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OBSERVATION OF A LIKELY EXAMPLE OF THE DECAY OF A CHARMED PARTICLE PRODUCED IN A HIGH ENERGY NEUTRINO INTERACTION

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ABSTRACT

In a study of neutrino interactions occurring in nuclear emulsion, an event has been found that is most readily interpreted as the decay of a charmed particle with lifetime a few times 10^{-13}s.

The only detector which makes possible the direct observation of particles of lifetimes in the range 10^{-12} to 10^{-14}s is nuclear emulsion. The existence of such particles (charmed hadrons, heavy leptons) has been postulated for many years[(1)] and evidence for their production in e^+e^- collisions[(2)], high energy neutrino[(3)] and photon[(4)] interactions has been recently reported by several groups.

This paper reports the observation of a likely example of the decay of such a short-lived charged particle produced in a high energy neutrino interaction in nuclear emulsion.

The experiment was performed in the wide band neutrino beam at Fermilab using a technique developed earlier[(5)] whereby spark chambers are placed downstream of nuclear emulsion stacks. A neutrino interaction occurring in the emulsion can be located by predicting for the tracks of secondary particles observed in the spark chambers their point of origin in the emulsion. Stacks containing altogether 18 litres of Ilford K5 emulsion, made up of pellicles of dimensions 20cm x 8cm x 0.6mm were placed in association with a double wide gap spark chamber followed by a detector of electromagnetic showers and a rudimentary muon identifier. A veto counter upstream discriminated against interactions in the emulsion produced by charged particles. The experimental set-up, shown schematically in fig.1 will be described in detail elsewhere.

The stacks were exposed to neutrinos produced by a total of about 7×10^{17} protons of energy 400 GeV on target. From the known neutrino flux it is estimated that some 150 neutrino interactions should have been produced in the emulsion. Approximately 250 candidates for these interactions have been seen in the spark chamber pictures and, to date, a search has been made for about one third of them. The search involves scanning a volume of the emulsion averaging about $0.7cm^3$, around the position of the vertex predicted from the measurements of the spark chamber film. So far 16 interactions have been located in the emulsion and analysed. Among these has been found an event in which one of the secondary particles presents the features to be expected of the decay of a short-lived particle.

Fig. 2 shows a photomicrograph of the event as seen in the emulsion. Fig. 3 shows a schematic drawing based on the spark chamber photographs associated with the event. At the neutrino interaction, vertex A in fig.2, are seven tracks due to low energy protons or nuclear fragments. There are in addition five tracks with a specific ionization, as measured in the nuclear emulsion, compatible with minimum ionization. One of these, track 4, is found to give rise to three further tracks of minimum ionization at vertex B after a distance of 182 μm. As there is no sign of a nuclear recoil track the event has the characteristics to be expected of the decay of an unstable particle.

The four remaining tracks of minimum ionization from the neutrino interaction vertex and two of the tracks from vertex B(tracks 41 and 43) were followed to the stack edge. The particle giving rise to track 42 interacted at a distance of 3.7mm., emitting a single heavily ionizing particle.

As can be seen from Table 1, the event was found within the volume predicted from the measurements of the tracks seen in the wide gap chamber. There was no other candidate in the predicted volume.

The table also shows the angles of the tracks as measured in the emulsion at the vertices A and B and in the wide gap chamber. The detection efficiency of the wide gap chamber becomes quite low for oblique tracks making angles greater than 20° with the axis of the system. Taking this into account and also the effect of the multiple scattering suffered by the particles along their path in the emulsion, the correlation between the angles measured in the wide gap chamber and in the emulsion is seen to be very good. Similar correlations were observed for the other 15 events analysed up to now.

Track W1, seen both in the second gap of the wide gap chamber and in the narrow gap chambers of the shower detector, and track S1 of large azimuth, seen only in the shower detector, do not correlate with any tracks in the emulsion. Nevertheless, because these occur on the same spark chamber photographs as the tracks from the neutrino interactions, they must be correlated in time to within 1 μs and, therefore, are almost certainly related in some way to the event. The lines of tracks W1 and S1 pass each other at a minimum distance compatible, within the errors, with an intersection at a point near the centre of the wide gap chamber. These tracks are most probably to be interpreted as due to the charged decay products of a neutral V particle originating from either vertices A or B of the event.*

