: the 12 bunches are separated by 220 ns and each bunch is roughly 20 ns long; that means that the protons when they circulate come in peaks with a 1/10 duty cycle. This was used to gate our apparatus by means of a Čerenkov looking at the target and effectively we were open for 3.5 μsec per pulse. Since we took roughly 1.7 million pulses in the course of the experiment, we have been open altogether for 5½ sec: *the duration of the experiment in real time was 5½ sec.* This will be an important parameter in deciding what cosmic ray background is to be expected.

C. RESULTS

Let me give you a definition of what we call an event. The neutrinos are coming from the left (Fig. 1). If ionization starts in the chamber, and progresses to the right, provided the beginning of the track is in the middle of the chamber, this is called an event. It may have only one track, or it may be an event in which more than one track leaves a common origin. Of course we do not know whether it starts in the middle and goes out or comes in the rear and stops. But the only thing which can enter the rear and stop are cosmic rays. These will be discussed separately later.

Now, in order to be absolutely sure that there is no difficulty with tracks which may be just barely entering, we have established a fiducial region whose boundaries lie 4″ from the front and back walls of the chamber, and 2″ from the top and bottom walls. In addition, for a single track, if you extrapolate back for two gaps towards the neutrino source and it still remains within the fiducial region, only then will it be considered as an event.

There are four categories of events which fit the criteria which I have established here.

I. Single short tracks

Tracks with apparent momentum, if they are μ mesons, less than 300 MeV/c; by "less than", I mean all that is seen in the chamber is less than 300 MeV/c. Of course if a track leaves the chamber after traversing only a few plates of aluminium it may very well be much more than 300 MeV/c. However, all that we can testify to is the observation of something less than 300 MeV/c. So $P\mu < 300$ MeV/c is one category. These are of course not necessarily all μ mesons either. It is just that if they were μ mesons, this would be their characteristic.

This category has 49 events, largely because in the first half of the run there was a fair flux of neutrons, apparently of not very high energy entering the chamber from underneath the shielding wall. In the second half of the run there were only 3 that fell into this category. These are for the most part tracks which involve only 3, 4, 5, perhaps 6 sparks and some rather longer. We feel quite sure that, by making the cut-off at 300 MeV/c which corresponds to roughly 15 sparks, we have eliminated the major part of the neutron background that existed in the experiment. Of course, some of these events which left the chamber before going any appreciable distance could also be μ mesons—some of them certainly are.

II. Single long tracks

This category contains events with $P\mu > 300$ MeV/c. There are 34 such events. Fig. 3 shows a few examples of single long tracks. Both categories I and II consist of single tracks with at the most 2 other sparks which may be due to a nuclear recoil.

III. Vertex events

There are 22 such events. Three of them are shown in Fig. 4.

Fig. 3 a The beam of neutrinos is coming from the left. This is one of the sets of chambers. We photographed them independently. This is interpreted as a μ meson which traverses $2\frac{1}{2}$ chambers. For orientation, a strongly interacting particle will normally go through the order of $1\frac{1}{2}$ chambers before interacting. You see also on this track some sign of a δ-ray.

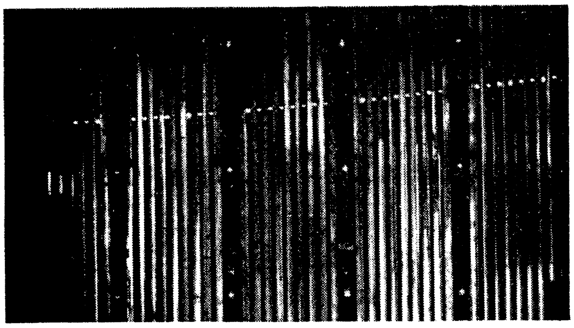

Fig. 3 b Here is a rather spectacular one, which traverses in fact $4\frac{1}{2}$ chambers or about over 3 nuclear mean-free paths and again is interpreted as a μ meson. Notice the clean straight character of the track, the lack of double sparks and the fact that you can draw a fairly decent straight line through the track.

