no experiment

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

"ARE NEUTRAL LEPTON CURRENTS COUPLED IN NATURE?"

T. Massam, Th. Muller and A. Zichichi

G e n e v a

3rd May, 1964

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* * *

The purpose of this paper is two-fold:

i) to present a general review on the experimental information concerning the existence of neutral lepton currents in order to call attention to the fact that during the last two years the situation has drastically changed, thanks to the discovery of the ν_μ [1] and to the work of Franzini [2], Cabibbo [3] and of the Lagarigue group [4];

ii) to present an experimental proposal.

GENERAL REVIEW

Prior to the discovery of the neutretto, ν_μ, the following experimental limits of the branching ratios were considered valid evidence for the lack of coupling of neutral leptonic currents in strangeness conserving weak interactions, i.e.

$$\frac{\mu \to 3e}{\mu \to e\nu_e\nu_\mu} \leq 2.6 \times 10^{-7} \qquad (1)$$

$$\frac{\mu N \to e N'}{\mu N \to \nu N'} \leq 2.4 \times 10^{-7} \;. \qquad (2)$$

The existence of the muonic quantum number implies a complete absence of processes 1 and 2, thus forbidding any conclusion to be drawn from the above-measured branching ratios concerning the existence of neutral lepton currents.

The only available source of information is, by now, the CERN neutrino experiment, where the lack of processes of the type

$$\nu + p \rightarrow \nu + p \tag{3}$$

gives a branching ratio of the order of $\sim 5\%$[5] for the neutral-to charged-lepton current processes, i.e.

$$\frac{\text{rate of } (\nu + p \rightarrow \nu + p)}{\text{rate of } (\nu + n \rightarrow \mu^- + p)} \simeq 0.05 .$$

So, for strangeness conserving weak interactions the upper limit for the rate of processes involving neutral lepton currents, has gone up from 10^{-7} to $\frac{1}{2}10^{-1}$.

With regard to strangeness violating weak interactions the upper limits for the rates of process involving neutral lepton currents range from $\frac{1}{2}10^{-1}$ to 10^{-3}, depending upon the specific processes chosen. The experimental situation can be summarized as follows:

(see ref. 6) $$\frac{K^{\pm} \rightarrow \pi^{\pm} + (\text{neutral lepton pair})}{K^{\pm} \rightarrow \pi^{0} + (\text{charged lepton pair})} \lesssim 10^{-3} \tag{4}$$

(see ref. 7) $$\frac{K_2^0 \rightarrow \text{neutral lepton pair}}{K^{+} \rightarrow \mu\nu} \lesssim 10^{-3} \tag{5}$$

(see ref. 8) $$\frac{\Lambda^0 \rightarrow n + (\text{neutral lepton pair})}{\Lambda^0 \rightarrow p + (\text{charged lepton pair})} \lesssim \tfrac{1}{2}10^{-1} . \tag{6}$$

As we have seen, prior to the discovery of the ν_μ, the best experimental knowledge on the absence of neutral lepton currents coupling came from strangeness conserving weak processes (1,2) and was more than ten thousand times better than the information which came from strangeness violating weak processes. Now the situation is inverted, and our best source of information is the strangeness violating weak processes (4,5,6); but this source of information is four orders of magnitude worse!

Note that the above considerations are based on the hypothesis that the neutral lepton current coupling does not depend critically on the choice of a particular process, and that it is as universal as the charged lepton current coupling. In other words, if the neutral lepton current coupling is present in one process, it has to be present in all others with the same strength.

At this point the question might be raised: "why do we want to have neutral lepton currents?" It could be that only the charged ones exist for a reason (which has to be very deep) still to be understood. The answer is that if we believe in the validity of the ($\Delta I = 1/2$) rule, we have to believe that neutral non-leptonic currents exist. If neutral non-leptonic currents exist, then the most natural formulation[9] of a (current) $\times$ (current) Universal Fermi Interaction, implies the existence of neutral lepton currents. So, let us review the situation concerning the validity of the ($\Delta I = 1/2$) rule. No distinction is made here between the ($\Delta I = 1/2$) rule "non-leptonic" and "leptonic". This is because in a most natural formulation of the UFI[9] the validity of the ($\Delta I = 1/2$) rule "non-leptonic" implies the validity of the ($\Delta I = 1/2$) rule "leptonic".

In Table 1 we report the experimental results supporting the validity of the ($\Delta I = 1/2$) rule; in Table 2 we list the experimental results contradicting the predictions of the ($\Delta I = 1/2$) rule. These tables summarize the experimental situation up to 1962. However, to date, three experimental results have disappeared from the list of experiments contradicting the validity of the ($\Delta I = 1/2$) rule, namely:

1) The Ely et al. experiment repeated by the Ecole Polytechnique group[4] seems to yield no evidence for $\Delta Q = -\Delta S$;

2) The triangular relation for the amplitudes of the Σ decays was shown by Franzini[2] to be, within experimental errors, perfectly compatible with the $(\Delta I = \frac{1}{2})$ rule;

3) The value of the ratio

$$R = \frac{\text{rate of } K_1^0 \to 2\pi}{\text{rate of } K^+ \to \pi^+\pi^0}$$

need not be $\sim (137)^2$ if we want to believe in the validity of the $(\Delta I = \frac{1}{2})$ rule, but it might well be ~ 700 (as experimentally measured) because of the forbiddeness of the decay $K_1^0 \to 2\pi$ dictated by the SU_3 invariance properties of the Weak Interaction Lagrangian, as shown by Cabibbo[3].

It follows that the only experimental evidence left against the validity of the $(\Delta I = \frac{1}{2})$ rule are the rates of K^+ and K^0 decays.

The conclusion of this review is, that the old days of very low $(\sim 10^{-7})$ branching ratios for neutral lepton currents and the great suspicion towards the validity of the $(\Delta I = \frac{1}{2})$ rule, are now over.

This is why we would like to propose an experiment which is able to bring the upper limit, for the rate of processes involving neutral lepton currents, down by three orders of magnitude.

Table 1

Predictions of the ($\Delta I = \frac{1}{2}$) rule
which are confirmed by experimental results

Theoretical predictions of the $\Delta I = \frac{1}{2}$ rule	Experimental results
$\frac{K_1^0 \to 2\pi^0}{K_1^0 \to \pi\pi} = \frac{1}{3}$	0.294 ± 0.021 Cretien et al. 0.329 ± 0.013 Brown et al. 0.260 ± 0.024 Anderson et al. Proceedings of 1962 International Conference on High-Energy Physics at CERN.
$\frac{\Lambda^0 \to p\pi^-}{\Lambda^0 \to n\pi^0} = 0.660$	0.685 ± 0.017 Anderson et al. loc. cit.
$\frac{\alpha_\Lambda\ (n\pi^0)}{\alpha_\Lambda\ (p\pi^-)} = 1.00$	1.10 ± 0.27 Cork et al. Phys.Rev. 120, 1000 (1960).