A geometrical analysis of the tracks from vertex B establishes that the tracks 42 and 43 lie on the same side of the plane containing tracks 4 and 41 so that at least one neutral particle must be assumed to come from this vertex if it is to be interpreted as a decay. It is found indeed that

$$\underline{\hat{n}} \cdot \underline{\hat{p}}_{42} = 0.12 \pm 0.03 \quad ; \quad \underline{\hat{n}} \cdot \underline{\hat{p}}_{43} = 0.13 \pm 0.03$$

where $\hat{n}$ is the unit vector normal to the plane containing tracks 4 and 41, and $\hat{p}_{42}$, $\hat{p}_{43}$ are unit vectors along the directions of tracks 42 and 43, respectively.

The direction of the neutral V particle derived from the spark chamber pictures makes it a good candidate for the missing neutral particle from the vertex B, taking off at least part of the imbalanced transverse momentum.

The muon identifier recorded the passage of at least one particle, correlated in time with the spark chamber pictures, through the 1.35 m lead screen. The total pulse height recorded by the electron multipliers of the shower detector indicates the absence of any high energy electron cascade.

All observations are consistent with the interpretation of vertex B as the decay point of the particle which gives rise to track 4, irrespective of whether the V^o candidate is associated with it. There are, however, two alternative hypotheses to be considered. In order to estimate the size of these backgrounds, the possible association of the V^o candidate with vertex B will be ignored.

The first concerns the possibility of the event being due to a hadronic secondary emitted from the neutrino interaction undergoing an interaction with a nucleus in the emulsion. A reliable estimate of this may be made from the number of events of similar topology found in an experiment in which the interactions of 300 GeV protons in nuclear emulsion were examined for charmed particle decays[6]. In this earlier experiment the secondary particles from a total of 62,000 proton

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* The alternative possibility that the observed configuration arises from a nuclear interaction of a neutral particle is remote as the only matter in this region is a 2mm aluminium plate separating the two gaps.

interactions were followed for 150 μm in the search for stars consisting only of an odd number of minimum ionizing particles and no nuclear recoil or low energy electron. Ten events with this topology were found. However, as there are no examples of associated production and as the path length distribution for the particles producing these events was found to be flat, it was concluded that these decay candidates arose from nuclear interactions of charged hadrons. Taking account of the relative multiplicities in high energy proton interactions in emulsion ($\sim$ 15) and in the neutrino interactions observed in the present experiment ($\sim$ 5), the probability that the event in the present experiment is due to a nuclear interaction is estimated to be at the level of one in thousand.

Background from the decay of known particles has also been considered. The only possible decays compatible with the emission of three charged particles and at least one neutral particle are $K^{\pm}$ decays into one charged particle and a π^o which in turn decays giving a Dalitz electron pair; a Σ^+ decay to a proton and π^o, which also decays giving a Dalitz pair; and K_{e_4} or K_{μ_4} decays. Even if strange particle production occurred in each neutrino interaction the chance of any such decay occurring within 182 μm is at most one in 10^6.

The observation of the V particle, assuming it to come from decay point B, makes it possible to balance momentum in the decay without postulating the emission of other neutral particles. Assuming it to be either a Λ^o or K^o and using the measured angle between tracks W_1 and S_1, the small angle θ_o between the direction of W_1 and of the V particle can be determined in terms of the momentum, P_o of the latter. The particle producing track S_1 is seen to pass through 44gm/cm^2 Pb equivalent in the shower detector so that its momentum (if a pion) is greater than 185 MeV/c. If in addition the line of flight of the V is required to pass through the decay vertex B within the measurement accuracy of 1^o, these considerations provide the following constraints on the characteristics of the V particle :-

If it is assumed to be a Λ^o, θ_o is limited to the range $1.3^o - 2.5^o$ and P_o from 2.2 to 2.9 GeV/c while its flight time corresponds to 1.8 to 2.4 mean lives.

If it is assumed to be a K^o, θ_o is limited to the range $1.7^o - 2.5^o$ and P_o from 1.8 to 2.7 GeV/c with corresponding flight time 2.7 to 4 mean lives.

