4th LECTURE
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THE BROOKHAVEN NEUTRINO EXPERIMENT

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Extensive details of the experimental set-up, the classification of the events and the proof that they are due to neutrino interactions are given in references (1), (2) and (3). We will simply list the essential features of the experiment and we will take special care in discussing the final interpretation of the experimental results.

I. Experimental Set-up(Fig. 1)

1) Source of Neutrinos: Pions and kaons produced by 15 GeV protons hitting a beryllium target at the beginning of a three-metre straight section of the AGS. Usable particles were emitted at a mean angle of 7.5° and had a 22 metre path to decay. Neutrino spectra are shown on Fig. 2.

2) Detector: Ten spark chambers, one ton each, made of nine aluminium plates (4 x 4 feet, 1 inch thick) and of plexiglass frames. The chambers are placed in two superimposed rows; anticounters in front, top and back (B, C, and D), a pair of coincidence counters in between each pair of chambers (A) (Fig. 3)

3) Shielding: 13.5 metres of iron in front; a lead pile to stop the zero degree particles. On the machine side the shielding had to be made stronger for the second half of the run; slow neutron infiltrations had been detected leading to events with a rate equivalent to neutrino event frequency.

4) Trigger: A rapid beam deflector sends the protons against the target leading to a 25 microsecond pulse. The internal

beam has an RF structure which is maintained in the secondary beam and allows the possibility of gating on each bunch, reducing the sensitive time to 3.5 microseconds per pulse. A trigger consists of the coincidence: Gate + any A pair + $\bar{B}$ + $\bar{C}$ + $\bar{D}$.

II. Results

- Total running time (testing + experiment) : 800 hours.
- Average machine intensity : 1.9×10^{11} protons/pulse.
- Number of pulses (experiment) : 1.6×10^{6}.
- Total sensitive time (experiment) : 5.6 seconds.

1) Classification of the events: Inside a fiducial region whose boundaries lie 10 cm from the front and back walls of the chamber and 5 cm from the top and bottom walls (for a single track the extrapolation of the track two gaps back towards the neutrino source must still remain within the fiducial region), we obtained 113 events corresponding to 3.48×10^{17} accelerated protons, classified into four categories.

- 49 short tracks (visible momentum if μ's < 300 MeV/c)
- 34 long tracks (visible momentum if μ's > 300 MeV/c)
- 22 vertices
- 8 "showers".

Owing to neutron leakage through the machine side of the shielding during the first part of the experiment, which gave the major part of the short track events, we consider only, for the demonstration which follows, the 34 long tracks and the 22 vertices. We will deal with the 8 "showers" in a separate paragraph.

2) Neutrino origin of the events:

(a) Not produced by cosmic rays: We counted, removing the gate, 80 cosmic rays/second, the anticounters being on. A separate experiment, done on cosmic rays alone, gave us the result that out of 1800 cosmic rays, 21 would have been accepted as events. This leads to the estimate that:

$$\frac{5.6 \times 80 \times 21}{1800} = 5 \pm 1 \text{ cosmic rays}$$

are included in the 34 long tracks.

(b) Not produced by neutrons: Three facts contribute to demonstrate this point.

- We have no attenuation in event production, which would not be the case if strongly interacting particles coming from the target produced the events.
- We have no asymmetry in the projected angular distributions which are centred around the beam line and show that the events are produced by particles coming from the target direction (and not by neutrons coming from the side).
- We removed 1.20 metres of iron from the main shielding which would have increased by a factor e^5 any contribution due to neutrons. For 3×10^{16} accelerated protons only two events were observed under these conditions (the mean rate would lead to a production of 4 ± 2 events).

(c) Produced by decay products of pions and kaons: Removing 1.20 metres of iron from the main shielding and replacing it by lead, two metres away from the target, we kept the total interaction path constant, and we eliminated ~ 90% of the pions and kaons before they had enough time to decay. The result is an event rate of $0.3 \pm 0.2/10^{16}$ accelerated protons compared to the normal rate of $1.46 \pm 0.2/10^{16}$ protons.