Table 2

Predictions of the $(\Delta I = \frac{1}{2})$ rule
which are in contradiction with experimental results

Theoretical predictions of the $(\Delta I = \frac{1}{2})$ rule	Experimental results
$2R_+ = R_1 = R_2$ 1st check $2R_+ = R_2$ ⟵	$2R^+ = (16.5 \pm 1.18) \cdot 10^6\ s^{-1}$ $R_2 = (9.31 \pm 2.49) \cdot 10^6\ s^{-1}$ Alexander et al. Phys.Rev.Lett., 9, 69 (1962). $2R^+ = 8.4 \pm 1.2 \times 10^6$ (Bmi et al 1958) ⟶ $16.5 \pm 1.18 \neq 9.31 \pm 2.49$ *)
2nd check $\frac{R_1}{R_2} = 1$ ⟵	$\frac{R_1}{R_2} = 11.9^{+7.5}_{-5.6}$ Ely et al., Phys.Rev. Lett. 8, 132 (1962). $\frac{R_1}{R_2} = 6.6^{+6.0}_{-4.0}$ Alexander et al., Phys. Rev.Lett. 9, 62 (1962).
where: $R_+ = R(K^+ \to e^+ \pi^0 \nu)$ $R_1 = R(K_1^0 \to e^\pm \pi^\mp \nu)$ $R_2 = R(K_2^0 \to e^\pm \pi^\mp \nu)$ ⟶	$\frac{R_1}{R_2} = 3.5^{+3.9}_{-2.7}$ Crawford 1959 CP invariance confirmed by $\frac{K_L^0 \to \pi^- e^+ \nu}{K_L^0 \to \pi^+ e^- \nu} = 0.9 \ldots$ (Neagu, PRL 6, 552, 1961)
$R(K_2^0 \to \pi^+\pi^-\pi^0) = 1.032 \cdot$ $\cdot\ 2R(K^+ \to \pi^+\pi^0\pi^0)$ ⟵	$R(K_2^0 \to \pi^+\pi^-\pi^0) = (1.44 \pm 0.43) \cdot 10^6\ s^{-1}$ $R(K_+ \to \pi^+\pi^0\pi^0) = (1.39 \pm 0.11) \cdot 10^6\ s^{-1}$ Alexander et al., Proc. of 1962 Int.Conf. on High-Energy Physics at CERN, p. 450 ⟶ $2(1.39 \pm 0.11) \neq (1.44 \pm 0.43)$
Triangular relation between $A_+ A_- A_0$ in the decay of $\Sigma^+ \to n\pi_+, A_+$; $\Sigma^+ \to p\pi^0, A_0$ $\Sigma^- \to n\pi^-, A_-$	The experimental results are off by about three standard deviations Tripp et al., Phys.Rev.Lett., 9, 66 (1962)
$\frac{K^+ \to \pi^+\pi^0}{K_1^0 \to \pi\pi} = \left(\frac{1}{137}\right)^2$	$\frac{K^+ \to \pi^+\pi^0}{K_1^0 \to \pi\pi} = \frac{1}{700}$

*) A more recent value is $14.5 \pm 1.0 \neq 9.9 \pm 2.0$ (see ref. 8)

8857/p/cm

THE EXPERIMENTAL PROPOSAL

The processes we would like to study are:

$$K^+ \rightarrow \pi^+ \mu^+ \mu^-$$
$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad .$$

In Table 3 we list all decay processes of the K^+ known so far, along with the relative branching ratios.

Table 3

$K^+_{\mu 2} \rightarrow \mu^+ \nu_\mu$	$(64.2 \pm 1.3)\%$
$\Theta^+ \rightarrow \pi^+ \pi^0$	$(18.6 \pm 0.9)\%$
$K^+_{\mu 3} \rightarrow \mu^+ \pi^0 \nu_\mu$	$(4.8 \pm 0.6)\%$
$K^+_{e3} \rightarrow e^+ \pi^0 \nu_e$	$(5.0 \pm 0.5)\%$
$\tau^+ \rightarrow \pi^+ \pi^- \pi^+$	$(5.6 \pm 0.3)\%$
$\tau'^+ \rightarrow \pi^+ \pi^0 \pi^0$	$(1.7 \pm 0.2)\%$
$K^+_{e4} \rightarrow \pi^+ \pi^- \nu e^+$	$(\sim 0.003)\%$

Figure "0" shows the value of the momentum of the π^+ emitted in each decay mode. When the decay process is not a two-body process the value of the π^+ momentum represents the end-point value of the π^+ spectrum.

It is easy to see that for the processes we are looking for

$$K^+ \rightarrow \pi^+ \mu^+ \mu^-$$
and
$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

the most serious source of background is the τ^+ decay and the Θ^+ decay, respectively.

First we will study the possibility of detecting the decay mode:

$$K^+ \rightarrow \pi^+ \mu^+ \mu^- .$$

The beam we wish to use is the high-intensity K beam (m_4 beam)[10] where the intensity of K^+ mesons is expected to be of the order

$$5000\ K/10^{11} \text{ protons at } 1.5\ GeV/c .$$

The technique which we wish to use is to allow the K to decay in flight at not too high momentum and then identify the three charged particles by means of accurate range and direction measurements.

To help one visualize the problem, we consider the special cases shown in Figures 1 and 2 in which the decay plane is perpendicular to the beam direction. The 3π decay is chosen with equal sharing of the kinetic energy between the three particles. In the $\pi 2\mu$ decay, pion $\pi 1$ has the same energy and the residual energy is shared equally between the two muons. We now investigate the possibility of confusing these two events in the laboratory system. Table 4 shows the parameters of these two decays in the laboratory.

Table 4

Particle	DIRECTION		Kinetic energy	Momentum	Range in Copper
	Azimuthal angle	Polar angle			
π	120°	68°	94 Mev	187 Mev/c	36 gm/cm²
μ	168°	84°	126 Mev	208 Mev/c	60 gm/cm²

These characteristics are very different for the two particles, but we may ask if it is possible for a pion to decay into a muon with the same angle and energy as the muon from K decay.

The smallest angle between $\pi 2$ and $\mu 2$, when transformed to the laboratory system is 16.5°. Now for 95 MeV pions, the maximum angle between a muon and its parent pion is 12.5°, so we would see that the angles of particles '2' and '3' are incorrect by 4° each. Further, at this decay angle, the muon has only 60 MeV instead of 126 MeV kinetic energy. To see the significance of these differences, we now estimate the experimental errors which we may expect:

Experimental accuracy

a) Directions A one mm uncertainty in the spark location and 25 cm separation between spark chambers gives 0.25° uncertainty in angle.

b) Range and Energy At 100 MeV, a calculation of the Bohr straggling gives a standard deviation of 2.6 gm of Copper or 4.3 MeV. Figure 3 shows a range measurement made near 100 MeV in rather poor geometry so that there was already some restriction on the straggling accepted. In this case, the standard deviation of the range determination was 1.8 gm/cm or 3 MeV.

Conclusion of feasibility

We see that the differences between the two processes are large, compared with the experimental errors; in terms of standard deviations, the difference is some 80 standard deviations. This excellent rejection of τ decays in the special case, gives us confidence that the rejection will be sufficient (5 standard deviations) in all cases. A computer programme is at present being developed to check this and to calculate the expected rate which is estimated below.

Design of the apparatus

Figures 4 and 5 show a preliminary design of the set-up. The effective length of the beam from which decays are observed is 50 cm. Four identical telescopes are arranged symmetrically about the beam, allowing a 2π azimuthal acceptance by the use of an 'any three telescopes out of four' coincidence requirement. A double coincidence between the first two counters of a telescope indicates the entrance of a particle.

It is shown later that the sum of the ranges in the three telescopes which are struck, is nearly constant over a wide range of energy partition between the three particles. This fact is used to reduce the trigger rate from τ decay, by imposing that the total number of counters, which fire in the telescopes giving the coincidence, is greater than some minimum value, which is 17 in the present design. Thus the trigger requirement will look like:-

Telescope	Up	Down	Right	Left			
Counter	(1.2)	(1.2)	(1.2)	(1.2)	(Any three)	and	At least 9 other counters in the three telescopes

Counter $\bar{A}$ is placed in anticoincidence to avoid random coincidences caused by many pions decaying before the beam reaches the investigated decay region.