Considering first only the primary particle 4 and the V particle and supposing the latter to have the above range of angle and momentum the missing mass at the decay point can be estimated as follows, assuming the primary to have one of the masses already observed for the particles Λ_c^+ (2.25)[4] and D^+ (1.87)[2b]:-

For the decay $\Lambda_c^+ (2.25) \rightarrow \Lambda^0$ + anything, the range of missing mass is 0.95 - 1.10 GeV/c^2.

For the decay $D^+ (1.87) \rightarrow K^0$ + anything, 1.0 - 1.25 GeV/c^2.

These results are nearly independent of the primary momentum.

Multiple scattering measurements have been made on tracks 41, 42, 43 giving $p\beta$ estimates, in MeV/c, of 430 ± 50, 265 ± 50, 270 ± 40 respectively for the particles producing these tracks. The errors quoted are statistical only. The effect on $p\beta$ measurements of possible distortions due to processing the emulsions off glass is not known. Their maximum influence has been estimated by assuming that the observed "multiple scattering" of particle 1 from vertex A ($p\beta$ = 750 ± 180 MeV/c) is entirely due to noise. Assuming the other $p\beta$ measurements are subject to the same noise, upper limits of $p\beta$, in MeV/c, of 525 ± 110, 285 ± 60, 290 ± 45 are estimated for particles 41, 42, 43 respectively. Upper limits of the invariant mass calculated from these estimates are 0.55 ± 0.04 GeV/c^2 assuming all three particles are pions and 1.24 ± 0.03 GeV/c^2 assuming 41 and 42 are kaons and 43 a pion.

Comparing these invariant masses with the missing masses derived above it is possible to state the observations are not consistent with either of the decay schemes

$$\Lambda_c \ (2.25) \rightarrow \Lambda^0\pi\pi\pi \quad \text{or} \quad D(1.87) \rightarrow K^0\pi\pi\pi.$$

These statements remain valid even if the observed V is unassociated with the decay.

However many other decay schemes are possible. For example the invariant masses could be consistent with the schemes,

$$\Sigma_c \ (2.48)^{(4)} \rightarrow \Lambda^0K^+K^-\pi^\pm \quad \text{or} \quad D(1.87) \rightarrow K^0K^+K^-\pi^\pm.$$

Other decay schemes such as

$$\Xi_c \to \Sigma^0 K^+ K^- \pi^\pm \quad \text{or} \quad \Lambda_c^+ \to \Xi^0 K^+ \pi^+ \pi^-$$
$$\hookrightarrow \Lambda^0 \gamma \qquad\qquad\qquad \hookrightarrow \Lambda^0 \pi^0$$

can also be envisaged but since these involve the assumption of an undetected γ or π^0 they cannot be tested quantitatively.

It should be emphasised however that there is no way of positively ascribing the observed V to the decay vertex B, so that a decay of type $\Lambda_c \to nK\pi\pi$ is conceivable. Nor can the possibility of interpreting the event as a leptonic decay be ruled out from the observations. However the conclusion remains that the event most probably represents a massive new short-lived particle decaying after an observed flight time of $\sim 6 \times 10^{-13}$s with characteristics compatible with those expected for the decay of a charmed particle.

We are grateful to the staff of the Fermilab whose cooperation and help made the experiment possible and especially to the Director, Professor R.R. Wilson, for his personal interest and encouragement. We are grateful also to CERN for providing facilities for testing the wide gap spark chamber, calibrating the shower detector, and processing the nuclear emulsion.

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TABLE 1

COMPARISON OF OBSERVED AND PREDICTED FEATURES OF NEUTRINO INTERACTION

	Observed (emulsion) Pellicle No.	X (mm)	Z (mm)	Predicted (Spark Chamber) Pellicle No.	X (mm)	Z (mm)	Remarks
Event Position	E58	39	69	E60±3	38±3	71±10	