(d) The single tracks are not interacting: For this part of the demonstration we will use, to avoid introducing any bias, all the single tracks, short and long, obtained during the second half of the experiment. We observed 820 cm of single tracks, which means we should have seen eight clear interactions: we saw none. Five tracks end inside the chamber; if we assume that these are in fact charge exchange pion interactions, we should have seen about ten normal scatterings.

We can conclude that the 29 single long tracks (excluding cosmic ray background) are due to particles which show very little interaction; they are presumed to be muons due to neutrino interactions.

3) "Shower" events:

(a) - are essentially short tracks with some discontinuity (sparks not in line or missing, double sparks ---). Only six of them, if they were muons, would have fallen into the long single track category.

(b) - were all obtained during the first half of the experiment when the side shielding was weak.

(c) - a calibration run done at the cosmotron with electrons of known energy, shows that the energy of those six showers is much lower than the mean energy of the 29 long tracks.

(d) - an efficiency measurement of our triggering system for 400 MeV/c electrons gave 67%.

III. Interpretation.

1) Universality assumed: If there is only one neutrino ($\nu_\mu = \nu_e$), we should then produce the same number of electrons

and muons, which is obviously not the case. Lapidus[4)], increasing the contribution of the pseudoscaler term in the cross section, gets a prediction of five muons for one electron which, he says, is in agreement with the experiment. This change would also multiply by a factor 5 the cross section for the reactions:

$$\bar{\nu} + p \rightarrow n + \mu^{+}$$

$$\nu + n \rightarrow p + \mu^{-}$$

This is in contradiction with our experiment which gives for the "elastic" events a rate:

$$0.84 \pm 0.16 \text{ events}/10^{16} \text{ protons}$$

to be compared with the computed value from the classical cross section:

$$0.75 \pm 0.25 \text{ events}/10^{16} \text{ protons.}$$

Furthermore, the angular distribution of the single long tracks (Fig. 4) is in good agreement with the theoretical prediction for a normal pseudoscalar turn, but is in complete contradiction with the Lapidus assumption[5)]. With our experimental results, in order to preserve universality, one has to assume the existence of two neutrinos - ν_{μ} and ν_{e}.

2) Universality is not assumed[6)] we then use the fact that in our experiment we had roughly equal numbers of neutrinos and antineutrinos. Consider now the reactions:

$$\nu + n \rightarrow p + e^{-} \qquad (1)$$

$$\bar{\nu} + p \rightarrow n + e^{+}. \qquad (2)$$

we have:

$$\frac{d\sigma_{(1)} + \sigma d_{(2)}}{2} = d\sigma_{V} + d\sigma_{A}$$

where $d\sigma_{V}$ and $d\sigma_{A}$ are respectively the squares of the vector and axial parts of the amplitude.

In the case of our experiment we can write

$$d\sigma = \frac{d\sigma_1 + d\sigma_2}{2} \geqq d\sigma_V$$

If we assume that the CVC hypothesis, which has now good experimental confirmations7), is valid, we can get from the electron proton scattering experiments the values of the vector form factor. We then compute a lower limit for the number of electrons we should have observed from the value of $d\sigma_V$ if $\nu_e = \nu_\mu$;

We get

$$Ne \geqq 12$$

which is not in agreement with the experimental results.

3) <u>Neutrino flip hypothesis</u>: Our neutrino flux from kaon decay should have produced five or six single tracks. If the neutrino flip hypothesis is valid, these should be electrons of 1 GeV/c or more, extremely easy to identify. We have seen none, which seems to be good evidence against the neutrino flip.

4) <u>Vertices and intermediate boson</u>: Table I gives a complete list with as many relevant details as possible. What are those events? Theoretical estimates of the pion production have been made by Bell and Berman, Dennery, Dombey, introducing the (3/2, 3/2) resonance, but no $\pi\pi$ interaction. The effect of the vector part should lead to cross sections $\sim 10^{39}$ cm^2. The axial contribution is more difficult to evaluate even in the case of very rough approximations.