Each telescope consists of three thin plate spark chambers, separated by 25 cm, to give angular measurements; then there are six range chambers and a final counter 7. Each range chamber consists of a one cm thick plastic scintillator and a brass spark chamber with three plates, each three mm thick. This thickness is chosen to give uncertainty in the range measurement from the plate thickness, which is half the straggling standard deviation.

Rate of events

Figure 6 shows the phase space spectrum in the K system of the pion from $K \rightarrow \pi\mu\mu$. At each value of the momentum, we assume an isotropic distribution of the pion and see what range of centre of mass angles can be accepted in our telescope. We assume 2π azimuthal acceptance for the pion. Below about 40 MeV/c, the pions are emitted at too small an angle in the laboratory to be accepted. At 90 MeV/c, Fig. 7 shows that we have 80% solid angle, and at 140 MeV/c it is 50%. The curve of phase space X(solid angle)/4π is shown dotted in Fig. 6 and gives a mean acceptance of 50% for the pion.

A pessimistic estimate of the muon detection efficiency is to assume that it is half that of the pion (since once the pion enters one of the four telescopes, the muon has a choice of only two), and then to assume that the muons are independent of the pion and of each other. This gives 0.06 detection efficiency for the muon: about 30% of the pions will interact before the end of their range, so the overall detection efficiency will be:

$$0.7\times 0.5\times 0.06 = 0.02$$

For 500 Mev/c K mesons, 15% will decay in 50 cm;
Assume 2×10^4 K's/burst at 2 sec repetition;
Let F = fraction of K's decaying to $(\pi\mu\mu)$ then:

$$\text{Rate} = \frac{2\times 10^4 \text{ beam K/burst}}{2 \text{ sec/burst}} \times \frac{0.15 \text{ K decay}}{\text{beam K}} \times \frac{F(\pi\mu\mu)}{\text{K decay}} \times \frac{0.02 \text{ events}}{\pi\mu\mu}$$

$$= 30 \text{ F/sec.}$$

Hence for $\frac{K\to\pi\mu\mu}{K\to\pi\pi\pi} = 10^{-4}$, we expect

14 events/day.

Trigger rate from τ decay

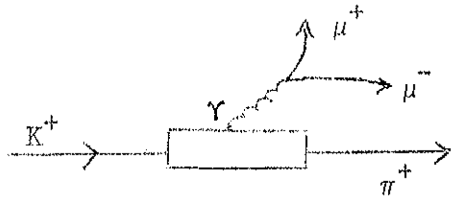
It is to reduce the trigger rate from this process that we have imposed a total range restriction. Figure 8 shows the values of the sum of the ranges of the three charged particles in the ideal case of Figs. 1 and 2. The minimum range which we accept, 'B' at 142 MeV/gm/cm^2 is the mass of two range chambers below the $\pi\mu\mu$ line. We see at once that we accept only those τ decays in which both pions have decayed to muons. Since these curves are for the ideal case, we have investigated how the total range varies with the energy partition. We have taken at random, pions between 50 and 150 MeV and muons between 30 and 200 MeV, keeping the total energy constant, and we find that the total range varies between 154 and 171 gm/cm^2 as indicated on Fig. 8. This means that we have to accept the area over AC of the curve $K\to 3\pi^{\pm}\to\pi\mu\mu$.

The mean distance from the beam to the range telescope is 80 cm, the mean decay length of the pions is 10 m and 10% of the cases where double decay occurs are accepted by our range selection; so the range selection gives an efficiency of 6.4×10^{-4} for τ decay. τ events in which all the pions decay give a small contribution to this rate.

Assuming that the solid angle for τ decay is the same as for $\pi\mu\mu$ we find a trigger rate from τ decay of 3.6 triggers/hour.

FINAL REMARKS

1) The process we want to look for $K^+ \rightarrow \pi^+\mu^+\mu^-$ has an intrinsic limitation which is dictated by the rate of occurrence of the same process via the production of the lepton pair through internal conversion of a virtual γ ray. This is illustrated in the following diagram.



According to Jackson[11] the order of magnitude for this rate, compared to the $K_{\mu 3}$ - decay rate is $\sim 10^{-8}$, thus giving us a factor one hundred with respect to the limit we wish to establish for the neutral current channel. Notice however that if μ-pairs would be detected, we could establish if their origin is "electromagnetic" or "weak" via the study of their longitudinal polarization, which has to be zero for the "electromagnetic" production.

2) We are studying the possibility of detecting the decay

$$K^+ \rightarrow \pi^+ \nu\bar{\nu}$$

which has no contribution from "internal conversion" of virtual gamma's and is therefore purely weak.

3) Two possible by-products of our experiment are:

i) the momentum distribution of the "unlike" pion in the K decay. (See appendix for details). This momentum distribution is related to the $\pi\pi$ interaction in the $J = T = 0$ state. Notice that we can do this with K^+ and K^- because our experiment is "in flight".

ii) the polarization of the μ^+ in $K^+_{\mu 3}$ decay; this polarization is a very good probe for the structure of the strangeness violating weak interactions.

APPENDIX

NOTE ON THE INVESTIGATION OF $\pi\pi$ INTERACTION IN τ DECAY

A) Accuracy $M^2 = E^2 - P^2$

$$M^2 = m_1^2 + m_2^2 + 2E_1E_2 - 2P_1P_2 \cos\Theta_{12}$$

so

$$dM = I/M \left(\sum_{\substack{i=1 \\ j\neq i}}^{2} \left(Ej - 2Pj\, \frac{Ei}{Pi} \cos\Theta_{ij}\right)^2 \Delta E_i^2 - (P_1P_2 \sin\Theta\, d\Theta)^2 \right)^{1/2} .$$

Try some numbers: say

$T_1 = 50$ MeV	$T_2 = 150$ MeV
$P_1 = 129$ MeV	$P_2 = 255$ MeV
$E_1 = 269$ MeV	$E_2 = 295$ MeV
$m_1 = 140$ MeV	$m_2 = 140$ MeV
$\Delta E = 4$ MeV	$\cos\Theta = 0.75$

Substituting: $dM = I/M(4^2 \times 700^2 + 4^2 \times 45^2 + 84^2) = .2800\ \text{MeV}^2/M$.

The value of M will be at least $m_1 + m_2 = .280$ MeV

Hence our resolution will be 10 MeV.

B) Rate If we put upper and lower limits on the total range discrimination, we can avoid triggering when the pions decay in flight. This reduces the efficiency to 77%.

Now we must identify the π^- by pulse height measurement at the end of the range. Only 12% of the pions stop in scintillators so the pion detection efficiency of the telescope is 9%. Hence the total rate of good events is 0.4/burst at a beam intensity of 2×10^4 K's/burst. If we do not use pulse height measurement in the counters, the trigger rate is 3/burst.

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11) Jackson - private communication.