Track No.	Length of track followed (mm)	Observed Azimuth $\phi(\pm\frac{1}{2}^{\circ})$	Observed Dip $\theta(\pm1^{\circ})$	Predicted Azimuth $\phi(\pm1^{\circ})$	Predicted Dip $\theta(\pm1^{\circ})$	Remarks (Errors do not appl to track S_1)
1	16.2	-6.7°	-8.2°	-6.6°	-9.6°	
2	12	-7.0°	$+9.5^{\circ}$	-	-	Not seen in spark chamber.
3	13.3	-3.5°	$+14.0^{\circ}$	-4.5°	$+14^{\circ}$	
4	0.182	$+9.7^{\circ}$	-7.1°			Track that breaks u after 182 μm.
41	13.8	-5.5°	$+5.8^{\circ}$	-5.7°	$+6.2^{\circ}$	
42	3.7	$+23.8^{\circ}$	-8.3°			Interacts in emulsion.
43	8.2	+28.0	-11.1°			Oblique tracks not expected to be see in spark chamber.
5	19	$+31.5^{\circ}$	-8.6°			(Oblique tracks not expected to be see in spark chamber.)
W1				$+3.1^{\circ}$	-9.7°	Seen in both wide and narrow gap spark chambers, not in emulsion.
S1				$19.5\pm3^{\circ}$	$+4.5\pm2^{\circ}$	Seen in narrow gap spark chamber only not in emulsion.

FIGURE CAPTIONS

Fig.1 – Lateral view of experimental set-up indicating spark chamber triggering logic. The event vertex is determined within a small fiducial volume by tracing back into the emulsion stack the tracks observed in the wide-gap chamber.

Fig.2 – a) Microphotograph showing a neutrino interaction (Vertex A) involving the emission of a charged particle (track 4) which undergoes a secondary process (nuclear interaction or decay) after 182 μm (Vertex B). Three minimum ionizing particles with negative dip are seen to be emitted from B. Two further tracks of minimum ionizing particles (tracks 2 and 3 with positive dip) are not shown in the photograph. The blob to the left of B is unassociated with the event.

Fig.3 – Schematic drawing based on the spark chamber photographs associated with the event. The tracks seen in the wide gap spark chamber are shown by thick lines. (The first gap was less efficient and not all the tracks were seen in it). Tracks 5, 43 seen in emulsion as well as S_1, seen in the narrow gap chambers of the shower detector are too oblique to have been seen in the wide gap chamber. Track 42 interacts before leaving the emulsion. Track 2 seen in emulsion is not seen in the spark chamber although it might have been expected to be seen there. The dotted line indicates the flight path of the neutral particle interpreted as a V^o.