Fig. 3 c This is a rather slow μ meson. It still falls in the category of having a momentum greater than 300 MeV/c, but it does stop in the chamber and it shows in fact a rather typical multiple scattering as it comes to rest.

IV. " Shower " events

They are defined as any event which could conceivably be an electron. That does not mean that it is an electron because there are many possible ways a μ can look like an electron. However, it means that, if you use your imagination enough, each of these could be electrons. There are 8 " Showers "; all of them were obtained during the first half of the run with a weaker shielding. Out of these 8 events only 6 will be referred to from here on for comparison with the number of μ mesons, since only 6 of these have enough potential path in the chamber so that if they had been μ mesons they would have fallen in category II.

Table I contains a summary of all events falling in categories I, II, and III. In the following, only the 56 events of categories II and III will be referred to as events.

TABLE I

Classification of " Events "

Single Tracks		Vertex Events	
$p_\mu < 300$ MeV/c (*)	49	Visible energy released < 1GeV	15
$p_\mu > 300$	34	Visible energy released > 1GeV	7
$p_\mu > 400$	19		
$p_\mu > 500$	8		
$p_\mu > 600$	3		
$p_\mu > 700$	2		
Total " events "	34		22

(*) These are not included in the " event " count.

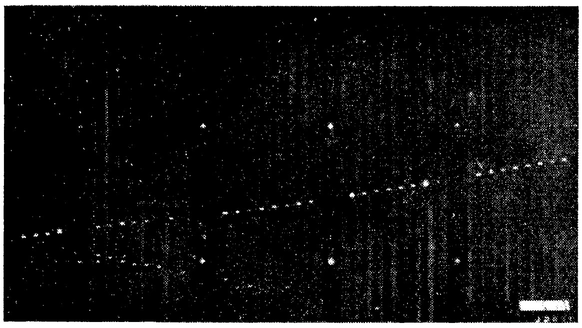

Fig. 4 a This is one of our vertex events and in fact one of the more fascinating of the vertex events. There is what you would normally call a μ meson. Then looking up you notice an assembly of sparks which looks characteristically different from the assembly of sparks below. If you look along the track, you will see that these sparks are no longer on a straight line, but are much more randomly oriented and there are double and triple sparks, and also missing sparks. This has the absolutely typical appearance of an electron shower. And in fact, according to our calibration pictures, this thing would correspond roughly to a 500 MeV electron. Our tentative interpretation is that this appears to be a μ meson $+$ a γ-ray pointing back to the origin of the μ meson.

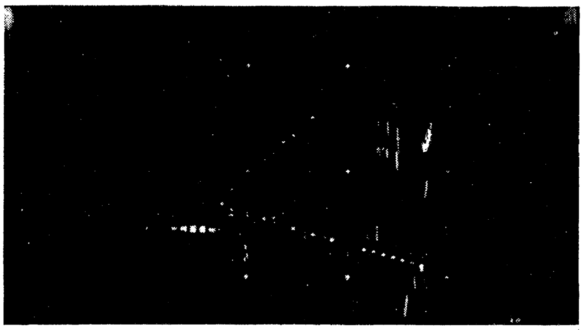

Fig. 4 b This is another of the vertex events. It is consistent with both prongs being μ mesons. This could correspond to the production of an intermediate boson w^+, followed by the decay $w^+ \rightarrow \mu^+ + \nu$.

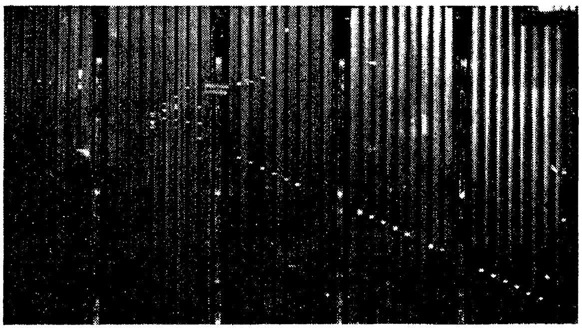

Fig. 4 c This is a more complicated event where there is apparently a μ meson, with some additional tracks. It is of course impossible to make any reasonable interpretation as to what actually took place here.