For comparison, the mean elastic cross section for neutrinos and antineutrinos, with our spectrum, was about 3×10^{-39} cm^2. Even if the contribution of the $\pi\pi$ interaction becomes important at high neutrino energies only, one could certainly expect the inelastic and the elastic cross sections to be of the same order of magnitude. Furthermore, there are not really 22 inelastic events for 29 elastic events, because no requirement like $P_\mu > 300$ MeV/c has been put for the inelastic events. In fact, that particular condition eliminates in the Brookhaven case 30% of the elastic events, which shifts the relative frequencies to

41 elastic against 22 inelastic events.

It is rather difficult to say how many events among those vertices could in fact be elastic events with high momentum transfer to the nucleon. An upper limit is obviously obtained by taking all the events with two prongs only, and nothing else, to be elastic events - amounting to eight events, of which only six have $P_\mu > 300$ MeV/c.

As far as the intermediate boson is concerned, it is difficult to say very much; the main argument is that the decay product of the W should take the maximum of the visible energy. In particular, this criterion excludes all but one of our events of the type (1p + 1 Se). In the case of the decay $W \to \mu + \nu$, which would correspond to two visible muons, one must also have a sufficiently small angle between the incoming neutrino and one of the muons, which must be the energetic one; two or three of the two prongs meet this criterion. In our four prong events, the energy is mainly concentrated in the presumed muon, and only one event (22306) could be a case of $W \to 3\pi$, associated with a muon. Finally, one extremely spectacular event (18891) with 1.5 GeV released in a charged pion + 2_γ probably coming from a π^0 could be a good example of $W^\mp \to \pi^\mp + \pi^0$. These five or six events constitute in a certain way an upper limit of the number of events which could be due to intermediate boson production in the Brookhaven experiment. The inelastic cross-section will certainly increase by a factor two or three in the case of the CERN experiment; we should, therefore, consider very seriously the possibility that a good proportion of the inelastic events will simulate intermediate boson events, and we should find a way of identifying this last type of event in a completely unambiguous manner.

TABLE I

Frame	Type*)	$P\mu$(Mev/c)	$\theta\mu$	Comments
14993	1p + 1 Se	>250	27°	
15871	1p + 1 Sγ	>600	8.5°	shower = 500 Mev/c from calibration.
17204	1p + 1 Se	>500	18.5°	
17991	2p + 1 Se	=190	50°	
18891	2p + 2 Sγ	>600	30°	apparently $\mu^{\pm} + \pi^{\mp} + \pi^{0}(2\gamma$'s)-presumed charged pion scatters inside the chamber. $\pi^{0} \sim 1$ Gev KE.
19142	2p	>420 =280	26° 47°	could be 2 μ's.
21132	2p	>300	16°	could be elastic event with high momentum transfer (450 Mev/c).
21989	3p	>400	53°	
22306	4p	~250	0-20°	visible kinetic energy roughly 250 Mev per particle, could be an example of $W \rightarrow 3\pi$.
22516	1p + 1 Se	=200		
22892	2p	=270 =310	53° 62°	
23241	2p	>345 >215	33° 66°	could be two μ's.
23369	4p	>420	26°	3 other prongs quite short.
23405	2p	>350	10°	could be two μ's.
23451	2p + 1 Sγ	>440	55°	shower roughly 250 Mev/c.
23620	3p	=250	38°	
23661	2p	>150 =195	49° 21°	
24394	2p	>250 >320	36° 40°	
25498	1p + 1 Sγ			prong interacting could be π + γ.
25866	4p	>600	36°	3 other short tracks,
29086	1p + 2 Se	>420	60°	
29136	2p	>440	27°	

*) p = prong.
Se= shower starting from creation plate.
Sγ= shower not starting from vertex.

References

1) G. Danby, J. M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, J. Steinberger, PRL 9, 36 (1962).

2) G. Danby et al - International Conference on High Energy Physics CERN (1962) page 809.

3) L. M. Lederman, Scientific American (March, 1963) page 60.

4) L. I. Lapidus, Preprint, Dubna E1120 (1962).

5) Løvseth - Private communication.