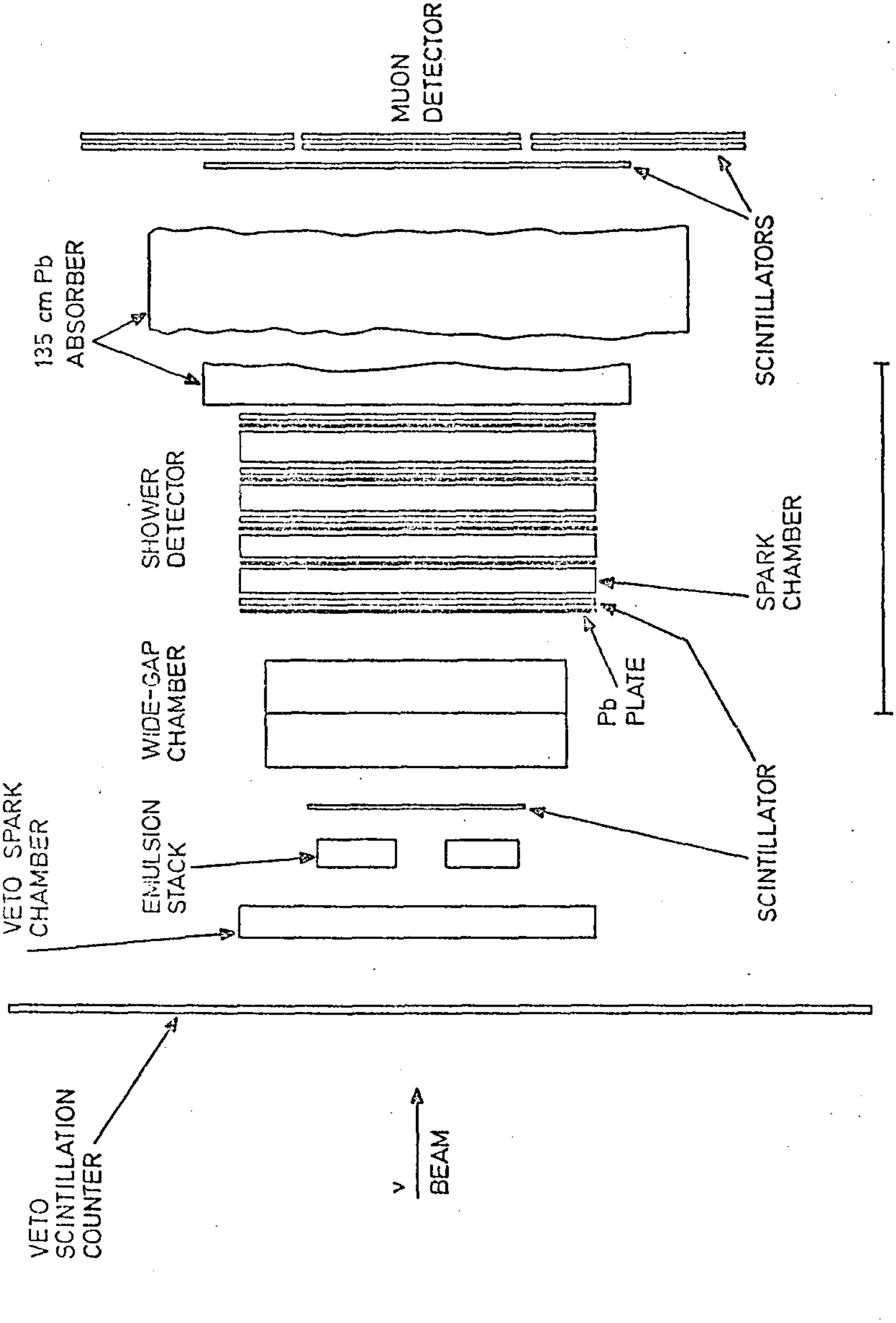

MUON
DETECTOR
SCINTILLATORS
135 cm Pb
ABSORBER
SHOWER
DETECTOR
SPARK
CHAMBER
100 cm
WIDE-GAP
CHAMBER
Pb
PLATE
SCINTILLATOR
VETO SPARK
CHAMBER
EMULSION
STACK
SCINTILLATOR
VETO
SCINTILLATION
COUNTER
ν
BEAM