D. NEUTRINO ORIGIN OF THE EVENTS

I will present now a series of arguments on the neutrino origin of these events.

1. Can these events be due to cosmic rays?

In order to investigate this, we have allowed the cosmic rays to trigger the chamber while the machine was not running, just as though they were in fact neutrino events. All other conditions were the same.

We have observed 1800 cosmic ray events. Out of these 1800 cosmic ray events, there were 21 which satisfied every criteria for category II. Of course, cosmic ray events will never make things which satisfy criteria for category III because they are μ mesons coming in from outside. This means that 1 in 90 cosmic rays triggering the chamber is a simulated " event ".

Now we measured the rate for cosmic ray triggers of the chamber which turns out to be 80 triggers per second. As I said before, we are on for a total of 5.5 sec; we would expect then 440 cosmic rays in the chamber, and this is apparently very close to what we get. Therefore we would expect roughly 5 ± 1 cosmic ray events which simulate an event of category II. So from the number of 34, we will have to subtract a background of 5. In addition, a relevant point is that of these 34 events, about 20 can be guaranteed not to be of cosmic ray origin at all for at least one of the following reasons: they are pointing down; there are two additional sparks at the beginning; they may have a δ-ray, or they may start and stop in the chamber. So there is no question that the majority of these events are not produced by cosmic rays.

2. Can these events be due to neutrons?

In this experiment we performed numerous checks. You will see, in fact, that we can demonstrate fairly conclusively that our events were not due to neutrons. There are four points involved in this.

a) Angular distributions (Fig. 5): The 34 μ's are plotted in those angular distributions; the zero degree line is the direction of the neutrino beam. There appears to be no question whatsoever, that these events are pointing back to the target. Indeed, the reason we first began to suspect the neutron origin of many of our shorter tracks (category I), was that when we made such a distribution for the first half of our run, the tracks appeared to be pointing back to a particular section of the floor; we then knew precisely where to put our extra-shielding. Now, of course you may ask, can our neutrons be penetrating the main wall of the shielding? Obviously, since the events are pointing back to the target, if they are induced by neutrons, the neutrons would be coming through the 42 ft of iron. And so, we have done a very simple check. In the last day of the experiment we removed 4 of these 42 ft of iron; if the events were due to neutrons, then the rate should increase by a factor of 100 and we should have seen something of the order of 300 events in that run. In fact we saw 2 events and so there seems to be no question whatsoever that these are not due to neutrons, which penetrate the main shielding wall.

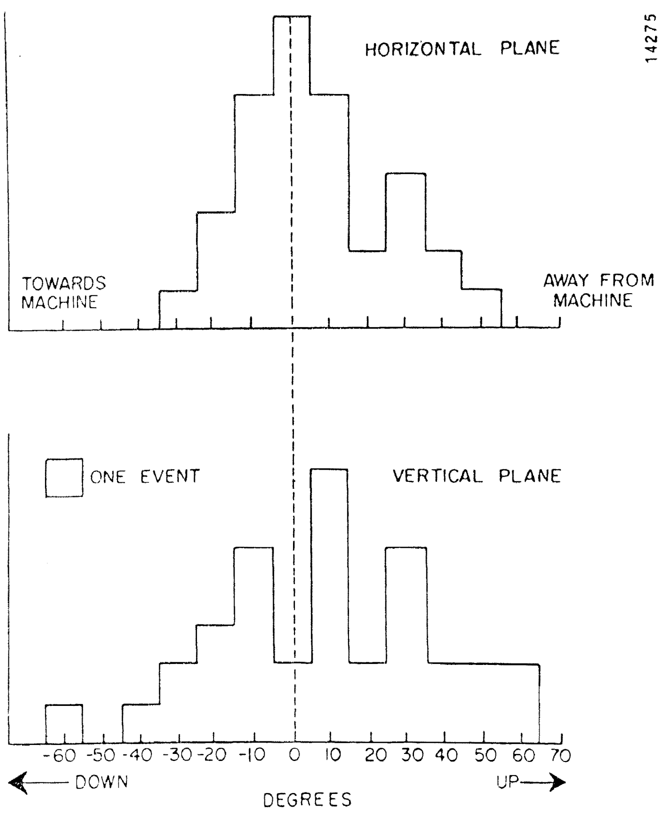

Fig. 5 Projected angular distributions.