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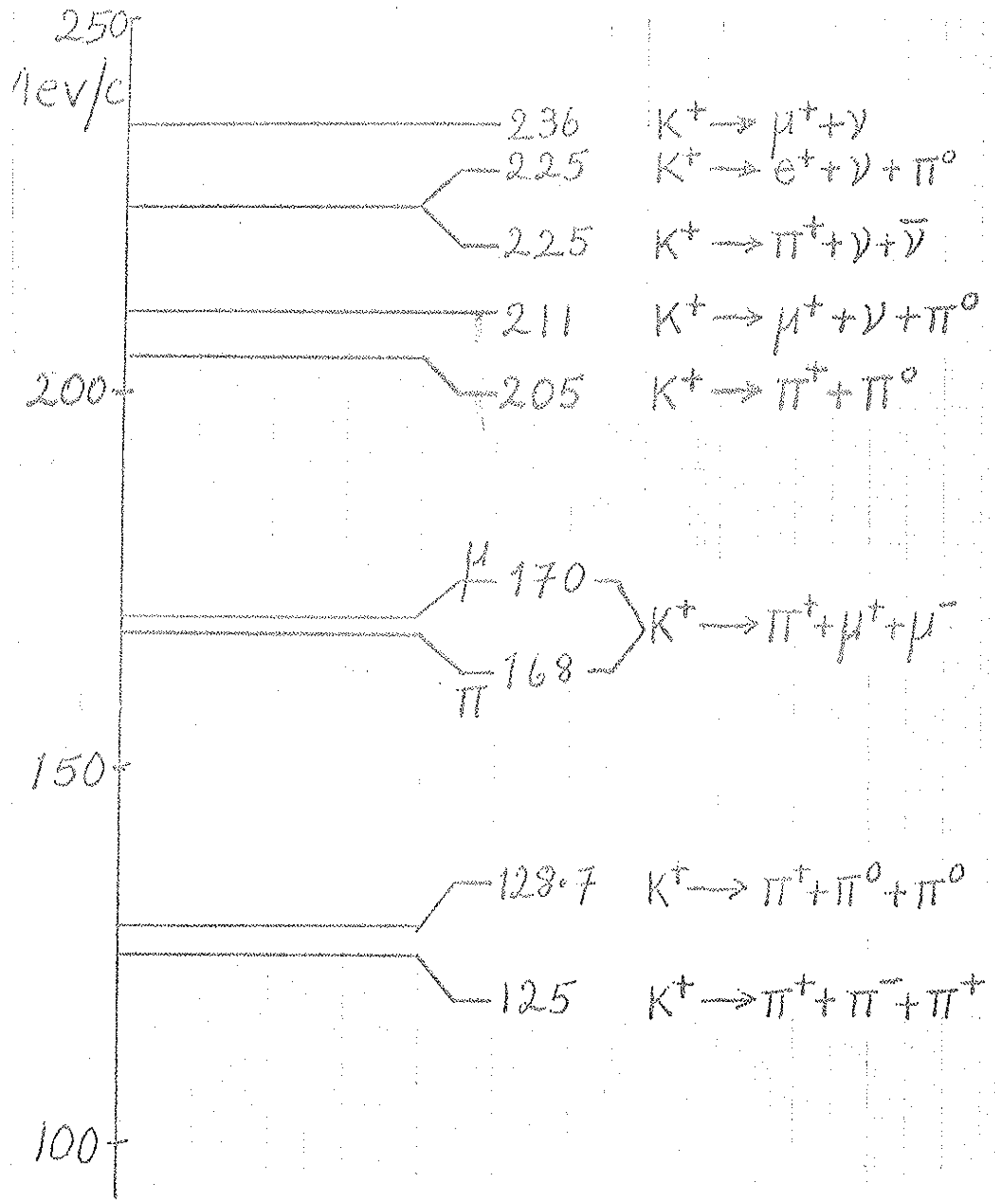


Fig 0 Showing the momentum (or end point momentum) of the charged particle in K^+ decay