Fig. 1

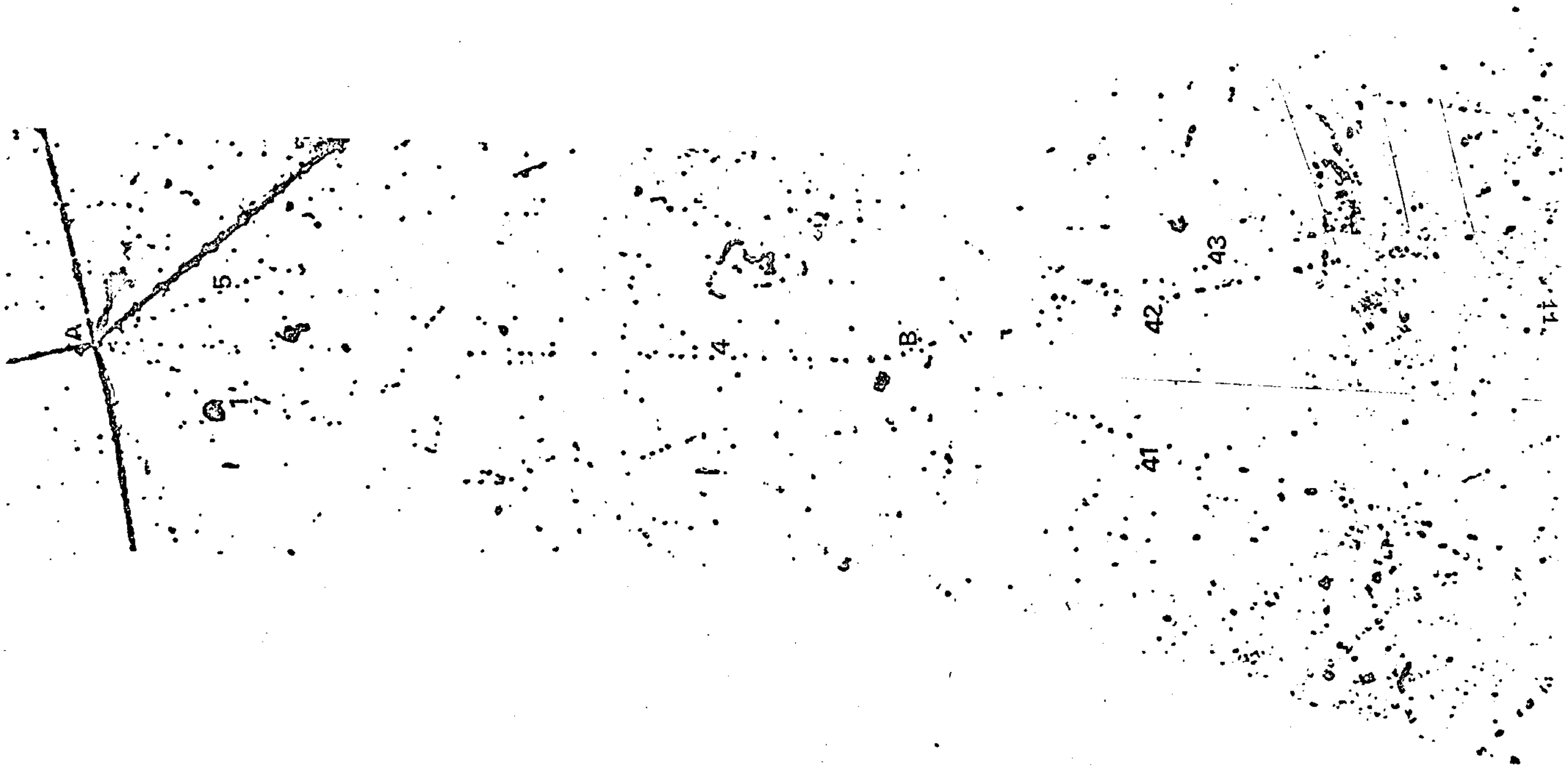
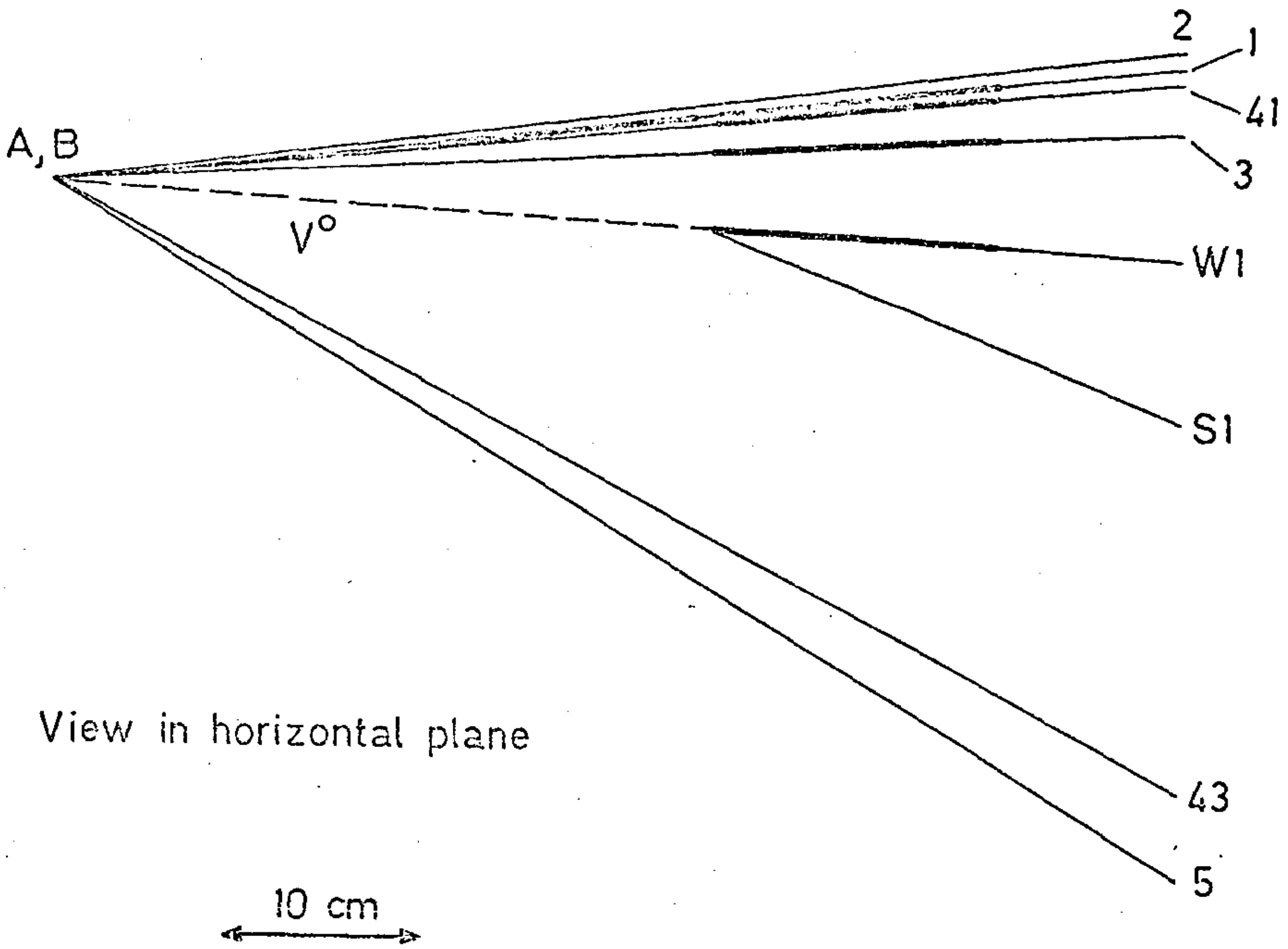