Furthermore if these events were due to neutrons which were coming in from some place, then they would of course tend to cluster along the face or along the side which was pointing to the source of neutrons. But we have plotted up the position of the events in the chamber, and except for the obvious bias given by the requirement that $P\mu$ be greater than 300 MeV/c, we have seen no sign of any clustering of events. In fact the events seem to be perfectly well distributed throughout the chamber.

b) Interaction of the secondaries. Obviously, if we are producing μ mesons, then they will not interact. On the other hand, if we were producing pions we should see some level of interaction. If you give us the liberty of making the argument on the basis of the second half of the run, we observed there μ mesons traversing a total of 820 cm of aluminium. In these 820 cm of Al, there have been 5 endings of tracks of μ mesons. There has been no case of anything which is clearly recognized as a nuclear interaction. Of course, you may ask the question: can an ending be a nuclear interaction? In fact, it can. However, we have calibrated these chambers to discover how often we see a nuclear interaction when we are dealing with π mesons of essentially the same momentum. And we discovered that on the average you need to traverse 100 cm of aluminium before you see a clear nuclear interaction. So we should have seen 8 clear nuclear interactions, and we saw none. Another way of making the argument, is to say that even if each of these presumed μ mesons were in fact π mesons, then we should only have to traverse 40 cm per nuclear interaction—if we include also endings of tracks—and we should have seen 20 nuclear interactions, but we saw only 5. There is no reason to believe that these 5 are nuclear interactions; they are quite likely to be μ mesons which are stopping in the chamber.

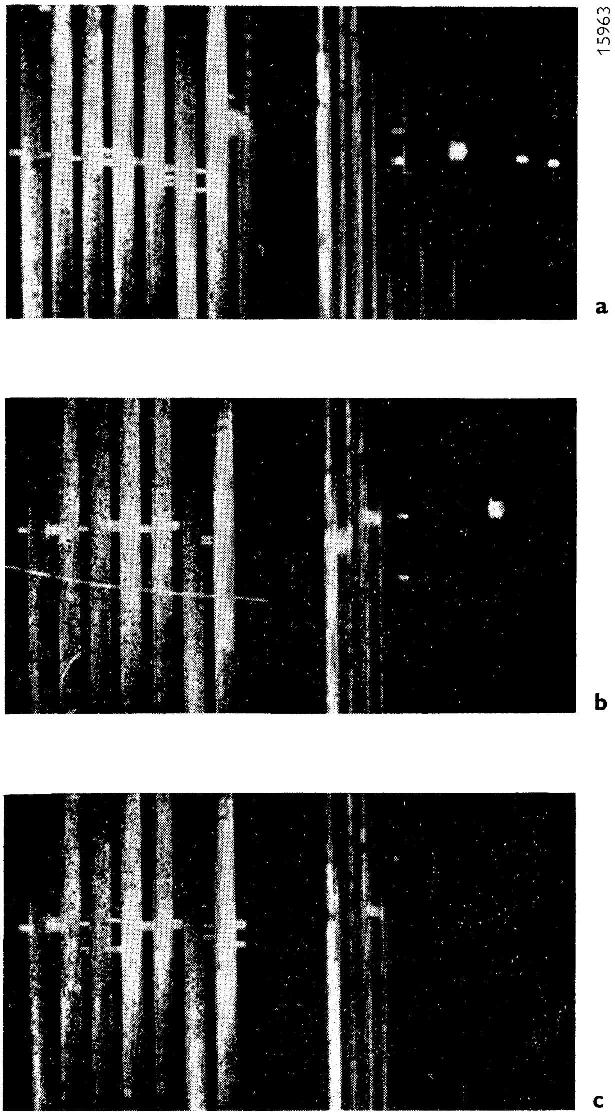

Fig. 6

One more point on this question: we have seen 29 such single tracks; if they were π mesons, then we should have seen of the order of 15 single π^0's. Having seen no single π^0 at all, it seems to us that this again is fair evidence against our events being due to π mesons.