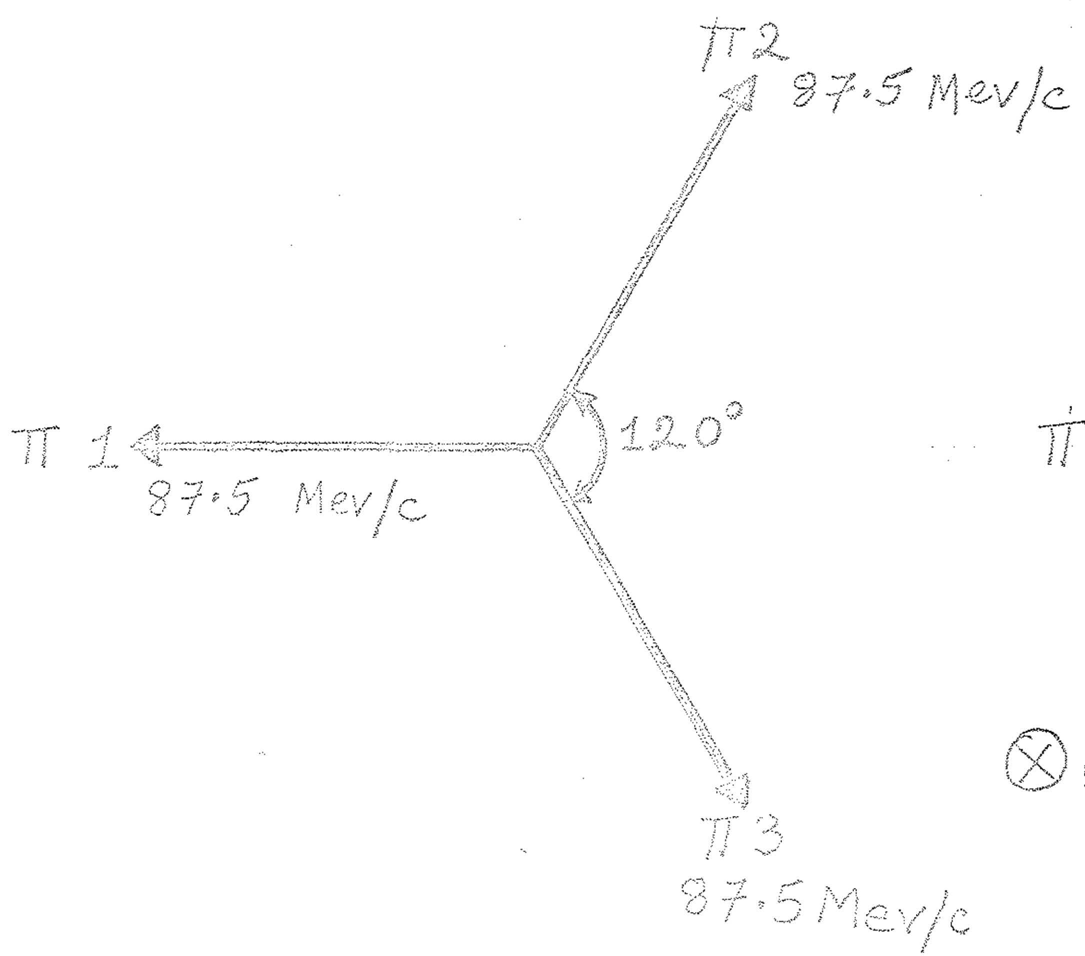


Fig 1

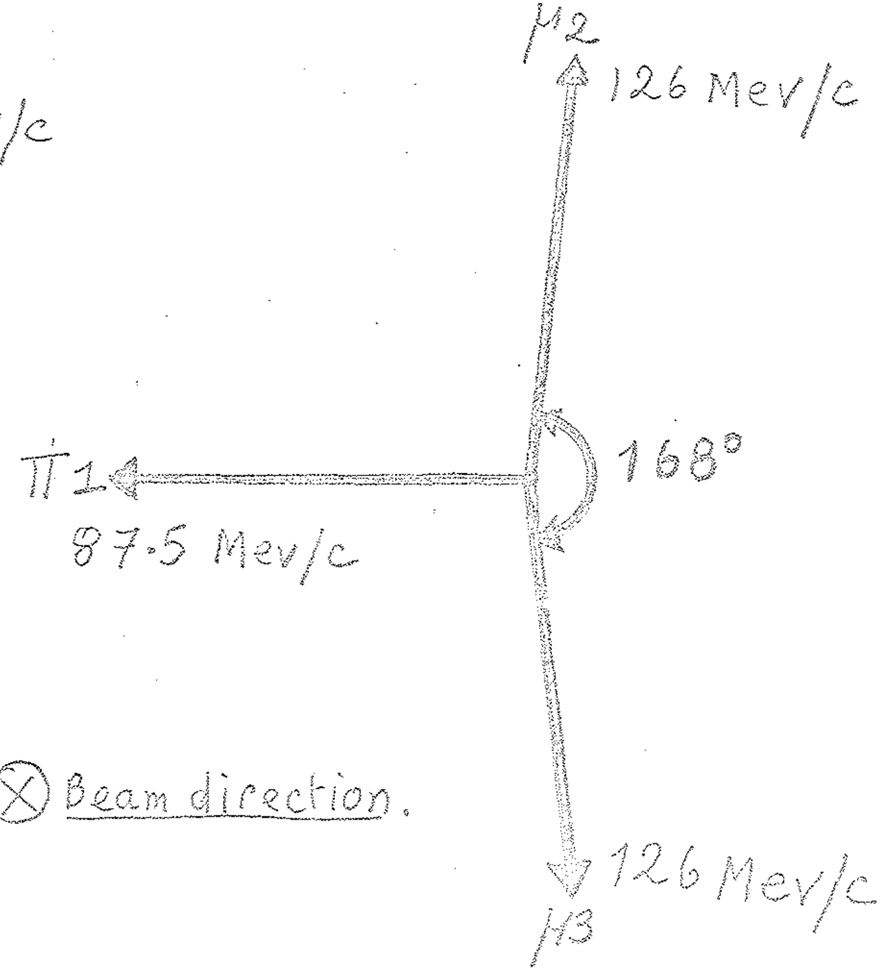


Fig 2

$K \to 3\pi$ and $K \to \pi 2\mu$ shown in the K system

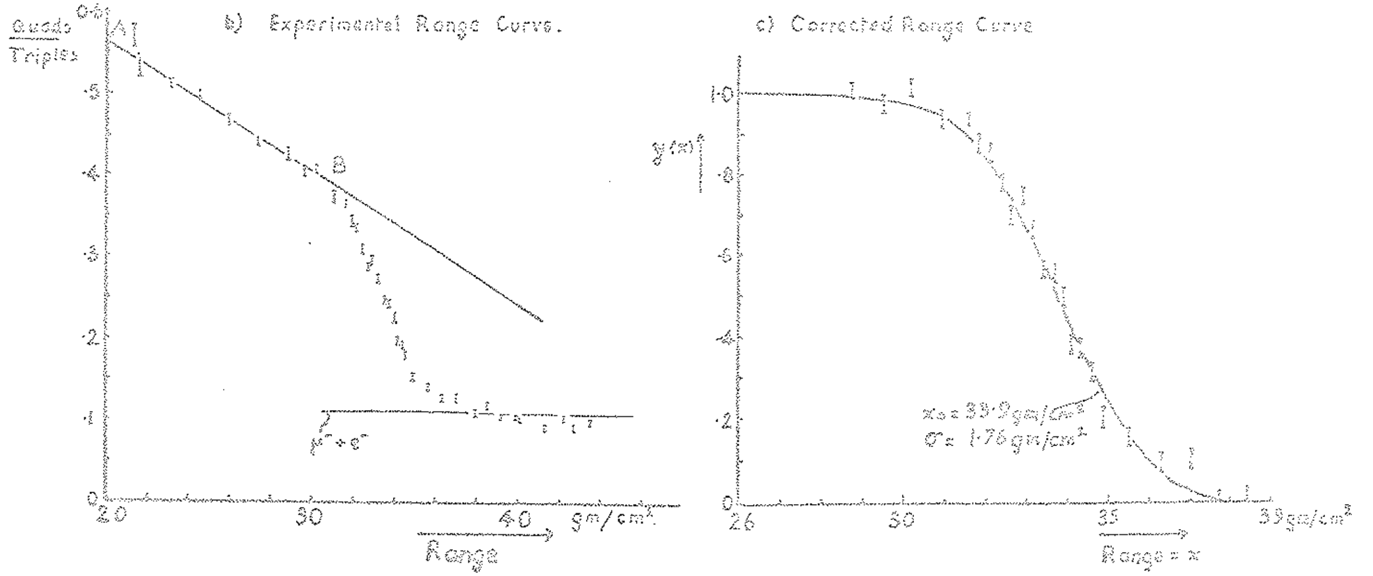
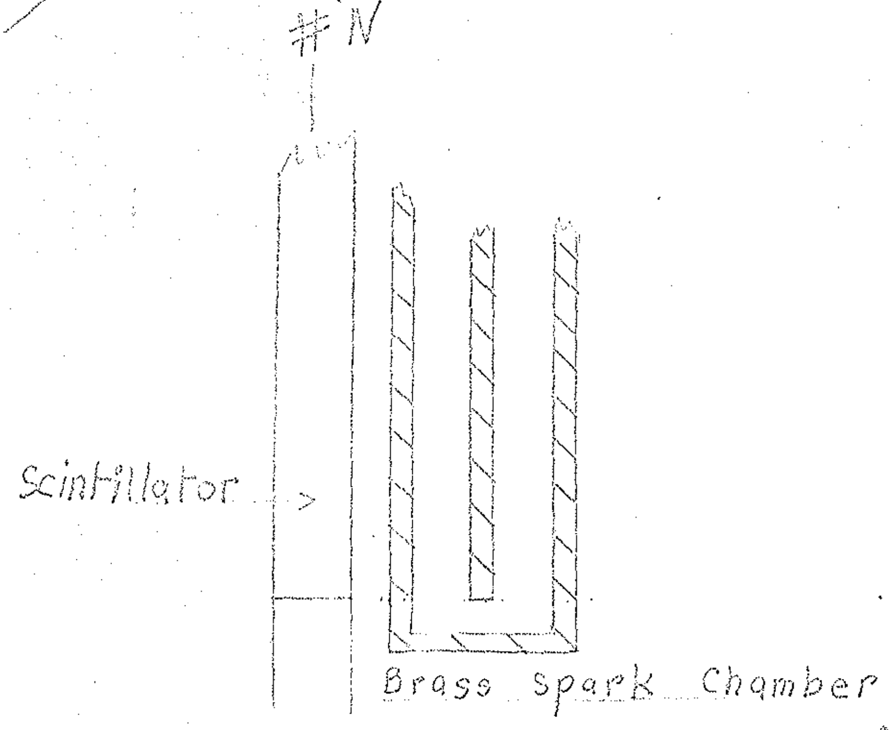
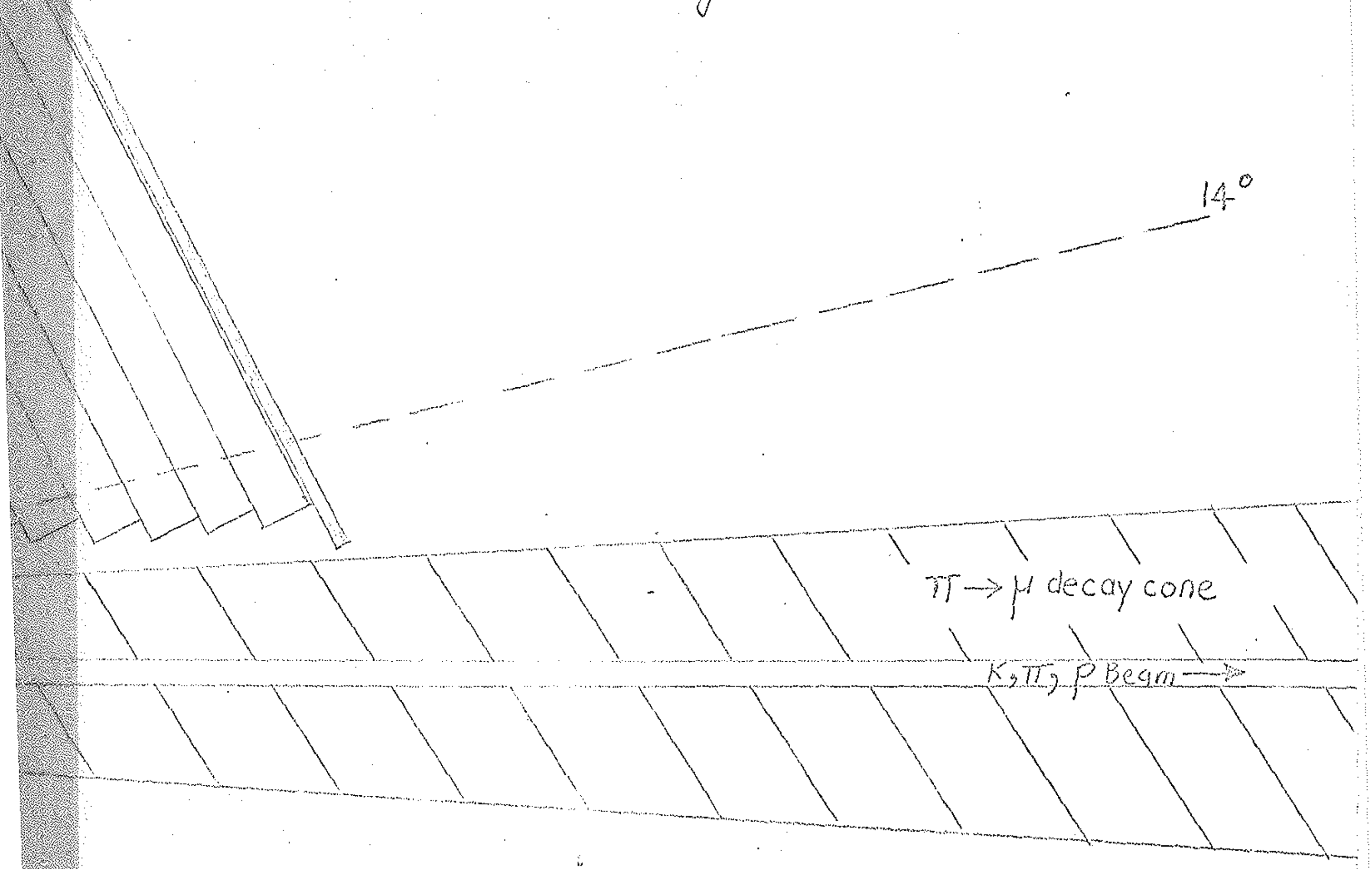