6) G. Danby, J. M. Gaillard, K. Goulianos, L. M. Lederman, T. D. Lee, N. Mistry, M. Schwartz, J. Steinberger PRL 10, 260 (1963).

7) Depommier et al, International Conference on High Energy Physics CERN (1962) p. 411.

Y.K. Lee, L.W. Mo, C.S. Wu, PRL, 10, 253 (1963).

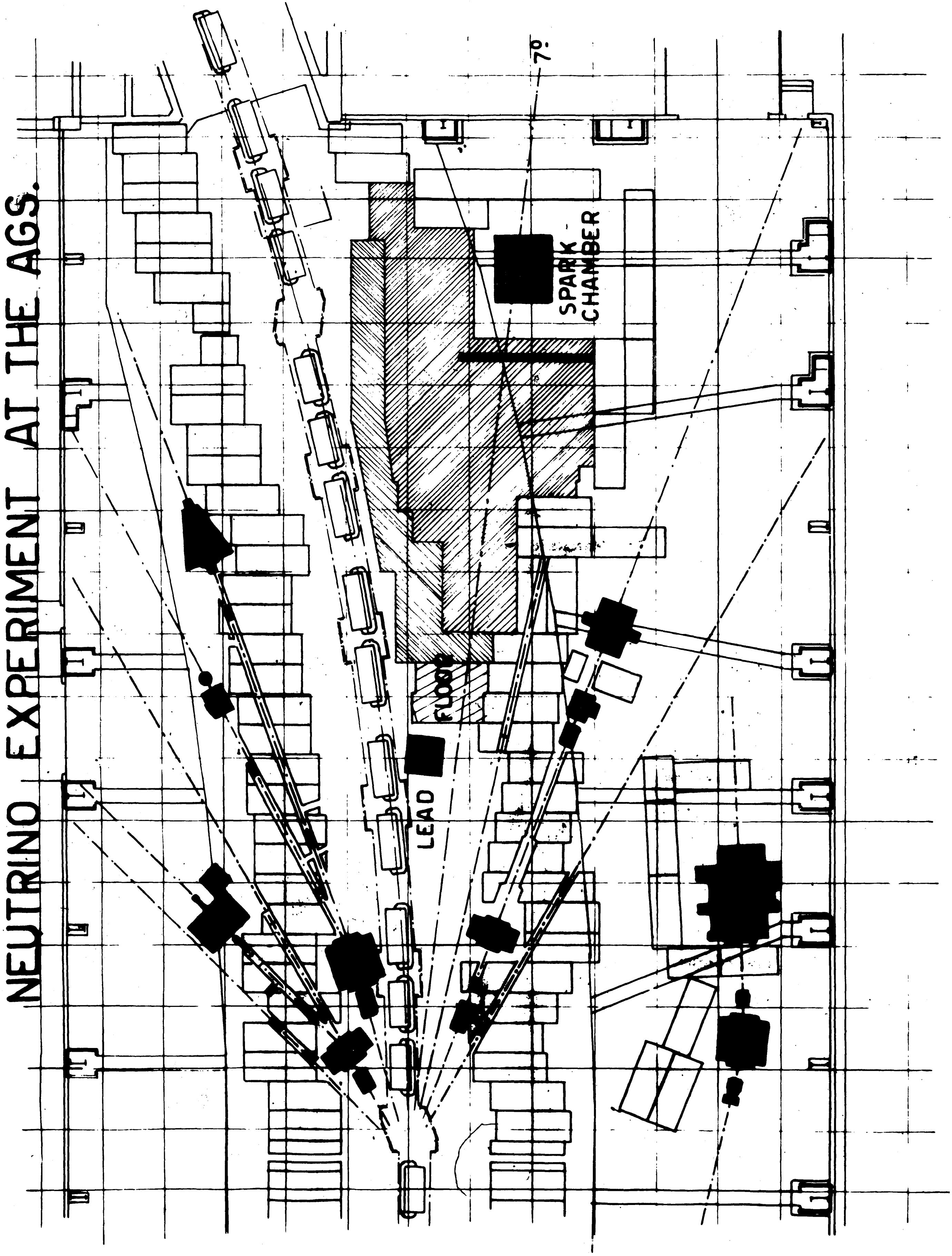


Fig. 1

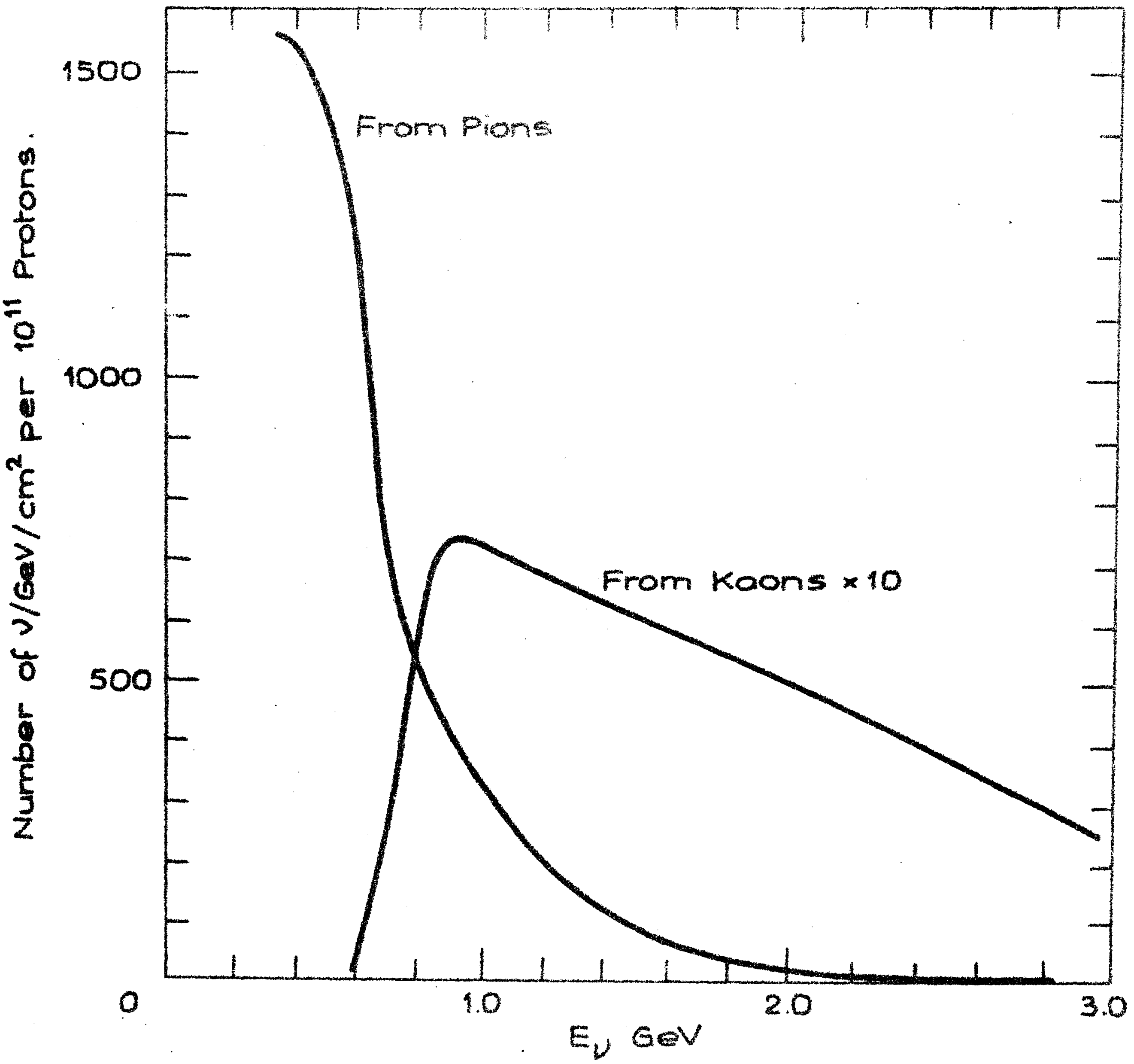

Number of ν/GeV/cm² per 10¹¹ Protons.
1500
1000
500
0
1.0
2.0
3.0
E_ν GeV
From Pions
From Kaons ×10