3. Neutrino origin of the events

One characteristic of these events, if they were in fact neutrino events, would be the following: if we stop the π mesons before they had any time to decay, we should also of course kill the neutrinos and kill the events. Unfortunately, it is impossible to completely turn off the neutrinos by this method, and the best we can do is to stop the π mesons after they have had the shortest free path to decay. In order to do that, we removed 4 ft from the shielding wall and replaced them by 4 ft of lead, 5 ft away from the target, so that the total number of nuclear mean-free paths seen by the chamber was the same. Then the question was: how many events are seen during this running time? During the normal running, there were 3.5×10^{17} protons circulated, and we saw actually above cosmic ray background 51 things which are called events, which amounts effectively to 1.46 ± 0.2 events per 10^{16}. With the modification to our shielding I have just described, we ran 8.6×10^{16} and saw above cosmic ray backgrounds 2.5 events. This amounts to a rate of 0.3 ± 0.2 events per 10^{16}. This is quite consistent with what we expected, which was $\sim 10\%$ of the normal rate.

E. CONCLUSIONS

1. Cross-sections

In so far as the cross-sections are concerned, if you consider just the second category of events (long μ's) it amounted to (and I will quote cross-sections in an unfamiliar number, namely events per 10^{16}) 0.84 ± 0.16 per 10^{16}. For the vertex events the cross-sections are 0.63 ± 0.14 per 10^{16}. For comparison, the theory when integrated with our expected momentum distribution of neutrinos yields 0.75 per 10^{16} for events corresponding to category II which is a quite reasonable agreement.

2. The question of 1 or 2 neutrinos

We will deal here with the 6 shower events. The first question is of course: can we recognize electron showers? The second question is: are we sensitive to electron showers, in so far as triggering of chambers is concerned? Both of these questions were investigated by putting electrons at various energies into chambers which were set up at the cosmotron. In particular, to see what electron showers of 400 MeV would look like, and secondly to measure directly the triggering efficiency for these electrons. Fig. 6 (a, b, c) are typical pictures of what 400 MeV electron showers look like. You notice the number of double sparks, triple sparks, missing gaps. In Fig. 6 b the beginning of the electron could have easily been confused with a μ meson, and in fact 10% of the showers could have been confusing, except that quite often they have some missing gaps, and then some more signs of sparks later on.

To perform the efficiency calculations, all we did was to imagine a pair of counters in all the various possible positions along the shower path and we discovered that the triggering efficiency was 67%, i.e. 67% of electrons looking like those 400 MeV electrons would have triggered the chamber.

In order to make a quantitative study of what we should have expected, if in fact there was only one type of neutrino, namely, if we were really getting as many electron events as μ meson events, we made a graph with our 400 MeV electron pictures which is shown in Fig. 7. For comparison the lower curve contains the six " shower events " which are really observed. And so it seems to us fairly conclusive that these are not consistent with the prediction based on universal theory with $\nu_\mu = \nu_e$.

One interesting point is the fact that in the second half of the run we saw none of these so-called showers. As regards the origin, it is extremely hard to say; it is very likely that they might be associated with the neutrons which we had earlier in the experiment.