Fig 3. Range measurement in copper at 91·6 Mev.



Detail of range chamber N° 'N'. Scale 1/1



Scale 1/5

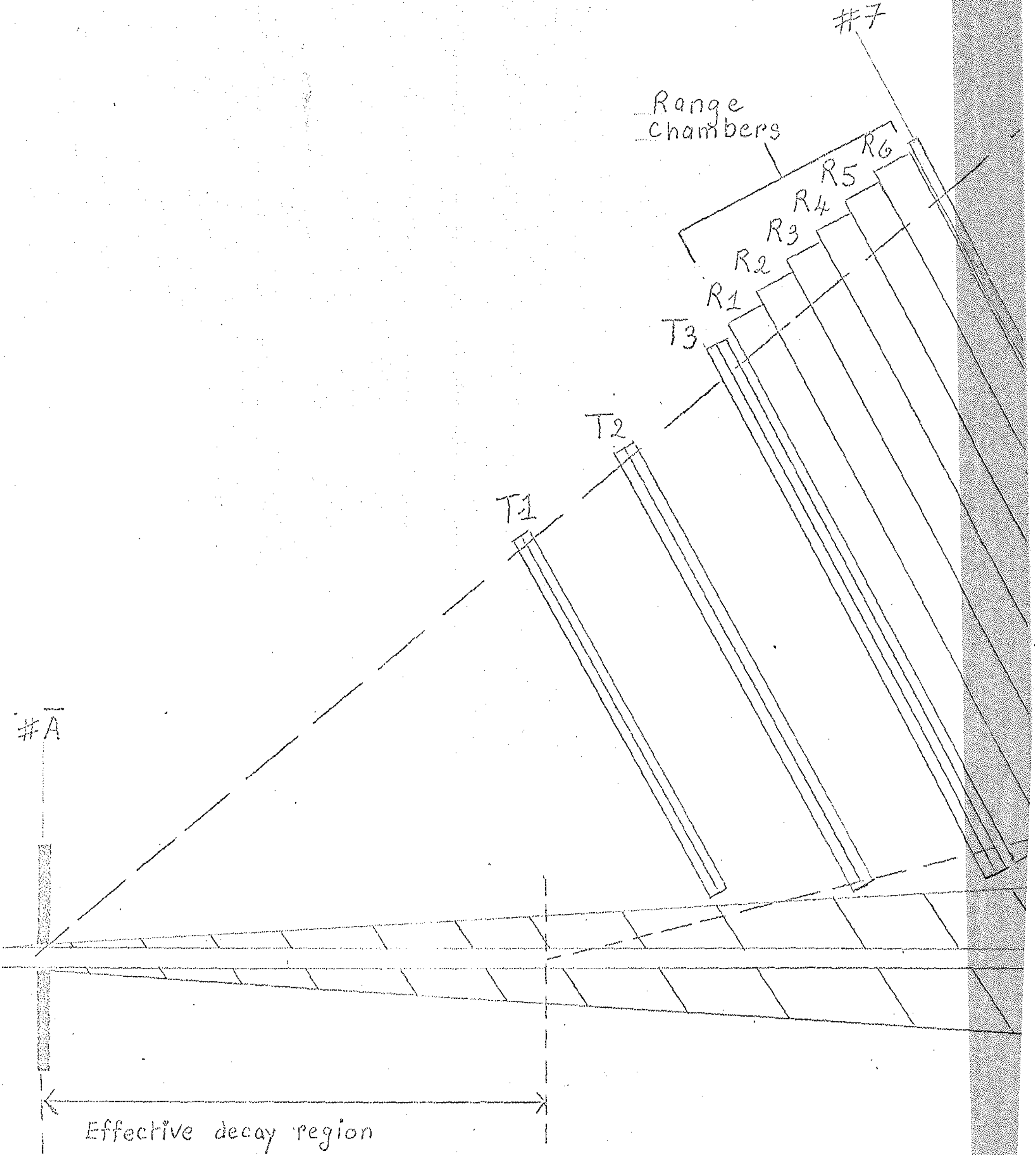
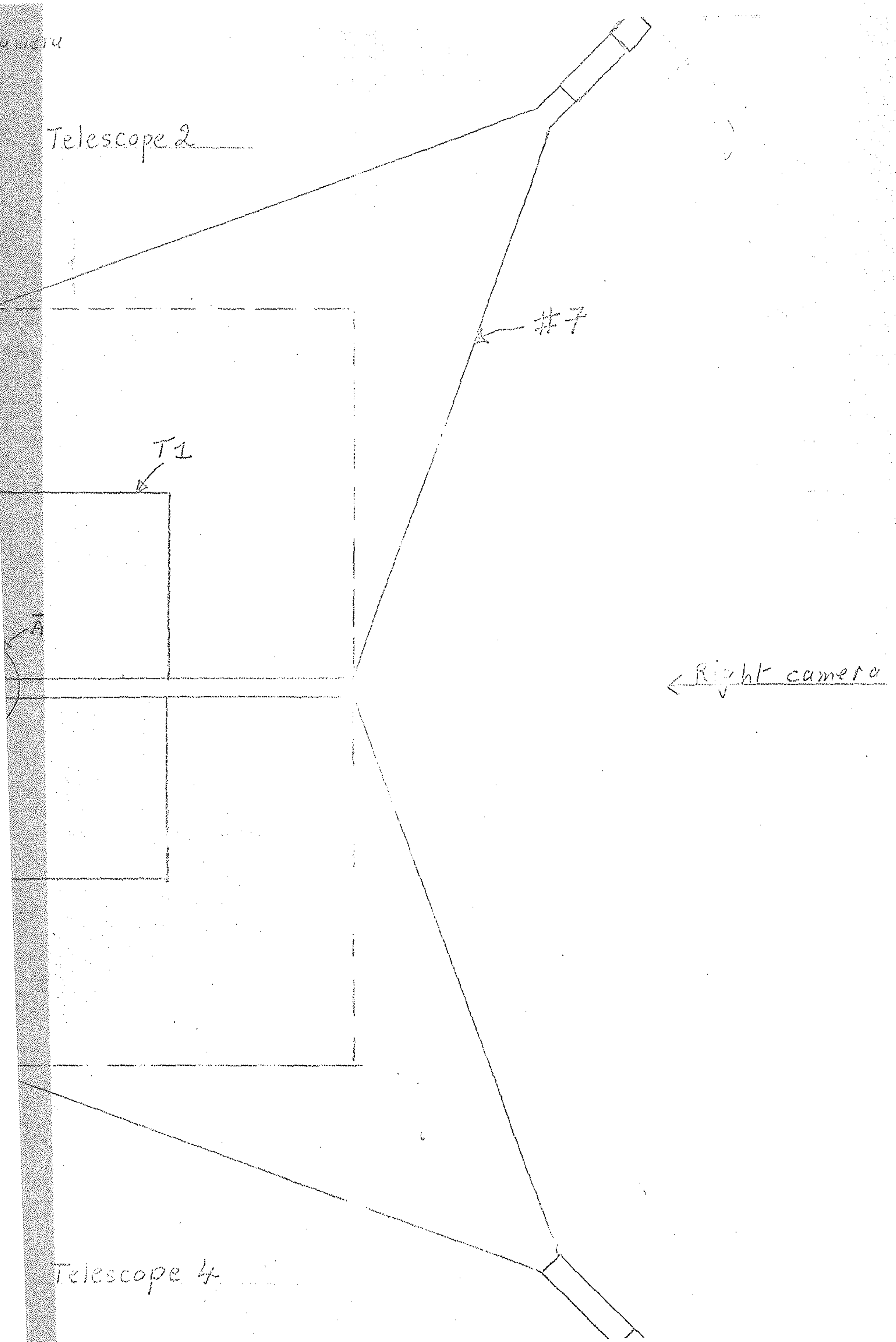