FIG. 2

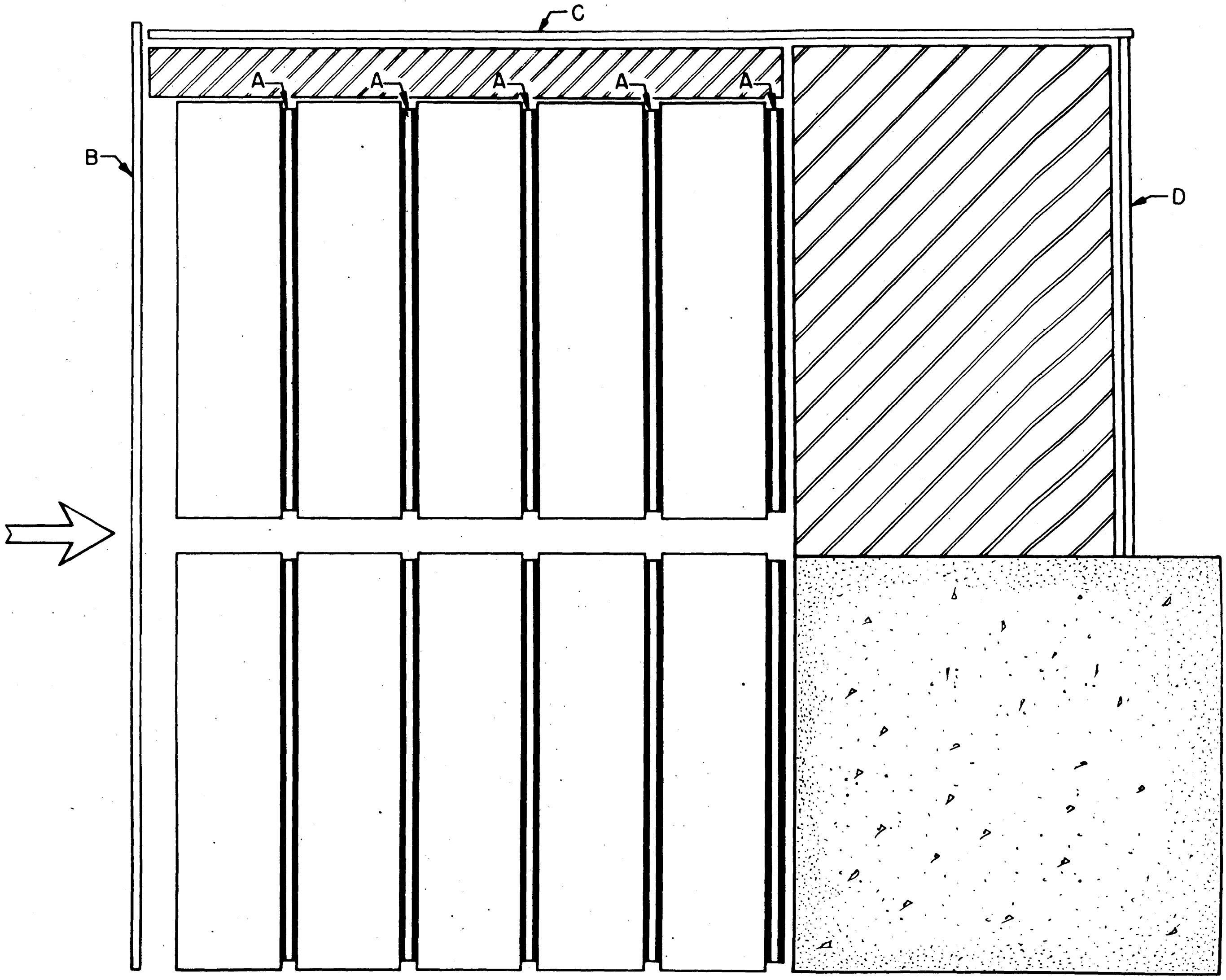
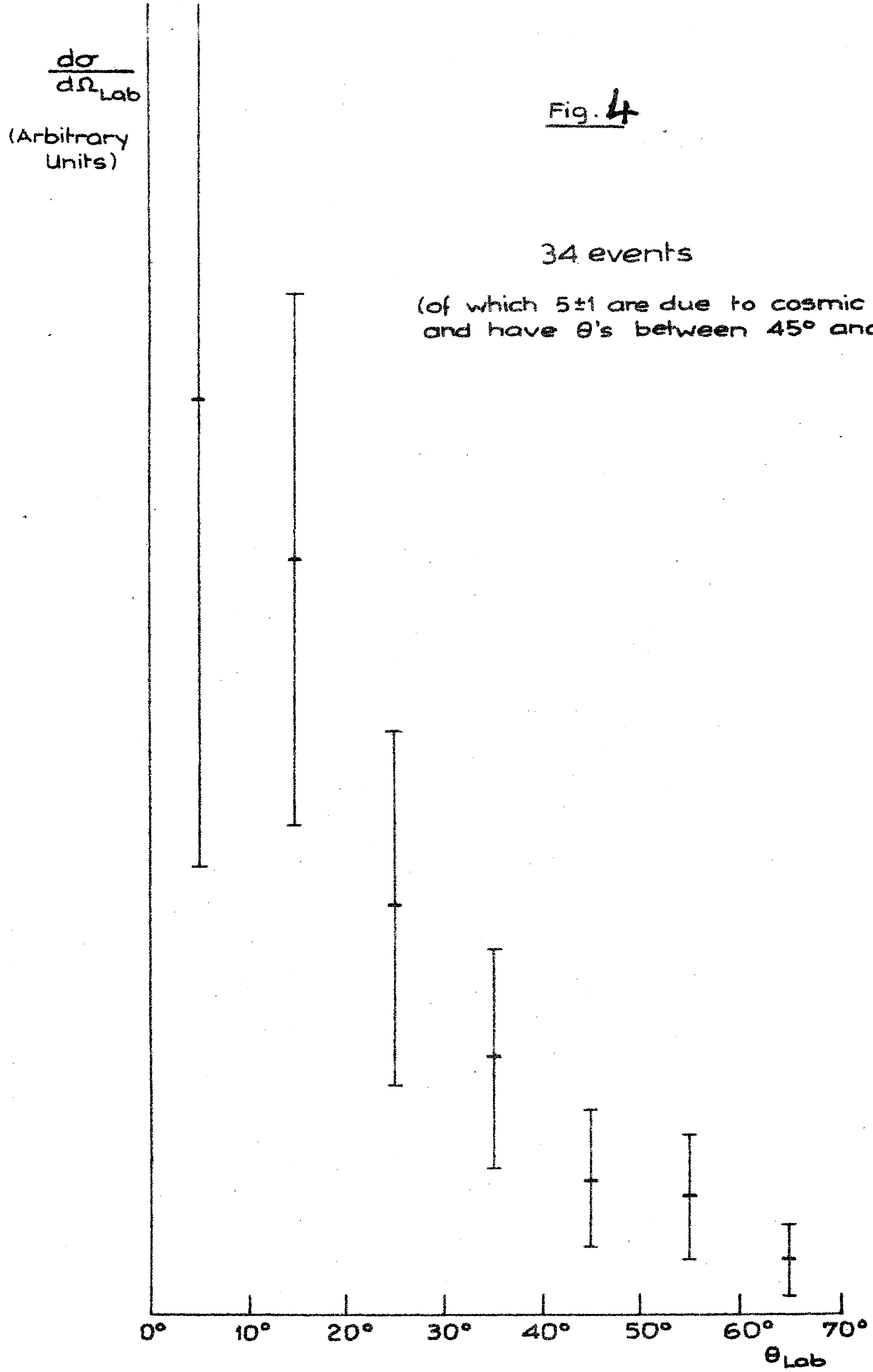


Fig. 3

Fig. 4



34 events

(of which 5±1 are due to cosmic rays and have θ's between 45° and 65°)