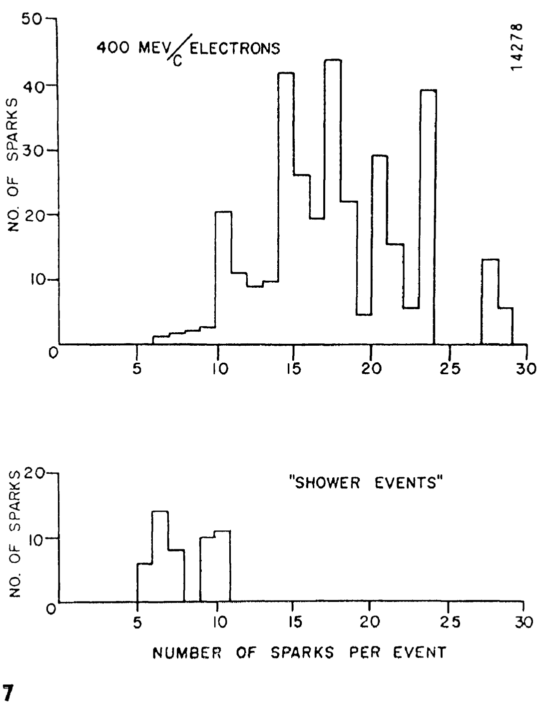

Fig. 7

It seems to us, at this stage, that—at least from the evidence that you have seen—we are producing μ mesons, but not electrons, and so perhaps the simplest conjecture is that there are two types of neutrino.

3. The neutrino flip

We have calculated what the neutrino spectrum should look like from the K decay, and we have calculated how many events we should have seen in the chamber, due to neutrinos from the $K\mu_2$ decay. And the number turns out to be 5. The error in the calculation is of the order of 30%. We have seen no case of a shower typical of what one should get from neutrinos, of the energies gotten from K decay.

I remind you K decay neutrinos have energies substantially higher than the average neutrinos from π decay, even though there are fewer of them; their average energy is more like 2 or 3 GeV, instead of being under 1 GeV. To the extent that we should have seen 5 and have seen none, it seems to us that there is some evidence against the neutrino flip hypothesis.

4. Intermediate boson

Using our neutrino flux and specially what you get from K decay, you would expect $\sim$20 bosons produced using Lee-Yang cross-sections, if the mass of the boson were 500 MeV. A mass of 1 GeV implies only 2 bosons. Of course, it becomes very rapidly 0 as you increase the mass of the boson. If we had seen no candidates whatsoever that could possibly be a boson, it would of course be an interesting piece of information. You could then discuss the possibility that the boson does not lie between these two limits. However, we have seen 5 things which could conceivably be bosons; some of them are in fact somewhat suggestive and I would just end the talk by saying that we have no evidence for the existence of a boson, however we have a fair bit of inspiration for pressing on.

DISCUSSION

PANOFSKY: Could you comment on the angular distribution of single μ events?

SCHWARTZ: It matches what was expected. Although it is hard to say since the expected assumes that the axial form factor is the same as the vector. For a while it looked a little narrower, namely less high momentum transfer than expected on the assumption that the 2 form factors are identical, but I think it is quite consistent. There are not enough events really to make a sensible comparison.

FAISSNER: You have discussed only 5 of your 22 vertex type events. What are the remaining 17 vertices likely to be?

SCHWARTZ: I discussed these 5 and showed you slides of 3 others. The remainder have many of the same characteristics. For the most part they appear to be a pion produced along with the muon. But the only thing that distinguishes them from the others is the presence of more than 2 extra sparks.

OKUN: What are the upper limits you can get from your experiment for processes:

$$\nu+Z\rightarrow\nu+Z+\mu^{+}+\mu^{-}$$
$$\nu+N\rightarrow\nu+N$$

SCHWARTZ: There are only 2 events which could possibly be a production of a μ pair. They are not μ pairs the way you would normally produce them in the Coulomb field, of course. You would presumably produce them both forward. There were no such events, to my recollection. The upper limit would then be of the order of 1/50 of 10^{-38}.

OKUN: And on the elastic scattering of neutrinos?