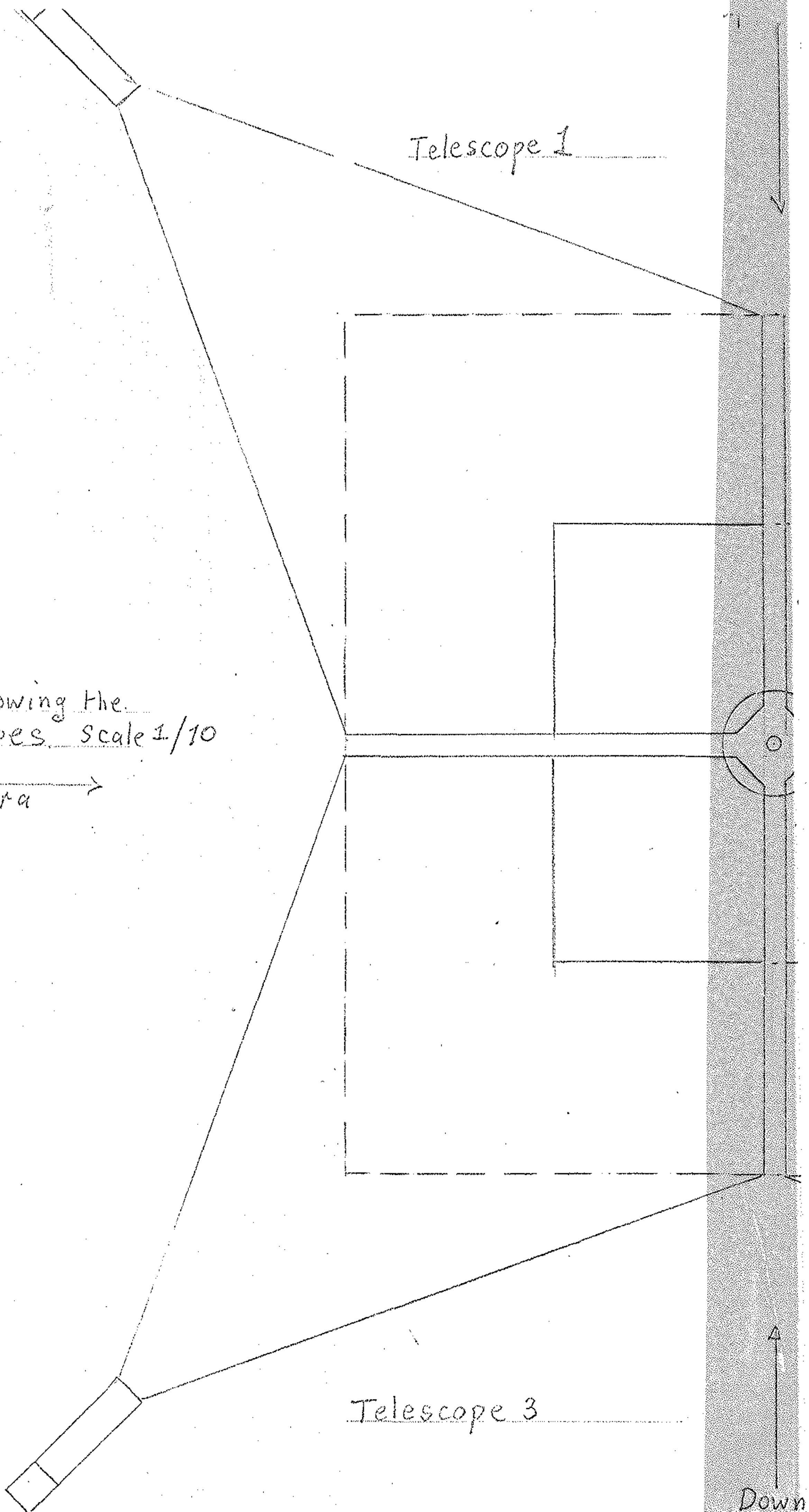
Fig 4

Side view of beam geometry and one of the telescopes

T are thin plate spark chambers.



Telescope 2
#7
T1
Right camera
Telescope 4



'Beam' view showing the four telescopes. Scale 1/10

Left camera

Fig 5

Fig 6 PHASE SPACE FOR PION IN $K^+ \to \pi^+ + \mu^+ + \mu^-$

----- MODIFIED BY ANGULAR ACCEPTANCE.