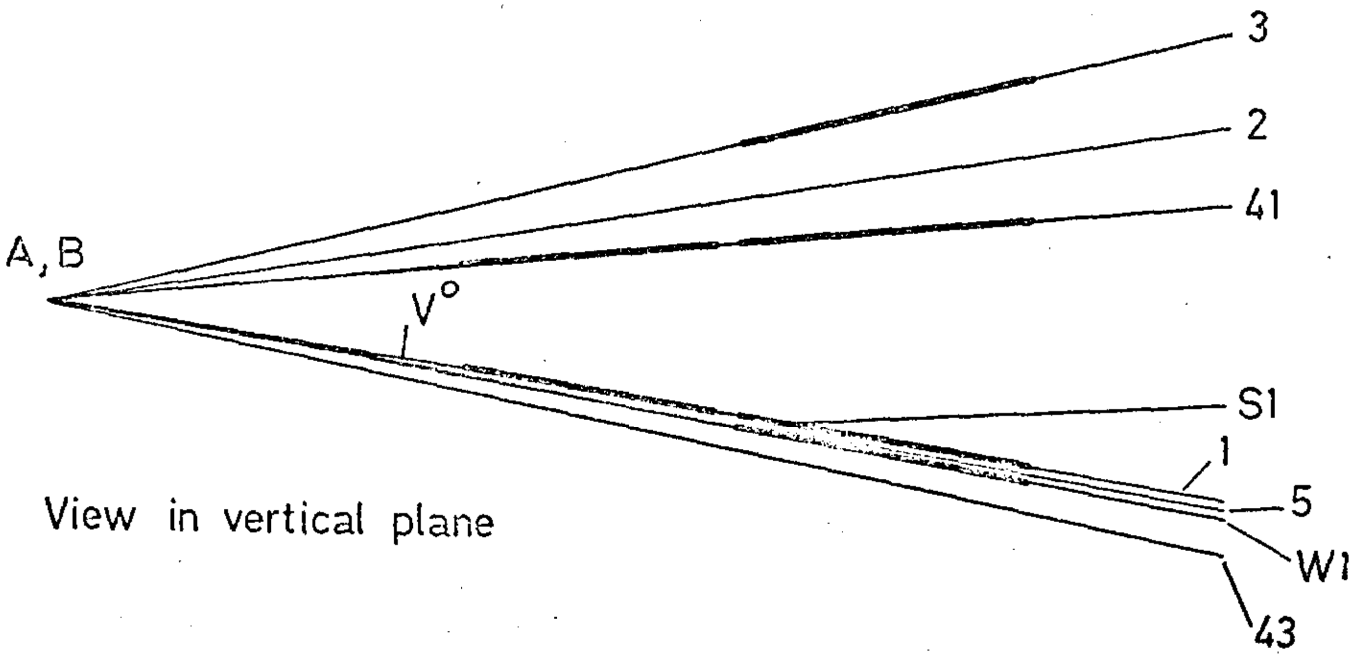


Fig. 2



View in horizontal plane



View in vertical plane

FIG. 3