SCHWARTZ: An elastic scattering of a neutrino would, of course, look very much like the neutron events we had in the early part of the experiment. They are both essentially just nucleon recoils. As a result we can really say nothing about it, except that the cross-section is not 10 times the cross-section for ordinary neutrino interactions. However, there are 2 events we have seen which do not have any visible lepton coming out. They could have a lepton coming at a large angle where we would not have seen it, because of the structure of the chamber.

FAISSNER: Your first two candidates for boson production look very much like muon production associated with one or two π^0's . Is this interpretation excluded?

SCHWARTZ: In none of these cases can you exclude the explanation that you are producing a muon along with a pair of π's or with 3 π's.

MARSHAK: Could you state what is the best estimate of the inelastic cross-section for the production of pions?

SCHWARTZ: Some fraction of the so-called vertex events may be inelastic scatterings with a larger recoil than normal. With the resolution we have it is impossible to say how many. However, if you accept all the vertex events as inelastic, then the cross-section would be just 22/29 of the elastic, or 22/51 of the total.

MARSHAK: Berman made some theoretical estimates, I understand.

BERMAN: Some estimates of the inelastic cross-section were made by myself and J. S. Bell. We estimate that for your neutrino energies, about 500 MeV, the inelastic single π production cross-section should be slightly less than half the elastic, which is, I think, compatible with your data.

CRONIN: I recall that the existence of the vector boson would give a considerable enhancement of the neutrino interaction cross-section. What is the situation with respect to this idea?

SCHWARTZ: The enhancement is only in the production of the bosons themselves. If the boson were of the order of 500MeV, we should have produced about 20. We do not have 20 candidates.

ERICSON: What is the lower limit on the intermediate boson mass implied by your five possible vector meson events?

SCHWARTZ: We prefer not to say.

ERICSON: It should be possible to obtain this lower limit essentially by the same method you have used to estimate the number of such events.

SCHWARTZ: There are too many uncertainties in the calculation.

FEINBERG: From the fact that you have seen no events in which a single π^0 and no charged lepton is produced, while you have seen about 20 events with a single π and a charged lepton, it seems reasonable that the coupling of $\bar{\nu}\nu$ current with nucleons is less than the coupling of the $\bar{\mu}\nu$ current by a factor of 5-10.

NOVEY: Can you distinguish between protons and muons by difference in intensity of the spark?

SCHWARTZ: No.

LAPIDUS: My question refers to the interpretation of your experiment. I think it is possible, using a suitable theoretical model, to obtain for an experiment around 1 GeV quite a big ratio of muons to electrons because the pseudoscalar contribution in the frame of one neutrino hypothesis gives mainly muons and practically no electrons. We know very little about axial and pseudoscalar form factors. The bad knowledge of this last form factor makes all estimates quite uncertain. For instance if we use Yamaguchi's results with all form factors identical but with a pseudo-scalar coupling constant three times larger, then pological estimates give (this is not in disagreement with low-energy muon capture data) about 2.5-3 times more muons than electrons. Different form factors could give an additional factor 3 or more. We know that pseudoscalar contributions are small at small and infinite energy, but at energies of the order of nucleon-mass this contribution is maximal. It is possible to give an answer to this question by doing experiments at other energies. What can you say about this uncertainty in the interpretation of your experimental results?

SCHWARTZ: Not only do we find a certain ratio between muons and electrons, but we can establish an upper limit to the cross-section for making electrons. If you use the coupling constant from low energies, then you will calculate in fact a certain cross-section for making electrons. This is independent of the pseudoscalar part which applies only to muons.

LAPIDUS: You say the upper limit is only from the contribution of the vector form factors, and that is bigger than you can see?

SCHWARTZ: If you assume the axial form factor is the same as the vector, then you would expect of the order of 30 electrons produced independent of the number of muons.

MARSHAK: Lapidus is referring, I think, to the induced pseudoscalar interaction which you get with the virtual pion emitted. At first sight it might look as if the virtual pion will act like a free pion and give many more muons than electrons, and this could explain the results within the framework of one neutrino. Okubo at Rochester made the same calculation and found that it will not work. The induced pseudoscalar interaction would have to be 10 times larger to explain the results.