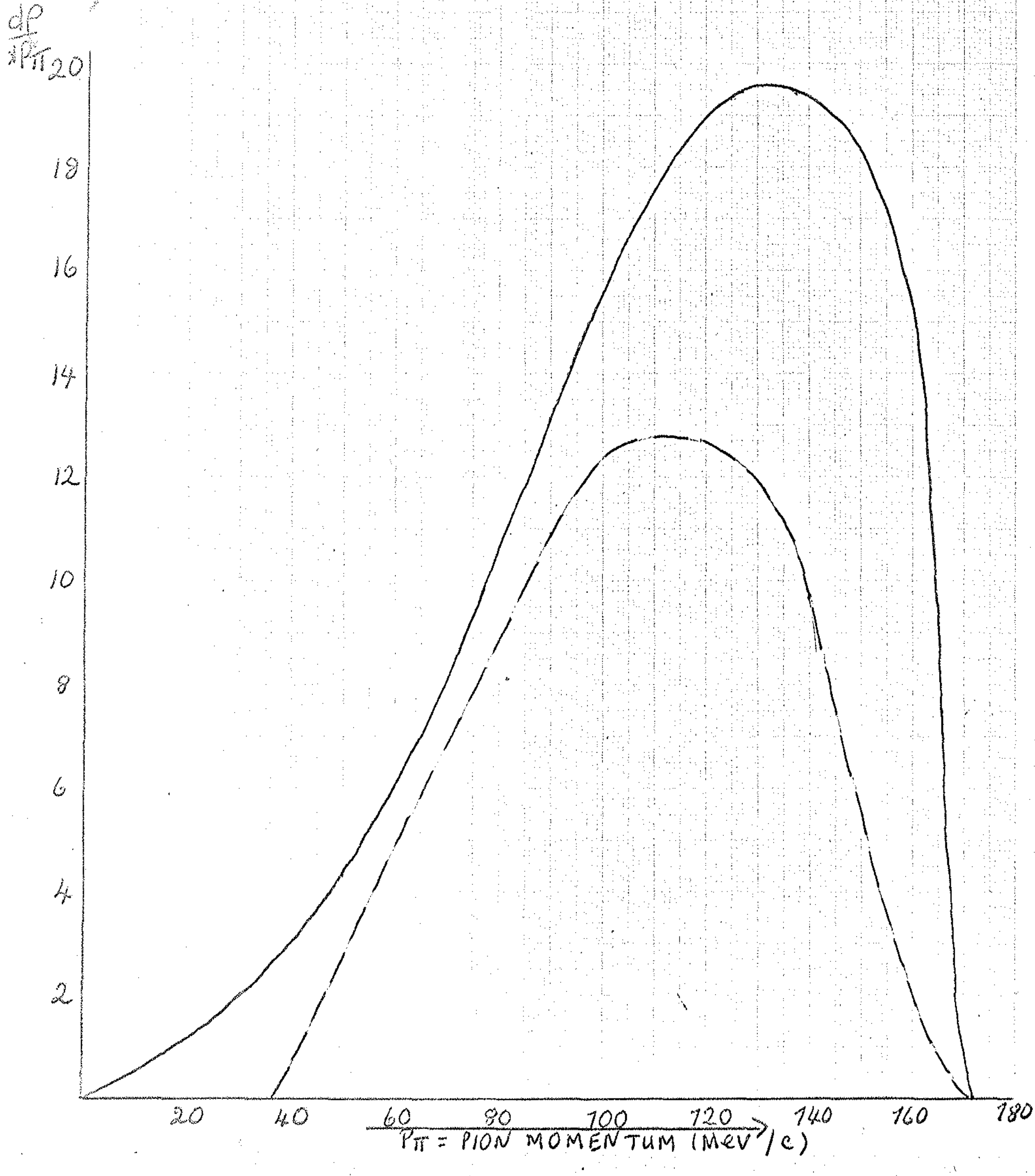


Fig 7. Showing θ_{LAB} as function of θ_{cm} for pions of 86 Mev/c ~~pions~~ in the K meson rest system.

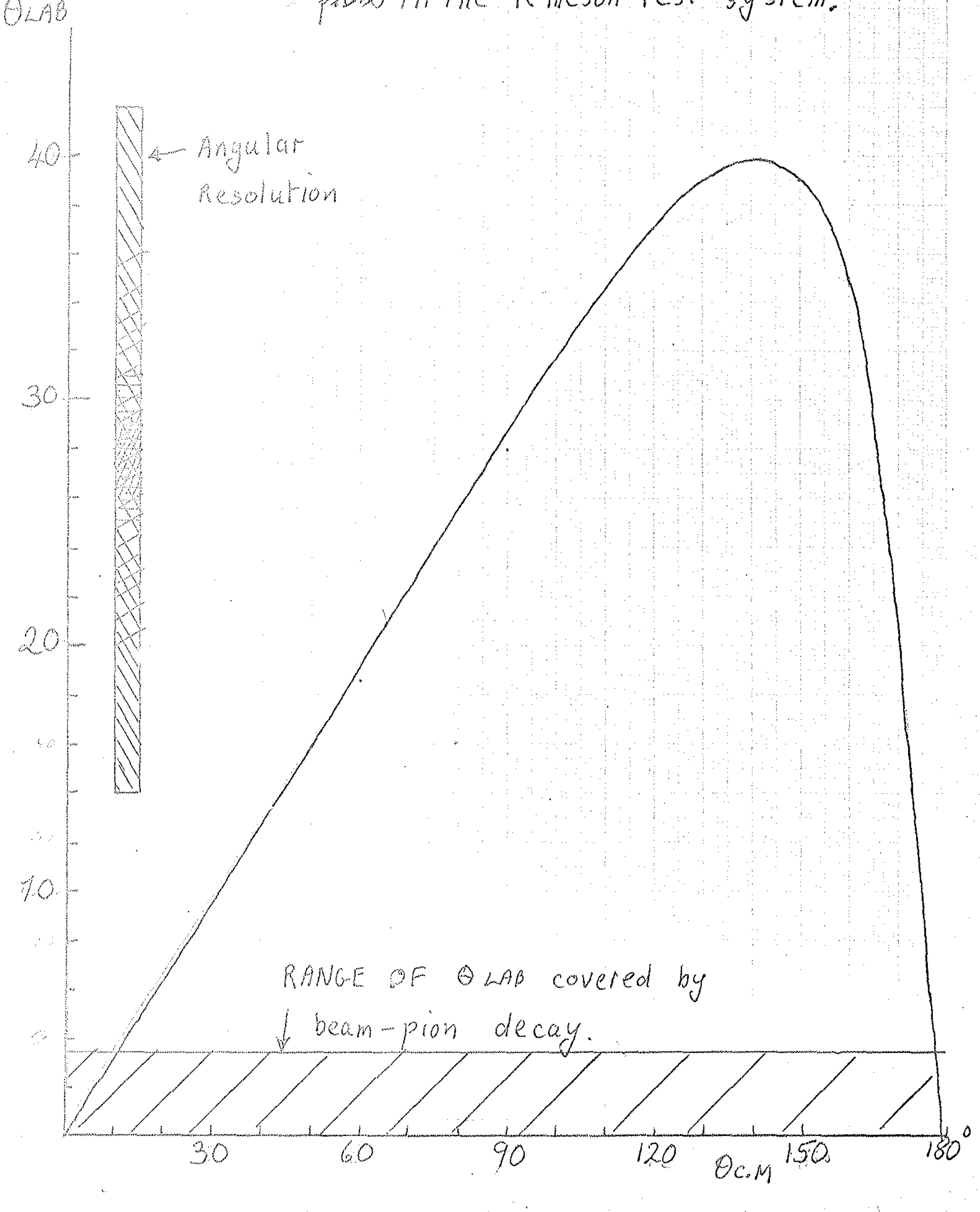


Fig 8 Showing the distribution of the sum of the ranges of the three detected particles.